GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L22S03, doi:10.1029/2005GL023507, 2005

Cloud and aerosol measurements from GLAS: Overview and initial results

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Received 16 May 2005; revised 12 July 2005; accepted 18 August 2005; published 28 September 2005.

[1] Global space borne lidar profiling of atmospheric clouds and aerosol began in 2003 following the launch of the Geoscience Laser Altimeter System (GLAS) on the Ice, Cloud and land Elevation Satellite. GLAS obtains nadir profiles through the atmosphere in two wavelength channels, day and night, at a fundamental resolution of 76.8 m vertical and 172 m along track. The 532 nm channel uses photon-counting detectors and resolves profiles of observed backscatter cross sections to 10^{-7} 1/m-sr. The 1064 nm channel employs analog detection adequate to 10^{-6} 1/m-sr and with greater dynamic range. By 2005 approximately seven months of global data are available. Processing algorithms produce data products for the corrected lidar signal, cloud and aerosol layer boundaries and optical thickness and extinction and backscatter cross sections. Operational sensitivity is shown by the frequency distribution for cloud optical thickness peaking at approximately 0.02. **Citation:** Spinhirne, J. D., S. P. Palm, W. D. Hart, D. L. Hlavka, and E. J. Welton (2005), Cloud and aerosol measurements from GLAS: Overview and initial results, *Geophys. Res. Lett.*, *32*, L22S03, doi:10.1029/2005GL023507.

1. Introduction

[2] Since the advent of satellite remote-sensing, passive imaging radiometers of multiple types have provided observations of global cloud and aerosol layer distributions. Yet there are issues of increasing importance where passive sensing alone is not adequate. Both cloud feedback and the influence of aerosol are considered major uncertainties for predictions of global warming. Global observations should be sufficient to provide adequate information for climate models, but also of sufficient sensitivity to monitor critical component variability in response to climate change. Passive instruments do not provide direct and accurate observations of the height distribution of aerosol along with accurate extinction and absorption information. Similarly for cloud cover, errors in height and coverage from passive retrieval are typically large in comparison to the impact on infrared forcing from increasing greenhouse gasses. Active laser remote sensing of the atmosphere has the major advantage of a direct and unambiguous detection and height measurement of all scattering layers, and thus space borne lidar observations will be an important addition to existing satellite observations.

[3] The first polar-orbiting satellite lidar instrument, the Geoscience Laser Altimeter System (GLAS), was launched on board the Ice, Cloud and land Elevation Satellite in January 2003 and has provided extensive global data on cloud and aerosol distributions. As part of the NASA Earth Observing System (EOS) project, the GLAS instrument is intended as a laser sensor fulfilling complementary requirements for several earth science disciplines [*Zwally et al.*, 2002; *Spinhirne and Palm*, 1996]. The overall approach takes advantage of the good technical compatibility of cloud and aerosol profiling with laser altimeter measurements for ice sheet and land requirements. In addition, a mission that combines surface altimetry and high quality atmospheric measurements best overcomes inter related remote sensing problems such as the effect of cloud scattering on precision altimetry [*Duda et al.*, 2001].

[4] In this paper we present an initial description of the GLAS atmospheric observations. Specific examples of the application of GLAS data to a range of issues are given in this special section [*Hlavka et al.*, 2005; *Palm et al.*, 2005a, 2005b; *Spinhirne et al.*, 2005; *Hart et al.*, 2005]. The stated measurement requirement for GLAS was to profile all radiative significant cloud and aerosol layers. The measurement result from the fully operational instrument meets the requirement. An important part of the development of the GLAS project was the construction and testing of automated data processing algorithms capable of operational production of higher-level research parameters. We describe the GLAS cloud and aerosol data products available to the science community, starting September 2004.

2. GLAS Observation Requirements and Examples

[5] The lidar measurement requirements for clouds and aerosol from space were based on a long experience with airborne and ground based observations. The stated requirement to profile all significant cloud and aerosol translates to detection at appropriate spatial resolution of layers of optical depth down to 0.01. The requirement then further translates to the observation of backscattering cross sections to below 10^{-7} 1/m-sr. Airborne observations indicate that there is a "background" aerosol mode into the troposphere with cross sections at visible wavelengths on the order of 10^{-9}–10^{-8} 1/m-sr [*Menzies et al.*, 2002]. Thus some aerosol concentrations exist below the stated measurement requirement, but these aerosol are considered below the definition of radiative significant.

[6] The GLAS instrument is a dual-frequency, nadir-viewing laser radar system (J. Abshire et al., Geoscience Laser Altimeter System (GLAS) on the ICESat mission:

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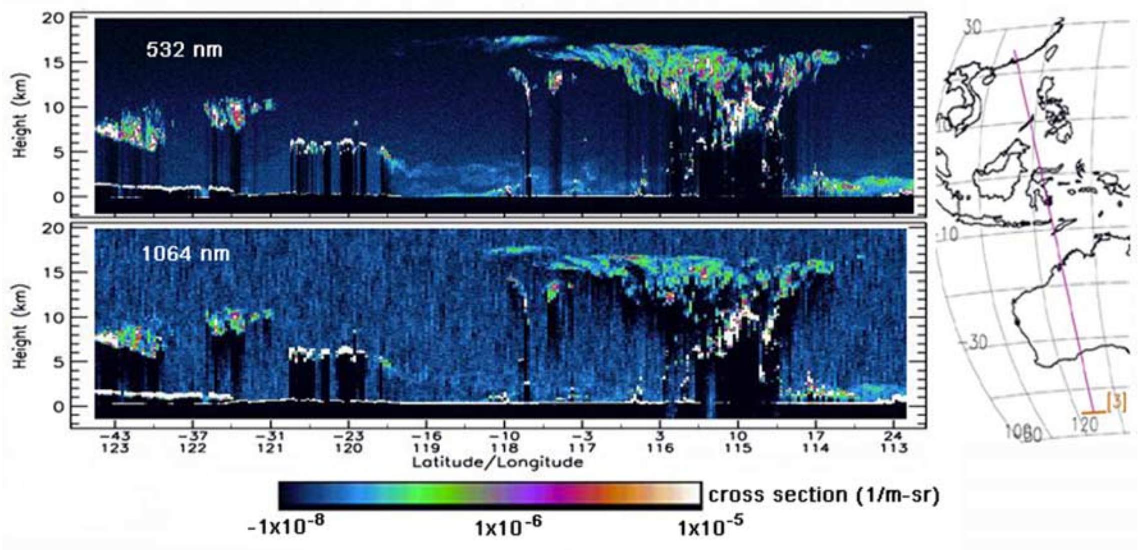

Figure 1. GLAS (top) 532 nm and (bottom) 1064 nm data (orbit track 10) over Western Australia to South China is shown as a function of latitude and longitude. The photon counting 532 nm channels has a significantly higher signal-to-noise ratio than the analog 1064 nm channel. The data are an October 23, 2003 nighttime case of the attenuated backscatter cross-section (GLA07) product with the color scale showing the values for the 532 nm channel.

On-orbit measurement performance, submitted to *Geophysical Research Letters*, 2005, hereinafter referred to as Abshire et al., submitted manuscript, 2005). Diode pumped, 0.1 J Nd:YAG lasers transmit pulses at both the fundamental and doubled wavelengths at 40 Hz giving a nominal 172 m footprint spacing along track. Fundamental to the design is a dual-wavelength, dual-purpose 1 m receiver. The 1064 nm channel applies analog signal acquisition for surface ranging and profiling dense cloud tops. The 532 nm channel was designed to meet the requirement of profiling the thinnest cloud and aerosol layers, and thus uses high efficiency solid-state detectors for photon counting signal acquisition. To obtain the necessary sensitivity over noise in daytime, important aspects of the 532 nm receiver channel are a small field-of-view, 0.19 mr, and a very narrow band filter, 24 pm, to minimize the solar background. Since dense cloud signals could saturate the photon counting, the full atmospheric signal is acquired with analog detection at 1064 nm, but with an expected signal over noise performance an order of magnitude or less than the 532 nm channel. The fundamental vertical sampling resolution of the two atmospheric channels is 76.8 m, and 15 cm for the altimetry channel. Special design features of GLAS for surface altimetry are an advantage for the atmosphere measurements. These include a precise measurement of the surface pulse magnitude, and the ability to point to inter-comparison targets to within ±30 m accuracy.

[7] The initial on-orbit full operation of the GLAS instrument began with the turn on of the second of three lasers (termed period 2a) on 28 September 2003. (A first period, 1a, of data in February and March of 2003 was acquired with only the 1064 nm channel.) An example of GLAS 532 and 1064 nm data acquired at nighttime is shown in Figure 1. The data cover approximately 11 minutes

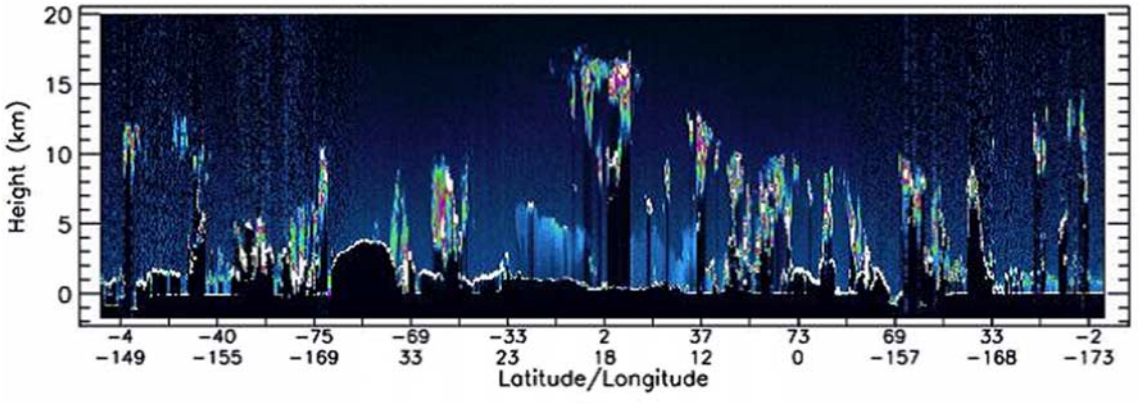

Figure 2. The 532 nm lidar signal of GLAS depicted for an entire global orbit from October 6, 2003. The signal scaling is the same as for Figure 1. The track starts in the central Pacific, crosses Antarctica, proceeds across Africa and Europe and then crosses northern Greenland and Alaska.

Table 1. GLAS Atmospheric Data Products

	Data Product	Product Description
GLA02	Level 1A Global Atmosphere Data	532 and 1064 normalized lidar signal at 40 Hz
GLA07	Level 1B Global Backscatter Data	Calibrated, attenuated backscatter cross section profiles for 532 and 1064 at 40 Hz and 5 Hz
GLA08	Level 2 Global Planetary Boundary Layer and Elevated Aerosol Layer Heights	Planetary Boundary Layer height and elevated aerosol layer top and bottom height at 5 Hz and 4 seconds
GLA09	Level 2 Global Cloud Heights Including Multiple Layers	Cloud layer top and bottom height at 40 Hz, 5 Hz, 1Hz and 4 seconds
GLA10	Level 2 Global Aerosol and Thin Cloud Vertical Structure	532 attenuation corrected backscatter and extinction profiles at 1 Hz and 4 seconds
GLA11	Level 2 Global Thin Cloud and Aerosol Optical Depth Data	Thin cloud and aerosol layer optical depths at 1 Hz and 4 seconds

and extends 4700 km from the southern ocean, over Western Australia to the southern coast of China, and represents the information from 26,500 laser pulses. Both channels show smoke-related aerosol emanating from convective clouds over Australia, but structure is much better resolved in the 532 nm data. The parameter shown in the image is the calibrated attenuated backscatter cross section (data product GLA07). The basic GLAS processing algorithm automatically applies signal corrections, subtracts offsets - particularly the solar background - and applies a cross section calibration derived from molecular scattering in the stratosphere where the cross-section can be calculated. At the level of signal averaging inherent in creating the data image from multiple laser pulses, the 532 nm observation clearly shows aerosol structure at cross sections to below 10^{-7} 1/m-sr. The 1064 nm data are less sensitive, but both channels measure boundary layer aerosol with cross sections greater than 10^{-6} 1/m-sr. Similarly for clouds the 532 nm channel cleanly depicts the structure of very thin cirrus at the tropical tropopause, but though detected at 1064 nm, the structure is much less distinct. The example shown is for nighttime observations. Daytime data show increased noise, especially above brighter surfaces such as clouds. However daytime data meet the basic stated requirement of GLAS atmospheric measurements [*Hlavka et al.*, 2005]. Extensive additional examples of data images, including daytime, can be found at http://glo.gsfc.nasa.gov/.

[8] The 532 nm data for an entire ICESat orbit (project track # 1130) on October 6, 2003 - nearly 0.22 million laser pulses - are shown in Figure 2. Data are again color scale coded in the image as the attenuated backscatter return. This typical full orbit profile illustrates the unprecedented ability to accurately and uniquely measure the height distribution of global cloud and aerosol. The data show boundary layer aerosol and PBL height over the clean Pacific, elevated dust layers over Africa, the distribution of high thin cloud (and associated tropopause height) and multi-layer clouds. Many specific, unique atmospheric phenomena have been profiled for the first time on a global basis.

3. Atmospheric Data Products

[9] An important part of the development of the ICESat project was the construction and testing of automated data processing algorithms capable of near real time production of higher level research parameters. There are two signal and four higher-level products for atmospheric observations (Table 1). GLA07 contains the lidar signal with instrument corrections and calibration. GLA08 through GLA11 contain derived quantities dependent on the particular algorithms developed by the GLAS atmospheric group. The basis of the data processing procedures is described in an EOS Algorithm Theoretical Basis Document [*Palm et al.*, 2002].

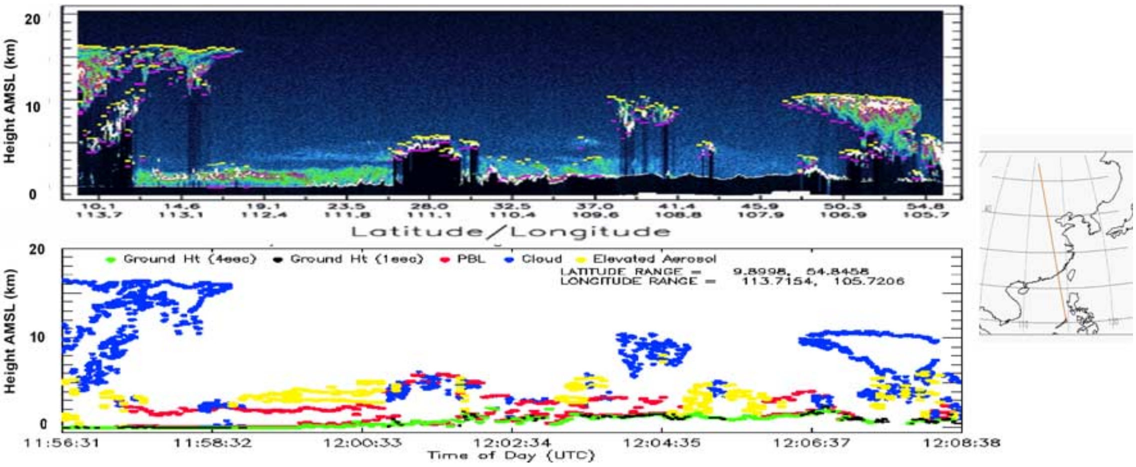

Figure 3. GLAS cloud and aerosol signal over China on October 23, 2003. Also shown are the GLAS cloud and aerosol layer height level data products produced from analysis of the signal.

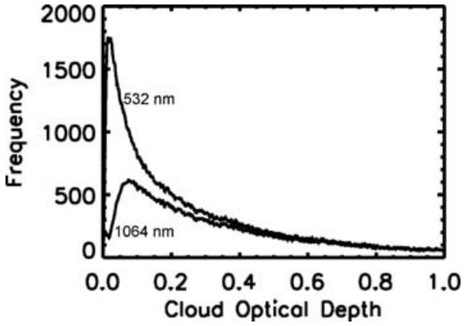

Figure 4. The relative frequency of cloud optical depth retrieval from GLAS for clouds above 4 km altitude from the 532 nm channel for all global observations in October 2003. The lower line indicates the relative frequency clouds are also flagged as detected in analysis of the 1064 nm channel alone. The individual data points are derived from 8 pulse, or 5 Hz, average profiles.

[10] An illustration of parameters contained in GLA07-10 is shown in Figure 3 for daytime data of extensive cloud and aerosol layers from a portion of a GLAS orbit track over central China on October 18, 2003. In Figure 3 (top) is shown the signal at 532 nm (GLA07). Figure 3 (bottom) shows the derived boundaries for the cloud and aerosol formations from GLA09&08. In Figure 3 both cloud and separate aerosol boundaries are shown. The processing algorithms employ a sophisticated segregation of aerosol and cloud layers, described in references [*Palm et al.*, 2002; *Hart et al.*, 2005], and they are flagged accordingly in the data products. The planetary boundary layer (PBL) height in GLA08 is derived from the aerosol profile but is maintained as a separate product from the aerosol layer heights [*Palm et al.*, 2005b]. Once the detection of aerosol layer boundaries has been accomplished in the GLAS data processing, the signal within layers is applied to derive the layer optical thickness, the extinction cross section and the attenuation corrected backscatter cross-sections – within the limits of signal attenuation [*Hlavka et al.*, 2005].

[11] The ability of the GLAS data to detect and derive the optical depth of layers down to a level much lower than previous satellite missions is illustrated in the Figure 4. The figure shows the distribution of frequency of occurrence of thin clouds versus optical depth as derived in the GLAS data processing. The result is for all data from October 2003. For the 532 nm channel, the distribution extends smoothly down to optical depths of 0.02. A 0.02 optical depth is consistent with a 100 m thick layer of cross section 10^{-7} 1/m-sr and thus within measurement limits. Separately shown are the similar results for the 1064 nm channel. The lower sensitivity of this channel is clearly seen, but most cloud layers to an optical depth of 0.1 are detected.

4. Conclusions

[12] The goal of the GLAS instrument to detect and profile all radiatively significant cloud and aerosol layers in the atmosphere has been verified through the analysis of data and initial intercomparison to aircraft data [*Hlavka et al.*, 2005]. Both the information on the unambiguous height structure of aerosol, direct measurement of cloud height and layering and the optical depth retrievals down to very low values are new measurements for global satellite observations. Initial application of the data include analysis of limitations in passive satellite retrievals of cloud cover [*Mahesh et al.*, 2004] where, despite the limitation of nadir direction only data, it has been possible to assemble thousands of coincident GLAS measurements and MODIS observations made within seconds of the other. The measurements enable a much improved ability to track and model global aerosol transport. Coverage is sufficient to produce meaningful monthly mean statistics on cloud and aerosol distribution at a one degree grid resolution [*Spinhirne et al.*, 2005]. The data provide a new tool for examining the performance of global weather and climate models [*Palm et al.*, 2005b]. Overall the ICESat mission has clearly demonstrated the important applications of spaceborne lidar in atmospheric science and created a unique data set from thousands of orbits with many research applications.

[13] The GLAS instrument was designed with three lasers to obtain a three to five year mission life. Life testing indicated that each laser should last for two years, but there have been three major on orbit problems with the lasers (Abshire et al., submitted manuscript, 2005). Following the two months of full operation in the fall of 2003, the GLAS instrument is being operated for a one-month periods out of every three to six months in order to extend the time series of measurements. The laser reliability failure limits the use of the data for applications requiring continuous long term measurements. However by spring 2005, two years after launch, over seven months of global measurements are now recorded and partial operation of GLAS continues. GLAS data are freely available through the NASA Distributed Active Archive Centers (DAAC) system (see below). Both data sets and data input and visualization tools are available. Overall the mission has clearly demonstrated the important applications of space borne lidar in atmospheric science and created a unique data set from thousands of orbits with many research applications.

[14] **Acknowledgment.** We thank the NSIDC for distribution of the ICESat data, see http://icesat.gsfc.nasa.gov and http://nsidc.org/data/icesat.

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