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Forest Vertical Parameters from Lidar and Multi angle Imaging Spectrometer Data

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Abstract Vegetation spatial structure including plant height, biomass, vertical and horizontal heterogeneity is an important factor influencing the exchanges of matter and energy between the landscape and atmosphere, and the biodiversity of ecosystems. Most remote sensing systems, although providing images of the horizontal organization of canopies, do not provide direct information on the vertical distribution of canopy elements. The lidar waveform signature from a large footprint lidar instrument, such as the Laser Vegetation Imaging Sensor (LVIS), has been successfully used to estimate the tree height and forest above ground biomass. But the most lidar instruments do not have the mapping capability, and provide only sample data in a region. Other remote sensing data, such as a multi-angle spectral, a hyper spectral, a temporal spectral radiometer, or radar data, will be needed to extrapolate the GLAS sample measurements into continuous regional coverage for forest structure parameters.

The ability to image the surface through various angles by the Multi angle Imaging Spectrometer (MISR) instrument provides canopy structure information through the anisotropy of the BRDF. Combining the vertical sampling of lidar with MISR's mapping capability provides a possibility of mapping forest spatial parameters in regional, even global scales. The data from the Geoscience Laser Altimeter System (GLAS) on ICESat and data from MISR on Terra are potential dataset for regional or global forest structure parameter mapping. The objectives of this study are to evaluate the GLAS data and to investigate the ability of MISR-like data for forest structural parameter estimation. The LVIS, a MISR, and GLAS data were used in this study. The comparisons between GLAS tree height measurement and the average tree height from LVIS within the GLAS footprint show the high correlations. The study also shows the capability of multi angle imaging spectrometer data to predict tree height information, which will be further explored for regional forest structural parameters mapping.

Key words Lidar; GLAS; multi angle imaging spectrometer; forest; tree height

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利用激光雷达和多角度频谱成像仪数据估测森林垂直参数

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摘要: 植被的结构参数如植被高度、生物量、水平和垂直分布等, 是影响陆地与大气能量交换乃至生物圈多样

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性的重要因素。多数遥感系统虽然可以提供植被水平结构的图像,但是不能提供植被成分垂直分布的信息。大尺度激光雷达仪器如 LVIS 产生的激光雷达信号,已成功地用于估计树高和森林生物量,然而大多数激光雷达仪器不具备图像能力,只能提供一个区域内的采样数据。其他的遥感数据如多角度光谱、多频率多时相辐射计或雷达数据,可根据 GLAS(Geoscience Laser Altimeter System)采样的测量用来推断出连续的森林结构区域覆盖参数。

MISR(Multi-angle Imaging Spectrometer)对陆表多角度的成像能力,可以通过 BRDF 的各向异性提供植被的结构信息。结合激光雷达的垂直采样和 MISR 的图像,区域内乃至全球性的森林空间参数的成像是可能的。ICESat 卫星上的 GLAS 数据、Terra 卫星上的 MISR 数据为区域或全球性森林结构参数提供了可能。本文的研究目的是评估 GLAS 数据,分析类似于 MISR 的数据对森林结构参数的估计能力。本文中使用了 LVIS A1MISR 和 GLAS 数据。通过对 GLAS 树高的测量与 GLAS 像元内来自 LVIS 的平均树高对比,发现它们是高度相关的。同时还探讨了多角度频谱成像仪数据预测树高信息的能力,这将在今后区域内森林结构参数映射加以研究。

关键词: 激光雷达; GLAS; 多角度频谱成像仪; 森林; 树高

1 INTRODUCTION

Vegetation spatial structure must be known to adequately monitor and model the carbon cycle and forest ecosystem dynamics. Most remote sensing systems, although providing images of the horizontal organization of canopies (e.g., Landsat MODIS), do not provide direct information on the vertical distribution of canopy elements. The lidar waveform signature from a large footprint airborne lidar instrument such as the Laser Vegetation Imaging Sensor (LVIS)^[1] has been successfully used to estimate tree heights and above-ground forest biomass^[2-6].

Lidar derived forest vertical parameters are being used with ecological model to model forest carbon storage and flux^[7]. In a study by Lefsky *et al.*^[8], stand age mapped by iterative unsupervised classification of a multi-temporal sequence of Landsat TM images was cross tabulated with estimates of stand height and aboveground biomass from lidar remote sensing to estimate the aboveground net primary production of wood (NPPAW). These studies showed the power of combining vegetation height information from lidar data with ecosystem models or other data for estimates of carbon stocks and net carbon fluxes. Extending these analyses to larger scales will require the development of regional and global lidar data sets and the continued development and application of height structured ecosystem models^[7].

NASA and other agencies are interested in using spaceborne large footprint lidars (i.e., laser

illuminated ground areas on the order of 10–100m). However, current and proposed space lidar systems do not have mapping capability. A European mission concept Carbon 3-D, proposed to use a multi-angle imager in combination with a vegetation canopy lidar to extend the lidar derived information to broader spatial coverage. The ability to image the Earth's surface through various angles by new instruments such as the Multiangle Imaging Spectroradiometer (MISR) provides information through the anisotropy of the bidirectional reflectance distribution function (BRDF). Studies using MISR data indicate the usefulness of off-nadir data for surface heterogeneity and vegetation structure^[10-11]. Bidirectional reflectance distribution functions (BRDF) observed from different landcover^[12-13] are related to structural differences.

Combining the vertical sampling of lidar with multiangle mapping capability provides a possibility of mapping forest spatial parameters in regional and even global scales. A problem that limits the effective use of multiangle data is the difficulty in acquiring sufficient ground truth over the large areas in question. Lidar can provide a dense network of measurements that can supply forest structural characteristics such as maximum canopy height, mean canopy heights, crown shape^[14], and other vertical canopy structure^[3].

In this study, The GLAS data was evaluated by comparison with the LVIS height measurements. Then the GLAS data were used as ground reference information to establish a relationship between multi-angle spectrometer reflectance from A1MISR and forest height. The A1MISR data were aggregated into MISR resolution to examine data from spaceborne systems

2 STUDY SITE AND DATA

2.1 Study Site

The test site for this study is the forests within the Beltsville Agricultural Research Center, USDA, just the North to the NASA's Goddard Space Flight Center (GSFC) in Maryland located at 39°N, 76°50'W. Fig. 1 shows the AirMISR images of the nadir camera (left: IR, R, and G bands as RGB), and LVIS top

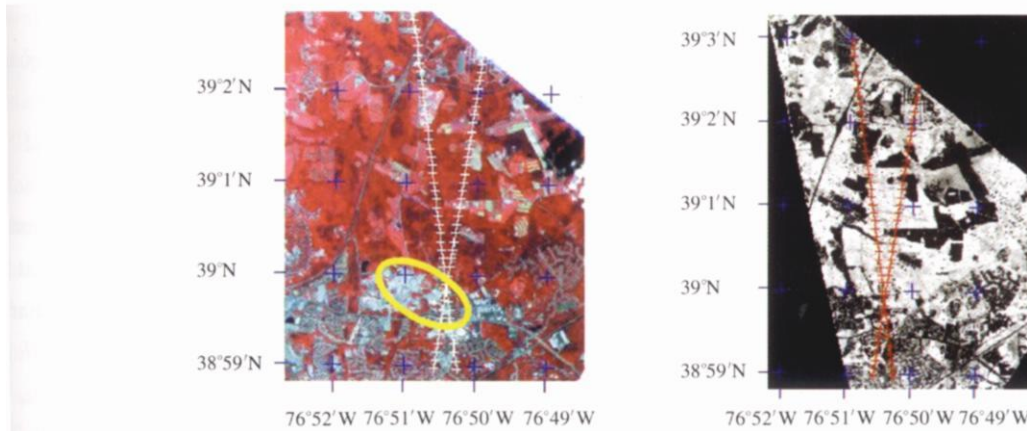


Fig. 1 Left-AirMISR images of Nadir camera; IR, Red and Green bands as RGB colors. Yellow ellipsoid indicates the location of Goddard Space Flight Center; right-Top tree height from LVIS. The white crosses at left and red crosses at right are GLAS footprints used in this study

2.2 LVIS Data

NASA's Laser Vegetation Imaging Sensor (LVIS) is an airborne laser altimeter system designed developed and operated by the Laser Remote Sensing Laboratory, Goddard Space Flight Center. In 2003, LVIS obtained sub-canopy and canopy top topography data as well as canopy vertical structure information for forested sites in New England to generate the most detailed forest structural data sets currently available for these regions. The data used in this study is the Nominal 20m-spaced LVIS Ground Elevation Data^[15] obtained on August 14, 2003.

Measurements derived from the lidar waveforms were used to characterize the canopy vertical structure. First, various ranging points were extracted including the elevations of the lowest and highest detectable returns (above a threshold noise level) and the mean ground elevation and various energy quartile heights

(tree height (dark-white, 0–38m)). The yellow ellipsoid indicates the location of GSFC. The two lines of crosses are the two orbits of GLAS footprints. The orbit from northwest to southeast was taken on Oct 11, 2003, and the other one was on Oct 24, 2003. The forests in the area are mixed forests dominated by pines and oaks. Tallest trees can reach a height of about 40m. Some of the GLAS footprints were located using GPS, and dominant trees within the footprint were measured.

(Fig. 2)^[11]. H25 is the 25% quartile height and is calculated by subtracting the elevation at which 25% of the returned energy occurs from the ground elevation. H100 is the canopy top height and is calculated by subtracting the elevation of the highest detectable return from the ground elevation.

A typical forest waveform and the definition of

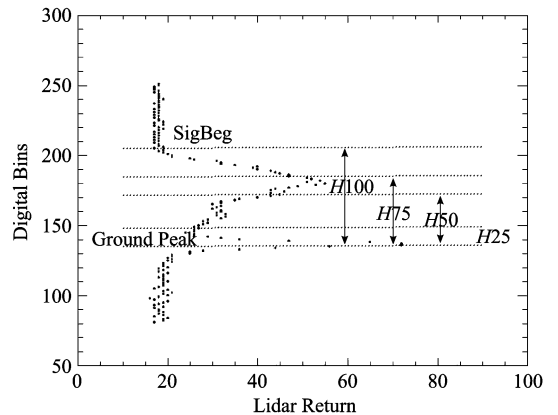


Fig. 2 A typical LVIS waveform and the definitions of energy % quartiles

these canopy structure measures are shown in Fig 2. These quartile heights are a relatively direct measure of the vertical profile of canopy components. In addition, waveform measures are a function of the complex and variable 3-D structure of canopy components and their spectral properties including the spectral properties of the ground/litter. This 3-D structure defines the gap distribution as a function of canopy height which largely determines the proportion of energy reaching a given height. This gap distribution along with the spectral properties of the components determines the proportion of energy scattered at a given height.

2.3 GLAS Data

The Geoscience Laser Altimeter System (GLAS) instrument aboard the Ice, Cloud, and Land Elevation (ICESat) satellite launched on 12 January 2003^[16, 17]. Because of the reduced lifetime of the laser system, GLAS started to use a 91-day repeat orbit to complete a global coverage. From early October to November 19, 2003, GLAS completed a 33-day sub-cycle of the 91-day repeat orbits. Since then several 33-day sub-cycle data has been acquired in February-March, May-June, October-November, 2004, and February-March, 2005, and May-June, 2005. These 33-day sub-cycles are nearly the repeat pass of the October-November 2003 data, providing a capability for seasonal and inter-annual change monitoring. The Oct-Nov 2003 data is a good dataset acquired using the second laser on ICESat. The third laser has been turned on for several data take periods since Oct 2004 and continues working.

The GLAS is the first lidar instrument for continuous global observation of Earth. GLAS records the returned laser energy from an ellipsoidal footprint. The nominal footprint diameter is about 80m in diameter, but its size and ellipticity have varied through the course of the mission. The GLAS data products, such as level 2 product GLA14 (Land/Canopy Elevation), are intended for use by the GLAS Science Team, and by the EOSDIS data user community. The GLA14 are generated using algorithms and parameters which are more appropriate for complex, multi-peaked waveforms (such as for rugged

and/or vegetated landscapes). The original waveforms were smoothed using filters and the signal beginning and ending were identified by noise threshold. The smoothed waveform was initially fitted using many Gaussian peaks at different heights, then the peaks were reduced to six by iteration. Assuming that the last peak near the ground is from surface reflection, the distance from the signal beginning and this ground peak will be the height of top canopy. The waveform can be extracted from GLA01 product. For this study, waveforms of all footprints shown on Fig.1 were extracted and processed to estimate the energy quartile heights as those from LVIS product.

2.4 AirmISR Data

The Airborne Multi-Angle Imaging Spectrometer (AirmISR) is a four-channel digital camera that flies on the high altitude ER-2 aircraft. The four channels employed on AirmISR are 446.4nm (blue), 557.5nm (green), 671.7nm (red), 866.4nm (near IR), with bandwidths of 41.9nm, 28.6nm, 21.9nm, 39.7nm, respectively. The AirmISR camera uses a MISR brassboard lens and a MISR engineering model focal plane, giving the airborne sensor spectral and radiometric characteristics very similar to the satellite instrument. AirmISR is a "pushbroom" sensor which images a cross-track slit beneath the aircraft during each scan. A two-dimensional scene is built up by successive scans as the spacecraft or aircraft moves over the scene. The Satellite instrument MISR has nine cameras which image the earth continuously, however, AirmISR has a single camera that is swiveled to 9 successive look angles from 70.5° looking forward of the aircraft through nadir then out 70.5° looking aft of the aircraft as the aircraft passes over the site of interest.

The AirmISR data used here was acquired between on July 21, 2001. Fig 1 shows a nadir color composite image of the site. The forward looking camera acquires backscattered radiance and the aft looking camera acquires forward scattered radiance. The aircraft flew at about 20km altitude providing view angle dependent variable ground spatial resolutions and swath widths. The data were normalized to a common

resolution of 27.5 m and co-registered to a common swath width of 11 km (http://eosweb.larc.nasa.gov/PRODOCS/aim_isr/table_aim_isr.htm).

3 DATA PROCESSING METHOD

The height of 100% energy level (H_{100}) of LVIS data for the study area was gridded to $27.5\text{m} \times 27.5\text{m}$ pixels corresponding to the pixel size of the AiMISR data using linear interpolation in ENVI. A sub-region was displayed in Fig 1. The common area covered by LVIS, AiMISR were identified (Fig 1). The GLAS data available within this area were searched from GLA14 data and the laser shot index location (lat/lon), elevation, signal beginning waveform centroid, fitted Gaussian peaks, etc. were retrieved and the top tree height was calculated for each of the footprints falling in to the area. GLAS waveform of these footprints in the area were extracted from GLA01 according to the laser shot index. Fig 3 shows a GLAS waveform with signal beginning and end and six Gaussian peaks used to fit the waveform.

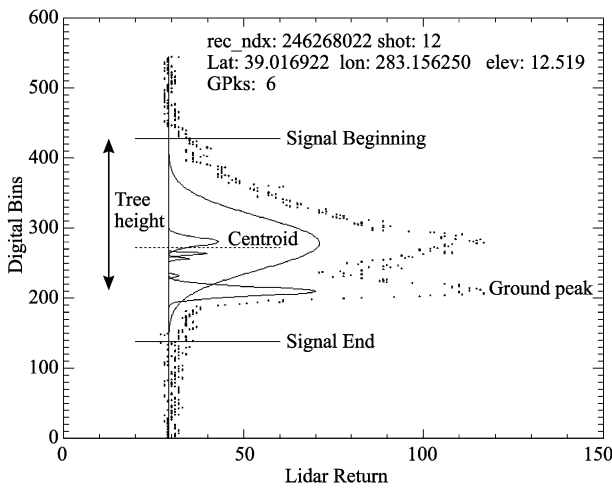


Fig 3 A GLAS waveform extracted from GLA01 data product and the signal beginning and end six Gaussian peaks used to fit the waveform extracted from GLA14 data product

In order to calculate the height of % quartile from GLAS waveform, a software was developed. The waveform was first smoothed by a Gaussian filter with the similar width of the transmitted laser pulse. It was found that a 12-bin ($\sim 1.8\text{m}$) width was adequate for the smoothing. The GLA01 gives the estimated noise

level, i.e. the mean and standard deviation of background values in the waveform. But it was found that for many cases the noise level before the signal beginning was lower than the noise after the signal ending. Instead we estimated the noise levels before the signal beginning and after the signal ending from the original waveform separately using a method based on the histogram.

Using three standard deviations as a threshold above the noise level, the signal beginning and ending then can be located. The total waveform energy was calculated first. Starting from the signal ending, the position of the 25%, 50%, 75% of energy can be located by comparing the cumulated energy with total energy. Since the heights of these quartiles were referred to the ground surface, not the signal ending, the ground peak in the waveform needs to be located. Searching backward from the signal ending, find the first peak. If the peak is too close to the signal ending, i.e. the distance from signal ending to the peak is less than the half width of the transmitted laser pulse, searching will continue. The tree height was the distance from signal beginning to the ground peak. Because of slope, the ground peak of the waveform becomes wider and the signal beginning appears earlier by the similar distance. The top tree height can be adjusted by this distance.

All LVIS shots within a 120m circle centered at each GLAS footprint were extracted and the mean and maximum of the quartile heights (H_{25} , H_{50} , H_{75} and H_{100}) were calculated. The height indices derived from GLAS waveform and LVIS data were compared and the correlations were calculated.

For each GLAS footprint, the lat/lon information was used to locate the center pixel on AiMISR images, and both 3×3 window, and 9×9 window were used to get average multi-angle spectral reflectance corresponding to the GLAS footprint. A 3×3 window represents an area similar to a GLAS footprint, and a 9×9 window is used to mimic AiMISR 275m pixel. Then the correlation between GLAS derived tree height and AiMISR reflectance was investigated using stepwise regression analyses.

4 RESULTS

Table 1 lists the tree heights from field measurements, LVIS and GLAS. It can be seen that the Maximum heights from field measurements and LVIS data, and the *H100* *H14* from GLAS data are similar. The correlations between tree height indices derived from LVIS and GLAS were listed in Table 2 for the GLAS data of Oct 12, 2003. It can be seen that

the averaged LVIS indices have much higher correlations with indices derived from the GLAS waveforms. The GLAS *H75* and *H50* instead of *H100* have the highest correlations with the mean LVIS tree height indices. Fig 4 shows the comparison of GLAS *H75* with the LVIS *H75* averaged within the GLAS footprint. The GLAS *H75* is systematically higher than the averaged LVIS *H75*. Fig 5 shows the comparison of GLAS *H75* with the LVIS *H100* averaged within the GLAS footprint. These two indices are very similar.

Table 1 Tree height indices from field measurements. GLAS and LVIS *H14* is the tree height from GLA14 product. *H_{tadj}*, *H50* and *H100* were estimated directly from GLAS waveform.

Rec_ndx_shot	Field Data		GLAS				LVIS <i>H100</i>	
	Max <i>h</i>	Mean <i>h</i>	<i>H100</i>	<i>H_{tadj}</i>	<i>H14</i>	<i>H50</i>	Max	Mean
246268022_10	29.72	24.37	33.73	31.93	31.26	17.39	27.10	24.46
246268022_11	35.68	28.82	32.83	30.88	36.13	15.44	33.62	23.42
246268022_12	20.68	18.05	34.78	32.83	30.66	8.99	33.70	22.57
246268022_13	41.68	33.42	38.07	36.20	31.02	21.59	33.16	25.24
246268022_14	29.85	24.11	39.27	37.32	32.64	17.99	32.26	23.66
257070723_15	32.06	23.33	35.23	33.43	33.14	16.64	27.42	20.67

Table 2 Correlations (R^2) between the tree height indices derived from GLAS waveforms and aggregated LVIS data within the footprints. The $R^2 > 0.5$ are in bold.

LVIS	Derived from GLAS waveforms						
	<i>H100</i>	<i>H75</i>	<i>H50</i>	<i>H_{tadj}</i>	Mean <i>h</i>	Med <i>h</i>	QMCH
Max <i>H100</i>	0.1233	0.3745	0.2916	0.1233	0.3176	0.3266	0.3369
Max <i>H75</i>	0.242	0.5354	0.4084	0.2417	0.4714	0.4791	0.489
Max <i>H50</i>	0.2741	0.5359	0.3836	0.2761	0.5062	0.5019	0.5214
Mean <i>H100</i>	0.5692	0.8906	0.837	0.5697	0.7095	0.7559	0.7262
Mean <i>H75</i>	0.5729	0.9088	0.8643	0.5736	0.7111	0.7673	0.7277
Mean <i>H50</i>	0.5811	0.9195	0.8965	0.5819	0.697	0.7637	0.7115

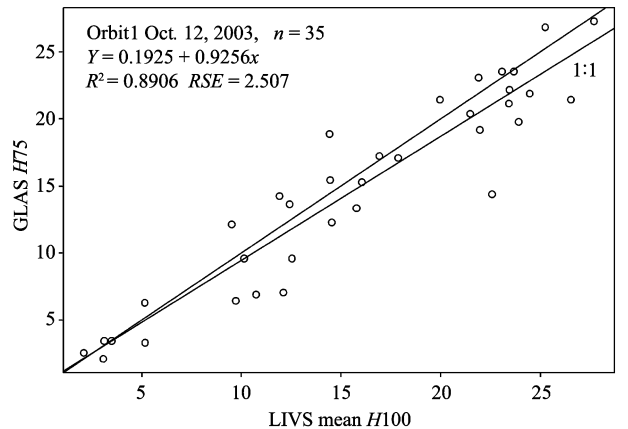
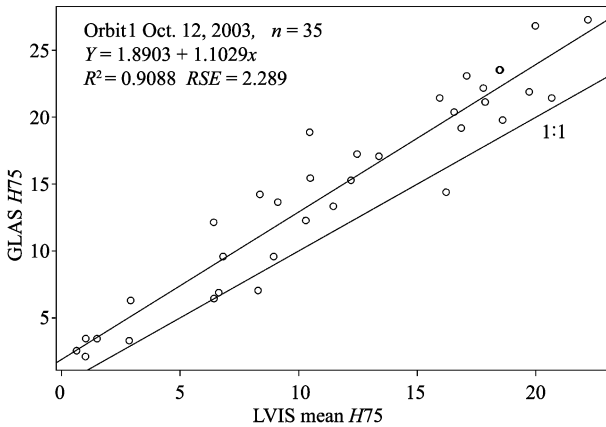


Fig 4 Comparison of GLAS derived *H75* with the LVIS *H75* averaged within the GLAS footprint.

Fig 5 Comparison of GLAS derived *H75* with the LVIS *H100* averaged within the GLAS footprint.

Fig 6 compares the top tree height derived from GLAS waveform with those predicted by AirMISR data. For Fig. 6 (a), a 3 by 3 window was used to get average AirMISR signature and a 9 by 9 window was used in Fig. 6 (b). It seems that when data resolution

was lower (from window size 3 to 9), and multi date GLAS data was used, the correlations between GLAS derived tree height and predicted by multi angle spectrometer data is lower. But the correlation is still significant.

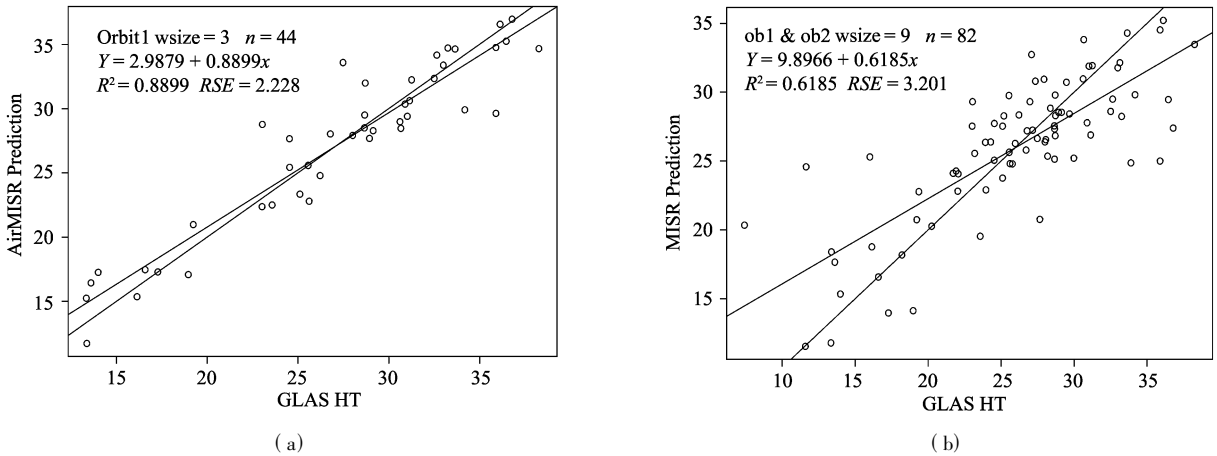


Fig 6 Tree height derived from GLAS waveform and predicted by AirMISR. A-window size 3 and B-window size 9

5 CONCLUSIONS

The Geoscience Laser Altimeter System (GLAS) is the first lidar instrument for continuous global observation of the Earth. It samples the earth surface every 175m along track with an ellipsoid footprint. The airborne Laser Vegetation Imaging Sensor (LVIS) with scanning capability and smaller footprint provides much more samples of the surface. It is difficult if not impossible to know if the footprints from GLAS and LVIS cover the exact same canopy. But in terms of sampling techniques, this study shows that both instruments give reasonable measurements of canopy vertical structure and that the measurements from these two instruments are highly correlated. Airborne lidar data has been proved to be a good index of forest biomass, the GLAS data therefore will be useful for biomass sampling in regional to global scales. Though caution should be taken in terms of the data acquisitions season as well as other factors such as the terrain slope and forest types. This study has also briefly demonstrated that multi angle spectrometer data may be used to predict the tree height measurements from GLAS, so a regional estimation of forest vertical

parameters may be obtained.

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