# TA Energy Scale: Methods and Photometry

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**Abstract:** The energy determination of ultra-high energy cosmic rays in fluorescence measurement of the Telescope Array (TA) experiment is described.

**Keywords:** Ultra-high energy cosmic rays, fluorescence technique, Telescope Array

## 1 Introduction

The fluorescence detection method in air shower observation is a powerful technique in determining primary energies of ultra-high energy cosmic rays. Because of the calorimetric nature of the fluorescence technique, air shower energies can be measured without a complete theoretical basis of the air shower phenomenon. However, the absolute energy scale of a fluorescence measurement is dependent on assumptions on the fluorescence yield (number of fluorescence photons produced per energy deposited by charged particles in the air shower), and phototube calibration. Moreover, there are several sources of uncertainty in the energy determinations, such as the transparency of the atmosphere, time variation of phototube gains, and an incompleteness in air shower reconstruction procedures. In this paper, we discuss the method of energy determination in data analysis of the Telescope Array (TA) experiment, which has been in stable operation since 2007 in Millard County, Utah.

## 2 TA energy scale: Strategy

Telescope Array (TA) is the largest cosmic ray detector in the northern hemisphere using a ground surface detector (SD) array with 507 scintillation counters, and fluorescence detectors (FDs) installed in the three stations. The details of the detectors are given elsewhere (e.g. [1]). Here we review the basic concept of the TA data analysis.

### 2.1 The fluorescence measurement

The fluorescence detectors measure photons emitted from or around air showers with phototubes exposed to the night sky to determine the longitudinal profiles. The longitudinal profile of an air shower as a function of atmospheric depth $X$ is written by the Gaisser-Hillas function,

$$f(X) = \left(\frac{X - X_0}{X_{\max} - X_0}\right)^{\frac{X_{\max} - X_0}{\lambda}} \exp\left(-\frac{X - X_{\max}}{\lambda}\right) \quad (1)$$

where $X_{\max}$ is the depth at the maximum development of an air shower, $X_0$ is the first interaction point, $\lambda$ is a characteristic length of particle interaction. This equation was originally proposed to describe the development of the number of charged particles [2], and is also applicable to an energy deposit profile which can be directly measured with FDs. The *calorimetric energy* of the air shower is obtained by integrating the longitudinal profile,

$$E_{\mathrm{cal}} = N_{\max} \int \left\langle \frac{\mathrm{d}E}{\mathrm{d}X} \right\rangle f(X)\mathrm{d}X = \int \mathcal{E}(X)\mathrm{d}X \quad (2)$$

where $N_{\max}$ is the shower size at $X_{\max}$, $\left\langle \frac{\mathrm{d}E}{\mathrm{d}X} \right\rangle$ is the mean energy deposit of charged particles per unit length, and

$\mathcal{E}(X) \equiv \mathcal{E}_{\max} f(X)$ is the energy deposit profile of the shower. The primary energy of the cosmic ray which induced the shower is obtained from $E_{\rm cal}$ by taking into account the *missing energy* which is an *invisible* component of the shower energy carried away by neutral particles.

### 2.2 Measurement with the surface detector array

Shower particles at the ground level of the TA site are detected by the SDs with $3\,\mathrm{m}^2$ area, which are of double-layered scintillation counters [3]. From the lateral distribution of the shower particles determined from the local densities at SDs [1], an energy estimator, $S_{800}$, the density at 800m from the shower core is evaluated. In order to take into account different atmospheric attenuation of inclined showers, we construct a lookup table for conversion from the observables $(S_{800}, \sec\theta)$ to the energy $E_{\rm SD}$ by using a CORSIKA based Monte Carlo (MC) developed for TA (Figure 1) [4]. The SD shower analysis program is tuned to reproduce MC-thrown energies from the estimators $(S_{800}, \sec\theta)$ of reconstructed showers. The advantage of SD is its $\sim 100\%$ duty cycle (c.f. $\sim 10\%$ for FD) i.e. high statistics.

However, because of the lack of our knowledge of details of ultra-high energy hadronic interactions, there are rather large systematic uncertainties in energy determination from the shower particle measurement at the ground compared to the calorimetric measurement by FDs. This is a long-standing problem in cosmic ray physics, and has been documented in comparisons between AGASA, an SD based experiment, and HiRes, which used FDs. In order to define a "unified" TA energy scale, we use *hybrid* events, which are detected by both SD and FD. From an $E_{\rm SD}^{\rm Hyb} - E_{\rm FD}^{\rm Hyb}$ plot, where $E_{\rm SD}^{\rm Hyb}$ and $E_{\rm FD}^{\rm Hyb}$ are energies determined by the SD and FD reconstruction of the hybrid events respectively, we determine an overall scale factor $< E_{\rm FD}^{\rm Hyb}/E_{\rm SD}^{\rm Hyb} >$ to obtain the energy of each SD event (the figure will be presented at the Conference in Beijing in August). Therefore the energy of an SD event, which is not necessarily a hybrid event, is given by $E =< E_{\rm FD}^{\rm Hyb}/E_{\rm SD}^{\rm Hyb} > E_{\rm SD}$, where $E_{\rm SD}$ is the energy determined from the SD reconstruction.

## 3 Absolute energy scale in TA FD

### 3.1 Fluorescence yield

In order to know the number of charged particles or energy deposit at which the photons detected by phototubes exposed in the night sky were emitted, we need a *fluorescence yield*, the number of fluorescence photons emitted per unit charged particles' energy deposit for each molecular spectral line. We use the spectral lines and their relative intensities obtained by the FLASH experiment in the wavelength range is $300-420$ nm [5]. The absolute values are normalized so as to give the total yield reported in [6] in the range $300-400$nm, in which the measurement was carried out. Therefore the fluorescence yield model used in the TA

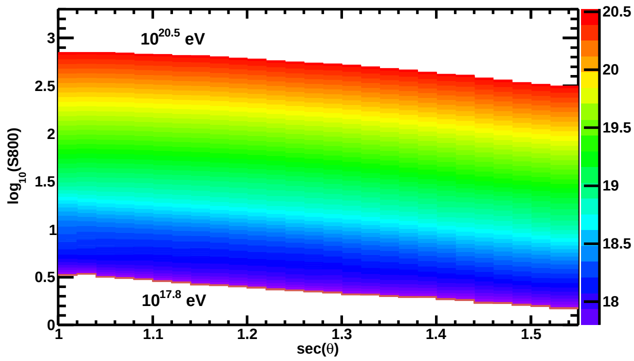


Figure 1: The SD energy chart

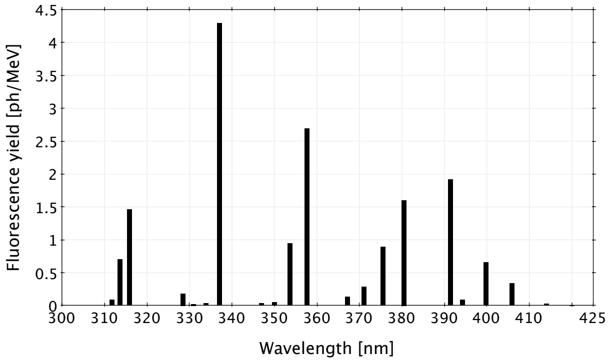


Figure 2: The fluorescence yield model used in the TA FD analysis.

FD analysis is written as

$$\mathrm{FLY}_{\rm TA}(\lambda) \equiv \frac{K f_{\rm FLASH}(\lambda)}{\int_{300}^{400} f_{\rm FLASH}(\lambda) \mathrm{d}\lambda} \quad (3)$$

where $f_{\rm FLASH}(\lambda)$ is the FLASH spectrum in the range $300-420$nm [5], $K$ is the reference total yield in $300-400$nm [6] (Figure 2). The total fluorescence yield in the whole range amounts to $\int_{300}^{420} \mathrm{FLY}_{\rm TA}(\lambda)\mathrm{d}\lambda = 16.4$ [ph/MeV] at 1013 hPa/293K. The dependences on the atmospheric density and temperature are also taken into account using the equation in [6].

It is not a trivial task to evaluate the systematic uncertainty in the fluorescence yield. An estimate can be given from a comparison with the PierreAuger Observatory FD analysis: if the TA fluorescence yield model described here is applied to the Auger analysis, the energy increases by $\sim 9\%$ [7]. The temperature and humidity dependences also give $3\%$ and $5\%$ uncertainties respectively. In total, we evaluated $11\%$ uncertainty related from the fluorescence yield.

1. The measured values are not necessarily proportional to number of particles: SDs measure mean energy deposit by shower particles, in terms of vertical muons.

### 3.2 Calibration of phototubes and electronics

The output from the phototubes of the TA FDs are digitized with synchronized 40MHz ADCs and recorded as time series data of 100ns interval after summing four consecutive data points. In order to obtain the ADC-number of photons conversion factor, we carried out an absolute gain calibration of the phototube-electronics-ADC system of TA FD [8, 9]. As a light source, we used a nitrogen laser (337.1nm, 200nJ/shot) in a gas-filled chamber (25cm in radius and 20cm in height). A phototube to be calibrated was equipped at a distance of $\sim$ 30cm from the beam line just outside of the chamber viewing the laser through a small window. Since the number of photons to be detected by the phototube can be calculated precisely, we can obtain the conversion factor by using the same electronics and signal cables used at the TA FD sites. The systematic uncertainty in this phototube calibration is evaluated as $7\%$ [8]. Two or three phototubes calibrated in the lab as described here have been installed in each FD camera at the sites which is comprised of $16\times16$ phototubes. The gains of all the phototubes in each camera are equalized using a Xe flasher installed on each camera once in an hour during FD operation [9]. The relative gain between different cameras are measured with portable light sources, as a handy laser, a UV LED and a roving Xe flasher [10]. The total uncertainty in the FD calibration including the phototube calibration, hourly gain monitoring, mirror reflection etc.) is $10\%$ [9].

## 4 Uncertainties in FD energy determination

### 4.1 Atmosphere

In order to measure the transparency of the atmosphere above the TA sites, a LIDAR system operates at the beginnings and ends of FD observation nights [11]. The LIDAR data is used to estimate the distribution of aerosols in terms of the vertical atmospheric depth (VAOD), $\tau(h)$, as a function of height $h$. Since the LIDAR operation has not been carried out on all nights, we define an average VAOD model $\tau(h)$ using 136 LIDAR data. We evaluated an energy uncertainty due to our use of an average VAOD model using MC air shower events. MC showers with a fixed energy are generated using VAODs randomly chosen from the 136 nights of the LIDAR data. Then these events are reconstructed using both the measured VAOD used in the MC shower generation and the average. The distribution of the difference between the two reconstructed energies has a width of $\sim 11\%$ and mean close to zero (Figure 3).

Another source of atmospheric uncertainty comes from the measurements of atmospheric pressure and temperature. We use the data of radiosonde soundings launched close the TA site (launched at the Elko RAOB station), to model the atmospheric depth, pressure, temperature and humidity as functions of height. We constructed a radiosonde database, as monthly average models, and found that the difference in energy determination between a use of a monthly aver-

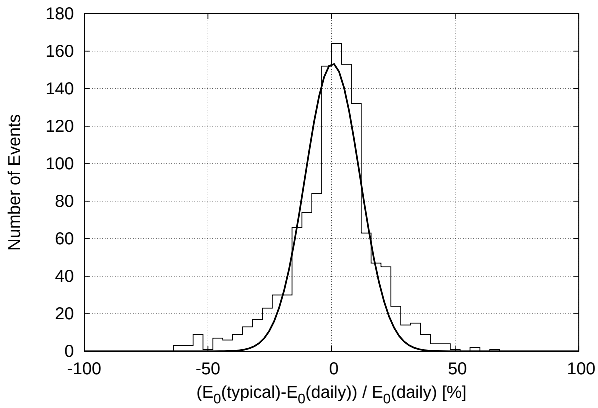


Figure 3: Energy uncertainty introduced by the use of the "typical" model of the aerosol distribution.

age model and the daily data is smaller than $1\%$. Therefore we conclude that the energy uncertainty which is related to the atmospheric condition is $11\%$ in the TA FD analysis.

### 4.2 FD shower reconstruction

Directly calculating the number of charged particles using phototube signal and a given reconstructed air shower geometry is difficult due to the complexities of the FDs, as well as, accounting for the effects of Cherenkov light in the shower. For this reason, an *Inverse Monte Carlo* (IMC) method is employed. Using an IMC method, showers with varying $X_{\max}$ and $N_{\max}$ (or $\mathcal{E}_{\max}$) are simulated and the number of measured photo electrons is compared with that produced by the simulated showers. Simulation of the air shower allows for the treatment of Cherenkov radiation and ray tracing methods are used to understand the acceptance of photons produced on the shower axis. Here we can include all the effects, such as photon shadowing by structures, mirror reflectances, and other calibration related matters. We use *independently developed* FD reconstruction programs utilizing the inverse Monte Carlo method. From the differences between energies determined by the two codes, and together with $\sim$ $5\%$ and $\sim$ $3\%$ uncertainties which originate from non-predetermined primary nuclear types and the missing energy correction, the energy uncertainty from the reconstruction procedures is evaluated as $\sim$ $10\%$. The systematic differences in the energies determined by the two reconstruction codes is at most $10\%$. In addition, a $5\%$ uncertainty has been determined due to the non-predetermined primary nuclear types. The uncertainty in the missing energy correction is $3\%$. In total, we find a $12\%$ systematic uncertainty in the FD reconstruction procedure.

| **Source** | $\Delta E/E$ |
|---|---|
| Fluorescence yield | $11\%$ |
| Atmosphere | $11\%$ |
| Calibration | $10\%$ |
| Shower reconstruction | $12\%$ |
| **Total** | $22\%$ |

Table 1: TA energy uncertainty budget

## 5 Summary

The energy determination in the TA data analysis is described, and the possible uncertainties are discussed. The sources of the energy uncertainties are listed in Table 1. By adding all the items in quadrature, the total systematic uncertainty in the TA analysis is $20\%$. At the conference in Beijing in August, we will show more details with figures and updated data.

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