DEVELOPMENT OF THE HAMPTON UNIVERSITY LIDAR SYSTEM AND THE CREST LIDAR NETWORK

Kevin Leavor
Advisor: Dr. M. Patrick McCormick
Hampton University, Department of Atmospheric and Planetary Sciences, 23 Tyler St., Hampton, VA, 23668

Abstract

As a remote sensing technique, lidar is a staple of atmospheric measurement techniques. Short-wavelength scattering allows measurements from molecular and particle or aerosol components of the atmosphere. These features are of particular importance to studies of weather, climate, and the underlying radiative transfer processes that drive them. Furthermore, these quantities or the scattering processes themselves may be linked to other quantities, such as temperature, which can then yield dynamic and thermodynamic information about atmospheric layers, such as the planetary boundary layer, and the general atmosphere. Hampton University, in order to further knowledge and understanding of the atmosphere, air quality, climate, and lidar techniques, continues to make lidar measurements of aerosols and clouds, but has also added rotational Raman temperature sensing to its list of capabilities. Furthermore, its steps to develop and join a network of similar lidar stations in the United States and the rest of the world have advanced into a regime of simultaneous measurements between a number of stations. Finally, an automated satellite observation program for tracking volcanic emissions is presented to showcase the possibilities of combining measurements from multiple satellites with ground-based measurements.

Introduction

Light Detection And Ranging, or lidar, is a critical atmospheric remote sensing technique. Like its analog, radar, lidar provides a means to measure atmospheric properties at range, thus avoiding the necessity of placing an instrument in situ for observations. Retrieved quantities include extinction and backscatter coefficients, temperature, or number densities of specific atmospheric constituents such as ozone, water vapor, or aerosols. The last of these is exceedingly important to understanding the atmosphere, weather, and climate, since they are highly variable and poorly understood, especially in comparison to many other atmospheric properties [IPCC, 2007]. Furthermore, these aerosols, especially those of small sizes, can pose serious risks to human health, particularly in the young, elderly, or those with existing health conditions [U.S. EPA, 2004].

Lidar’s has a number of strengths making it ideal for atmospheric remote sensing measurements. First, lidar is an active remote sensing technique, a laser provides a light source, allowing for measurements even in the absence of an external source of radiation. Second, lasers having high repetition rates and short pulsewidths allow for incredibly high-resolution measurements in range, often on the order of tens of meters or better. Third, the incredibly narrow wavelength band of radiation emitted by a laser provides the ability to tailor the equipment to the measurement of specific quantities that may be uniquely active at those wavelengths. For these reasons, Hampton University utilizes a lidar for atmospheric measurements of aerosols, water vapor, and temperature.

Additionally, while lidar provides highly-resolved ranged and temporal measurements, ground stations such as Hampton University’s are typically stationary, and even mobile ground-based lidar stations are limited in spatial scope and have an implicit dependence between location and time. To overcome these limitations, Hampton University has made efforts to join and develop the Center for REmote Sensing Technology (CREST) Lidar Network (formerly the Regional East Lidar Mesonet or REALM). A number of US East Coast lidar stations have agreed to take simultaneous measurements at prescribed times in order to measure atmospheric quantities not only in range and time but also in space along the path connecting them.

As an added measurement of aerosols, Hampton University is closely related to the Cloud-Aerosol Lidar and Infrared Pathfinding Satellite Observation (CALIPSO). This space-based, Earth-orbiting satellite provides global lidar measurements from a sun-synchronous, polar orbit. To better understand and observe aerosols locally and in regards to the lidar network, a volcanic aerosol monitoring project has been instated. Volcanic activity is monitored on a weekly basis, and CALIPSO and other satellite observations are used to monitor volcanic aerosols.
which may, after transport, be seen later over Hampton University.

These studies aim to provide a continuation of work presented previously regarding aerosol and water vapor measurements taken over Hampton University and its efforts to become part of a forming lidar network. New measurements of aerosol extinction are presented, with an emphasis on long-duration measurements extending through day-night cycles. Furthermore, newly added measurements of temperature are also presented. Additional information regarding the recent formation of the CREST lidar network, its goals, and operating procedures are also detailed herein. Finally, the automated volcanic observation system implemented at Hampton University is described and results presented.

**Lidar Methodology**

Lidar can be considered a three-part remote sensing technique. As an active remote sensing technique, a laser acts to transmit electromagnetic radiation into the atmosphere. Molecules and particles scatter this radiation, and a receiver collects backscattered photons. The collected photons are then counted and digitized using a data acquisition system connected to the receiver. The positioning of these components and the types of scattered photons measured determine the type of lidar.

Hampton University’s lidar system is a monostatic orientation in which the laser is transmitted at the same location that the receiver collects scattered photons. Table 1 lists the lidar system’s specifications. From the three transmitted wavelengths (1064, 532, and 355 nm), aerosol extinction coefficients are determined from elastic backscatter measurements. In addition, vibrational Raman scattering measurements are taken to determine water vapor mixing ratio, while rotational Raman scattering is used for temperature profiles. Both Raman techniques use the 355 nm wavelength as the fundamental scattering wavelength.

Each wavelength of measured light is separated through a series of beam splitters and interference filters in order to decrease the amount of solar background noise measured by the detectors. For normal operation, profiles are generated as 2000 shot averages of return signals, corresponding to 100 s of operation. To derive atmospheric parameters, these signals are then rebinned based on wavelength in both time and range in order to increase the number of counts per bin and decrease noise. Descriptions of elastic backscatter aerosol extinction and Raman temperature retrievals are given in the following sections.

**Elastic Backscatter**

Elastic backscatter lidar refers to lidar which measures photons that have been scattered without losing energy. Elastic scattering, as a result, preserves the wavelength of the transmitted photons.

The fundamental governing equation for elastic backscatter returns is the lidar equation:

\[
P(R) = P_0 \eta \left( \frac{A}{R^2} \right) \left( \frac{c \tau}{2} \right) \beta(R) \exp \left[ -2 \int_0^R \alpha(r) \, dr \right]. \tag{1}
\]

\(P(R)\) is the power of the return signal from range \(R\), \(P_0\) is the transmitted laser power, \(\eta\) is system efficiency, \(A\) is the receiver’s effective area, \(c\) is the speed of light, \(\tau\) is the laser’s pulse duration, \(O(R)\) is an overlap factor between the receiver’s field of view and the scattered photons indicating the amount of laser light scattering that is within the telescope’s field of view with a value between 0 and 1, \(\beta(R)\) is the backscatter coefficient of the atmosphere at range \(R\) indicating the probability of light being scattered into the field of view of the telescope, and \(\alpha(r)\) is the atmospheric extinction coefficient at range \(r\) indicating the probability of light being attenuated by the atmosphere.

The first few terms are typically constant, so it is often more useful to write Equation 1 in the form

\[
P(R) = C \left( \frac{O(R)}{R^2} \right) \beta(R) T(R), \tag{2}
\]

where

\[
C = P_0 \eta \left( \frac{c \tau}{2} \right) A \tag{3}
\]

\[
T(R) = \exp \left[ -2 \int_0^R \alpha(r) \, dr \right]. \tag{4}
\]
Equation 5 is commonly referred to as the “Lidar Constant,” and Equation 4 is the lidar transmission, or the probability of photons returning to the telescope along the path from the telescope to the scattering point and back.

In its earliest uses, lidar has been used to detect atmospheric aerosol particles [Fiocco and Smullin, 1963]. Unfortunately, the lidar equation has two unknowns related to atmospheric properties: $\alpha$ and $\beta$, with no separate equation providing more information to solve for one of them. However, techniques have been developed to separate and measure these quantities. First, a few useful constructs are

\[
\alpha(R) = \alpha_a(R) + \alpha_m(R) \tag{5}
\]

\[
\beta(R) = \beta_a(R) + \beta_m(R), \tag{6}
\]

where the subscripts “a” and “m” denote aerosol and molecular components of extinction and backscattering, respectively. Another quantity,

\[
L_a(R) = \frac{\alpha_a(R)}{\beta_a(R)} \tag{7}
\]

\[
L_m(R) = \frac{\alpha_m(R)}{\beta_m(R)} = \frac{8\pi}{3} \text{ sr} \tag{8}
\]

is known as the lidar ratio or extinction-to-backscatter ratio. Knowing the lidar ratio and either extinction or backscatter coefficients will yield the other. Note that the molecular lidar ratio is constant with both range and wavelength.

Finally, Equation 1 may be simplified by substituting

\[
Y(R) = L_a(R) \left[ \beta_a(R) + \beta_m(R) \right]. \tag{9}
\]

Equation 9 is known as the normalized total backscatter coefficient [Sasano et al., 1985].

Substituting Equations 8, 7, and 9 into Equation 1 to replace the extinction coefficient terms $\alpha_a$ and $\alpha_m$ yields

\[
X(R) L_a(R) \exp \left\{ -2 \int_0^R \left[ L_a(r) - L_m \right] \beta_m(r) \, dr \right\}
\]

\[= CY(R) \exp \left( -2 \int_0^R Y(r) \, dr \right), \tag{10}\]

where the additional substitution

\[X(R) = R^2 P(R),\tag{11}\]

known as the range-corrected lidar signal, has been made. Differentiating the logarithm of both sides of Equation 10 produces a Bernoulli differential equation with solution

\[
\beta_a(R) + \beta_m(R) = 
\]

\[
X(R) \exp \left\{ -2 \int_0^R \left[ L_a(R) - L_m \right] \beta_m(r) \, dr \right\}
\]

\[\frac{X(R_0)}{\beta_a(R_0) + \beta_m(R_0)} - 2 \int_0^R L_a(r) X(r) T(R_0, r). \tag{12}\]

using the boundary condition

\[Y(R_0) = L_a(R_0) \left[ \beta_a(R_0) + \beta_m(R_0) \right]. \tag{13}\]

Thus if the extinction and backscatter is known at a reference range, and the lidar ratio is known, the backscatter, and thus the extinction, can be determined throughout the entire profile. Equation 12 is commonly referred to as the “Fernald method” for determining lidar extinction and backscatter [Fernald, 1984].

Raman Temperature Sensing

Unlike elastic backscatter lidar, Raman lidars make use of inelastic scattering processes from molecules which results in wavelength shifts from the fundamental wavelength. These shifts have the benefit of being unique to the scattering molecule, and furthermore, the shifts are constant in the wavenumber domain.

Rotational Raman scattering refers to scattering in which energy absorbed from a photon causes an excitation in the molecule’s rotational state. The strength of these rotational scattering lines is directly dependent upon temperature. The intensity of a rotational Raman branch is given by

\[I = Ab J g_J (2J + 1) \exp \left[ -\frac{\beta h c}{kT} J(J + 1) \right], \tag{14}\]

where $A$ is a normalization constant, $b_J$ is the relative line strength, $g_J$ is the nuclear spin weight, $\beta$ is the molecular rotational constant, $k$ is Boltzmann’s constant, $c$ is the speed of light, $J$ is rotational quantum number, $T$ is temperature, and $h$ is Planck’s constant [Cooney, 1972]. Two Raman signals are used and ratioed, one on-peak and one off-peak. Hampton University uses rotational Raman scattering at 354.2 nm and 353.35 nm. This ratio is then normalized to a reference temperature, generally from a balloon sounding at Wallops Island, VA.

The method presented by Behrendt and Reichardt [2000] is used by Hampton University in order to derive temperature from the Raman scattering signals. This method serves to minimize the noise generated by the inversion technique. The ratio, $R$, of the 353 nm to 354 nm signal is fit to the function

\[R(T) = \exp \left( \frac{a}{T^2} + \frac{b}{T} + c \right), \tag{15}\]

which when inverted yields

\[T = \frac{-b \pm \sqrt{b^2 - 4a(c - \ln(R))}}{-2a}, \tag{16}\]

where the negative discriminant in Equation 16 is expected to yield the physical solution.
The following sections present the results to date of Hampton University’s aerosol and temperature sensing endeavors, as well as the development of the CREST lidar network. Additionally, preliminary proof of concept of an automatic volcanic emissions tracking system are shown in the final section.

Aerosols

Hampton University has begun a series of long-duration lidar measurements in order to gauge day-to-day differences in aerosols, general structure of aerosols in the atmosphere over Hampton Roads, and changes in aerosols during daytime and nighttime. These measurements range on the order of 12+ hours in length, a number of these extending 24+ hours. Results are rebinned according to wavelength, with 1064 nm extinction rebinned on a 2x2 vertical x temporal grid, 532 nm extinction on a 5x4 grid, and 355 nm on a 10x4 grid. For reference, these correspond to 15 m vertical resolution by 200 s temporal resolution for 1064 nm, 45 m vertical resolution by 400 s temporal for 532 nm, and 75 m vertical resolution by 400 s temporal for 355 nm. 1064 nm aerosol extinction coefficient results will be presented below.

Figure 1 shows aerosol extinction coefficients at 1064 nm taken at Hampton University on March 19, 2010 for a record of over 10 hours. Thin, multilayer clouds can be seen developing from mid-afternoon into evening. The upper layer can be seen ascending over a two hour period before descending later. A low-level aerosol layer beginning at approximately 15:30 can also be seen descending from 4 km down to two as the afternoon wore on into evening. During the late evening, this layer increased intensity.

Figure 2 shows another time series of vertical profiles of aerosol extinction coefficients at 1064 nm. This record is much longer, spanning 34 hours, extending from April 1-2, 2010. Dense aerosol coverage is visible extending well through and above the planetary boundary layer. Sporadic cloud cover is also visible from 10 km upward. A very intense aerosol layer developed from 3 AM local time on April 2 at an altitude of approximately 2 km. This layer persisted for over 9 hours, first intensifying before dissipating just before 13:00. Also visible from this extended record are a number of thin, higher-altitude cloud layers below 10 km. This feature is visible during both April 1 and 2. This pattern is mimicked in the lower-altitude aerosol layers seen around 5-6 km.

Temperature

Coinciding with the above results, Hampton University has also produced vertical temperature profiles using the Raman temperature methods described previously. Temperature data is binned 50x15 on a vertical x temporal grid to increase counts per bin and decrease noise, corresponding to 187.5 m vertical resolution and 25 min temporal resolution. Measurements typically have a maximum altitude of between 8-10 km during nighttime and 4-6 km during daytime.

Figure 3 shows an example plot of lidar-retrieved vertical temperature profiles at Hampton University at 20:00 EST on April 2, 2010 in comparison with the corresponding Wallops Island balloon sounding at the same time. While there is significant deviation at low altitudes, as is
to be expected due to the different geographical qualities of the two sites and lidar overlap considerations, there is also a significant warming at higher altitudes as well in the lidar-retrieved profile. However, taken into consideration with Figures 2 and 4 there is significant aerosol loading over Hampton University at the time of this temperature profile. As aerosols contribute to atmospheric absorption of radiation, they contribute to atmospheric warming in the aerosol-laden region. This is clearly visible as areas with significant warming or strong inversions in Figure 3 strongly correlate to regions in which aerosol layers are present in Figure 4.

In contrast, as an island-based station close to the ocean, Wallops is more likely to exhibit cleaner air, especially at higher altitudes, which explains the difference in temperature and structure between the two profiles. In clean air regions, such as near 6 km, the lidar profile tends toward the Wallops profile before attenuation degrades the signal between 6-8 km.

CREST Lidar Network

In February 2009, Hampton University joined with City College of New York (CCNY), University of Maryland, Baltimore County (UMBC), and University of Puerto Rico, Mayagüez (UPRM) to form the CREST Lidar Network. Consisting of five lidar systems along the East coast of the US, the CREST network aims “to provide the nation with aerosol and trace gas profiling in the lower atmosphere in significant areas of the country in order to help NOAA NESDIS STAR validate its observations from satellites, to help NOAA NWS validate its forecast models of aerosols, ozone and weather, and to help NOAA NCDC in the creation of long term climate data records of the lower atmosphere” (Hoff et al., 2009).

The CREST Lidar Network will add to the Global Atmosphere Watch’s (GAW) GAW Atmospheric Lidar Observation Network (GALION). GALION serves as a global network of ground-based lidar systems, adding a spatial component to otherwise stationary measurements (Bösenberg et al., 2008).

As of January 2010, all stations have committed to simultaneous measurements on a routine schedule. These lidar observations are synchronized to Mondays near solar noon, Monday evenings through two hours after dusk, and Thursday evenings through two hours after dusk, with the total data collection exceeding at last 5 hours. Additionally, these data are made available through each center’s website. To date, Hampton University’s data are ready and the distribution site is under development using a similar template to its AIM data product page found at http://aim.hamptonu.edu/sds/index.html.

Volcanic Observations

An automated system to track volcanic activity and plot relevant data has been developed at Hampton University to supplement its lidar studies. This system takes input from The weekly CAP feed from the Smithsonian Institute’s Global Volcanism Program (http://www.volcano.si.edu). This feed is downloaded and a Perl script parses it for volcano names, locations, and dates of activity. The active volcanoes are then plotted for reference based on this information, an example of which is shown in Figure 5.

These volcanoes are written to a queue file which keeps track of all volcanoes and dates to be run as data are made available. Currently, CALIPSO, FORMOSAT-3, OMI, and MODIS are used for data processing.
Figure 5: A plot of all volcanic activity for the week from March 18, 2009 to March 24, 2009 generated from the Smithsonian Institute’s Global Volcanism Program feed.

Figure 6: A curtain plot of CALIPSO 532 nm total attenuated backscatter. The data are taken following Redoubt’s March 2009 eruption.

CALIPSO provides vertical profiles of lidar backscatter, FORMOSAT-3 vertical temperatures of water vapor mixing ratio and temperature via GPS occultation, OMI measurements of sulfur dioxide and aerosol optical depth, and MODIS contextual images and aerosol optical depth. CALIPSO and FORMOSAT data are stored on Hampton University’s Center for Atmospheric Science data servers. OMI and MODIS data are downloaded as required and available. A final routine plots these data for each volcano and instrument.

Figures 6, 7, and 8 show example data from the March 22-23 eruptions of Mount Redoubt. Figure 6 shows a curtain plot of CALIPSO total attenuated backscatter for the 532 nm channel. An elevated level of backscatter is visible amidst low clouds, indicating the presence of aerosols near the surface due to Redoubt’s emissions. Figure 7 shows a composite of OMI total column sulfur dioxide content from its mid-troposphere center of mass product (TRM) for March 23-25 during Redoubt’s eruption. The East-Southeast transport is visible, as are the multiple distinct peaks corresponding to separate eruption events. Finally, Figure 8 shows a FORMOSAT temperature profile taken over the same location as Figure 6 a few hours earlier. The typical, near-linear decrease of temperature with altitude is disturbed by inversions both near 3 km and 10 km due to aerosol absorption features as suggested by the CALIPSO curtain plot.
Conclusions and Future Work

The presented research illustrates many of the strengths lidar offers to atmospheric science. High resolution profiles of atmospheric properties, such as aerosol extinction coefficients and temperature highly detail some of the more transient atmospheric properties related to weather and climate. The lidar network and the addition of satellite measurements supplements and alleviates some of the weakness of ground-based lidar stations.

A remaining limitation is noise reduction in retrieved lidar signals. This is commonly alleviated by a high degree of multi-shot averaging and rebinning as indicated earlier. However, as a counting process, signal-to-noise can, at best, improve only as a factor of the square root of the number of counts. Furthermore, to level the signal the background level subtracted to normalize the signal to what should be the component due solely to the laser. In doing so, any variance due to the background is still left retained by the signal.

Data close to the noise level can be obscured by the random fluctuations in the data. This is especially true once signals become weak, such as higher altitude Rotational Raman temperature retrievals as evidenced in Figure 3. Furthermore, the Fernald method utilizes a reference altitude at which the aerosol extinction is known. As this is typically determined by way of an atmospheric clean point, that is a point with little to no aerosols, noise can potentially influence the selection of this reference region. However, a number of new techniques can aid in noise reduction and feature identification.

Wavelet analysis has been used frequently in data reduction due to its ability to maintain information in a signal without degrading the energy it contains. It also serves as a means to model nonlinear signals. Wavelet has been successfully applied to lidar signals as a means of determining low frequency components such as the height of the planetary boundary layer [Davis et al., 2000]. This technique, however, uses a simple Haar wavelet with a square wave mother. A slightly more complex Daubechies wavelet may be more appropriate both for noise reduction and feature identification, as layered atmospheric features, while typically displaying strong gradients in lidar signals, do not necessarily turn on and off sharply, and the Daubechies waveform may be more apt to determining noise with altitude.

Another technique, the Hilbert-Huang Transform (HHT) is another signal processing technique developed primarily for the treatment of nonlinear and nonstationary data [Huang et al., 1998]. The technique determines intrinsic mode functions (IMFs) derived explicitly from the data using a method known as empirical mode decomposition. These IMFs are generated from highest frequency to lowest frequency until some threshold is reached. The IMFs have the property that their summation with nearly no loss of information, if at all. As noise processes in lidar signals will typically be much higher frequency than other atmospheric information, omission of the high frequency components can effectively remove the signal’s noise while retaining much of the signal’s information by recombining the remaining IMFs.

As the boundary layer, clouds, and aerosol layers are all important to understanding dynamic and radiative effects on climate, these potential improvements to lidar retrievals could produce new information and clearer understanding from lidar profiles.

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