BayesWavEx

Returns you can trust.

Efficient point cloud extraction from full waveform LiDAR data with extended attributes and uncertainty computation

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QUICK DOCUMENTATION AS OF 4/30/2022

BayesWavEx 1.3 build 5/2/2022

LASlib 210720* / PulseWaves 190805** / RiVlib 2.5.10***

The use of this software subject to licensing:

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

What is WavEx and what is it for?

This software package extracts 3D points from raw, full waveform LiDAR files. It can also georeference raw point clouds from online waveform scanners, and resolve MTA ambiguities.
A rigorous Bayesian approach to waveform decomposition 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 makes use of multi-core architectures (multi and hyper-threading) and is fully cloud compatible.

New features (version 1.1):

- Direct decoding of Riegl SDF files (compatible with 560, 680, 780 and 1560 scanner series)
- Single pass decoding, processing, georeferencing and LAS/LAZ/ASCII file generation
- Automatic MTA (multiple times around) resolution
- Advanced waveform modeling and optimal pre-calibrated sensor parameters
- Automatic amplitude-based range, amplitude and width corrections
- Channel fusion and pulse ordering

New features (version 1.2):

- Linux version available
- Georeferencing Riegl SDC point clouds
- Georeferencing Riegl RXP point clouds with auto MTA (Linux and Windows only) in parallel
- PulseWaves export from Riegl SDF waveform files, optional outgoing waveforms
- Filtering options: line and point subsampling, first and last returns
- Swath footprint, center polyline and point cloud transect export (ASCII)
- Atmospheric corrections using file with parameters at flight altitude

New features (version 1.3):

- Advanced MTA resolution algorithms compatible with high PRR (1-2 MHz)
- Automatic cloud/fog detection and noise filtering
- Improved outlier filtering and classification
- Auto split according to scan direction for circular and elliptical scanners
- Process multiple RXP or SDC files from the same mission in parallel

Main features:

- Ground extraction robust to overlaps due to low vegetation and noise (waveform)
- Underground false alarm suppression using pulse shape (impulse response calibration option) (waveform)
- Fast, accurate, rigorous waveform decomposition proprietary algorithm (waveform)
- MTA range ambiguity resolution compatible with high pulse frequencies
- Ultra-fast extraction options for quick preview
- Physically meaningful target attribute extraction (intensity, thickness, widening) (waveform)
- Uncertainty attribute export options as LAS extended attributes (LAS/LAZ 1.4 compatible) (waveform)
- Basic outlier filtering (high/low point flagging, low density point flagging with MTA resolution)
- Intensity correction options (incidence angle, range, atmospheric attenuation)

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*. 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.

Please note that this is not a manual, but a documentation listing all commands, options, inputs and inputs systematically. . There will be a manual and tutorials, please check back on bayesmap.com!

1. INTRODUCTION - THE BASICS

WavEx 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.

INSTALL INSTRUCTIONS

All platforms

- Create a folder and put the **executable** file [and persistent option file] in it
- Create a **Geoids** folder in the same location as the executable and download only the needed geoids
- Floating license: set up the **RLMUSER** and **RLMPW** environment variables using your credentials, or set them directly on the command line on linux/mac only (RLMUSER=x RLMPW=y wavex ...)
- Update the **PATH** environment variable to include the new software location
- *Repeat if planning to run multiple instances in parallel; symbolic links can be used, pointing to the first install files, making updates easier and avoiding duplicating geoid data.*

Windows

- Put the **LASlib** DLL in the same folder as the executable
- If needed (error message 0xc000007b), install the Visual C++ Redistributable Packages for Visual Studio: https://www.microsoft.com/en-us/download/details.aspx?id=53587

Linux

- Put the **LASlib** and **PulseWaves** libraries in **/usr/local/lib** and run **sudo ldconfig**
- Install **libjpeg** or **libtiff** or **libcurl** if not already installed
  (Ubuntu: use **sudo apt-get install libjpeg9 libtiff5 libcurl4-openssl-dev**)

OPTIONS AND ARGUMENTS

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

GENERAL OPTIONS

Directory

-I l idir <dir>	Set input directory (unless explicit path is given) [default: current]
-O l odir <dir>	Set output directory [default: current]

Processing

-mem <MB>	Memory made available to the program in MB [default: 1024]
-N l nthreads <n>	Max number of simultaneous threads [default: depends on processor]
-mul	Allow multiple instances (useful for I/O limited processing) [default: 0]

Behavior

-q l quiet	Quiet mode, no text output, no progress bar [default: 0]
-progress	Display progress bar [default: 1]

LiDAR input

-i l input <files>	Input file names (SDF/LAS/PulseWaves waveforms, SDC and RXP point clouds)

LAS/LAZ output

-o l out <str>	Output naming convention and extension [default: laz, same base name as input] *Use prefix*suffix.ext to specify custom name and format, eg. -o*_ex.las*
-oparse <str>	Use the column format parse string for ASCII output, as defined in las2las [link]
-oext	Write extended LAS point attributes, main [default: 1]
-oext2	Write extended LAS point attributes, secondary [default: 0]
-ounc	Write uncertainty attributes for waveform data only [default: 0]
-olax	Write LASindex file, appended or separate file (see next option) [default: 0]
-lax_append	Append LASindex data to LAS/LAZ output [default: 0, separate file]
-split	Split according to scan direction (RXP input, circular scanners only) [default: 0]
-nil	Disable LiDAR data output [default: 0]
-o12	Set the LAS/LAZ version to 1.2 [default: 0, version 1.4]
-id <n>	Set the File Source ID LAS header field and all LAS point source ID [default: 0]
-inc_id <n>	ID increment for multiple file input (ID, ID+n, ID+2n...) [default: 1]
-ch <n>	Override channel info (LAS scanner channel attribute) [default: from LO/HI]
-guid_1 <hex string>	Set the Project ID - GUID data 1 LAS header field, compatible with lasinfo [default: 0]
-scale_xy <float>	Set the horizontal scale factor or discretization step [default: 0.01]
-scale_z <float>	Set the vertical scale factor or discretization step [default: 0.01]

PulseWaves export *waveform only*

-opls	Export PLS/WVS PulseWaves files (uncompressed) [default: 0]
-oplz	Export PLZ/WVZ PulseWaves files (compressed) [default: 0]
-outgoing	Export outgoing pulse [default: 0]
-out_sub	Subsample outgoing pulse by factor 2 if exported [default: 0]

Logs and text output

-log	Leave a copy of the latest log files in the output directory [default: 1]
-log_flush	Empty log file buffer after each write to help debugging [default: 0]
-clear_log	Clear log history from exe directory
-llog	Write scanline statistics and other info to log file, or to _rxp.log for RXP input [default: 0]
-olstat	Write statistics text file, one row per scanline [default: 0]
-osdfstat	Export misc. histograms and stats with base name set by -name [default: 0]
-name	Set name for debug info and SDF histograms and stats [default: out]

Footprint and transect text output

-fp	Generate footprint polygon text file [default: 0]
-ct	Generate center polyline and transect point clouds text files [default: 0]
-ct_sa <float>	Set the scan angle limit for the center transect [default: 0.05 deg]
-poly_sub <n>	Set the scanline subsampling factor for footprint and center polygons [default: 10]
-obj	Output footprints in .obj format [default: 0]

Information

-h l help	Display brief documentation and usage examples
-v l version	Display the version and license information

Scan/dump commands

-scan	Scan beginning of files and determine which files sync with PO file
-sdfscan	Scan SDF file and output basic stats, waveform checking
-sdfscanfast	Faster SDF scan, get time interval and count records, waveform decoding disabled
-dump_wav	Dump PulseWaves waveforms as one point per sample to las/laz 1.2
-dump_max	Dump PulseWaves max location for all waves to las/laz 1.2
-outgoing	Dump outgoing waves instead of returns (wav and max commands only) [default: 0]
-dump_geo	Dump PulseWaves pls/plz geometric info (first/last only) to las/laz 1.2
-first	Dump first sample only (geo command only) [default: 0]
-last	Dump last sample only (geo command only) [default: 0]
-nl_max <n>	Extract or dump only the first n scanlines instead of entire file (scan or extract commands)

PROCESSING COMMANDS AND PARAMETERS

Speed-up	[default: iterative refinement, optimal speed] - *waveform only*
-f l fastest	Fastest processing, no iterative refinement [default: 0]
-s l fastsep	Fast processing (no iterative refinement) if separated peaks (no overlap) [default: 0]
-a l auto	Fast options (-f or -s) only: *enable iterative refinement if deviation exceeded or overlap detected [default: 0]*
-slow	Slower iterative refinement when enabled (better convergence) [default: 0]
Extraction	*waveform only except outlier and cloud options*
-d l det <float>	Detection threshold in noise std.dev. units [default: 4.5]
-lm_det <float>	... same for last of many returns only [default: 0, disabled]
-out_flt	Outlier wave/point filtering, all types [default: 1]
-hi_flt	Outlier wave/point filtering, high (air) [default: 1]
-em_flt	Emitted pulse cross-talk filtering [default: 0]
-cloud_flt	Cloud/fog noise point filtering, scanlines with roughness above threshold [default: 0]
Extraction, expert	*waveform only except -out_max_h -out_max_r and -cloud_min -cloud_max -cloud_r0*
-out_min_a <float>	Minimum angle with neighbor points for outlier wave rejection [default: 2.0]
-out_max_h <float>	Maximum height difference for outlier wave rejection / point detection [default: 50.0]
-out_max_r <float>	Maximum range for outlier point detection [default: 4.0]
-width_min <float>	Keep only returns with minimum width, in impulse response FWHM units [default: 0.8]
-width_max <float>	Keep only returns with maximum width, in impulse response FWHM units [default: 10.0]
-bge	Automatic background level estimation [default: 1]
-decay_a	Decay amplitude coefficient [default: auto]
-decay_t	Decay time constant [default: auto]
-ww_min <float>	Withhold waves having a background level above specified threshold [default: disabled]
-cloud_min <float>	Set the roughness threshold for cloud/fog noise point filtering [default: 1.0]
-cloud_max <float>	Set the roughness threshold for cloud/fog noise scanline elimination [default: 5.0]
-cloud_r0 <float>	Set the range threshold for cloud/fog noise scanline elimination [default: 4.0]
Time interval selection	
-t_min <float>	Minimum timestamp [default: disabled]
-t_max <float>	Maximum timestamp [default: disabled]
-t_adj	min/max timestamps in adjusted GPS time [default: 0, week seconds]
Simple filtering	*filtered points are deleted except for theta filtering*
-w l drop_withheld	Delete points marked as withheld [default: 0, keep]
-l l withheld_ld	Mark MTA low density points as withheld [default: 0, keep as class 28]
-first	Keep only first or single returns, preserve return numbers [default: 0]
-last	Keep only last or single returns, preserve return numbers [default: 0]
-l_sub <n>	Scanline subsampling factor [default: 1, disabled]
-p_sub <n>	Pulse (or point for point clouds) subsampling factor [default: 1, disabled]
-range_min <float>	Delete points with range below raw value (before MTA resolution) [default: 0.5]
-range_near <float>	Delete points with range below min (after MTA resolution) [default: 0.0]
-range_far <float>	Delete points with range above max (after MTA resolution) [default: 10000.0]
-ref_min <float>	Delete points with reflectance below min for RXP (in dB) [default: -100.0]
-ref_max <float>	Delete points with reflectance above max for RXP (in dB) [default: 100.0]
-amp_min <float>	Delete points with raw amplitude below min for RXP (in dB) [default: 0.0]
-amp_max <float>	Delete points with raw amplitude above max for RXP (in dB) [default: 100.0]
-theta_min <float>	Filter points with internal angle below min (set withheld bit) [default: -90.0]
-theta_max <float>	Filter points with internal angle above max (set withheld bit) [default: +90.0]
MTA (range ambiguity)	
-mta	Automatic determination of MTA zone [default: 1]
-mta_zone <n>	Set manual value for MTA zone and disable automatic determination [default: 0]
-mta_min <n>	Set lower limit for MTA zone automatic determination [default: 0]
-mta_max <n>	Set upper limit for MTA zone automatic determination [default: 24 for RXP, 12 for SDF]

MTA, RXP only

-mta_algo <n>	Override MTA algorithm: 0 basic, 1 enhanced, 2 advanced [default: depends on PRR]
-mta_r0 <float>	Set the spatial resolution for the advanced algorithm [default: 4.0]
-mta_tall	Optimize for tall and complex objects for the advanced algorithm [default: 0]

MTA, RXP only, expert *advanced algorithm only*

-mta_extra	Extra iteration for more accurate outlier classification [default: 1]
-mta_amb_min	Select the min MTA zone if ambiguity is not resolved [default: 0]
-mta_veg	Optimize for vegetation if -mta_tall option is enabled [default: 0 for tall, 1 otherwise]
-mta_nl <n>	Sets the number of scanlines to use simultaneously [default: 16]
-mta_jmax <n>	Sets the max scale for the iterative algorithm, range 0-2 [default: 2]

Timing/range correction *waveform only except -gps_date -t_corr -n_ppm -atm -agl*

-ibrc	Amplitude based range/timing correction from SDF data [default: 1]
-utc	SDF timestamps are in UTC [default: 0, GPS]
-gps_date <str>	Override date from input file name, format YYYY-MM-DD [default: 0, SDF file name]
-t_corr <float>	Time offset to add to timestamps [default: 0.0]
-t_err <float>	Set the minimum system timing error (unit: ns) [default: 0.02]
-n_ppm <float>	Set the air refractive index (unit: PPM) [default: 0, get from SDF file]
-atm <file>	Compute n_ppm from atmospheric conditions file (at flight altitude) *file column format: {h,t,rh,p} in m, degC, %(0-100), mbar*
-agl <float>	Set the approx. mean AGL for n_ppm computation, required by option -atm
-odd_dt <float>	Shift odd samples by x sampling units (useful for some digitizers) [default: 0.0]
-ibrc_fit	Use model fit for SDF correction tables (reduce noise) [default: 0]

Amplitude, intensity & width correction *waveform only except -ref -icf -icr -ica*

-ref	Intensity is reflectance, range [-32,32] dB [default: 0]
-icf	Intensity shading correction assuming flat terrain [default: 1]
-icr <float>	Intensity range-based correction using reference range r0 [default: 1000 m]
-ica <float>	Intensity atmospheric attenuation correction, a in dB/km [default: disabled]
-ibic	Amplitude based amplitude correction from SDF data [default: 1]
-awc <float>	Amplitude dependent width correction coefficient for LO power channel [default: auto]
-awc1 <float>	Amplitude dependent width correction coefficient for HI power channel [default: auto]

PO data

-po <file>	Set PO data file name [default: none, georeferencing disabled]
-po_adj	PO timestamps in adjusted GPS time [default: format-dependent]
-auto_adj	Auto detect adjusted GPS time [default: disabled]
-po_day	PO timestamps in day seconds [default: 0, week seconds]
-po_rad	PO attitude data in radians [default: 0, deg]
-pof_unit	Use POF unit (UTC time format) [default: 0, ignore]
-po_parse <str>	Column format string for ASCII PO data *t x y z w p k # for time longitude latitude ell.height roll pitch heading skip, respectively*
-po_sub <n>	Set the decimation factor for the exported ASCII PO file [default: 10]
-otraj	Export projected, subsampled trajectory text file [default: 1]
-plot_po <str>	Export subsampled and projected PO file as ASCII *(use georeferencing options to specify the projection)*
-sync	Sync only (no processing) input files with PO data to *_sync.log and *_rej.log

Geometry

-mount <file>	IMU/BODY or ICS/BODY rotation angle file, format {Rx Ry Rz} [default: none, 0 0 0]
-calib_corr <file>	Calibration correction file [default: none, all 0] *Format: LeverArms {X Y Z} Boresight {roll pitch yaw} Internal {e0...e5 [e6 e7]}*
-riparam	Use Riegl mount and calibration instead of standard LiDAR eqn. or StripAlign [default: 0]
-oi	Scan angle rank is internal [default: 0, LAS spec]
-vux	For RXP, use VUX-type internal geometry (z,y,-x) instead of (y,z,x) [default: 0]

Georeferencing

-wkt <file>	Use WKT file to define a TM/LCC/AEAC projection, optional unit [default: UTM]
-utm <n>	Set the UTM zone manually [default: auto]
-geo	Use geodetic coordinates [default: 0]
-ecef	Use ECEF coordinates [default: 0]
-geoid <str>	Use geoid (file w/o extension from Geoid directory in exe directory) [default: none]
-metre	Set unit=metre, override WKT [default: 0, from WKT or m]
-feet_us	Set unit=US or survey foot, override WKT [default: 0, from WKT or m]
-feet	Set unit=international foot, override WKT [default: 0, from WKT or m]
-dumv <float>	Use fake velocity to help visualize the file in BODY coordinates (no georef) [default: 0.0]

EXAMPLE USAGE

To keep example command lines short, input and output directory options have been omitted.

```
> wavex -i data.sdf -po file.pof -fastest
```

extracts a point cloud in LAZ 1.4 format (same name as input) from input file data.sdf, using fastest algorithm (no refinement, but uncertainties are computed and exported along all other extra attributes); georeferencing done using PO data in POF format and default UTM projection (default unit m) with ellipsoidal heights; global stat file and subsampled projected PO data are exported.

```
> wavex -i data.sdf -po file.pof -lstat -o12 -oplz
```

same with LAZ 1.2 output and refined, accurate extraction; scanline stats are exported; compressed PulseWaves (plz+wvz) exported.

```
> wavex -i data.sdf -po file.pof -lstat -olas -olax
```

same with LAS 1.4 output and LAS index file (as a separate .lax file).

```
> wavex -i data.sdf -po file.pof -lstat -I indir -O outdir -ounc 0 -o*_abc
```

input and output directories are specified; uncertainty attribute computation and export disabled; file base names have _abc appended.

```
> wavex -i indir/*.sdf -O outdir -po podir/file.pof -fastest -oext 0
```

same as first example using all files from indir, using explicit output directory, and using fastest possible extraction setting (all extended attributes are disabled).

```
> wavex -i indir/*.sdf -O outdir -po sbet.out -wkt proj.txt -geoid g2012bu0
```

same as first example using all files from indir, using explicit output directory, SBET PO file, accurate extraction, and custom projection (TM or LCC) and unit defined in WKT file with manually specified geoid name (WKT geoid is not parsed); the wkt info is written into the LAS file.

```
> wavex -i indir/*.sdf -O outdir -po sbet.out -wkt proj.txt -calib_corr cal.txt
```

same without geoid, and with calibration corrections (lever arms, boresight angles and internal distortions).

```
> wavex -i indir/*.sdf -O outdir -po sbet.out -utm 55 -feet -calib_corr cal.txt -mount mnt.txt
```

same with UTM projection and manual zone, survey feet; BODY/IMU mount angles specified in file mnt.txt.

```
> wavex -i indir/*.sdf -O outdir -po sbet.out -calib_corr cal.txt -utc -t_corr 0.72 -t_min 82300 -t_max 82400
```

same with default projection and time options: SDF file in UTC, time offset 0.72 s (added to SDF timestamps); extraction only for the specified time interval (use -t_adj to use adjusted GPS time for this option)

```
> wavex -i data.sdf -po file.txt -A -po_parse xyztwpk -fastest
```

same as first example, with ASCII PO file (custom column format and adjusted GPS timestamps).

```
> wavex -i data.sdf -po file.txt -A -po_parse xyztwpk -fastest -geo
```

same without projection: geodetic coordinates are exported, and the projection can be done with another software.

```
> wavex -i data.sdf -fastest -dumv 50
```

same as first example without georeferencing (data exported in body frame coordinates); use option -dumv to specify a fake aircraft velocity that allows the point cloud to look georeferenced for visual inspection.

```
> wavex -i data.sdf -det 6 -lm_det 10
```

accurate extraction, detection threshold set to 6 noise std devs, and 10 for last of many returns.

```
> wavex -i data.sdf -po file.pof -oplz -ofp -oct
```

accurate extraction, georeferencing with default UTM projection, export compressed PulseWaves files, and generate footprint and center polygons as well as transect point cloud text files.

```
> wavex -i data.sdf -fastest -po file.pof -p_sub 2 -l_sub 2
```

fastest extraction and georeferencing with default UTM projection, extract every other line and every other pulse (overall subsampling factor ~4), faster than extracting all and subsampling later.

```
> wavex -i data.sdf -fastest -po file.pof -last
```

same without subsampling and keeping only last or single returns.

```
> wavex -i data.sdf -fastest -oext 0 -nil
```

fastest possible extraction and output disabled; use for detailed scanning and readable stat file generation.

```
> wavex -sdfscan -i data.sdf -name scan
> wavex -sdfscanfast -i data.sdf -name scan
```

scans a SDF file and writes various histogram and stat files starting with name scan; displays basic stats; useful to check the integrity of a file and get the LiDAR time interval; use -sdfscanfast for a faster, more basic scanning without waveform data decoding.

```
> wavex -i data.sdc -po file.pof -ofp -oct
```

SDC point cloud georeferencing with default UTM projection, generate footprint, center and transect text files.

```
> wavex -i data.rxp -po file.out -ofp -oct
```

same with SBET PO format and RXP point cloud.

```
> wavex -i *.rxp -po file.out -wkt proj.txt -mount mnt.txt -calib_param calib.txt -riparam -mta_max 8
```

multiple parallel RXP point cloud georeferencing, MTA resolution (max zone 8), using WKT, mount and calibration using the Riegl parameter convention

```
> wavex -scan -i *.sdf -po file.out -name myname
```

generates a file list myname_sync.log containing all SDF data files that sync with PO file file.out, rejected file names are saved into myname_rej.log.

```
> wavex -i data.sdf -fastest -oext 0 -nil
```

fastest possible extraction and output disabled; use for detailed scanning and readable stat file generation.

```
> wavex -h
```

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

```
> wavex -v
```

shows the version and licensing info.

```
> wavex -clear_log
```

deletes all the archived log files from the exe directory.

PERSISTENT OPTION FILE EXAMPLE (wavex.opt.txt)

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

This allows the same options to be used often without having to specify them in each command line; if they are found in the command line they override those from the file.
For multiple instances (parallel runs) each install must have its own persistent option file.

2. INPUT FILES

SDF waveforms, SDC/RXP point clouds

Currently only Riegl files are supported (560 to 1560 including V-line scanners).
Waveform files have to be in SDF format (original or exported).
WavEx can also process point clouds in SDC or RXP formats for fast georeferencing and LAS/LAZ output in a single pass; the software can solve MTA automatically for RXP data (enabled by default).

PulseWaves waveforms

Currently PulseWaves data are only supported via dump commands and not full processing (helpful to check the exported PulseWaves output).

PO data (required for georeferencing)

PO data is required for georeferencing but not for extraction. The software can produce body frame points that can be later georeferenced by other software if necessary.
The data file must contain GPS timestamps (day seconds, week seconds or adjusted), position in geodetic coordinates (longitude latitude ellipsoidal height) and attitude (roll pitch heading). Other data are not used.
This is supported by formats such as SBET, POF, SOL and any ASCII file (using the -po_parse option to specify the column format, and other options for attitude and time unit).

Calibration corrections & mount (recommended)

Option -calib_corr is used to specify the ASCII file containing lever arms, boresight angles and internal corrections. These parameters are fully compatible with StripAlign. If a calibration flight is processed with StripAlign, then the parameters (3 lever + 3 bore + 6 internal) can be pasted directly into an ASCII file and used for optimal geometric accuracy of body frame coordinates, thus simplifying any further correction. Format for the correction file:
Lever arms: X Y Z
Boresight: roll pitch yaw
Internal: [optional]
e1: range bias
e2: range scale - 1
e3: angle distortion order 1
e4: angle distortion order 2
e5: angle distortion order 3
e6: misalignment [not used by WavEx]
e7: optional - angle bias [WavEx only]
e8: optional - LO/HI range bias [WavEx only]

If mount and calibration parameters come directly from Riegl files, use option -riparam to read them without conversion (not needed for parameters from a StripAlign calibration run). This is due to a different convention or LiDAR equation. BayesMap software use the textbook equation R_IMU(R_B p + L) and Riegl uses R_B R_IMU p + L.
Use -mount to input a text file with the 3 rotation angles (Rx Ry Rz), meaning IMU to BODY rotation by default and ICS to BODY when using -riparam.

Atmospheric range corrections

Option -n_ppm sets the air refractive index PPM (eg. 250) manually.
Option -atm along with -agl computes the refractive index automatically using an atmospheric model and physical parameters **at flight altitude**. Option -atm specifies an ASCII file with space separated values: height (m), temperature (deg C), relative humidity (% 0-100), pressure (mbar). Option -agl is required when using -atm, and specifies the approx. mean AGL for the swath. Note that variations of a few hundred meters only account for a few mm of possible range error. In most cases, a single set of parameters per swath (or per project) is sufficient for a sub-cm accuracy.

3. OUTPUT FILE FORMAT

LIDAR POINT CLOUD (LAS/LAZ 1.2-1.4)

The timestamps are always exported as **adjusted GPS time** and are automatically determined from the input file or by manually specifying the date with option -gps_date if necessary.
Depending on options -oext -oext2 and -ounc (on by default) the following **extra attributes** are exported.
Note that TargetThick, DevRatio, WideRatio, RawAmp and RangeErr only apply to waveform data.

Name	*Description*	*Scale*	*Offset*	*Type*	*Bytes*	*Option, default*	
TargetThick	Target thickness (m)	0.008	0.0	unsigned char	1	oext	1
DevRatio	Residual-Noise, Chi2 stddev unit	0.100	0.0	unsigned char	1	oext	1
WideRatio	Pulse widening ratio (%)	0.025	0.5	unsigned char	1	oext2	0
RawAmp	Raw amplitude	1.000	0.0	unsigned short	2	oext2	0
MTA	MTA zone			unsigned char	1	oext2	0
Channel	Riegl power channel (LAS 1.2 only)			unsigned char	1	oext	o12
RangeErr	Range std. dev. (m)	0.001	0.0	unsigned char	1	ounc	0

User data byte: contains information specific to the fitting algorithm for each waveform.

Bit 0	iterative refinement used
Bit 1	peak overlap detected
Bit 2	timing divergence requiring extra refinement
Bit 3	received wave overlapped by emitted pulse (cross-talk) case 1
Bit 4	received wave overlapped by emitted pulse (cross-talk) case 2
Bit 5	bad timing due to emitted pulse overlapped by received pulse (cross-talk)
Bit 6	saturation detected
Bit 7	extreme saturation detected, wave truncated

Withheld bit: points classified as outliers (low, air/high points or points with insufficient density when using the advanced MTA algorithm), derived from withheld waves, or having a bad timing (EM wave contaminated by cross-talk) or outside internal angle bounds are marked as withheld, not deleted (unless option -drop_withheld is set).

LAS class: For SDF data, withheld points are assigned a custom class as specified in the SDF stat file (30 default, 31 withheld waveform, 29 bad timing). For RXP data, withheld outliers are classified (7 low point, 18 high point, 25 very low density, ie. isolated points). Low density points are classified as 28 but not withheld.
(Other points are left unclassified or class 0).

Point source ID: equal to the file source ID.

Channel (LAS 1.4): contains the Riegl power channel number (0 LO, 1 HI) used for intensity computation.

Scan angle rank: LAS spec. by default, or internal angle if -oi is set

Scanline edge: is set for the last point of the scanline as in the latest LAS spec.

All other attributes are computed according to the LAS specs.

Option -split should be used for circular and elliptical scanners to split the data into two files depending on scan direction (forward and backward half of the ellipse), especially when planning to use StripAlign for alignment.

LIDAR POINT CLOUD (ASCII)

If the output format is set to ASCII (eg. with -otxt) then the -oparse string is used to define the column format, consult the las2las documentation for more info: rapidlasso.com/lastools/las2las
Example: -oparse txzyi will only export time and 3D coordinates followed by intensity.

TRAJECTORY FILE (ASCII)

The exported trajectory is stored as an ASCII file with each row as follows:
Time X Y Z Roll Pitch Heading Lon Lat H
The timing information is in the same format as the LiDAR file and X Y Z are in the same coordinate system.
If a PO file is used, attitude information is also exported. The PO info is subsampled (see -po_sub to set the factor).

PULSEWAVES EXPORT (PLS/PLZ+WVS/WVZ)

With options -plz or -pls the waveform data from SDF files can be georeferenced and exported as PulseWaves.
Outgoing waveforms are discarded by default, use -outgoing to export them. If exported, they can be subsampled with option -out_sub to reduce storage space.
There are 3 pulse descriptors (lo, hi, lo+hi) or (out+lo, out+hi, out+lo+hi), variable number of segments, variable segment size.

The pulse classification field contains information about possible channel cross-talk as a bit field:

Bit 0	bad timing or contaminated emitted wave
Bit 1	contaminated received waves, type 1, at least one segment affected
Bit 2	contaminated received waves, type 2, at least one segment affected

The current library does not allow to store extra attributes (such as LAS scan angle) so they have to be retrieved from the extracted LAS/LAZ file using timestamps for pulse identification.

FOOTPRINT, CENTER, TRANSECT (ASCII)

With option -fp the footprint can be extracted (from any type of data, waveform or point cloud) as a polygon in ASCII format, named *_fp.txt, using extreme points for each scanline. The scanline subsampling factor is set with the option -poly_sub.

With option -ct the center polyline *_ctr.txt and center transect point cloud *_trans.txt can also be exported in ASCII. The polyline is also controlled by the scanline subsampling factor with option -poly_sub. It is generated by averaging points within a maximum LAS scan angle, set with option -ct_sa. These points within a maximum angle from nadir are used for the transect file.

STAT FILES (ASCII)

The global stat file (_stat.log) is saved as a human readable file, and contains information on runtime, SDF file and format, decoding and extraction, as well as PO data, georeferencing and output file (only available for SDF input).

The scanline extraction stats are stored as a text file (_lstat.txt), with each row corresponding to one scanline:
gps_time nw np np_xtalk np_thetaout np_filtered np_merged np_air np_low np_range np_atm np_ibrc np_ibic nw_empty nw_saturated nw_refined1x nw_refined2x nw_deleted nw_truncated n_georef AGL
(where np, nw are for number of points and waveforms, respectively)
See exported global stat file for more explicit names.
Scanline stats are written to the log file if -llog is enabled.

RXP log info is written to the _rxp.log file if option -llog is enabled.

4. NOTES

EXTRACTION PARAMETERS *waveform only except subsampling and filtering*

Detection thresholds (-det and -lm_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 sigma (default setting) 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.

For noisy scanners (eg. early 780) high peaks tend to have unusually high and unpredictable ringing, so we recommend to use option -det_lm with a higher value (eg. 10) so that last of many returns are processed with this threshold, which reduces the low point rate (and helps the outlier filtering that cannot cope with a high density of low points). For other scanners or if the first extraction attempt looks good, ignore this option.

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 filtering parameters (-out_min_a, -out_max_h, -out_max_r)

Nearest neighbors in the scanline are considered when performing outlier waveform detection. Only waves having a height jump over max_h compared to both neighboring points will be rejected (and counted as low if they are more than max_h below the neighbors, or high if they are more than max_h above the neighbors). The rejection happens only if the angle formed by the wave anchor 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.

While outlier waveforms can be safely rejected, outlier points (after return extraction from waveforms) are analyzed and outliers are detected but only marked as withheld and classified accordingly. The point based algorithm may produce false detections and ultimately a high level classifier should be used if possible (if not, withheld points can be removed). The max_r parameter helps detect low points for noisy scanners, or rare returns that are above the detection threshold but underground or isolated.

See subsampling and filtering below for general outlier filtering options.

Clouds and fog noise filtering (-cloud_flt, -cloud_min, -cloud_max, -amp_min)

The cloud and fog noise filter can be enabled with option -cloud_flt. For close range return elimination, option -range_min should be used instead. If clouds are present at longer or unknown ranges then -range_min can cause too much data loss (see paragraph about subsampling and filtering) and the cloud filter should be used.

Default thresholds work in most scenarios, but for some datasets they might need to be set manually. The min value required to apply the filter is set with -cloud_min (default 1), any scanline having a roughness below that value will not be affected by the filter. The max admissible value can be set with -cloud_max (default 10), any scanline having a roughness above that will be rejected without filtering. Filtered points are classified as high noise and also marked as withheld, not deleted. The roughness-based filter should only be used when clouds are present. Enabling the filter and setting a low min threshold can result in some data loss in vegetated areas (a few % max).

For difficult cases, using the -amp_min option is recommened. Clouds are dark in NIR so filtering out weak returns immediately helps in cases where MTA reconstruction is affected by heavy cloud noise. Just like -range_min, this option causes data loss and should only be used with caution, and with cloudy data.

Finally, the range parameter of the roughness filter can be adjusted (default 4 m). Higher values yield fewer false alarms (vegetation points classified as noise 18) but may affect the detection success for cloud points. Lower values should only be used if cloud elimination is a priority and loss of points in rough, vegetated areas is not an issue.

Other parameters (background, decay etc.)
The default values have been calibrated for each type of instrument, so we do not recommend to change them. In some cases, instruments may exhibit unusual characteristics and require manual settings, usually through interaction with client support.

Subsampling and filtering
Scanline and pulse subsampling parameters -l_sub -p_sub are available for speed-up and should not be used for production. Fast extraction can be achieved by ignoring a subset of scanlines and waveforms or points so they are never processed, and the output file in small, generated quickly for inspection purposes.
First and last return options -first and -last are also available and work the same way as in las2las.
Range filtering is controlled with options -range_near and -range_far, and filter points based on MTA resolved range. This can be useful to remove some MTA artifacts or sensor noise for topo-bathy scanners. To remove close-range returns from a dirty window or fog, use option -range_min (before MTA resolution) to specify a value other than the default 0.5 m. Note that this option will produce a blind zone of depth equal to the specified value, occurring at a distance equal to a multiple of the MTA range ambiguity (so a large value is not recommended).
Filtering options described above delete points. There are two internal scan angle filtering options -theta_min and -theta_max that only mark points as withheld without deleting them.
All these options are useful to filter the data on the fly without having to first process all the data then run a filtering step on a large file.
For SDF and RXP processing, only scanlines having a minimum number of samples are kept, others are ignored to avoid MTA artifacts (a warning is generated when it happens).
Outlier filtering (for all types of data) can be controlled with -out_flt, and air point filtering can be controlled separately with -hi_flt (disable if power lines are marked as air points). For non-waveform data -out_max_h and -out_max_r can be used to set the outlier detection thresholds (height above/below the main surface, and range threshold). Outliers are marked as withheld, not deleted, and classified as low or high noise.

OUTPUT PARAMETERS

Uncertainty output (-ounc) *waveform only*
Even if most existing software do not know how to use predictive uncertainty, we recommend to export and inspect the range uncertainty attribute. It will be supported by future products (such as accurate gridding). In certain cross-talk cases (emitted pulse contaminated by received wave) the timing is inaccurate and the uncertainty is set to the maximum. It means that the range estimate is not reliable (this is also valid for intensity and the related uncertainty attribute) and they should be given less weight when computing derived quantities.

Extended attribute output (-oext, -oext2)
For simple applications and quick inspection, extended attribute export can be disabled, and computation will also be faster in most cases. In general, attributes are very useful for classification and should be exported. For instance, pulse widening or target thickness help during classification, as no other attribute is equivalent (the geometry of the target, as well as its roughness, directly determine the pulse width; the software compensates for instrumental artifacts such as amplitude-dependent widening to provide physically meaningful quantities).

POINT CLOUD GEOREFERENCING

WavEx can also process already extracted points (SDC) or point clouds collected from online waveform processing scanners (RXP). It takes a set of input files, a PO file, and generates LAS/LAZ (and optional footprints and transects) on the fly, with automatic MTA resolution for RXP (up to 32 zones). Different RXP files are processed in parallel.
Subsampling and filtering options are available. Option -ref is available to export reflectance as intensity and original amplitude in dB (range [-32,+32] dB).
The available processing options for point clouds are a subset of the options for waveform processing. Extraction speed, detection thresholds, background, decay, IBIC/IBRC corrections and other waveform-specific options have no effect on point cloud processing and are simply ignored.
For attribute export, exported attributes are amplitude and deviation with -oext (default 1), and MTA with -oext2 (default 0).

AUTOMATIC MTA RESOLUTION

SDF files are processed using a fast, effective MTA resolution algorithm that works well for PRR up to 500 kHz.
RXP files from latest generation scanners can have a PRR up to 2 MHz and require an advanced algorithm (the algorithm is determined automatically from the PRR; use -mta_algo to override). Algorithms 0 and 1 use a single scanline, 1 being more robust than 0.
Algorithm 2 is the most advanced and combines multiple scanlines to process complex objects (such as power lines and poles) effectively. It comes in two flavors, regular and tall, depending on the expected height of the structures compared to the MTA range ambiguity.
Option -mta_tall should only be used for large and complex structures (hi-rise buildings, tall wind turbines etc) as it can generate more artifacts than the default setting. If needed, it can be combined with -mta_veg in more vegetated terrain to produce fewer noise artifacts.
The advanced algorithm uses a resolution parameter (default 4 m) that can be set with option -mta_r0, which relates to the radius used for point aggregation (points too distant will be labeled as low density and withheld). Larger values produce fewer noise artifacts but may negatively impact object separation in areas where the range ambiguity causes unwanted overlaps (eg. power line intersecting with ground).

USEFUL COMMANDS

PO data plot
The command -plot_po (along with PO input options) exports an ASCII version of the binary PO file and can be used to plot the data or diagnose issues.

PO data and LiDAR file sync
The command -scan (along with LiDAR file and PO file inputs) helps find which LiDAR files sync to a particular PO file, and the result is written as a list of synced files out_sync.log and rejected files out_rej.log, option -name can be used to replace out with any custom name.
This works with any of the input formats.
It does not do any processing, only scans the beginning of the files, and writes no other output than log files.

SDF file scan *waveform only*
Option -sdfscan helps scan SDF files and output basic stats, and performs basic waveform checking as well as MTA correction. Option -sdfscanfast is faster than -sdfscan, provides the time interval and count records, but all the waveform decoding is disabled.

PulseWaves file dump *waveform only*
Commands -dump_wav -dump_max and -dump_geo are provided to test PulseWaves files but not to process them thoroughly. The first one exports one point per waveform sample and may produce large files. The second one exports one return (maximum intensity) per waveform and performs a fast, simple extraction. The third one only dumps the geometry information and not the waveforms.

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-us/download/details.aspx?id=48145 and follow the instructions

ERROR: stopping due to option argument errors (use -h for help)
Cause: some options have wrong argument types, are unknown, or arguments are missing
Solution: check previous error messages and supply correct arguments

ERROR: ... environment variable undefined
Cause: forgot to define RLMUSER and RLMPW environment variables to set up the floating license
Solution: see install instructions

ERROR: could not verify license for Bayes-WavEx with user ...
Cause: see previous error message from RLM license manager, usually explicit (*incorrect password, user not in database...*)
Solution: check the credentials provided; check internet connection; contact support for temp. node-locked license if needed; *license already in use*: wait 10 min for auto checkin if NOT running multiple instances (may happen after a crash)

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: Unsupported full waveform format...
Cause: only Riegl SDF files are currently accepted
Solution: use version 1.0 for LAS 1.3 FWF, use Riegl export utility for VQ scanners

ERROR: one instance already running!
Cause: parallel runs would not improve performance and are disabled to avoid potential issues.
Solution: run only one instance!

ERROR: missing bin file for geoid...
Cause: misspelled geoid name, or geoid .bin file not installed, must be in "Geoids" directory in exe directory
Solution: create "Geoids" directory in exe directory and download .bin files from the WavEx distribution Google drive or from the NGS website www.ngs.noaa.gov/GEOID/models.shtml (USA only)

ERROR: PO data format cannot be used, PO file...
ERROR: failed to read PO file...
Cause: PO file not recognized, not in geodetic coordinates, or does not have attitude data
Solution: provide PO data in one of the formats: SBET, POF, SOL or ASCII

ERROR: WKT string parse error
Cause: projection parameters not found or unsupported projection
Solution: use Transverse Mercator only and check the syntax (must be OGC WKT)

ERROR: georeferencing error: lon/lat out of bounds for selected geoid
Cause: wrong geoid used given geodetic coordinates in PO file
Solution: check geoid name (preferably use full geoids instead of regions, eg. g2012bu0)

ERROR: georeferencing error: timestamp not found in PO file
Cause: error in time correction or conversion, timestamp outside of PO time interval because (wrong or incomplete PO file)
Solution: check file name, check date if manual options, and other time options if used; ok if partial PO file

ERROR: SDF unsupported type xxx
Cause: not a SDF file, format error in SDF file header, or unsupported instrument type
Solution: contact support if the displayed type matches the supported type list

ERROR: SDF Type xxx format / SDF Type xxx header decoding
Cause: format error in SDF file (possibly correct but unsupported) / header parameter decoding issue
Solution: none, file is not readable; contact support if file is readable with other software

A2. CURRENT LIMITATIONS

- RXP point cloud support only
- Supported projections (via WKT): UTM, TM, LCC, AEAC (all US state planes except Alaska FIPS 5001) including datum transformation with TOWGS84 (7 parameter Helmert)
- PulseWaves: no extra attributes (not implemented in library)
- Fixed impulse response (amplitude independent), might not be rigorous for all scanners
- Scanline-based outlier detection method simple, fast but not guaranteed to flag all outliers
- No explicit bathymetric waveform modeling (but RXP processing works for all scanners)
- LAS FWF input disabled (use version 1.0 if needed)
- PulseWaves input not supported (only for test dump)

A3. PLANNED FEATURES

- Riegl RXP waveform input
- Other commercial waveform scanners
- PulseWaves and LAS waveform input
- More projections supported
- Model-based outlier rejection algorithm