

# BayesWavEx

*Returns you can trust.*

Efficient point cloud extraction from full waveform LiDAR data  
with automatic calibration and uncertainty computation

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QUICK DOCUMENTATION AS OF 9 / 6 / 2016

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BayesWavEx 1.0 (latest build) with LASlib 950605\*

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Questions and bug reports: email [support@bayesmap.com](mailto:support@bayesmap.com)

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- New users: visit [bayesmap.com/licensing](http://bayesmap.com/licensing) for information and to request a demo license.
- Existing users: please check your EULA for conditions and restrictions.

\* Based on LASlib V 150605 - LASlib with LASzip (c) 2007-2015 [martin.isenburg@rapidlasso.com](mailto:martin.isenburg@rapidlasso.com)  
Latest version: <http://www.lastools.org/download/LASools.zip>

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## What is BayesWavEx and what is it for?

This software package extracts 3D points from raw, full waveform LiDAR files. A rigorous approach helps get more points and more accurate results even at high altitude and in difficult cases with low vegetation. High throughput is achieved through the use of efficient algorithms and an optimized implementation.

WavEx is fully optimized to run on multi-core architectures using multi and hyper-threading. It is best run as a single process, not only parallel runs will not improve performance but they will affect the consistency of log files.

**Main features:**

- Ground extraction robust to peak contamination and overlaps due to low vegetation and noise
- Underground false alarm suppression using pulse shape (combining Gaussian return and system response)
- Automatic radiometric calibration (noise, background) and impulse response calibration
- Fast, accurate, rigorous waveform decomposition proprietary algorithm
- Ultra-fast extraction options for quick preview or when accuracy is not paramount
- Physically meaningful target attribute extraction (intensity, target thickness...)
- Range / attribute uncertainty attribute export options as LAS extra attributes
- Basic outlier filtering (high/low point elimination)
- Intensity correction options (incidence angle, range, atmospheric attenuation)
- No trajectory file needed (can be exported)

Please refer to the end of this document for common error messages (appendix A1), and current software requirements and limitations (appendix A2).

Should anything unexpected happen, please re-run with option `-ostat` to write all text outputs, send bug reports along with the text files, including the latest log files, to [support@bayesmap.com](mailto:support@bayesmap.com). Log files are in the output directory (or current directory if not specified); in case of crash they are still in the executable directory, with the archived ones.

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*Please note that this is not a manual, but a documentation listing all commands, options, inputs and outputs systematically. It might also be incomplete, we are doing our best to finish it up and keep it up to date.  
There will be a manual and tutorials, please check back on [bayesmap.com](http://bayesmap.com)!*

# 1. INTRODUCTION - THE BASICS

BayesWavEx is a command-line tool that requires a terminal (e.g. cmd or ConEmu on Windows, Terminal on Mac OS) or an external interface to be run. Currently it has no interface, so *double-clicking on the icon will not do anything*, as the software requires the user to select the input dataset and enter some optional parameters. Complex tasks can be achieved automatically with a simple command line. Good results can be achieved with default (missing) options in most cases so the command can be really very short. Commands can also be used in sequences in batch files, and invoked through high-level software interfaces.

## OPTIONS AND ARGUMENTS

|                                 |   |
|---------------------------------|---|
| <i>-n   name &lt;arg&gt;</i>    | option: short form n, long form name; argument <arg> (if any); options are case-sensitive |
| <i>Conventions</i>              | [] means optional,   means mutually exclusive, ... means multiple                         |
| <i>Argument syntax</i>          | -n<arg>, -n <arg>, -n=<arg>, -name <arg>, -name=<arg> equivalent                          |
| <i>Spaces</i>                   | Separate multiple arguments, or must be in "" if part of argument (file names etc.)       |
| <i>Missing boolean arg.</i>     | Equivalent to 1 (-n same as -n1)  |
| <i>Units</i>                    | Meters and decimal degrees, unless specified  |
| <i>Persistent option file</i>   | Text file stripalign.opt in exec. dir.; command-line options override persistent options. |
| <i>Persistent option syntax</i> | name=<arg> (only form accepted), one per line, "" not necessary, see example below.       |

## GENERAL OPTIONS

### Directory

|                              |  |
|------------------------------|--|
| <i>-I   idir &lt;dir&gt;</i> | Set input directory (unless explicit path is given) [default: current] |
| <i>-O   odir &lt;dir&gt;</i> | Set output directory [default: current]                                |

### Processing

|                                |  |
|--------------------------------|--|
| <i>-mem &lt;MB&gt;</i>         | Memory made available to the program in MB [default: 1024]         |
| <i>-N   nthreads &lt;n&gt;</i> | Max number of simultaneous threads [default: depends on processor] |

### Behavior

|                               |  |
|-------------------------------|--|
| <i>-q   quiet &lt;0 1&gt;</i> | Quiet mode, no text output, no progress bar [default: 0] |
| <i>-progress &lt;0 1&gt;</i>  | Display progress bar [default: 1]                        |

### LiDAR input/output

|                                |  |
|--------------------------------|--|
| <i>-i   input &lt;name&gt;</i> | Input file name (only LAS 1.3 waveform currently supported)                                      |
| <i>-o   out &lt;name&gt;</i>   | Output file name (LAS/LAZ 1.2) and base name for text outputs [default: out.laz]                 |
| <i>-oext &lt;0 1&gt;</i>       | Write extended LAS point attributes (amplitude, width etc.) [default: 1]                         |
| <i>-ounc &lt;0 1&gt;</i>       | If -oext activated, write uncertainty attributes (for amplitude, width, range etc.) [default: 1] |
| <i>-nil</i>                    | Disable output [default: 0]  |

### Logs and text output

|                           |   |
|---------------------------|---|
| <i>-log &lt;0 1&gt;</i>   | Logs high-level operations, keeps history in exec. dir., latest in output dir. [default: 1] |
| <i>-olog &lt;0 1&gt;</i>  | Leaves a copy of the latest log files in the output directory [default: 1]                  |
| <i>-clear_log_history</i> | Clear log history from exe directory  |
| <i>-ostat &lt;0 1&gt;</i> | Write statistics text file, one row per scanline [default: 0]                               |
| <i>-otraj &lt;0 1&gt;</i> | Compute and write trajectory text file [default: 0]   |

### Information

|                     |   |
|---------------------|---|
| <i>-h   help</i>    | Display brief documentation about general options |
| <i>-?   options</i> | Display the list of available options             |
| <i>-v   version</i> | Display the version and license information       |

## PROCESSING COMMANDS AND PARAMETERS

### Speed-up

[default: iterative refinement, optimal speed]  
-f | fastest <O1> Fastest processing, no iterative refinement [default: 0]  
-s | fastsep <O1> Fast processing (no iterative refinement) if separated peaks (no overlap) [default: 0]  
-a | auto <O1> Fast options (-f or -s) only:  
enable iterative refinement if deviation exceeded or overlap detected [default: 0]  
-slow <O1> Slower iterative refinement when enabled (more iterations, better convergence) [default: 0]

### Extraction

-d | det <T> Detection threshold in noise std.dev. units [default: 4.5]  
-min\_width <w> Keep only returns with minimum width, in impulse response FWHM units [default: 0.8]  
-max\_width <w> Keep only returns with maximum width, in impulse response FWHM units [default: 10.0]  
-out\_min\_a <a> Minimum angle with neighbor points for outlier rejection [default: 2.0]  
-out\_max\_h <h> Maximum height difference for outlier rejection [default: 30.0]

### Intensity correction

-F | icorr\_flat <O1> Shading correction assuming flat terrain [default: 1]  
-R | icorr\_range <r0> Range-based correction using reference range r0 [default: disabled]  
-A | icorr\_atm <a> Atmospheric attenuation correction, a in dB/km [default: disabled]

### Timing correction

-dt <x> Add x to estimated roundtrip time interval (unit: ns) [default: 0.0]  
-odd\_dt <x> Shift odd samples by x sampling units (useful for some digitizers) [default: 0.0]  
-t\_err <x> Set the minimum system timing error (unit: ns) [default: 0.01]

## EXAMPLE USAGE

```
> wavex -i waveform.las -o points.laz -fastest
```

extracts a point cloud in LAZ format named points.laz from input file waveform.las, using fastest algorithm (no refinement, but uncertainties are computed and exported along all other extra attributes); a calibration step is run prior to the extraction, so that noise and background parameters, as well as the impulse response, are estimated.

```
> wavex -i waveform.las -o points.laz -fastsep -traj -stat
```

same with trajectory export (file points\_traj.txt) and scanline statistics export (file points\_stat.txt); the fastest algorithm is used only if peaks are not overlapping, otherwise iterative refinement is used; slower than previous command but more accurate when peaks are not well separated.

```
> wavex -i waveform.las -o points.laz -I F:\\indir -O E:\\outdir -ounc 0
```

same but accurate refinement is used for all waveforms regardless of peak overlaps (default); input and output directories are specified; uncertainty extra attributes are not exported to the output file; slower than the two previous examples but also most accurate, even for isolated peaks especially when widening is significant.

```
> wavex -v
```

displays the version and license information.

```
> wavex -h
```

displays a basic documentation (general options and processing commands above).

## PERSISTENT OPTION FILE EXAMPLE (wavex.opt)

```
mem=4096  
det=5  
R=1000
```

## 2. OUTPUT FILE FORMAT

This section describes the format of the output file and optional text outputs.

### LIDAR POINT CLOUD (LAS/LAZ 1.2)

Depending on options `-oext` and `-ounc` (on by default) the following **extra attributes** are exported.

| <i>Name</i>             | <i>Description</i>               | <i>Scale</i> | <i>Offset</i> | <i>Type</i>    | <i>Bytes</i> |
|-------------------------|----------------------------------|--------------|---------------|----------------|--------------|
| <b>Widening</b>         | Pulse widening (%)               | 0.020        | 1.000         | unsigned char  | 1            |
| <b>Target Thickness</b> | Target thickness (m)             | 0.008        | 0.000         | unsigned char  | 1            |
| <b>Amplitude</b>        | Target amplitude                 | 1.000        | 0.000         | unsigned short | 2            |
| <b>Raw Amplitude</b>    | Raw return pulse amplitude       | 1.000        | 0.000         | unsigned short | 2            |
| <b>Deviation Ratio</b>  | Residual-Noise, Chi2 stddev unit | 0.050        | 0.000         | unsigned char  | 1            |
| <b>Range Error</b>      | Range std. dev. (m)              | 0.001        | 0.000         | unsigned char  | 1            |
| <b>Intensity Error</b>  | Corrected intensity std. dev.    | 0.200        | 0.000         | unsigned char  | 1            |
| <b>Widening Error</b>   | Pulse widening std. dev. (%)     | 0.002        | 0.000         | unsigned char  | 1            |
| <b>Thickness Error</b>  | Target thickness std. dev. (m)   | 0.001        | 0.000         | unsigned char  | 1            |

The **user data** byte contains information specific to the fitting algorithm for each waveform.

Bits 0-5 number of iterations if iterative refinement was used (0 if not used)

Bit 6 peak overlap detected

Bit 7 second refinement was necessary

Currently points having a deviation ratio larger than 3 are assigned **class 20** (undefined) and other points are left unclassified.

All other attributes are copied from the original file (scan angle, direction etc.).

### TRAJECTORY FILE

The estimated trajectory is stored as a text file with each row as follows:

gps\_time X Y Z

The timing information is in the same format as the LiDAR file and X Y Z are in the same coordinate system.

### SCANLINE STATISTICS FILE

The scanline extraction statistics are stored as a text file, with each row corresponding to one scanline, as follows:

gps\_time n\_waveforms n\_points n\_empty n\_filtered n\_merged n\_refined n\_air n\_low n\_range n\_atm

The timing information is in the same format as the LiDAR file.

The other numbers are respectively: waveforms read, final points extracted, empty waveforms (no valid returns), deleted invalid returns, merged returns, refined returns (using accurate iterative algorithm), deleted air points, deleted low points, range-corrected points, atmospheric attenuation-corrected points.

### 3. PROCESSING PARAMETERS AND EXAMPLES

More details about processing options are given in this section. Scanner-specific examples are given. More will be added in the future.

#### EXTRACTION PARAMETERS

##### Detection threshold (-det)

The parameter specified by -det is crucial, as the false alarm rate and the missed return rate depend on it. If an efficient point cloud filtering software is available it is recommended to set the threshold to a low value (4 sigma or less), so no returns will be missed, and the high number of false alarms (mostly low points, just a few meters below ground) will be filtered after extraction. Otherwise, we recommend setting a value of 4.5 or 5 sigma to keep a false alarm rate below 1/10000; in this case faint ground returns under vegetation might be lost. Here sigma stands for the noise standard deviation ratio (estimated automatically, as well as the correlation coefficient). A Gaussian, signal-independent noise model is assumed.

There is no simple rule giving the false alarm rate as a function of the threshold, since digitizer noise is correlated. The software takes into account this correlation for uncertainty estimation but the choice of the detection threshold is left to the user. Tables giving false alarm rates depending on threshold and correlation will be added here.

##### Minimum width of detected pulse (-min\_width)

The pulse minimum width is specified with respect to the system impulse response FWHM (estimated automatically). Due to noise, and to the variability of the impulse response function in real world digitizers, this minimum width should not be set to 1 otherwise peaks may be lost. However, a low value such as 0.2 would allow more false alarms, as peaks much narrower than the system response are very unlikely to occur. It is recommended to keep the default value (0.8) for most systems, and lower it to 0.5 for digitizers having an amplitude-dependent impulse response, (usually wider at higher amplitudes so that the estimated function is too wide for small peaks and the minimum width threshold filters out good peaks). Leica ALS-50 digitizers tend to behave this way.

##### Outlier rejection parameters (-out\_min\_a and -out\_max\_h)

Nearest neighbors in the scanline are considered when performing outlier (low or high point) filtering. Only points having a height jump over max\_h compared to both neighboring points will be rejected (and counted as low points if they are more than max\_h below the neighbors, or high points if they are more than max\_h above the neighbors).

The rejection happens only if the angle formed by the point and its two neighbors is below min\_a (very acute triangle). Default values should be used, unless there is no power line (in that case max\_h can be lower), in that case the maximum tree height should be considered. Default parameters are set to minimize data loss, and further filtering (e.g. ground filtering, classification) can be performed by other software.

#### EXAMPLES USING UNUSUAL PARAMETER VALUES

```
> wavex -i titan_C3.las -o points.laz -odd_dt -0.25
```

extracts points from Optech Titan data (NIR channel), using certain digitizers that need odd samples to be shifted by 1/4 of sample to avoid certain artifacts; -dt can also be used to add an extra time shift to all measured time differences and avoid range biases.

```
> wavex -i LDR100301_120340_4.LAS -o points.laz -min_width 0.5
```

extracts points from a 2010 NERC-ARSF sample dataset obtained with a Leica ALS50v2 scanner, which has a slightly amplitude dependent impulse response, such that peaks are narrower when lower; this requires the minimum peak width filtering to be less aggressive otherwise the faintest returns are lost.

## **A1. COMMON ERRORS MESSAGES, CAUSE, SOLUTION**

### **Nothing happens when I click on the icon...**

Cause: normal behavior, this is a command-line software

Solution: run wavex in a terminal window (cmd, conemu, etc.), please read the documentation!

### **Executable not starting properly, no error message**

Cause: antivirus software (e.g. Avast) may be blocking, or sandboxing "unsafe" or "unknown" executables

Solution: whitelist the application, or exclude the directory from scanning - please do not submit it to any virus scanning website, and use your antivirus to scan it instead.

### **The application was unable to start correctly (0xc000007b)**

Cause: missing or incompatible DLLs (Visual C++ Redistributable Packages for Visual Studio)

Solution: go to [www.microsoft.com/en-gb/download/details.aspx?id=40784](http://www.microsoft.com/en-gb/download/details.aspx?id=40784) and follow the instructions

### **ERROR: stopping due to option argument errors (use -h for help)**

Cause: some options have wrong argument types, or arguments are missing

(unknown options will NOT cause errors)

Solution: check previous error messages and supply correct arguments

### **ERROR: missing waveform file...**

Cause: no valid command arguments found, or no arguments given, or no input file name given

Solution: use option -i to specify an input file, or -clear\_log\_history to delete stored log files

### **ERROR: no waveforms in point data format x...**

Cause: LAS data format x can only store points, not waveforms.

Solution: provide a valid LAS 1.3 full-waveform file (point data formats 4 and 5)

### **ERROR: radiometric waveform calibration failed**

Cause: if none of the above errors, then there was not sufficient information in the file to run the calibration

Solution: provide a larger file, at least 100000 waveforms

## **A2. CURRENT LIMITATIONS**

- Input: LAS 1.3 FWF (full waveform) only
- Output: LAS/LAZ 1.2 with extended attributes (no LAS 1.4 due to LAZ incompatibility)
- Due to output limitations, number of returns and return number may be encoded incorrectly
- Fixed impulse response (amplitude independent), might not be rigorous for all scanners
- Automatic Gain Control causes artifacts on intensity/amplitude, gain information not available in LAS format
- Amplitude and range correction tables implemented but cannot be imported (yet)
- No manual calibration parameter or impulse response input, always automatic
- Outlier rejection method basic, depends on neighbor waveforms in same scanline, no ground model (yet)
- Single file processing, must use batch file to process multiple files sequentially
- Hard surfaces only! no bathymetric LiDAR modeling

## **A3. PLANNED FEATURES**

- Input: add PulseWaves reading capability to solve some of LAS 1.3 FWF limitations
- Output: add LAS 1.4 (uncompressed)
- Output: add LAZ 1.4 whenever it becomes available
- Take into account impulse response dependence on amplitude
- Plug in our model-based outlier rejection algorithm