OVERVIEW OF THE TERRESTRIAL ECOSYSTEM CARBON MONITORING SATELLITE LASER ALTIMETER

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ABSTRACT:
The Terrestrial Ecosystem Carbon Monitoring satellite will be the first satellite of China with multi-beams laser altimeter and repetition frequency equal to GLAS on the world first laser altimetry satellite ICESat, but smaller diameter than GLAS. This satellite will be a milestone of Chinese satellite laser altimetry from single elevation control application to multi-scene applications, such as the forest height, water level measurement and so on. In this paper, the basic parameters of multi-beams laser altimeter on the terrestrial ecosystem carbon monitoring satellite are introduced and compared with other satellite laser altimeters, especially the GLAS and CALIOP, and the working mode is illustrated, which is equal to the GF-7 satellite but different to ICESat. The laser altimetry data products and data processing flow to the standard product is designed. Moreover, the geometric calibration method without field site for the multi-beams full waveform laser altimeter is proposed, which will be continued and improved from the GF-7 satellite laser altimeter geometric calibration without field by the terrain matching and waveform matching, and the high resolution multi-spectral nadir camera will be calibrated and used as the new footprint image with more high resolution and spectral information. The simulated sample data is introduced and illustrated for better understanding of the satellite laser altimetry data. At last, the application of this satellite laser altimetry data product is prospected, and the standard product SLA03 will be produced and released in the Land Satellite Remote Sensing Application Center.

1. INTRODUCTION

1.1 Background

As a new and active earth-observing technology, satellite laser altimetry has a quick development from the 2003, in which the first laser altimetry satellite ICESat (Ice, Cloud and land Elevation Satellite) had been successfully launched and the GLAS(Geo-science Laser Altimeter System) loaded on the ICESat been widely used for scientific research, such as the polar iceberg change monitoring, forest biomass estimation, lake water level measurement, and global elevation control points surveying (Schutz et al., 2005; Harding, 2005; Carabajal et al., 2010). ICESat ended in 2009 and as the successor, the ICESat-2 was launched on September 15th, 2018 and is collecting valuable scientific data globally by the new generation photon-counting laser ATLAS (Advanced Topographic Laser Altimeter System), which has been widely used in the geoscience field (Markus et al., 2017; Martino et al., 2019; Xie et al., 2020). What's more, the GEDI (Global Ecosystem Dynamics Investigation) loaded on the SSI (International Space Station) succeed in 2018 to produce high resolution laser ranging observations for 3D structure of the earth by 8 beams, 242 Hz and 25m diameter size (Xie et al., 2018). Satellite laser altimetry data is good choice to measure the height of forest and evaluate the terrestrial carbon sink, which is of great significance to the realization of "peak emission of carbon dioxide and carbon neutralization" .
ICESat, ICESat-2 and GEDI all have been used as the data source to measure the forest height and motoring the biomass and carbon sink, but mainly for the scientific purpose. Different type of laser have different advantages, such as the linear full waveform laser GLAS, GEDI and the photon-counting laser ATLAS. Which type is the better and what is the best diameter of the laser altimeter for the forest height measurement still need analysis and validation.

1.2 TECM Satellite

China will launch the Terrestrial Ecosystem Carbon Monitoring satellite, which is shorted for TECM, equipped with multi-beams lidar in 2022, among them, five is used for land and forest observation and one is used for cloud and aerosol detection. The forest structural parameters, land elevation control points, cloud and aerosol parameters will be observed from the TECM-1 satellite, and the forest and carbon sink will be focused especially (Liu et al., 2021).
TECM is designed by the China Academy of Space Technology and the main users contain the Academy of Forest Inventory and Planning and the Land Satellite Remote Sensing Application Center, Ministry of Natural Resources. The laser altimetry standard product of TECM satellite will be produced

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by the Land Satellite Remote Sensing Application Center and released for the subsequent applications.

2. TERRESTRIAL ECOSYSTEM CARBON MONITORING SATELLITE LASER ALTIMETER

2.1 Basic Parameters

There are five laser beams for the land and forest surveying on the TECM -1 satellite, and the laser wavelength is 1064nm, the divergence angle is about 50 urad, which means the diameter of laser footprint is about 25 meter on the ground from the 500km satellite orbit. The frequency is 40Hz equal to the GLAS on the ICESat, but the diameter of footprint is smaller than GLAS with 70 meter. The laser emitted energy is 70mJ and the waveform vertical resolution and ranging accuracy is about 0.125 meter and 0.3 meter, in respectively. Moreover, there is one laser beam for the cloud and aerosol, just is equal to the CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization) on the CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation) satellite, which has been launched in 2006 for the cloud and aerosol detection, and is the milestone for the active atmospheric lidar (Winker et al., 2009). The basic parameters of TECM satellite multi-beams laser altimeter is illustrated on Table 1. As the first Chinese waveform recording and sampling laser altimeter on the GF-7 satellite for the earth observation, the comparison between the GF-7 and TECM-1 satellite laser altimeter also has been implemented on Table 1, and the apparent difference is the frequency and beam number. The ranging accuracy of TECM -1 satellite laser altimeter may be better than 0.3 meter, but which is depend on the on-orbit testing result. And there is a nadir high resolution linear array camera on the TECM, which can capture the multi-spectral image of the earth with 2.0 meter resolution and the receive telescope is the same with the multi-beams lidar, so the high resolution panchromatic image can be used for the laser points as the footprint image.

2.2 Working mode

The five laser beams and cloud/aerosol laser on the TECM-1 satellite are illustrated in Figure 1 and there are different pointing angle for the five laser beams, and the pointing angle are -0.85°, -0.425°, 0°, 0.425°, 0.85°, in respectively. Moreover, there is a backup for the cloud/aerosol laser.

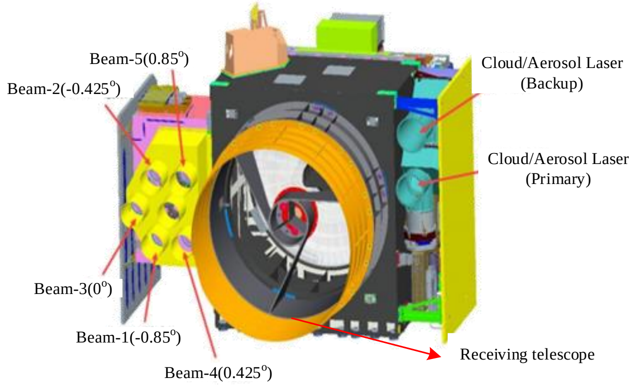

Figure 1. The laser altimetry system of TECM satellite

Table.1 Parameters comparison of different laser altimetry satellites.

Satellite	TECM		GF-7	ICESat	CALIPSO	
Load Name	SLA		SLA	GLAS	CALIOP	
Date	2022		2019	2003	2006	
Orbit/km	506		505	600	700	
Detected Target	Forest/Land	Cloud/Aerosol	Land	Land/Ice/Forest	Cloud/Aerosol	Cloud/Aerosol
Wavelength/nm	1064	532(polarization)/ 1064	1064	1064	532/1064	532(polarization)/ 1064
Frequency/Hz	40	20	3	40	40	20
Energy/mJ	70	110	180	75	32	110
Diameter/m	25	100	20	60-70	-	70
Beams	5	1	2	1	1	1
Vertical Resolution/m	0.125	30	0.075	0.15	76.8	30
Ranging accuracy/cm	30	-	10	10	-	-
FWHF/ns	⩽8	20	5-7	6	20	20

The working mode of the TECM satellite five beams laser for the land and forest detection is illustrated in Figure 2. Along the track, or the satellite flight direction, the interval is about 170 meter and the distance across the track is about 3.71km. The footprint camera of the laser is a panchromatic CMOS with the size about 1024 pixel by 128 pixel, and the resolution is about 8.0meter, which also can capture the ground image and the laser energy image like the GF-7 satellite laser footprint camera (Li et al., 2021). The small matrix CMOS camera can capture the centroid of the laser spot and monitor the location change by the centroid extraction from the images of long period. And there will be five spot on the CMOS images and present the five laser, in respectively, and the location change between different lasers points can be reflected the pointing change, which will be useful for the long-period geometric calibration or accuracy optimization.

Moreover, there is a nadir linear array camera can capture the high resolution multi-spectral of the ground images with the same receiving telescope for the laser altimeter. And the swath width of the multi-spectral high resolution image captured by the nadir camera is about 20km and can cover the five land and forest laser footprints on the ground. So, the different between the GF-7 and TECM satellite laser altimeter is that the footprint image resolution of TECM laser altimeter can be improved to 2.0 meter by the nadir multi-spectral image from 8.0 meter from the original panchromatic CMOS laser footprint camera.

The multi-spectral high resolution footprint image will be helpful for the subsequent application, such as the land cover classification and the interpretation of the target within 25 meter laser footprint on the ground, especially on the forest or other complex region.

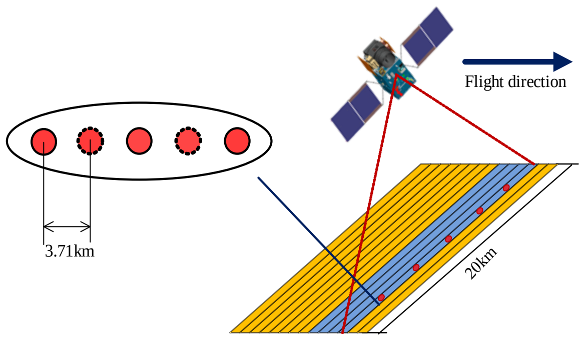

Figure 2. The working mode of TECM satellite multi-beams laser altimeter

3. LASER ALTIMETRY PRODUCT DESIGN AND DATA PROCESSING

3.1 Product Design

The laser altimetry product of the TECM satellite will be designed from SLA00 to SLA08 or continued in future according to the reality, which is in Table 2. The product design has referenced to the GF-7 satellite laser altimetry product design (Li et al., 2021) and the ATLAS products (Markus et al., 2017; Martino et al., 2019), even the ATLAS is just the photon-counting laser altimeter while the TECM and GF-7 satellite is the full waveform linear laser altimeter. Of course, there is difference to the ATLAS, such as the SLA05 global laser elevation control point product of TECM satellite.

The SLA00 product is just the original data from the satellite and the SLA01 is the product after decoding and resorting of SLA00 data.

SLA02 and SLA03 both are the geo-located laser altimetry product, while the SLA02 just has the primary geographic coordinate information of the laser footprint, which can be used as the input for the subsequent atmospheric and tidal correction. The SLA03 is the standard laser altimetry product with the global geo-located laser points depending on the precise satellite position and attitude data and the many kinds of geophysical correction, such as atmospheric delay correction, solid earth tides, ocean tides, pole tide, ocean loading tides and other tides corrections.

The SLA04 is the cloud and aerosol product and equal to the ATL04/09 product of the ATLAS on the ICESat-2 (Palm et al., 2019), which will be mainly produced by the cloud/aerosol laser altimeter of the TECM satellite.

Considered on the global elevation control point application of TECM satellite laser altimetry data, the SLA05 product will be just the special product after quality control and automatic selection the high accuracy land laser points from the SLA03 product. SLA06 is the water level product derived from the SLA03 covering the global large lakes or the reservoirs, and SLA07 is the land ice product derived from the SLA03 covering the Qinghai-Tibetan Plateau glaciers or the polar ice sheets. SLA08 is the forest special product derived from the SLA03 covering the forest regions, which will contain the tree height and vertical structure parameters.

Moreover, according to the TECM satellite on-orbit reality, the other products, such as the sea ice product or the change monitoring product can be continued to generate in future, if it is possible.

Table 2. Laser altimetry products with different classification and the products illustration of TECM satellite.

Product	Product definition
SLA00	Binary data file derived from the satellite
SLA01	Decoding and resorting data from SLA00 data file
SLA02	Primary laser altimetry product with geographic coordinate information using the real-time attitude and orbit data.
SLA03	Standard laser altimetry product for the global geo-located laser points using the precision orbit, precision attitude, atmospheric and tidal correction and so on.
SLA04	Cloud and aerosol product with the optical thickness, cloud height and so on, mainly produced by the cloud/aerosol laser altimeter.
SLA05	Global elevation control points product after quality control and automatic selection from the SLA03 product
SLA06	Large lakes and reservoirs water level product derived from the SLA03 product
SLA07	Land ice elevation product derived from the SLA03 product covering the Qinghai-Tibetan Plateau Glacier and polar iceberg
SLA08	Global forest height product derived from the SLA03 product covering the forest region

3.2 On-orbit Geometric Calibration without field site

On-orbit geometric calibration of satellite laser altimeter is the fundamental step for the data processing. The geometric calibration parameters contain the pointing angle correction value and laser ranging correction value. There are two methods for geometric calibration, one is field calibration and other is without field. Field calibration needs huge amount detectors located on the ground, and the economic cost and engineering risk is tremendous. For the multi-beams laser altimeter, the geometric calibration without field site is recommended, which has been successfully implemented and validated on GF-7 satellite laser altimeter by the terrain matching and waveform matching (Li et al., 2022).

The first step is the terrain matching. The minimum sum of squares of height difference between the points corresponding to the laser point $\mathbf{P}$ and the actual terrain set $\mathbf{Q}$ is selected as the evaluation parameter, then there are a group of deviation values of laser pointing angles $(\mathrm{d}Ax, \mathrm{d}By)$, which satisfy the Equation 1.

$$k(d\rho, \mathrm{d}Ax, \mathrm{d}By) = \min \sum_{i=0}^{n} (z_i - h_i)^2, \{(x_i, y_i, z_i) \in \mathbf{P}, (x_i, y_i, h_i) \in \mathbf{Q}\} \quad (1)$$

After calculating the deviation value of pointing angles $(\mathrm{d}Ax, \mathrm{d}By)$, the average value of the height difference between laser point and reference terrain can be used as the initial value of the system ranging error $d\rho$.

The second step is the waveform matching. After the approximate true value of $(d\rho, \mathrm{d}Ax, \mathrm{d}By)$ is obtained by terrain matching, the laser locating position can be limited to a certain region. The serial simulated waveform data can be calculated from the transmitted waveform and the terrain of the footprint by moving the locating position of the laser point according to the terrain matching result. The similarity measurement of the simulated and reality waveform matching can be calculated by

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using the classical Pearson correlation coefficient, as shown in the Equation 2, $\mathrm{cov}(x,y)$ represents the covariance of variables X and Y, σx and σy represent the standard deviation respectively, and ρ is between [-1,1]. The closer it is to 1, the greater the positive correlation and the higher the similarity of waveforms.

$$\rho=\frac{\mathrm{cov}(x,y)}{\sigma x\cdot\sigma y} \qquad (2)$$

The waveform matching correlation coefficient distribution on different offset value of the terrain matching result is illustrated in Figure 3. The location of the correlation coefficient peak just means the best position of the laser footprint points. Then, the pointing angle corrected value can be calculated by this position and the result will be more accurate, which can be determined as the geometric calibration result. The laser ranging corrected value can be further refined by the referenced DSM data and the laser footprint points on the flat terrain.

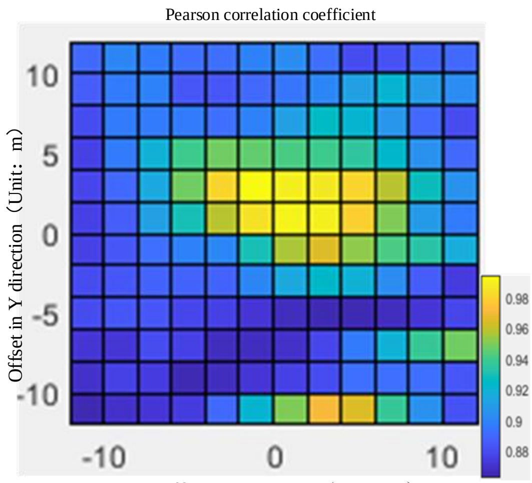


Figure 3. The waveform correlation coefficient distribution

The laser footprint camera with small panchromatic CMOS and 8.0 meter resolution can be calibration by the traditional geometric calibration method using the high accuracy DOM image. The method also can be used for the nadir high resolution multi-spectral image, which will be used as the refined laser footprint image data with much better resolution. The laser points located on the footprint image can be determined by the geography coordinates, when the spot centroid on the CMOS image change, the pointing angle and the locating position also can be updated.

3.3 Data Processing method

The laser altimetry standard product of the carbon monitoring satellite will be the important fundamental product for the future comprehensive application. The data processing of standard product will contain the atmospheric delay correction, the tidal correction, laser footprint images processing, full waveform data processing and the three-dimensional geometric positioning for every laser point. Moreover, the waveform characteristic parameters, such as the peak energy, the pulse width and so on, will be processed and recorded to inverse the forest vertical structure parameters. The processing flow is illustrated in Figure 4.

The processing model will be based on the laser altimetry rigorous geometric model (Tang, et al., 2016), which will contain the aberration correction, atmospheric delay correction, tidal correction, and other kinds of geophysical corrections. The atmospheric correction parameters will be continued to use the global NECP (National Center for Environmental Prediction) data.

The TECM satellite SLA03 product information will be almost the same with the GF-7 satellite laser altimetry SLA03 data product (Li et al., 2021). Moreover, the high resolution multi-spectral image of the nadir camera will be introduced to improve the original footprint image from 8.0 meter panchromatic to 2.0 meter multi-spectral, which will be the difference between the GF-7 and TECM satellite laser product.

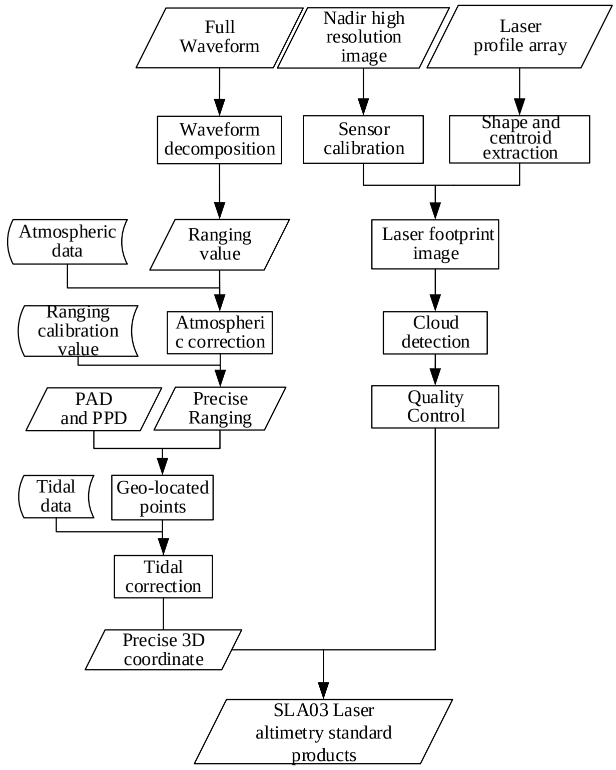


Figure 4. The data processing method of SLA03 laser altimetry standard product

4. DATA SAMPLE AND APPLICATION PROSPECT ANALYSIS

4.1 Simulated Data

The simulated data of the terrestrial ecosystem carbon monitoring satellite multi-beams laser altimeter with laser footprint images, laser profile array and full waveform is implemented and introduced to present the data structure and character, which is based on the referenced airborne LiDAR and DOM images with the refined laser simulated method (Men et al., 2018).

The sample data is illustrated in Figure 5, the red dots mean the laser footprint points of the five beams located on the image. The interval of the laser footprint points is about 170 meter and the diameter of the laser on the ground is about 25 meter. For one beam, the interval is almost equal to the GLAS, while the diameter is smaller than the GLAS with 70 meter. The panchromatic image is captured by the CMOS footprint camera with the 8.0 meter resolution. And the 2.0 meter high resolution multi-spectral image captured by the nadir camera with the same receiving telescope is integrated as the laser footprint image, which is exampled in Figure 6. Examples of original echo waveform data of GF-7 satellite laser altimeter on forest regions is illustrated in Figure 7, which is almost the same to the TECM satellite with the equal diameter and full waveform sampling and recording.

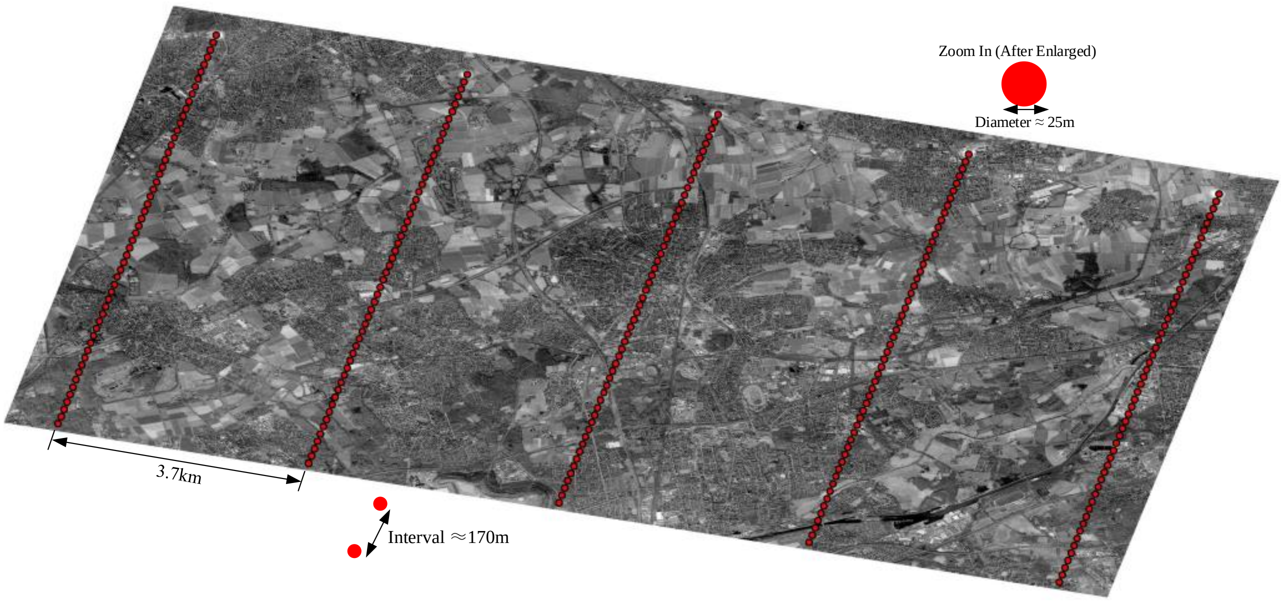
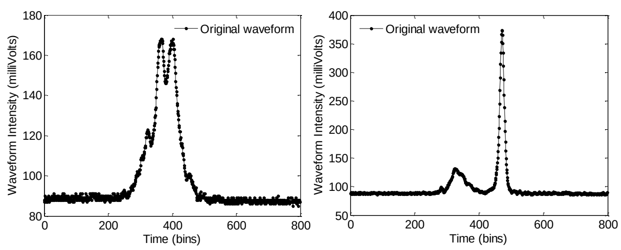


Figure 5. The sample laser altimetry data of TECM satellite after simulation according to the designed parameters

Figure 6. Sample data of one laser footprint point and the multi-spectral image



(a) Vegetation in mountain with a certain slope
(b) Layered vegetation with flat terrain
Figure 7. Examples of original echo waveform data of GF-7 satellite laser altimeter on forest regions

4.2 Application Prospect

Terrestrial Ecosystem Carbon Monitoring satellite will be the first satellite of China with multi-beams laser altimeter and repetition frequency equal to GLAS on the world first laser altimetry satellite ICESat, but with smaller diameter and synchronous high resolution multi-spectral image by the same receiving telescope. This satellite will be important milestone and can be widely used in the forest height measurement in special, elevation control points surveying as the GF-7 satellite laser altimeter, and lake and reservoirs water level and other new application fields.

Land Satellite Remote Sensing Application Center will continue to product the standard product SLA03 of the Terrestrial Ecosystem Carbon Monitoring satellite, and further boost the other products application, such as the global elevation control point database combined with the GF-7 satellite laser altimetry SLA05 product, and the global lake and reservoirs water level product SLA06, compared and integrated with the ICESat historical data and ICESat-2 ATL13 product for the global water resource balance. The forest product will be public and cooperative with the forest relative institutes for the professional application in the carbon sink.

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