Forest Measurements Using ICESat- Geoscience Laser Altimeter System -A Review

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Abstract: Forests play a vital role in carbon cycle and in maintaining climate balance. The measurement of three dimensional forest structural attributes has a profound impact on the forest ecosystem management. Active remote sensing systems provide the capability to quantify the three dimensional structural of forests by measuring both the vertical as well as horizontal structure of forests. Vertical forest measurements can be directly and accurately estimated by means of the space borne Light Detection and Ranging (LiDAR) and it has been often used to estimate the forest structural attributes. This paper provides an introductory review of application of the Geoscience Laser Altimeter System (GLAS) onboard NASA's Ice Cloud and Land Elevation Satellite (ICESat), for the three dimensional structural attribute measurements of forests. The review attempted to briefly explain the characteristics of ICESat/GLAS instruments, data processing and certain applications from the wide range of applications of GLAS data in forestry.

Index Terms: Forests, Structural measurements, ICESat, GLAS, Space borne Laser Altimetry.

1.INTRODUCTION

Precise monitoring of the forest distribution and biomass are very essential to understand the global carbon cycle. Traditional field based forest inventories are constrained by high expense and extensive time requirements. Even though the passive optical remote sensing technologies (both multispectral and hyper spectral) have the ability to cover large forest areas but are limited by their inability to provide the vertical three dimensional structure of forest. Light Detection and Ranging (LiDAR), an active remote sensing technology can successfully measure both the vertical as well as horizontal distribution of forests very accurately. The airborne LiDAR systems available can cover only limited area and are found to be very expensive, and the data processing requires a lot of time. Therefore, space borne LiDAR systems play an important role since it can cover large areas for the three dimensional structural measurements of forests.

The review focuses on the potential of satellite Light Detection and Ranging (LiDAR) for the retrieval and measurement of forest structural attributes. Review highlights the application of ICESat /GLAS in the three dimensional measurements of forests and their support in ecosystem and climate modelling.

2. ICESat

Geoscience Laser altimeter system (GLAS), a new generation space borne LiDAR onboard Ice Cloud and Land Elevation Satellite (ICESat) launched by National Aeronautics and Space Administration (NASA). GLAS was originally designed for ice elevation monitoring. Its primary objective is to measure long term polar ice changes and additional scientific objectives were obtaining global measurements of sea ice land vegetation oceans, forest canopy heights, land terrain changes and distribution of clouds and aerosols. [1], [2]. It can be used for vegetation analysis since it can offer global estimates of canopy height. The ICESat satellite is given in the Figure 1.

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Figure 1: ICESAT/GLAS satellite (Figure courtesy: https://icesat.gsfc.nasa.gov/icesat/spacecraft.php)

The main instrument on ICESat is Geoscience Laser Altimeter System (GLAS) with three lasers. The orbital altitude of ICESat is 600km with an inclination 94 degree and 183 day repeat pattern. GLAS is the first laser ranging instrument which enabled the continuous global observation of Earth. GLAS was successfully launched on January 12, 2003 abroad the ICESat from VanderBerg Air force Base. National Aeronautics and Space Administration (NASA) Goddard Space Flight Centre (GSFC) designed and implement the measurement instrument GLAS. The term altimetry is used for the range measurement to the earth surface. The three lasers namely laser1, laser2 and laser3 were mounted on a rigid optical bench with one laser operating at a time producing a 1024 nm pulse. The first laser operated from February 20, 2003 but failed on March 29, 2003. It had 119 equally spaced ground tracks to cover the earth with 8 day repeat orbit. Laser 2 also stopped working on October 2009 due to the energy loss caused by photo darkening near the laser frequency doubler. Laser 3 worked for 14 days and stopped working in October 2008.ICESat carried about 18 laser campaigns and remained seven years in orbit. [3], [4], [5], [6], [7]. Figure 2 illustrates how the GLAS instruments on Earth surface.
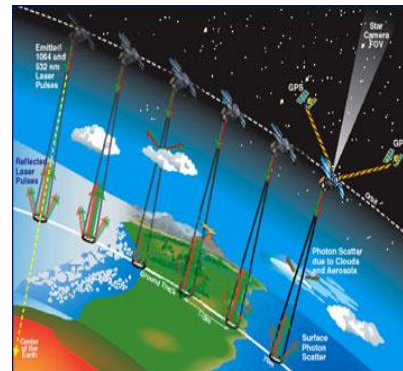

Figure *2:* Schematic illustration of the GLAS instrument making measurement from ICESat while orbiting the Earth. (Figure courtesy: https://attic.gsfc.nasa.gov/glas/about.html)

GLAS operates with infrared and visible light pulses at 532nm and 1064 nm wavelengths at eye safe signal levels. GLAS consisted of a laser system to measure distance, a GPS receiver (Global positioning system) and a star tracker attitude determining system. The laser transmits shot pulses (4ns) of infrared light (1064nm wavelength) and visible green light (532 nm). Photons reflected to the space craft from the surface of the earth and from the atmosphere, clouds etc were received by a telescope having diameter 1m to collect the reflected 1064nm laser light. Laser pulses were emitted at 40 times per second with pulses from NDYAG laser having footprints of diameter 70m and separated by 170m (560ft). The reflected photons were directed to an analogue digitizer and the digitized pulses are called laser waveforms. The time taken for sending and the receiving were computed, and pulse time of flight can be computed. Speed of light multiplied with half the time of flight generated the magnitude of the range vector [8], [9], [10]. The direction of the range vector from ICESat GLAS can be obtained from the Instrument Star Tracker (IST) and Hemispherical Resonator Gyroscope (HRS). Precision attitude determination (PAD) and precision orbit determination can be made in the instrument. The application of ICESat extends from cryosphere applications to numerous multidisciplinary applications. The elevation of the spot illuminated by the laser pulse is taken as the sum of the position vector and range vector which is the footprint giving latitude, longitude and height with respect to the reference ellipsoid. ICESat also provided information on the global distribution of clouds and aerosols. Laser energy emitted by GLAS have wavelength values 1064nm and 532nm.GLAS can measure precisely the time taken for the photons to pass through the atmosphere,

reflected off the surface or clouds, collected in the GLAS telescope. The distance from the ICESat to the laser footprint in Earth's surface can be obtained from the total travel time and the speed of light. The location of ICESat is tracked by the GPS receiver. For calculating the elevation and position of each point measurement on the Earth, the data including distance to the laser footprint on the surface, position of the satellite in space, and the pointing of the laser are all combined. (https://attic.gsfc.nasa.gov/glas/docs/ICESat_Broch ure.pdf).

3.DATA PRODUCTS

ICESat provided multiyear elevation data from 2003 to 2009 and covers the Earth from 86 Degree north to 86 Degree South. GLAS provided 15 data products including level L1A, L1B and L2 laser altimetry and atmospheric LiDAR data. The data products range from GLA01, GLA02, GLA03, etc to GLA15 and is given in the Table 1.

ID	GLAS data
GLA01	Altimetry Data
GLA02	Atmospheric data
GLA03	Engineering data
GLA04	LPA-LRS data
GLA05	Waveform based elevations corrections
GLA06	Elevation
GLA07	Backscatter
GLA08	Boundary layer and Elevated Aerosol Layer heights
GLA09	Cloud heights for multiple layers
GLA10	Aerosol vertical structure
GLA11	Thin cloud/Aerosol optical depth
GLA12	Elevations ice sheet
GLA13	Elevations sea ice
GLA14	Elevations land
GLA15	Elevations Oceans

Table 1: 15 Data Products of GLAS

Level 1A altimetry data (GLA01) contains transmitted and received waveforms from the altimeter. GLA02 Level 1A atmospheric data contains the normalised relative backscatter for the 532 nm and 1064 nm channels; and low level instrument corrections such as laser energy, photon coincidence and detector gain corrections. GLA04 Level 1A global laser pointing data contain 20 orbits of attitude data from the spacecraft star tracker instrument star tracker and laser reference system, and other spacecraft attitude data required to calculate precise laser pointing. GLA05 level 1B waveform data include output parameters from the waveform characterisation procedure and other parameters required to calculate surface slope and relief characteristics. GLA06 Level 1B Global elevation product contains elevation previously corrected for tides, atmospheric delays and surface characteristics within the footprints. GLA07 level 1B global backscattering data are provided at full instrument resolution. The product includes full 532 nm and 1064 nm calibrated attenuated backscattering profiles at 5 times per second and from 10 to 1km at 40 times per second for both channels. GLA08 level 2 planetary boundary layer (PBL) heights ground detection heights, top and bottom heights of elevated aerosols from -1.5 km to 20.5km and 20.5 km to 41km.GLA09 level 2 cloud height for multilayer clouds contain cloud layer top and bottom height data at sampling rates of 4sec, 1sec, 5Hz, 40Hz. GLA10 level 2 aerosol vertical structure data contains the attenuation corrected cloud and aerosol backscatter and extinction profiles at a 4 sec sampling rate for aerosols and a 1sec rate for clouds. GLA 11 level 2 thin cloud\aerosol optical depths data contain thin cloud and aerosol optical depths. A thin cloud is one that does not completely attenuate the LiDAR signal return which generally corresponds to clouds with depths less than about 2.0. GLA 06 is used in conjunction with GLA05 to create the level 2 altimetry products. Level 2 altimetry data provide surface elevation for ice sheets GLA12, sea ice GLA13, landGLA14 and oceans GLA15. ICESat data are distributed by National Snow and Ice Data Centre (NSIDC).

GLAS data products can be downloaded freely from NSIDC website. They were in binary format up to August 2017. From August 2017, all the GLAS data are provided in HDF5 format.

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ICESat profiles provides a global sampling of the elevation of the Earth land surface with unprecedented accuracy which can be used as a framework to evaluate and improve the accuracy of topographic maps acquired by other airborne and space borne remote sensing methods. It enabled the direct observation of topographic changes and provided unique information about the height dimension of the surface features within each laser foot print. The elevation of the ground and the height, density of the vegetation cover can be inferred from the return pulse. The vegetation information from ICESat enable estimation of above ground biomass and its loss due to deforestation which is an important link of carbon cycle.

4.APPLICATIONS OF ICESat GLAS IN FORESTRY

Three dimensional measurements of forest canopies play a significant role in the global carbon dynamics and biomass estimation. It is very essential to obtain the vertical distribution and structure of the forest canopies for understanding the forest ecosystem dynamics. Traditional field inventories are time consuming, laborious as well as cover only limited areas. Passive optical remote sensing technologies are limited to provide only the horizontal distribution of forest. ICESat can retrieve the forest canopy height in global level. Several studies have reported successful results of forest measurements by utilizing GLAS data. A few of the studies for estimating certain forests parameters are briefed below.

4.1 Canopy height estimation and canopy height modelling using GLAS ICESat.

Forest structural retrieval studies were done by many researchers by exploring GLAS data. ([11], [12], [13], [14], [15]. In earlier studies direct estimation of the canopy heights were done which was the difference between the vertical signal start of the GLAS waveforms and the ground peak [16], [17]. The signal start indicates the top of the canopy. But severe fluctuations limit the availability of accurate signal start and peaks and to reimburse the limitations several studies utilized Gaussian decomposition methods [16], [17] [18], [19]. But the number of Gaussian peaks increase with topographic variation and heterogeneity in vegetation [20].

The application of GLAS data set for forest monitoring and mensuration by the estimation of maximum canopy heights of Korean forests were elucidated by [21]. A new automated method of canopy height estimation was also proposed [22]. Canopy heights extraction from GLAS were found to be varied with [23]. Two methods direct and statistical methods are used for extracting canopy height estimates from GLAS data [14], [24]. Canopy heights were estimated by using GLAS ICESat waveform data [11]. Other methods like Gaussian components approach by fitting it to raw waveform [25] and least square regression approaches [26] were also explored for estimation of forest structural details. Multiple linear regressions and the Random Forest technique (RF) were used for estimating canopy heights using GLAS data in French Guiana [27]. GLAS LiDAR derived Global estimates of canopy heights from 2004-2008 were provided by [28]. Canopy heights were estimated from the GLAS data using error factor analysis in Hoikkodo, Japan [29]. Canopy heights were estimated by using Lorey's height with the help of GLAS data and optical imagery over Hyrcanian forests of Iran [30]. Canopy heights were estimated over sloped terrain by [31].

4.2 Biomass estimation using GLAS

Quantifying above ground biomass in forests has profound social and economic interests and to estimate carbon emissions. In high biomass areas, the space borne ICESat GLAS data were used for effectively estimating biomass [32]. In some studies, biomass was estimated by using GLAS metrics interpolations [33]. Forest canopy heights and above ground biomass were estimated by means of GLAS data [11] and by means of GLAS and SRTM data [34]. In Quebec provincial forest, Canada, resources including biomass were estimated by developing an equation relating airborne laser estimates of biomass to ICESat/GLAS measurements [35]. Genetic Algorithm Approach for Optimization of Biomass Estimation using GLAS data were also found to be explored [36]. Annual changes in biomass were found to be estimated by combining ICESat GLAS waveform, historical inventory data and time series optical and radar imagery in China [37]. In several studies, GLAS data and other spectral data were integrated to obtain more biophysical parameters of forests. For example, above ground biomass

mapping were done by MODIS and ICESat GLAS waveform in China [38]. Estimation of forest biomass in Changbai mountain region were done by using ICESat GLAS and Landsat/TM [39].

Various other forest parameters can be estimated by using GLAS data. Timber volume were estimated by the GLAS and MODIS data [40]. Three dimensional mapping of the mangrove forests were done using GLAS ICESat data [41] Vegetation vertical structure were estimated by means of GLAS wave form measurements [23]. Based on gap fraction model, Leaf area index were retrieved in discontinuous forests by means of GLAS ICESat waveform data [42]. GLAS data proved to capture the vertical structures of forest globally and applicable for forest parameter estimation and monitoring.

5. ICESat -2 MISSION

ICESat -2 was launched on September 15, 2018, a mission which measure heights, vegetation distribution across worldwide forests, heights across tropical and temperate regions of Earth along with other main applications. ICESat-2 carries a single instrument called Advanced topographic Laser Altimeter system and it measures the travel time of the laser pulses between the space crafts and Earth surfaces (ICESat-2.gsfc.nasa.gov). The Laser light is of 532 nm and sends 10, 000 pulses per sec which is at an incredible fast rate and can take measurements at every 2.3 feet along the satellite's ground path. ICESat-2 will provide accurate information on large scale vegetation biomass estimates by measuring vegetation canopy heights [7]. ICESat-2 can map forest productivity, forest height which is further appropriate for carbon management.

6. CONCLUSION

ICESat GLAS operations, data products and its application are briefly reviewed in the given paper. The application of ICESat GLAS in forestry for various vertical structural parameters were given in the review. Regional and national level forest monitoring programs can be informed using the application of space borne laser altimetry in reliable manner. Also, space borne data can be integrated with other satellite sensor imageries to extract wide range of forest parameters. The space borne laser altimetry measurements can be used as

an integral component of forest monitoring system. Thus, space borne GLAS can be used to represent the forest ecosystem and conditions in a timely and cost effective manner globally.

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