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Conceptual study of Earth observation missions with a space-borne laser scanner

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Conceptual Study of Earth Observation Missions with a Space-Borne Laser Scanner

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Abstract— The Japan Aerospace Exploration Agency (JAXA) has started a conceptual study of earth observation missions with a space-borne laser scanner (GLS, as Global Laser Scanner). Laser scanners are systems which transmit intense pulsed laser light to the ground from an airplane or a satellite, receive the scattered light, and measure the distance to the surface from the round-trip delay time of the pulse. With scanning mechanisms, GLS can obtain high-accuracy three-dimensional (3D) information from all over the world.

High-accuracy 3D information is quite useful in various areas. Currently, following applications are considered.

1. Observation of tree heights to estimate the biomass quantity.
2. Making the global elevation map with high resolution.
3. Observation of ice-sheets.

This paper aims at reporting the present state of our conceptual study of the GLS. A prospective performance of the GLS for earth observation missions mentioned above.

Index Terms—Space-borne laser scanner.

I. INTRODUCTION

High-accuracy three-dimensional (3D) information of global area is very useful in various fields, such as global observations of tree height, elevation, and ice sheet. Especially, there are pressing needs to advance understanding of how changes in the 3D structure of

terrestrial vegetation are affecting the global carbon dynamics and their implications for climate change. Thus new space assets are urgently needed to measure global maps of the 3D structure of vegetation [1].

The Japan Aerospace Exploration Agency (JAXA) has started a conceptual study of earth observation missions with a space-borne laser scanner (GLS, as Global Laser Scanner) which will enable us to obtain the high-accuracy 3D information from the globe. Fig. 1 shows a schematic diagram of GLS.

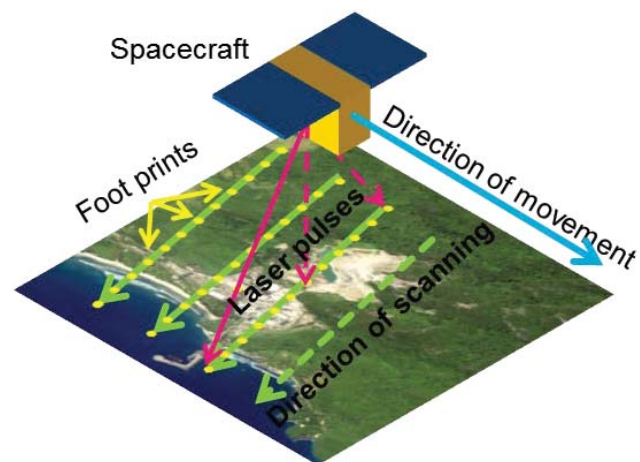


Fig. 1. Schematic diagram of GLS.

II. LASER SCANNER

Laser scanner is a system which transmit intense pulsed laser light to the ground from an airplane or spacecraft, receive the scattered light, and measure the distance to the surface from the round-trip delay time of the pulse. As shown in Fig. 2, echo laser waveforms from vegetated surfaces include returns from the top of tree

and ground, which enable us to measure the canopy height of tree.

The beam of the laser scanner is distributed into a certain swath of observation by scanning mechanism such as a galvanometer scanner or a polygon mirror scanner (see III–D). It enables us to observe the 3D information from not only the nadir of the spacecraft, but also off-nadir direction with uniform densities of footprints.

Air-borne laser scanner is widely used to capture 3D data of large areas, such as agricultural or forestry sites, urban areas, industrial plants, etc. On the other hand, space-borne laser scanner has not been realized yet. There was a space-borne laser altimeter observing the nadir direction, named the Geoscience Laser Altimeter (GLAS) which is the primary instrument of the Ice Cloud and Land Elevation Satellite (ICESat) of NASA [2]. NASA is planning to launch ICESat-2 whose primary instrument is the Advanced Topographic Laser Altimeter System (ATLAS). The ATLAS laser is divided into 3 pairs of tracks, with about 3 km between pairs [3].

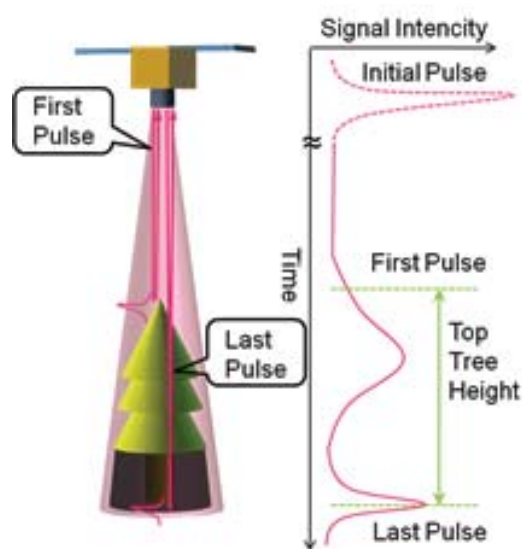


Fig. 2 Schematic overview of an observation for top tree height by GLS.

III. CONSIDERATIONS OF SPACE-BORNE LASER SCANNER

A. Space-Based Laser

JAXA has been investigating a laser transmitting system for active light ranging missions in near future. In this study, we assume that this “space-based laser” is

mounted to the GLS. Main specifications of the space-based laser are described below.

- **Power**...15W.
- **Wavelength**...1064 nm
- **Lifetime**...3-5 years
- **Others**...exhaust heat-, contamination-, and radiation- resistance.

B. Platform

Three candidates of platform are considered as below.

- **Earth observation satellite**...600 km.
- **International space station**...400 km
- **Super low altitude satellite**[4]...200 km

C. Eye Safety

In considering a future mission using space-based laser, eye-safety of people on the ground must be considered. The safety standards of laser irradiation are prescribed by the International Electrotechnical Commission (IEC) [5].

These standards define the maximum permissible exposure (MPE) of a single laser pulse to the eyes is 50 mJ/m^2 at $\lambda = 1064 \text{ nm}$.

In the case of space-borne laser scanner, the situation that observer on the ground is viewing through a telescope (30 cm diameter) and all the laser light which enter the telescope aperture passes through his/her pupil (7 mm in diameter) is considered. In this case, the MPE is $27 \text{ } \mu\text{J/m}^2$ at $\lambda = 1064 \text{ nm}$, which is $(30 / 0.7)^2$ times more strict criteria than the standard of the IEC.

D. Scanning Mechanism

Two candidates of scanning mechanism, galvanometer scanner and polygon mirror scanner, are considered, and schematic diagrams of footprints distributed by galvanometer scanner and polygon mirror scanner are shown in Fig. 3. As shown in Fig.3, Density of footprints put by the galvanometer scanner is relatively high at the edges of the observation swath and low at the nadir. On the other hand, the polygon mirror scanner put footprint with uniform density. In this paper, the polygon mirror scanner is assumed to be a scanning mechanism of the GLS. More detailed trade-off study is needed until the final decision of the scanning mechanism is made.

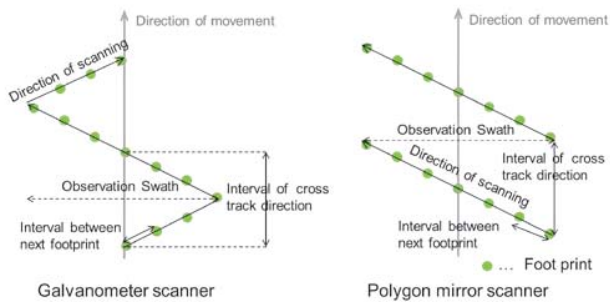


Fig. 3 Schematic diagram of footprints by galvanometer scanner (left) and polygon mirror scanner (right).

IV. MISSION CONSIDERATION

A. Observable Areas

Assuming that the space-based laser is the light source of the GLS, maximum laser power is 15 W. According to limitation of eye safety, a laser pulse with 1 mJ must be expanded to 37 m² area at the ground (atmospheric extinction is not considered). In this case, the total area of footprint per one second is about 56 ha (= 5.6 × 10⁵ m²). Thus, about 1.7 Gha is observable per year, and it is corresponding to 3.3 % of all surface area of the Earth (overlaps between footprints are ignored.).

B. Placement of the Footprints

As a result of simple simulation for the GLS signal, we consider that about 15 mJ of laser pulse energy can be needed to obtain the data from which canopy height of tree can be estimated. Thus, the laser pulse energy is assumed to be 15 mJ in this paper. According to limitation of eye safety, this laser pulse of 15 mJ is expanded to about 560 m² area at the ground and the diameter of the footprint is about 27 m. And, maximum pulse rate frequency of the GLS is supposed to be 1000 Hz since the maximum laser power is 15 W, at this time.

As a function of interval between next footprints, required scanning rate frequency, maximum numbers of footprints per a scanning line, maximum observable swath, maximum observable frequency per year, and full scan angle are estimated, and they are summarized in Table 1. With smaller interval of footprints, higher frequency of the scanning rate are required and maximum observable swath is narrower, hence maximum observable frequency per year is lower than those of larger interval between next footprints.

In terms of the observation for terrestrial vegetation, 4 observations per a year is preferable [1]. To make 4 observations per year, about 15 km observation swath is necessary (probability of cloud is not considered). The estimation is below.

$$\text{Swath} = \frac{\text{Length of the Equator}}{2 \times \text{Cycle number} \times \text{Recurrent days}}$$

TABLE 1. Required scanning rate frequency, maximum numbers of footprints per a scanning line, maximum observable swath, maximum observable frequency per year, and full scan angle for each interval of footprints.

Hight of platform ... 600 km				
Interval of footprints.	100 m	250 m	330 m	500 m
Required scanning rate frequency	78 Hz	31 Hz	23 Hz	16 Hz
Maximum numbers of footprints per a scanning line	13	32	43	63
Maximum observable swath	1.3 km	8.0 km	14 km	31.5 km
Maximum observable frequency per year	0.4	2.4	4.2	9.3
Full scan angle	0.4 deg.	2.3 deg.	4.1 deg.	9.0 deg.
Hight of platform ... 400 km				
Interval of footprints	100 m	250 m	330 m	500 m
Required scanning rate frequency	77 Hz	31 Hz	23 Hz	15 Hz
Maximum numbers of footprints per a scanning line	13	32	43	67
Maximum observable swath	1.3 km	8.0 km	14 km	34 km
Maximum observable frequency per year	0.4	2.3	4.1	9.5
Full scan angle	0.2 deg.	1.1 deg.	2.1 deg.	4.8 deg.
Hight of platform ... 200 km				
Interval of footprints.	100 m	250 m	330 m	500 m
Required scanning rate frequency	76 Hz	30 Hz	23 Hz	15 Hz
Maximum numbers of footprints per a scanning line	13	33	43	67
Maximum observable swath	1.3 km	8.3 km	14 km	34 km
Maximum observable frequency per year	0.4	2.2	3.9	9.1
Full scan angle	0.1 deg.	0.8 deg.	1.4 deg.	3.2 deg.

Length of the Equator: 40075 km
Cycle number: 15 day⁻¹
Recurrent days: 365/4 days

This swath is corresponding to full scan angles of 4.2, 2.1, and 1.4 degrees at 200, 400, and 600 km, respectively. Since required scan angles are relatively low, the waveform can be observed at the edge of the 15 km swath without much difficulty.

Thus when the interval of footprints is larger than 330 m, 4 observations per year can be achieved with the space-based laser which has been studied by JAXA.

For the optimization of the footprints placement, we have discussed with assumed users and further study will be required.

C. Simulation of Waveform from Vegetation Area to Estimate Canopy Height of Tree

To develop analysis algorithm for waveform of the GLS and to estimate observation accuracy of tree canopy height by the GLS, waveforms from some vegetation areas are simulated. Fig. 4 shows two examples of the waveform simulations, (a) from cedars, and (b) a zelkova (they are usual trees in Japan). Canopy height of the cedars and the zelkova are about 27 m and 11 m, respectively. 3D illustrations of the trees are in the charts. Thin cylinders above the trees represent laser footprints and diameters of the both cylinders are same. While a number of cedars were used for the waveform simulation, only one zelkova was generated in the fields of simulation since the zelkova has a large canopy area corresponding to the footprint.

Noise of the signals have not been simulated, thus the waveforms only represent intensity and observed time of photons reflected from the trees and the ground. In the case of cedars, there are interspaces between each cedars and intensity of return pulse from the ground is relatively high. On the other hand, a large part of photons are refracted by the zelkova and intensity of return pulse from the ground is low.

In the case of cedars which have acuminate shape, rising of the waveform is relatively slow. On the other hand, waveform of the zelkova shows relatively sharp initial rise. It is indicated that the ideal waveform represents vertical profile of projected area of trees. The initial rise of waveforms are fitted by the Gaussian function, and the half width at half maximum (HWHM) of the initial rise are 6.6 ns and 5.2 ns for the cedars and the zelkova, respectively. In these simulations, HWHM of the laser was 2 ns. Thus, contributions of the tree-

canopy shapes to the HWHM are roughly estimated to be 6.3 and 4.8 for the cedars and the zelkova, respectively. Through the simulation and analysis as above, appropriate algorithm for the analysis of the GLS waveform has been studied.

There are various methods of analysis to estimate canopy height of tree from the waveforms obtained by the ICESat/GLAS [6], and a large part of the tree height error is likely to be caused by waveform analysis algorithm. Thus, the further study of the analysis algorithm of GLS waveform is important to improve the accuracy of the canopy height.

D. Other Application of the GLS

Space-borne laser scanner will provide other information on a wide range of Earth surface characteristics and processes. For example, the GLS will provide the global elevation map with high resolution which is potentially useful to understand and forecast damage that a stricken area may suffer. Observation of ice-sheets is also a candidate of the GLS mission, and the thickness of the ice-sheets in the polar region is considered to be one of the important observation objects to understand the global warming.

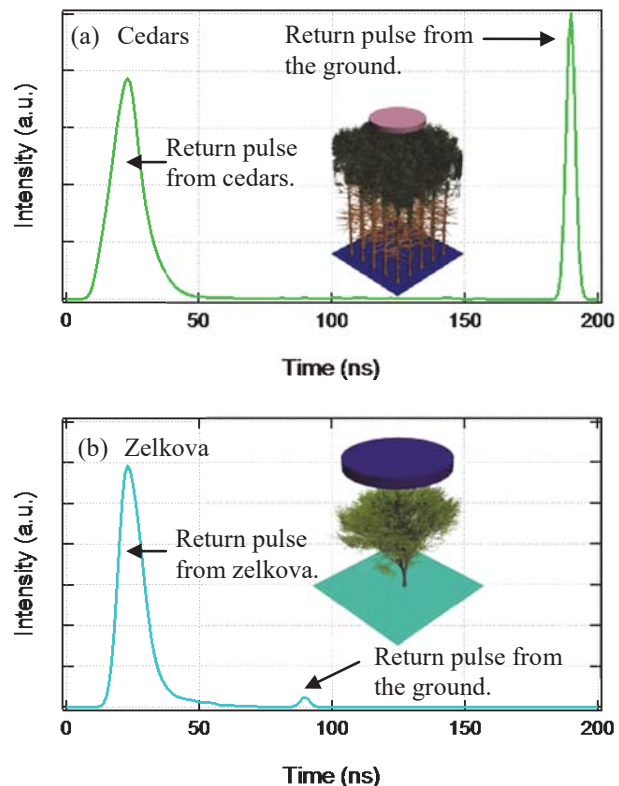


Fig. 4. Waveform simulations (a) from cedars and (b) a zelkova.

V. CONCLUSION AND FUTURE WORK

High-accuracy three-dimensional (3D) information of global area is very useful in various fields, such as global observations of tree height, elevation, and ice sheet. The Japan Aerospace Exploration Agency (JAXA) has started a conceptual study of earth observation missions with a space-borne laser scanner (GLS, as Global Laser Scanner) which is especially expected to observe canopy height of tree from the globe.

Assuming that the space-based laser which has been studied in JAXA is the light source, maximum laser power of the GLS is 15 W. We consider that about 15 mJ of laser pulse energy can be needed to obtain meaningful data. According to the limitation of eye safety, the laser pulse of 15 mJ is expanded to the footprint with about 27 m diameter at the ground. Maximum pulse rate frequency of the GLS is supposed to be 1000 Hz from the restriction of space-based laser. The total area of footprint per one second is roughly estimated to be 56 ha ($= 5.6 \times 10^5 \text{ m}^2$). Thus, about 1.7 Gha is observable per year, and it is corresponding to 3.3 % of all surface area of the Earth.

Some candidates of the footprint placement are studied. When the interval of footprints size is larger than 330 m, 4 observations per year can be achieved.

For the optimization of the footprints placement, we have discussed with assumed users and further study will be required.

To develop analysis algorithm for waveform of the GLS and estimate observation accuracy of tree canopy height by the GLS, waveforms from cedars and a zelkova are simulated. It is indicated that the ideal waveform represents vertical profile of projected area of trees. Since a large part of the tree height error is likely to be caused by waveform analysis algorithm in the case of ICESat/GLAS, the further study of the analysis algorithm of GLS waveform will provide important contribution to the expected accuracy of the canopy height of tree by the GLS.

The GLS will provide other information on Earth surface characteristics and processes, such as the global

elevation map with high resolution and observation of ice-sheets.

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