

# CFLOS statistics for design of future space based lidars

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## Introduction

For future laser based remote sensors for space, the issue of clouds will have a significant impact on the both the instrument design as well as its operations plan. While space based passive imagers have provided the community with cloud statistics<sup>1</sup> for several decades, those cloud data have been derived mainly from images with ~ 1 km resolution. Furthermore, in most cases, the accounting for multiple layers of clouds has been hampered by pixel resolution and lack of direct ranging. The 14 day LITE (Laser In-space Technology Experiment) mission in 1994 provided the first opportunity to develop cloud statistics with sampling on the scale of a few 100 meters. More recently, global measurements of aerosol and cloud properties with <70 m sampling resolution have been provided by the Geoscience Laser Altimeter System (GLAS) instrument on-board the Ice, Cloud and land Elevation Satellite (ICESat). GLAS/ICESat was launched in January 2003 with a near circular and 94 degree inclination orbit at an altitude of 600 km. The GLAS laser is a diode pumped Nd:YAG laser with 40 Hz pulse repetition; 75 mJ at 1064 nm and 35 mJ at 532 nm.

A study was conducted to analyze the cloud data from GLAS<sup>2</sup>. The primary objectives were to construct cloud and cloud penetration statistics that can be used to guide the design of future lidars in space. Specifically, the study addressed the following statistics and issues:

- probability of Cloud Free Line Of Sight (CFLOS) opportunities for a laser beam with a footprint less than 100 meters in diameter
- probability of getting surface returns when clouds are present
- probability of multiple level intercept of clouds

- probability of contiguous CFLOSs for various duration of beam stares and shot integration for a series of trade studies involving energy per pulse and pulse repetition frequency

The GLAS statistics were compared with results and statistics compiled from a very limited data set collected during the 1994 Lidar In-space Technology Experiment (LITE). The results from previous analysis<sup>3</sup> of the 532nm LITE data showed a ground return was provided approximately 60-65% of the time, which was much more often than existing cloud climatologies based on passive imagers suggested (30-40%). In addition, the LITE data also showed that between 37% and 50% of profiles with cloud returns also provided a surface return. This "cloud plus ground return" has been used to express cloud porosity for lidar beam dimensions.

## The GLAS study

In this study, various cloud statistics were computed for a full week's worth of GLAS09 cloud data. This included statistics relating to ground detection, cloud detection, CFLOS and multiple cloud layers. The statistics were calculated for the individual shots (40 Hz) and three other multi-shot integration products (Table 1): High resolution (8 shots), Medium resolution(40 shots) and Low resolution(160 shots).

Product Name	# shots averaged	Horizontal Resolution (km)*	Vertical Resolution (m)
Low	160	27.2	~70
Medium	40	6.8	~70
High	8	1.36	~70
Full	1	.170	~70

Table 1: Sampling resolutions of the GLAS cloud data product. \* assumes 6.8 km/sec orbit speed

Table 2 summarizes some results providing insight into the relative distribution of cloud and ground returns. Looking at Table 2, one feature that stands out is the number of individual shots and multi-shot products where clouds are not detected but where the ground is also not reported (the last column). This happens over 50% of the time for the individual shots and over 20% for the High resolution products. These “no cloud/no ground” cases for Full and High resolution data are most confounding to a satisfactory climatology of cloud penetration statistics. Given the vertical piecewise manner in which clouds are detected by the GLAS algorithms, it is possible for a very thick layer of very thin cloud to attenuate the signal enough to squelch a detectable ground return but be weak enough to miss being classified as cloud. Another possibility is that no cloud was present but the surface was smooth water and did not provide a direct reflection. Attempts to partition these cases between “cloud w/ground” and “no cloud w/ ground” have not been defensible and thus we must await a better data set to address cloud porosity on the single shot level.

Resolution	Cloud and Ground	Cloud and No Ground	No Cloud and Ground	No Cloud and No Ground
Low	55.0%	25.0%	18.7%	1.3%
Low (532 only)	54.9%	25.0%	18.9%	1.2%
Medium	36.2%	37.0%	22.5%	4.3%
Medium (532 only)	26.7%	28.5%	32.0%	12.9%
High	15.8%	33.2%	28.8%	22.2%
Full	14.6%	20.1%	14.3%	51.0%

**Table 2: Percentage breakdown of all shot products over land and water.**

However, using the assumption that any GLAS profiles without clouds indicate that a useful level of backscatter was available from the ground (even if the surface wasn't reported due to flat water or a faulty ground return algorithm), we can argue that the ground would be viewable for a more powerful lidar for between 80 to 85% of all individual shots (14.6 % + 14.3% and 51% in Table 2). This conclusion must be accompanied with the reminder that these

results are dependent on the GLAS instrument's EAP and efficiencies. However, it is our opinion that the main difference between the GLAS instrument's performance (CFLOS wise) and any future and more sensitive lidar will be primarily realized with the non-cloud (aerosol) returns between and below attenuating cloud layers. While this claim is based upon some assumptions, it is probably one of the most important findings of this study; i.e. **80% of individual laser shots have a reasonable chance of getting a ground return.**

For total cloud coverage, the GLAS data has revealed global total cloud values (~80%) which are very close to those found with a small set of data from LITE. These values are higher than values determined from ISCCP, suggesting that active optical remote sensing is revealing higher cloudiness. Perhaps this difference is insignificant given the types of data involved, but the sense is that the more sensitive and higher resolution active sensors will continue to sense more cloud than in the past. Even with the new AIRS, the issue of cloud contamination has become more acute with higher sensor sensitivity and resolution. It is noteworthy that the GLAS instrument is of very modest sensitivity compared to the recently launched CALIPSO and future DIAL and Doppler lidars.

Number of cloud layers	High (all surfaces)	High (land surfaces)
1	70.7	64.2
2	19.4	24.2
3	6.9	8.3
4	2.2	2.4
5	0.6	0.6
6	0.2	0.2
7	0.03	0.03
8	0.002	0.001
9	0	0
10	0.	0

**Table 3: Number of cloud layers (percentage) when clouds are detected for the High resolution GLAS product.**

An advantage of lidar cloud detection is the ability to detect multiple layers of clouds and to provide information on the physical and optical thicknesses of the layers (Table 3). In the case of GLAS, two layers of clouds were

detected over 35% of the time (when any cloud was present) at the High resolution. This bodes well for instruments using aerosol detection for winds since the signal from clouds should be strong enough for accurate measurements within the cloudy layers given that the instrument will probably be designed for the lower backscatter from aerosols.

Based upon the discussions above, the presence of a ground return in the GLAS data is evidence that the GLAS instrument had sufficient transmitted energy to get a return under the given circumstances. A more sensitive instrument may get more ground returns; a weaker instrument, fewer returns. Thus generalizations must be considered with caution. By the same token, the absence of a ground return in the GLAS data does not mean the lidar beam did not arrive at the surface with insufficient energy to provide a backscattered return from a favorable ground cover. The surface might have been smooth, mirror like water or the ground detection algorithm may have failed. Thus the % of shots with ground returns is understated in the GLAS analyses.

A primary utility of the GLAS data is in the specification of the integration interval necessary for achieving a target measurement accuracy in the presence of clouds. In some cases the instrument trade may involve trading greater energy per pulse for a lower pulse rate, simply having to increase the overall EAP to get sufficient return over less time (shorter integration distances). In the case of direct detection, the performance of the system is usually directly scaled to the number of photons used in the measurement. When multiple shot integration is required to obtain the needed photon count, the question is then "How often do clouds preclude getting the required photon count?" Another way to ask that question is "What are the probabilities of getting the required number of individual shots through to various levels of the atmosphere when clouds are in the target area?" While there are unlimited variations on the choice of target integration times and signal return requirements, we can make a few general summary statements:

1. Clouds in a Lidar LOS are the rule (~80%). Whether the cloud is detected and penetrated depends upon the lidar's capability and the optical depth of the cloud. The lidar's sensitivity to optically thin clouds and aerosols can be improved by shot integration. However, reliable shot integration can be frustrated by cloud cover variation within targeted sampling windows.
2. In cloudy situations, the longer the integration time (distance) the less likely all shots will reach a target layer beneath clouds. However, the success rate does not scale linearly to the integration distance. For example, going from 80% success at 75 km may only improve by a few % by going to 25 km integration.
3. The data suggest that more vertical coverage is gained by increasing the sensitivity of the lidar (higher EAP) rather than increasing the integration time (distance).

## Summary

The results of the GLAS data analyses and the earlier LITE data analyses support the basic 80/80 expectation of 80% cloud return and 80% surface return for individual lidar shots from space. The recent launch of CALIPSO provides additional information on the issues address in the study reported here. If the 80/80 results stand after further investigation, the goal of full tropospheric soundings with laser based instruments is much more likely than could be proven before the LITE, GLAS and CALIPSO instruments were flown.

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## References

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<sup>3</sup> Winker, D. M. and G. D. Emmitt, 1997: Relevance of Cloud Statistics Derived from LITE Data to Future DOPPLER Wind Lidars, 9th Conference on Coherent Laser Radar, June 23-27, 1997, Linkoping, Sweden, 144-147.