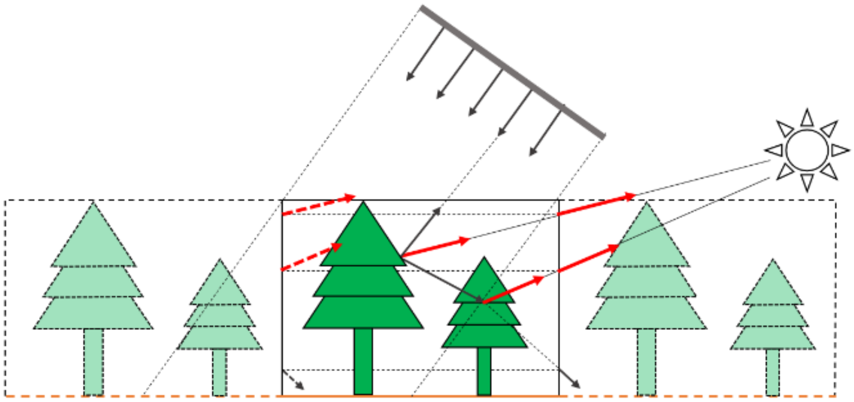
LESS User's Manual

Version 2.0



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1. Introduction

Three-dimensional (3D) radiative transfer (RT) modeling of the transport and interaction of radiation through earth surfaces is a challenging and difficult task. The difficulties lie in the complexity of the landscapes and also in the intensive computational cost of 3D RT simulations. To reduce computation time, current models work with schematic landscapes or with small-scale realistic scenes. The most accurate and efficient models (known as renderers) are from the computer graphics community, but the usages are not straightforward for performing scientific RT simulations. That's the reason why we developed this model.

Basically, LESS employs a forward photon tracing method to simulate bidirectional reflectance factor (BRF) or flux-related data (e.g., downwelling radiation) and a backward path tracing method to generate sensor images (e.g., fisheye images) or large-scale (e.g. 1 km^2) spectral images from visible to thermal infrared spectral domain. We also provide a user-friendly graphic user interface (GUI) and a set of tools are developed to help construct the landscape and set parameters. LESS has already been evaluated with other models in terms of directional BRF and pixel-wise simulated images. It can be used as benchmarks for validating physical models or training artificial neural network (ANN) to do parameter inversion.

2. Fundamentals of LESS

2.1. Forward photon tracing (FPT)

2.1.1. Photon tracing

Forward photon tracing (FPT) traces photon packets with the power $P(\lambda)$ into the scene from light sources. The initial power $P^0(\lambda)$ of each packet is determined by the power of light sources and the number of generated packets N. When generating photon packet in a scene with multiple light sources, a light source is randomly chosen according to the importance weight w_k, which is proportional to the power of each light source, i.e., $w_k = \frac{L_k(\lambda)}{\sum_{k=1}^{K} L_k(\lambda)}$ with $L_k(\lambda)$ being the power of light source k and K being the number of light sources. This mechanism guarantees that a light source with larger power has more sampled photon packets. The initial power of each packet, in terms of watt (W), is given as

$$P^0(\lambda) = \frac{\sum_{k=1}^{K} L_k(\lambda)}{N} \tag{1}$$

When a photon packet enters the scene along a path defined by its origin and direction of propagation, its intersection with landscape elements is tested for. If an intersection is found, the power of this packet will be scaled according to the optical properties of the intersected surface, i.e., the reflectance or transmittance. For a packet with Q times of scattering before it escapes from the scene, the power becomes

$$P^Q(\lambda) = P^0(\lambda) \cdot \prod_{q=1}^{Q} \left[\pi f(q, \omega_{i,} \omega_{o,} \lambda)/p\right] \tag{2}$$

where the $f(q, \omega_{i,} \omega_{o,} \lambda)$ is the bidirectional scattering distribution function (BSDF) at the q^{th} intersection point during its trajectory. $\omega_{i,}$ and ω_o are the incident direction and outgoing direction of a photon packet, respectively. Since the scattering law of surfaces in LESS is defined as Lambertian, the BSDF is interpreted as bidirectional reflectance distribution function (BRDF) or bidirectional transmittance distribution function (BTDF), according to $\omega_{i,}$, surface normal ω_n and ω_o, i.e.,

$$f(q, \omega_{i,} \omega_{o,} \lambda) = \frac{1}{\pi} \begin{cases} \rho_{\perp,\lambda} \cdot \text{sgn}(\omega_n \cdot \omega_{i,}) + \tau_\lambda \cdot \text{sgn}(-\omega_n \cdot \omega_{i,}), \; \omega_o \cdot \omega_n \geq 0 \\ \rho_{\top,\lambda} \cdot \text{sgn}(-\omega_n \cdot \omega_{i,}) + \tau_\lambda \cdot \text{sgn}(\omega_n \cdot \omega_{i,}), \; \omega_o \cdot \omega_n < 0 \end{cases} \tag{3}$$

where $\mathrm{sgn}(x) = \begin{cases} 1, & \mathrm{x} \geq 0 \\ 0, & \mathrm{x} < 0 \end{cases}$; $\frac{\rho_{\perp,\lambda}}{\pi}$ and $\frac{\rho_{\top,\lambda}}{\pi}$ are the upper and bottom surface BRDF, respectively; $\frac{\tau_\lambda}{\pi}$ is the BTDF. In LESS, the transmittances of the surface from both the upper and the bottom side are assumed to be the same; The outgoing direction of a photon packet after scattering is determined by randomly sampling the BSDF function. For Lambertian surfaces, the model chooses a random direction in the outgoing hemisphere. Since a single photon trajectory can be used to simulate BRF for any wavelength by updating the power according to the spectral reflectance/transmittance, we have omitted the symbol λ in the following equations for simplicity.

A photon packet is collected by the sensor if it exits the scene through the top boundary. Lateral boundary effects are considered in order to simulate horizontally infinite scenes with a repetitive pattern. As shown in **Figure 1**, the photon packet which exits from the lateral boundaries will re-enter the scene from the opposite side with the same photon direction until it escapes through the top boundary of the scene. When the scattering order of a packet exceeds a user-defined threshold (e.g., 5), the propagation of the packet is randomly stopped according to the "Russian roulette" mechanism (Kobayashi and Iwabuchi, 2008), which terminates the trajectory of a packet with a probability p (e.g., 5%). If the packet survives, its power will be multiplied by $\frac{1}{1-p}$.

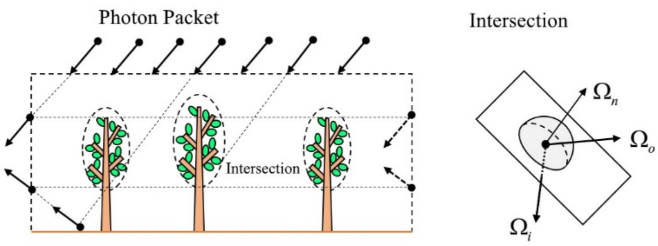


Figure 1. Forward photon tracing.

The collection of the escaped photon packets is achieved by placing a virtual hemisphere above the scene (Govaerts and Verstraete, 1998). As shown in **Figure 2**, the hemisphere is partitioned into N_P small surface elements (SE) with equal area $\Delta S = \frac{2\pi}{N_P}$ by utilizing the partition scheme of a disk via the equal area projection, i.e., $\Delta\Omega = \Delta S$. The zenithal zones are partitioned through (Beckers and Beckers, 2012):

$$\theta_i = \theta_{i-1} - \frac{2}{a_{aspect}} \sin\frac{\theta_{i-1}}{2}\sqrt{\frac{\pi}{k_{i-1}}}, k_i = k_{i-1}\left(\frac{r_i}{r_{i-1}}\right)^2 \tag{4}$$

Where (θ_i, θ_{i-1}) defines a zenithal zone on the hemisphere with $\theta_0 = \frac{\pi}{2}$; k_i is the total number of SEs inside a zenithal angle θ_i with $k_0 = N_P$; r_i is the radius corresponding to θ_i with $r_i = 2\sin\frac{\theta_i}{2}$ for a unit sphere due to the equal area projection; a_{aspect} is the aspect ratio of each SE, which is approximately enforced to 1. For each zenithal zone, it has $k_{i-1} - k_i$ SEs with equal area.

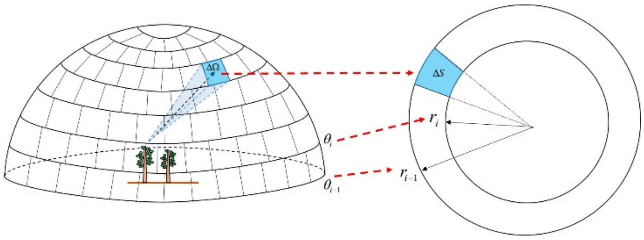


Figure 2. Unit hemisphere partition. The hemisphere is projected to horizontal plane as a disk using equal area projection. The radius r_i in the disk indicates zenith angle θ_i in the hemisphere.

When a photon packet exits the scene, the outgoing SE (solid angle) is determined by the photon direction only, i.e., the hemisphere is placed at an infinite position. The BRF in this SE can be estimated with (Govaerts and Verstraete, 1998)

$$f_{BRF_i} = \frac{\pi P_i^A}{\Delta\Omega_i \cdot \cos\theta_i^c \cdot P_{scene}} \tag{5}$$

where P_i^A is the power (watt) of all the captured photons in SE i, i.e., $P_i^A = \sum_{P^Q \in \Delta\Omega_i} P^Q$; $\Delta\Omega_i = \frac{2\pi}{N_P}$ is the solid angle of each SE; θ_i^c is the central zenith angle of solid angle $\Delta\Omega_i$; P_{scene} is the power of all the direct incident photon packets on a reference plane at the top of the scene, i.e., the incident radiation at the top of the scene. Once the power in each SE is determined, the scene albedo is computed as

$$\omega_{albedo} = \frac{\sum_{i=1}^{N_P} P_i^A}{P_{scene}} \tag{6}$$

1.1.1. Virtual photon

The real photon approach (described in section 2.2.1) estimates BRF by using small SEs on the sphere. More photon packets are needed to reduce the variance when smaller SEs are used. To solve this problem, a virtual photon approach, similar to the *virtual direction* in DART model (Yin et al., 2015), *secondary ray* in Rayspread model (Widlowski et al., 2006) or some “local estimates” methods (Antyufeev and Marshak, 1990; Marchuk et al., 1980), is introduced. If a packet is intercepted by an object (e.g., a tree) in the scene without complete absorption, the packet will be scattered in a direction which is randomly sampled by the BSDF function, and a virtual photon packet will be sent to each of the defined virtual directions. The possible scattered energy, in terms of intensity ($\mathrm{W} \cdot \mathrm{sr}^{-1}$), is calculated as

$$I = V \cdot P^{q-1} \cdot f(q, \omega_i, \omega_v) \cdot \cos < \omega_v, \omega_n > \tag{7}$$

where P^{q-1} is the power of the incident photon packet at the q^{th} intersection point along its trajectory; ω_v is a virtual direction; V is a visibility factor which equals to zero if the a landscape element occludes the virtual photon packet, and equals to 1 otherwise. When sending the occlusion testing rays, the lateral boundary effect is also considered (**Figure 3**). The final BRF is then given as

$$f_{BRF_v} = \frac{\pi I_v^A}{\cos\theta_v \cdot P_{scene}} \tag{8}$$

where I_v^A is the power per unit solid angle ($\mathrm{W} \cdot \mathrm{sr}^{-1}$) in virtual direction v and θ_v is the zenith angle of the virtual direction. An advantage of calculating a directional BRF using virtual photon approach is that the BRF is estimated within an infinity small solid angle (Thompson and Goel, 1998), which is the real directional BRF of a scene.

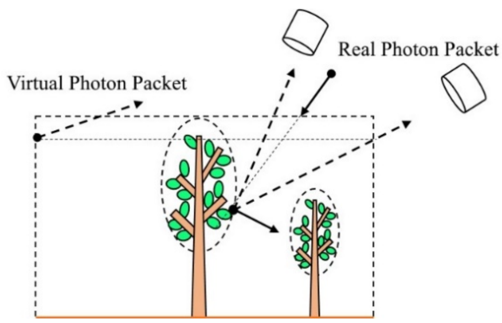


Figure 3. Virtual photon approach to calculate BRF.

1.2. Backward path tracing (BPT)

Instead of tracing photon packets from light sources, backward path tracing sends rays from sensors into the scene. The ray directions are controlled by sensor configurations (field of view, position, orientation, etc.). The main task of this ray-tracing algorithm is to establish a connection, which is called "path", between light sources and sensors and to determine the radiance incident onto the sensor. The radiance is estimated for every pixel in the output image. Radiance along direction ω_o can be calculated according to a rendering equation (Kajiya, 1986)

$$L_o(q,\omega_o) = L_e(q,\omega_o) + \int_{4\pi} f(q,\omega_i,\omega_o)\, L_i(q,\omega_i)|\cos\theta_i|d\omega_i \quad (9)$$

where $L_o(q,\omega_o)$ is the outgoing radiance from point q along direction ω_o; $f(q,\omega_i,\omega_o)$ is the BSDF of the intersected surface, which determines the outgoing radiance along direction ω_o at point q induced by incoming radiance along direction ω_i; $L_i(q,\omega_i)$ is the incoming radiance; θ_i is the angle between ω_i and the surface normal and $L_e(q,\omega_o)$ is an emission term (e.g., thermal emission), which is described in detail in section 2.4. The algorithm that solves this equation is illustrated in **Figure 4**. A ray from the sensor intersects the elements in the scene at the point q. The outgoing radiance induced by the sun (or sky) is then calculated according to the BSDF. To calculate the multiple scattering radiation, a new ray is launched from the point q with a direction that randomly samples the BSDF. If this ray intersects the scene at another point q_1, the same procedure is applied to q_1. The outgoing radiance at point q_1 along the randomly selected direction is the incoming radiance of q along direction ω_1. The multiple scattering procedure is performed recursively until reaching the maximum scattering order (e.g., 5) specified by the user. To prevent energy loss due to the termination of scattering, the random cut-off technique ("Russian roulette") used in FPT is also applied to the sensor ray.

When simulating a horizontally infinite scene, the lateral boundary effect is considered for both the sensor ray and the illumination ray. At each intersected point (q_i), an illumination ray, which is built by randomly sampling a point q_e on the emitter, is sent towards the emitter. If this ray traverses the lateral boundary of the scene, it is also reintroduced into the scene to test whether the intersected point is occluded by other landscape elements or not.

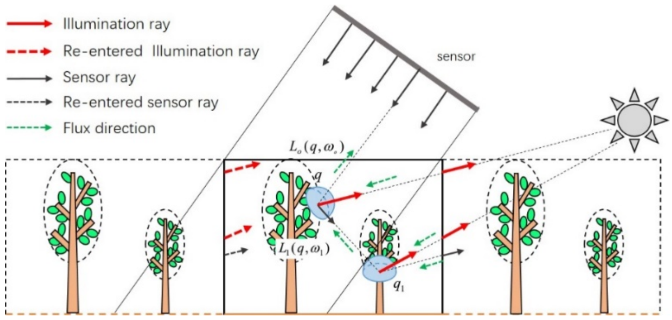


Figure 4. Backward path tracing.

1.3. BPT in simulating thermal infrared brightness temperature (BT)

When simulating thermal infrared radiation, the object itself, instead of the sun, becomes an "emitter", which emits thermal radiation according to Planck's law and its emissivity. Since the incident energy of the sun in thermal infrared bands (e.g., 10 μm) is too weak, we ignore this part of energy in our simulation. However, the presence of sun radiation will greatly influence the temperature distribution of objects due to the shadows cast between them. This generally classifies the scene elements into four components with specific temperatures, i.e., sunlit soil, shaded soil, sunlit leaves and shaded leaves (**Figure 5**). The determination of these four components is computed on the fly instead of a precomputing step adopted by most of other forward models (e.g., DART). This on-the-fly approach avoids the storage of emission points, which can greatly reduce the memory usage, especially for scenes with a large number of leaves.

If a sensor ray is intersected in the scene (i.e., q in the scene), an emission term at this point is added. To determine the emission power, an occlusion ray is traced towards the sun. If this point is directly illuminated, i.e., the occlusion ray intersects nothing, the temperature of the sunlit component is used. Otherwise it uses the temperature of the shaded component. The emitted radiation is calculated by using Planck's law with emissivity provided. Except for the emission term, another component of the power that goes into the sensor is the reflected power, which is emitted by other objects in the scene or sky radiation. In order to consider this part of the power, a random point on a randomly selected emitter (including the sky) is sampled (e.g., q_e in **Figure 5**). When this point is not on the sky, the emission power is determined by sending an occlusion ray towards the sun. The contribution of power from this point is calculated by using the BSDF defined at point q if this point is not occluded by other objects. This procedure can be recursively repeated, which is the same as the procedure described in section 2.2 except for the emission term. Finally, a thermal infrared image, which records the radiance value, can be simulated.

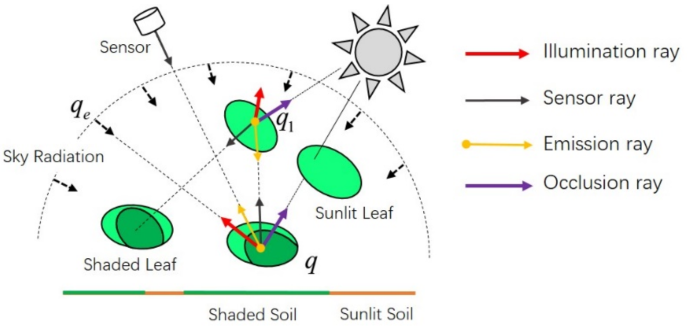


Figure 5. Simulation of thermal infrared radiation using backward path tracing.

3. Installation

• Windows

Download the installer from http://www.lessrt.org. All you need is just to choose a place to install it. (Usually, LESS cannot be installed in c:\program files, since it does not have administrative rights.). After installation, LESS will be automatically started.

4. Graphic User Interface (GUI)

LESS window is divided into four areas (**Figure 6**):

✧ The area 1 is Preview Panel
✧ The area 2 is Parameter Control Panel
✧ The area 3 is Progress Panel
✧ The area 4 is Menu Panel

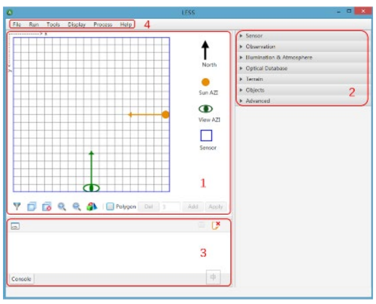


Figure 6. Main Screen of LESS

4.1. Preview Panel

Preview Panel is for displaying some information, such as view azimuth angle ( ), sun azimuth angle (●), sensor footprint (□) and tree positions. This will make it easier for user to set parameters, because this display is automatically updated when related parameters are changing.

Background Image ( ) - When you click the icon, you can choose a picture as background image, make sure that the image represents the same area defined in LESS.

Delete Background Image ( ) - When you click the icon, background image will be delete.

Zoom-in ( ) - This icon allows you to zoom-in the area covered by grids.

Zoom-out ( ) - This icon allows you to zoom-out the area covered by grids.
3D Viewer ( ) - If you click this icon, 3D Viewer will be activated. In 3D Viewer windows, you can visualize the scene in advance (before actual simulation) to verify the 3D scene.
Polygon (Polygon) - When you check the icon, you can draw a polygon in the area covered by grid and set polygon parameter (such as the minimum distance between trees, tree position in the polygon) in the panel after it (Del 3 Add Apply). If you just want to allocate objects in some particular areas, the solution is using Polygon tool. Check the option of Polygon under the display panel. This time when your mouse enters the display panel, it will become a hand. you can create a polygon by left click. If you want to remove the polygon, just use your right click of mouse. After the creation of polygon, you can delete or add object instances in this area. If you click Add, then all the generated instances will only apprear in the polygon, the position and number of each object are still random within the polygon. However, if you choose one of the objects in the Objects List. then the generated instances only contains this object. This tool can create some forest scene which contains one species of trees in some area and another species of tree in another areas.

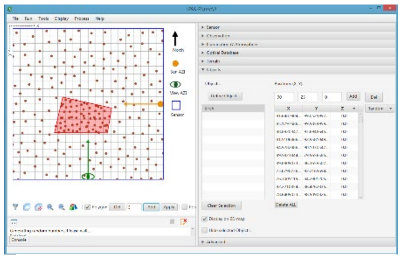


Figure 7. Polygon tools

Point (Point) - When you check the icon, you will see the cursor changing to a hand. You can choose the position of tree by clicking the place where you want the tree to be, without inputting coordinates.

4.2. Parameter Control Panel

Parameter Control Panel is for setting parameter which can control the scene you simulate.

4.2.1. Sensor

To simulate a sensor you can input parameters here to control image type, the number of pixels in width and height, sample count per pixel.
Type - Up to now, there are four types that you can choose. They are orthographic, perspective, CircularFisheye, PhotonTracing.
Width - The number of pixels in width.
Height - The number of pixels in height.
Samples - sample count per square meter. Usually 128 is sufficient. If you increase to 256, 512, the quality of the simulated image will be better.
Spectral Bands - It represents the which band you want to simulate. For example, RED and NIR: 660nm，900nm. Now, you must also input a bandwidth for each band with the format of “center band: bandwidths”, e.g. 660:10,900:10. These bandwidths will be used for determining the irradiance. If you have no special requirement, it can just set the bandwidth to zero. And when you click [Define], you can define the bands by input some parameter in the pop-up window (**Figure 8**).

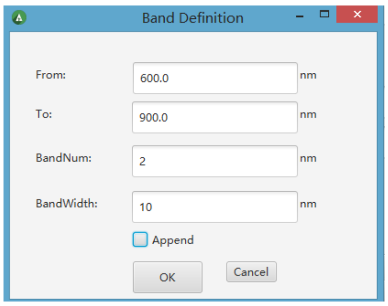


Figure 8. Spectral bands

Image Format - “Spectrum” means generating spectral image. “Synthesized RGB Image” means generating RGB image.
Only First Order? - If it is true, it means LESS only simulate the first-scattering event (sun * radiation reflected by objects only one time). If set to false, then both first-scattering and multi-scatting will be simulated.
Virtual Plane – When you check it, a virtual plane is defined, and only the radiant that exits through the plane is calculated. In **Figure 9**, you can define the location of the virtual plane in “Center” and the size of the

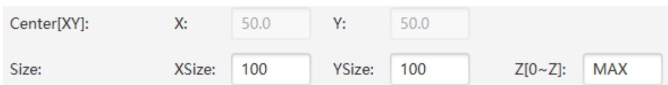


Figure 9. Virtual plane

virtual plane in "Size". Usually, the height of the plane (Z) should be left as default, i.e., MAX.
Thermal Radiation - When you need to get thermal infrared image, you can check it. After checking, you can input surface temperature parameter in Optical Database (**Figure 10**).

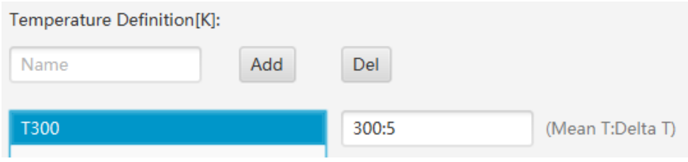


Figure 10. Temperature definition

NoData Value - Set the background value when sensor footprint is beyond the scene scale. If the image opened by ENVI, you should set it as "0".
Repetitive scene - Sets the number of copies that distributed around the scene.
Width Extent/Height Extent - The actual extend of the orthographic sensor can simulate. It is similar to FOV of perspective sensor.
Four Components Product - If you check it, a classification image will be generated. The classification image has four components, and they are sunlit ground, sunlit canopy, shaded ground and shaded canopy. The corresponding pixel values are 1, 2, 3 and 4, respectively. Please note that some pixels may mixed pixels, in this case, the dominant component is set as the pixel component type. However, if you set the number of bands >= 5, the generated four component image will contain 5 spectral bands, the first band is the classification image, the other four bands are the proportions of the four components. This can be used to estimate directional gap fraction of forest canopy.

4.2.2. Observation

View Zenith - Set view zenith angle (angle between vertical direction).
View Azimuth - Set view azimuth （0° is north, clock-wise to 360°).
Sensor Height - Set the height of the sensor.

4.2.3. Illumination & Atmosphere

There are two groups of illuminations, one is from sun, other is from atmosphere.
Sun Zenith - Zenith angle of sun.
Sun Azimuth - Azimuth angle of sun (0° is north, clock-wise to 360°).
This defines the position of sun. That means if you set it as 90° (East), then it will produce shadows in West.
Sun Position Calculator - If you clicked it, you can fill in above two parameters by inputting the time and place parameters for the scene.
Next is the parameter setting for the sky.
Type - It represents the type of atmosphere radiation, now only one option can be used - "SKY_TO_TOTAL", it means the ratio between diffuse radiation and total incident radiation. Thus (1-SKYL) * T (T is sun radiation above atmosphere) is the sun radiation under atmosphere. Under this mode, atmosphere is isotropic diffuse radiation from upper hemisphere.
Percentage - It defines the actual ratio between atmosphere radiation and total radiation. What should be noticed is that when you input the values, the number of values should be equal to the number of bands (under the sensor section). That is, for each band, it may have different values.
Input solar spectrum manually - If you check it, you can input the solar spectrum and the sky spectral in terms of wavelength manually (in W/m^2/nm).

4.2.4. Optical Database

Since objects in LESS are represented as triangular meshes, thus for each triangle, it can have at least three kinds of optical properties: reflectance of front side, reflectance of back side, and transmittance (we assume transmittance of both side is the same). In Optical database, we should first define some optical model, and then they can be used in the following terrain or forest definition. By default, there are three optical models defined. Please note that, these three optical models cannot be modified, if you want to use them with modified value, you should copy a new one and then perform the modification You can also add new optical model directly. For each reflectance or transmittance, values of different bands are connected by comma.

Please note that for some object component, such as trunk, the normal of some triangles may face inside, which shows a zero reflectance outside. To avoid this situation, a convenient solution is to set the reflectance of both outer and inner side to the same values, but with zero transmittance.

4.2.5. Terrain

There are mainly three types of terrain: PLANE, RASTER, MESH.
PLANE just represents simple plane lies at altitude of 0. RASTER is a raster image file in ENVI standard format.
XSize - Size in the X direction.
YSize - Size in the Y direction.
There are two BRDF types: Lambertian, Soilspect. If Lambertian is chosen, it means you think of the ground as a Lambertian. If Soilspect is chosen , you can input parameters to define the model.
Land Cover - If you check it, you can input surface classification data generated by ENVI, and then set different spectrum for different ground classes.

4.2.6. Objects

Objects define what you want to put in the scene. For example, forest is formed by a number of single trees, which are describe by triangle mesh (obj file) in LESS. Usually, we cannot input a obj for each single trees, since forest contains a lot of trees and a tree itself contains numerous triangles, it may not be possible even for large memory computers. The alternative is to use a “instance” technique. That means we define a single tree, and we can place it at different places, just using reference, thus the program only keeps one copy of the triangle mesh, but it represents trees at different places (they have exactly the same structures, but we can do rigid transformations).

Objects window is divided into three areas:
• The area (1) is Objects Define Panel;
• The area (2) is Position Parameter Control Panel;
• The area (3) is Display Panel.

(1) Objects Define Panel

The first step is to define some objects (single tree).
Define Object… - You can click it to define objects. It will open a new dialog that allows to import obj file (**Figure 11**).
Add - We give a name for our first object, such as “birch”. After clicking [Add] button, “birch” will appear in the Objects list.

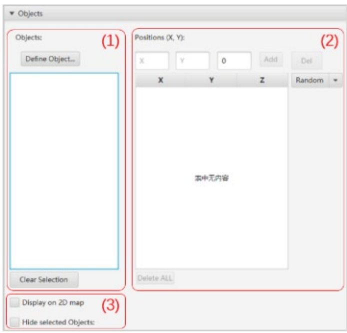


Figure 11. Objects definition

Import OBJ - Selecting the name we write in “Objects” area, then the button [Import OBJ] is activated. If you click the [Import OBJ], you can choose a obj file in the window and input it as the object (**Figure 12**). And then you need to determine the scale by the units of the tree model that you enter into. If the units of the tree model that you enter into is “cm”, the scale should be 0.01. And if the units of the tree model that you enter into is “m”, the scale should be 1.00.

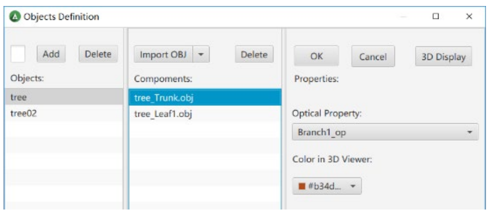


Figure 12. Import obj file

Import from RAMI - Import objects from the model file on the rami website. After importing objects, each component of the obj file will appear in the “Components” list. Component is a part of the object, e.g. a tree contains leaves and branches (usually they have different optical properties). **You should be aware that the obj file itself will be copied to the simulation folder, so you can safely delete it from your original place.**

Optical Property - Selecting one of the components, the [Optical Property] is activated and you can choose an optical property for the selected component. These optical properties are also from "Optical Database". If you need to define a new optical model, you can go back to "Optical Database" page without closing the current window. When you finish, the optical models are automatically synchronized.
3D Display - After clicking it, you can see the 3D model of object (**Figure 13**).

Figure 13. 3D Display

After defining objects, you should click [OK] button, and then we will go back to Objects page with the defined objects shown in Objects list.

(2) Position Parameter Control Panel

If we select the defined objects, we can define its positions. There are three methods to define positions. The first method is inputting coordinate for the object directly. The second method is using [Point] tool provided by LESS (introduced in Preview Panel). The third method is using [Random] tool provided by LESS. The last method is import CHM data to control position.
Add - You can enter coordinates in the table before [Add] button, and then clicking [Add], the object is added to the specified location.
Random - Clicking the button [Random], it will open a new window, now the only choice is Poisson distribution (This is very normal for trees in forest). The only parameter you need to provide is the minimum distance between two objects. Click [OK], then LESS will automatically generate instances of defined objects. The number and position of each object in the Objects list is also random. Thus, you can get a reasonable distribution of objects.
From CHM - Clicking the inverted triangle next to the button [Random], you can open the drop-down menu, and find the [From CHM] button. If click it, you can choose a CHM data as a basis for objects location.

(3) Display Panel

Display on 2D map - If a position is added when you check it, the position will appear on the grid area in Preview Panel, which will help you to check whether it is correct.
Hide selected Objects - If there are multiple plants in this scene, you can hide the location of the model you don't want to see by checking it.

4.3. Progress Panel

This panel shows the running state of the current program. When an error occurs, you can find the reason of the error by reading this panel.

4.4. Menu Panel

Menu bar holds 6 menus: **File, Run, Tools, Display, Process and Help**

4.4.1. File menu

File > New Simulation - Create a new simulation.
File > Open Simulation - Open a chosen LESS file and load its parameter values into LESS modeler.
File > Save - Save current parameter values on a disk as LESS file.
File > Save as - Save the tree image into another file.
File > Close - Close the simulation.

4.4.2. Run menu

Run > Run All - Run this program and output results.
Run > Generate 3D Model - Generate 3D objects, e.g., convert obj file into binary format.
Run > Generate View & Illumination - Generate viewing parameters for simulation.
Run > less - Run less simulation

4.4.3. Tools menu

Tools > Open Results Folder - Open Results Folder of current simulation.
Tools > Batch Tools - Do batch processing.
Tools > Server Setting - Do network parallel simulation
Tools > LAI Calculator - Calculate LAI in different resolution, and output the results as txt.
Tools > Python Console - Run Python scripts (under experiment).

4.4.4. Display menu

Display > 3D Viewer - Display scene you simulate from multiple angles.
Display > 3D Viewer (Bounding BOX) - Display scene you simulate from multiple angles with replacing objects with boxes.
Display > 2D Polygon - Draw a polygon in the area covered by grid and set polygon parameter (such as the minimum distance between trees, tree position in the polygon) in the panel after it.

4.4.5. Process menu

Process > BRF Processing - Generate BRF image.
Process > Brightness Temperature Processing

4.4.6. Help menu

Help > Documentation - Documentation of LESS.

5. Examples

5.1. FPAR simulation

FPAR is the fraction of total absorbed radiation, usually from 400 to 700 nm. Therefore, to simulate FPAR using LESS, we need first to set the band range from 400 to 700 nm (or other spectrum if you want), the band number can be, e.g., 30. Then you need to set the leaf and soil optical properties in [**Optical Database**] section, the number of spectrum bands should be the same with the band number you set in the [**Sensor**] section, e.g., the 30 you have previously set.

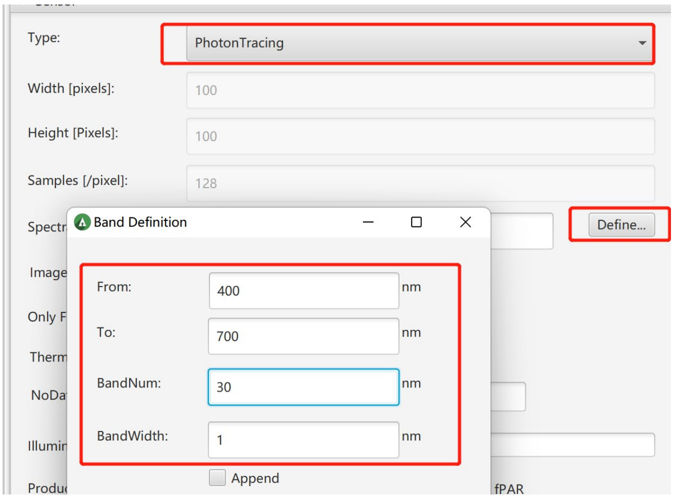


Figure 14. Set the spectral bands for FPAR simulation.

Next step is to enable the FPAR option in [**sensor**] section as illustrated in **Figure 15**. An important parameter is the **Layer definition (Start:Interval:End),** which defines how FPAR is outputted. Specifically, LESS only outputs the FPAR values between **Start** and **End** range with interval equal to **Interval.** For example, if you define it as 0:2:10, then you will get FPAR for layers: [0,2), [2,4) , [4,6) , [6,8) , [8,10).

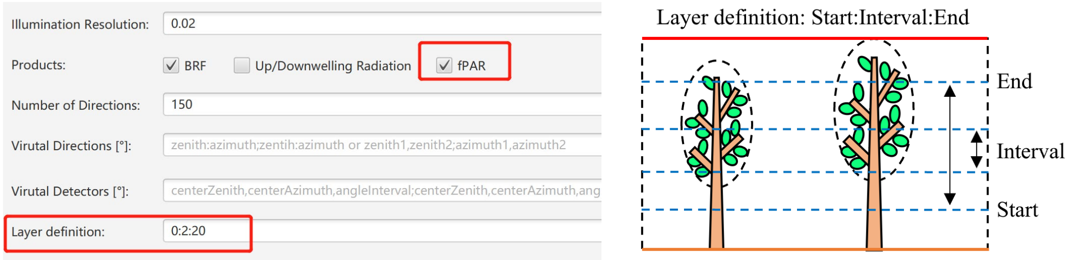
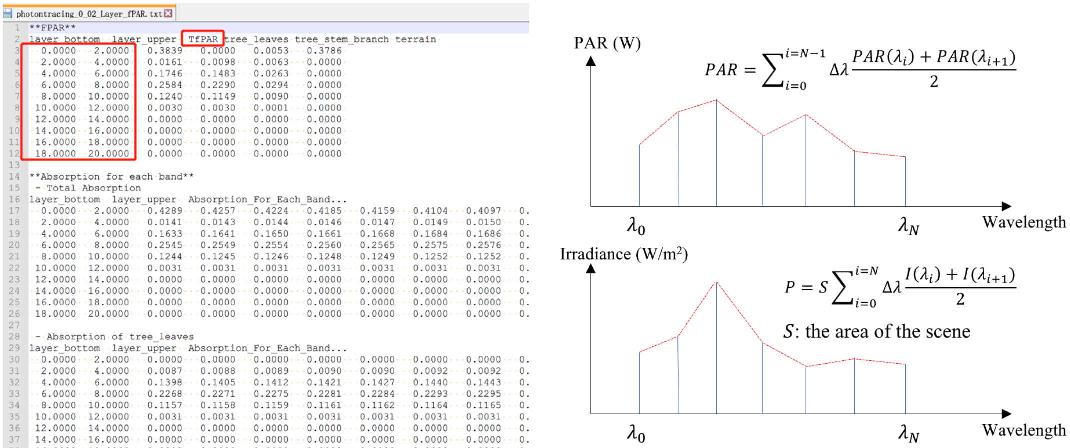


Figure 15. Enable FPAR simulation in LESS and define layers.

A simulation example is shown in **Figure 16**, the file can be found in the Results folder within the simulation folder. The results five two kinds of product, one is the spectrally integrated total FPAR, the other is the absorption for each band. For each layer, we first integrate the total PAR over the whole spectrum range, and then divided by the total incident energy received by a plane at the top of the canopy （also integrated over the whole spectrum range）(**Figure 16**). The total FPAR is presented at the top of the result file ((**Figure 16** left), it illustrates the total FPAR (TfPAR) for each layers, e.g., from 0 m to 2 m, the total FPAR is 0.3839, which may be mainly absorbed by soil. If you are interested in leaves, maybe you should look at the 4th column, it outputs the FPAR for the leave components. Please note that the name of the column is not fixed, it is according to the component you defined in LESS when you import your OBJ file into LESS. If you don't want the spectrally integrated FPAR, you can refer to the **Absorption for each band**, here, the FPAR for each band is presented. '- Total Absorption' means the total absorbed energy for all the landscape components (e.g., leaves, soil and branches) for each band. The column means the spectral bands, thus you would see 32 columns if you set the spectral bands to 30, the first two columns are layer heights. Next content is the FPAR or absorption for other landscape components, for example the tree_leaves. In conclusion, if you are interested in the total and spectrally integrated FPAR, you only need to refer to the first section of the result file.



```
photontracing_0_02_Layer_fPAR.txt
**FPAR**
layer_bottom  layer_upper  TfPAR tree_leaves tree_stem_branch terrain
  0.0000   2.0000   0.3839   0.0000   0.0053   0.3786
  2.0000   4.0000   0.0161   0.0098   0.0063   0.0000
  4.0000   6.0000   0.1746   0.1483   0.0263   0.0000
  6.0000   8.0000   0.2584   0.2290   0.0294   0.0000
  8.0000  10.0000   0.1240   0.1149   0.0090   0.0000
 10.0000  12.0000   0.0030   0.0030   0.0001   0.0000
 12.0000  14.0000   0.0000   0.0000   0.0000   0.0000
 14.0000  16.0000   0.0000   0.0000   0.0000   0.0000
 16.0000  18.0000   0.0000   0.0000   0.0000   0.0000
 18.0000  20.0000   0.0000   0.0000   0.0000   0.0000

**Absorption for each band**
 - Total Absorption
layer_bottom  layer_upper  Absorption_For_Each_Band...
  0.0000   2.0000   0.4289   0.4257   0.4224   0.4185   0.4159   0.4104   0.4097   0.
  2.0000   4.0000   0.0141   0.0143   0.0144   0.0146   0.0147   0.0149   0.0150   0.
  4.0000   6.0000   0.1633   0.1641   0.1650   0.1661   0.1668   0.1684   0.1686   0.
  6.0000   8.0000   0.2545   0.2549   0.2554   0.2560   0.2565   0.2575   0.2576   0.
  8.0000  10.0000   0.1244   0.1245   0.1246   0.1248   0.1249   0.1252   0.1252   0.
 10.0000  12.0000   0.0031   0.0031   0.0031   0.0031   0.0031   0.0031   0.0031   0.
 12.0000  14.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.
 14.0000  16.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.
 16.0000  18.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.
 18.0000  20.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.

 - Absorption of tree_leaves
layer_bottom  layer_upper  Absorption_For_Each_Band...
  0.0000   2.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.
  2.0000   4.0000   0.0087   0.0088   0.0089   0.0090   0.0090   0.0092   0.0092   0.
  4.0000   6.0000   0.1398   0.1405   0.1412   0.1421   0.1427   0.1440   0.1443   0.
  6.0000   8.0000   0.2268   0.2271   0.2275   0.2281   0.2284   0.2293   0.2295   0.
  8.0000  10.0000   0.1157   0.1158   0.1159   0.1161   0.1162   0.1164   0.1165   0.
 10.0000  12.0000   0.0031   0.0031   0.0031   0.0031   0.0031   0.0031   0.0031   0.
 12.0000  14.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.
 14.0000  16.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.
```


Figure 16. FPAR simulation example: simulation results (left); total FPAR calculation.

5.2. LiDAR simulations

Up to now, less has provided airborne laser scanning (ALS) and ground laser scanning (TLS) data simulation in graphical user interface, The simulator can get different types of data through file configuration, such as full waveform and 3D point cloud data, including single-band, multi-band and even hyperspectral LiDAR scanning (HLS) data. The laser simulator is located in GUI extension module. You should use the mouse to indicate [**Extensions**] and click on the button [**LiDAR Simulator**]. You can see **Figure 17** for the specific operation of opening the simulator.

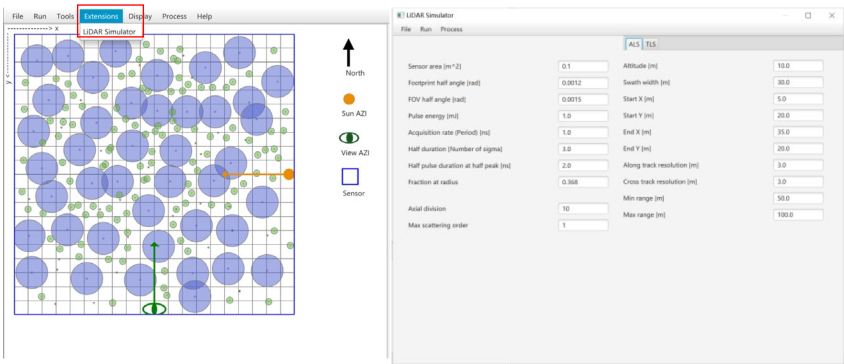


Figure 17. LiDAR simulator interface

Before starting the simulation, you also need to understand the configuration of each parameter so that you can get interested LiDAR data in the simulator. Parameters are divided into two categories. The sensor parameters are located on the left side of the GUI, and the platform parameters are located on the right side. The meaning of each parameter is presented in Table 1, Table 2 and Table 3, Some parameters are also presented in **Figure 18** to help users better understand.

Table1. Sensor parameters	
Sensor Area	Sensor size (area) of LiDAR receiving energy, The sensor size (area) of LiDAR receiving energy, the larger the sensor area, the more energy it can receive.
Footprint half angle	Field angle of LiDAR pulse. Note: This is half of the cone angle of the field of view.
FOV half angle	FOV represents the field of view range of LiDAR receiving energy, which is set to half of the cone angle of the field of view. The larger the value, the larger the acceptable range. Generally, you need to set FOV half angle larger than footprint half angle. See Figure. 15 specifically
Acquisition rate (Period)	The acquisition rate represents a certain sampling interval and is usually determined by the instrument itself.
Half duration (Number of sigma)	The emission energy of laser pulse is usually assumed to be a Gaussian distribution function related to time and amplitude. ±3σrepresents the effective information range of the whole pulse energy. Note: Half duration represents half of the effective energy range.
Half pulse duration at half peak	Half pulse duration at half peak represents the standard deviation of Gaussian pulse energy. Half duration and Half pulse duration at half peak together determine the effective information range of pulse energy.
Axial division	The cross section of laser pulse is divided into n*n equal parts, and then sub-beams are emitted. The n here is the Axial division. This is only valid for multi-ray point cloud simulation. The larger the value, the finer the simulation of each pulse, but the simulation time is longer.

Table 2. ALS platform parameters	
Altitude	The flying height of the platform where the LiDAR is located, which is relative to the zero point of the scene rather than the terrain. See Figure. 15 specifically.
StartX, StartY, EndX, EndY	The start point and end point of ALS scanning, the projection of these points on the ground, the platform will fly in a straight line from the point (StartX, StartY, Altitude) to (EndX, EndY, Altitude). See

	Figure. 15 specifically.
Swath width	Width of Lidar scanning (horizontal width of vertical to flight direction). See Figure. 15 specifically.
Along track resolution (Yaw resolution)	Pulse interval along flight direction (ground distance). See Figure. 15 specifically.
Cross track resolution (Range resolution)	Pulse interval of vertical to flight direction (ground distance). See Figure. 15 specifically.
Min range, Max range	The range data [Min range, Max range] in this vertical direction can be collected and saved by the LiDAR sensor. See Figure. 15 specifically.
Table 3. TLS platform parameters	
TLS position X, Y, Z	Location of TLS scanning. X, Y is the horizontal projection position of the ground, and Z is the height of the instrument.
Center zenith, Center azimuth	The position of the bisector of zenith angle or azimuth angle.
Delta zenith, Delta azimuth	Range size of zenith angle or azimuth angle. Zenith angle range is generally set from 0 to180. Azimuth angle range is generally set from 0 to 360.
Resolution zenith, Resolution azimuth	The angle formed by two connected sampling points in zenith angle or azimuth is called angular resolution. The higher the angular resolution, the higher the point cloud density.
Cross track resolution (Range resolution)	Pulse interval of vertical to flight direction (ground distance). See Figure. 15 specifically.
Echo Detection Model	LiDAR simulator provides two detection modes, one is simple and the other is Gaussian. Gaussian decomposition is used to solve the parameters, and the waveform is decomposed to obtain discrete points, so the simulation is slow but accurate.

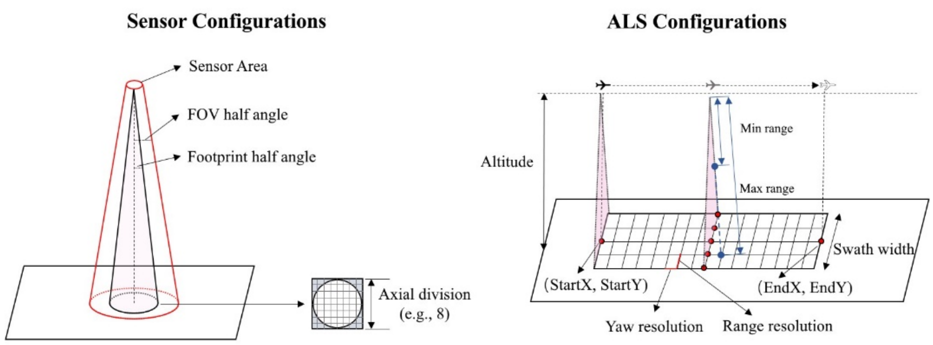


Figure 18. Illustration of LiDAR related parameters

5.2.1. Discrete point cloud data simulation

Note that before starting the simulation, you must build a project and configure the scenes you are interested in according to the operation tutorial in section 4.2. Furthermore, you need to configure the parameters of sensors and platforms according to the simulator interface. Finally, you can start your discrete point cloud simulation work. Using the mouse to indicate [**RUN]** and click the button [**Generate ALL**], The simulator starts to generate 3D scenes and LiDAR configuration parameters. Then click button [**Single ray point cloud**] or button [**Multi rays point cloud]** to simulate point cloud. The former emits one light for each pulse, so the computer is faster. The latter emits multiple rays for each pulse (the number is determined by Axial division). In this mode, the full waveform is first simulated internally, and then discrete points are obtained by Gaussian decomposition, so the calculation speed is slower than [**Single ray point cloud**] mode. The simulation results can be found in the **Results** file. The results of two different modes correspond to **singleRay** and **pointcloud** folder. The results of point cloud generated by [**Single ray point cloud**] and [**Multi rays point cloud**] are presented in **Figure 19**, respectively.

X	Y	Z	PulseIndex	Intensity(675)	Intensity(825)	Name
5.0000	15.0000	0.0000	0	1.83450e-06	2.51621e-06	terrain
5.0000	16.0000	0.0000	1	1.86166e-06	2.55346e-06	terrain
5.0000	17.0000	0.0000	2	1.88805e-06	2.58966e-06	terrain
5.0000	18.0000	0.0000	3	1.91360e-06	2.62470e-06	terrain
5.0000	19.0000	0.0000	4	1.93822e-06	2.65847e-06	terrain
5.0000	20.0000	0.0000	5	1.96183e-06	2.69085e-06	terrain
5.0000	21.0000	0.0000	6	1.98435e-06	2.72174e-06	terrain
5.0000	22.0000	0.0000	7	2.00571e-06	2.75104e-06	terrain
5.0000	23.0000	0.0000	8	2.02583e-06	2.77864e-06	terrain
5.0000	24.0000	0.0000	9	2.04465e-06	2.80445e-06	terrain
5.0000	25.0000	0.0000	10	2.06208e-06	2.82836e-06	terrain
5.0000	26.0000	0.0000	11	2.07806e-06	2.85028e-06	terrain
5.0000	27.0000	0.0000	12	2.09254e-06	2.87014e-06	terrain
5.0000	29.0217	8.7577	13	4.00534e-07	4.64366e-06	tree1_Leaf1
5.0000	29.9790	9.7899	14	2.11269e-07	2.44939e-06	tree1_Leaf1
5.0000	30.8073	9.6877	15	4.97938e-07	5.77293e-06	tree1_Leaf1
5.0000	31.0000	0.0000	16	2.13435e-06	2.92748e-06	terrain
5.0000	32.4446	8.8911	17	2.54089e-07	2.94582e-06	tree1_Leaf1
5.0000	33.3049	9.1484	18	3.43702e-07	3.98477e-06	tree1_Leaf1
5.0000	34.0000	0.0000	19	2.14770e-06	2.94579e-06	terrain
5.0000	35.0000	9.1080	20	4.12051e-07	4.77718e-06	tree1_Leaf1
5.0000	35.8618	8.2949	21	2.24102e-07	2.59817e-06	tree1_Leaf1
5.0000	37.0000	0.0000	22	2.14502e-06	2.94211e-06	terrain
5.0000	38.0000	0.0000	23	2.14056e-06	2.93600e-06	terrain
5.0000	38.4124	8.8141	24	2.25419e-07	2.61344e-06	tree1_Leaf1
5.0000	39.2575	8.9098	25	3.45684e-07	4.00775e-06	tree1_Leaf1
5.0000	41.0000	0.0000	26	2.11676e-06	2.90336e-06	terrain
5.0000	42.0000	0.0000	27	2.10546e-06	2.88786e-06	terrain
5.0000	43.0000	0.0000	28	2.09254e-06	2.87014e-06	terrain
5.0000	44.0000	0.0000	29	2.07806e-06	2.85028e-06	terrain
5.0000	43.4983	9.0101	30	3.35240e-07	3.88666e-06	tree1_Leaf1

X	Y	Z	PulseIndex	BandIndex	ReturnNum	NumReturns	Intensity
53.0000	46.9771	0.1144	2000	1	1	1	2.15038e-06
53.0000	46.9771	0.1144	2000	2	1	1	2.94948e-06
53.0000	47.9956	0.0204	2001	1	1	1	2.12195e-06
53.0000	47.9956	0.0204	2001	2	1	1	2.91048e-06
53.0000	48.9795	0.0881	2002	1	1	1	2.09187e-06
53.0000	48.9795	0.0881	2002	2	1	1	2.86922e-06
53.0000	49.9938	0.0248	2003	1	1	1	2.06027e-06
53.0000	49.9938	0.0248	2003	2	1	1	2.82588e-06
53.0000	48.5781	9.0821	2004	1	1	2	5.72125e-08
53.0000	50.9676	0.1215	2004	1	2	2	1.67580e-06
53.0000	48.5781	9.0821	2004	2	1	2	6.63303e-07
53.0000	50.9676	0.1215	2004	2	2	2	2.29854e-06
53.0000	49.2021	9.8748	2005	1	1	3	2.24636e-07
53.0000	49.8688	7.5220	2005	1	2	3	4.64638e-08
53.0000	51.9752	0.0877	2005	1	3	3	2.82069e-08
53.0000	49.2021	9.8748	2005	2	1	3	2.60436e-06
53.0000	49.8688	7.5220	2005	2	2	3	5.38686e-07
53.0000	51.9752	0.0877	2005	2	3	3	3.86888e-08
53.0000	50.3086	8.9712	2006	1	1	3	5.22393e-08
53.0000	50.6953	7.6825	2006	1	2	3	1.36147e-07
53.0000	52.9795	0.0683	2006	1	3	3	5.65521e-07
53.0000	50.3086	8.9712	2006	2	1	3	6.05645e-07
53.0000	50.6953	7.6825	2006	2	2	3	1.57844e-06
53.0000	52.9795	0.0683	2006	2	3	3	7.75671e-07
53.0000	52.2239	5.6087	2007	1	1	2	1.31766e-07
53.0000	53.9800	0.0631	2007	1	2	2	9.25912e-07
53.0000	52.2239	5.6087	2007	2	1	2	5.80169e-07
53.0000	53.9800	0.0631	2007	2	2	2	1.26999e-06
53.0000	54.9761	0.0716	2008	1	1	1	1.84281e-06
53.0000	53.5541	4.3377	2008	2	1	2	5.03726e-08
53.0000	54.9761	0.0716	2008	2	2	2	2.52761e-06

Figure 19. Simulation results of single ray point cloud (left); Simulation results of multi ray point cloud (right).

- **Single ray point cloud simulation results**

Single ray point cloud simulation results are located in the **singleRay** folder, the results of single ray point cloud simulation record the XYZ coordinates, intensity and other related information of discrete point cloud data (Figure16). Less In order to meet the needs of different users, better use LiDAR simulator to obtain more useful data. It is worth noting that when users input spectral information of different bands, multi-spectral or even hyperspectral discrete point cloud data will be obtained in [**Single ray point cloud**] mode. At the same time, the [**Single ray point cloud**] mode may provide users with more humanized data, and the simulation results also record the types of ground objects that each pulse touches during transmission, which may make users analysis more convenient. Different types of ground objects touched by lidar pulses are recorded in the last column of the result file. An example of simulating discrete point clouds with a single ray is shown in **Figure 20**.

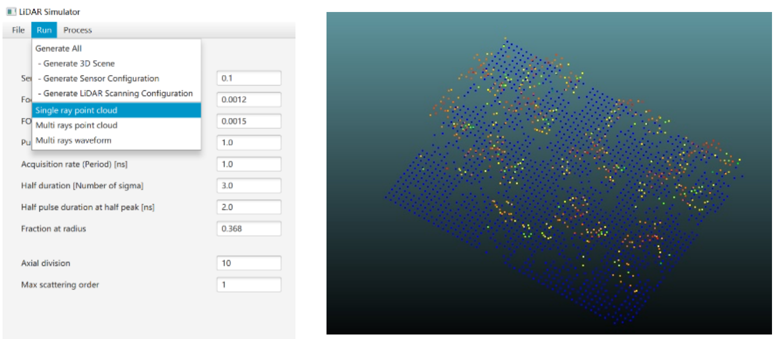


Figure 20. Example of simulating discrete point cloud with single ray.

- **Multi ray point cloud simulation results**

Multi ray point cloud simulation results are located in the **pointcloud** folder, the results of Multi ray point cloud simulation record the XYZ coordinates, Return Number, Number of Return, intensity and other related information of discrete point cloud data (Figure17). Note that the result file also records the band index fields of different point clouds. Therefore, multispectral or even hyperspectral discrete point cloud data acquisition is also supported in [**Multi rays point cloud]** mode. Compared with [**Single ray point cloud**] mode, [**Multi rays point cloud]** mode requires users to further filter and separate the discrete point cloud data of different bands according to the band index fields. An example of simulating discrete point clouds with a Multi rays are shown in **Figure 21**.

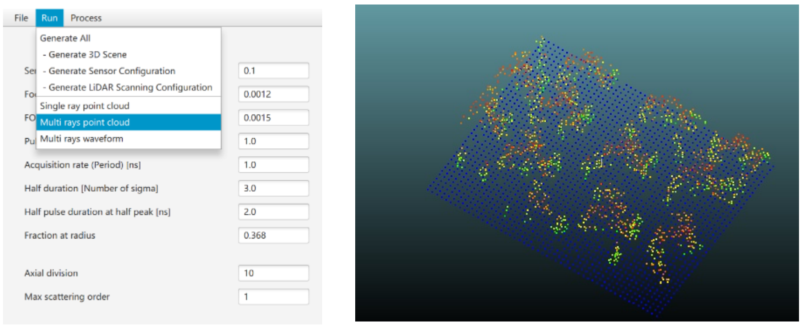


Figure 21. Example of simulating discrete point cloud with multi ray.

The above shows the LiDAR point cloud data simulated in two different modes: [**Single ray point cloud**] and [**Multi rays point cloud]**. Compared with [**Multi rays point cloud]** mode, [**Single ray point cloud**] provides more friendly simulation results, which is convenient for users to further analyze. [**Multi rays point cloud]** mode obtains finer results， In the above example, two different modes simulate the same scene, and the number of point clouds obtained by [**Single ray point cloud**] mode and [**Multi rays point cloud]** mode is 2091 and 6172 respectively.

Of course, in addition to the above two modes, LESS also provides an advanced mode of [**Multi rays point cloud]**. The user can use the mouse to indicate [**Advanced]** and click the [**Muti rays point cloud incident**] button (Figure 20). Like other simulation forms, users can find the results of advanced version simulation in the **Results** folder. The corresponding folder is **pointcloudIncident**. [**Muti rays point cloud incident**] mode is based on the development of [**Multi rays point cloud]** mode, Therefore, the simulation results not only record the results of [**Multi rays point cloud]** mode, but also record the incident energy of each pulse and the energy intercepted by ground objects during the pulse transmission, Incident energy and intercepted energy are recorded in the last two columns in the result file respectively. Different modes depend on the research needs of users, which also allows users to choose different modes of simulation data more flexibly.

X	Y	Z	PulseIndex	BandIndex	ReturnNum	NumReturns	Intensity	Incident	Intercept
53.0000	46.9918	0.0409	2000	1	1	1	1.67906e-06	1.00000e+00	1.00000e+00
53.0000	46.9918	0.0409	2000	2	1	1	1.88476e-06	1.00000e+00	1.00000e+00
53.0000	46.9918	0.0409	2000	3	1	1	2.03193e-06	1.00000e+00	1.00000e+00
53.0000	46.9918	0.0409	2000	4	1	1	2.22007e-06	1.00000e+00	1.00000e+00
53.0000	46.9918	0.0409	2000	5	1	1	2.40905e-06	1.00000e+00	1.00000e+00
53.0000	46.9918	0.0409	2000	6	1	1	2.58800e-06	1.00000e+00	1.00000e+00
53.0000	46.9918	0.0409	2000	7	1	1	2.70674e-06	1.00000e+00	1.00000e+00
53.0000	46.9918	0.0409	2000	8	1	1	2.78701e-06	1.00000e+00	1.00000e+00
53.0000	46.9918	0.0409	2000	9	1	1	2.84053e-06	1.00000e+00	1.00000e+00
53.0000	46.9918	0.0409	2000	10	1	1	2.90157e-06	1.00000e+00	1.00000e+00
53.0000	48.0115	-0.0529	2001	1	1	1	1.66238e-06	1.00000e+00	1.00000e+00
53.0000	48.0115	-0.0529	2001	2	1	1	1.86604e-06	1.00000e+00	1.00000e+00
53.0000	48.0115	-0.0529	2001	3	1	1	2.01175e-06	1.00000e+00	1.00000e+00
53.0000	48.0115	-0.0529	2001	4	1	1	2.19802e-06	1.00000e+00	1.00000e+00
53.0000	48.0115	-0.0529	2001	5	1	1	2.38512e-06	1.00000e+00	1.00000e+00
53.0000	48.0115	-0.0529	2001	6	1	1	2.56229e-06	1.00000e+00	1.00000e+00
53.0000	48.0115	-0.0529	2001	7	1	1	2.67985e-06	1.00000e+00	1.00000e+00
53.0000	48.0115	-0.0529	2001	8	1	1	2.75932e-06	1.00000e+00	1.00000e+00
53.0000	48.0115	-0.0529	2001	9	1	1	2.81231e-06	1.00000e+00	1.00000e+00
53.0000	48.0115	-0.0529	2001	10	1	1	2.87274e-06	1.00000e+00	1.00000e+00
53.0000	48.9965	0.0151	2002	1	1	1	1.64468e-06	1.00000e+00	1.00000e+00
53.0000	48.9965	0.0151	2002	2	1	1	1.84617e-06	1.00000e+00	1.00000e+00
53.0000	48.9965	0.0151	2002	3	1	1	1.99032e-06	1.00000e+00	1.00000e+00
53.0000	48.9965	0.0151	2002	4	1	1	2.17461e-06	1.00000e+00	1.00000e+00
53.0000	48.9965	0.0151	2002	5	1	1	2.35972e-06	1.00000e+00	1.00000e+00
53.0000	48.9965	0.0151	2002	6	1	1	2.53500e-06	1.00000e+00	1.00000e+00
53.0000	48.9965	0.0151	2002	7	1	1	2.65131e-06	1.00000e+00	1.00000e+00
53.0000	48.9965	0.0151	2002	8	1	1	2.72994e-06	1.00000e+00	1.00000e+00
53.0000	48.9965	0.0151	2002	9	1	1	2.78236e-06	1.00000e+00	1.00000e+00
53.0000	48.9965	0.0151	2002	10	1	1	2.84215e-06	1.00000e+00	1.00000e+00
53.0000	50.0120	-0.0479	2003	1	1	1	1.62601e-06	1.00000e+00	1.00000e+00

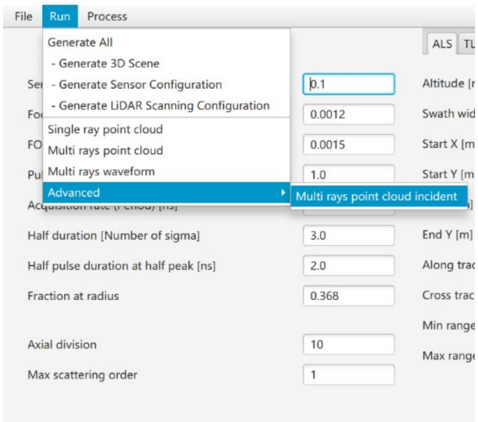


Figure 22. Example of simulating Muti rays point cloud with incident mode.

5.2.2. Full-waveform Multi/Hyperspectral Lidar

Using the mouse to indicate [**RUN]** and click the button [**Generate ALL**], The simulator starts to generate 3D scenes and LiDAR configuration parameters. Then click button [**Single ray point cloud**] or button [**Multi rays waveform]** to simulate the data. The simulation results can be found in the **Results** folder. The results of two different modes correspond to **singleRay** and **records** folder. However, the result is only the data of intermediate process, which is not the full waveform data that can be used effectively. Using the mouse to indicate [**Process**] and click button [**Convolve]** to perform convolution operation. Finally, the full waveform data is obtained, and the results can be found in **convolved_waveform** folder. This result is composed of two files, It's **0.txt** and **pos_0.txt** respectively (**Figure 23**).

[**0.txt**] records all waveform data.

The number of pulses is the number of rows of recorded data divided by bins in which each pulse is dispersed. Therefore, the first pulse is 0 to the **NumberofBinsForEachPulse-1** line. The second pulse is **NumberofBinsForEachPulse to the 2* NumberofBinsForEachPulse-1** line. By analogy, all pulses can be read. The first column of the file is the distance from the starting position of each pulse bin to the sensor, and the second column to the last column is the echo intensity of each band. The visualization of full waveform multispectral LiDAR data is shown in.

[Pos_1.txt] records the position information of the pulse.

The first three columns are the XYZ coordinates of the pulse starting position, that is the sensor position. The last three columns are the reflection direction of each pulse, at the same time, the coordinate system is consistent with the coordinate system of LESS GUI.

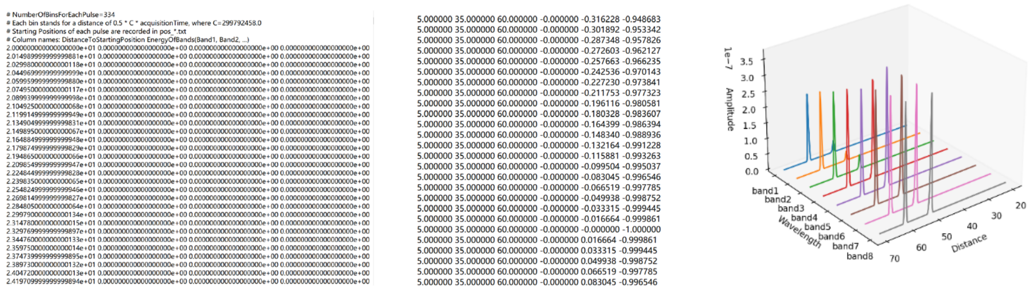


Figure 23. Example of 0.txt (left); example of pos_0.txt (middle); simulated hyperspectral waveform (right).

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