# LIDAR measured vertical atmospheric scattering profiles

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## Abstract

The vertical structure of the atmosphere, which is of invaluable interest to meteorologists, geo-physicists and environmental researchers, can be measured with LIDAR. A method has been proposed and applied to invert lidar signals from vertical soundings to height resolved scattering coefficients. In situ measurements have confirmed the applicability of this lidar technique. A fully computer controlled lidar system allows the study of the dynamic behaviour of the atmospheric mixing layer.

## Introduction

The lidar technique (LIght Detection And Ranging), based on the detection of scattered light from atmospheric particles, provides a unique method for the remote sensing of the atmosphere at the appropriate wavelengths up to tens of kilometers [1]. Both meteorologists, physicists and environmental scientists are interested in this method since the range and area which can be scanned within limited time, are large compared to conventional local monitoring equipment. Atmospheric, range resolved parameters which can be measured with lidar are e.g. scattering properties, temperature, pressure, wind velocity and wind direction, cloud height and gas concentrations.
In this paper some features of a small lidar system, used for atmospheric investigation, are presented. A selection of the more common inversion techniques is reviewed. These are applied to the determination of the horizontal and the slant path visibility and the vertical atmospheric structure. The time development of the mixing layer is visualized by routinely measuring the vertical structure over periods of days.
Vertical lidar data have been verified by airborne measurements of the appropriate parameters. The results confirm that lidar is a useful tool for vertical probing of the atmosphere.

## Lidar model and inversion techniques

The basic single scattering model for lidar returns (1) has already been described by Collis [2] in 1966 and is still in use. It describes the amount of radiation returned from an intense light pulse (transmitted into the atmosphere) as a function of range P(r), system constant C and atmospheric backscatter and extinction coefficients B(r) and A(r):

$$(1) \quad P(r) = C * B(r) * \exp\left[ -2*\int_0^r A(x)\,dx \right] / r^2$$

At this point a distinct difference can be made between homogeneous and inhomogeneous atmospheres. In the first case, which often occurs when measuring in the horizontal direction, the r dependency of A and B vanishes and the calculation of both parameters is possible, provided the system constant C is known. The calculation method to invert A and B, which expire via the slope of the natural logarithm of the range corrected signal, is often called the slope method [3].
The extinction coefficient A and the backscatter coefficient B are dependent on the aerosol properties. Thus far no mathematical problems are met and a good method is available to test the realibility of lidar systems.
By performing measurements in a non horizontal direction, one will often be confronted with signals from inhomogeneous atmospheres. In this case an inversion method for both A and B as a function of range is needed since two unknowns are to be derived. Additional information is required which can be acquired by lidar itself or other equipment. Several methods exist which solve the problem more or less, each with its appropriate advantages and disadvantages.
One method, described by Spinhirne [4], is to perform lidar measurements under different angles of elevation and assuming that the atmosphere is stratified horizontally. The additional transmission losses in the same height interval, measured under a smaller elevation angle, is ascribed to the extinction coefficient. Substituting this value in the lidar equation yields the backscatter coefficient. This iterative process is continued until one of the two signals vanishes in the noise and the maximum elevation angle is reached. The disadvantage of this method is that the measurements have to be performed under sequential elevation angles in limited time, to maintain the coherence between the signals.
A second method is the assumption or an independent measurement of the relation between A

and B. Together with equation (1) this yields two equations from which it is possible to invert the lidar signal numerically, provided the constant C is known and the signal P(r) is available from zero range. As in most cases the last condition is almost never met, an inversion technique is applied which is equivalent with the one used by Hitschfeld and Bordan [5] in 1954 for rain rate calculations from radar signals. This method has also been mentioned by Collis [3] in 1969. Assuming a linear or exponential relation between the extinction and the backscatter, a differential equation of the kind of Bernoulli, leads to a solution in the form of an integral equation described in (2):

$$A(r) = \frac{S(r)}{\frac{S(ro)}{A(ro)} - \frac{2}{k} * \int_{ro}^{r} S(x)\,dx} \qquad (2)$$

in which:

$$S(r) = \exp\left[ \frac{\ln( P(r) * r * r ) / C}{k} \right]$$

$B(r) = c * A(r)$
k = exponent in the relation B and A
ro = start of the calculations
A(ro)= input boundary value for the extinction

Although this equation has been worked out for the extinction A, it is also possible to deduce an analoguous formula for the backscatter coefficient B.

Some remarks have to be made at this point:

1. the lidar system needs not to be calibrated in an absolute sense
2. an input boundary A(ro) (or B(ro)) is needed to solve the equition
3. a relation between A and B must be available
4. a singularity in the inversion can occur for $ro<r$; either caused by noise in S(r) or an error in A(ro).

To overcome the last problem, Klett [6] suggested to change the sign in the denominator and the direction of integration. However, then the input boundary Ao must be available at the far end of the lidarsignal where the signal to noise ratio is worst and therefore difficult to determine. The advantage of this method is that in very turbid conditions, the result converges rapidly to the correct value as the integral dominates. However it is doubtful whether the situation of large optical depth is met in practical measurements.
In the majority of cases equation (2) can be solved with the forward integration method Kunz [7]. An input boundary condition Ao is substituded which is measured horizontally in the lower (homogeneous) part of the atmosphere by means of the same lidar system. The solution is independent of the integration direction, provided the input boundary is correct.

## Validation of the method

To test the validity of lidar derived profiles, a trial was organized, to compare lidar results with airborne in situ measurements. This test was carried out as a joint collaborative effort between institutes from UK, US, Denmark and the Netherlands, following a proposal made by the Atmospheric Sciences Laboratory, White Sands, NM. The Physics Laboratory TNO participated with a small lidar system, operating at 1060 nm. Some examples of vertical profiles, obtained using the forward integrating method, are presented in Figure 1. The solid lines represent the airborne visibility meter results, while the lidar data are dashed. The horizontal axis represents the extinction coefficient in 1/km on logarithmic scale. The vertical axis represents the height in m above groundlevel. The visibility meter results are converted to extinctions by means of the relation derived by Loehle [8].

A represents a vertical homogeneous atmosphere.
B represents a ground haze situation, where the extinction up to 100 m is a factor of 5 larger than above 200 m.
C represents a gradient in the extinction up to the cloud base.
D presents the results of a low stratus cloud.

Lidar derived profiles compare well when the extinction coefficient is slowly varying with altitude. When clouds are present with large extinctions, the penetration depth of the laser light and the length of the laser pulse become comparable. This effect becomes noticable when the extinction is larger than 10 1/km. Extinctions larger than 50 1/km are indistinguishable. Due to this effect the signal cannot be inverted reliably. Either this will generate a singularity in the solution within the cloud or that part of the profile will be incorrect. However in the majority of the cases a good correlation was found between the lidar derived profiles and the results of the balloon borne instruments.

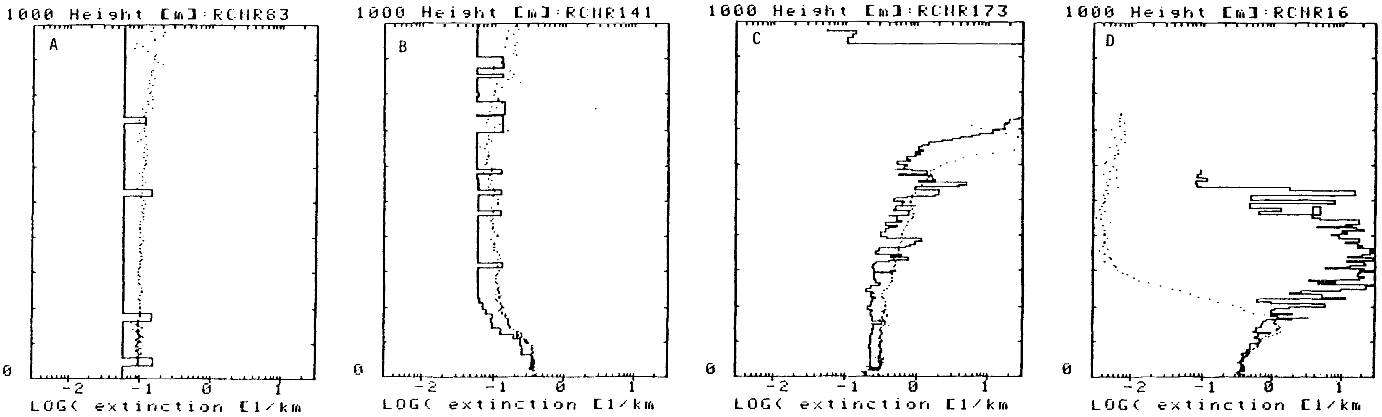


Figure 1: Examples of lidar derived extinction profiles (dashed) and airborne AEG visibility meter derived profiles (solid line) for different weather conditions.

## Marine vertical structure

To characterize the optical properties of the marine atmosphere, experiments have been performed aboard MS Cumulus in May/June 1983, at 57 N, 20 W at the North Atlantic Ocean. Besides aerosol equipment, a visibility meter, and instruments to measure meteorological parameters, a mini-lidar was installed to measure the marine vertical extinction profiles at a wavelength of 1060 nm. These profiles were measured automatically from sea level to a height of about .5 km. An example of a lidar derived vertical marine extinction profile is shown in figure 2.

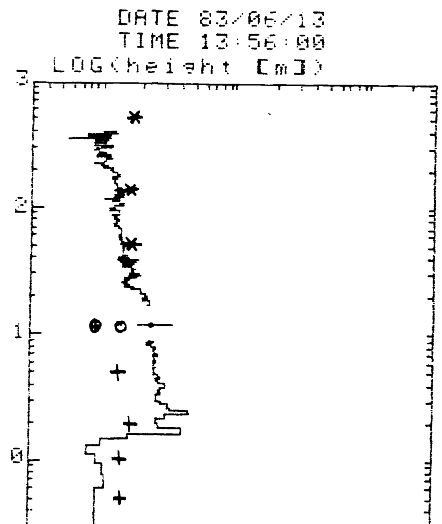


Figure 2: Vertical atmospheric extinction profile at the North Atlantic measured by lidar aboard a ship. The * signs indicate the results derived from airborne aerosol measurements; the + signs and the O sign indicate extinction coefficients calculated from shipboard aerosol measurements

Both the extinction and height on respectively the horizontal and vertical axes, are represented on log-scale. At altitudes between 1 and 4 meters, sea wave reflections can be seen. The signal below this level should be neglected because it is caused by the detector response due to intense reflections. The horizontal extinction 11 m height represents the results of the horizontal measurement at ship-deck level. This profile is representative for the structure during a period that airborne aerosol measurements were performed by means of impactor rods as well. The Mie calculated exticion coefficients derived from these results are indicated by * signs. Also data are available derived from shipboard aerosol measurements with optical particle counters and impactor rods. These are represented respectively by + and O signs. Due to differences in sampling time and measurement principle, some differences in the results are possible. At some occasions during the experiment the atmosphere over the ocean was so pure, that the lidar could not detect enough scattering to calculate a useful profile.

## Profile measurements over a longer period

By performing lidar measurements over a longer period, a history of the vertical structure is obtained. It has been observed that the atmospheric scattering profiles can change within several minutes without a noticeable change of temperature, wind or pressure. This may be caused by a change in origin of the air mass. An example of vertical profiles measured during a whole day is presented in Figure 3.

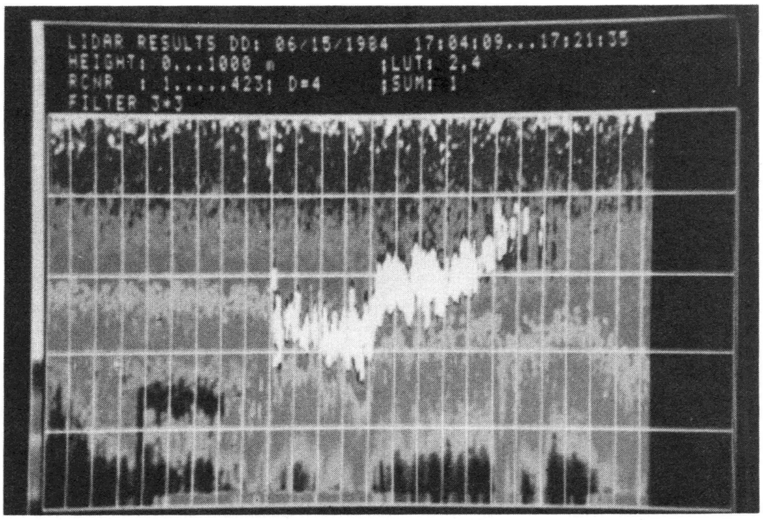


Figure 3: Time dependency of the vertical extinction profile on 15/16 June 1984. The heigt, on a linear scale from ground level up to 1000 m, is plotted along the y axis; the time over a period of 24 hours is plotted along the x axis. Color coded extinction coeffients are represented here in gray values. The white vertical bars indicate an hourly clock.

The time of the day is set along the horizontal axis; the vertical axis reprsents the heigth on a linear scale from ground level to 1000 m. The value of the scattering coefficient is normally presented in color but here printed in black and white. The extinction coefficient is calculated in a range between 0.03 and 30 1/km and pltted on a log scale. (By scaling in a linear way, more structure can be observed.) Black means low scattering; white means a high amount of scattering. The time scale on the horizontal axis runs from 17:04 to 17:21 the next day. During sunset, the mixing depth decreases while at groundlevel the extinction is increasing. At 02:00 cloudsare formed with cloud base at 500 m height which rises during sunrise (06:00) and vanishes at noon. Some structure in the boundary layer is seen during the rest of the day at about 400 m height. The changes up to 100 m during the whole period is observed.

## Conclusion

Single ended lidar measurements under positive elevation angles provide an excellent way of exploring the vertical structure of the atmosphere. The results are not only of importance for meteorological sciences but also for avionical and environmental purposes. Verification with baloon borne results indicate the validity of the forward integration method and reveals the limitations during some special atmospheric cicumstances. Vertical atmospheric structure measurements will be performed at the Physics Laboratory TNO, in conjunction with meteorological observations and acoustic sounder, on a routine base, to evaluate models of the vertical atmospheric scattering structure.

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