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Interactive Visual Simulation of Satellite-borne Lidar Echo Scenes

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***Abstract*-Satellite-borne Lidar is widely used for both atmospheric observation and terrestrial scene observation. However, in the existing Satellite-borne Lidar simulation system, it is hard for the users to simulate the Satellite-borne Lidar over different photorealistic scene interactively. In this paper, we implement a simulation system of Satellite-borne Lidar echo with realistic scenes: First, a theoretical model is constructed based on the principle of Satellite-borne Lidar. Then, a set of realistic urban scenes as well as a serial of field scenes are built and the waveform simulation of Satellite-borne Lidar over the photorealistic scene is implemented. Thirdly the relevant parameters of the forestall scene together with the urban scene is inverted from the waveform acquired from the Satellite-borne Lidar. Also, a photorealistic scene of a specific area is built and the comparison between our simulation result and the echo of Satellite-borne Lidar in such area is taken. The experiment confirms the accuracy of our system on simulation of Satellite-borne Lidar echo scenes. Our system provides an efficient and convenient approach to the design and the application of Satellite-borne Lidar.**

Keywords-interactive visual simulation; satellite-borne lidar echo; waveform simulation; realistic scenes; parameter inversion

I. INTRODUCTION

Recently, the techniques of Satellite-borne Lidar echo has been found wide applications in the areas such as city planning, land surveying & mapping, Climate change observation and military affairs, etc. However, it's very expensive to launch a set of such satellites with Lidar. It's necessary to make a large amounts of computer simulation experiments to simulate the detecting ability of Satellite-borne Lidar under various complex atmosphere states and surface environments before launching the satellites. And it has been proven to be an effective and reliable way to enhance the design function of satellite.

Current simulation algorithms of satellite-borne Lidar echo mainly focus on the simulation of numerical calculation and lack intuitive and effective interactive methods for users to simulate different atmospheric and earth surface situations. As the rapid development of computer graphics and virtual reality, it becomes possible to realize the interactive visual simulation of satellite-borne Lidar Scene Echo with realism.

In this paper, we propose a new interactive method to simulate the Satellite-borne Lidar echo with realistic scene. Our method bases on the physical principles of Lidar echo and pre-established multiple surface kinds with realistic 3D scenes. For different atmosphere states and surface environments,our simulation system can interactively real-time calculate and display the results of satellite-borne Lidar echo scenes. By changing the parameters of terrain, vegetation, etc., we can determine the optimized design indexes of satellite-borne Lidar. Experiments shows that the calculation accuracy of our simulation system is superior to that of Microsoft Bing Map and the echo waveform shapes are similar to that of NASA ICESat, which proves the reliability of our simulation system.

II. RELATED WORKS

In past two decades, many works have been done about the simulation of Satellite-borne Lidar echo. Carlsson et al [1] proposed a Signature simulation model of Lidar echo. Lovell et al [2] used a simulation way to find optimal Lidar acquisition parameters for forest height inversion based on Physical model. Sun et al [3] established a model between Lidar echo and forest canopies. Harding et al [4] retrieved the closed-canopy and broadleaf forests from Lidar echo. Chauve et al [5] modeled the raw signals to extract full-waveform Lidar data. Holmgren et al [6] studied the effects of Lidar scanning angle on the estimation of mean tree height and canopy closure. Ni-Meister et al [7] analyzed the relationship between Lidar waveforms and forest parameters.

However, above works mainly focus on the simulation of satellite Lidar echo and the theoretical models of scene parameter inversion, little works have been done about satellite Lidar echo simulation with realistic scenes with interactive visual display manner. Wang et al [8] partially realized the visual display of Lidar echo simulation model, but the scenes were too simple with some basic geometrical elements such as planes, bevels and ellipsoids, etc., which could hardly represent the diversity of real surfaces. In this paper, we propose a new method to realize a satellite-borne Lidar echo scenes simulation system. Our simulation system can pre-establish various kinds of 3D surface with photorealism by modeling and rendering techniques of Computer Graphics, and can real-time calculate and interactively display the surface parameters (such as building height, vegetable density, etc.) based on the physical calculation models of satellite-borne Lidar echo. Below we will describe the principle and simulation models of satellite Lidar-borne echo.

III. PRINCIPLE OF SATELLITE LIDAR ECHO MODEL

The principle of satellite-borne Lidar can be described as following: it emits a high-energy laser beam to the surface area to be detected. The laser beam is scattered after it reaches the surface of targets, and the echo is received by Lidar on the satellite. By processing the echo signal, the echo densities from the detected areas at different intervals are acquired by Lidar receiver after laser pulses being launched. The surface form characters of the detected areas are thus obtained by echo waveform analysis. We can also calculate the parameters such as object height on the detected surface areas.

According to above working principle of satellite-borne Lidar, we establish theoretical simulation models of Lidar. They are: satellite-borne Lidar launching model, satellite-borne Lidar laser beam dividing model, satellite-borne Lidar echo model and satellite-borne Lidar noise model. Below we will describe them, respectively.

A. Satellite-borne Lidar Emitting Model

The temporal distribution of energy of single laser pulse beam of satellite-borne Lidar can be regarded as Gaussian distribution [9]. Here we adopt a Gaussian distribution function to describe it:

$$E(t) = E_0 * \frac{1}{\sqrt{2\pi}\sigma} e^{\left(-\frac{(t-t_0)^2}{2\sigma^2}\right)} \quad (1)$$

where E_0 represents the total energy of single laser pulse of satellite-borne Lidar. t_0 is the launch interval of laser pulse. According to the 3σ principle of normal distribution function, we can regard approximately that major energy of pulse locates within the range of [-3σ,+3σ] as the center is pulse launch time. Suppose the wavelength of launch laser beam is L_0, thus the value of σ in Eq. (1) can be determined as:

$$\sigma = \frac{L_0}{3c} \quad (2)$$

B. Satellite-borne Lidar Laser Beam Dividing Model

During the simulating calculation, we need to divide the laser beam for fine calculation. The beam can be regarded a parallel light and the shape of projection on earth surface can be regarded as a circle with radius R. To satisfy the different requirement of simulation resolution ratio, we set a parameter, resratio, to control the precision of laser beam. Then, according to the resolution ratio of laser beam, we divide the laser beam into many small cuboids which have square bottom with same side length, R_0. The value of R_0 can be determined as:

$$R_0 = \frac{R}{2 * resratio} \quad (3)$$

When the value of R_0 is large (i.e. $R_0 \geq 100$), the corresponding light projected area of each element cuboid is small enough, thus we can regard the inside body of the divided beam has the property of spatial consistency and we can use the axis of each divided element beam as its common body direction. The emitting energy of each element beam can be determined as:

$$E_{xy}(t) = \frac{A_{xy}(t)}{\sum_{(x,y)} A_{xy}(t)} E(t) \quad (4)$$

Where the term, $E(t)$, has the same meaning as in Eq. (1); (x, y) are the coordinates of projected area of certain element beam; $A_{xy}(t)$ represents the value of 2D Gaussian distribution density function and its value is:

$$\begin{cases} A_{xy}(t) = \frac{1}{2\pi\sigma^2} e^{-\frac{1}{2}\left(\frac{x^2+y^2}{\sigma^2}\right)} & x^2 + y^2 \leq R^2 \\ A_{xy}(t) = 0 & x^2 + y^2 > R^2 \end{cases} \quad (5)$$

C. Satellite-borne Lidar Echo Model

When a laser beam is launched from the satellite, it transmits through the atmosphere, then is reflected back from the surface of objects on the earth and transmits through the atmosphere again before it reaches the light receiver of the satellite. Here we establish two kinds of echo models: Earth surface object reflection model and Laser beam transmission and receiving model. Below we will describe them, respectively.

1) Earth surface object reflection model: When the laser beam reaches the surface of objects on the earth, mirror reflection and diffuse reflection occur. For simplicity, here we only consider the effect of diffuse reflection. The laser density reflecting from the surface of object can been expressed as:

$$Eout_{xy}(t) = E_{xy}(t) * RL(x, y) \quad (6)$$

Where $E_{xy}(t)$ is the light density of incident laser beam on the surface with coordinates (x, y) at time t. $RL(x, y)$ is the reflectivity of element beam when it is incident on the first mesh of an object.

2) Laser beam transmission and receiving model: When the laser beam is reflected back from the earth surface, it transmits through the atmosphere and finally reaches the receiver on the satellite-borne Lidar. The received energy of each element beam can be expressed as[10]:

$$Eret_{xy}(t) = Eout_{xy}(t)\frac{\eta T^2 D^2}{4Dis_{xy}^2} \quad (7)$$

Where η is the efficiency coefficient of satellite receiver. Dis_{xy} is the distance from the emitting point of laser on the satellite to the first object the element beam collides with. T is the unidirectional atmospheric transmittance. D is the diameter of satellite-borne laser receiver. At time t, the total energy collected by satellite receiver can be expressed as:

$$Efin(t) = \sum Eret_{xy}(t) \quad (8)$$

D. Satellite-borne Lidar Noise Model

When the satellite-borne laser launch, transmit and receive the light beam, noise from the environment (like sunlight) or from its own launcher and receiver occurs. We use the random model to simulate this kind of noise:

$$E_{noise} = k * random(0,1) \quad (9)$$

Where k is the noise coefficient and its value can be adjusted.

IV. REALIZATION OF SATELLITE-BORNE LIDAR ECHO SIMULATION SYSTEM

Based on above theoretical models, we realize a satellite-borne Lidar echo simulation system. Our simulation system hire Unity3D engine as development platform. The overall framework of the system can be expressed as following,

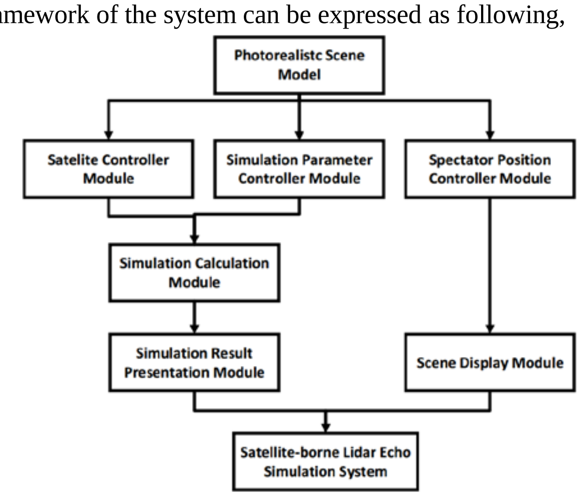

Figure 1. Framework of the satellite-borne Lidar echo simulation system.

All the modules within the simulation system can be divided into three parts: 1) 3D modeling of earth surface scenes; 2) Satellite-borne Lidar echo calculation; 3) Earth surface parameter inversion. Below we will describe them, respectively.

A. 3D Modeling of Earth Surface Scenes

Dietrich et al [10] and Deussen et al [11] did some modeling works for forest scenes, and Hu et al[12] did some similar modeling works for urban scenes. But little works have been done to model large-scale photorealistic scenes for satellite-borne Lidar echo simulation.

To realistically display the diversity of earth surface scenes, in our system we use photorealistic 3D modeling techniques of Computer Graphics to model and render the natural and urban scenes which are used for satellite-borne Lidar echo simulation. These scenes include: Forest scene with multiple vegetation (like trees, shrub and grass); River & Lake scene; Hill & mountain scene; Plain scene and urban scene with various kinds and sizes of buildings. Furthermore, by hiring GPU accelerating technique, we successfully realize the interactive display of these photorealistic scenes in real time.

B. Satellite-borne Lidar Echo Calculation

To realize the satellite-borne Lidar echo calculation, we propose an algorithm and its steps are described as below:

- Regard the laser launcher of satellite-borne Lidar as a point light source and launch a radial to each laser beam mentioned above.
- By a radial class we define, the distance between the radial to the first mesh of surface object is acquired and its value can be assigned to *Disxy* in Eq. (7). The reflectivity of the object is thus assigned to *RL(x,y)* in Eq. (6).
- Sign the length between the laser launcher and the first surface object as MINL and that between the laser launcher and the last surface object as MAXL. Here we use the laser beam distance as a coordinate with MINL-half laser wavelength as lower limit, MAXL+ half laser wavelength as upper limit and DELTAL as step, to establish an accumulator to store and sum the laser energy the receiver acquires at different interval.
- According to Eq. (7), we can calculate the energy of each element laser beam at each interval at accumulator and sum the energy at different time quantum. In this way an energy-time histogram can be drawn.

C. Earth Surface Parameter Inversions

The main function of this part can be divided into two sub-functions: urban surface scene parameter inversion and forest scene parameter inversion.

1) Urban surface scene parameter inversion: As the urban scene comprises different shape and height buildings, the main task of this part is to inverse the height of buildings. The height inversion algorithm steps can be described as:

- As the received echo include noise and need to save the wave peak for laser height calculation, we should undergo bilateral filtering for energy-time histogram.

- For the processed energy-time histogram, we use the Maximum Between-Class Variance method to distinguish the time threshold of earth surface from these of buildings.
- For the earth surface part, we calculate its location of center of gravity, average echo time is thus acquired.
- For the building part, as the projected laser facula area sometime cover several buildings of different height, we need to calculate these correspond heights. We can find the location of each wave peak in the histogram to calculate its corresponding echo time.
- Subtract the echo time of each building from that of earth surface, we acquire the time difference. The half value of the product of time difference and light speed is the height of the building.

2) Forest scene parameter inversion: The Forest scene usually includes various kinds of trees, thus the main inversion parameter of a forest scene should be the average plant height and average forest density. The corresponding algorithm step can be described as:

- Apply the Bilateral Filtering to the energy-time histogram and save the wave peak while receiving the echo noise.
- For the processed histogram, we use the Maximum Between-Class Variance method to distinguish the time threshold of earth surface from these of buildings.
- For the earth surface part and object part, we respectively calculate their echo times corresponding to their location of center of gravity.
- Subtract the echo time of each object from that of earth surface, we acquire the time difference. The half value of the product of time difference and light speed is the average height of the forest.
- Sum the echo energy of earth surface part, and is divided by the total echo energy, the forest density of the area is thus obtained.

V. RESULTS AND ANALYSIS

According to above calculation model and algorithms, we establish a intuitionistic and efficient satellite-borne Lidar echo simulation calculation and display system which can run on a common person computer. In the system, we realize the function of parameter setting, real-time walkthrough, simulation calculation and display of height inversion of objects. Figure 2 shows the simulation interface of forest surface scene. Figure 3~ Figure 5 show the different types of earth surface. From the figures we can see that our system includes various kinds of the earth surface and these surface scenes are quite realistic.

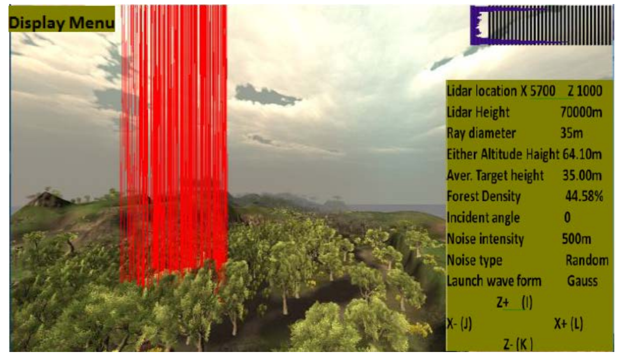

Figure 2. Simulation interface of forest surface scene (the red ray cluster is the laser beam launched from Lidar).

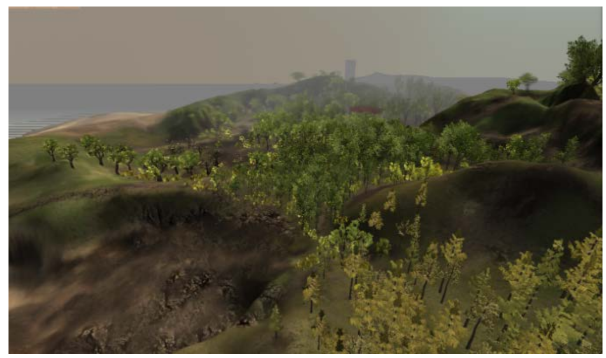

Figure 3. Hill surface scene.

Figure 4. Lake surface scene.

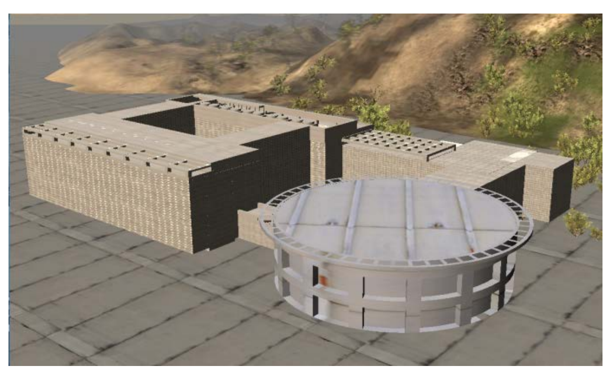

Figure 5. Urban building scene.

To analyze the results of Lidar echo simulation, here we take two kinds of earth surfaces (Forest scene and urban building scene) as example to show the function of our simulation system.

*1) Forest surface scene echo simulation:*We choose a forest surface area as the object of our Lidar echo simulation. During the simulation, we can add different amount of noise intensity to simulate the effect from its own launcher and the environment. Figure 6 show the Lidar echo relative intensity acquired by satellite receiver. In this case, the noise intensity k=100, the vertical axis represents the relative echo intensity, and the horizontal axis represents the relative height from Lidar to the objects. We can see from the figure that there are three wave peaks which are the echoes of tree crown, bottom bush and the ground, respectively. In this way, we can easily calculate the heights of various objects on the earth surface. Of course, when the intensity of system noise becomes big enough, some scene parameter (the height of bottom bush in this case) is lost.

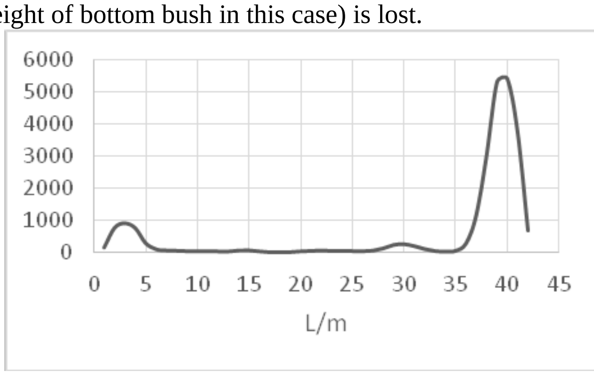

Figure 6. The Lidar echo intensity distribution with relative distance L.

2) Urban building scene echo simulation: For urban building echo simulation, We choose a building called Mengmenwei Building (See Figure 5) as tested object, which locates in Zijingang campus, Zhejiang University. The analysis of simulation results are listed on Table 1. From the Table we can see that the error rate between the simulated value and measured value for East wall and West wall are 3.98% and 2.51%, respectively. And the average error rate thus is 3.25%. So the simulation precision of our system is quite satisfactory.

TABLE 1 ECHO ANALYSIS OF A URBAN BUILDING

Object name	Average height (m)	Standard deviation	Measured value (m)	Error rate
East wall	21.706	0.297	22.6	3.98%
West wall	16.574	0.438	17.0	2.51%

To further verify the reliability of our simulation system, we will compare our results to the measured data of ICESat [13]（Ice, Cloud, and land Elevation Satellite）, a famous Lidar satellite. ICESat is a part of NASA’s Earth Observation System and its main goal is to measure ice terrain & its time varying elevation, the characteristics of cloud & atmosphere, as well asto measure the land terrain, ground targets and vegetation characters along its orbit.

Figure 7. The satellite image of the detected area.

The verification algorithm steps of Lidar echo waveform simulation can be described as below:

- Based on the satellite Lidar echo data of ICESat (data file names: GLA01~GLA14), apply the waveform filtering method to waveform information of candidate points.
- Choose the interested target point and acquire its longitude and latitude data. Here the interested target point locates in Shaoxing, Zhejiang, China (with longitude 120.35398°E, latitude 30.132548°N), which is a factory area (See Figure 7).
- By measure the heights of this area, we establish its precise 3D geometric model.
- Introduce the 3D geometric model into our satellite Lidar echo simulation system to be simulated.
- Compare the simulated echo waveform to that of ICESat in the same area, the similarity between is thus verified.

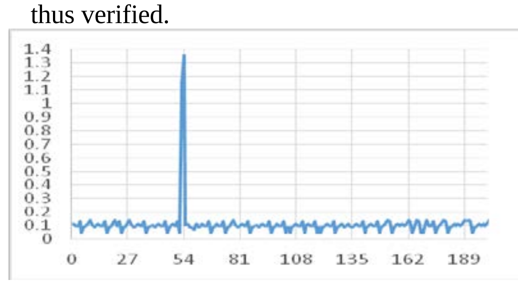

Figure 8. The simulated echo waveform of the area shown in Figure 7.

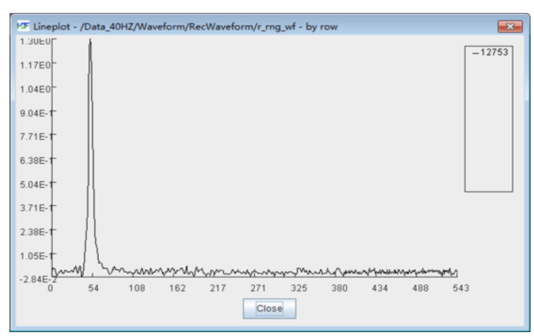

Figure 9. The corresponding echo waveform of the area from ICESat.

Figure 8 is the simulated echo waveform of the area shown in Figure 7, and Figure 9 is the corresponding echo waveform of the area from ICESat. In the figures, the vertical axis represents the Lidar echo relative intensity, and the horizontal axis represents the time sampling points. From the figures we can see that simulated waveform is quite similar to that of mesaured results from NASA ICESat.

To quantitative verify the similarity between the simulated waveform and that from NASA ICESat, we choose a serious data points around the wave peaks and use Pearson correlation coefficient method [14] to verify. The calculation result shows that the similarity between the simulated waveform and the actual measured waveform (NASA ICESat) reaches to 93.61%. This demostrates the effectiveness and reliability of our satellite Lidar echo simulation system.

VI. CONCLUSIONS AND FUTURE WORKS

In this paper, we propose a new satellite-borne Lidar echo scene simulation algorithm which has great application potential in the design of satellite-borne Lidar and the efficient fulfillment of Lidar echo simulation under various complex weather conditions and with different earth surface scenes. The main contribution of this paper includes:

- We propose and realize a visual simulation system satellite-borne Lidar echo scenes based on multidisciplinary knowledge including Computer Graphic, Atmosphere Optics and laser echo measurement, etc. Unlike other current satellite-borne Lidar echo simulation system, our system has the advantage of operation intuitiveness, and can interactively set the parameters of earth surface and atmosphere. The user can real-time display the simulated results.
- The simulation system are based on physical working principles of satellite-borne Lidar echo and establish various theoretical calculation models including: laser beam launching model, laser beam dividing model, Echo received model and noise model, which ensure the theorical reliability of our simulation system.
- As our simulation system pre-establishes various kinds of 3D earth surface scene models, users can realistically display and walkthrough these surface scenes and can easily choose any area for Lidar echo waveform simulation. Further more, the simulation system can inverse the surface parameters (such as height of objects) of various urban and field scenes like forest, hill, ice terrain and water body, etc.

Experiments show that the simulation calculation accuracy are quite satisfactory, and the Lidar echo waveforms of simulation have high-similarity with these of satellite-borne Lidar data from NASA ICESat, which demostrates the effectiveness and reliability of our satellite Lidar echo simulation system. Our new method offer a new technique way for the design and application of satellite-borne Lidar.

Our future works will consider the spectral reflectance properties of the earth surface objects and perfect the atmosphere loss model to make the simulation results more accurate and forecast the biomass yields of certain surface area determined by our simulation system.

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REFERENCES

[1] Carlsson T, Steinvall O, Letalick D. Signature simulation and signal analysis for 3-D laser radar, Month, 2001, 4: C4ISR.

[2] Lovell J L, Jupp D L B, Newnham G J, et al. Simulation study for finding optimal lidar acquisition parameters for forest height inversion, Forest Ecology and Management, 2005, 214(1): 398-412.

[3] Sun G, Ranson K J. Modeling lidar returns from forest canopies, Geoscience and Remote Sensing, IEEE Transactions on, 2000, 38(6): 2617-2626.

[4] Harding D J, Lefsky M A, Parker G G, et al. Laser altimeter canopy height profiles: Methods and validation for closed-canopy, broadleaf forests[J]. Remote Sensing of Environment, 2001, 76(3): 283-297.

[5] Chauve A, Mallet C, Bretar F, et al. Processing full-waveform lidar data: modelling raw signals, International archives of photogrammetry, remote sensing and spatial information sciences 2007. 2008: 102-107.

[6] Holmgren J, Nilsson M, Olsson H. Simulating the effects of lidar scanning angle for estimation of mean tree height and canopy closure, Canadian Journal of Remote Sensing, 2003, 29(5): 623-632.

[7] Ni-Meister W, Jupp D L B, Dubayah R. Modeling lidar waveforms in heterogeneous and discrete canopies, Geoscience and Remote Sensing, IEEE Transactions on, 2001, 39(9): 1943-1958.

[8] Wang Chunhui, Li Xu, Peng Huan. Research on Simulation and Analysis of Spaceborne Full Waveform Laser Altimeter, Laser & Optoelectronics Progress, 2015, 52(10).

[9] Krawczyk R, Goretta O, Kassighian A. Temporal pulse spreading of a return lidar signal, Applied optics, 1993, 32(33): 6784-6788.

[10] Dietrich A, Colditz C, Deussen O, et al. Realistic and interactive visualization of high-density plant ecosystems[C]. Eurographics. 2005: 73-81.

[11] Deussen O, Hanrahan P, Lintermann B, et al. Realistic modeling and rendering of plant ecosystems[C]. Proceedings of the 25th annual conference on Computer graphics and interactive techniques. ACM, 1998: 275-286.

[12] Hu J, You S, Neumann U. Approaches to large-scale urban modeling[J]. IEEE Computer Graphics and Applications, 2003, 23(6): 62-69

[13] http://icesat.gsfc.nasa.gov/

[14] https://en.wikipedia.org/wiki/Pearson_productmoment_correlation_coefficient