Atmospheric Monitoring for Transmission Corrections to Air Fluorescence Signals

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Abstract

The next generation air fluorescence experiments studying cosmic rays near 10^{20}eV require significantly better atmospheric monitoring than the original Fly's Eye experiment. In this paper we present one method to monitor the aerosol transmission factor for the High Resolution Fly's Eye (HiRes) experiment.

1 Introduction:

The atmospheric corrections to data from the High Resolution Fly's Eye (HiRes) experiment (Sokolsky, 1999) are of two forms. The first is the correction for the finite transmission of light from the extensive air shower to the fluorescence telescopes. In practice the observed signal includes both air fluorescence plus some scattered air Cherenkov light from the air shower. The latter must be subtracted as part of the shower reconstruction/analysis and constitutes the second correction to the fluorescence data.

Thus various properties of the atmosphere must be known to allow the correction of the observed fluorescence plus scattered air Cherenkov light signal back to the source fluorescence signal at the air shower:

a) the vertical profile of the atmosphere: density, $\rho(z)$, and temperature, $T(z)$, as a function of the height, z, above the fluorescence detector eyes. To first order this is well represented by values at the ground, $z = 0$, combined with the U.S. Standard Atmosphere model (Martin, 1999).

b) the vertical profile of aerosols, also as a function of the height above the fluorescence detector eyes.

c) the Rayleigh scattering total and differential cross section as a function of wavelength (which are known).

d) the aerosol Mie scattering total and differential cross sections (Tessier, 1999) as a function of wavelength in the range: $310nm \leq \lambda \leq 410nm$.

Our goal is to make the minimum number of measurements that will allow us to correct HiRes data for atmospheric transmission losses and for backgrounds from air Cherenkov light scattered into the air fluorescence signal. To proceed we use a 1-dimensional model, *i.e.* variation only with height, for the atmosphere and for the aerosols. This is a very good model for the molecular atmosphere. It is also good first approximation for night time aerosols on the horizontal scale of the present HiRes experiment (Sokolsky, 1996).

In this paper we describe only the subset of the atmospheric measurements needed to provide quantitative measurements of the transmission corrections. We first measure the total, *i.e.* combined molecular and aerosol transmission, $T^m \cdot T^a$, at one wavelength near the middle of the wavelength acceptance of HiRes using scattered laser light from frequency tripled YAG lasers (355nm) at fixed elevations, z, viewed by the fluorescence detectors at different angles, α_i, from the horizontal. The aerosol transmission, T^a, is obtained by dividing by the comparatively well known molecular transmission, T^m. The measurements of T^a provide a direct measurement of the aerosol optical depth, $\tau^a(z)$, versus height above HiRes. This measurement will also provide information on the vertical profile of aerosols. To make corrections over the full wavelength acceptance of HiRes, $310nm < \lambda < 410nm$, we will measure the wavelength dependence of the aerosol horizontal attenuation length at the level of the HiRes eyes, $z = 0$.

2 Aerosol Transmission Correction:

Mie scattering of light on aerosols in the atmosphere results in an exponential decrease of the light intensity of a light beam passing through the atmosphere. The multiplicative *aerosol transmission* is given by:

$$T^a \equiv T^a(z, \alpha_i, \lambda) = e^{-\int_0^z \frac{\tilde{\rho}^a(z)dz}{\Lambda^a(\lambda)} \cdot \frac{1}{sin(\alpha_i)}} \tag{1}$$

where $\tilde{\rho}^a(z) = \frac{\rho^a(z)\sigma^a(z,\lambda)}{\rho^a(0)\sigma^a(0,\lambda)}$ is the normalized density of aerosols *versus* elevation and $\Lambda^a(\lambda) = \frac{1}{\rho^a(0)\sigma^a(0,\lambda)}$ is the aerosol horizontal attenuation length (*e.g.* in meters) at $z = 0$ as a function of wavelength, λ. The aerosol transmission can be re-expressed in terms of the *aerosol optical depth*, $\tau^a(z, \lambda) = \int_0^z \frac{\tilde{\rho}^a(z)dz}{\Lambda^a(\lambda)}$ and the slant factor, $\frac{1}{sin(\alpha_i)}$:

$$T^a(z, \alpha_i, \lambda) = e^{-\tau^a(z,\lambda) \cdot \frac{1}{sin(\alpha_i)}} \tag{2}$$

3 Measurement of the Aerosol Optical Depth:

To measure the aerosol optical depth, $\tau^a(z)$, we need known intensity, pulsed, UV light sources placed more or less throughout the atmosphere above the HiRes aperture. For the light sources we propose to use side *scattered* light from frequency tripled YAG laser beams. The relative brightness of each source will be known based on monitoring the intensity of each laser pulse and by making a (small) correction for variations in the scattering probability versus laser light scattering angle (*i.e.* the angle between the initial laser beam direction and the final direction toward the monitoring fluorescence telescope); more details are provide below.

Now at a given wavelength and with our 1-dimensional model for the aerosols, $\tau^a(z)$ depends only on the light source height, z, above the fluorescence telescope(s). Thus $\tau^a(z)$ is the same for light from all light sources at the same height z above the fluorescence eye(s). Furthermore for our 1-dimensional aerosol model the aerosol transmission factorizes into z-dependent and into α_i-dependent parts as shown in Eqn. 2.

Using scattered laser light we *place* known intensity, I_0, light sources at the same height, z, above a fluorescence eye but at different horizontal distances from the eye. These will be viewed with different slant factors and will have different observed intensities. If we denote the observed intensities, corrected for simple geometrical effects (*e.g.* the r^{-1} dependence with distance (r) for *line* light sources) and for Rayleigh scattering, by $\tilde{I}_{obs}(\alpha_i)$ then:

$$\tilde{I}_{obs}(z, \alpha_i) = I_0 \cdot e^{-\tau^a(z) \cdot \frac{1}{sin(\alpha_i)}}$$

The natural logarithm of $\tilde{I}_{obs}(\alpha_i)$ is then:

$$ln(\tilde{I}_{obs}(z, \alpha_i)) = ln(I_0) - \tau^a(z) \cdot \frac{1}{sin(\alpha_i)}$$

The slope of $ln(\tilde{I}_{obs}(z, \alpha_i))$ *versus* $\frac{-1}{sin(\alpha_i)}$ gives the aerosol optical depth, $\tau^a(z)$. Alternatively for two measurements with very different values of $\frac{1}{sin(\alpha_i)}$ we obtain:

$$ln(\frac{\tilde{I}_{obs}(z, \alpha_{large})}{\tilde{I}_{obs}(z, \alpha_{small})}) = \tau^a(z) \cdot (\frac{1}{sin(\alpha_{small})} - \frac{1}{sin(\alpha_{large})})$$

where α_{small} is a small angle to the horizontal and corresponds to light from a very distant source, and α_{large} is a large angle to the horizontal and corresponds to light from a nearby source. **This relation provides a direct measurement of the aerosol optical depth $\tau^a(z)$.**

Two possible geometries for the scattered laser light sources are given by:

1. <u>Fixed Radius Multi-source Geometry</u>:
   In this geometry we would place vertically directed lasers at a **fixed radius** around **one** fluorescence eye. This eye is the *monitor* eye and provides the measurement of the relative shot to shot laser intensity – only azimuthal symmetry need be assumed. A second, *attenuation*, eye views these at different distances. Thus for a given z the *attenuation* eye views these at different values of $\frac{1}{sin(\alpha_i)}$ as required.

2. <u>Fixed Radius Single-source Geometry</u>:
   In this geometry we would locate a <u>single</u> steer-able laser at a large ($20 \sim 30$km) distance from the *attenuation* eye. The shot to shot intensity of the laser(s) are monitored. This provides the relative shot to shot laser intensity for points at **fixed radius**, from the laser; only azimuthal symmetry need be assumed. A range of z and $\frac{1}{sin(\alpha_i)}$ is obtained by directing the laser beam at various azimuth and elevation angles.

In these two geometries the scattering angle of the laser light, β, is effectively restricted to a range of angles where molecular (Rayleigh) scattering dominates. For the HiRes vertical field of view the laser light scattering angle is in the range: $90^\circ \sim 120^\circ$ for the *fixed radius multi-source* geometry. For the *fixed radius single-source* geometry we add one additional restriction that the light scattered out of the laser beam is viewed at a radius of $\sim 1.05\times$ the laser – *attenuation* eye separation. Under these conditions the light scattering angle is in the range: $100^\circ \sim 150^\circ$.

To estimate the laser light scattering probability *versus* angle, we show in Fig. 1 the normalized molecular (Rayleigh) and predicted aerosol (Mie) (Longtin, 1988) scattering differential cross sections. The fraction, $f^a(\lambda)$, of laser light that undergoes aerosol (Mie) scattering in a vertical depth, dz, of the atmosphere is given by:

$$f^a(\lambda) = \frac{\tilde{\rho}^a(z)}{\Lambda^a(\lambda)} \cdot \left(\frac{\frac{d\sigma^a(cos(\beta),\lambda)}{d\Omega}}{\sigma^a}\right) \cdot \frac{dz}{sin(\tilde{\alpha})} \cdot \Delta\Omega \quad (3)$$

where $\tilde{\alpha}$ is the angle of the laser beam to the horizontal, $\Delta\Omega$ is the angular acceptance of the entrance aperture of a given fluorescence telescope, the ratio of aerosol cross sections, $\frac{\frac{d\sigma^a(cos(\beta),\lambda)}{d\Omega}}{\sigma^a}$, is called the *aerosol phase function* and other quantities are defined in Eqn. 1. A similar expression applies to the fraction of the laser light that undergoes Rayleigh scattering in the atmosphere. The total scattering probability is the sum of the Mie and Rayleigh contributions.
At 355nm the relative horizontal attenuation lengths for aerosol and molecular scattering at the HiRes experiment are predicted to be approximately equal (Longtin, 1988). In practice the HiRes experience is that the typical aerosol horizontal attenuation length at the HiRes experiment, Dugway Utah, is about $1.4\times$ longer than the Longtin, 1988 prediction (Sokolsky, 1996).

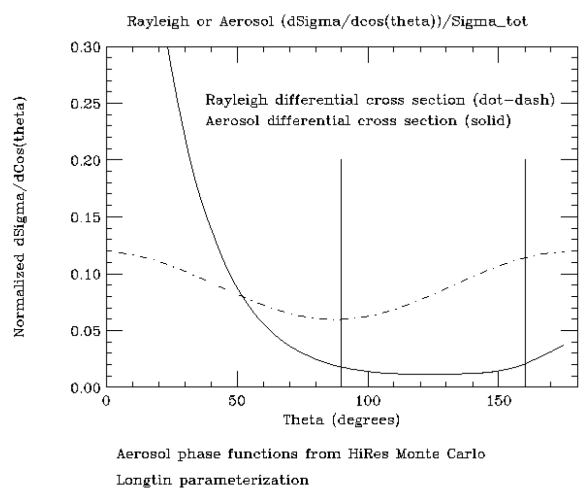

Figure 1: Normalized Rayleigh and representative Mie (Longtin, 1988) scattering differential cross sections plotted *versus* scattering angle, β.

In Fig. 2 we show the expected total scattering probability (sum of Rayleigh plus Mie normalized to the Rayleigh cross section) for three cases: Rayleigh attenuation length is twice the Mie attenuation length ... this corresponds to a night with much larger than expected levels of aerosols; Rayleigh attenuation length equals the Mie attenuation length; Rayleigh attenuation length is one-half the Mie attenuation length ... this corresponds to a typical night with low levels of aerosols. Except for nights with much larger than expected levels of aerosols the total Rayleigh plus Mie cross section (normalized to the Rayleigh cross section) is approximately constant over the angular scattering range: $100^\circ \leq \beta \leq 150^\circ$. Thus we anticipate that only small corrections will be needed to *normalize* the scattered light intensities at the different values of $\frac{1}{sin(\alpha_i)}$ for each fixed value of z. Furthermore, the corrections become smaller, *i.e.* the ratio in Fig. 2 approaches 1.0, as the height of the sources increases. Specifically in Eq. 3 $\tilde{\rho}^a(z)$ for aerosols decreases with a typical scale height of ~ 1.2km whereas $\tilde{\rho}^m(z)$ for the molecular atmosphere decreases with a scale height, ~ 7.5km.

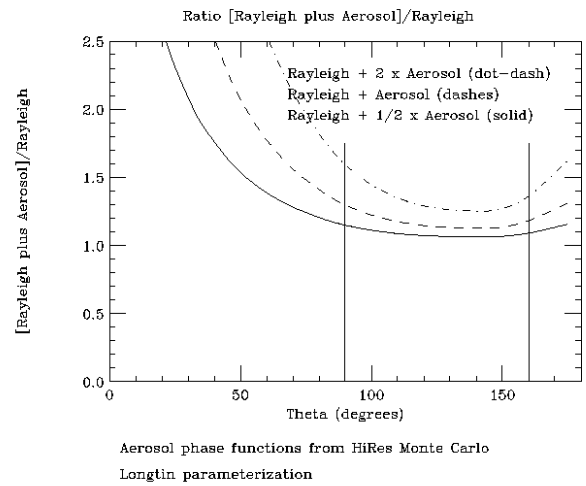

Figure 2: The sum of Rayleigh plus Mie scattering differential cross sections normalized to the Rayleigh cross section for three cases; see text.

These measurements differ from other proposed monitoring methods. First the fluorescence detectors read out the scattered light. Thus a separate steer-able mirror/DAQ system, such as with conventional LIDARs (Hayashida, 1999), is not needed. Furthermore the large area fluorescence mirrors allow the light transmission (atmospheric calibration) measurements to be made over the same distances scales as the air shower (data) events. Second the laser and *attenuation* eye geometries are chosen so that light path from the laser to the point of scattering is a constant (at a given height, z). Thus apart from azimuthal symmetry, no other assumption need be made about the initial transmission from the laser source to the point of light scattering (toward the *attenuation* eye). This differs from proposals (Teshima, 1999) that model the entire light path.

4 Conclusions:

This paper reviews the light transmission correction for air fluorescence experiments in a 1-dimensional aerosol model for the atmosphere. One of the methods proposed for monitoring the aerosol transmission corrections for the HiRes experiment is presented.

5 Acknowledgments

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