Analysis of atmospheric attenuation using the Telescope Array central laser data

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Abstract. Located in the western desert of the state of Utah, the Telescope Array (TA) experiment measures the properties of ultra high energy cosmic ray (UHECR) induced extensive air showers. TA employs a hybrid detector comprised of a large surface array of scintillator detectors overlooked by three fluorescence telescopes stations. The TA Low Energy extension (TALE) detector has operated as a monocular Cherenkov/fluorescence detector for nearly five years, and has recently been complemented by a closely spaced surface array to operate in hybrid mode. The TAx4 upgrade is underway and aims to, as the name suggests, quadruple the size of the surface array to improve statistics at the highest energies (post-GZK events).
The analysis of the TA fluorescence detectors (FD) data requires knowledge of the degree of the atmospheric attenuation of UV light produced by shower particles. This attenuation depends partially on the amount of aerosols present in the atmosphere at the time of shower observation. Being highly variable, real time measurement of the aerosols light attenuation is accomplished through the use of a central laser facility (CLF) located at the center of the surface array, and in the field of view of the three FDs, as well as, the TALE FD.
In this proceeding we will describe the experiment, and the CLF data and analysis, and give results on measured aerosols attenuation, yearly averaged. FD measurements of shower energy and X_{max}, involve corrections for atmospheric attenuation due to the presence of aerosols. We discuss the errors introduced into the shower parameters reconstruction due to uncertainty about aerosols attenuation.

1 Introduction

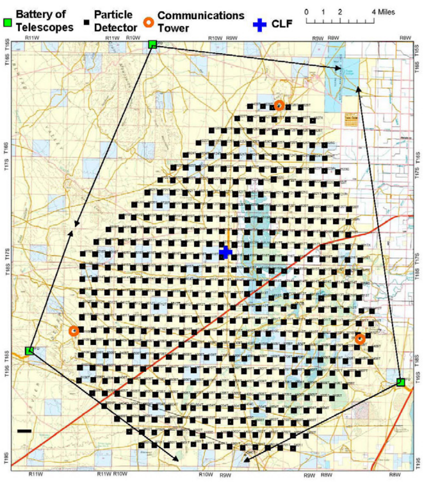

Figure 1. Map of the Telescope Array surface detector and the three fluorescence detectors overlooking the array. The CLF location is indicated by the blue "+" at the center of the SD array. The green squares mark the locations of the three FD stations: Black Rock (BR) near bottom right, Long Ridge (LR) near bottom right, and Middle Drum (MD) near top of figure.

The Telescope Array experiment is located in the West Desert of Utah, about 150 miles southwest of Salt Lake City, and is the largest cosmic ray detector in the northern hemisphere. TA has operated since 2008. The detector consists of 507 surface detectors (SD), arranged in a square grid of 1.20 km spacing [1]. Three FD stations, comprised of 38 telescopes, are located at the periphery of the SD array [2, 3]. The FD telescopes observe the airspace above the SD array. This arrangement of detectors is shown in Figure 1. The goal of TA is to clarify the origin of ultra-high energy cosmic rays (UHECR) and related extremely high energy phenomena in the universe. The results of measuring the energy spectrum, composition, and anisotropy in the arrival direction distribution for energies above $10^{18.2}$ eV have been published [4–6]

At the time of this writing, TA is being expanded to an area roughly four times the size of the current array; this updated detector is referred to as TAx4. Some 500 surface detectors, scintillation counters, and 12 telescopes (two FD stations) are being constructed to accomplish the expansion.

2 Aerosols measurements using CLF

The TA experiment employs a laser system located at the center of the array to provide data for aerosols characterization. The laser points vertically and fires in a fixed direction. Typical laser pulse energy is a few milli-Joules,

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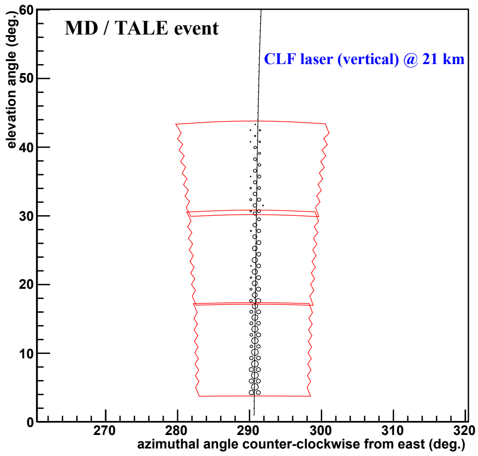

Figure 2. Event display of a CLF laser shot as recorded by the MD/TALE FDs. Two MD, and one TALE telescopes (mirrors) participate in the event, mirror boundaries shown in red. The track starts at the bottom of the lowest elevation viewing mirror.

Table 1. Mean VAOD measured using CLF data collected at two FD sites

year	BR	LR
2009	0.027 ± 0.019	0.024 ± 0.017
2010	0.034 ± 0.026	0.038 ± 0.026
2011	0.034 ± 0.019	0.037 ± 0.020
2012	0.040 ± 0.026	0.043 ± 0.027
2013	0.031 ± 0.021	0.031 ± 0.021
2014	0.028 ± 0.022	0.026 ± 0.018

bright enough to be seen by the three FD stations at a distance of ~21 km. An event recorded by the MD/TALE telescopes is shown in Figure 2 as an example.

An analysis on the CLF data observed by three FD stations over a number of years was carried out to measure the mean Vertical Aerosols Optical Depth (VAOD). CLF data is collected every half hour (300 laser shots). Each set of shots observed by one of the three FDs provides one measurement point. Data from each FD was averaged for each year of operation to obtain a mean VAOD as measured by that station. Results from the BR and LR stations are summarized in Table 1. Data from the MD station was also analyzed and compared to the other two stations. The results from MD were found to be consistent with those from the other two stations.

3 Shower Energy and X_{max}

The simulation and reconstruction of extensive air showers observed by the FDs employ an aerosols model which describes the attenuation of light using a vertical aerosols density and a horizontal extinction length. The aerosols density is assumed constant from ground level up to a “mixing-layer height”, h_m, decaying exponentially above h_m, with a scale height of h_0. The horizontal extinction length, L, gives the extinction length of light at a wavelength of 334 *nm*. A slowly varying function of wavelength corrects for different light wavelengths. The relation $VAOD = (h_m + h_0)/L$, connects the vertical optical depth to the model parameters. In practice, we set $h_m = 0$, and allow the other two parameters to vary. The choice of $L = 25$ km and $h_0 = 1$ km produces a mean VAOD = 0.04 and is the standard value used for various TA analyses. This value is consistent with those measured using the CLF data reported in section 2.

In this section we use MD observed data to examine the effect on the reconstruction of shower energy and X_{max} of using this mean value of VAOD. Given the RMS values in Table 1, we compare the results to those obtained with VAOD values of 0.02 or 0.06. In addition we report on a MC study of using a mean value of VAOD in place of a time dependent measurement of aerosols. In particular, we simulate showers using aerosols distributions sampled from a database of actual measurements, and then reconstruct these showers using either the true model parameters or the mean value and compare the results.

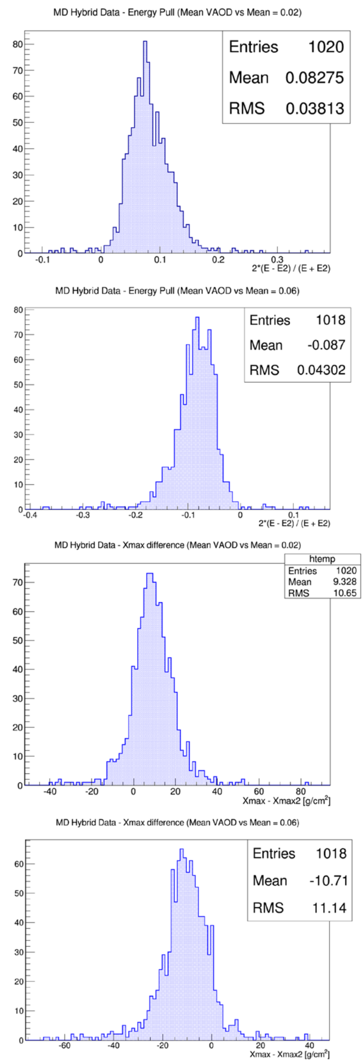

Figure 3. Energy and X_{max} Pull: Mean VAOD = 0.04 vs mean values at $\sim 1\sigma$

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For the energy and X_{max} systematics check, we look at real shower data measured using the Middle Drum FD site in hybrid mode with the TA SD. Hybrid measurement insures accurate geometrical reconstruction, needed for reliable energy and X_{max} reconstruction. This data sample, with additional quality cuts, was used as the basis of two TA publications [5, 7].

Keeping the aerosols model scale height at 1 km, we change the horizontal extinction length to produce a VAOD value of 0.02 or 0.06. We compare the reconstructed shower energy and X_{max} on an event by event basis. Results are shown in Figure 3. As can be seen from the figure, we can quote a systematic uncertainty of roughly ΔE = 8.5%, and $\Delta X_{max} = 10$ g/cm^2 due to aerosols.

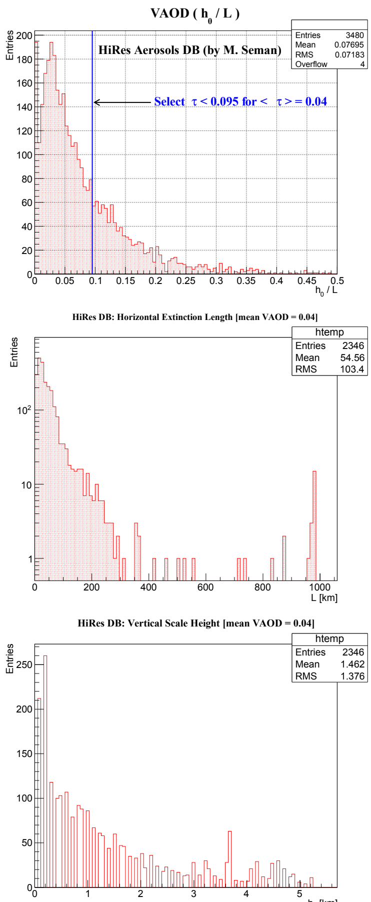

Figure 4. HiRes Aerosols database: Reconstructed hourly aerosols parameters. Fit paramaters, L and h_0, , with resulting $\tau \equiv VAOD$ on the bottom.

For the MC study we rely on aerosols measurements performed by HiRes [8]. HiRes employed a laser system for aerosols characterization. The measured laser data was analyzed and used to construct a data base of hourly aerosols density profile parametrizations. Model parameters and resulting VAOD are shown in Figure 4. TA is located close enough to where HiRes was located (∼ 60 miles) that we can use the HiRes DB as a proxy for the TA aerosols.

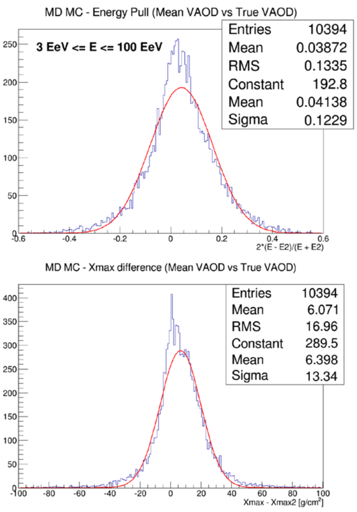

Figure 5. Energy and X_{max} Pull: Mean VAOD vs MC thrown "true" parameters.

The MD detector response to showers generated with a random sample of aerosols parameters drawn from the DB was performed. Nights where the aerosols concentration was too large (shower data would be discarded) were not included in the simulation; resulting in a mean value of 0.04 for the VAOD.

Detector observed events were then reconstructed using the mean VAOD value, L = 25 km and h_0 = 1 km, or using $L = L_{thrown}$ and $h_0 = h_{0,thrown}$. In both cases the thrown shower geometry was used in the reconstruction to mimic accurate geometrical reconstruction. A comparison of the two reconstructions is shown in Figure 5. As can be seen in the figure, the contribution to the reconstruction resolution due to the use of a mean VAOD can be estimated at ΔE = 12%, and $\Delta X_{max} = 13$ g/cm^2.

4 Summary

A laser system located at the center of the TA detector (CLF) is used to measure the aerosols light attenuation. An analysis of the CLF data was performed to measure a yearly mean value for the VAOD. Results shown in Table 1. While variable in time, a mean value, $VAOD$ = 0.04, is used in the analysis of shower data recorded by the TA FDs. A simple analysis of the effect of using this mean value on shower energy and X_{max} gives estimates for systematic errors of roughly ΔE = 8.5%, and $\Delta X_{max} = 10$ g/cm^2. Reconstruction resolution is affected at the levels of ΔE = 12%, and $\Delta X_{max} = 13$ g/cm^2.

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