Specification of the CHP toolkit

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Acknowledgement

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General information

This document describes the functionality of the Canopy Height Profile program. The Program requires PulseWaves (https://github.com/PulseWaves) format as input file (.pls and .wvs) and it is designed to convert relatively small raw full-waveform small-footprint LiDAR datasets over vegetated areas into leaf area index (LAI) and vegetation vertical profiles (CHPs). The program consists of four modules:

- **Module 1** – reads PulseWaves format and converts the data into "*_fulwvs.txt" file over a selected area
- **Module 2** – reads the "*_fulwvs.txt" and detects the position, amplitude, width of peaks in the returned waveform data (simple pulse detection algorithm)
- **Module 3** – uses data from Module 2 to filter ground points from single-peak returns and from last returns
- **Module 4** – uses files from Module 1, 2, 3 and processes to obtain leaf area index estimates as well as canopy height profile

Additionally Module 2, 3 and 4 are provided with visualization option ("_VIS" extension). The visualizations were created using PLplot library (http://plplot.sourceforge.net/index.php) therefore using the source code of those modules will require downloading that library. Executable files will also require copying the PLplot files included in the share folder into the directory where those executable file sit. The visualization plots are saved to a postscript *.psc file.

The program is provided with three example file case studies to illustrate the usage and application.

A brief description of the methodology is given in the introduction of this document. Further information can be found in the following article http://www.sciencedirect.com/science/article/pii/S092427161500060X. If you happen to use this program you are kindly asked to acknowledge it by citing Fieber et al. (2015) Validation of Canopy Height Profile methodology for small-footprint full-waveform airborne LiDAR data in a discontinuous canopy environment. ISPRS Journal of Photogrammetry and Remote Sensing. Volume 104, 144-157.

This program is designed to provide estimates of LAI and CHP for tree-covered areas. It is not meant for small crops especially if they are shorter than half of the transmitted pulse width. In such a case calculation of LAI from discrete returns (after full decomposition with optimisation of Gaussian fit) may be an alternative, however may still not provide good results. The program allows calculation of LAI and CHP in small grid cells, whose size can be adjusted to the heterogeneity of the vegetation. One needs to remember that in case of LAI saturation (lack of ground return) in a particular cell, LAI for the whole site will still be calculated by either removing the saturated cells or replacing them with the highest calculated grid-level LAI in the tested site. While for LAI calculation, gridding may help provide better site level LAI estimate in discontinuous canopies, in the case of CHPs one should use a grid-cell size giving rise to no or very few saturated cells. Saturated cells are removed from the calculation of CHP, therefore with a high number of those, the profile will be biased. Due to its relative character, heterogeneity of vegetation should have less impact on the CHP profile then removal of saturated cells.

1 Introduction - Canopy Height Profile methodology

The waveform methodology is based on the SLICER Canopy Height Profile processing proposed by Harding et al. (2001). This methodology was adapted to small-footprint LiDAR and tested by Fieber et al. (2015) in discontinuous canopies. Canopy Height Profile (CHP) represents the relative vertical distribution of canopy surface area (vertical vegetation profile), and accounts for occlusion of the laser energy by the canopy. Leaf area index is derived as one of the stages of CHP processing. The CHP procedure is performed in five stages: waveform alignment, returned energy profile, canopy closure profile, cumulative leaf (plant) area index profile, and canopy height profile. The advantage of the waveform method over point methods is that it does not require the full decomposition with optimisation procedure of the waveform data or calibration of the data. The knowledge about approximate position of the first and the last pulse within the waveform obtained after initialisation step of decomposition is sufficient, which is much less timeconsuming and requires much less processing power. There is a need for DTM information though, but if the full-decomposition is not performed, DTM can also be derived from other sources of data or approximated from the initialisation step.

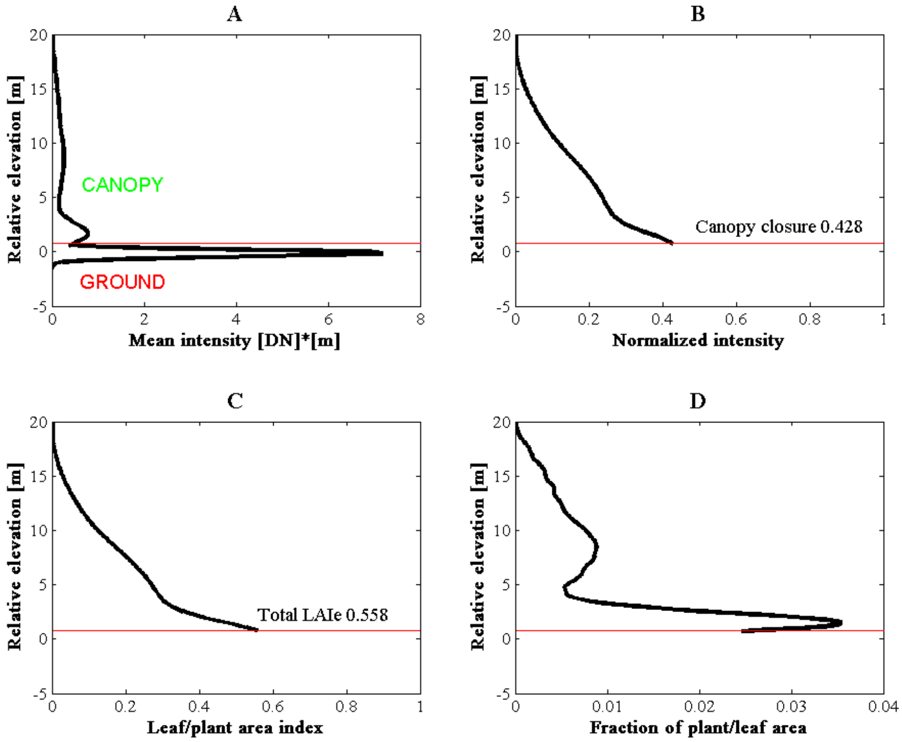

Figure 1. Example of CHP processing stages for Site 10: A. Returned energy profile; B. Canopy closure profile; C. Cumulative leaf/plant area index profile; D. Canopy height profile. Red line represents the beginning of ground return. (Fieber et al. 2015)

Waveform alignment

Received waveforms as well as the DTM and information about first and last peak location within the waveform are first used to align waveforms according to the elevation above ground level. This is done by computing the coordinates of the last peak within the waveform train and finding the corresponding mean ground elevation in the DTM. The mean noise is subtracted from each raw-waveform and the beginning of the first and end of the last pulse identified. The relative elevation of the beginning of the first pulse was then calculated and used as an offset when combining with other waveforms to ensure that the ground is at the same level.

Returned energy profile

The area underneath each waveform is calculated separately for each height bin according to:

$$A_r(i+1) = \frac{a_{bin,i} + a_{bin,i+1}}{2} * (-\Delta Z)$$

(1-1)

where $a_{bin,i}$ is the amplitude of i-th bin in the amplitude train (corresponding to elevation z AGL, from the top to bottom of the canopy) and ΔZ is the elevation change per 0.15m bin. This area was then matched with the appropriate 0.15m height bin z (AGL). The returned energy profile is subsequently obtained by bin-wise averaging across the dataset whether that be within grid cells, over a plot or over the site (Figure 1A).

Canopy Closure

Canopy closure is the probability of the laser pulse being intercepted before reaching the ground and therefore it is equivalent to 1- P in point and hybrid methods, where P is the probability of laser pulses reaching the ground. Returned energy profiles, corrected for the vegetation-ground reflectance difference, are turned into canopy closure profiles (Figure 1B). First, the ground return is separated from the vegetation part of the return energy profile. Second, the cumulative area underneath the energy graph corresponding to vegetation was calculated from top (z_{max}) to bottom (z_{min}) of the canopy (first to last canopy bin). The profile is then normalized by the total cumulative area A_{rt} of the whole energy graph including ground return ($A_{rt} = \sum_{z_{max}}^{z_{ground}} A_r(z)$, where z_{ground} is the last ground bin).

$$closure(z) = \frac{\sum_{z_{max}}^{z_{min}} A_r(z)}{A_{rt}}$$

(1-2)

Effective leaf area profile and index

To correct for the effect of occlusion, the profile of canopy closure was then converted into a cumulative leaf area graph (Figure 1C). The last vegetation bin value is treated as the total $LAIe$ value for the dataset. This profile can also be referred to as plant area profile. The conversion is performed by applying the following transformation (Lefsky et al., 1999)

$$LAIe = -\ln(1 - closure)$$

(1-3)

Canopy Height Profile (CHP)

The leaf area profile is finally turned into Canopy Height Profile by converting the normalized cumulative leaf area index profile into an incremental height distribution (Figure 1D). CHP represents the relative vertical distribution of canopy components (Harding et al., 2001). In the case of grid-processed datasets the aggregation of cells is performed prior to normalization of the profile.

Reflectance ratio

Reflectance ratio r is calculated according to Armston et al. (2013). The areas of light returned from vegetation part R_v and ground part R_g underneath the averaged energy profile in the aggregation area are calculated and used together with an average area of a single ground return

S_g within that area as follows assuming that ground reflectance is constant and its mean converges to a normal distribution:

$$r = \frac{\rho_v}{\rho_g} = \frac{-R_v}{R_g - S_g}$$

Program workflow

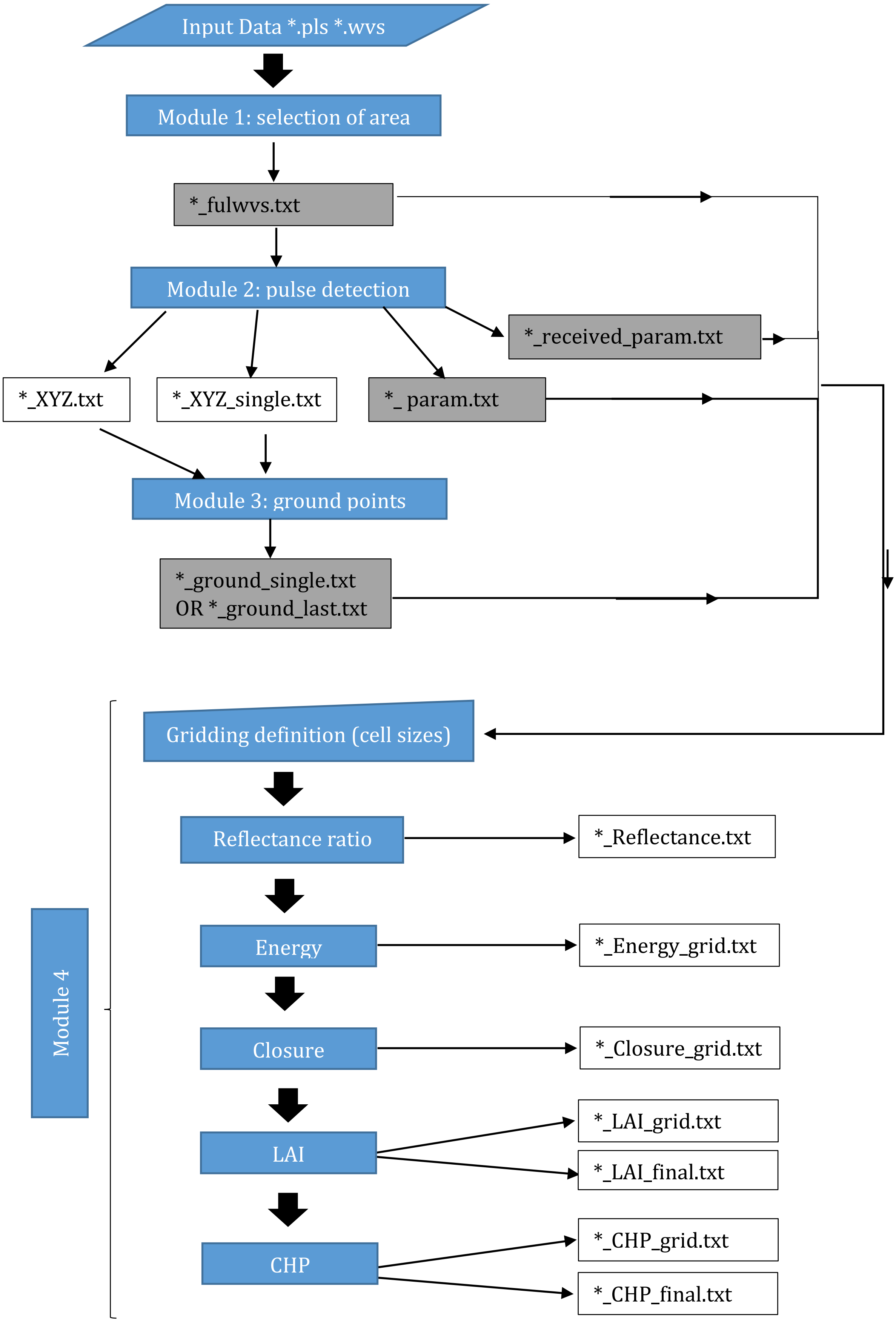

Figure 2. Program workflow

CHP toolkit User Manual

1 Module 1

Module 1 of the program allows reading PulseWaves *.pls/*.wvs files and selecting the area of interest. The data from the selected area are then output to a text file to allow further analysis. Module 1 first reads the *.pls file and provides the user with information on the extent of the data and number of waveforms in the file. Before the *.wvs file is read the user has the possibility to limit the data to a desired area by either typing in the coordinates or by reading in a parameter file with area specification.

1.1 INPUT

The program requires input files in PulseWaves format: *.pls/*.wvs. PulseWaves is an open source program that reads LiDAR data from a wide range of instruments and formats and can be obtained here: https://github.com/PulseWaves. Pulse2pulse tool will allow the user to convert their data into PulseWaves format. Module 1 will first prompt the user to provide the name of the file to be processed (i.e. if the name of the file is TestData.pls/ TestData.wvs, TestData alone should be typed in). Data information such as number of waveforms in the file as well as data extents will be then shown on the screen. The user is then asked to specify whether they want to use a parameter file with the parameters of the area to process. If yes, then they should create a file named TestData_parameter_area.txt. The structure of this input file is provided below in section 1.1.1. If the answer is no, then the user will be prompted to specify the area of interest and all its parameters. Like in the case of parameter file there are four processing options available: all data (0), circle (1), rectangle (2) and cuboid (3). Putting in 0 will make the whole file be processed.

1.1.1 *_parameter_area.txt (optional)

Parameters file contains information about the location and character of the area of interest to be extracted. It should be named "[file_name]_parameter_area.txt" (eg. TestData_parameter_area.txt) and its first line should describe the type of the area i.e. 0 = all data, 1 = circle, 2 = rectangle, 3 = cuboid. The data structure is as follows:

- All data (0) - If all data is to be extracted then 0 or any other number (other than 1 to 3) should be selected. The program will then output all the data in the file it is reading.

  Example: 0

- Circle (1) - if circle is to be extracted then the Easting and Northing coordinate of the circle centre and the radius in meters need to follow in subsequent lines.

  Example:
  ```
  1
  6169300
  55393400
  15
  ```

- Rectangle (2) - if rectangle is selected, its Easting (west edge, East edge) and Northing (south edge, north edge) boundaries need to be provided in subsequent lines.

  Example: 2
6169300
6169330
55393400
55393500

- Cuboid (3) - If cuboid is selected, its Easting (West edge, East edge) and Northing (South edge, North edge) boundaries need to be provided followed by the Elevation boundaries (low edge, high edge) and extraction amplitude threshold. The extraction threshold is the minimum amplitude that a single bin has to have within the cuboid in order for the entire waveform to be extracted. So if a waveform passes through the cuboid, but none of its bins within the cuboid are greater than the threshold, then the waveform is ignored. It is to make sure only strong returns in the area cause the waveform to be output.

  Example: 3
6169300
6169330
55393400
55393500
150
200
20

1.2 OUTPUT

Each of the modules produces an info file, entitled [file_name]_info_ModulX.txt where general information about the processing and data are stored. Therefore if the program happens to quit for some reason, it is good to check the info file as it is likely that there will be some clues in it.

1.2.1 *_info_Module1.txt

Contains information on user input while running the program as well as the general data information such as: number of waveforms in the original file, data extents, number of waveforms in the selected area, number of multi-segment waveform, and length of returned waveforms with their count etc. If the user's data do not contain transmitted waveform this will also be noted in the info file.

1.2.2 *_fulwvs.txt

This is the main file output by Module1 of CHP program. It contains the following information in each line separated by comas:

- Waveform ID, GPS time, sampling unit [ns], pulse descriptor,
- pulse origin Easting, pulse origin Northing, pulse origin Elevation,
- number of samples in transmitted waveform,

- for i=1 to i<= number of samples in transmitted waveform
    - transmitted waveform amplitude samples[i],
- Easting vector, Northing vector, Elevation vector,
- total number of segments,
- consecutive segment number, Number of bins from pulse origin (offset),
- Easting of waveform first bin (in particular segment), Northing of waveform first bin, Elevation of waveform first bin,
- number of samples in the returning waveform,
- for i=1 to i<= number of samples in the returning waveform
    - returning amplitude samples [i],
- maximum waveform elevation (elevation of the strongest amplitude bin)

Example:
1,0,1,1,54307097.750000,6141055.920000,699.840027,98,2,1,2,2,2,3,3,2,1,1,2,10,38,90,154,208,180,115,
59,25,11,8,6,6,8,8,9,8,6,6,7,7,6,5,5,5,5,5,6,5,5,5,5,4,4,3,2,3,4,4,3,3,3,4,4,4,3,3,2,3,3,3,3,2,1,3,2,3,3,4,3,3,2,2,3,
3,3,2,3,3,3,3,2,3,3,2,2,1,2,3,3,3,3,1,1,1,1,1,-0.055640,0.026090,-
0.136670,1,1,2004,54306986.247438,6141108.204360,425.953360,98,2,1,1,1,1,0,0,0,1,1,2,2,8,28,76,140,
211,206,134,75,33,14,9,5,6,7,8,8,6,6,5,5,4,4,4,4,5,4,4,5,5,4,4,3,3,3,4,5,5,5,4,3,3,3,4,3,3,3,3,3,3,2,3,2,2,1,2,3,4,
4,4,3,3,3,3,2,2,3,3,3,2,1,2,3,3,3,3,3,2,2,2,2,2,2,3,3,4,2,423.629970

2 Module 2/Module 2 VIS

This module reads the data from *_fulwvs.txt file and carries out simple peak detection procedure. Similar to those used in Fieber et al. (2013). The user is prompted to provide the file name. This should be exactly the same as in the Module 1 e.g. TestData. Transmitted waveforms are processed first to determine parameters such as:

- mean amplitude of transmitted pulse
- mean width of transmitted pulse
- mean noise within transmitted waveform
- ringing ratio (amplitude of ringing echo to amplitude of the transmitted echo)

Once these are known, the program will ask the user whether they want to change the value of the mean noise or mean ringing ratio. If the answer is yes ("y") then the user will be able to provide the new values that will be used in peak detection procedure. Once they are provided the peak detection algorithm will be carried out on received waveforms. Up to 6 returns are detected.

If the data does not contain transmitted waveforms, then the user will be prompted to give approximate values of the parameters above in order to enable peak detection processing. Some suggested values will be provided by the program but the user can also determine them by looking at *_fulwvs.txt file as well as by checking the specification of the instrument (e.g. pulse width).

An additional function of **Module 2 VIS** is that it provides a visualization of all points detected in the waveforms. This visualization is meant to give the user the idea of the data included in the dataset. It is advisable that the user imports the data into an interactive visualization program (e.g. FUSION) to verify the quality. In order for the Module 2 VIS to work, the user needs to copy the Plplot share files into the working folder.

2.1 INPUT

The input file required by Module 2/Module 2 Vis is *_fulwvs.txt with the structure described in 1.2.2.

2.2 OUTPUT

Module 2 produces one info file (*_info_Module2) and four other output files. The structure of the files is described below. In case of Module 2 VIS a *_all_XYZ.psc visualization file is also saved.

2.2.1 *_info_Module2.txt

Contains information on user input while running the program as well as the general data information such as: number of waveforms processed, number of 1-, 2-, 3-, 4-, 5-, and 6-peak waveforms, total number of detected points etc.

2.2.2 * _received_param.txt

This file contains information about the peaks detected in the received waveforms. The data structure is as follows:

- Waveform ID number,
- number of peaks in the waveform,
- For i=1 to i<=number of peaks in the waveform
  - Peak position[i] from the beginning of the waveform (in bins), peak amplitude[i] in digital numbers, peak width[i] – full width at half maximum (FWHM) in ns

Example: 2,3,25.00,98.00,4.750894,30.50,49.00,4.565105,37.50,22.00,3.821948

2.2.3 *_param.txt

This file contains data parameters such as:

- Total number of waveform processed
- Total number of single-return waveforms
- Total number of peaks detected (if the user wants to use their own DTM file in Module 4, this value needs to be changed before running Module 4 to specify the number of points included in the user's DTM)
- Sampling unit (e.g. 1ns)
- Mean transmitted amplitude
- Mean transmitted pulse width (FWHM)

- Mean received amplitude of single-return peaks
- Mean received width of single-return peaks
- Mean noise in transmitted waveforms
- Mean elevation vector

Example: 28307
3455
76740
1
120.000000
9.000000
96.037337
12.481759
12.500000
0.148465

2.2.4 * _XYZ.txt

This file contains parameters of every detected peak. The file structure is as follows:

- Waveform ID number
- Consecutive peak number within the waveform
- Total number of peaks within the waveform
- Amplitude
- Width (FWHM)
- Easting
- Northing
- Elevation
- Angle of incidence

Example: 2,1,1,75,4.953030,55393444.580060,6169253.453920,127.686960,10.961400

2.2.5 * _XYZ_single.txt

This file contains parameters of single peaks detected (where there is only one return within a waveform). The file structure is as follows:

- Waveform ID number
- Peak number
- Amplitude
- Width (FWHM)
- Easting
- Northing
- Elevation

Example: 1,1,101,13.416667,448968.106235,211161.155806,67.690722

3 Module 3/ Module 3 VIS

Module 3 is aimed at providing an approximation of a digital terrain model (DTM). The program goes through the single and last returns trying to establish the ground level. Two ground point files are produced. As in the case of Module 1 and 2 the user first needs to specify the file name, which should be exactly the same as in the previous modules e.g. TestData. Then the program prompts the user to choose between two options of elevation comparison. Depending which option (mean or weighted mean) is chosen, the program compares the elevation of each single or last return point (from *_XYZ_single.txt or *_XYZ.txt) to the mean or weighted mean elevation (respectively) of points within specified search area. If that elevation is higher or lower than a certain threshold then the new elevation of mean or weighted mean is assigned to that point. In the case of weighted mean, the inverse square of the distance from the target is used as weight. Subsequently, the dimension of the search area needs to be provided.

It is advisable that before proceeding to Module 4 the user verifies the quality of the ground point files and choses the better one for further analysis. **Module 3 VIS** provides a simple visualization of the ground points selected from single and last returns to help the user decide which option is better for further processing. It is however advisable that the user imports *_ground_single.txt and *_ground_last.txt into interactive visualization program (e.g. FUSION) to verify the quality (eg. compare to XYZ point cloud file 2.2.4). If there is a problem with ground point elevation, different search areas can be tested or the files can be edited or other source DTM can be used.

3.1 INPUT

This module requires *_XYZ_single.txt, *_XYZ.txt and *_param.txt as input files.

3.2 OUTPUT

Two output files are generated *_ground_single.txt and *_ground_last.txt. The info file is also provided. In case of Module 3 VIS a *_ground_last.psc and *_ground_single.psc visualization file are also saved.

3.2.1 *_info_Module3.txt

Info file provides the information on the user input parameters as well as which files have been processed and how many ground points were in single and last return ground point selection.

3.2.2 *_ground_single.txt

This file contains Easting, Northing and elevation of single-return based ground points

Example: 55393359.902160, 6169328.804800, 122.320696

3.2.3 *_ground_last.txt

This file contains Easting, Northing and elevation of last-return based ground points.

Example: 55393359.902160, 6169328.804800, 122.320696

4 Module 4/Module 4 VIS

Module 4 generates leaf area index and canopy height profile estimates in a specified area/grid. After specifying the name of the file to process (the same as in the case of previous Modules i.e. TestData) the user needs to decide which file with ground returns they want to use. Selecting 1 will make the program use *_ground_single.txt file; selecting 2 will mean that *_ground_last.txt file will be used. The user also has the option to provide their own file with digital terrain model (DTM) by selecting 3. In such case the DTM file needs to be in the same format as the other ground point files (Easting, Northing, Elevation) and should be named *_ground_own.txt. The value of the total number of peaks detected in *_param.txt (2.2.3) file should also be changed to the total number of points in the user's own DTM file. Once the ground point file is specified the user will be prompted to provide the following parameters:

- Lower left corner coordinates of the area of interest (South West corner)
- Grid cell size
- Site dimensions
- Default reflectance ratio
- Approximate tree height
- Default location where the canopy ends (in bins, counting from the ground level)

Module 4 VIS includes the same functionalities as Module 4 with addition of visualization of the Canopy Height Profile and LAI map. Alternatively the plots can be generated by separate programs: CHP_plot.exe and LAI_plot.exe.

Lower left corner, grid cell size, site dimensions

The lower left corner coordinates (South West) and site dimensions should be within the extents of the data provided in *_info_Module1.txt file. If the user wants to process the whole file at once without gridding, the grid cell size and site dimension should be the same and equal (or larger) to extents provided by *_info_Module1.txt file. If the user wishes to process a circular area, then they should specify the desired circular area of interest in Module1. In such case LAI and CHP generation should only be performed for the whole area at once. Gridding should not be performed on circular plots as in such case the weighting system should be applied in site-level LAI calculation for the cells that are not completely covered by the data, and that is not implemented in the current version of the program.

Default reflectance ratio

Default reflectance ratio between vegetation and ground reflectance is very important. This value will be used in case the dataset-adjusted reflectance ratio cannot be calculated. The default value will depend on the laser wavelength. For instruments with 1064nm wavelength this value should be around 2, whereas for 1550nm wavelength it should be in the order of 0.5. It may be an idea to process the whole site at once to get initial estimate of the reflectance ratio value for specific dataset and then providing it is plausible, use it as default value when calculation is performed in grid cells.

Approximate tree height

This is just an approximate height above ground level (AGL) of the vegetation canopy in the user's study area. If the value specified by user is too small the program will quit and the *_info_Module4 file will have such information in it.

Default location where the canopy ends

There is an option to set up at a cut-off point where the canopy finishes and ground return starts above ground level (AGL). This is for example if one wants to exclude shrubs/understory/grass below certain height from LAI/CHP calculation. For every waveform the peak of the ground return should be at the ground level 0 (assuming good quality of the DTM and shallow angle of incidence). Therefore for a waveform with width of transmitted pulse equal 4ns, in at least 2ns=30cm AGL the vegetation will not be distinguishable from ground. It is advisable to set this threshold to a value equal more than half the transmitted pulse width (FWHM) to avoid having ground return included in the calculation of LAI and CHP or leave it to up to the program (by typing -999) to determine where the separation is. In the latter case a minimum bin value of return energy (prior to scaling of the ground return with reflectance ratio) profile will be searched from the ground level up to one bin above the transmitted pulse width (so if width is 9ns, the search area will be 10ns = 1.5m AGL). If a minimum bin value is not found in that range a default value of half the pulse width + 2ns is used.

4.1 INPUT

Module 4 requires four input files *_fulwvs.txt, *_param.txt, *_received_param.txt and *_ground_single.txt or *_ground_last.txt or *_ground_own.txt.

4.2 OUTPUT

Module 4 produces three default output files and five optional output files. One of the default files is the info_Module4.txt file; there are further two files with the final output of LAI and CHP and five optional detailed files which provide data at each stage of the CHP methodology for all of the cells. In case of Module 4 VIS two visualization files are also saved: *_LAI.psc and *_CHP.psc.

4.2.1 *_info_Module4.txt

The info file provides the information on the parameters specified by user as well as the final site LAI estimate for the whole area and potential cells with no data or no ground return. For comparison three possible site LAI values are provided to account for the case when some of the cells are saturated (do not have a ground return):

- when the saturated cells are replaced with the highest LAI cell value prior to computation of the site mean LAI
- when saturated cells are replaced with the above site LAI value prior to computation of the site mean LAI
- with saturated cells removed

4.2.2 *_LAI_final.txt

This file provides LAI values for each cell to enable plotting a LAI map. First the grid cell size in X (Easting) and Y (Northing) are provided, followed by site dimensions and lower left corner (South West) coordinates. LAI values of each cell follow (starting from South West corner).

Example:

```
10.000000, 10.000000
50.000000, 50.000000
448900.000000, 211130.000000
0.276251,0.307215,0.339103,0.260284,0.162760,
8.318441,8.318441,5.474961,5.109528,8.318441,
4.576699,5.600142,2.288512,2.927912,1.992333,
4.889554,3.535178,1.541712,2.653752,2.240345,
2.065623,7.064571,1.450549,1.552772,8.318441,
```

4.2.3 *_CHP_final.txt

This file provides the final CHP for the whole site ready for plotting. It consists of the number of height bins and list of height bin values followed by the number and corresponding CHP values for each bin.

Example:

```
51
5.925000,5.775000,5.625000,5.475000,5.325000,5.175000,5.025000,4.875000,4.725000,4.575000,4.425
000,4.275000,4.125000,3.975000,3.825000,3.675000,3.525000,3.375000,3.225000,3.075000,2.925000,2
.775000,2.625000,2.475000,2.325000,2.175000,2.025000,1.875000,1.725000,1.575000,1.425000,1.2750
00,1.125000,0.975000,0.825000,0.675000,0.525000,0.375000,0.225000,0.075000,-0.075000,-0.225000,-
0.375000,-0.525000,-0.675000,-0.825000,-0.975000,-1.125000,-1.275000,-1.425000,-1.575000,
51
0.000000,0.000000,0.000000,0.000000,0.000001,0.000006,0.000027,0.000095,0.000284,0.000741,0.001
689,0.003434,0.006321,0.010632,0.016477,0.023686,0.031724,0.039830,0.047268,0.053481,0.058152,0
.061172,0.062605,0.062656,0.061698,0.060082,0.057986,0.055420,0.052341,0.048793,0.044732,0.0399
32,0.034108,0.027271,0.020148,0.017208,0.000000,0.000000,0.000000,0.000000,-999.000000,-
999.000000,-999.000000,-999.000000,-999.000000,-999.000000,-999.000000,-999.000000,-
999.000000,-999.000000,-999.000000,
```

4.2.4 *_1_Energy_grid.txt (optional)

This file consists of information on the energy profile for each cell (best viewed in Excel). First the height bin values are provided and followed by the profile of each cell. For easier reading, the cell address in the form of [row, column] is provided at the beginning of each line. Be aware that Easting corresponds to columns and Northing to rows. Values of -999 mean no data in the cell.

Example:

Cell_no,,,5.925000,5.775000,5.625000,5.475000,5.325000,5.175000,5.025000,4.875000,4.725000,4.575000,4.425000,4.275000,4.125000,3.975000,3.825000,3.675000,3.525000,3.375000,3.225000,3.075000,2.925000,2.775000,2.625000,2.475000,2.325000,2.175000,2.025000,1.875000,1.725000,1.575000,1.425000,1.275000,1.125000,0.975000,0.825000,0.675000,0.525000,0.375000,0.225000,0.075000,-0.075000,-0.225000,-0.375000,-0.525000,-0.675000,-0.825000,-0.975000,-1.125000,-1.275000,-1.425000,-1.575000,

[1,1],,0.000000,0.000000,0.000000,0.000000,0.002796,0.013059,0.032609,0.081323,0.182013,0.343921,0.593991,0.955374,1.412800,1.949234,2.490380,2.962670,3.316746,3.470788,3.465949,3.321262,3.046426,2.729668,2.395693,2.064824,1.765890,1.493915,1.280253,1.125673,1.034276,0.975201,0.869299,0.708700,0.504938,0.327247,0.207273,0.358919,1.618876,4.192162,7.992008,11.720048,12.073935,8.626510,4.812900,2.260248,0.929341,0.400513,0.095963,0.000000,0.000000,0.000000,0.000000,

4.2.5 *_2_Closure_grid.txt (optional)

This file consists of information on canopy closure profile for each cell. The structure is exactly the same as that of *_1_Energy_grid.txt (4.2.4).

4.2.6 *_3_LAI_grid.txt (optional)

This file consists of information on the LAI profile for each cell. The structure is exactly the same as that of *_1_Energy_grid.txt. At the end of the file there is also information about the total site LAI value (same as in the info_Module4.txt file).

4.2.7 *_4_CHP_grid.txt (optional)

This file consists of information on CHP profile for each cell. The structure is the same as that of *_1_Energy_grid.txt (4.2.4).

4.2.8 *_5_Reflectance.txt (optional)

This file contains information on cell reflectance calculation. Values of Vegetation Energy, Ground energy reflectance ratio and mean single ground energy are provided for each cell. Finally at the bottom of the file, the reflectance ratio array is given and total site reflectance ratio provided.

Example:

Cell no: Vegetation Energy, Ground Energy, Reflectance Ratio, Mean single ground energy
[1,1]: 45.483110, 54.226028, 0.500701, 145.064972,
[1,2]: 42.806864, 61.955782, 0.497392, 148.018407,
[1,3]: 43.607339, 61.190714, 0.492910, 149.659958,
…..
Reflectance array
row1,
0.500701,0.497392,0.492910,0.520975,0.525979,0.528765,0.496542,0.517460,0.516568,0.500703,0.503095,0.537041,0.505638,0.472977,0.508375,
row2,
0.502243,0.502420,0.534281,0.528301,0.505362,0.512302,0.520412,0.524115,0.503193,0.524329,0.502009,0.516290,0.499090,0.508830,0.493192,
row3,
0.498597,0.537368,0.534152,0.554309,0.546586,0.531259,0.534030,0.522773,0.532168,0.536730,0.545160,0.510156,0.527434,0.508679,0.508156,
row4,
0.539764,0.499895,0.525872,0.586439,0.596006,0.569076,0.622587,0.583754,0.540320,0.541890,0.536848,0.521268,0.510310,0.515417,0.513240,

row5,
0.549521,0.577699,0.586989,0.618875,0.694932,0.677560,0.645151,0.602885,0.568697,0.555113,0.564154,0.575453,0.530981,0.567183,0.521936,
row6,
0.672480,0.640381,0.689444,0.647089,0.657274,0.643076,0.606304,0.606927,0.603246,0.584730,0.601477,0.598325,0.554688,0.525224,0.536557,
row7,
0.670800,0.708782,0.624260,0.593895,0.612972,0.613450,0.569700,0.515204,0.554552,0.531404,0.576114,0.584497,0.548691,0.593387,0.556404,
row8,
0.582240,0.552753,0.500000,0.530690,0.577232,0.581606,0.563975,0.570767,0.562063,0.517763,0.525467,0.532333,0.518421,0.561723,0.500000,

Total site reflectance ratio 0.553894

5 CHP_plot.exe and LAI_plot.exe

CHP_plot reads the *_CHP_final.txt file and produces a CHP plot, while LAI_plot reads *_LAI_final.txt file and produces LAI map. The latter one is only useful if the site was processed in grid cells. In both cases, all the user needs to provide is the name of the file without its ".txt" extension.

6 References:

Armston, J., Disney, M., Lewis, P., Scarth, P., Phinn, S., Lucas, R., Bunting, P. & Goodwin, N., 2013. Direct retrieval of canopy gap probability using airborne waveform lidar. Remote Sensing of Environment 134 (0), 24-38.

Fieber, K. D., Davenport, I. J., Ferryman, J. M., Gurney, R. J., Walker, J. P. & Hacker, J. M., 2013. Analysis of full-waveform LiDAR data for classification of an orange orchard scene. ISPRS Journal of Photogrammetry and Remote Sensing 82 (0), 63-82.

Fieber, K. D., Davenport, I. J., Tanase, M. A., Ferryman, J. M., Gurney, R. J., Becerra, V. M., Walker, J. P. & Hacker, J. M., 2015. Validation of Canopy Height Profile methodology for small-footprint full-waveform airborne LiDAR data in a discontinuous canopy environment. ISPRS Journal of Photogrammetry and Remote Sensing 104 (0), 144-157.

Harding, D. J., Lefsky, M. A., Parker, G. G. & Blair, J. B., 2001. Laser altimeter canopy height profiles: methods and validation for closed-canopy, broadleaf forests. Remote Sensing of Environment 76 (3), 283-297.

Lefsky, M. A., Cohen, W. B., Acker, S. A., Parker, G. G., Spies, T. A. & Harding, D., 1999. Lidar Remote Sensing of the Canopy Structure and Biophysical Properties of Douglas-Fir Western Hemlock Forests. Remote Sensing of Environment 70 (3), 339-361.