Validation of Satellite Borne Lidar Systems by Ground Based and Airborne Instruments

Validación de Lidar en Satelites Utilizando Instrumentos en la Superficie y en Aviones

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ABSTRACT:

Two satellite borne lidar systems to measure atmospheric parameters have been deployed and one is scheduled for launch this year. The first system was LITE a "proof of concept" lidar on Space Shuttle mission STS-64 in September 1994. The second is the GLAS system on ICESat, whose purpose is primarily to measure changes in elevation of the Greenland and Antarctic ice sheets, but it also gives determinations of cloud heights and the vertical structure of clouds and aerosols. The CALIPSO satellite, which will be a part of the A-train constellation of satellites, has three instrument on board. One of these is CALIOP, a lidar system dedicated to studies of aerosols and clouds. We describe these three systems and validations of their science products.

Key words: lidar, satellite, aerosols, clouds, validation.

RESUMEN:

Dos sistemas lidar que miden parámetros atmosféricos han sido colocados en satélites. El primero era LITE, un experimento de prueba de concepto que voló en el trasbordador espacial en setiembre de 1994. El segundo es el lidar GLAS montado en el satélite ICESat cuyo meta principal es la medida de cambios en las capas de hielo de Groenlandia y Antárdida, pero también realiza mediciones de las alturas de nubes y la estructura vertical de nubes y aerosoles. El satélite CALIPSO, que formará parte de la constelación de satélites llamada "A-Train," llevará a bordo tres instrumentos. Uno de ellos es CALIOP, un lidar dedicado a estudios de aerosoles y nubes. Presentamos una descripción de los tres sistemas y las validaciones de sus productos cientificos.

Palabras clave: lidar, satelite, peroles, nubes, validación.

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1. Introduction

We describe three space borne lidar systems (LITE, GLAS and CALIPSO) designed for atmospheric studies and we discuss validation techniques for these systems using ground based and airborne instruments.

The usual meaning of validation in the context of scientific data products retrieved from satellite borne sensors, is the assessment of the accuracy and precision of the derived science product by independent means. For example, the stated validation success criterion for CALIPSO is the following: science data products will be considered validated if (a) the uncertainty estimates for the geophysical products have been shown to hold based on comparisons with independent data products of high quality that have already been validated themselves, or (b) the discrepancies between such comparisons have been understood and explained (Winker et al., 2004).

2. Overview of the Satellite Lidar Systems

2a. LITE

LITE stands for "Laser in Space Technology Experiment." This was a proof of concept experiment in which a down-looking lidar on the space shuttle (STS-64) was activated for over 50 hours between September 9 and September 20, 1994. The feasibility of a space-based lidar was demonstrated and many interesting atmospheric measurements were obtained.

The LITE laser was a Nd:YAG laser operating at 1064 nm, 532 nm, and 355 nm. The laser firing rate was 10 Hz. The shuttle ground track speed was 7.4 km/sec, so the column profile measurements were separated by about 740 m. The vertical sampling had a resolution of 15 m. The atmospheric sampling column diameter was between 275 meters and 450 meters (depending on the wavelength). The Cassegrain (coma-free Ritchey-Cretien design) receiving telescope had a diameter of 0.95 m. The return signal from above about 5 km was weak at 1064 nm, but the other two channels had signals sufficiently strong to yield information on aerosol backscatter (as well as temperature, which is not usually a lidar derived quantity).

The LITE experiment was the first time a lidar system was able to obtain global coverage (albeit in a very narrow curtain) generating profiles for clouds, tropospheric and stratospheric aerosols, molecular density and temperature as well as surface reflectance.

Results obtained include aerosol layers over the Atlantic Ocean resulting from the transport of Saharan dust, continental haze over North America extending across much of the Northern Atlantic, and indications of biomass burning over Brazil and Southern Africa. Urban aerosol plumes were seen near various cities, including Taiwan, Los Angeles and San Francisco. Other measurements included multiple cloud and

aerosol layers and vertical profiles of frontal system.

These results are usually presented as signal intensity vs. altitude as a function of horizontal location along the ground track. This yields a visually interesting set of results in which clouds and aerosol plumes are easily identified. As an example, the 532 nm data in Figure 1 were obtained on orbit 34 (September 12) over the Sudan.

For a deeper understanding of the measurements, it is necessary to invert the lidar equation to derive aerosol backscatter, extinction and optical depth (cf., Klett, 1985). To do so involves, of course, a number of assumptions. For example, Reagan and Liu (1997), using the 532 nm data, assumed a constant aerosol extinction to aerosol backscatter ratio of 35.

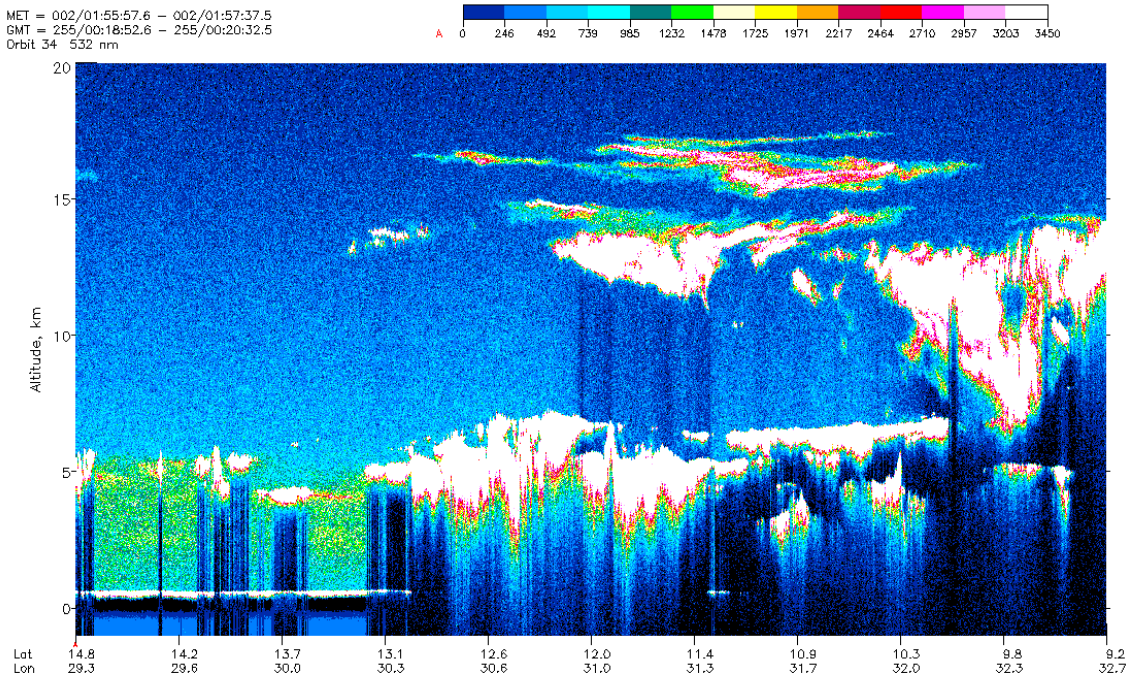

Figure 1. Voltage received at LITE receiver at 532 nm during orbit 34 on September 12, 1994 between latitudes 14.79 to 9.21 and longitudes from 29.26 to 32.65. Image from http://www-lite.larc.nasa.gov/n_theimages.html.

2b. GLAS

GLAS stands for "Geoscience Laser Altimeter System." This instrument is mounted on ICESat, the Ice, Cloud and Land Elevation satellite. It was launched in January 2003 and is, to date, the only satellite-borne laser carrying out measurements of the Earth's atmosphere. ICESat is in a near polar orbit at an altitude of about 600 km. As the name indicates, the GLAS instrument was designed as a precision surface altimeter to determine temporal changes in ice sheet topography. However, GLAS is also an atmospheric lidar. It has two wavelength channels, at 1064 microns and 532 microns and is used to observe aerosol layers and thin clouds. The main purpose of the 1064 micron channel is to determine surface topography and dense cloud and aerosol layers. The 532 nm channel is designed to observe thin cloud layers and aerosols. GLAS data yields vertical distributions of clouds and aerosol layers with a 75 meter altitude resolution. The laser footprints are about 70 meters spaced at 170 m along-track. (Zwally , 2004)

The instrument was expected to operate continuously for three to five years.

It was equipped with three lasers and each successive laser was to be used in case of a failure of the previous one. The GLAS laser 1 was activated on February 20, 2003 and it failed on March 29, after providing about 36 days of data. Since that time, the instrument has only been turned on for periods of 33 days every 3 to 6 months. The failure of laser 1 was traced to a problem in the manufacturing of the laser diode arrays in which an excess of indium solder resulted in a reaction between indide and gold conductors which degraded the gold conductors at a rate dependent on temperature. Since all three lasers were manufactured in the same way, similar failures are expected in the other lasers, but to ameliorate the situation somewhat, the operational temperature was decreased by a few degrees, and the scope of operations was drastically restricted.

The atmospheric data contain a great deal of information of scientific interest, such as cloud climatologies in high latitudes and cloud top altitudes. Polar clouds have also been observed. Other scientifically interesting data include forest canopy heights, a vital factor in estimating the global carbon budget.

2c. CALIPSO

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite is scheduled to launch on September 11, 2005. The payload on the CALIPSO satellite is a lidar system denoted CALIOP and two other instruments (an imaging infrared radiometer and a wide field camera). The lidar system uses two redundant, diode-pumped Nd:Yag lasers. The receiving system has three channels at 1064 nm, and 532 nm (with parallel and perpendicular polarizations). The pulse repetition rate is 20.25 Hz. Beam expanders are used to reduce the angular divergence of the laser beam to a diameter of 70 m at the Earth's surface. A narrowband etalon is used in the 532 nm channel to reduce the solar background illumination. A dielectric interference filter provides sufficient solar rejection for the 1064 nm channel. Dual digitizers on each channel provide the effective 22-bit dynamic range needed to measure both cloud and molecular backscatter signals. An active boresight is used to ensure the alignment of the transmitter and the receiver. The profiles will be calibrated by normalizing the return signal to the predicted molecular backscatter coefficients from the region 30 to 35 km. The 532 perpendicular channel will be calibrated relative to the 532 parallel channel and the 1062 nm channel will be calibrated relative to the 532 nm total backscatter signal from optically thick cirrus clouds.

The resolution of the lidar is 30 meters in the vertical and 333 meters in the horizontal. Backscatter will be acquired from the surface to 40 km with 30 meters vertical resolution. The pulse energy is 110 mJ each wavelength. (Winker and Pelon, 2003).

The satellite orbit is a sun-synchronous 705 km circular orbit. The ascending node equatorial crossing time will occur at 13:30 local time on each orbit. The orbit is highly inclined and will give measurements of clouds and aerosols over a wide range of latitudes. An interesting aspect of the orbit, is that CALIPSO will fly "in formation" as part of the Aqua constellation of satellites which will also contain Aqua, Aura, CloudSat and Parasol (also known as the A-train).

Motivation for the Calipso system is the fact that model estimates of global aerosol forcing of climate are highly uncertain largely because observations are insufficient to constrain or verify key assumptions in the models. The largest uncertainties in predicting climate are associated with modeling a variety of cloud-radiation-climate feedback processes. Synergistic measurements from the A-train will enable the first observationally based estimate of direct aerosol forcing. Calipso measurements will be combined with near

simultaneous measurements from A-train instruments of aerosol optical parameters and radiative fluxes to provide estimates of direct aerosol forcing. Furthermore, the effects of clouds on Earth's radiation balance (particularly on longwave fluxes within the atmosphere and at the surface) depend on having accurate knowledge of the location of clouds vertically, on their multi-layer structure and their ice/water content. Using Calipso data along with CloudSat radar measurements will allow one to map the vertical structure of clouds over the globe with an unprecedented accuracy.

The data from the three instruments will be used to determine radiative and physical properties of cirrus clouds and aerosols. The main product will be a global, vertically resolved measurement of aerosol distribution. Furthermore, the data will allow for a height resolved discrimination of various types of aerosols.

3. Validations

In this section we consider the validation efforts that have been carried out or are proposed for the three space lidar projects.

The validation of satellite borne lidar systems by ground based lidar systems is not straightforward. Difficulties include the fact that during a very short period of time, the space borne system will carry out measurements over a significant horizontal distance while the ground based system is localized, the only changes being due to atmospheric motion (which is usually fairly complex). That is, the viewing scenarios are inherently different.

To calibrate a space lidar system, the most obvious approach would be to compare measurements of atmospheric molecular scatter, a quantity that is well understood and quantified in terms of atmospheric pressure, and has the advantage of being horizontally homogeneous. However, molecular scattering is proportional to $1/\lambda^4$ and therefore is difficult to apply at the "long" wavelength of 1064 nm.

Furthermore, multiple scattering affects the two systems differently; in general, multiple scattering can be ignored for ground-based systems, but not for satellite borne instruments. This necessitates developing an operational procedure to quantify the effect of multiple scattering.

Another major problem encountered in validating satellite lidar aerosol data is the fact that the backscattered intensity measured by the receiver depends on the ratio of aerosol backscatter to aerosol extinction, also known as the lidar ratio (S), a parameter that is not known *a priori.* The lidar ratio is often assumed to be constant. Whereas this assumption is reasonable for an individual aerosol layer, applying a constant S to the entire atmosphere is, of course, more problematic. Work to assess the temporal and seasonal variability of the lidar ratio and its parameterization with more fundamental lidar derived quantities, e.g., lidar color ratios, is well underway (Omar et al., 2005, Catrall et al., 2005).

3a. LITE Validation

During the shuttle flight carrying the LITE instrument, some fifty ground based lidar systems carried out comparative measurements all over the world (Woods, 1994). As examples we will consider two of these, namely the validation experiment described by Gu et al. (1997) and that described by Cuomo et al. (1997).

Gu *et al.* carried out validations for the 532 nm and 355 nm LITE channels, not using the 1064 channel because the signal was too weak to be useful. They used two ground validation sites, the Starfire Optical Range in New Mexico and the Arecibo Observatory in Puerto Rico. At both sites

they utilized frequency doubled Nd:YAG lasers and measured tropospheric and stratospheric backscatter profiles during LITE overpasses. Additionally balloonsonde data were used.

The backscatter data obtained with the LITE system were compared with the Arecibo lidar for orbit 117. Although many orbits passed near the Starfire and Arecibo sites, weather conditions only allowed for the operation of the ground lidars during three coincidences. The coincidences were not particularly tight, the closest points being separated by 590 km, 911 km, and 2900 km. The backscatter profiles obtained by the lidar at Arecibo and that by LITE 590 km to the East were found to be quite similar. (The integration time was 50 s for LITE, corresponding to 370 km horizontal resolution, and 150 s for Arecibo.) The observation times were separated by 2.5 hours. The two profiles showed the presence of cirrus clouds between 12 and 14 km altitude. The clouds were part of a large homogeneous cloud system over much of the Caribbean. Above the clouds, between 15 and 32 km, the absolute backscatter ratios measured by both systems differ by less than 5%.

Temperatures can also be obtained from the LITE data from the molecular backscatter. Gu et al. found that the stratospheric temperatures derived from LITE were in very good agreement with the temperatures obtained from the balloonsondes. The rms differences between the corrected LITE profiles and the balloonsonde data were as low as 2K in the 15-30 km height range.

The LITE data were also validated by Cuomo et al. (1997). During the course of the LITE experiment, five different lidar systems in Italy carried out correlative measurements. The work described by Cuomo et al. was carried out at Potenza and at Naples. The Naples data were not used, however, in the comparison because they were taken during the day and the daytime LITE data were not available at that time. During the time period 11 to 18 September there were also fourteen radiosonde launches from Potenza, as well as solar irradiance measurements using a grating spectrometer. These measurements allowed for a characterization of the atmosphere during the period of the field campaign and to give profiles of water vapor and temperature. There were 6 overpasses of LITE with groundtracks within 2000 km of Naples and Potenza. Since the distances between the LITE measurements and the Potenza lidar soundings were rather large, no effort was made to compare the tropospheric aerosol backscatter.

To compare aerosol backscatter, it is necessary to remove the contribution of molecular backscatter to the returned signal. This in turn requires introducing a height dependent correction factor to account for aerosol extinction. The authors made the assumption that the ratio of extinction to backscatter is constant in stratospheric aerosol layer and has a value in the range of 35 to 63 sr at 532 nm and in the range of 23 to 41 sr at 355 nm. When comparing LITE and lidar data, different values of the extinction to backscatter ratio ($k_{\square}$ were used and this introduced small changes in the characteristics of the aerosol layer. Nevertheless, the differing values of the ratio did not affect the level of agreement between the Potenza lidar and the LITE measurements. For example, for the 355 nm measurements, values of $k_{\square}$ from 20 sr to 30 sr led to differences in the aerosol scattering ratio from 0.0 to 0.05, an insignificant variation. Similar values were found for the 532 nm measurements. Consequently, Cuomo and co-workers concluded that the lidar profiles were in agreement with the LITE data to with experimental uncertainty. Specifically, a least squares linear fit of the two data sets led to a correlation coefficient of 0.72 at 355 nm and 0.86 at 532 nm.

Finally, we mention that the LITE data was also subjected to a validation experiment using the Ames Airborne

Tracking Sunphotometer (AATS) but on the surface rather than in an aircraft. We mention this because the AATS instrument is a focus of our discussion of the CALIPSO validation as presented below. Ultimately, the results of these measurements (P. B. Russell, private communication) were not used in a LITE comparison because sun photometer measurements had to be made during the day and the quality of the LITE daytime data was not sufficiently high for a reasonable validation. This is particularly unfortunate because the sun photometer was mobile and was actually located directly on the overpass line and took data in two locations in California at the time and location of LITE overpasses.

3b. GLAS Validation

The GLAS lidar data was validated by McGill et al. using the NASA Goddard Cloud Physics Lidar (CPL) (McGill et al., 2005). The CPL is an elastic backscatter lidar system using an Nd:YVO_4 laser. It is normally mounted on the NASA ER-2 aircraft that typically flies at about 20 km, so it is an excellent emulation of a space based lidar. The similarity in vertical and horizontal structure of the two data sets is striking, as can be appreciated from figures presented by McGill et al.

Hlavka et al. (2004) compared studies made with the CPL during seven under flights of the GLAS orbit tracks. The ER-2 traversed in 46 minutes the track covered by ICESat in 1.5 minutes. Consequently, the two end points of the segment were out of synchronization with GLAS by up to 20 minutes, and different cloud and aerosol structures were observed by the two instruments. Hlavka et al. carried out a very complete validation of the GLAS data, starting with a comparison of the optical processing input parameters. For example, they show that the Rayleigh profiles used for GLAS and CPL are essentially identical. A number of similar tests verified that the GLAS method for incorporating meteorological information and the molecular backscatter calculation is done correctly. They also showed that signal strengths for the two instruments agree, although the below cloud GLAS signal indicates that there is a problem with multiple scattering. Daytime cases with large background are not well calibrated, a problem that is being addressed. The optical properties of extinction, backscatter and optical depth were compared. It was found that a parameter used to calculate the multiple scatter factor was in error and has been corrected in later versions of the data products. Generally, the cloud comparisons were better than the aerosol comparisons. One reason may be the fact that aerosol S ratios for GLAS are automatically assigned from look up tables based on season and location whereas CPL uses S ratios that can be adjusted to fit the actual conditions more closely.

An interesting approach to the validation of GLAS measurements is presented by Thome et al. (2004). This approach is based on the "hard target method" where one assumes the spectral properties of the target are well understood. For example, one could use clouds as "hard targets" assuming the reflectance from clouds is known. During the early operation of GLAS the 532 nm band was not operational and Thome and co-workers opted to use the surface of Earth as the hard target. They used the ground at the White Sands Missile Range in New Mexico as a target. It was necessary, of course, to determine the backscatter reflectance of the ground site to predict the returned signal to GLAS. Three approaches were used to determine the backscatter surface reflectance, involving (1) a ground based passive sprectrometer, (2) a ground based active backscatter radiometer and (3) space based multispectral imagery, namely, results from the ASTER sensor.

Thome et al. concluded that the GLAS system behaves as expected from a radiometric standpoint. Further, they point

out that a combination of ground based passive and active data, combined with passive imaging data are useful for understanding the behavior of a spaceborne lidar system.

3c. Calipso Validation

The Calipso instrument has not been launched yet, so we can only report on plans for validations. It is interesting to note, however, that there is an extensive planning document that outlines the essential experiments that will be carried out to validate Calipso (Winker et al., 2004).

The Calipso aerosol products are optical depth, backscatter and extinction, and altitude and thickness of aerosol layers having backscatter coefficients greater than $2.5X10^{-4}$ /sr km. The cloud products are altitude and thickness (for clouds with backscatter greater than 10^{-3} /sr km), optical depth, backscatter, extinction, ice – water phase, ice cloud emissivity, and ice particle size.

Some of the science products are not amenable to direct validation. For example, it will be difficult to obtain comparison data sets for ice water content. In such cases, the validation will primarily consist of consistency checks.

Other science products will rely on specially designed instruments. Specifically, two new airborne High Spectral Resolution Lidar (HSRL) instruments have been developed, one by NASA and the other by Institut Pierre Simon Laplace. These instruments will yield the lidar ratio (S) directly. As mentioned above, for the GLAS data, a value of 35 was used for S. However, this ratio varies not only with wavelength, but also with the aerosol loading and type of aerosol and can vary from about 10 to over 100 (P. B. Russell, personal communication, 2005). The distribution of the lidar ratio for aerosols is not well known and is a major source of uncertainty in determining the extinction from the backscatter data. Although ground based Raman and HSRL lidars are available, they have the problem that ground based aerosol measurement systems are difficult to use to validate satellite systems because coherent space and time scales for aerosols are of the order of 100 km in distance and from minutes to hours in time. The Calipso preliminary guidelines for aerosol coincidences is that the ground track pass within 100 km of the instrument site and that data be taken within an hour of the satellite overpass, although airborne measurements of in situ and column integrated aerosol parameters have shown appreciable variability of aerosol optical properties on much shorter spatial and temporal scales (e.g., Redemann et al., 2005). Consequently, airborne instruments which can be flown under the overpass in the same direction as the satellite track are the most appropriate way to obtain correlative data.

Another planned validation uses the Nasa Ames Airborne Tracking Sun hotometer (AATS-14). The AATS-14 is mounted on one of various different aircraft platforms. A normal maneuver is an upward (or downward) spiral giving aerosol optical depth as a function of altitude. This can be differentiated to yield extinction. The measurements made with this instrument have been validated against many other instruments, and have been an important component of closure experiments. Consequently, it is, in many respects, an instrument with a proven, peer-reviewed record for vertically-resolved aerosol extinction measurements. The aerosol optical depth, columnar ozone and columnar water vapor obtained by the AATS-14 have been compared with a variety of other instruments, including AERONET. It has been used in satellite validation programs in over 20 field campaigns and has been used in the validation of TOMS, SAGE, POAM,

MODIS, MISR, AVHRR and other satellite systems.

Although validation plans for Calipso are fluid, there is science team mandate to validate aerosol extinction profiles within 135 days of launch. There will probably be a short intensive field campaign featuring a high spectral resolution lidar (HSRL) and possibly the NASA Ames Airborne Tracking Sunphotometer. The HSRL will fly in a nadir viewing configuration on board a high altitude Learjet while the AATS instrument will be flown concurrently at a lower altitude on a Jetstream-31. Coordinated flight plans will include stacked level legs by the low flying aircraft to underfly the lidar on the Learjet, both coordinated with CALIPSO and A-Train overpasses, followed by vertical profiles of the Jetstream for the derivation of aerosol extinction profiles from the AATS aerosol optical depth profiles.