P1.13 COLUMN OPTICAL DEPTH RETRIEVAL USING SURFACE REFLECTIVITY FROM GLAS

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1. INTRODUCTION

The Geoscience Laser Altimeter System (GLAS) was launched aboard the Ice, Cloud, and land Elevation Satellite (ICESat) in January 2003 and is the first satellite lidar mission with global coverage. Operationally, optical depth (OD) retrievals from GLAS are limited to the 532 nm atmospheric channel. This photon counting channel was designed to have the best signal-to-noise and calibration and (through a forward lidar inversion algorithm) produce reasonable (~ 30% error) optical depth analysis of all atmospheric particulate layer down to the attenuation of the signal (around 3-4 optical depth). Unfortunately, this channel produced quality profiles for only the Laser 2a (October-November 2003) period and the first half of the Laser 2b (February-March 2004) period because of deteriorating laser energy for 532 nm in the succeeding Laser 2 and 3 periods. The 532 channel was not turned on for the short-lived Laser 1 period.

Attempts to use the other atmospheric channel at 1064 nm for optical depth retrievals are much more difficult, subject to a noisy signal and an electronic droop effect after strong signals. The 1064 nm channel is sensitive enough for significant layer location detection, but will generally miss weak cirrus and aerosol layers. A summary of the GLAS atmospheric channels is provided in Spinhirne (2005).

Fortunately, in addition to the atmospheric scattering profiles at two wavelengths mentioned above, the GLAS measurement includes a precise, 15 cm resolution, acquisition of the surface waveform at 1064 nm as described in Zwally (2002). The primary science of GLAS involves the use of this waveform for accurate surface altimetry work. The fact that both this waveform and the atmospheric profile channels are on the same satellite is a unique feature of GLAS. One very useful data product from the waveform is the integrated pulse energy from the surface. This receive signal by the lidar is a function of the surface reflectance and atmospheric transmission. If one can model the surface reflectance with enough precision to ratio it out, the atmospheric transmission remainder would directly lead to retrievals of total column optical depth at 1064 nm.

In this paper we refer to an ocean model of surface reflectance as a function of wind speed described and tested with GLAS data by Lancaster (2005) that has shown enough precision to use in this approach. We will compare ocean surface reflectance optical depth results with optical depths from the forward lidar inversion algorithm, from two coincident island AERONET sites, and from an under-flight of the Cloud Physics Lidar (CPL) high resolution aircraft lidar, in the hope of developing a new operational GLAS 1064 nm total optical depth product. This new product will be able to expand optical depth retrievals beyond the restricted 532 nm analysis to cover the Laser 1 period and all of Laser 2 periods whenever the satellite is over ocean and a non-saturated surface return is detected.

2. DATA ALGORITHM

The ocean surface reflectance model we have chosen to use has its beginnings with work from Cox and Monk (1954) and Monahan and O'Muircheartaigh (1980). At 1064 nm wavelength, ocean reflectance consists predomi-

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nantly of Fresnel reflection plus a small contribution from scattering from whitecaps and sea foam. The ocean surface reflectance (R) can be written as:

$$R = (1-W)R_s + WR_f \tag{1}$$

where R_s is the Fresnel reflectance from the surface, R_f is the reflection due to whitecaps, and W is the fraction of the surface covered by whitecaps. R_s is, in part, a function of the variance of the distribution of wave slopes, which is a function of wind speed. The fractional coverage of white caps is also a function of wind speed. For details of this equation, refer to Lancaster (2005). Conveniently, the latest version (Release 26) of GLAS atmospheric data products contain meteorological data interpolated from the National Center of Environmental Prediction (NCEP) gridded data set for use in Global Climatic Model initialization and contains surface wind speed for every second of orbit track. The resultant R from equation (1) contains no atmospheric attenuation affects from Rayleigh or particulate (clouds and aerosol) scattering and is described as the ‘pristine’ surface reflectance one would retrieve from a satellite lidar given a known wind speed if there was no atmosphere. Valid surface reflectance results are generally limited to values less than 1.5 because of the instability in surface reflectance under calm wind conditions.

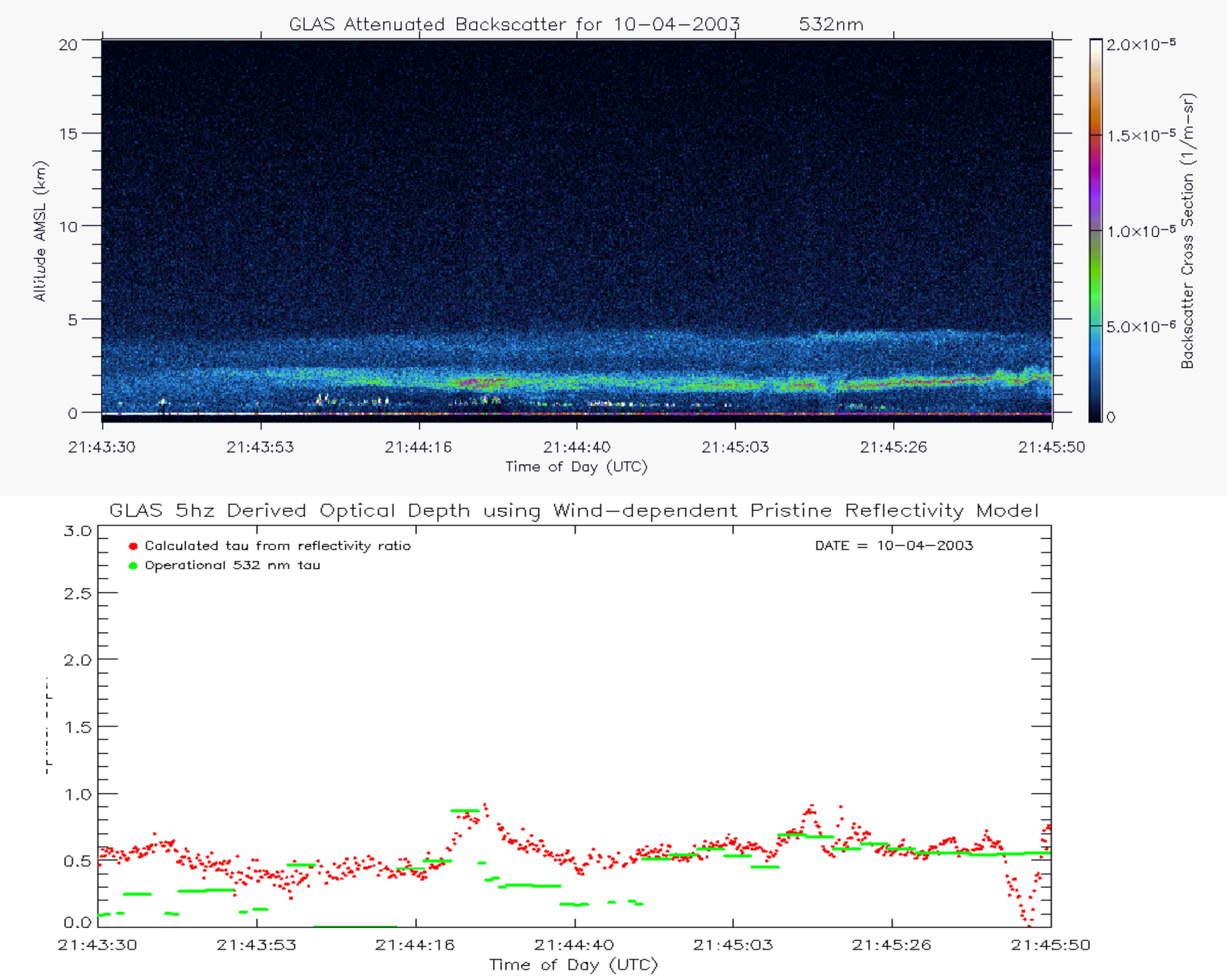

Figure 1. A Saharan dust event over the eastern Atlantic Ocean on October 4, 2003 is shown in an image of GLAS backscatter profiles in the top plot. The lower plot shows optical depth retrievals from the new 1064 nm surface reflectance algorithm (red) and 532 nm GLAS standard product lidar backscatter inversion (green). The plot shows the inefficiencies of the 1064 surface reflectance algorithm to retrieve optical depth during light winds (<3 m/s) before 21:43:53 UTC and the otherwise reasonable correlation between the surface reflectance method and the 532 standard optical depth product for dust particulates.

Table 1. Coincident Total Optical Depth Retrievals at 1064 nm (Aerosol)

AERONET SITE	DATE	TIME (UTC)	GLAS S. REFL OD (12 sec avg.)	AERONET OD (2.5 hr avg.)	ERROR	PERCENT ERROR
Lanai, Hawaii	25Oct03	05:52:20	0.05	0.0387	+0.0113	29.2
Capo Verde	30Oct03	08:56:08	0.57	0.7868	-0.2168	-27.6

The GLAS parameter of interest which retrieves the blend of the integrated pulse reflectance from the surface plus atmospheric attenuation is located in the standard data product GLA05 under the name *i_reflctUncorr* and is calculated at full resolution (40Hz or 175 meters horizontal). Three corrections to this parameter must be made before comparing to the pristine surface reflectance for particulate optical depth:

$$R_G = (R_i C_b)/(\cos(\theta)\overline{T}_m^2) \qquad (2)$$

where R_G is the resultant corrected GLAS reflectance, R_i is the initial *i_reflctUncorr,* C_b is a boresite calibration factor which periodically changes with time, θ is the tilt angle of the lidar with respect to nadir viewing (normally 0.1 but can reach 5.0), and $\overline{T}_m^2$ is the mean molecular two-way transmission for the entire atmospheric column at 1064 nm (~0.9853). Both the correction for the tilt angle and the molecular transmission are very minor. The relationship between the corrected observed GLAS reflectance (R_G) and the modeled pristine ocean reflectance (R) at the observed wind is described below:

$$R_G = R\,\mathrm{e}^{-2\tau} \qquad (3)$$

where τ is the optical depth of the particulates in the atmospheric column. Solving for τ results in the equation:

$$\tau = -\frac{1}{2}\ln(R_G / R) \qquad (4)$$

that would be valid for all conditions where the GLAS surface waveform is not saturated, where a surface signal is not extinguished by overlying clouds or aerosol, and where the ocean is not approaching a windless surface.

3. TOTAL OPTICAL DEPTH RESULTS

To demonstrate typical results comparing the surface reflectance optical depth with those independently derived from the forward lidar inversion algorithm from the atmospheric channels, we chose a case on October 4, 2003 above the Atlantic Ocean west of Africa with elevated dust layers. Because of larger particle size, the wavelength differences in optical depth due to dust are minor compared to urban pollution or smoke. Figure 1 shows a backscatter image of the case plus plots of two optical depth retrievals. The 1064 optical depth from the atmospheric channel lidar inversion is very noisy and has so far demonstrated limited usefulness. The 532 optical depth, pulled from the GLAS standard products, is also calculated from the lidar inversion algorithm but is better calibrated and has much higher signal to noise. It compares favorably to the 1064 surface reflectance OD in the main dust region. The surface reflectance model is overestimating OD in the weak wind area at the beginning because of erroneously high pristine reflectance calculated with the light winds. Note that the surface reflectance OD is at 5Hz resolution where the 532 standard product is at 4-second resolution.

Reliable independent measurements of optical depth are hard to come by at ocean locations, but we managed to find two island AERONET sites that were co-aligned within 2.5 hours and 7 km during the GLAS Laser 2A period. AERONET is a world-wide network of sun photometers developed for satellite validation (Holben, 1998). Complications do arise when comparing an instantaneous nadir orbit segment with a fixed location time series. However, preliminary studies have shown that a 2 to 3 hour average of the ground site is comparable to a 12 second (84 km) satellite segment average. Table 1 shows results from the inter-comparison of the surface reflectance technique with the AERONET ground truth. The error rates in this small sample of aerosol layers compares favorably with the GLAS 532 optical depth product average error.

Another set of independent comparisons available to GLAS during October 2003 were aircraft under-flights using the CPL lidar (Hlavka, 2005). This high-resolution lidar under-flew GLAS coincidently during an episode of thin cirrus clouds on October 24, 2003. Figure 2 plots the coincident segment from the GLAS view (A), the CPL view (B), GLAS optical depth results

(C), and CPL optical depth results (D). The CPL instrument is designed to have very low multiple scattering from clouds (5-8%) and high signal to

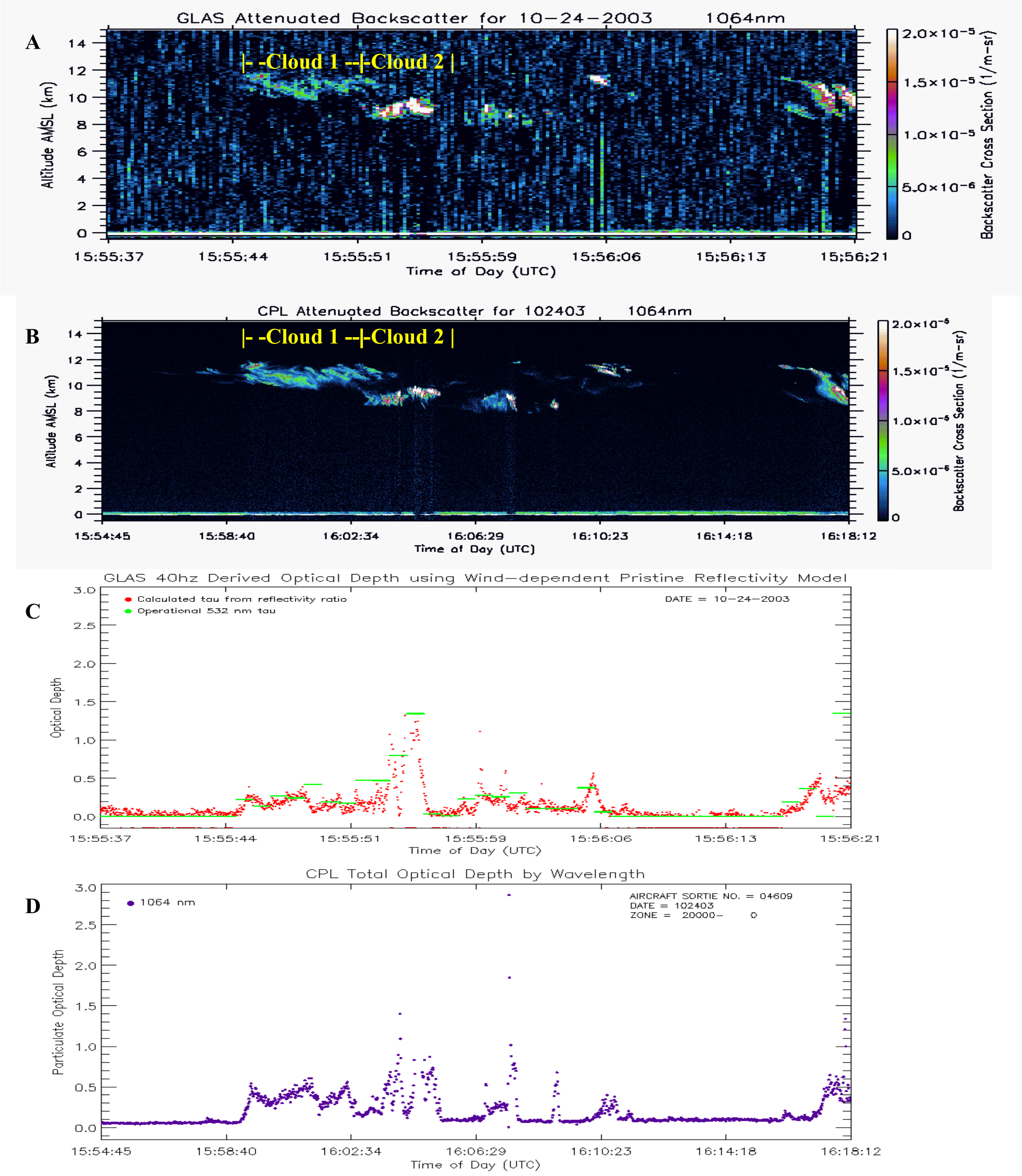

Figure 2. A thin cirrus event on October 24, 2003 is shown in an image of GLAS backscatter profiles in (A) over the Pacific Ocean west of California. Plot B shows the image of the ER-2 aircraft lidar (CPL) during the coincident under-flight. A close inspection of the image times shows that the exact time of coincidence is just to the left of the left-most cloud and that each cloud further to the right is sensed further apart in time by the two instruments. GLAS along-track resolution is 175 m while CPL is 200 m. Plot C graphs the GLAS surface reflectance optical depth (red) and 532 nm standard product optical depth (green). Plot D graphs the CPL 1064 nm optical depth retrievals.

Table 2. Coincident Total Optical Depth Retrievals at 1064 nm (Cirrus)

CIRRUS SEGMENT October 24, 2003	CPL TIME (UTC)	GLAS S. REFL OD (algorithm)	GLAS S. REFL OD (corrected for mscat)	CPL OD (cloud avg.)	ERROR	PERCENT ERROR
Cloud 1	16:00:00	0.22	0.24	0.34	-0.10	-29.4
Cloud 2	16:04:00	0.69	0.77	0..64	+0.13	+20.3

noise, allowing for its lidar inversion to be within 20% uncertainty during cirrus conditions such as this case. GLAS retrievals have higher multiple scattering (10-50%) potential based on a wider field-of-view. In this cloud case, multiple scattering should be on the low side because scattering out of high thin clouds will tend to cause the multi-scattered photons to leave the field-of-view. The surface reflectance retrievals in (C) have not been corrected for multiple scattering while the 532 retrievals from the standard GLA11 product have. Their good agreement supports the idea of low multiple scattering in this case. The exact coincident time of the under-flight occurred at 15:55:39 UT, just before any clouds were sensed. Cloud 1 (as labeled in the images A and B) has, on average, a 4.5 minute separation between instrument observations and Cloud 2 is sensed 8 minutes apart, due to the much slower aircraft speed compared to the satellite. Clouds further to the right are separated further in time, with the cloud furthest to the right being sensed 22 minutes apart. Table 2 displays optical retrievals from Clouds 1 and 2, where both instruments are more apt to sense the same clouds. Results from the GLAS surface reflectance algorithm are shown first with no multiple scattering (mscat) correction and then with an estimated 0.90 mscat factor. The errors shown are corrected for multiple scattering.

4. SUMMARY

The newly developed GLAS 1064 nm surface reflectance total optical depth algorithm is difficult to validate because of scarcity of independent optical depth measurements in the ocean environments of the world. Based on limited validation results, the average error for aerosol optical depth is 25% using AERONET island sites as ground truth, a bit better than the 30% accuracy of traditional lidar backscatter inversion methods such as the GLAS 532 operational aerosol optical depth product. The average error for cirrus cloud optical depth before correcting for multiple scattering effects is 7%, and after correcting is 3%, using the CPL aircraft lidar as ground truth. We have found this method to produce reliable optical depth results over ocean surfaces when the surface wind speed is known with the following caveats: 1) a reliable surface pulse is measured from GLAS [A thick cloud cover which extinguishes the signal or a saturated detector will retrieve an unusable surface pulse.] and 2) some wind [preferably greater than 3 m/s] is present to create wavelets and to avoid the unreliable reflectance model of a calm ocean. The surface reflectance method is expected to be more accurate than a noisy 1064 atmospheric channel inversion method that must use an assumed integration factor. Furthermore, results at the highest GLAS resolution possible (40 Hz or 175 m) are stable. A new GLAS product is planned using the surface reflectance method that should extend to more GLAS laser periods than the 532 nm atmospheric channel products could because of 532 nm signal degradation due to laser lifetime issues.

5. ACKNOWLEDGMENTS

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