

First Analysis of the Auger APF Light Source

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Abstract

Measurement of the aerosol phase function is required to perform atmospheric corrections on the reconstruction of fluorescence detector events. The APF Light Sources at the Pierre Auger Observatory measure this function regularly. We describe the fitting of an aerosol phase function to the data generated from the APF. This function varies significantly from night to night. It introduces an average energy correction of less than 1% when applied to the reconstruction of FD events. While the correction has been successfully applied to data, there remain several issues which must be addressed to ensure the quality of measurements.

1 Introduction

From the extensive air shower produced by a cosmic ray the fluorescence detector at the Auger Observatory can determine the cosmic ray's initial energy. This is done by measuring the integrated fluorescence light produced by the shower, which is proportional to the energy of the primary particle. In this measurement the atmosphere acts as a natural calorimeter. However, atmospheric conditions affect the amount of light that actually reaches the detector. These conditions must be regularly monitored and taken into account to accurately determine the energy in cosmic ray measurements.

There are two primary forms of atmospheric scattering. Molecular or Rayleigh scattering is mainly due to nitrogen and oxygen molecules while aerosol or Mie scattering is due to a combination of large molecules and particulate matter in the air. The Mie scattering is far more variable than the Rayleigh and as such the aerosol conditions should be measured often to increase the accuracy of fluorescence detector energy measurements.

The most prominent errors associated with the atmosphere in the fluorescence measurements can be attributed to uncertainties in the atmospheric transmission, light multiple-scattering and cloud corrections. Air Cherenkov light is also produced. It is forward-peaked, but still scatters into the detector contributing an additional uncertainty. There are a number of measurements which are made to minimize these uncertainties. To estimate the multiple-scattered and air Cherenkov light scattered, the aerosol phase function (normalized aerosol differential scattering cross section) must be known. The APF light sources in conjunction with the fluorescence detectors at the Auger Observatory are designed to measure this function regularly.

This paper is structured as follows. In section 2 the APF facilities at the Auger Observatory will be described. Section 3 describes determining the aerosol phase function from the APF data. In section 4 the effects of the aerosol phase function correction on the fluorescence

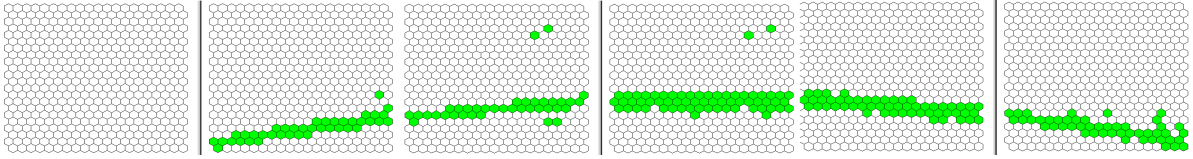


Figure 1: The APF pulse as seen by Coihueco using the FDEyeDisplay program.

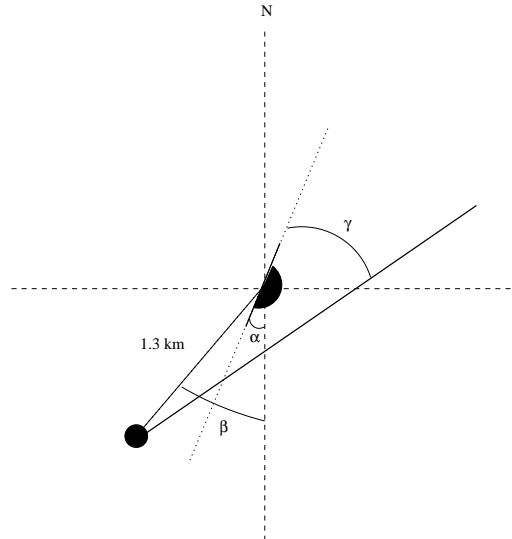
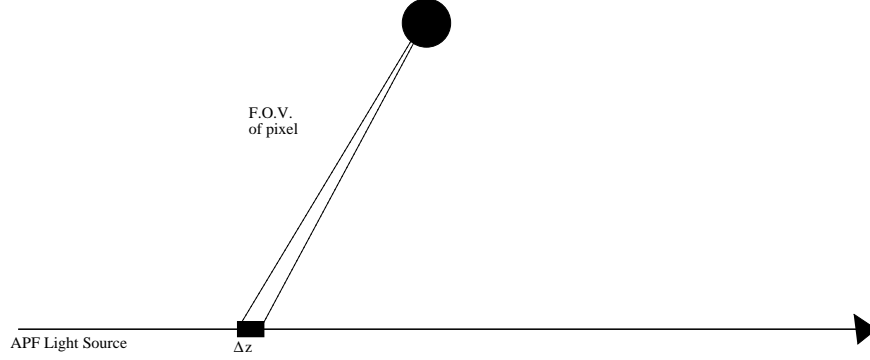


Figure 2: The Geometry of the Coihueco APF Light source. Located at the center is the Coihueco FD with its field of view indicated. The APF Light source's relative location is indicated. The value of α is 26 degrees and β is 38 degrees. The shot direction γ is roughly 20 degrees.

detector reconstruction are discussed. In the last section current problems with the APF light sources are mentioned as well as suggestions for what should be done to improve the quality of measurements.

2 APF Light Sources

There are two APF light sources, one is located near the Coihueco FD station and the other near the Los Morados FD station. The xenon light sources sit inside refurbished 20-foot shipping containers and the light is sent through UV transmitting windows. The light sources provide a nearly horizontal beam pulsed across the field of view of the near-by fluorescence detector. There are three different wavelength sources (330nm, 350nm and 390nm) which can measure the wavelength dependence of the phase function as well as cross check for accuracy. Currently only one is being used. There are five shots pulsed two seconds apart each hour. All of the analysis in this paper was done with the APF data at Coihueco. This is because Los Morados does not yet have a database of calibration constants for each pixel in the FD telescope. However, the general conclusions apply to both APF light sources. Figure 2 shows the supposed relative positions of the APF source and the FD. The direction of the beam

Figure 3: Schematic of track seen by i^{th} pixel.

(γ in figure 2) was determined from the data and will be explained at the end of the next section.

3 Determination of the Aerosol Phase Function

The signal from the APF light source in each pixel of the fluorescence detector is given by the following equation:

$$S_i = I_0 \cdot \frac{T}{r_i^2} \cdot \left(\frac{1}{\Lambda^m} \left[\frac{1}{\sigma^m} \left(\frac{d\sigma^m}{d\Omega} \right) \right] + \frac{1}{\Lambda^a} \left[\frac{1}{\sigma^a} \left(\frac{d\sigma^a}{d\Omega} \right) \right] \right)_i \cdot \Delta z_i \cdot \Delta \Omega_i \cdot \epsilon_i \quad (1)$$

where I_0 is the light source intensity, T is equal to $e^{-\text{lightpath}/\Lambda_{\text{tot}}}$, r_i is the distance from the beam to the detector, Λ is the total, molecular or aerosol extinction length, and $\frac{1}{\sigma} \frac{d\sigma}{d\Omega}$ is the aerosol or molecular phase function. Also, Δz_i , $\Delta \Omega_i$, and ϵ_i are the track length, detector solid angle, and the efficiency for the i^{th} pixel of the detector. The data comes in the form of total signal per pixel from a particular shot. This data is binned as a function of azimuth and averaged between the five shots taken within 10 seconds. In this analysis, 5 degree bins are used, however the fit is not very sensitive to number of bins. Each pixel of the FD is hexagonal and for those which lie at the boundary of two azimuth bins the fractional area of the hexagon in each bin is used to distribute the signal properly. The signal in each pixel is divided by Δz_i , $\frac{1}{r_i^2}$ and ϵ_i to correct for the geometry of the beam and pixel calibration. T is assumed to be 1. Interestingly, the Δz_i and $\frac{1}{r_i^2}$ corrections combine nearly perfectly to be a constant when both are divided.

At this point we have

$$C \cdot \left(\frac{1}{\Lambda^m} \left[\frac{1}{\sigma^m} \left(\frac{d\sigma^m}{d\Omega} \right) \right] + \frac{1}{\Lambda^a} \left[\frac{1}{\sigma^a} \left(\frac{d\sigma^a}{d\Omega} \right) \right] \right) \quad (2)$$

where C is a constant whose value is unimportant because arbitrary units are sufficient in determining the phase function. From the theory of Rayleigh scattering it is known that the Rayleigh phase function is $1 + \cos^2(\theta)$ multiplied by some constant. The aerosol phase function is assumed to be of the form

$$\frac{1 - g^2}{4\pi} \left(\frac{1}{(1 + g^2 - 2g\mu)^{3/2}} + f \frac{3\mu^2 - 1}{2(1 + g^2)^{3/2}} \right) \quad (3)$$

where μ is equal to $\cos(\theta)$. Data is fit to the following function:

$$A \cdot (1 + \mu^2) + B \cdot \frac{1 - g^2}{4\pi} \left(\frac{1}{(1 + g^2 - 2g\mu)^{3/2}} + f \frac{3\mu^2 - 1}{2(1 + g^2)^{3/2}} \right) \quad (4)$$

with A , B , g and f as the fit parameters.

The errors on each bin are determined by taking the standard deviation of the five shots which are averaged. The fit was found to be unstable in ROOT using the Chi-Squared minimization algorithm, but works much better when the log likelihood method is selected.

Each fluorescence detector consists of six separate mirrors with a field of view of roughly 30 degrees each. At the boundary between each mirror there is some overlap in the fields of view of pixels. This overlap produces a double counting of signal resulting in the value of bins at boundaries being too large. To correct for this these bins are simply ignored.

Figure 4 shows a couple of examples of binned data and fits. Both the aerosol, molecular and total phase function are shown. The aerosol phase function is obtained by subtracting the molecular component determined by the fit. The f parameter is zero in essentially all fits, and there is no sensitivity to small changes of f . The angle at which the APF light source shoots (γ in figure 2) is necessary to make the geometrical corrections in binning the data. This angle was determined by finding a night in which the aerosol scattering was negligible. A suitable night was found by looking at VAOD measurements from the CLF. The data from this night was then fit to only a Rayleigh component of the phase function, however instead of requiring the minimum be at 90 degrees this was added as a fit parameter. The value of this angle determined by the fit was used to deduce the direction which the APF light source shoots. A FD Reconstruction was applied to the shot to determine the elevation angle which was then appropriately corrected for. These are probably good estimates, but to be certain of the APF geometry, angles and distances should be measured carefully on site.

4 Reconstruction

After the aerosol phase function is measured it needs to be applied to the reconstruction of FD events to make the proper corrections. Currently an aerosol phase function obtained from an air force simulation [1] is being used in the reconstruction. The phase function is stored in an AugerOffline file (ParametricXMLMieModel.xml) which lists the value of the function every two degrees from 0 to 180. For this analysis the first two bins were unchanged and the rest of the function was normalized to have the same integrated value as the currently used function. The first two bins are unchanged because small scattering angles can not be observed due to the angle of the APF shot. We also attempted to input the fit aerosol phase function for angles greater than 10 and less than 170 degrees, but decided that the method described above was more representative of the true function.

There is one main problem with the normalization procedure used. The ratio between the first two and the remainder of bins is fixed, so the value of the phase function for high values compared to very small angles is trusted entirely to the original simulation used. It would be beneficial to measure the APF another way at very small angles and combine this to the phase function measured here.

The measured phase function was applied to the reconstruction for several nights with differing aerosols and compared to the reconstruction with the original, currently used function. The percentage difference of the energy for the same events with different phase functions is shown in figure 5. The corrections are on the order of a fraction of a percent.

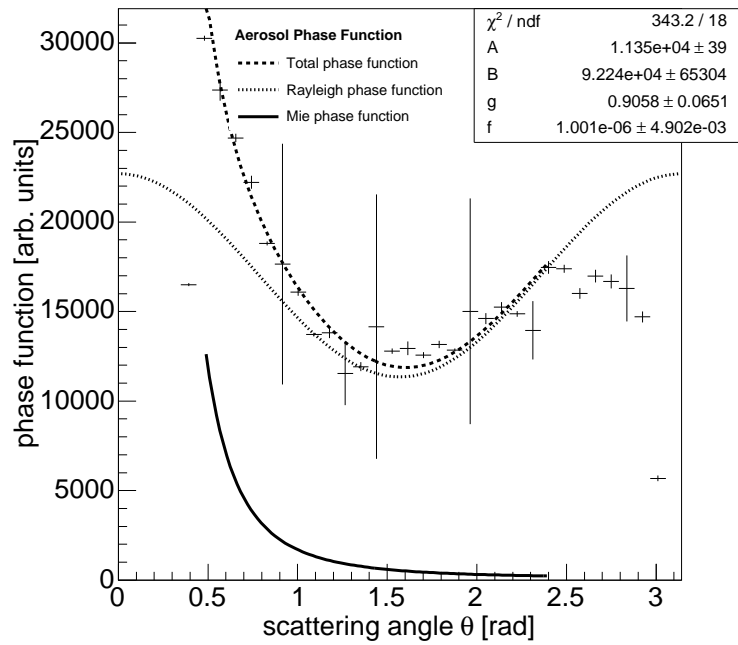
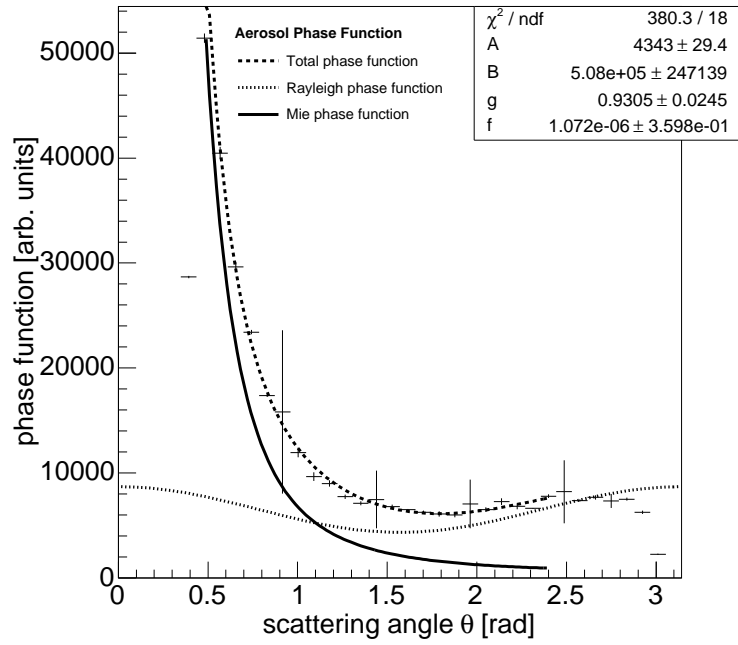


Figure 4: APF data Fits. The bins with large error bars are at mirror boundaries and ignored when fitting.

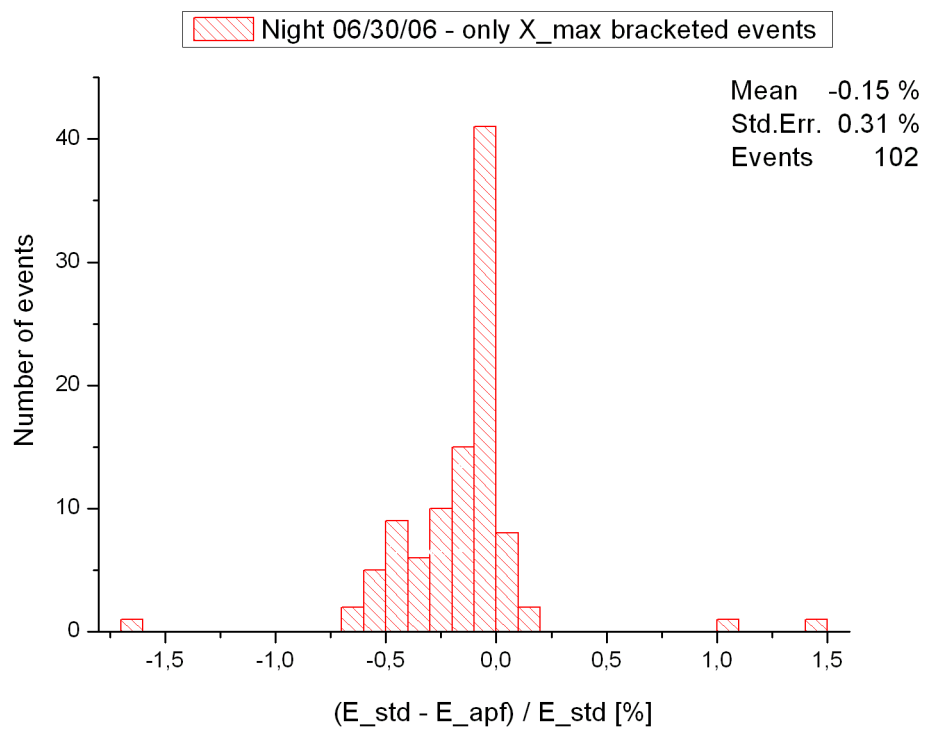


Figure 5: Energy Correction Due to Change in Default Aerosol Phase Function

5 Future Work

While this analysis of the APF and its uses have been largely successful there a number of unresolved issue which should be further investigated. For nights where the total phase function is dominated by the Rayleigh component the fit appears match the data, but ROOT outputs that the fit has problems. In these cases the g parameter gets very close to one and the B parameter is very high.

While the angle at which the APF source points seems to have been correctly determined as described, this angle should actually be measured on site to ensure that everything is consistent. It may even be beneficial to realign the APF to a smaller angle so the FD can see smaller scattering angles. However lowering this angle to allow viewing the most scattering angles would place it directly on the FD at the closest point. It is not readily apparent how small of an angle is optimal. It is probably unnecessary to have the angle of the APF source point at anything less than 10 degrees. The elevation angle measured from the FD reconstruction may not be accurate.

The fit does not appear to match the data for very high angles. This may be due to the geometry of the beam and the detector or attenuation of the light. Because the value of the fit is very small for these high angles it can sometimes have very small negative values. Since this is not physical, they are currently set to zero.

All data examined thus far is of the same wavelength. It will be interesting to look at the wavelength dependence of the phase function. Perhaps this will require 30 seconds of APF shots every hour instead of the current 10 seconds.

Eventually, if $\frac{1}{\Lambda^a}$ and $\frac{1}{\Lambda^m}$ can be measured or estimated in real time the A and B parameters can be removed from the fit. This could help to increase the stability of the fit.

The last issue which must be monitored is the quality of the data. For much of the data only a fraction of the mirrors actually obtain data during an APF shot. This is a critical issue because it is necessary to have mirrors 1-5 working properly to obtain a good fit. In the period between April 2004 and March 2006 there are less than 4000 good events recorded while there should be over 20,000. In the last few months the situation appears to be improving, but still needs to be carefully monitored.

6 Conclusions

With the APF light source it is possible to measure the aerosol phase function and apply corresponding corrections to the FD reconstruction. However, the change in energy caused by these corrections is less than 1%. There are a number of additional steps which can be taken to improve the quality and reliability of current APF measurements.

7 Acknowledgements

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References

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