Aerosol and cloud optical depth from GLAS: Results and verification for an October 2003 California fire smoke case

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[1] Data from the satellite lidar Geoscience Laser Altimeter System (GLAS) has provided a new means to retrieve height and optical depth of transmissive cloud and aerosol layers globally. We compare data sets from GLAS and an airborne under-flight of the Cloud Physics Lidar (CPL) during a unique smoke opportunity as part of a validation experiment in October 2003. The CPL has known layer identification and optical retrieval performance. GLAS data products, including calibrated attenuated backscatter profiles, layer identification, and optical depth, are compared to simultaneous aircraft lidar retrievals with similar model assumptions with a goal toward discovering algorithm biases in GLAS. The case described here involves heavy smoke layers from large-scale fires in southern California and thin cirrus clouds. The GLAS optical retrievals agree with the CPL data when the GLAS aerosol lidar ratio, S, is reset from default maritime to smoke and in inland urban pollution localities.
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1. Introduction

[2] 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. An objective of the ICESat mission is to improve the knowledge on the global distribution and radiative influence of aerosol and cloud layers. In other papers in this special section, the GLAS aerosol and cloud retrievals are introduced (J. D. Spinhirne et al., Cloud and aerosol measurements from the GLAS space borne lidar: Initial results, submitted to *Geophysical Research Letters,* 2005, hereinafter referred to as Spinhirne et al., submitted manuscript, 2005) and the accurate detection and discrimination of aerosol and cloud layers are described (W. D. Hart et al., Height distribution between cloud and aerosol layers from the GLAS space borne lidar in the Indian Ocean region, submitted to *Geophysical Research Letters,* 2005). In addition to the direct measurement of cloud and aerosol height, a major advantage presented by lidar is an independent means to retrieve the optical depth (OD) and height resolved backscatter and extinction inside layers. The ICESat atmospheric data products produced include the derived OD and extinction cross-section for aerosol and thin cloud layers (Spinhirne et al., submitted manuscript, 2005). In this paper we summarize the GLAS OD retrieval technique, and describe GLA07-11 data product results that are supported by coincident airborne field experiment results.

2. Intercomparison Procedures

[3] The processing of the ICESat lidar data for OD is described in the algorithm theoretical basis documents for the mission [*Palm et al.*, 2002]. The processing algorithms employ two independent procedures to derive the OD depending on atmospheric conditions. For cases where the lower boundary of the layer is at the surface or within a kilometer of another aerosol or cloud layer, a forward integration solution of the lidar equation is employed using the aerosol or cloud extinction-to-backscatter ratio (lidar ratio or S) obtained by a look-up table. The table is based on the location, season, and humidity of the layer for aerosol and temperature of the layer for cloud, and the OD values derived are thus dependent on the accuracy of the S assigned. For sufficiently isolated aerosol and cloud layers, it is possible to use the known signal from molecular scattering [*Palm et al.*, 2002] as a boundary condition and thus independently derive S and OD. In both cases a correction for the apparent reduction of attenuation due to multiple scattering is applied. Typically, multiple scattering corrections are less than 10% for aerosol but are much larger for clouds. An operational procedure has been developed for GLAS to quantify multiple scattering using the multiple scattering factor derived from Monte Carlo simulation look-up tables [*Palm et al.*, 2002].

[4] There are a number of possible biases and errors in the retrievals. When the forward integration is employed using modeled S, the results are model dependent. It is important to understand the biases that result, so that in time we can improve the model, leading to improved OD estimates. Thus validation experiments are necessary to determine the accuracy of results. Both ground-based and airborne experiments have been used. The ground-based experiment is primarily a comparison to AERONET [*Holben et al.*, 1998] and MPLNET [*Welton et al.*, 2001] built up over time from closely coincident observations. A larger initial set of coincident results is possible from focused aircraft-based validation experiments.

[5] GLAS has both 1064 and 532 nm backscatter lidar channels for atmospheric profiling. The more accurate

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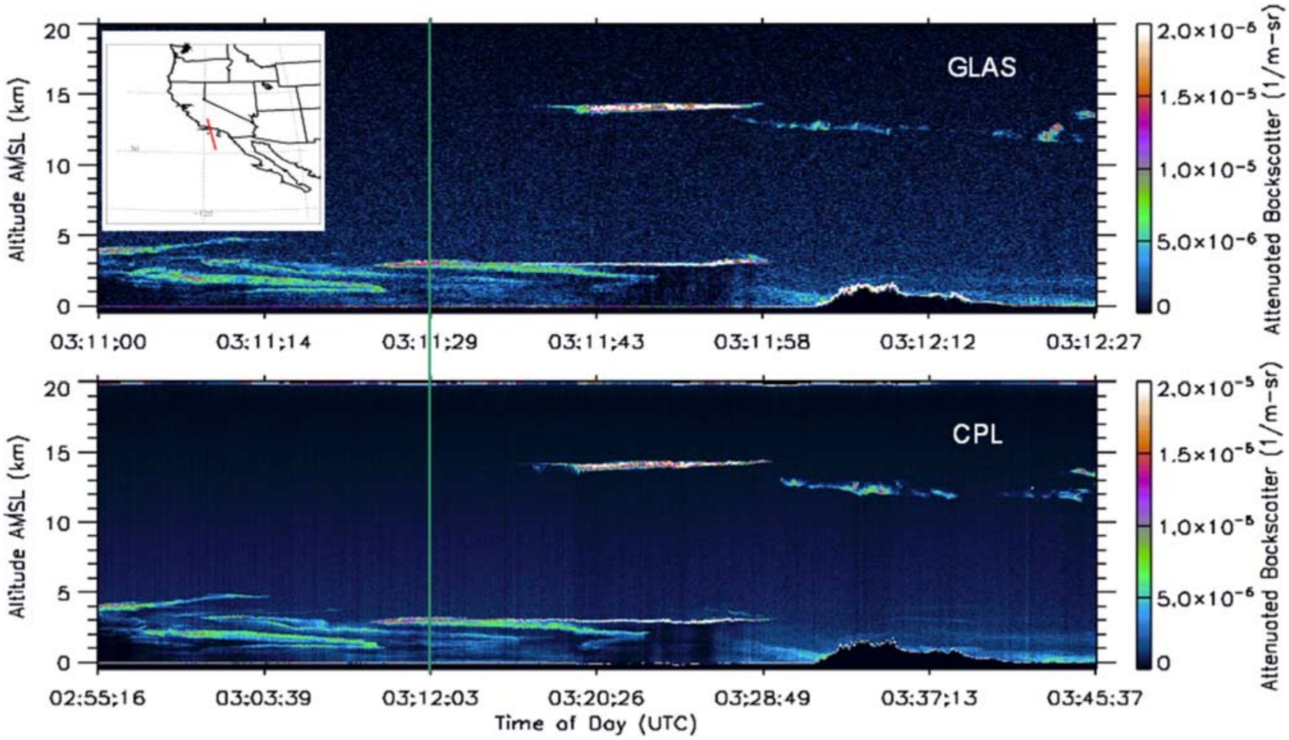

Figure 1. Images from 532 nm calibrated attenuated backscatter retrievals from GLAS and CPL during a coincident orbit track of October 28, 2003 showing cirrus clouds (above 7 km) and smoke layers (below 5 km). The red line in insert map shows coincident track, south to north. The vertical green line shows the exact time of coincidence at 03:11:29 UTC. Note the time differences between the two instruments. The vertical scale used is altitude above mean sea level.

532 nm channel is used for optical retrievals. Level II products from GLAS, such as optical retrievals, are at 1-second and 4-second (7 km and 28 km) horizontal resolution for clouds and aerosol respectively as described by Spinhirne et al. (submitted manuscript, 2005). Vertical resolution is 76.8 meters. The GLAS products referred to (GLA07-11) are from Release 18 of the operational code. The results shown are from October 28, 2003, orbit track #0095, during laser operation period 2a.

[6] The Cloud Physics Lidar (CPL) is a compact and versatile 3-wavelength (1064, 532 and 355 nm) lidar system that flies on the NASA ER-2 and WB-57 aircrafts and has served as the simulator instrument for GLAS and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) atmospheric retrievals. Details on the CPL instrument can be found in the work of *McGill et al.* [2002]. The CPL field of view is small enough to reduce multiple-scattered signals to less than 10% of the total from clouds. Optical processing algorithms for CPL ignore multiple scattering. The full algorithm discussion is too detailed to be included here but is given by *McGill et al.* [2003] and *Spinhirne et al.* [1996].

[7] In October 2003, a GLAS Validation Experiment was executed from NASA Dryden Flight Research Center in Edwards, California. The high-altitude NASA ER-2 aircraft with CPL onboard under-flew seven ICESat tracks. Serendipitously, the timing and location of the experiment provided an opportunity to target smoke clouds generated by major fires occurring in Southern California. Special capabilities of the ICESat lidar and ER-2 aircraft allowed co-incident measurement locations to within 50 m cross-track. In general, the ER-2 followed a 46-minute traverse of a precise ICESat ground track, a distance that ICESat covered in 1.5 minutes. No compensation was made to the ER-2 track to allow for wind drift of the clouds or aerosol although this data was monitored. For each CPL flight and corresponding ICESat track, operational processing models were used to extract the optical retrieval products. The aerosol S models are the same for both instruments, but the assignment methods are different.

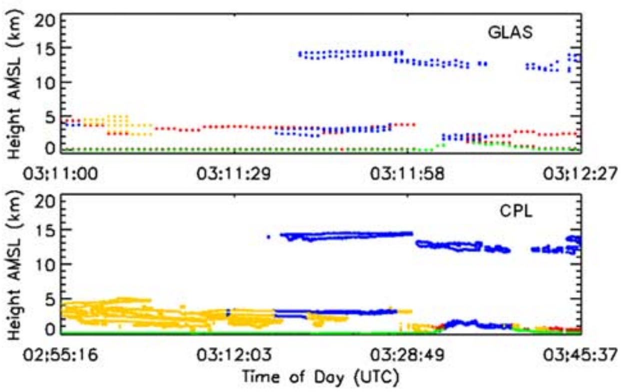

Figure 2. Results of GLAS and CPL layer type and location algorithms on October 28 that are inputs into the respective optical properties models. PBL layers are red; elevated aerosols are yellow; clouds are blue; and ground height is green. The higher resolution output of CPL is evident but GLAS results agree with CPL in general.

Table 1. Coincident Lidar Retrievals (10-28-03)

Parameter	GLAS Org. (7 km)	GLAS Smoke (7 km)	CPL 35-sec (7 km)
Layer Top amsl, m	3480	3480	3400
Lidar Ratio (S) Used	21.24	53.24	61.00
Retrieved Optical Depth	0.194	2.173	2.230
Multiple Scattering Factor Used	0.97	0.98	1.00

GLAS assigns based on generic geographic defaults, while CPL incorporates manual assignments for each of its defined time segments. This difference pertains to aerosol layers only, not clouds. Only in the exact second of ICESat overpass are the two instruments perfectly co-aligned. However, cloud signals observed by CPL within ±10 minutes of the ICESat overpass generally matched closely with the GLAS measurements. This procedure could also be used to validate the upcoming similar CALIPSO satellite lidar although the cross-track accuracy will be less.

3. Intercomparison Results

[8] We focus on the intercomparison during the October 28 (03:11 UTC) under-flight that sensed thick smoke and thin cirrus clouds off the Southern California coast around 8:11pm local time October 27. This track/under-flight pair had the best smoke coverage of any of the 7 under-flights and provided a unique case for remote sensing of large fresh smoke plumes.

3.1. Calibrated Backscatter Retrievals and Layer Identification

[9] Figure 1 shows independently calibrated attenuated backscatter profiles (a GLA07 GLAS product) from the two instruments along the ICESat track on October 28. A qualitative comparison immediately shows that both lidars detected the location of the strong smoke layers and the scattered thin cirrus above mean sea level (AMSL). Figure 1 also shows that the signal strengths of the backscatter profiles are visually correlated, although GLAS has lower signal-to-noise ratio (SNR) outside dense layers caused mostly by the much larger range from the instrument. After 03:12:02 UTC in the GLAS image, the instruments' sampling times were separated by over 20 minutes and were beginning to sense different cloud structures. Because of relative horizontal homogeneity and the slower drift speeds of the smoke layers, both instruments appeared to sample the same smoke signatures throughout the length of coincident segment.

[10] The layer identification algorithms from GLAS and CPL along the track are compared in Figure 2. A very important requirement of lidar processing algorithms is to identify and separate cloud (GLA09) and aerosol layers (GLA08). Because of its higher resolution both vertically and temporally and its higher SNR, the CPL algorithm identifies the layering details of the whole Planetary Boundary Layer (PBL) structure. The GLAS algorithm identifies the vast majority of the smoke as one PBL layer (a GLA08 product). This is a consequence of coarser resolution and search thresholds. Compared with the CPL standard, GLAS layer discrimination correctly separates aerosol and cloud layers, including the overlying cirrus. There is a possibility that the cloud layer at 3.5 km sensed by both instruments is actually a very dense smoke layer with similar retrieved signatures as a cloud. Our analysis shows that the minimum backscatter signal necessary to sense a layer with GLAS is on the order of 2×10^{-7} 1/m-sr.

[11] At the moment of GLAS overpass (03:11:29 UTC), an average of 1-second of GLAS attenuated backscatter profiles (7 km) was compared to 35 seconds (7 km) of CPL profiles for this nighttime case. Both profiles are calibrated well with the Rayleigh scattering signal above the smoke.

3.2. Optical Properties Retrievals for Thick Smoke Aerosol and Thin Cirrus Cloud

[12] The smoke aerosol in this case study is atypically strong for the region because the east winds drifted the massive plumes from several large fires out over the Pacific Ocean, which is generically dominated by marine sea salts. Selecting an accurate S for the optical inversion process is crucial to retrieving quality OD estimates. The generic operational GLAS processing has no information about special situations such as fresh smoke. The default S assumes a marine boundary layer environment. Operational CPL processing with knowledge of the smoke location assigns a much higher S typical of smoke. To compare results, we reran the GLAS processing program using an aerosol S more typical of smoke but restricted to a S value which allowed for processing to the bottom of the PBL. Table 1 shows data product results from GLAS and CPL from optically processing the coincident profiles discussed in the paragraph above. The table shows results from the original GLAS algorithm and when GLAS uses a smoke regime S [*Campbell et al.*, 2003]. Differences in the aerosol top location in Table 1 are due to both CPL's higher resolution and tighter search threshold due to higher SNR. Effects of multiple scattering in GLAS are small in aerosol situations. The OD value of 2.17 retrieved from GLAS using the smoke S at the coincident location compares favorably to the CPL retrieval, with GLAS measuring only 0.06 below what CPL retrieved. The original GLAS operational run with no knowledge of the smoke calculated a low OD of 0.19 (a GLA11 product) by using an S of 21.2.

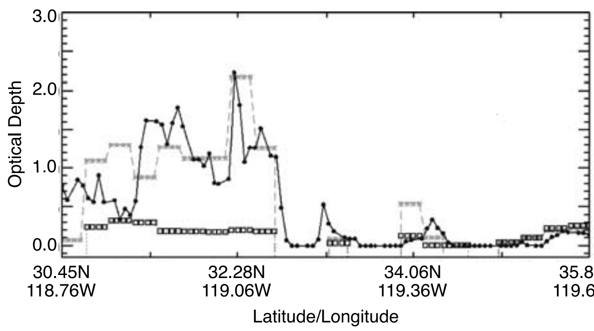

Figure 3. Plots from GLAS operational run (black squares), GLAS smoke run (gray asterisks), and CPL (black dots) showing total aerosol optical depth from October 28. The GLAS operational run has no knowledge of the advected smoke and assigns a low marine S for the smoke layer over the ocean. The GLAS smoke run corrects for this. Because of the homogeneity of the smoke, both instruments sensed the same aerosol layers even though the time separation was over 15 minutes toward the endpoints of the segment.

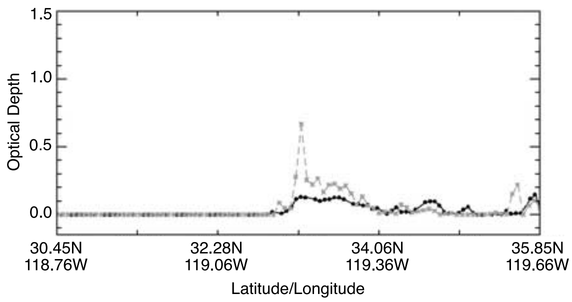

Figure 4. Plots from GLAS (dashed gray) and CPL (solid black) showing total cirrus cloud optical depth during coincident orbit track of October 28. CPL results were averaged to match the 7 km GLAS horizontal resolution. Both plots were restricted to layers above 7 km. North of 34.31N, the instruments were separated by over 20 minutes and were sensing different clouds.

[13] The aerosol OD comparison was expanded to cover the whole orbit segment by averaging CPL retrievals horizontally to 7 km to match the extrapolated GLAS 28 km retrievals. Aerosol OD plots are shown in Figure 3. The comparison continues to show good agreement between CPL and the GLAS smoke run across the smoke layers, with smoke OD ranging from 0.5 to 2.2. The operational GLAS run has an OD that averages generally 0.23 over the ocean. After landfall at 34.1N through urban pollution areas, it agrees well with CPL as its S rises to the standard continental pollution default. Obviously, improved GLAS operational runs will have to ingest updated knowledge of transient PBL aerosol type to resolve cases like this.

[14] A similar plot for cirrus cloud OD across the segment is shown in Figure 4. The fact that the profile times of the two lidars are 13 minutes apart in the closest cirrus to the coincident time introduces small variability that is sensed by the two instruments. The main cloud area between 33.18N and 34.06N had a retrieved average OD of 0.20 for GLAS and 0.10 for CPL, with GLAS processing including a correction factor for multiple scattering in clouds. This cloud was generally too thin for GLAS to retrieve many samples of directly calculated S, with CPL retrieving a higher percentage because of higher SNR. As a result, CPL used S's generally in the low 20's while GLAS used S's near 30 sr from its lookup table, explaining much of the difference in the OD results. A low multiple scattering factor also contributed to the higher S of GLAS. The spike in the GLAS results at 33.24N is caused by an erroneous noise-induced direct calculation of S applied at that second. After 34.31N, the instrument retrievals were separated by over 20 minutes and were sensing different clouds. Another coincident day (October 17) that views thicker cirrus and where both instruments calculate the layer S directly shows good agreement at the coincident time with GLAS-derived OD calculated at 0.40 and CPL-derived OD calculated at 0.34.

4. Conclusion

[15] CPL products provide unique validation information for the GLAS standard data products during October 2003. The comparison case shown here is of special interest due to the dense smoke layers, but it is beyond the capability of the current operational GLAS aerosol optical processing algorithm to know the smoke situation. Based on comparisons when a smoke S is used, generally stable and acceptable performance is found and application confidence is justified, which is a prime goal of the comparison. The GLAS lidar backscatter profiles appear to be well calibrated at night.

[16] GLAS retrievals show much promise. GLAS resolution of atmospheric layer location is good; though of lower SNR and lower vertical resolution than the airborne CPL. Using GLAS profiles, atmospheric layers can be sensed down to a backscatter of 2×10^{-7} 1/m-sr.

[17] The study of the October 28 smoke case successfully demonstrates the capabilities and limitations of backscatter lidar optical depth retrievals such as GLAS for this type of dense aerosol and thin cirrus. Generic operational processing of GLAS aerosol retrievals limit valid results to areas and times where S defaults match real layer characteristics. This limitation is much less of a problem in clouds. Very thin cirrus compared in this case show a small high bias for GLAS because of default S assignments and multiple scattering factors used. Continued analysis of the GLAS Validation Experiment data will show more elaborate comparisons of the two lidars' optical retrievals, especially clouds. Future releases of the GLAS Level 2 atmospheric products will contain improvements in layer identification and aerosol S assignments as more sophisticated assignment methods are developed.

[18] **Acknowledgments.** We thank NASA's ICESat Science Project and the NSIDC for distribution of the ICESat data; see http://icesat.gsfc.nasa.gov and http://nsidc.org/data/icesat/. The Cloud Physics Lidar is sponsored by NASA's Earth Observing System (EOS) office and by NASA Radiation Sciences (Code YS).

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