Optical Calibration of the Auger Fluorescence Telescopes

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John A.J. Matthews

New Mexico Center for Particle Physics

University of New Mexico

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3. Absolute optical calibration
   - *Piece-by-piece* calibration
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4. Relative optical calibration
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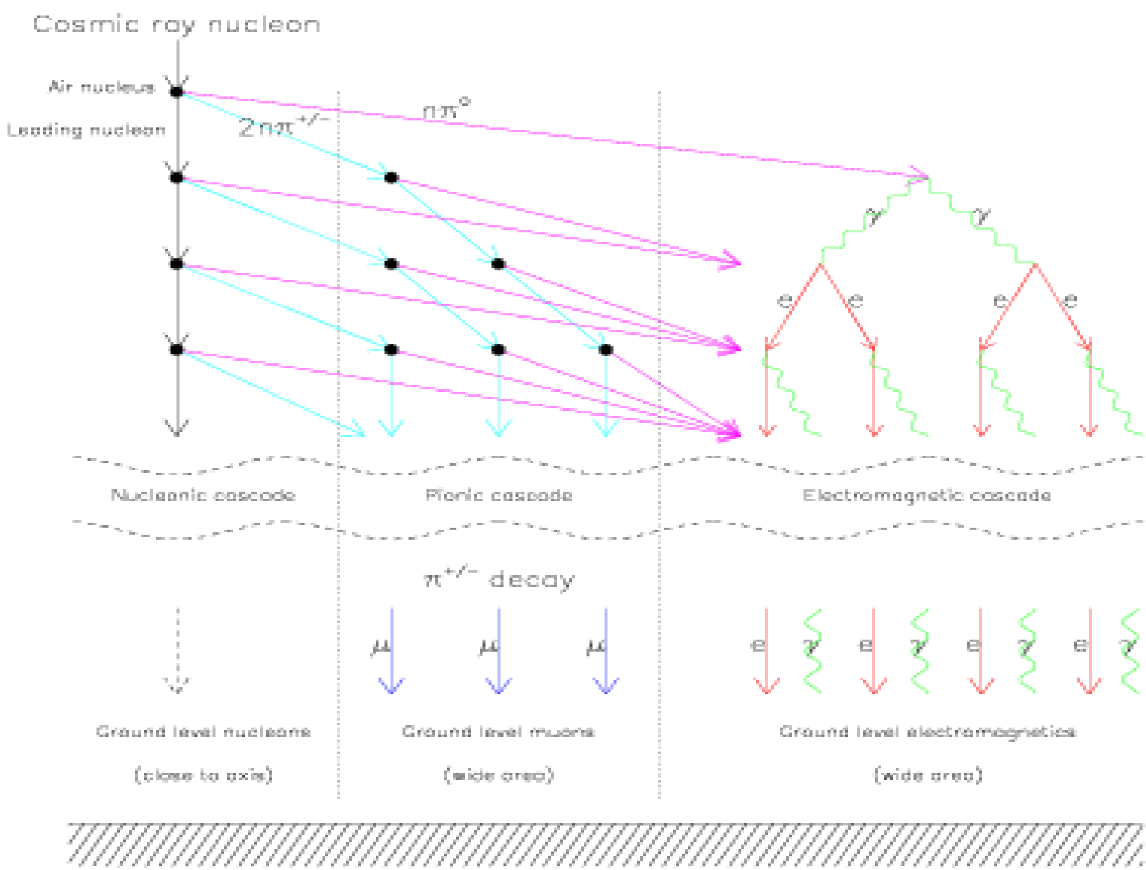
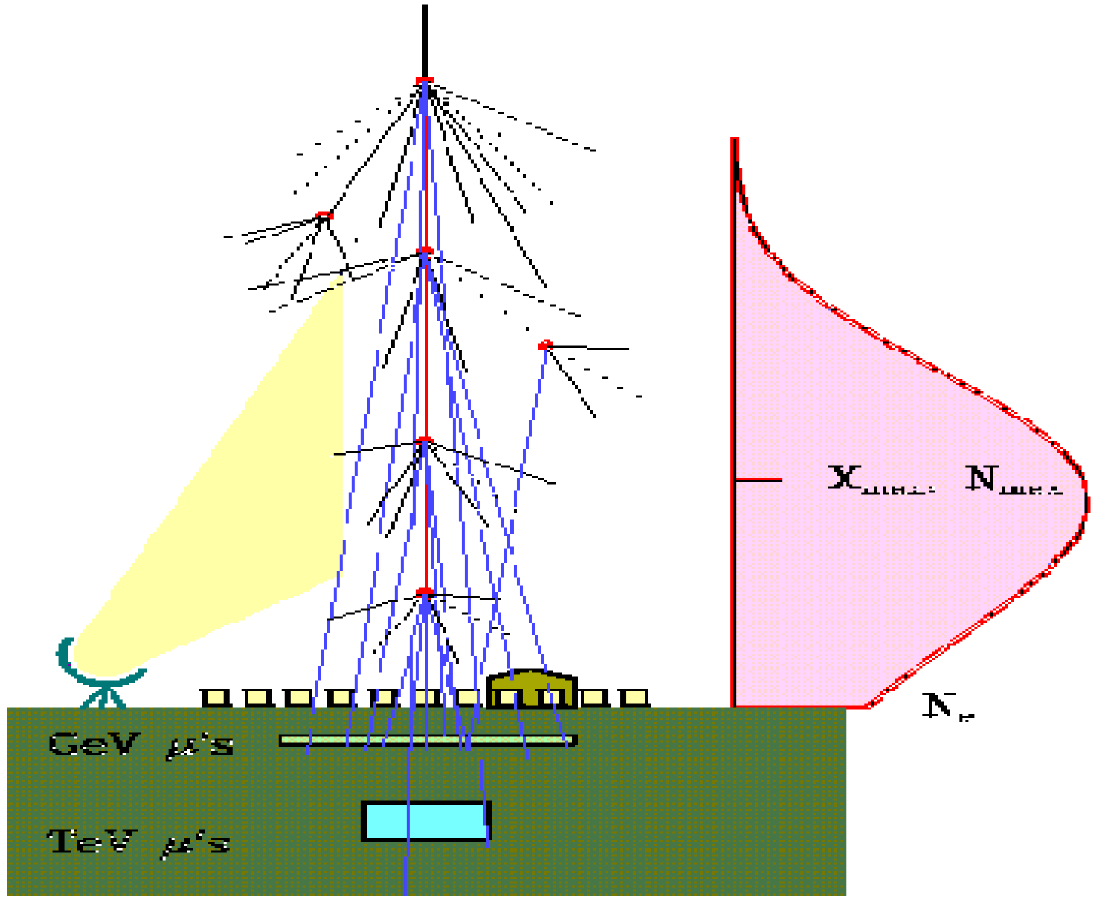
1. Background ... highest energy cosmic rays



Schematic of extensive air shower cascade

- **Energy scale:** - 10^{20} eV ≈ 16 Joules **...** <u>well</u> above future collider energies.
  1. cosmic rays are *observed* via the extensive air shower produced when they reach the earth's atmosphere
  2. 16Joules/∼ 16μsec (typical shower time) ≈ 1 MW !

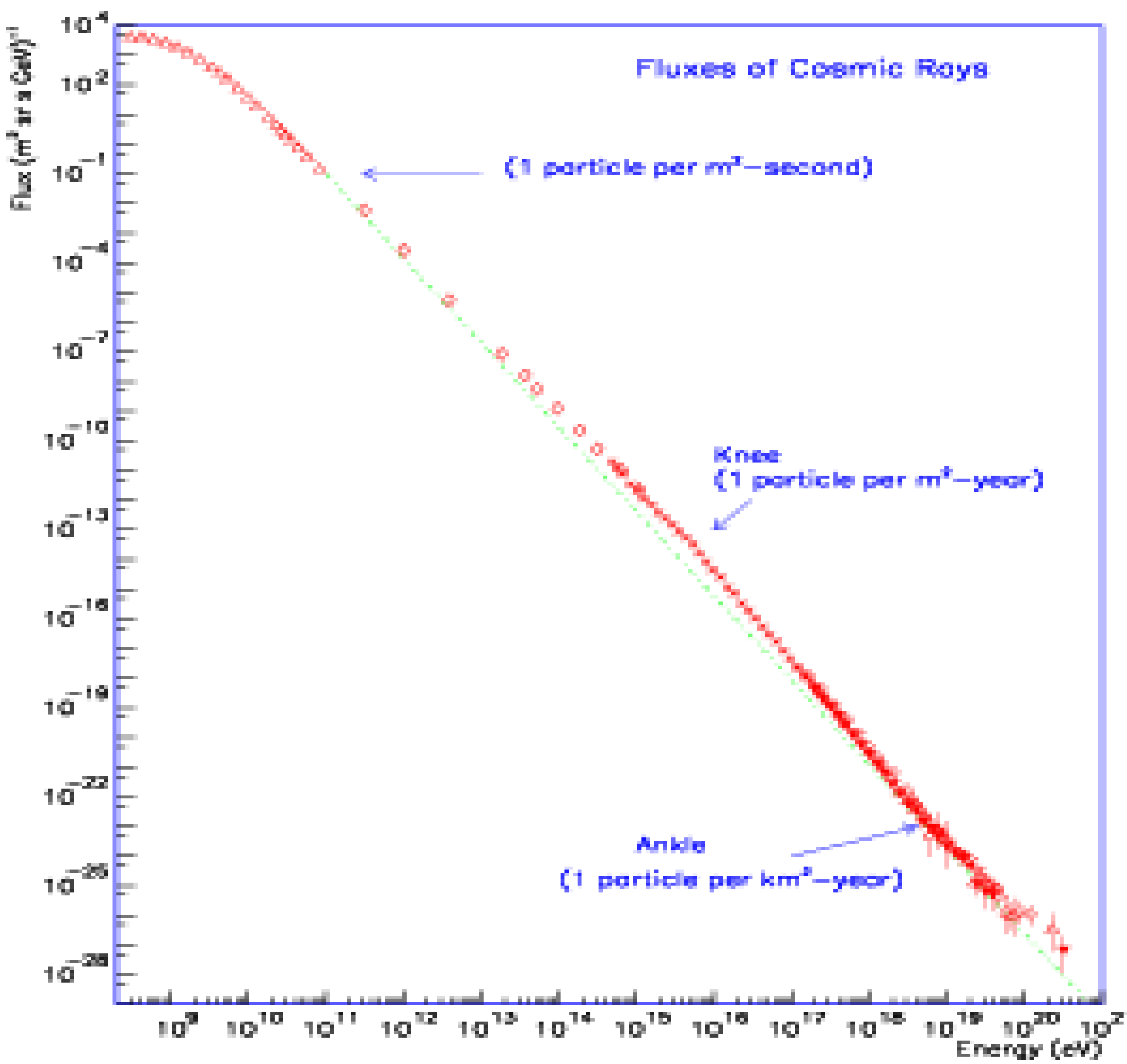
1. Background (con't) ...



Schematic of air shower measurements

- **Measurement of 10^{20}eV air showers:**
  1. km's *wide* at ground level ... sparse sampling OK!
  2. Composition of *primary* cosmic rays from depth of shower maximum, X_{max}, and/or from μ/e ratio.
  3. $\sim$ 50ppm of shower energy is re-emitted as nitrogen *fluorescence* light (290 $\sim$ 440nm) ... thus a 1-MW shower appears as a 50W relativistic *light bulb*!

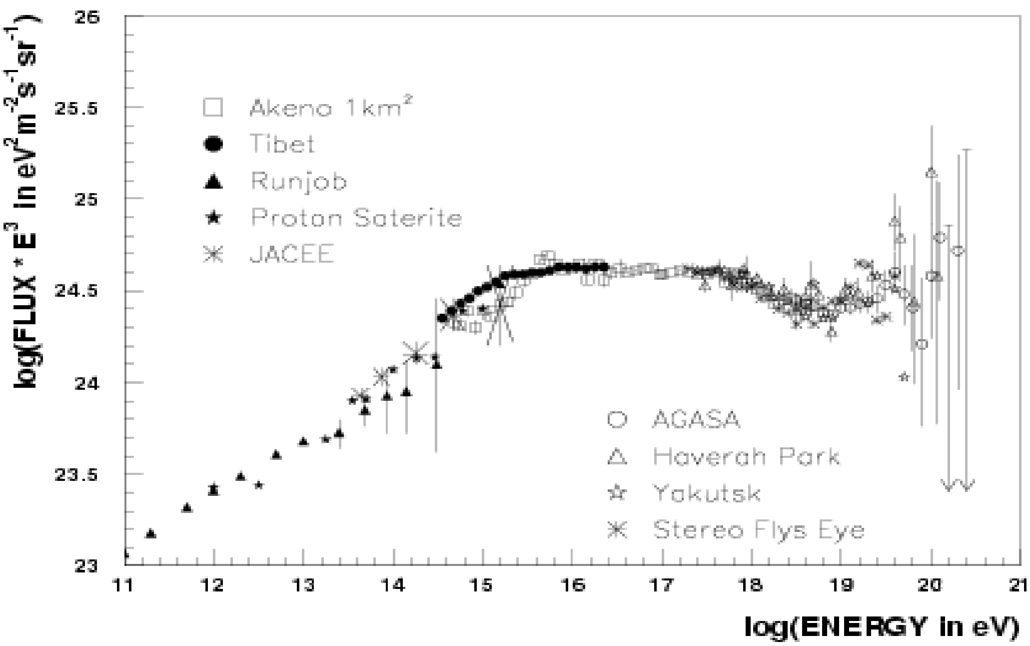
1. Background (con't) ...



Cosmic ray energy spectrum

- **Rate:** - low ($\sim 1/\text{km}^2/\text{century}$) **...** so need large experiments ... about the area of Rhode Island! Fluorescence based experiments need dry (desert) air with good visibility.

1. Background (con't) ...

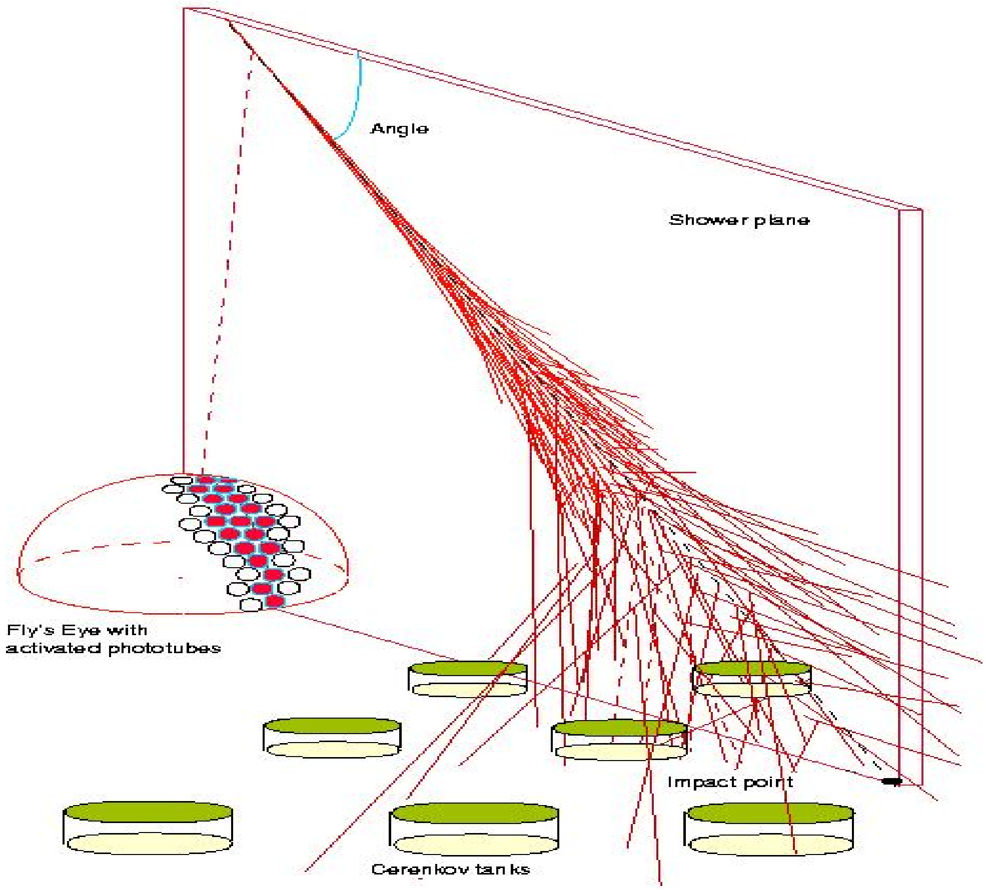


Cosmic ray flux scaled by E^3

- **Structure in a power law spectrum:**
  1. *knee* at $\sim 4 \times 10^{15}$eV
  2. second *knee* at $\sim 4 \times 10^{17}$eV
  3. *ankle* $\sim 4 \times 10^{18}$eV
  4. *cutoff* at $\sim 10^{20}$eV ... or not ... **therefore absolute energy scale is critical!**

1. Background (con't) ...

Detection method



Pierre Auger *hybrid* detection ...

1. Hybrid detection: simultaneous measurement of the air shower by a ground array and by fluorescence telescopes
2. Hybrid events cross-check and cross-calibrate the two types of detectors and provide the best *composition* measurement
3. Ground array (only) events provide most statistics (*i.e.* highest energy events)

1. Background (con't) ...

Typical Pierre Auger ground array detector ...

$10m^2$, 1.2m deep, water cherenkov detector

Solar powered, radio communication to central trigger

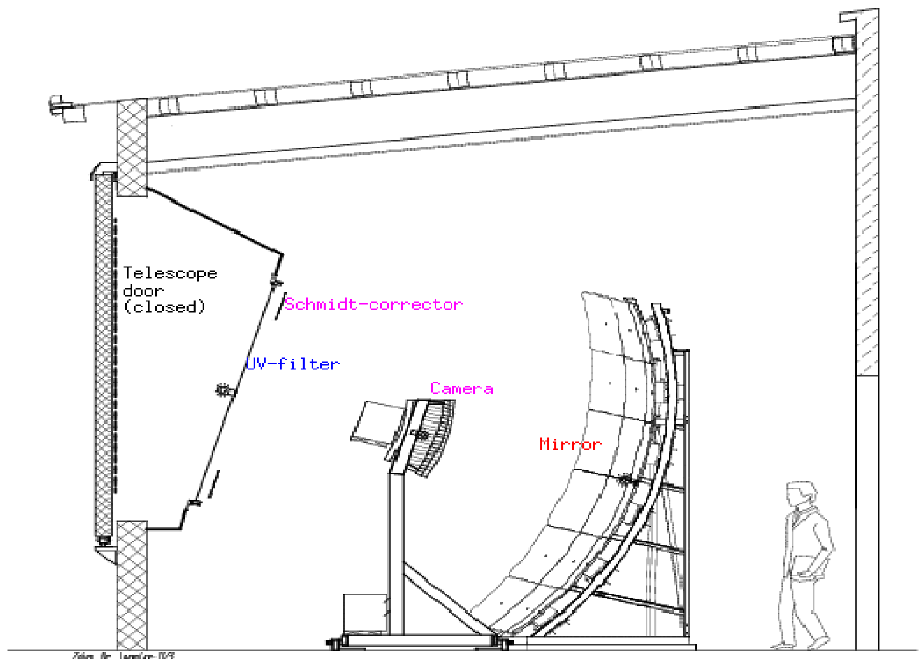
1. $>$ 30 of 1600 ground array detectors installed and running + 2 prototype fluorescence telescopes (*engineering array* **test from Nov. 2001 $\sim$ Mar. 2002**)
2. $\sim$ 100 ground array detectors and 12 of 24 fluorescence telescopes scheduled to be operational by summer 2003

1. Background (con't) ...

Los Leones **fluorescence detector building**

- **Auger experiment ...** ground array is overlooked by 4 *6-telescope* fluorescence detectors
- **Fluorescence detectors**:
  1. Image the shower (longitudinal) development,
  2. Provide a calorimetric measurement of the shower energy.
  3. **The validity of the shower energy relies on the absolute calibration of the fluorescence telescopes**.

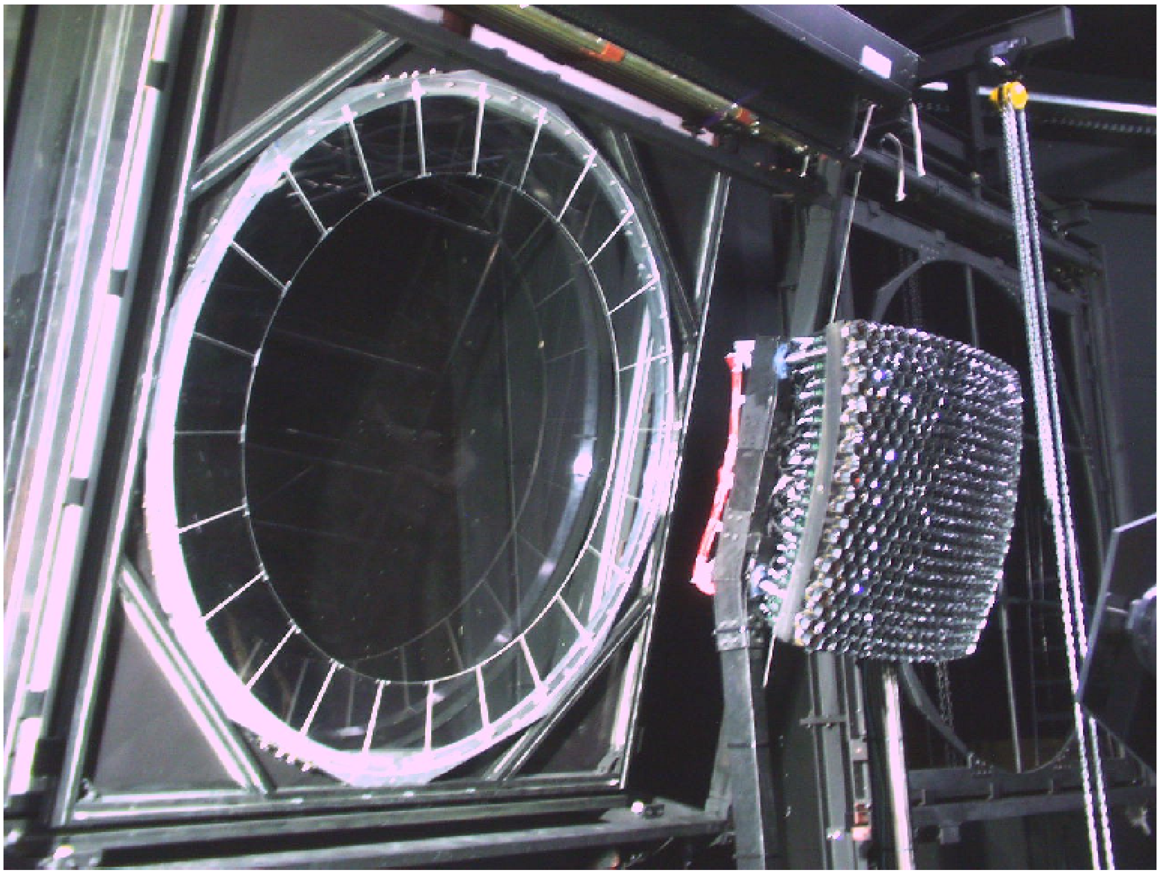
2. Fluorescence detector calibration ... overview



Schematic of the Auger fluorescence telescopes.

- The fluorescence light from the extensive air shower will be captured by the fluorescence telescopes, focused on cameras subdivided into 440 pixels, and digitized.
- **The telescope calibration provides the conversion between digitized signal, in ADC units, and photons incident on the 3.80m^2 telescope aperture.**
- The calibration *efficiency*, for the i^{th}-pixel in the j^{th}-telescope, is denoted: $\epsilon_{ADC}(\lambda)_{i,j}$ (ADC/photon).

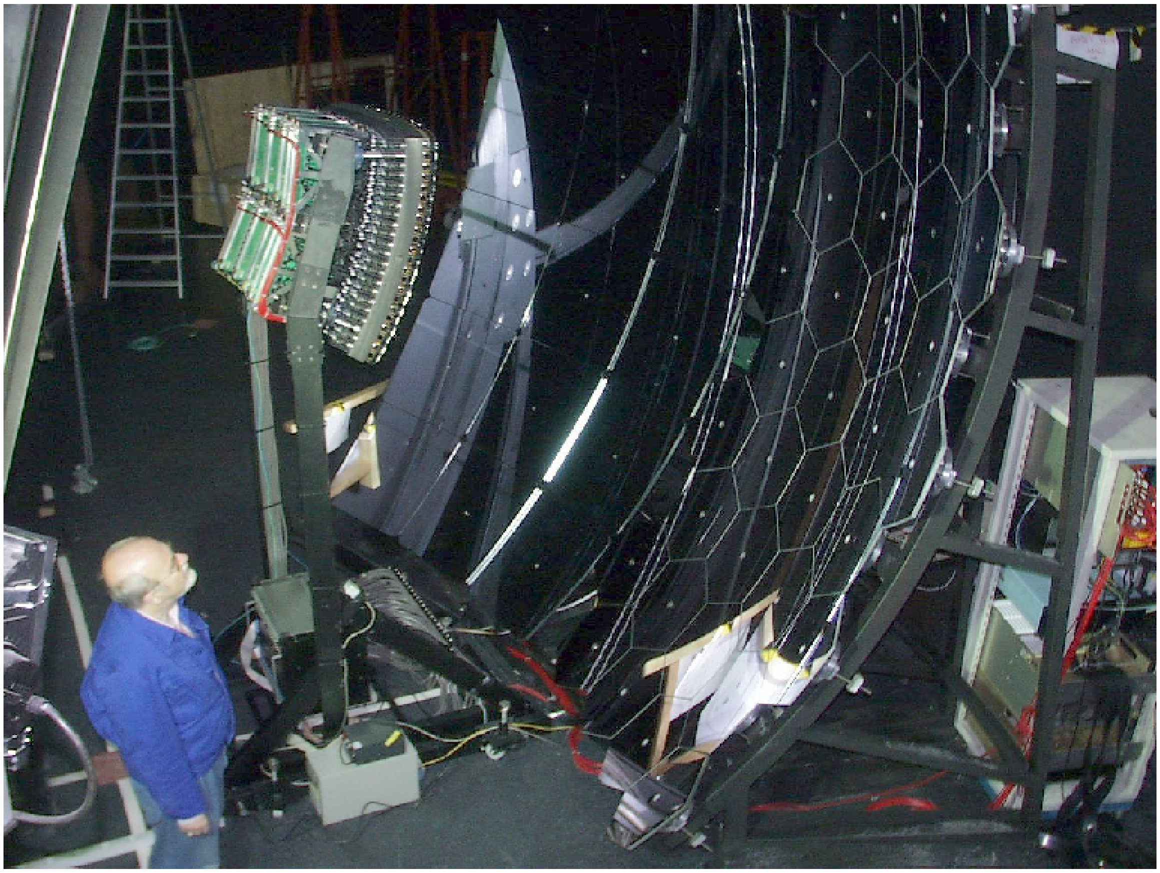
2. FD calibration overview (con't) ...



Auger fluorescence telescope.
Aperture and camera of prototype

- 2.2m diameter telescopes are a simple Schmidt system.
- UV filters, in the entrance aperture, provide a window and exclude light with wavelengths > 420nm.
- Schmidt corrector elements cover radii of $0.85m < r < 1.1m$.

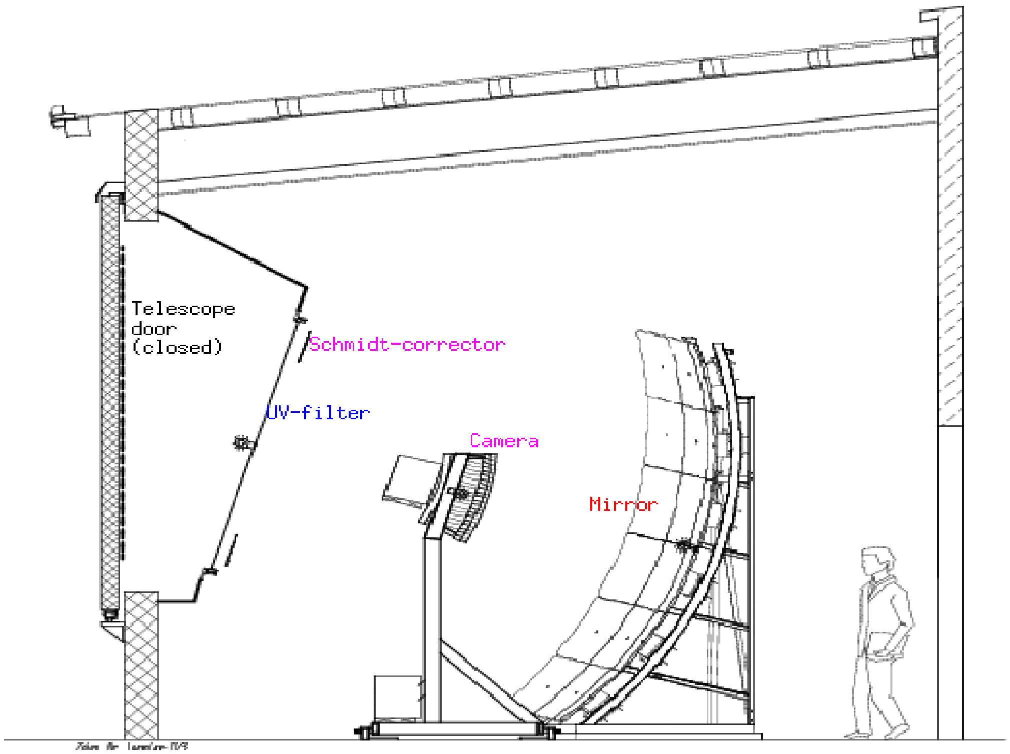
2. FD calibration overview (con't) ...



Mirror and camera of prototype fluorescence telescope.

- Light is focused by a large 3.9m x 3.9m spherical mirror (needed to accommodate the $30° \times 30°$ field of view).
- The camera contains 440 PMTs on a spherical surface.
- Cracks between PMTs are covered by reflective triangular inserts termed *Mercedes*.
- **The calibration must incorporate all the details!**

2. FD calibration overview (con't) ...



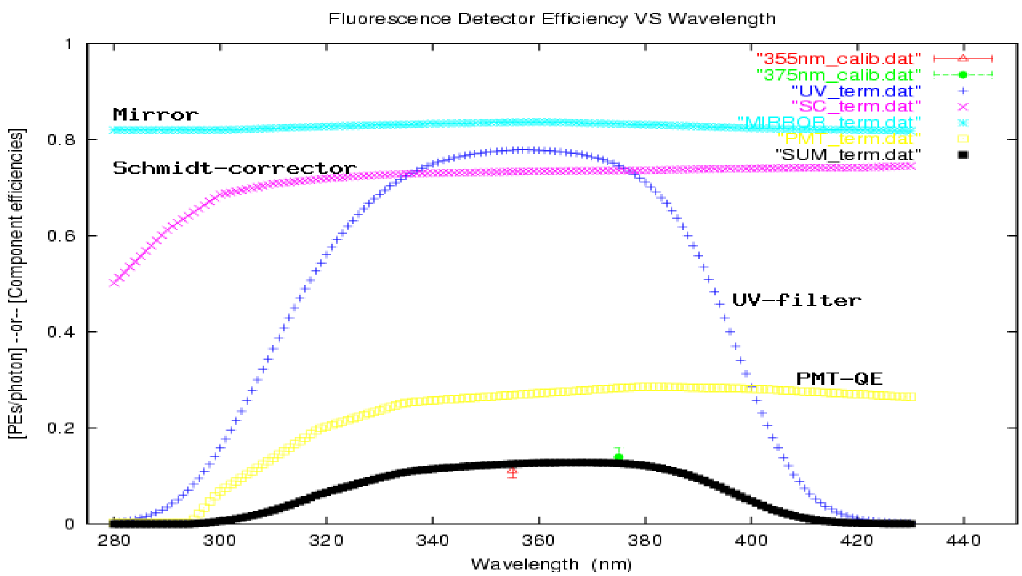
Schematic of the Auger fluorescence telescopes.

- The combined efficiency for all of the components must be known and changes in the efficiencies with time must be tracked.
- **This calibration task has been broken down into two separate sub-tasks:**
  - **absolute** calibrations which are infrequent, and
  - **relative** calibrations which are frequent.

2. FD calibration overview (con't) ...

- The **relative** calibrations are to monitor time dependent changes between absolute calibrations.
- The **absolute** calibrations are done in three separate ways:
  - *piece-by-piece* estimate,
  - *Rayleigh* scattering from 355nm pulsed laser beam(s),
  - flat-field *drum illuminator*(s) with 375±12nm LED pulsed source.
- The *Rayleigh* and *drum illuminator* calibrations provide an absolute, end-to-end calibration of the fluorescence telescopes.
  - By **absolute** we mean that the flux of photons on the telescope aperture is independently measured and known to an absolute precision: nominally $\sim 5\%$.
  - By **end-to-end** we mean that the calibration procedure includes all efficiencies and geometrical effects. **The end-to-end calibration procedure measures the ADC/photon efficiency, $\epsilon_{ADC}(\lambda_{source})_{i,j}$, at wavelength λ_{source} in one step.**

3. Absolute optical calibration

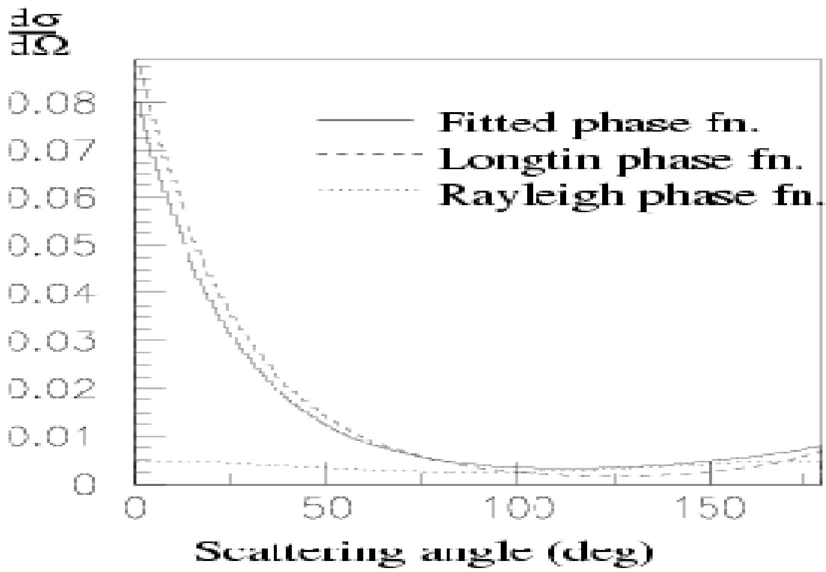


Piece-by-piece **calibration:** $\epsilon_{PE}(\lambda)$ (PE/photon).

Note: the *Schmidt-corrector* contribution includes the combined effect of the corrector ring and the camera shadow.

- Transmission and reflection efficiencies are measured for each telescope component.
- These are combined in a ray-tracing program to estimate the PE/photon efficiency, $\epsilon_{PE}(\lambda)_{i,j}$.
- The ADC/photon efficiency is given by: $\epsilon_{ADC}(\lambda)_{i,j} = \epsilon_{PE}(\lambda)_{i,j} \cdot g_{i,j}$ where $g_{i,j}$ is the electronics gain (ADC/PE) ... typical values were ~ 1.8 ADC/PE.
- **The (current)** *piece-by-piece* **calibration uncertainty was estimated at $\sim 20\%$.**

3. Absolute optical calibration (con't)

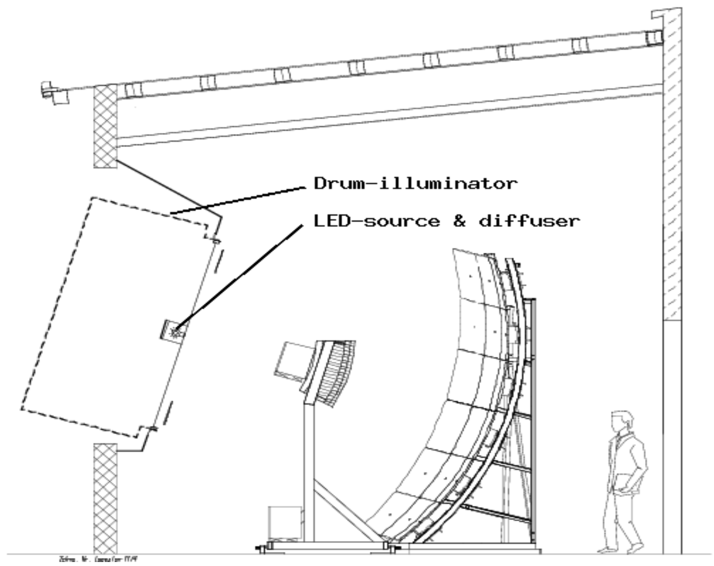


Rayleigh calibration:

Mie : Rayleigh fraction was minimized by viewing the scattered light at scattering angles, $92° < \theta < 122°$, ... and $\Lambda^{aerosol} > 40$km.

- A 355nm laser was positioned a few kilometers from the fluorescence telescope to be calibrated.
- The laser was directed near-vertical and the pulse to pulse intensity monitored to a precision of $\sim 5\%$.
- Light was scattered from the beam by Rayleigh scattering (on the molecular atmosphere) and by Mie scattering (on aerosols).
- The scattered light was then used to calibrate the telescope(s).
- **Absolute calibration values obtained for telescope-4 were: 5.1 photons/ADC and 4.9 photons/ADC with estimated uncertainty $\sim 10\%$.**

3. Absolute optical calibration (con't)

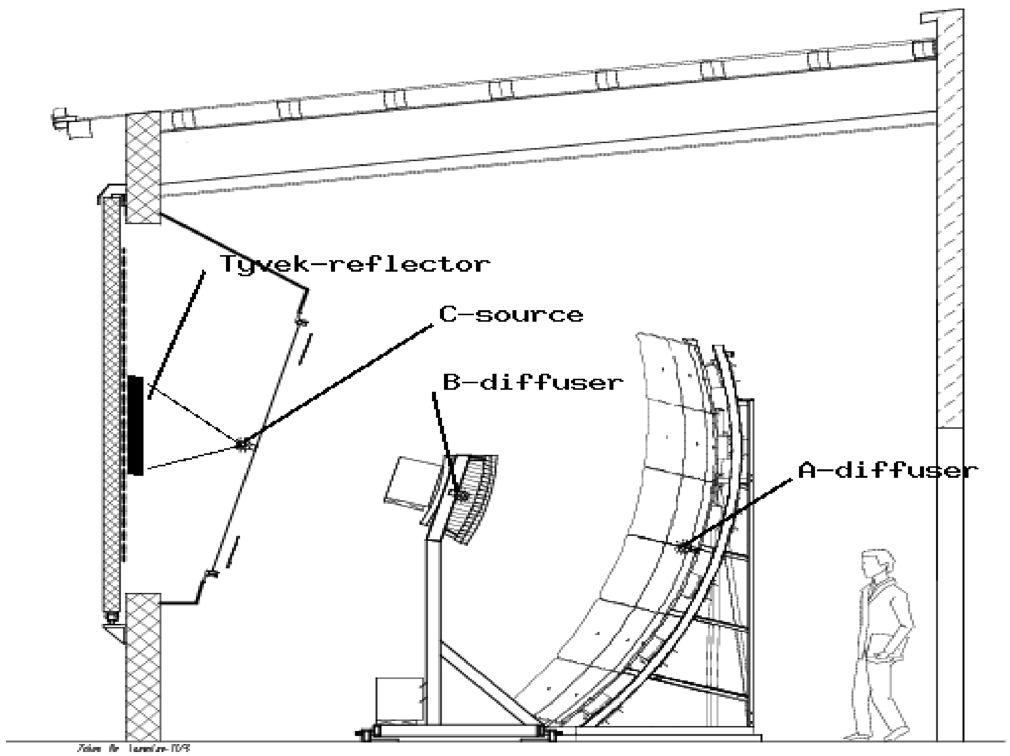


Drum illuminator **calibration:**

Schematic of *drum illuminator* positioned at the entrance aperture of one of the Auger fluorescence telescopes.

- In the *drum illuminator* calibration a drum-shaped, diffused, pulsed, light-source was positioned at the entrance aperture of the telescope under calibration.
- The *drum illuminator* provided rather uniform illumination over the entrance aperture of the telescope.
- A calibrated PMT measured the absolute light flux (from the *drum*) to a precision of $\sim 5\%$ before each telescope calibration.
- **The preliminary analysis for telescope-4 measured an average calibration of 4.0 photons/ADC with estimated uncertainty of $\sim 7\%$.**

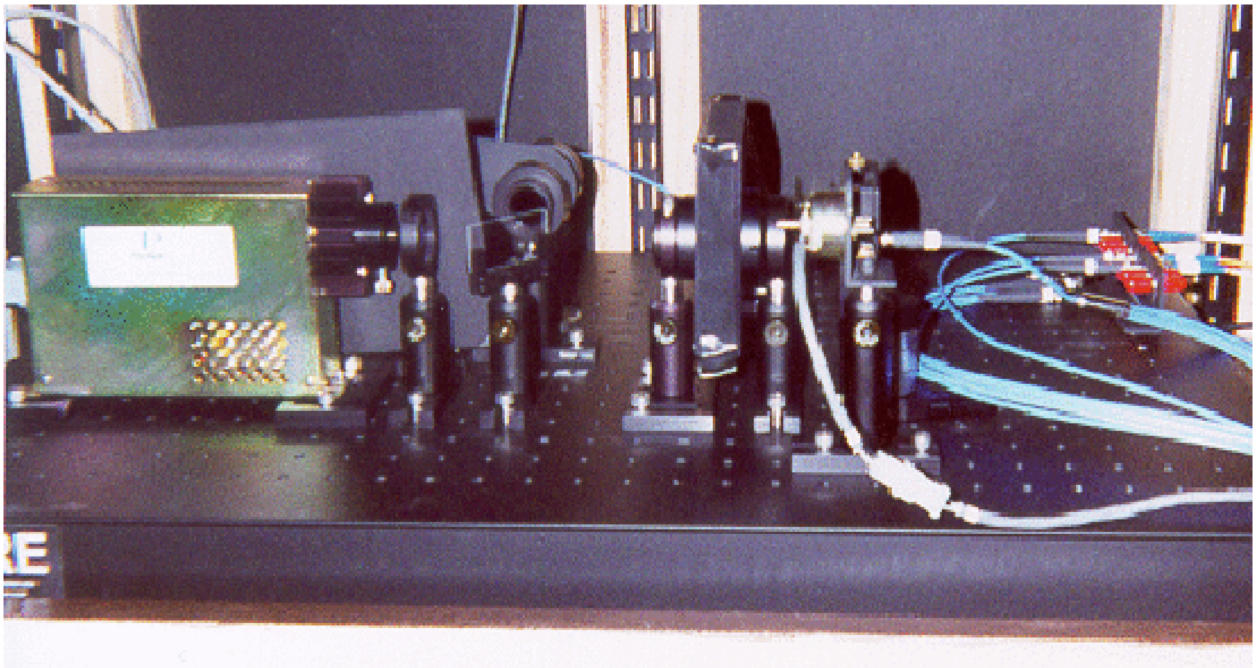
4. Relative optical calibration



Schematic of Auger fluorescence telescopes showing *relative calibration* **diffusers.**

- **The relative optical calibration system was used to monitor time variations in the telescope calibration between absolute calibrations.**
- This was done with three xenon flash lamp light sources coupled to optical fibers to distribute light signals to three different destinations (denoted A, B and C) on each telescope.

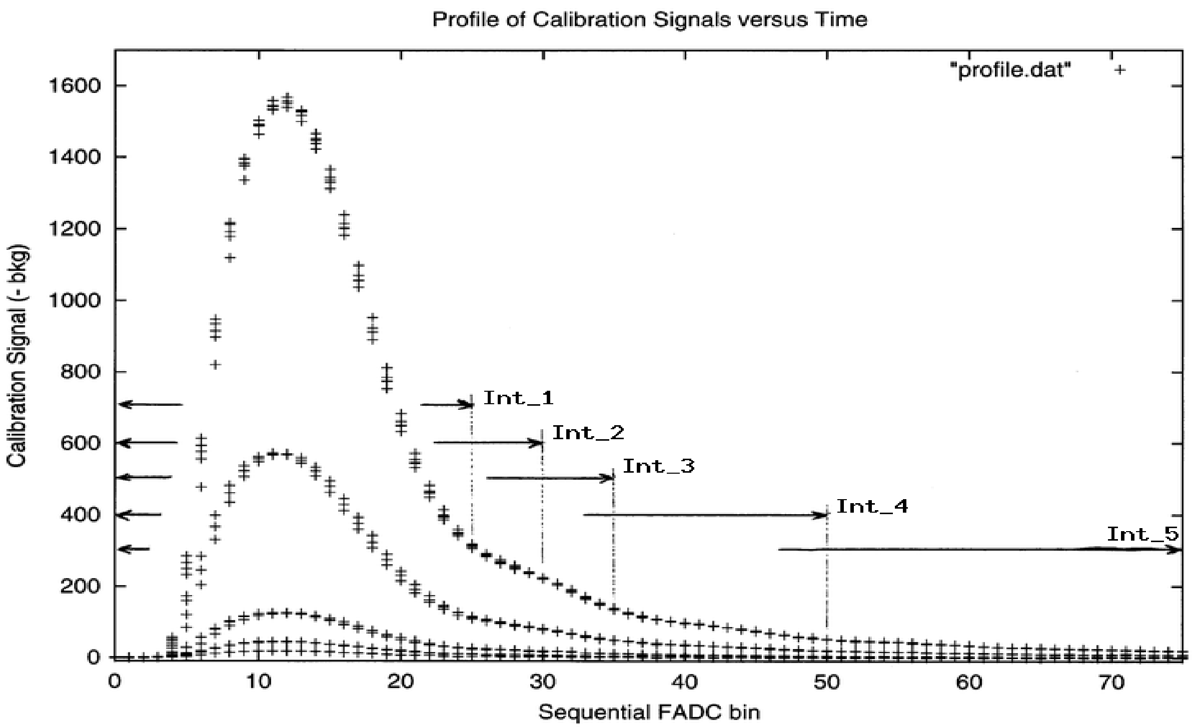
4. Relative optical calibration (con't)



Photograph of one of the three optical calibration light sources at each fluorescence detector site.

- Each calibration light source included a xenon flash lamp at the focus of a f/1.5 lens, quartz beam splitter (to a monitoring fiber), filter wheel and f/2.4 lens focusing onto a 1:7 optical fiber splitter.
- Quartz optics were used through-out.
- The optical calibration light sources mount on a 18" × 30" optical bread-board which are in-turn supported on simple wall-mounted shelves.

4. Relative optical calibration (con't)

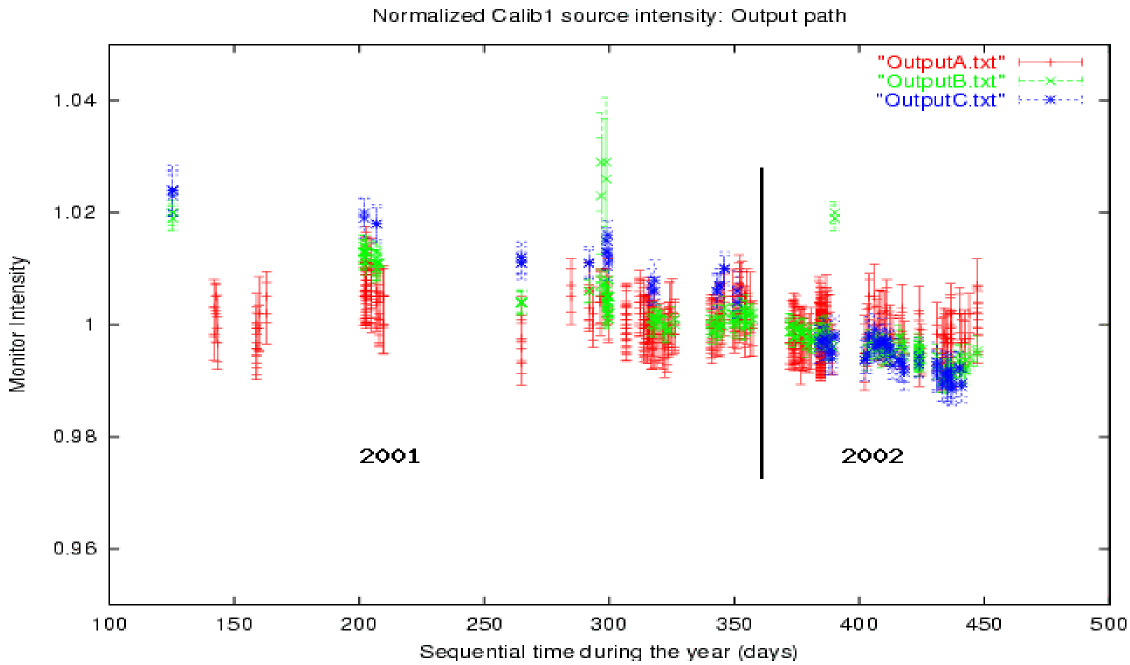


Typical light pulses from the "A"-source.

Each time bin is 100nsec. The *arrows* show different integration times used to monitor the observed signal.

- The A-source included a Johnson-U filter that approximated the wavelength acceptance of the fluorescence telescopes and a filter wheel with 5 different neutral density filters that provided a dynamic range of ~ 100.

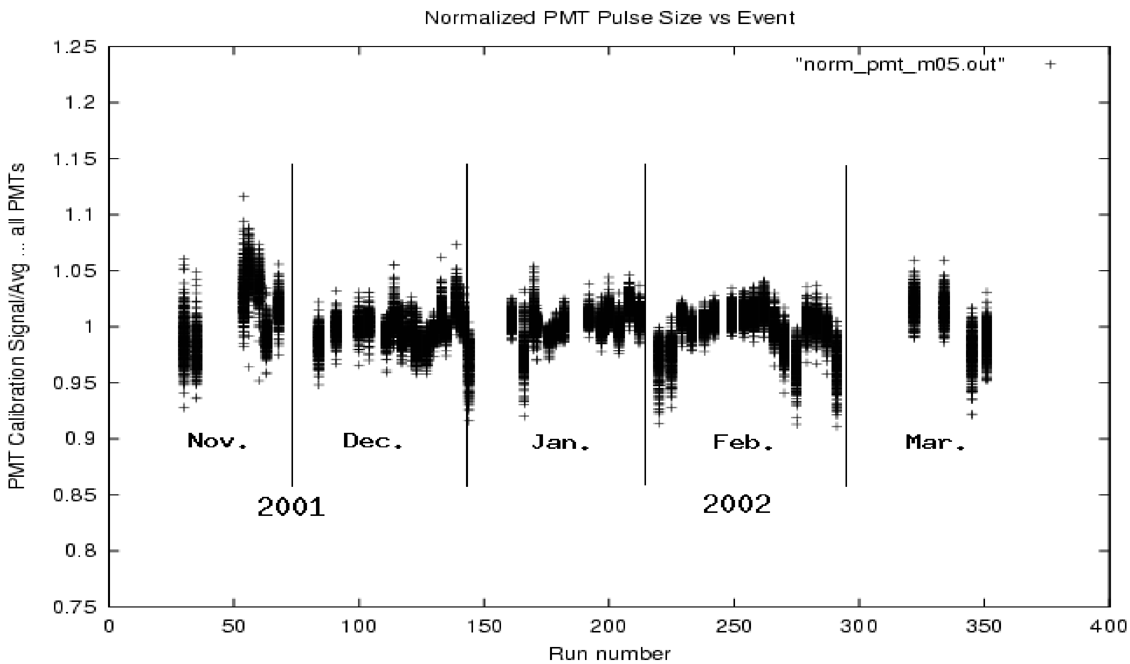
4. Relative optical calibration (con't)



Optical calibration sources' intensity during the last year. The plot shows the light pulse intensities (average ± RMS) *versus* sequential day since January 1, 2001. The intensities are normalized to the average intensity for the entire time period.

- The xenon light pulses were very stable with an RMS/average-pulse-intensity of $\sim 0.5\%$ for typical 50-pulse calibrations.
- **Over many months of operation the xenon calibration pulses varied by $\sim 1\%$.**

4. Relative optical calibration (con't)

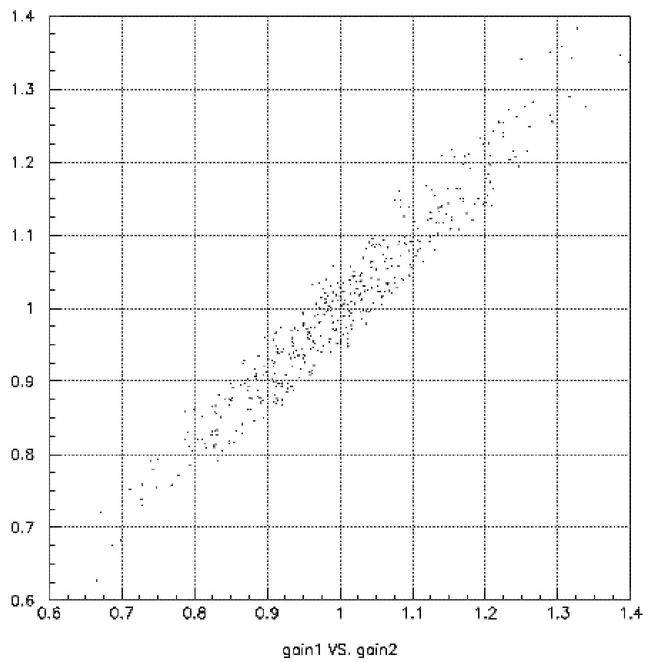


Time history of the *normalized* A-source calibration signals. All 440 pixels (PMTs) of telescope-5 are shown.

The vertical axis records each pixel's observed signal *normalized* by the average of that pixel's signal during the 5-month period. The horizontal axis is the sequential calibration *run* number.

- The vertical *smear* for each calibration run shows that the gains of individual pixels changed in time in comparison to the average (coherent) pixel trends.
- The vertical motion of the centroid of each *smear* shows that there were some coherent time variations of the pixel gains.
- **The relative pixel to pixel variations with time, and the coherent variations with time, were typically $< 5\%$.**

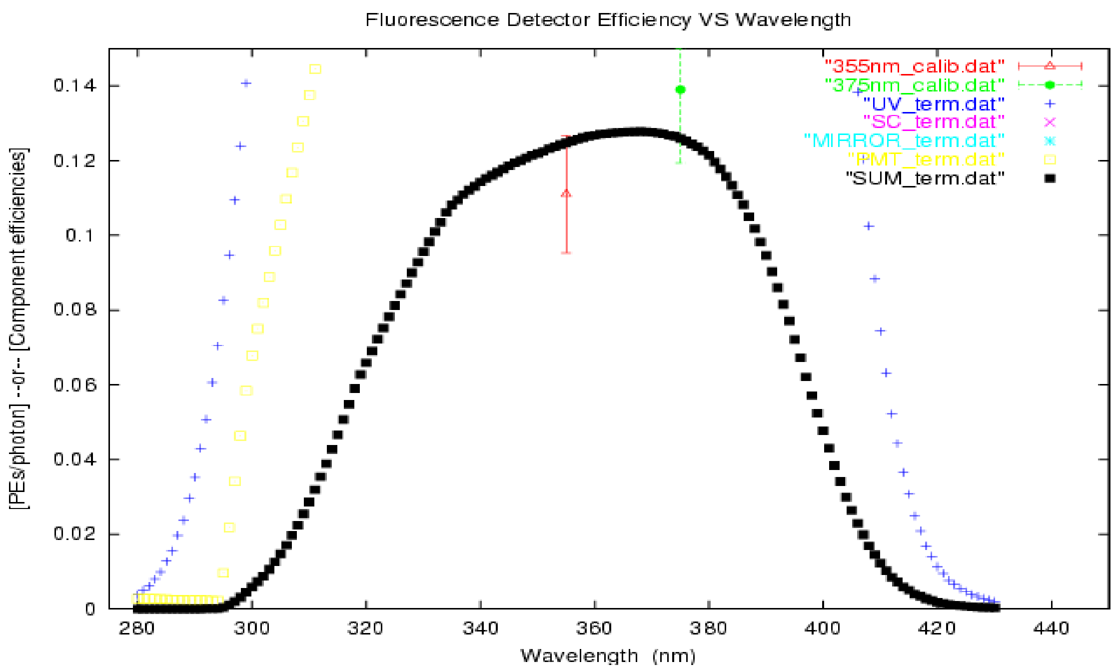
4. Relative optical calibration (con't)



Normalized **relative pixel gains from** *A-source* **calibrations**: **(vertical axis) corrected signal technique** *versus* **(horizontal axis) variance/mean-intensity technique.**

- A semi-empirical model corrected for position dependences of the light intensity at each pixel. The corrected signal in each pixel was then a direct measure of the pixel gain.
- The signal variance was used to estimate the gain, ADC/PE, in the i^{th} pixel of the j^{th} telescope: $g_{i,j} \approx \frac{\sigma_{i,j}^2}{\overline{ADC}_{i,j} \cdot 1.41}$ where $\sigma_{i,j}^2$ was the pixel signal variance and $\overline{ADC}_{i,j}$ was the pixel signal mean.

5. Summary



Comparison of the *piece-by-piece* (solid-box points), *Rayleigh* ("red"-point) and *drum illuminator* ("green"-point) calibration results. The (preliminary) gain $g = 1.8 \pm 10\%$ ADC/PE was used to plot the *Rayleigh* and *drum illuminator* absolute calibration results on this figure.

- **Auger** ***engineering array*** **test provided an opportunity to evaluate the proposed fluorescence detector calibration procedures, associated hardware and software.**
- The three calibration procedures gave commensurate results at about the 20% level.
- Work is ongoing to improve each of the procedures and we expect consistency with better accuracy in the future.