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Atmospheric analysis techniques at HiRes

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Abstract. To fully exploit the atmospheric fluorescence technique it is necessary to understand both the attenuation and scattering properties of the atmosphere within the detector aperture. The need to understand these properties instantaneously over a large area (4000 km^2) presents a considerable challenge. This paper will present techniques used at HiRes to characterize the atmosphere, based on the analysis of steerable laser systems located at both HiRes detectors.

1 Introduction

For the purpose of atmospheric fluorescence measurements the atmosphere is comprised of two main components: the molecular atmosphere and aerosols. The molecular atmosphere, comprising mainly nitrogen and oxygen, has absorption and scattering properties that are well understood and are stable with only small variations due to height dependent changes in temperature and pressure. The properties of the aerosols, in contrast, are known to be highly variable on short time-scales. The aerosols have a wide range of sources, from dust and sand to cloud, smoke and man-made pollutants. The density at ground level, vertical distribution and the scattering and absorption properties of the aerosols can all change within one night of observing. Atmospheric monitoring at HiRes is, therefore, an attempt to understand the time dependent distribution of aerosols in the detector aperture.

The HiRes experiment has two fluorescence detectors (HiRes-1 and HiRes-2), located at sites separated by 12.5 km. At HiRes the majority of atmospheric characterization is done with steerable laser systems located at each of the Fluorescence detectors (Wiencke et al. , 1999).

The laser at one site fires a beam into the aperture and the light scattered from this beam is recorded by the fluorescence detector at the other site, an arrangement known as a bi-static LIDAR. This arrangement has number of advantages over a backscatter LIDAR, where the laser and detector are co-located. Using a bi-static LIDAR a range of scattering angles from the laser beam can be studied allowing a determination of the differential scattering cross section (phase function) of the aerosols. Also, by using the fluorescence detectors as a LIDAR receiver we can take advantage of the large mirror areas and absolute calibration of these detectors.

Ideally, for each recorded cosmic ray track, we would determine the immediate atmospheric transmission correction to each point in the track. In practice this approach is difficult. It requires that cosmic ray tracks be identified quickly and accurately from a large background of random triggers. The typically large distances at which the events are seen requires high laser energies, and the scattered light can have larger dynamic range and time delay than can be recorded by the fluorescence detectors. More fundamentally, the variable nature of the differential scattering cross section of the aerosols means that the laser propagation equations can't be solved unambiguously to yield atmospheric attenuation.

The strategy at HiRes has been to make a global parameterization of the aerosol distribution in the entire aperture for each hour of detector operation. By using a variety of laser shot geometries, and assuming that the aerosol distribution is horizontally invariant, we can determine the optical thickness of the aerosols as a function of height. The general uniformity of the aerosols around the detectors can be tested by looking at laser tracks that are symmetric about the fluorescence detectors.

Of particular concern are small localized regions of dense aerosols. These regions could scatter large numbers of Cherenkov photons from a cosmic ray track, leading to an overestimate of primary energy. We are developing routines that will identify cosmic ray tracks and steer the lasers to fire towards these events within a few minutes of their being detected. The continuity of the scattering of light from these tracks can then be tested for local inhomogeneity in the aerosol distribution.

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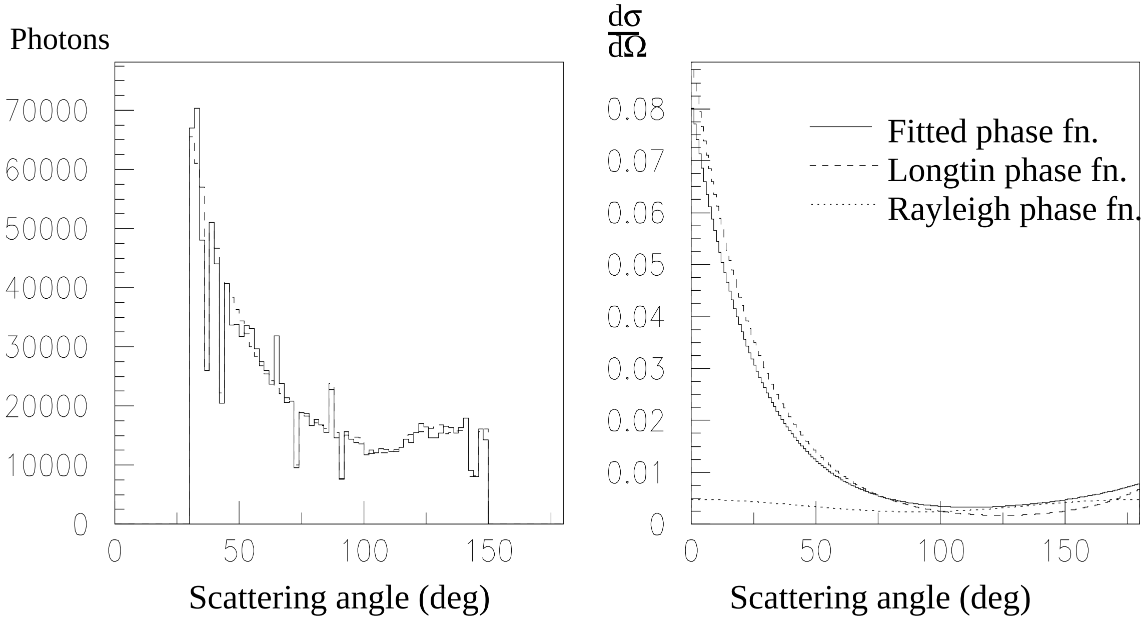

Fig. 1. The left plot shows the intensity of light as a function of scattering angle for a laser beam from the HiRes-2 steerable laser passing close to the HiRes-1 fluorescence detector. The solid line is the measured photon intensity and the dashed line is the result of a fit for phase function and horizontal extinction length. In this example the aerosol horizontal extinction length was found to be 7.2 km. The right plot shows the aerosol phase function that resulted from the fit. Also shown, for comparison, is a typical aerosol phase function derived from Mie scattering theory (Longtin , 1998). The Rayleigh phase function used to describe the molecular scattering is also displayed. The absolute vertical scale of the right hand plot is arbitrary, but the relative normalization of the phase functions shows the relative contribution from the different scattering sources at each scattering angle.

2 Atmospheric parameters

2.1 Horizontal extinction length and aerosol phase function

The horizontal extinction length is the extinction length at a height near to ground level (100m-200m). The aerosol phase function describes the differential scattering cross-section of the aerosols as a function of scattering angle. For our analysis we assume that the single scatter albedo of the aerosols is near unity, so the extinction length is equivalent to the total integral of the phase function. These parameters are extracted from laser shots from one fluorescence detector site, that are fired toward the other detector (passing within a few hundred meters of the detector). For each of these horizontal shots a large range of scattering angles are measured (30$^{\mathrm{o}}$ to 150$^{\mathrm{o}}$). A simultaneous fit to both extinction length and phase function is then performed. We assume that the phase function has the form

$$\mathrm{Ae}^{(-\mathrm{B}\theta)} + \mathrm{Ce}^{(\mathrm{D}\theta)} \qquad (1)$$

where θ is the scattering angle and A,B,C and D are variable parameters.

Figure 1 shows the result of this fit on a laser track, and the subsequent aerosol phase function that is derived.

The HiRes detectors have a minimum viewing angle of 3$^{\mathrm{o}}$ above the horizon, so the horizontal extinction length is not useful for correcting real cosmic ray data. These data are very useful, however, for understanding the systematics of measuring laser scattering in the atmosphere with fluorescence detectors. We can compare the horizontal extinction length measurement from this method with other independent measurements (Roberts et al. , 2001). In addition, looking at horizontal laser shots is the only way we can measure the aerosol phase function, which is needed to estimate the scattering of Cherenkov light from air showers. The best estimate of the statistical uncertainty of the horizontal extinction length parameterization can be obtained by comparing results from identical shots on either side of a fluorescence detector. These results indicate that the total horizontal extinction length (molecular and aerosol) is measured to an accuracy of around 10%. The absolute precision of the measurements, which depends mainly on the absolute calibration of the fluorescence detector, will be better understood after the installation of independent horizontal extinction length monitors. The distribution and seasonal variation of horizontal extinction lengths will be presented elsewhere (Wiencke et al. , 2001).

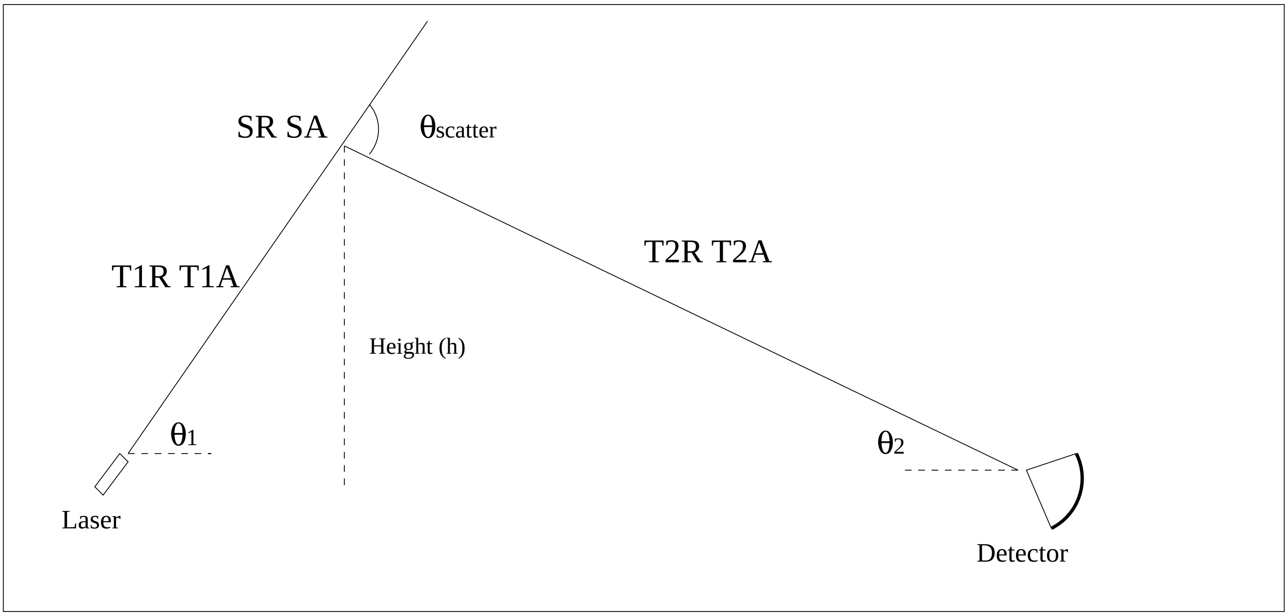

Fig. 2. Extraction of vertical optical depth at height h. The number of photons that reach the point of scattering point at h is given by the number emitted from the laser, reduced by the Rayleigh and aerosol transmission coefficients TR1 and TA1. The number of photons seen at the detector depends on the efficiency of the Rayleigh and aerosol scattering at h, and the subsequent transmission to the detector (TR2,TA2). If the number of photons expected for a purely molecular day can be determined, through Monte Carlo or other means, then the optical depth can be determined from the expression in equation 2.

2.2 Vertical optical depth

We define the vertical optical depth (VOD) as the integrated vertical optical depth from ground (detector) level to a given height. The VOD, corrected for slant depth, is used to apply attenuation corrections to the fluorescence light signal seen from cosmic ray tracks.

The method used to extract the VOD is illustrated in figure 2. At the fluorescence detector a laser track is seen as a source of light whose intensity varies as a function of height. The amount of light seen at each height (h) depends on how much light emitted at the laser reached h, how much of that was scattered into the solid angle of the detector, and how much of this scattered light actually reached the detector. By looking at scattering angles where the aerosol phase function is minimized (90° to 120° of scattering angle), we can make the approximation that all of the scattering is from the well understood molecular atmosphere. This approximation is clearly best when the aerosol attenuation length at the point of scattering is low. The assumptions made about the shape of the aerosol phase function are confirmed by the measurements discussed previously (see figure 1 as an example).

If the transmission through the molecular atmosphere is well understood then the aerosol optical depth (AOD) at any point along the laser track can be calculated from

$$\mathrm{AOD} = -\ln(\mathrm{measured}/\mathrm{predicted}) \tag{2}$$

where (measured) is the number of photons measured at each track point and (predicted) is the number of photons predicted if the atmosphere were molecular (no aerosols). Assuming horizontal uniformity this can easily be converted to give the aerosol vertical optical depth (AVOD)

$$\mathrm{AVOD} = \mathrm{AOD}/(1/\sin(\theta 1) + 1/\sin(\theta 2)) \tag{3}$$

using the nomenclature of figure 2.

The most accurate determination of AVOD is generally made high in the atmosphere, where the aerosol density at the point of scattering is expected to be low and where the effects of multiple scattering are small. For the HiRes bistatic LIDAR the maximum height at which the AVOD can be characterized is around 4km.

At the present time we have two separate analysis schemes that determine aerosol optical depth.

The first scheme uses only vertical laser tracks. By using a single geometry the interaction between the scattered laser light and the detector can be understood in great detail. We can also simulate multiple scattered light in this geometry. The multiple scattered light signal arises because the Rayleigh and Mie processes scatter rather than attenuate light. There is a small but finite probability that some of the scattered light will re-scatter to be temporally and spatially coincident with the single scattered light from the beam. For vertical beam geometries we can exploit the cylindrical symmetry between detector and laser beam to efficiently simulate this process.

The second scheme to extract AVOD uses a series of laser tracks, fired at an elevation of 15° and at a variety of azimuth directions. The section of each track that is viewed at scattering angles between 90° to 120° are included in the analysis of AOD described previously. The number of tracks used makes understanding the measurement systematics more difficult than for a single vertical track, but more of the atmosphere is sampled and the longer path lengths of the tracks makes the measurement potentially more precise.

The results of the characterization of the vertical structure of the aerosols for the two schemes described above will be presented elsewhere (Wiencke et al. , 2001).

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