VoxLAD$_{RT}$ User Guide

Riegl VZ ground lidar data acquisition and processing tools to map forest leaf/wood area density in 3D using voxels

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FAIR USE

PLEASE READ CAREFULLY

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2. Introduction

The VoxLAD$_{RT}$ model was developed as a tool to study the interconnection between forest canopy structure and the scattering and absorption of solar radiation, as well as provide vertical profiles of leaf and wood area density as inputs to biophysical models simulating forest canopy functions, including photosynthesis and evapotranspiration, as well as the exchanges of heat within the canopy air space. It has, as of Jan 2026, been used solely in broad-leaved deciduous forests, and several theoretical aspects of the methods used (mainly related to the size of needles relative to the laser pulse size) make it unsuitable for direct application to needle-leaved trees without proper consideration and remediation of the associated implications.

The 3D mapping of leaf area index (LAI) from ground lidar is a relatively complex process, for two main reasons: 1) the amount of data to process is large, and 2) the number of processing steps is high. There are also very important considerations related to efficiency of data processing tools to process large amounts of 3D data, and the availability of certain required information for this process to hold true to theoretical basis. This last point is the main reason why the methods described here require a Riegl VZ instrument. The VZ instrument presents the following advantages on other systems for the purpose at hand:

- The instrument records the deviation of each laser pulse, this enables the efficient removal of ghost points (points that result from multiple contacts recorded as one between the laser photons and two or more objects located along the laser pulse path)
- The Riscan Pro software enables target-less registration in forests, which reduces field time by a factor of about 4-5. This method has been successfully used in dense temperate and tropical forests
- The instrument provides apparent reflectance, which does however benefit from a second calibration process since it was shown to be of modest accuracy for Riegl standards
- The Riegl file format RXP records the direction of emission for each pulse, which has shown to be essential for accurate ray tracing
- The instrument is reliable and robust for deployment in forest. And the Riscan Pro software is efficient in processing large amounts of data.

The series of algorithmic tools presented here consist in the following broadly defined steps:

1. Alignment of all scans to a common spatial reference coordinate system, this generates a coordinate transformation matrix in Riscan pro for each scan position which define the scanner position and orientation in this "project", or plot level coordinate system
2. Reading the native Riegl file format which contains information about each emitted pulse from each scan position, i.e. the direction in which it was emitted, and the event or events (an event is a recorded energy return following a pulse interception), including the intensity of the returned energy and the recorded pulse deviation. This information is used to perform a first point classification based on return intensity and deviation into leaf, wood and noise
3. The Lewos model is then used to improve the initial classification by changing the class of some leaf points to wood, and some wood points to noise based on the probability of a given point being associated to wood by the Lewos model
4. A ray tracing algorithm computes the leaf and wood area density at the voxel scale based on gaps and hits statistics and the contact frequency theory
5. Occluded voxels are identified and gaps in the data are filled using vertical profiles of leaf and wood area density for non-occluded voxels
6. Leaf and wood area density voxel arrays are combined to enable their use as input into radiative transfer models such as FLiESvox and DART

3. Field acquisition and data management

3.1. Pre campaign check list

We use a tilt mount which enables inclining the VZ instrument, the tilt mount and instrument are connected by an alignment pin to ensure the instrument does not rotate on the tilt mount.

Check that the alignment pin is not broken between instrument and tilt mount, if it is, replace with new pin taking care to place instrument at exact same position over pin. This is important to use the tilt mount calibration already performed which uses a file saved inside the instrument.

3.2. Setting up the survey grid

One consideration regarding plot size is that it is needed to select a size that fits an **integer number of voxels**. For example, 30 cm voxels fit well in a 60 x 60 m^2 plot, having 200 x 200 voxels. A **non integer number of voxels** will result in edge voxels being cut and inaccurate statistics for those voxels and may incur an error in wooRayTrace. It is thus preferable to **choose 48 x 48 m^2 instead of 50 x 50 m^2**, resulting in a 160 x 160 voxels plot, for a 7 x 7 survey grid spaced 6 m apart. The same consideration also applies to the **voxel matrix height**. In my research I've used grids of 11 x 11 scan positions spaced 5 m for 60 x 60 m^2 plots, and 7 x 7 positions spaced 6 m for a 48 x 48 m^2 plot, the latter requires significantly less field time. The grid of scan positions is marked prior to start of the TLS survey with small flags inserted in the ground.

3.3. Scanning

Orientation of first scan is important, as it sets the orientation of the entire plot, because all scans will be aligned to this first scan of the series. I usually aim the tilt mount plate in the direction of the next scanning position along a scanning line, f.ex. if the scanning line is running north south, I orient the plate south for all scan positions of this line. While setting up the instrument, a bubble level set on the tilt mount is used to put the instrument roughly horizontal. At each position, a first scan with the TLS in vertical position is performed, and the operator moves as the instrument rotates so that no one is in the field of view. The TLS is tilted in horizontal position to perform a second scan which only covers the area above head which is not covered by the vertical position scan (with some overlap). While the vertical scan is running, the operator moves to the next scanning position and finds an area with clear above head and moves tree branches if needed. All scans are usually done at 0.04 or 0.03 degree resolution, depending on scan position density. A map of scan positions and scan numbers is drawn in the filed book, along with wind conditions, north position, plot GPD coordinates, and any relevant comments.

4. Data pre-processing in Riscan Pro and input files preparation

The methods developed aimed at streamlining the field data acquisition process as well as the data processing. The high number of scan positions required to cover a dense forest plot with reasonable occlusion effects means the data volume is very high, this renders workflow efficiency paramount. It is recommended to perform the processing using a solid state drive (SSD).

System requirements

- Riscan Pro with multi station adjustment
- Matlab with Computer Vision System Toolbox

The methods described here were developed and tested on version 2.6.2 of the Riscan Pro software. This version is available for download here:
https://drive.google.com/file/d/1J19s4ATkwDvBAfnGc96Hrgn1QKSfyuPL/view?usp=share_link
A valid licence from Riegl is required to use this software.

4.1. Setting up the project in Riscan Pro

You should have one project file for each day of field survey, for example 2023-08-21.001.riproject. Time to create a Riscan Project, use Project.. new. Then to import : menu help.. download and convert. Select one folder at a time corresponding to one field day, starting with the first. Select next, use shift to select all scans, then right click check, then check box at bottom “main scans only” (this removes the mon files which are not needed). Select next, files are imported and converted. Do the same for other survey days, but importantly, chose Append, so that the scan 1 of the second day becomes the scan position x+1 where x is the last scan of day 1. Odd scan numbers should always be the vertical scans, and even numbers the horizontal scans (the ones looking upward). You should now have in total $2x^2$ scan positions where x is the number of scans on one side of the survey grid, e.g, for a 7 x 7 grid you have 98 scan positions.

4.2. Scan alignment

Import tilt mount calibration file (this calibration is unique to each VZ instrument). Left pane, chose calibrations.. tiltmounts.. new.. lower left import. The tiltmount calibration can be imported from any project that used the calibration previously (see file list below, File 2), or from the project used to create the calibration.

Start with aligning scan 2 on scan 1 using the tilt mount calibration. Right click on scanpos001.. attributes..tilt mount. Select tilt mount. Select assign tilt mount, position of tilt mount is vertical 0 deg. Then same process for scan 2, select link to scanposition.. scanpos 001. Position of tilt mount is position 90. Open both scans by dragging the scan point cloud (last item under scanpos001) into the view window, select unique color for each scan, and assess the goodness of fit.

Unlink scan 2: attributes.. tiltmount, unselect tilt mount box. Run multistation adjustment: settings.. select plane patch filter.. max 0.02, min 300m min search 0.256, max 32.768. in data, list view, select all using shift. Export SOP matrix for scan 2, use file name ScanPos002, this is the transformation matrix that will be used later to align all even scans to odd scans.

Run automatic registration 2 **on odd scans only**, use control to select all odd scans, then registration.. automatic registration 2**.** Scenario outdoor non urban.

Export SOP matrices for all odd scans, use registration.. multiple SOP export, use ctrl key on all odd scans, chose DAT format box only. Use Matlab File 2 to create a SOP matrix for all even scans on the basis of the DAT file created for scan 2, this applies the transformation matrix associated with the tilt mount to all even scans on the basis of the SOP of all odd scans created above. In Riscan, for each even scan, right click on SOP..import and select corresponding DAT file. This aligns the even scans to the odd scans.

For a thorough alignment, check visually all scan pairs, assigning one scan to one unique color to assess the quality of the spatial match. Be careful in this evaluation, as for local areas there may be a mispatch because of a wind gust, which does not mean that the alignment is inaccurate globally. Large stems are a reliable indication of a mismatch. If a mismatch occurs on smaller branches it should be miscible in branches from different areas in the point cloud. If unsatisfactory alignment between odd and even scan is found, use multi station adjustment.. start adjustment. Deactivate all scans, and activate only the targeted odd and even scans. Have both scans up in view window, one color per scan, to visualize the corrected alignment. For the odd scan, right click and select lock position and orientation. Select even scan right click and select lock position. Now only the even scan roll, pitch, yaw you wish to move around should have green check boxes. In search radius use 0.02 on the first run, if no solution is found, use 0.25, and do a another run using 0.15. This can be done a few times, to undo load the DAT file for the even scan in SOP. From my experience it may not be needed to go through visualizing all odd even pairs, fine adjustments may not be needed if I see no issue after visualizing a few random pairs.

4.3. Output additional needed files

Export RPY (scan positions) and DAT (rotation/translation matrices) files for all scan positions. Use Registration.. multiple SOP export. Check ROT and CSV boxes, then delete all . ROT and .CSV files as they are not needed., keep RPY files.

4.3.1. Histograms for apparent reflectance threshold in the leaf/wood classification

Analysis of the apparent reflectance of the point cloud is needed to identify appropriate separation thresholds to classify leaf and wood, thus the histogram of apparent reflectances needs to be analysed. To create the histogram, first export the point clouds to ascii, using right click on one of the point clouds.. export.. then select back, this will bring the list of point clouds, select all of them, next, export format ascii, select x,y,z, deviation, reflectance, target index , target count (in this exact order). Use project coordinate system. Uncheck combine data.

Now we need to rename these files, use File 3 to create batch file and execute it (under windows). We need to know the xyz coordinates of the plot, this is the area covered by the scans you wish to represent, we will call these coordinates bbox, for bounding box. Identify the scan numbers corresponding to the plot corners. Look at their coordinates in the RPY file and determine which are going to be the plot coordinates, these are integer numbers, and the plot typically has 60 x 60 m^2 or 48 x 48 m^2 dimensions (should be a multiple of 0.3m or whichever is the voxel size), if the plate of the tilt mount was well oriented towards the first survey line, the delta x dimension between the 2 first corners should be close to 0. Find the situation where the scan positions are centered within the plot boundaries. Use File 4 to create the histograms. This process is slow and I've been running on the diagonal scan positions.

From the histograms, use a software or code to fit the function sum of two Gaussians to the histogram data, I use Prism. Then display the leaf and wood Gaussians individually as in the figure below. The Excel file 5 can be used.

The apparent reflectance threshold to separate leaves from noise should be half of the apparent reflectance at which the leaf Gaussian peaks, see figure below for example. The leaf-wood threshold should be placed near the tail of the leaf Gaussian, which is about 40% in the example figure below.

From Béland and Baldocchi 2021 AFM, supplementary materials:
The separation of leaves and wood

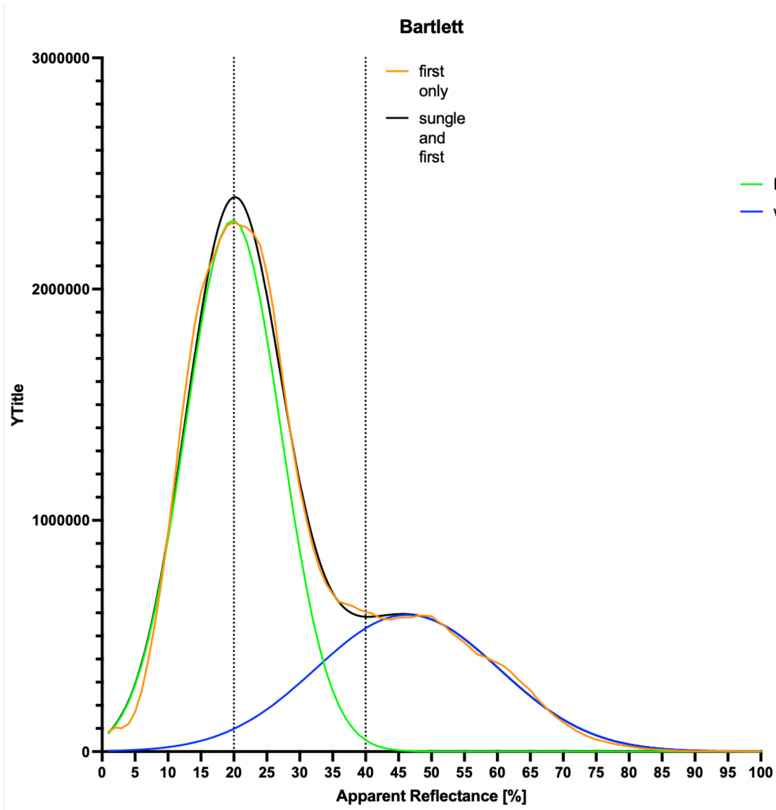

Figure 1: Example of histogram used for wood-leaf separation at the Bartlett site, lower threshold is 10% and upper threshold is 40%

Here we used a novel approach to improve the point classification results. The approach combines information on point reflectance and its spatial relation to neighbours. We first move the threshold on apparent reflectance to a higher value to include the majority of leaves (a value of 40 is used at Bartlett in the example shown in Figure 1). This implies that a significant amount of points which are actually wood are included (the area under the brown curve in Figure 1). The LeWoS model (Wang et al., 2019) is then used to derive the probability, for each point, that the point belongs to the wood class on the basis of recursive segmentation. The two classifications (based on apparent reflectance and recursive segmentation) and then compared, and the following rule is used to modify the reflectance-based classification: if a point is classified as leaf and is associated with a probability greater than 90% to be associated with wood by the recursive segmentation-based approach, then the point's class is modified to wood. This approach aims to include most of the leaves while significantly reducing the number of points associated to wood classified as leaves. On the basis of visual analyses of samples 7 meters in diameter at the center of each plot classified, this approach was found to significantly improve the results from both the classifications produced individually by both methods. The LeWoS model was found particularly efficient at classifying trunks and large branches, but missed several of the smaller branches. Hence, the approach used here, while providing very satisfactory results for the intended purpose, is believed to have resulted in the classification of some highly reflective leaves as wood, and some of the smaller branches as leaves.

Even if the leaf/wood separation threshold is quite high, there may still be a significant amount of leaves classified as wood, and this may significantly influence the wood structure matrix, especially in cases of very high pulse density scans. To reduce the number of incorrectly classified wood points, I added a second rule using the Lewos probability of points being wood points which was not presented in Beland and Baldocchi 2021 supp mat: a point classified as wood which has a Lewos probability less than 50% of being wood is reclassified as noise, because its class is too uncertain. These two above thresholds were selected based on visual evidence and a fit to best available estimates for temperate deciduous forests, they may require adjustment depending on canopy type and scanning configuration.

4.4. Preparing Riegl RXP files for Matlab analysis

This part requires all RXP files to be in a single directory and to be renamed for processing. Use File 6. A C++ compiled for usage on any PC was developed to extract the information from the RXP files which will be needed by the Matlab codes. Use File 7 in PC. To call this code, use the following command line in command window:
Example to call Read_RXP: readRXP_MB_binary_class -input ScanPos1.rxp -trans ScanPos001.DAT -output ScanPos1.bin -minRefl 10 -maxRefl 40 -bounds -6 -59 324 54 1 360

<u>Careful</u>: the readRXP_MB_binary_class C++ code classifies points with deviation higher than 25 as noise, and contains a normalization of the apparent reflectance which uses an equation (line 366 of CPP code) developed specifically for the VZ-400 instrument operated by the Digital Forest Lab, other instruments are known to have a different response signal and this may introduce inaccuracies in the apparent reflectance calculated when using another instrument.

All RXP and DAT files need to be in the same folder as the executable. Typically a .bat (batch) file is used to call this code for all scans. Use File 8.

4.5. Preparing files for Lewos

The Lewos model is used to estimate the probability of a point being wood on the basis of topological metrics. The point clouds need to be combined and down-sampled so that the total number of points is manageable to the Lewos code. To do this we will start by creating a copy of the entire Riscan project, since we will be deleting points.

From the copied project, right click one point cloud.. filter point cloud.. select back to have the list of scans.. right click select all. Select by attribute, match any. XYZ[0] gate below -70 above 70, same for XYZ[1], deviation greater than 25, target index greater than 1. This reduces the coverage of the point clouds, removes ghost points, and keeps only first or single returns.

Create octree file for Lewos, right click on one point cloud, use create pointcloud.. use back.. select all scans, check octree, check combine data, copy to new file, all resolutions at 0.02 m, min point 1, merge 0, output real data point.

Filter the resulting point cloud using bbox coordinates (in project coord system), use again right click on pointcloud which is under folder objects.. filter pointcloud. Manually remove the ground points on the octree point cloud, use selection mode.. delete selected area. Export only x,y,z coordinates, use right click on octree point cloud..export.

To launch Lewos use File 9. This file should be in folder Lewos along with a number of other files required to run the Lewos model. Will produce a binary file, with name ending with_LeWoS_results.bin.

Combine the Lewos results with apparent reflectance to classify noise, leaf and wood, following the procedure described in Beland and Baldocchi 2021 supp mat. Use File 10. This process takes about 30 minutes per odd scan position, it may be tempting to launch between different instances of Matlab and separate the scan positions between instances. The code produces a sample point cloud showing the classification result for a small area in the center of the plot for visualisation purposes. The file is ascii (.asc) and can be visualised with point cloud visualisation software. The point cloud has 4 colors:
black : wood remained wood
Red: leaf changed to wood
Blue: wood changed to noise
Green: leaf remained leaf
This sample point cloud is quite useful to verify the efficiency of the classification process.

5. Data processing in Matlab and product outputs

5.1. Leaf area density array

Run the ray tracing code, using File 11. This process is long and can be split between multiple instances of Matlab.

Run the statistics analysis code, which will compute leaf area density for each voxel, use File 12.

Run code to correct for occlusion and integrate the within voxel clumping factor. Use File 13. This step requires determining the Poisson correction factor, and the function parameters plateau, y0, k, and x0 used to assign a within voxel foliage clumping value to each voxels as a function of height above ground. The Poisson factor is set following Beland et al 2014 AFM. The foliage clumping parameters are obtained from Beland and Baldocchi 2021 AFM.

5.2. Wood area density array

Use File 14 to run ray tracing for wood. Adjust the number of scan positions if needed. Again, this process is long and can be split between multiple instances of Matlab.
Use File 15 to generate the wood area density array. Add the wood angle distribution function to line 285 for the site being processed. Use File 16 to remove the ground in the WAD array.

5.3. Joining the LAD and WAD arrays for radiative transfer modeling in FLiESvox

Use File 17 to join the LAD and WAD arrays in one single file formatted to be input into FLiESvox, or modified to comply with the DART model format. The FLiESvox format is : voxel xmin, ymin, zmin, xmax, ymax, zmax, leaf area density, G code, wood area density, 0, 0, 0 (these are later used for optical properties), within voxel foliage clumping factor.

5.4. Generating a foliage clumping vertical profile

This approach integrates clumping occurring at the within voxel (or shoot) scale, and the clumping occurring at larger scale, i.e. considering the aggregation of leaves in crowns. The principle draws from two contributions by Warren Wilson (1959) and Nilson (1971). The former proposed a method to estimate foliage clumping in crops by inserting a long needle through the canopy (penetrating a leaf upon contact) and counting the number of contacts between the needle and leaves, this method uses the relative variance in contact numbers. The former presented an equation based on the Markov model to calculate the probability to make n contacts with leaves when inserting a needle inside a volume where leaves are clumped. The integration of these two theoretical approaches to simulate the insertion of virtual needles through the voxel array is described in Béland and Baldocchi (2021). Run code in File 19 and File 20.

6. Visualize results and accuracy checks

It is important given the complexity of this process to perform check on the quality of the work done. This can be done by consulting outputs files like
XXXX_5mgrid_WAD_no_zeros.asc_statistics.asc and
XXXX_5mgrid_LAD_no_zeros.asc_statistics.asc. But also by visualizing the voxel matrix, this can be done using the Visit software :
https://visit-dav.github.io/visit-website/releases-as-tables/
And code in file 18 to generate the vtk input. In visit open the vtk file, then menu add, pseudocolor, LAD, and draw button.

7. List of required Matlab codes and other files

File name	File #
One Riscan project containing the tiltmount calibration	*File 1*
create_combined_transformation_matrices_from_SOP_matrices.m	*File 2*
create_batch_file_to_rename_files.m	*File 3*
used_copy_parse_riscan_files_and_create_histograms.m	*File 4*
leaf wood histogram gaussians.xlsx	*File 5*
batch_copy_and_rename_RXP_files.m	*File 6*
readRXP_mb_binary.exe	*File 7*
create_readRXP_batch_file.m	*File 8*
Launch_lewos.m and other files in Lewos folder	*File 9*
Read_LeWoS_pt_cloud_toconfirm_leaf_class_temp.m	*File 10*
wooRaytraceTests_mb_v3_binary_split_workers.m , wooRaytrace.mex64 and rayBoxIntersection.m	*File 11*
read_RXP_statistics_compute_LAD_multidirectional_pathlenght.m	*File 12*
generate_vertical_profile_correct_occlusion_50mplot_v4.m	*File 13*
wooRaytraceTests_mb_v3_binary_split_workers_for_wood	*File 14*
read_RXP_statistics_compute_wood_AD_multidirectional_pathlenght.m	*File 15*
remove_ground_from_WAD_array.m	*File 16*
Combine_LAD_and_WAD_arrays.m	*File 17*
convert_fliesvox_input_to_VTK_50mplot.m	*File 18*
generate_needle_grid.m	*File 19*
wooRaytraceTests_mb_v2_relative_variance_v2_withNilson.m	*File 20*

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