The Airborne Cloud–Aerosol Transport System: Overview and Description of the Instrument and Retrieval Algorithms

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ABSTRACT

The Airborne Cloud–Aerosol Transport System (ACATS) is a Doppler wind lidar system that has recently been developed for atmospheric science capabilities at the NASA Goddard Space Flight Center (GSFC). ACATS is also a high-spectral-resolution lidar (HSRL), uniquely capable of directly resolving backscatter and extinction properties of a particle from a high-altitude aircraft. Thus, ACATS simultaneously measures optical properties and motion of cloud and aerosol layers. ACATS has flown on the NASA ER-2 during test flights over California in June 2012 and science flights during the Wallops Airborne Vegetation Experiment (WAVE) in September 2012. This paper provides an overview of the ACATS method and instrument design, describes the ACATS HSRL retrieval algorithms for cloud and aerosol properties, and demonstrates the data products that will be derived from the ACATS data using initial results from the WAVE project. The HSRL retrieval algorithms developed for ACATS have direct application to future spaceborne missions, such as the Cloud–Aerosol Transport System (CATS) to be installed on the International Space Station (ISS). Furthermore, the direct extinction and particle wind velocity retrieved from the ACATS data can be used for science applications such as dust or smoke transport and convective outflow in anvil cirrus clouds.

1. Introduction

Current uncertainties in aerosol and cloud properties limit our ability to accurately model the earth’s climate system and predict climate change. There are several different types of lidar systems that can be used to measure cloud and aerosol properties and motion. Cloud–aerosol lidars measure the elastic backscatter from molecules and atmospheric particles to resolve vertical profiles of optical properties of clouds and aerosols. The two most common elastic backscatter lidar techniques are standard backscatter lidars and high-spectral-resolution lidars (HSRL). The data provided by these lidar systems are essential to investigations of cloud and aerosol properties for numerous reasons. The vertical structure of cloud and aerosol layers resolved by lidar systems cannot be accurately obtained from passive satellite or passive airborne sensors. Furthermore, thin cloud optical depths are often below the detection limits of millimeter cloud radar systems (Comstock et al. 2002). In situ instruments can provide critical measurements of cloud and aerosol microphysical properties. However, they do not easily provide vertical profiles of these measurements and can alter the physical properties of the particles (Jensen et al. 2009; Zhao et al. 2011). Information obtained from cloud–aerosol lidar systems can improve knowledge of cloud and aerosol properties, which in turn can be utilized as parameterizations to reduce the uncertainties introduced in GCMs.

Standard elastic backscatter lidars are the least complex and most common lidar systems used to study vertical profiles of cloud and aerosol properties. Ground-based
and airborne systems have been used in numerous field campaigns over the past few decades. In the last decade, as laser transmitters have become more reliable, the first space-based elastic backscatter lidar systems were designed and launched. The Geoscience Laser Altimeter System (GLAS; Spinhirne et al. 2005) was launched in January 2003 and the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) project (Winker et al. 2009) was launched in April 2006. These lidar systems fundamentally measure vertical profiles of attenuated total backscatter, without separation of particulate (Mie) and molecular (Rayleigh) scattering.

There have been many methods developed to retrieve the particulate extinction and particulate backscatter coefficients from a cloud–aerosol lidar return signal. One technique is an inversion using standard backscatter lidar data developed by Fernald et al. (1972) and Klett (1981, 1985). The Klett or Fernald method makes it possible to solve the standard lidar equation by assuming a ratio of aerosol extinction to aerosol backscatter coefficients, referred to as the lidar ratio, that is known and constant throughout a particulate layer. This assumption reduces the number of unknowns in the system to one. This method is commonly used to retrieve particulate extinction and backscatter coefficients from standard backscatter lidars such as CALIPSO (Young and Vaughan 2009) and the cloud physics lidar (CPL; McGill et al. 2002). The lidar ratio (sr) is highly dependent on the optical and microphysical properties of the atmospheric layer being measured. The lidar ratio typically varies from about 10 to 50 sr for tropospheric clouds (Del Guasta 2001; Seifert et al. 2007; Yorks et al. 2011a) and from about 20 to 80 sr for aerosol particles (Ackermann 1998). For cloud and aerosol layers with an optical depth greater than 0.30, a 30% error in the assumed lidar ratio can lead to an error in the extinction retrieval from elastic backscatter lidar systems greater than 50% (Young et al. 2013).

Another method for retrieving the particle backscatter and extinction coefficients from a lidar signal is an HSRL, based on the use of two measured profiles instead of only one. This method was first theorized by Fiocco et al. (1971) to distinguish the contributions of the molecular and particulate scattering using the difference in Doppler broadening of light backscattered by the two components. Since air molecules experience significant thermal velocities as a result of their small size, the scattering from air molecules is broadened by about 2 GHz (10^{-5} nm) at visible wavelengths (Young 1982). In contrast, particulate backscatter is hardly broadened (about 30 MHz or 10^{-5} nm) as a consequence of the relatively slow thermal motion of atmospheric cloud and aerosol particles. The narrow spectral shape of particulate backscatter can be characterized by the small frequency distribution of lasers (Esselborn et al. 2008). High-spectral-resolution optical filters are required to separate the particulate contribution from the molecular backscatter and to resolve particulate extinction and backscatter coefficients independently with no assumption about the lidar ratio required.

Only a few HSRL instruments have been successfully developed and operated to measure cloud and aerosol optical properties from ground or aircraft platforms. These HSRL systems employ either Fabry–Perot interferometers (Shipley et al. 1983; Grund and Eloranta 1991) or absorption filters to differentiate particle scattering from molecular scattering (Piironen and Eloranta 1994). The most common HSRL technique is the use of iodine absorption filters in the receiver system of the instrument, where the received atmospheric signal is split into two detector channels to discriminate between particulate and molecular backscatter. The total backscatter channel measures the total backscattered signal, which includes both the particulate and molecular components similar to a standard backscatter lidar, with no sensitivity to the spectral broadening of the two components. The molecular channel contains the iodine absorption filter, which rejects the particle backscatter and transmits the wings of the Doppler broadened molecular spectrum as a total molecular signal (Hair et al. 2008; Esselborn et al. 2008). Recently, airborne HSRL systems that employ iodine filters have been implemented and demonstrated on the National Aeronautics and Space Administration (NASA) King Air (B-200) research aircraft (Hair et al. 2008) and the German Aerospace Center Falcon research aircraft (Esselborn et al. 2008). However, a caveat of the iodine filter technique is that the particulate backscatter is not measured but inferred from the total and molecular backscatter, without resolving the spectral broadening of the particulate backscatter. The backscattered signal also contains additional information imparted in the scattering process, such as the Doppler shift caused by the mean velocity of the particle.

Doppler wind lidars use the frequency shift imparted on atmospheric aerosols and molecules to determine vertical profiles of the horizontal wind speed and direction. Providing these measurements on a global scale can progress understanding of atmospheric dynamics and improve numerical weather predictions (Baker et al. 1995). The two most common types of pulsed Doppler wind lidar systems are coherent (heterodyne) detection and direct (incoherent) detection. Coherent Doppler lidars use a heterodyning technique that mixes a pulsed lidar signal with a second laser signal to produce a beat frequency that is related to the Doppler shift. The second continuous laser beam is usually a local oscillator...
offset in frequency (Hall et al. 1984; Huffaker et al. 1984). Direct-detection lidars directly measure the frequency shift of the return signal using a high-spectral-resolution filter, such as a Fabry–Perot interferometer or etalon, and operate at shorter wavelengths than coherent systems (Benedetti-Michelangeli et al. 1972; Chanin et al. 1989; Garnier and Chanin 1992; Gentry and Korb 1994). One direct-detection method, termed multichannel (MC) by McGill and Spintherne (1998), measures the Doppler shift by imaging the etalon fringe pattern onto a multiple element detector (Abreu et al. 1992; Fischer et al. 1995). The MC direct-detection concept requires the etalon transmission function to be aligned with the laser wavelength. This method was demonstrated by McGill et al. (1997b) for a ground-based lidar developed at the University of Michigan, and the algorithms for retrieving the horizontal wind velocity from a multichannel Doppler wind lidar are outlined in McGill et al. (1997b,c).

The Airborne Cloud–Aerosol Transport System (ACATS) is a multichannel Doppler lidar system recently developed at NASA Goddard Space Flight Center (GSFC). A unique aspect of the multichannel Doppler lidar concept such as ACATS is that it is also an HSRL. Both the particulate and molecular scattered signal can be directly and unambiguously measured, allowing for direct retrievals of particle extinction. ACATS is therefore capable of simultaneously resolving the backscatter/extinction properties and motion of a particle from a high-altitude aircraft. The instrument has flown on the NASA ER-2 during test flights over California in June 2012 and as part of the Wallops Airborne Vegetation Experiment (WAVE) in September 2012. This paper will focus on the HSRL aspect of the ACATS instrument, since the method and retrieval algorithms have direct application to the Cloud–Aerosol Transport System (CATS) to be installed on the International Space Station (ISS) in late 2014. A description of the ACATS instrument design is provided, which includes details of the optical and mechanical components of the subsystems as well as the software that autonomously controls the instrument operation. This work advances the effort of McGill et al. (1997b,c) by demonstrating a new technique for directly retrieving HSRL cloud and aerosol products (i.e., extinction) from a multichannel direct-detection Doppler wind lidar, different from the iodine filter HSRL technique used to this point. Finally, the initial ACATS HSRL results and data products from the WAVE campaign will be presented.

2. ACATS method and instrument description

a. ACATS methodology

The ACATS instrument is an MC Doppler lidar system built for use on the NASA ER-2 high-altitude aircraft. The MC technique passes the returned atmospheric backscatter through a single etalon and divides the transmitted signal into several channels (wavelength intervals), which are measured simultaneously and independently (Fig. 1). The resulting spectral distribution is then compared to the outgoing laser distribution to infer the Doppler shift, as demonstrated in Fig. 2a. The outgoing laser distribution or “reference” spectrum is measured by the system, similar to the atmospheric backscattered light, before the laser light enters the atmosphere. Subsequent measurements of the atmospheric scattered light will reveal a wavelength offset that is proportional
to the Doppler shift and directly related to the velocity of the scattering particles (Fig. 2b). The basic concept is summarized in Figs. 1 and 2. The MC method was demonstrated using the ground-based University of Michigan Doppler lidar (McGill et al. 1997b,c).

A unique aspect of the MC Doppler lidar concept such as ACATS is that it is also an HSRL. Both the particulate and molecular scattered signal can be directly and unambiguously measured, since the broad Rayleigh-scattered spectrum is imaged as a nearly flat background, illustrated in Fig. 2c. The integral of the particulate backscattered spectrum is analogous to the aerosol measurement from the typical absorption filter HSRL technique in that the molecular and particulate backscatter components can be separated, providing exactly the same pieces of information as an iodine filter HSRL (Fig. 2d). The main difference between HSRL systems that use the iodine filter technique and the multichannel etalon technique used in the ACATS instrument is that the latter directly measures the spectral broadening of the particulate backscatter using the etalon to filter out all backscattered light with the exception of a narrow wavelength interval (1.5 pm for ACATS) that contains the particulate spectrum (gray, Fig. 1a). While previous ground-based MC systems have been built and operated (Benedetti-Michelangeli et al. 1972; Abreu et al. 1992; McGill et al. 1997b), there has been no airborne demonstration of the technique and the method has not been used to derive HSRL cloud and aerosol properties.

b. ACATS instrument description

The ACATS instrument is composed of three main subsystems: laser transmitter, telescope, and receiver optics. A picture of the ACATS instrument fully assembled, with the receiver and telescope subsystems, is shown in Fig. 3. A list of the ACATS instrument parameters is provided in Table 1. The instrument also includes a heating–cooling loop to provide stable thermal operation of the laser.

The frequency characteristics of pulsed lasers have recently been advanced due to the development of direct-detection Doppler lidars and HSRLs. These...
techniques impose further requirements compared to standard backscatter lidars, such as lasers that are single frequency on a single pulse basis and more stable in time (central frequency drift of less than 1 MHz min$^{-1}$). Lasers with a central frequency drift greater than 1 MHz min$^{-1}$ can introduce an error in the retrieval of the horizontal wind velocity greater than 5 m s$^{-1}$. An injection-seeded, pulsed Nd:YAG laser was developed that achieves these frequency characteristics (Hovis et al. 2004). This laser was later replicated for the ACATS instrument and provides a narrow wavelength distribution suitable for resolving the small frequency shifts due to the Doppler effect. The laser operates at an output power of about 10 mJ per pulse with a repetition rate of 250 Hz at 532 nm and is designed for use in the low-pressure environment of high-altitude aircraft.

The ACATS telescope employs a rotating holographic optic element (HOE) to fit the small volume envelope of the ER-2 superpod and to enable vector wind measurements, which requires more than one viewing direction (Fig. 3c). The telescope system is set for 45° off-nadir viewing and rotates on a bearing to permit step–stare operation. The number of scan angles (up to eight) and the dwell time at each scan angle are controlled by software and can be modified before flight. A schematic of the optical design is presented in Fig. 4. As the telescope rotates, the optical alignment changes and may lead to a loss in return signal if not corrected.
The heart of the ACATS receiver system is an etalon that provides the spectral resolution needed for the HSRL measurement and also resolves the Doppler shift inherent in the backscattered signal. Backscattered light collected by the telescope is passed through the etalon and an image of the etalon fringe pattern is created. A bandpass filter is used in tandem with the etalon to reject background sunlight, permitting daytime operation. The optical gap of the etalon is 10 cm with an operational diameter of 35 mm and a plate reflectivity of 85%. As with any MC system, it is critical to maintain the symmetry and shape of the etalon fringe pattern to avoid uncertainty in the measurement. A digital etalon controller was developed by Michigan Aerospace Corporation in which piezoelectric actuators control the etalon electronics to position and maintain the plate parallelism. Considerable work was performed to create autonomous flight software that maintains the etalon alignment over the entirety of an ER-2 flight. The signal transmitted by the etalon is then passed to the detector subsystem.

A holographic circle-to-point converter optic (McGill et al. 1997a; McGill and Rallison 2001) is placed in the focal plane to provide the spectral detection. The circle-to-point converter simplifies hardware requirements, improves efficiency of measuring the spectral content in the fringe pattern, and allows ACATS to utilize photon-counting detection. The holographic optic is coupled to a Hamamatsu H7260 linear array detector, which utilizes back-end electronics developed by Sigma Space Corporation to permit photon-counting detection at count rates in excess of 50 MHz. The ACATS receiver images ~1.2 orders over 24 detector channels. The

### Table 1. Primary system parameters for ACATS lidar; FWHH represents full width at half height.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser type</td>
<td>Nd:YAG, seeded</td>
</tr>
<tr>
<td>Wavelength</td>
<td>532 nm</td>
</tr>
<tr>
<td>Laser repetition rate</td>
<td>250 Hz</td>
</tr>
<tr>
<td>Laser output energy</td>
<td>~10 mJ per pulse</td>
</tr>
<tr>
<td>Telescope diameter</td>
<td>8 in.</td>
</tr>
<tr>
<td>Viewing angle</td>
<td>45°</td>
</tr>
<tr>
<td>Telescope FOV</td>
<td>350 μrad (full angle)</td>
</tr>
<tr>
<td>Bandpass filter</td>
<td>150 pm FWHH</td>
</tr>
<tr>
<td>Etalon spacing</td>
<td>10 cm</td>
</tr>
<tr>
<td>Etalon reflectivity</td>
<td>85%</td>
</tr>
<tr>
<td>Orders imaged</td>
<td>1.2</td>
</tr>
<tr>
<td>Free spectral range</td>
<td>0.05 cm⁻¹</td>
</tr>
<tr>
<td>Effective finesse</td>
<td>4</td>
</tr>
<tr>
<td>Etalon spectral resolution</td>
<td>1.5 pm</td>
</tr>
<tr>
<td>Detector channels</td>
<td>24</td>
</tr>
<tr>
<td>Raw range resolution</td>
<td>30 m</td>
</tr>
<tr>
<td>Horizontal resolution</td>
<td>1 s (~200 m)</td>
</tr>
<tr>
<td>Platform speed</td>
<td>~200 m s⁻¹</td>
</tr>
<tr>
<td>Platform altitude</td>
<td>~20 km (65 000 ft)</td>
</tr>
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</tr>
</tbody>
</table>

![Fig. 4](https://example.com/fig4.png)
ACATS etalon parameters result in a measurement dynamic range of \( \sim 400 \text{ m s}^{-1} \), more than sufficient for typical atmospheric motions.

An autonomous multichannel data system is the final component of the instrument and was based entirely on work completed by Sigma Space Corporation in support of the CPL lidars. The basis for the data system, the Advanced Multichannel Scaler (AMCS) card, was first applied in the ER-2 CPL instrument. The data acquisition software is included in the data system and has its heritage in the CPL and unmanned aerial vehicle (UAV)-CPL instruments. An important aspect of the ACATS data system, as developed for CPL and UAV-CPL, is the ability to downlink data in real time from the aircraft using the onboard air and navigation payload server. The data system also incorporates a Novatel model OEMV-3RT2i GPS receiver and an OEM-IMU-HS8 inertial unit to enable accurate correction for platform motion. The Novatel system provides greater than 20-Hz update rates with 2 cm s\(^{-1}\) velocity accuracy. The raw ACATS data file consists of photon counts at each horizontal record (1 s), range bin (30 m), and detector channel, which is then converted to atmospheric parameters such as backscatter and extinction coefficients.

c. ACATS calibration procedures

Several calibration parameters are required to accurately retrieve the wind velocity, particulate, and molecular backscatter from the ACATS data. These include normalization constants, instrument defect parameter, and detector nonlinearity. The illumination and sensitivity of the detector channels are not the same, necessitating normalization constants to compensate. The detector normalization coefficients are determined using a white light source to illuminate the telescope, while the receiving optics remains unchanged. These normalization constants describe the relative response of the detector to broad bandwidth illumination.

The alignment of the circle-to-point converter (HOE) and Fabry–Perot fringe pattern also must be characterized. Each ring in the circle-to-point converter represents a detector channel. Since the circle-to-point converter and etalon are manufactured separately, a ring can have a dissimilar centricity and diameter compared to the fringe pattern projected onto it, resulting in signal loss to the corresponding detector channel. To complicate matters, this loss of signal can vary in each channel. In the case of ACATS, the outer rings (higher detector channels) of the circle-to-point converter are not perfectly concentric with the fringe pattern, requiring normalization constants to compensate. The normalization coefficients are determined using the peak transmission of the etalon calibration data in each channel. Assuming perfect alignment in all channels, the peak transmission will remain constant over a 5–10-min interval as the signal is stepped through all detector channels. Thus, the ACATS channel with the highest transmission represents the best alignment, allowing all other channels to be normalized to the “best aligned” channel. These normalization constants describe the relative signal loss of the detector channel due to alignment imperfections.

To characterize the instrument defect parameter, an etalon calibration procedure has been developed for ACATS similar to the one outlined in McGill et al. (1997b). The etalon transmission equation as a function of detector channel \( j \) is expressed as (McGill 1996)

\[
T(\Delta \lambda, j) = \sum_{n=0}^{\infty} A_n \cos \left( 2\pi n \left( \frac{\Delta \lambda}{\Delta \lambda_{\text{FSR}}} + \frac{j}{N_{\text{FSR}}} \right) \right) \sin \left( \frac{n}{N_{\text{FSR}}} \right),
\]

where \( \Delta \lambda_{\text{FSR}} \) is the free spectral range and is defined as the change in wavelength necessary to change the order of interference by one. The free spectral range can also be determined by the number of channels necessary to change the order of interference by one, \( N_{\text{FSR}} \). The narrow wavelength interval that the system resolves, which is approximately 1.5 pm for ACATS (gray, Fig. 1a), is represented by \( \Delta \lambda \). The function \( A_n \) is defined as

\[
A_n = 2 \left( 1 - \frac{\ell}{1 + R} \right)^2 \left( 1 - R \right)^R \left( 1 + R \right)^{-R} e^{-4\pi n^2 \Delta d_0^2 \lambda_0^4},
\]

where \( \ell \) is the loss of light due to absorption or scattering by the etalon plates and \( R \) is the plate reflectivity. The center wavelength of the etalon is \( \lambda_0 \). The etalon transmission Eq. (2.1) is for an idealized etalon. Several effects, such as plate bowing, microscopic plate defects, detector broadening, and off-axis aberrations, will broaden a real etalon function.

For the purpose of this study, it is sufficient to use an instrument defect parameter \( \Delta d_0 \) to represent the etalon broadening effects and to tune the etalon model so that it matches the measured ACATS etalon response function. There are two important assumptions in determining the ACATS defect parameter. First, the defect parameter varies with the detector channel to account for the variability of the etalon finesse with the channel. It is also assumed that any broadening effects, and thus the etalon defect parameter, will follow a Gaussian distribution. The ACATS defect parameter is then determined by a calibration procedure similar to the one demonstrated in McGill et al. (1997b). The software runs a calibration procedure at least once per
flight that varies the etalon gap using piezoelectric actuators. Varying the etalon gap moves the interference fringe pattern across the detector in 128 small steps, sampling nearly 3 orders (42 points per order). One can then determine the defect parameter for each channel by performing a least squares fit to match the modeled etalon transmission function to the ACATS measured etalon response function using a similar technique to McGill et al. (1997b). The light source used to measure the ACATS etalon response is the same laser that is used for atmospheric measurements.

The measured ACATS spectrum can become distorted due to detector dead time and must be compensated for the effect. All lidar systems that employ photon-counting detection experience this effect, which is a limitation on the number of photons that can be counted in a given time interval. For ACATS, the large near-field return pushes the detector into a nonlinear counting region. The nonlinear effects for this type of detector can be quantified by a detector dead time coefficient. This coefficient represents the fact that only one photon event can be counted at once, and the detector system has a certain time delta, or dead time, before it can count another. A typical Hamamatsu linear array detector, such as the one employed in ACATS, has a discriminator dead time of 65–75 ns for a discriminator maximum count rate on the order of 15 MHz. To improve this performance, the ACATS Hamamatsu linear array detector is customized with a discriminator built by Sigma Space Corporation under Small Business Innovative Research (SBIR) funding that has a shorter discriminator dead time. This permits photon-counting detection at count rates in excess of 40 MHz before there is a 10% reduction in the observed count rate. The ACATS detector rarely experience count rates higher than 10 MHz in atmospheric bins below 17 km (assuming an ER-2 altitude greater than 19 km). Therefore, the detector dead time coefficient is less than 1.05 for 99.5% of atmospheric bins with the exception of the near-field return.

3. Development of ACATS retrieval algorithms

ACATS provides data products similar to other cloud–aerosol lidars, HSRL systems, and Doppler wind lidars. The system is currently set for 45° off-nadir viewing, and the telescope rotates to allow for two orthogonal line-of-sight (LOS) wind measurements, which are then used to compute vertical profiles of horizontal wind velocity and direction within particulate layers. The ACATS retrieval algorithms and data products for the horizontal wind velocity will be presented at a later date. This paper focuses on two types of aerosol/cloud products available from ACATS data that are directly applicable to the ISS CATS instrument. Standard backscatter products are computed similar to CPL and CALIPSO (McGill et al. 2007). HSRL products are produced at coarser resolutions (450 m vertical and 5 km horizontal), but include direct retrievals of attenuated particulate backscatter, optical depth, as well as particulate extinction and backscatter coefficients. These products are similar to those produced by other HSRL systems.

a. Development of standard backscatter algorithms

If the measured ACATS photon counts are summed over all channels as to neglect the spectral information provided by the etalon, then vertical profiles of total backscatter can be retrieved from ACATS data. Similar to a standard backscatter lidar system (i.e., CALIOP), this total signal is composed of both the particulate scattering and molecular scattering. It should be noted that only a small portion of the Rayleigh backscattered spectrum is measured by ACATS (Fig. 1a) compared to standard backscatter lidars, and the total molecular signal measured depends on the atmospheric temperature at each range bin. The total signal is typically represented by the single-scattering lidar equation, which describes the number of photon counts $N(r)$ detected from the range $r$ (Measures 1984; McGill 2003):

$$N(r) = \left( \frac{E_{\lambda}}{hc} \right) \Delta r O_E T_O O_A(r) \left( \frac{A}{r^2} \right) \times \left\{ [P_P(\pi, r)\beta_P(r) + P_M(\pi, r)\beta_M(r)] e^{-2 \Gamma \Delta r} \right\} + B_D + B_S.$$

(3.1)

The appendix provides the definition and dimensions of the variables in the photon version of the lidar equation (the equation can also be written in terms of power transmitted and power received). It is important to note that this equation neglects the effects of multiple scattering, which can be significant for lidar systems with a large field of view (FOV) or space-based lidar systems (Winker 2003). Furthermore, the assumption that the laser pulse length is much less than the range bin length $\Delta r$ is invoked.

The single-scattering lidar equation as written here is grouped into three main contributions to the measured signal. The first group represents the instrument parameters, with the $E_{\lambda}A/hr$ term converting the laser energy into units of photon counts. The solid angle viewed by the receiver is denoted by the second set of brackets, $A_{sr}$ (McGill 2003). The atmospheric physics is specified in the third bracket, which contains the phase function $P(\pi, r)$, volume total scattering coefficient $\beta(r)$,
and volume total extinction coefficient $\sigma(r)$. This term can be simplified by combining the phase function and volume total scattering coefficient $P(\pi, r)\beta(r)$ into the volume angular backscatter coefficient $\beta(\pi, r)$ (km/sr$^{-1}$), composed of both molecular $\beta_M(\pi, r)$ and particle $\beta_P(\pi, r)$ components. The attenuation of the atmosphere represented by the volume total extinction coefficient $\sigma(r)$ is a result of absorption and scattering from molecules ($\sigma_M$) and particles ($\sigma_P$). For purposes of a standard backscatter lidar, the absorption is neglected.

The standard lidar expression [Eq. (3.1)] can be restructured and solved for the attenuated total backscatter (ATB or $\gamma$) (km/sr$^{-1}$) defined as

$$\gamma(\pi, r) = [\beta_M(\pi, r) + \beta_P(\pi, r)] e^{-2\int_0^r \sigma_P dr},$$

$$= \frac{[N(r) - B_s(r)]^2}{E_r O_A(r) C}, \quad (3.2)$$

The molecular backscatter coefficient ($\beta_M$) is determined from Rayleigh scattering theory (Tenti et al. 1974; Young 1982) and is proportional to atmospheric density. Furthermore, the molecular extinction coefficient ($\sigma_M$) is resolved from the molecular backscatter coefficient though the relationship $\sigma_M(r) = \beta_M(\pi, r) (8/3)\pi$. The ACATS standard ATB is computed using the standard lidar expression [Eq. (3.2)]. The calibration constant ($C$) is computed by normalizing the signal to the molecular backscatter profile at high altitudes, where aerosol loading is weakest (Russell et al. 1979; Del Guasta 1998). This calibration technique is the well-accepted method of calibrating backscatter lidar signals and is used in CALIPSO and CPL retrievals (McGill et al. 2007). ACATS cloud- and aerosol-layer boundaries are determined using a similar method to CPL (Yorks et al. 2011b). The advantage of using this retrieval scheme is that the particulate layer properties can be obtained at higher resolutions, both vertically and horizontally, than using the HSRL retrieval algorithms. Therefore, this “standard” lidar method is used to compute ACATS attenuated total backscatter, as well as cloud and aerosol layer boundaries at a vertical resolution of 40 m and a horizontal resolution of 400 m (2 s).

### b. Development of HSRL algorithms

The ACATS HSRL retrieval algorithms are unique and different compared to the algorithms of current iodine filter HSRL systems (Hair et al. 2008). The inclusion of an etalon in the ACATS instrument design results in a more complicated ACATS lidar equation compared to the standard lidar equation and iodine filter HSRL equations. The etalon transmission function [Eq. (2.1)] is convolved with the standard backscatter lidar expression [Eq. (3.1)] to yield the expression for the number of photon counts detected per channel ($j$), as derived in McGill (1996):

$$N(r, j) = \frac{E_T A}{hc} O_A(r) A_T \Delta r Q_E T_0 T_F(\lambda) \frac{n(j)}{n_c} \times \sum_{n=0}^{\infty} A_{n,j} \sin(\frac{n}{N_{FSR}}) \exp\left(-\frac{\pi n^2 \Delta \lambda_L^2}{\Delta \lambda_{FSR}^2}\right) \left[\alpha(r) + \omega(r) \exp\left(-\frac{\pi n^2 \Delta \lambda_M^2(r)}{\Delta \lambda_{FSR}^2}\right)\right] \cos\left(2\pi n \frac{\lambda_0 - \lambda_c - 2U_{LOS}(r)\lambda_0 \sin\phi}{c \Delta \lambda_{FSR}} - \frac{j}{N_{FSR}}\right). \quad (3.3)$$

The first term represents the instrument parameters and the definitions of individual parameters are shown in the appendix. The second term contains the laser broadening $\Delta \lambda_L$ and molecular broadening $\Delta \lambda_M(r)$ terms, as estimated in McGill et al. (1997b), as well as the atmospheric physics. The molecular broadening requires knowledge of the atmospheric temperature at each range bin and is thus a function of range. The etalon calibration technique, described in section 2c, automatically compensates for any uncertainty in computing the laser broadening, since the laser width follows a Gaussian distribution similar to the etalon defect parameter. The attenuated particulate backscatter ($\omega$) and attenuated molecular backscatter ($\alpha$) are expressed as

$$\omega(\pi, r) = \beta_M(\pi, r) e^{-2\int_0^r \sigma_P dr}, \quad (3.4)$$

$$\alpha(\pi, r) = \beta_P(\pi, r) e^{-2\int_0^r \sigma_P dr}. \quad (3.5)$$

The Doppler shift is characterized by the second part of the third term, where $U_{LOS}$ is the LOS wind velocity in meters per second. The attenuated particulate backscatter, attenuated molecular backscatter, and LOS wind velocity are the three unknown variables in Eq. (3.3). Since there are 24 detector channels, the ACATS
system is an over-determined set of equations. These three unknowns are determined using a method developed by McGill et al. (1997c). First, the ACATS lidar expression [Eq. (3.3)] is linearized by expanding the relevant variables in a Taylor series. The equation is then written in matrix form as

\[
\Delta N = G \Delta x. \tag{3.7}
\]

An iterative weighted least squares fitting technique is employed to resolve these three parameters and their corresponding uncertainty, in which the solution is

\[
\Delta x_{\text{est}} = (G^T W G)^{-1} G^T W \Delta N, \tag{3.8}
\]

where \( W \) is the weighting matrix and \( G \) is the generalized matrix to be inverted. The solution for the molecular and particulate signals is linear, but nonlinear for the Doppler shift. This least squares fit method was tested and proven by McGill et al. (1997c) to retrieve the horizontal wind velocity. This work advances the effort of McGill et al. (1997b,c) using the definitions of attenuated particulate backscatter [Eq. (3.5)] and attenuated molecular backscatter [Eq. (3.4)] to develop HSRL retrievals of cloud and aerosol properties. The first step is to compute the molecular backscatter coefficient \( (\beta_M) \) and two-way transmission \( (T_p^2) \) from Rayleigh scattering theory and meteorological data from a World Meteorological Organization (WMO) upper-air station radiosonde closest in space and in time to the ER-2 flight track for each flight. The definition for the attenuated molecular backscatter [Eq. (3.4)] can be rewritten in terms of the two-way transmission, corrected for the slant path, and solved for the two-way particulate transmission \( (T_p^2) \) using

\[
T_p^2(r) = \left[ \frac{\omega(\pi,r)}{\beta_M(\pi,r)T_M^2(r)} \right] \cos \theta. \tag{3.9}
\]

Therefore, the two-way particulate transmission can be determined without making unnecessary assumptions about the lidar ratio, as in the Klett or Fernald method (Fernald et al. 1972; Klett 1972, 1985). The transmission form of the slant angle lidar equation is written in terms of \( T^\theta \), where \( y = \sec \theta \) (Spinhirne et al. 1980), thus to convert the 45° slant angle transmission to a vertical two-way transmission, and the \( \cos \theta \) exponent is applied to the ACATS transmission term. Once \( T_p^2 \) is known, the definition of the attenuated particulate backscatter [Eq. (3.5)] can be rewritten and used to directly retrieve the particulate backscatter coefficient \( (\beta_p) \) using

\[
\beta_p(\pi,r) = \frac{\alpha(\pi,r)}{T_p^2(\pi,r)}. \tag{3.10}
\]

The particulate optical depth is then

\[
\tau_p(r) = -\frac{1}{2} \ln[T_p^2(r)]. \tag{3.11}
\]

The particulate extinction coefficient \( (\sigma_p) \) is directly retrieved using the equation

\[
\sigma_p(r) = \frac{\partial \tau_p(r)}{\partial r}. \tag{3.12}
\]

and the particulate lidar ratio is

\[
S_p(\pi,r) = \frac{\sigma_p(r)}{\beta_p(\pi,r)}. \tag{3.13}
\]

This method is used to compute profiles and layer-integrated values of the aforementioned variables at a vertical resolution of 450 m and a horizontal resolution of 5 km (25 s). Their corresponding uncertainties are computed using propagation of errors. If high-resolution optical properties are desired, then the directly retrieved lidar ratio can be utilized as a parameterization to compute high-resolution optical properties using the Klett or Fernald method.
4. Initial results from WAVE campaign

During the period of 9–27 September 2012, ER-2 aircraft flights were conducted out of Wallops Island, Virginia, as part of the WAVE project. These flights were planned over land, targeting specific land and vegetation surfaces with a scientific objective of simulating Ice, Cloud, and Land Elevation Satellite 2 (ICESat-2) data using the Multiple Altimeter Beam Experimental Lidar (MABEL; McGill et al. 2013). ACATS was a payload on a total of 13 ER-2 flights, which included observations of thin cirrus clouds and smoke layers. During these flights, software directed the ACATS telescope to rotate counterclockwise to four look angle positions denoted by azimuth angle relative to the aircraft nose: 0° (fore), 90° (right), 180° (aft), and 270° (left). At each look angle, the dwell time was set for 60 s. The WAVE campaign represents the first science flights for the ACATS instrument in which the telescope rotated and more than one look angle was used. An example of the photon counts summed across all 24 detector channels at each of the four look angles from the 26 September 2012 flight is shown in Fig. 5 and demonstrates the ability of ACATS to observe cirrus clouds (between 10 and 12 km) at multiple look angles.

Overall, ACATS collected science data with a high signal-to-noise ratio (SNR) in at least one look angle during 8 of the 13 total WAVE flights. Because of limited time before the project, the telescope alignment was optimized only at the 270° look angle. This look angle was chosen as the “home” position of the telescope bearing and is thus most critical to align. The telescope alignment for the other three look angles was performed in the field using the in-flight telescope alignment procedure, but proved difficult because of a wobble in the telescope bearing. Portions of flights, and in some cases entire flights, were used to test and refine the etalon calibration procedure and telescope alignment. Furthermore, only two look angles were used for some flights if proper telescope alignment was not achieved at all four look angles. A new telescope bearing has been installed so that the telescope alignment and LOS wind retrievals will be improved during future ACATS flights. This study will focus on ACATS retrievals of cloud and aerosol properties from the WAVE project, particularly those at the 270° look angle and high-quality data from the other look angles.

There were several flights during WAVE in which ACATS collected quality data at multiple look angles. Perhaps the best ACATS performance was on the 26 September ferry flight back to Palmdale, California, when all four look angles were well aligned. Figure 6 shows the 532-nm ATB (km$^{-1}$sr$^{-1}$) computed using the standard method (Fig. 6a), the attenuated particulate backscatter (km$^{-1}$sr$^{-1}$) using the HSRL method (Fig. 6b), and the directly retrieved particulate extinction coefficient (km$^{-1}$) at the 0° look angle (Fig. 6c) for the flight on 26 September 2012. Clearly visible in these images are cloud layers observed by ACATS as the ER-2 flew over the Ohio River valley (2028:05–2130:00 UTC) and over North Dakota (about 0024:10 UTC). ACATS also measured a large smoke plume (0024:10–0210:00 UTC) that extended as high as 6 km over Montana. The images in Fig. 6 demonstrate the typical ACATS cloud and aerosol data products.

The extinction and backscatter values shown in Fig. 6 are typical for cloud and smoke layers and appear to be similar across retrieval methods. The cirrus clouds observed by ACATS over the Ohio River valley (2028:05–2130:00 UTC) had an ATB of greater than 0.02 km$^{-1}$sr$^{-1}$ and an extinction of 0.1 km$^{-1}$, with higher values of extinction (1–10 km$^{-1}$) at cloud base. The smoke plume...
(0024:10–0210:00 UTC) observed over Montana had an ATB of 0.003 km$^{-2}$ sr$^{-1}$ and an extinction of 0.1 km$^{-2}$, both fairly consistent throughout the layer. Also observed near the smoke plume were embedded cumulus clouds with higher values of extinction, about 10 km$^{-2}$. These values of ATB and extinction are consistent with coincident CPL data, which flew on the opposite ER-2 wing pod during the WAVE campaign. The CPL imagery from this project can be found at the CPL website (http://cpl.gsfc.nasa.gov).

The ACATS telescope alignment on the 14 September flight at the 270$^\circ$ look angle was the best for the entire campaign, making it a good case to assess biases in the two retrieval methods. Figure 7 shows the 532-nm ATB computed using the standard method (Fig. 7a) and using the HSRL method (Fig. 7b). The latter is essentially $\alpha + \omega$. Cirrus clouds between 9 and 13 km are observed throughout the flight. Figure 8 shows the mean profiles of 532-nm ATB computed using the standard method (blue) averaged to the resolutions of the HSRL products, as well as the ATB using the HSRL method (red) for the gray-shaded box in Fig. 7b centered around 2232:22 UTC. Both ATB profiles follow the modeled molecular profile closely above the cirrus layer and show similar structure inside the cirrus layer. The standard ATB
retrieval is 15% higher than the ATB computed using the HSRL method within the cirrus layer, within the combined uncertainty of both the retrievals. Above the cirrus layer, the standard ATB retrieval is about 5% lower than the HSRL ATB. Since the standard ATB retrieval was calibrated between 15 and 17 km, the slightly larger HSRL ATB may indicate the presence of particles. The error in the ACATS Rayleigh normalization calibration constant \( C \) from Eq. (3.2) is similar to the CPL calibration constant, estimated to be around 5% at 532 nm due to signal noise and the presence of aerosols in the upper troposphere (Campbell et al. 2008; Vaughan et al. 2010). Errors in the determination of the etalon defect parameter and HOE normalization values can lead to errors of 5%–10% in the HSRL-retrieved attenuated molecular and particulate backscatter. Although this comparison provides confidence in the ACATS HSRL algorithms, it does not resolve any possible instrument biases. To address this issue, the ACATS standard backscatter and HSRL products will be compared to coincident CPL cloud and aerosol properties during the WAVE campaign in the future.

5. Summary

A new multichannel direct-detection Doppler wind lidar has been developed at NASA GSFC for use on the NASA ER-2 called the Airborne Cloud–Aerosol Transport System (ACATS). ACATS employs a Fabry–Perot interferometer to provide the spectral resolution needed to retrieve the Doppler shift, similar to the ground-based University of Michigan MC direct-detection Doppler wind lidar (McGill et al. 1997b). The ACATS

![Fig. 7. The ACATS 532-nm ATB computed using (a) the standard method and using (b) the HSRL method at the 270° look angle for the ER-2 flight on 14 Sep. The gray box focuses on a 35-min segment in which the mean profiles are compared in Fig. 8 for cirrus clouds.](image)

![Fig. 8. The ACATS mean profiles of the 532-nm ATB computed using the standard method (blue) averaged to the resolutions of the HSRL products, as well as the ATB using the HSRL method (red) for the gray-shaded box in Fig. 7b (2211:43–2246:21 UTC).](image)
instrument design includes a seeded laser and circle-to-point converter, as well as a heating–cooling loop for stable laser performance during airborne operation. The ACATS telescope rotates to four look angles to permit the retrieval of the horizontal wind velocity within atmospheric layers. ACATS also advances the technology of an MC direct-detection Doppler wind lidar by demonstrating the utility of such an instrument for HSRL retrievals of cloud and aerosol properties.

The nature of an MC direct-detection Doppler wind lidar such as ACATS permits three types of cloud and aerosol lidar retrievals: standard backscatter lidar products, such as ATB and layer boundaries; directly retrieved cloud and aerosol optical properties, such as extinction and lidar ratio, using the HSRL technique; and the horizontal wind velocity of the cloud or aerosol particles within an atmospheric layer. This paper outlines the retrieval algorithms for two of these types of ACATS data products, focusing on the HSRL-derived cloud and aerosol properties. The first ACATS science flights were conducted during the WAVE project in September 2012. Initial results demonstrate the effectiveness of ACATS as an airborne HSRL system. The HSRL ATB retrieval for cirrus observed during the 14 September flight at the 270° look angle agrees with the ATB derived using the standard backscatter method to within 15%. Since the ISS CATS HSRL receiver is designed similar to ACATS, the algorithms and data products developed for ACATS have direct application to this future spaceborne mission. Furthermore, the ACATS HSRL and wind products can be used for science applications such as aerosol transport, smoke plume properties, and convective outflow in tropical storms.

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**APPENDIX**

**Definitions of Parameters Found in the ACATS Lidar Equation**

The appendix provides the definition and dimensions of the variables in the photon version of the lidar equation.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N(r) )</td>
<td>Number of photons detected per range bin</td>
<td>—</td>
</tr>
<tr>
<td>( r )</td>
<td>Distance to the scattering particle ( \text{m} )</td>
<td></td>
</tr>
<tr>
<td>( j )</td>
<td>Detector channel</td>
<td>—</td>
</tr>
<tr>
<td>( E_T )</td>
<td>Transmitted laser energy ( \text{J} )</td>
<td></td>
</tr>
<tr>
<td>( \lambda )</td>
<td>Laser wavelength ( \text{m} )</td>
<td></td>
</tr>
<tr>
<td>( h )</td>
<td>Planck’s constant ( \text{J sec} )</td>
<td></td>
</tr>
<tr>
<td>( c )</td>
<td>Speed of light ( \text{m sec}^{-1} )</td>
<td></td>
</tr>
<tr>
<td>( \Delta r )</td>
<td>Range bin width ( \text{m} )</td>
<td></td>
</tr>
<tr>
<td>( Q_E )</td>
<td>Detector quantum efficiency</td>
<td>—</td>
</tr>
<tr>
<td>( T_O )</td>
<td>System optical efficiency</td>
<td>—</td>
</tr>
<tr>
<td>( T_F )</td>
<td>Optical filter efficiency</td>
<td>—</td>
</tr>
<tr>
<td>( O_A(r) )</td>
<td>Overlap function</td>
<td>—</td>
</tr>
<tr>
<td>( p_\alpha(r, r) )</td>
<td>Particle backscatter phase function ( \text{sr}^{-1} )</td>
<td></td>
</tr>
<tr>
<td>( P_M(r, r) )</td>
<td>Molecular backscatter phase function ( \text{sr}^{-1} )</td>
<td></td>
</tr>
<tr>
<td>( B_r(r) )</td>
<td>Particle vol total scattering coefficient ( \text{m}^{-1} )</td>
<td></td>
</tr>
<tr>
<td>( \beta_M(r) )</td>
<td>Molecular vol total scattering coefficient ( \text{m}^{-1} )</td>
<td></td>
</tr>
<tr>
<td>( \sigma(r) )</td>
<td>Volume total extinction coefficient ( \text{m}^{-1} )</td>
<td></td>
</tr>
<tr>
<td>( B_D )</td>
<td>Thermal noise background signal</td>
<td>—</td>
</tr>
<tr>
<td>( B_S )</td>
<td>Solar background signal</td>
<td>—</td>
</tr>
<tr>
<td>( n_c )</td>
<td>Number of detector channels</td>
<td>—</td>
</tr>
<tr>
<td>( \eta(j) )</td>
<td>Detector normalization</td>
<td>—</td>
</tr>
<tr>
<td>( N_{\text{FSR}} )</td>
<td>Free spectral range (channel number)</td>
<td>—</td>
</tr>
<tr>
<td>( \Delta \lambda_{\text{FSR}} )</td>
<td>Free spectral range (wavelength) ( \text{m}^{-1} )</td>
<td></td>
</tr>
<tr>
<td>( \lambda_{\text{L}} )</td>
<td>Laser broadening 1/e width ( \text{m}^{-1} )</td>
<td></td>
</tr>
<tr>
<td>( \Delta \lambda_M )</td>
<td>Molecular broadening 1/e width ( \text{m}^{-1} )</td>
<td></td>
</tr>
<tr>
<td>( \alpha(r) )</td>
<td>Attenuated particulate backscatter ( \text{m}^{-1} \text{sr}^{-1} )</td>
<td></td>
</tr>
<tr>
<td>( \omega(r) )</td>
<td>Attenuated molecular backscatter coefficient ( \text{m}^{-1} \text{sr}^{-1} )</td>
<td></td>
</tr>
<tr>
<td>( \phi )</td>
<td>Off-nadir pointing angle ( \text{deg} )</td>
<td></td>
</tr>
<tr>
<td>( U_{\text{LOS}} )</td>
<td>LOS wind velocity ( \text{m sec}^{-1} )</td>
<td></td>
</tr>
<tr>
<td>( \Delta \lambda )</td>
<td>Spectral resolution of the etalon ( \text{m} )</td>
<td></td>
</tr>
<tr>
<td>( \lambda_0 )</td>
<td>Center wavelength of the etalon ( \text{m} )</td>
<td></td>
</tr>
<tr>
<td>( \lambda_c )</td>
<td>Center position of the laser line width ( \text{m} )</td>
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**REFERENCES**


Gentry, B., and C. L. Korb, 1994: Edge technique for high accuracy
Garnier, A., and M. L. Chanin, 1992: Description of a Doppler
Klett, J. D., 1981: Stable analytical inversion solution for pro-
Jensen, E. J., and Coauthors 2009: On the importance of small ice
Hovis, F. E., and Coauthors, 2004: Single-frequency lasers for
Fischer, K. W., V. J. Abreu, W. R. Skinner, J. E. Barnes, M. J.
Hall, F. F., Jr., R. M. Huffaker, R. M. Hardesty, M. E. Jackson,
Fiocco, G., G. Beneditti-Machelangeli, K. Maschberger, and
Comstock, J. M., T. P. Ackerman, and G. G. Mace, 2002: Ground-
——, 2001: Simulation of LIDAR returns from pristine and de-
Del Guasta, M., 1998: Errors in the retrieval of thin-cloud optical
Hovis, F. E., and Coauthors, 2004: Single-frequency lasers for
Pierson, P., and E. W. Eloranta, 1994: Demonstration of a high-
Russell, P. B., T. J. Swisler, and M. P. McCormick, 1979: Method-
Tenti, G., C. D. Boley, and R. C. Desai, 1974: On the kinetic model
description of Rayleigh–Brillouin scattering from molecular

Vaughan, M. A., Z. Liu, M. J. McGill, Y. Hu, and M. D. Obland,
2010: On the spectral dependence of backscatter from cirrus
clouds: Assessing CALIOP’s 1064 nm calibration assumptions
using cloud physics lidar measurements. J. Geophys. Res., 115,

Winker, D. M., 2003: Accounting for multiple scattering in re-
treivals from space lidar. Lidar Scattering Experiments,
C. Werner, U. Oppel, and T. Rother, Eds., International So-
ciety for Optical Engineering (SPIE Proceedings, Vol. 5059),

Yorks, J. E., D. L. Hlavka, W. D. Hart, and M. J. McGill, 2011a:
Statistics of cloud optical properties from airborne lidar
measurements. J. Atmos. Oceanic Technol., 28, 869–883,

Zhao, Y., G. G. Mace, and J. M. Comstock, 2011: The occurrence
of particle size distribution bimodality in midlatitude cirrus as
inferred from ground-based remote sensing data. J. Atmos.