# "Mobile ACE" - New Approach to Reduce Systematic Errors in the Absolute Energy by Fluorescence Detectors

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## Abstract

Observation of atmospheric fluorescence has been widely used by Ultra High-Energy Cosmic Ray (UHECR) experiments such as Fly's Eye, HiRes, Pierre-Auger and EUSO. Although this technique has an advantage of being totally calorimetric (compared to ground arrays), unfortunately, there is no "standard candle" in nature to establish the absolute energy scale (unlike vertically-penetrating cosmic-ray muons for ground arrays.) To reduce systematic uncertainties caused by this problem, an innovative calibration method, "**Mobile-ACE** (**A**rtificial **C**osmic ray **E**mitter)" is proposed, which introduces a "standard candle" normalized by the real energy deposit in atmosphere in situ.

## 1. Propagation of Systematic Errors

Currently, two distinct methods are widely adopted to observe Ultra High-Energy Cosmic Rays (UHECR); Fluorescence Detectors (FD) and Surface Detectors (SD) as ground arrays. It is generally believed that FD is better suited to measure the absolute energy of cosmic rays, thanks to its sensitivity to totally calorimetric energy deposition in atmosphere. However this view is overly simplified. At first, there is no "standard candle" in nature which calibrates the absolute scale of fluorescence photon intensity per energy deposit. Second, due to atmospheric scattering along the photon's path to the detector, one must make large, non-linear corrections which strongly depend on atmospheric conditions (and distance) between the cosmic ray shower and the detector. As a result, to estimate the absolute energy, an enormous amount of different quantities must be calibrated piece by piece. In order to demonstrate this problem more visually, one can express the relation between measurable quantities and observed signals both in photon yield measurement and in a real experiment. In the photon yield measurement, the observed amount of signal per $dX$ is given by

$$\begin{aligned}\frac{dS'(\lambda)}{dX} &= \frac{dE'}{dX}(E') \cdot Y(\rho', T', \lambda) \cdot \frac{1}{r'^2} \\ &\times \; O'(\lambda) \cdot QE'(\lambda, \theta') \cdot CE'(\vec{B}') \cdot G'(HV', T', I'_A) \qquad (1)\end{aligned}$$

pp. 861–864 ©2003 by Universal Academy Press, Inc.

Here, the "prime" of each quantity indicates that these are the quantities measured in the laboratory which is separated from real cosmic ray experiments. In the real cosmic ray experiments, the observed signal per $dX$ is given by

$$\begin{aligned} \frac{dS(\lambda)}{dX} &= \frac{dE}{dX}(E) \cdot Y(\rho(t,\vec{x}), T(t,\vec{x}), \lambda) \cdot \frac{1}{r^2} \cdot \exp(-\frac{r}{\Lambda(\lambda,t,\vec{x})}) \\ &\times\ O(\lambda) \cdot QE(\lambda,\theta) \cdot CE(\vec{B}') \cdot G(HV,T,I_A) \end{aligned} \tag{2}$$

Finally the total visible energy of the cosmic ray can be obtained by equalizing the photon yields, $Y$ (per unit energy loss) in Equations (1) and (2), and given by

$$\begin{aligned} E_{vis} &= \int\int \frac{dX}{dS'(\lambda)} \cdot \frac{dE'}{dX}(E') \cdot \frac{Y(\rho',T',\lambda)}{Y(\rho(t,\vec{x}),T(t,\vec{x}),\lambda)} \cdot \frac{r^2}{r'^2} \cdot \exp(\frac{r}{\Lambda(\lambda,t,\vec{x})}) \\ &\times\ \frac{O'(\lambda) \cdot QE'(\lambda,\theta') \cdot CE'(\vec{B}') \cdot G'(HV',T',I'_A)}{O(\lambda) \cdot QE(\lambda,\theta) \cdot CE(\vec{B}) \cdot G(HV,T,I_A)}\, dS(\lambda)\, d\lambda \end{aligned} \tag{3}$$

The following table summarizes the definition of parameters used above. Please note that, time, position and/or environmental dependence of these parameters are specifically expressed to indicate the propagation of systematic errors. For example, $QE$ depends on wavelength ($\lambda$) and incident photon angle ($\theta$), whereas $CE$ depends on external magnetic field ($\vec{B}$) and so on.

| Symbol | Definition |
|---|---|
| $S(\lambda)$ | Amount of the signal recorded by the detector system for given wavelength ($\lambda$). |
| $QE(\lambda,\theta)$ | PMT Quantum Efficiency as a function of wave length ($\lambda$) and photon incident angle ($\theta$). |
| $CE(\vec{B})$ | Correction Efficiency as a function of external magnetic field ($\vec{B}$). |
| $G(HV,T,I_A)$ | PMT Gain as a function of High Voltage ($HV$), temperature ($T$) and Anode Current ($I_A$). |
| $dE/dX$ | Energy loss per unit gramic-length [$MeV/(gram/cm^2)$]. |
| $Y(\rho,T,\lambda)$ | Photon yield per unit energy loss [$\#Photon/MeV$] as a function of atmospheric density ($\rho$) and temperature ($T$) for given wavelength ($\lambda$). |
| $\Lambda(\lambda,t,\vec{x})$ | Effective attenuation length of fluorescence photons for given wavelength ($\lambda$), time ($t$) and location ($\vec{x}$). |
| $O(\lambda)$ | Photon acceptance of optical system for given wavelength ($\lambda$). |

It is clear from (3) that the fundamental difficulty of absolute energy measurement by FD comes from the fact that the detector system for photon yield study and that for real cosmic ray observation are totally different, thus all the systematic errors are not canceled but accumulated, piece by piece.

## 2. Systematic Errors in Photon Yield Measurements and HiRes

So far, all the ongoing FD (such as HiRes and Pierre-Auger) rely on the photon yield measurements which are independently carried by others such as Bunner[1], Kakimoto[2] and Nagano[3]. Let's take the most widely used one, Kakimoto[2] as an example. They did not measure $QE'(\lambda, \theta')$ nor $CE'(\vec{B}')$ by themselves, but rather they trusted the measurement provided by the PMT manufacturer. It is a very dangerous game, as $QE$ depends on the incident angle of photons and $CE$ depends on the external magnetic field. Their assumption of 10% systematic error on $QE$ and $CE$ together appears too optimistic, and one can argue that it should be $\sim 20\%$ or more.

Recent publications show that the energy spectrum of UHECR observed by HiRes[5] is about a factor of two lower than that of AGASA[4]. As pointed by Olinto[6] and others, $\sim 30\%$ energy shift (by one experiment to match the other) could explain this discrepancy, as the energy spectrum is more like $\sim 1/E^3$. One should point out that, according to Equation (3), the poor (non) calibration of the PMT used by Kakimoto's photon yield measurement (which is the base of HiRes energy estimate) can easily be blamed for this discrepancy.

Even if the PMT calibration in photon yield measurements was carefully performed, as shown in (3), the total energy depends on so many other parameters: photon yield ($Y$) depends on density ($\rho$) and temperature ($T$) of local atmosphere, atmospheric scattering ($\Lambda$) depends on local condition of aerosol, and PMTs in the telescope have different $QE$, $CE$ and Gain, one by one. Needless to say, most of them are time dependent as well. The energy spectrum by HiRes[5] does not take into account of any of these effects, and they are not addressing the systematic uncertainties due to these factors either.

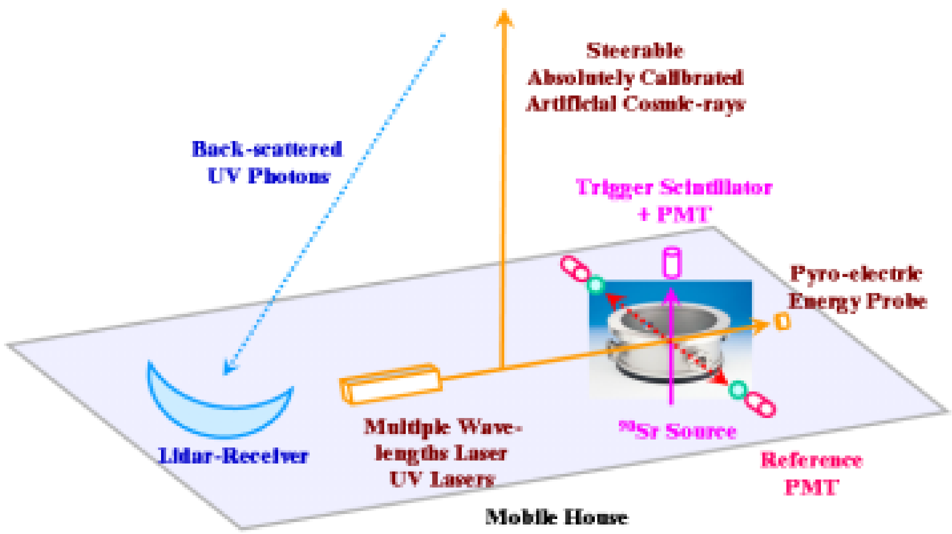
In conclusion, the current level of calibration for FD, such as HiRes, is still too premature to derive the absolute energy scale of UHECR at an accuracy, say, better than $\sim 30\%$.

## 3. Concept of "Mobile ACE"

¿From the above argument, it is clear that traditional "piece-by-piece" calibration accumulates unacceptable amount of systematic errors. (More detail is presented in [7].) The fundamental problem arises from the fact that photon yield/emission, propagation and detection have never been measured nor calibrated by the same detection system in situ. How can we overcome this? The obvious solution would be to shoot high-intensity electron beams (with known energy/flux) into the sky. Unfortunately, such a method seems impractical.

Then the question is, how can we achieve something similar in more realistic way? To answer this, the concept of "Mobile ACE (Artificial Cosmic ray Emitter)" is shown in the figure below. The system would be setup in situ (Utah or Malargue). Basically it starts from a $\beta$ source which emits $\sim 2MeV$ electrons into the local air stored in an enclosed chamber (like Kakimoto's experiment). The photon yield is measured by the well-calibrated PMTs which are shared by the rest of calibration system (such as the drum calibration in Pierre-Auger FD). More importantly, a laser beam is shot into the same chamber, and its side scattered light is monitored by the same PMTs. This way, energy deposit by electrons in the air is directly transfered into the intensity of the laser beam, totally independent of any calibration constant of the PMT. As a result, the intensity of the side scattered light from the laser beam is absolutely calibrated against the energy deposit of charged particles in the air. This beam can be shot to high sky to mimic cosmic rays, thus "Artificial Cosmic ray Emitter" is realized. To monitor atmospheric condition, back-scattered light should be traced by a LIDAR.

Once such a system is setup in a mobile house (or on a track), it can be moved from Malargue to Utah to cross calibrate Pierre-Auger and HiRes. It could be used to transfer the constant from Pierre-Auger to EUSO as well by observing the same laser shots by the two experiments simultaneously.




## References


1. Bunner A. 1967, PhD Thesis (Cornell University)
2. Kakimoto F. et al. 1996, NIM **A372**, 224
3. Nagano M. et al. 2003, astro-ph/0303193, submitted to Elsevier Science
4. Takeda M. et al. 1998, Phys. Rev. Lett. **81**, 1163
5. Abu-Zayyad T. et al. 2002, astro-ph/0208301, astro-ph/0208243
6. Olinto A. et al. 2003, astro-ph/0301497, astro-ph/0303177
7. Arisaka K. 2002, Talk presented at First International Conference on Air Fluorescence, Utah