Atmospheric Monitoring for the Auger Fluorescence Detector

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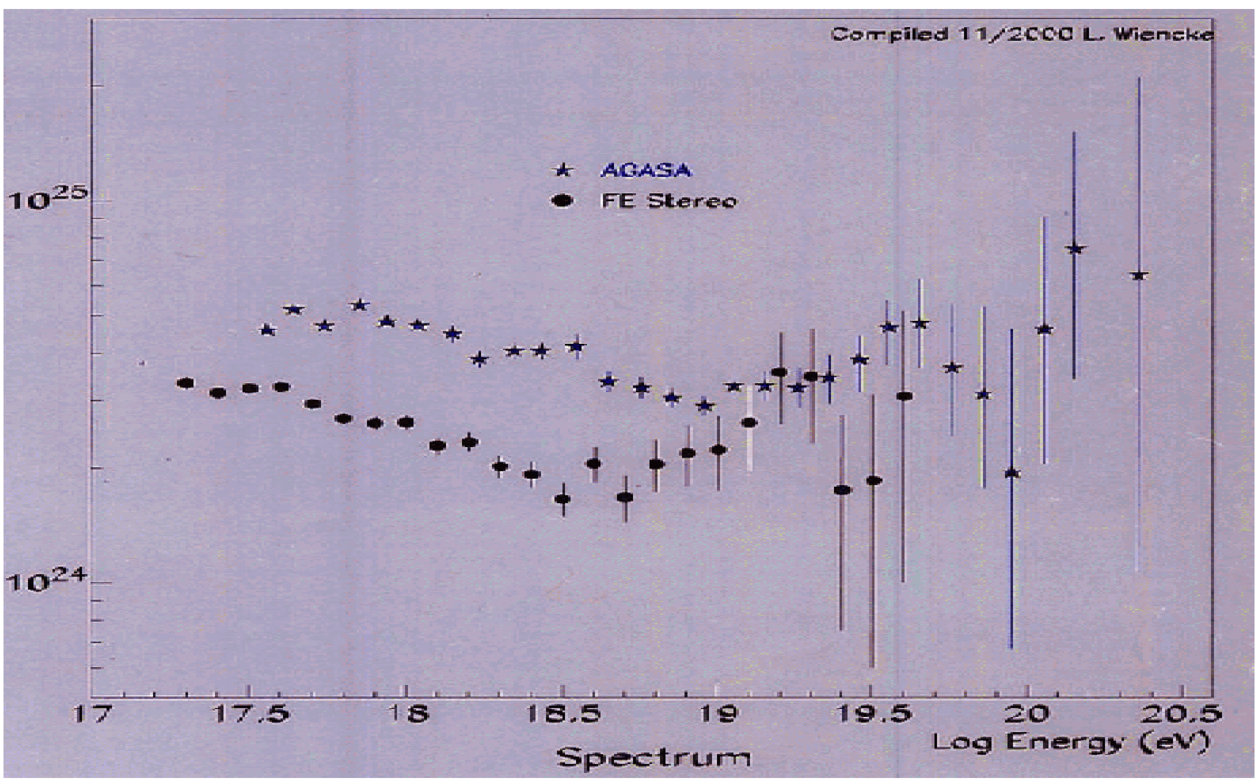
1. Air shower measurements by fluorescence detectors
2. Atmospheric characterization and corrections in Auger
   - Transmission corrections:
     (a) horizontal extinction length monitor
     (b) optical depth monitor
   - Aerosol phase function monitor
   - Cloud detection and monitoring
3. Summary

† **for the Pierre Auger Observatory Collaboration**

Air shower measurements by fluorescence detectors

- The Pierre Auger Observatory is designed to study air showers near and above the GZK cutoff.
- As a consequence we place a high importance on the precision of the *absolute energy scale* and the *energy uncertainty* of the reconstructed showers.



Comparison of AGASA and Fly's Eye spectra. The *ankle* and *normalization* provide information on differences in the absolute energy scales.

Air shower measurements by fluorescence detectors

- The Auger fluorescence measurements will set the *energy scale* for the experiment.
- Approximate 50 parts per million of the deposited shower energy is isotropically re-radiated in fluorescence emission at near-UV wavelengths.

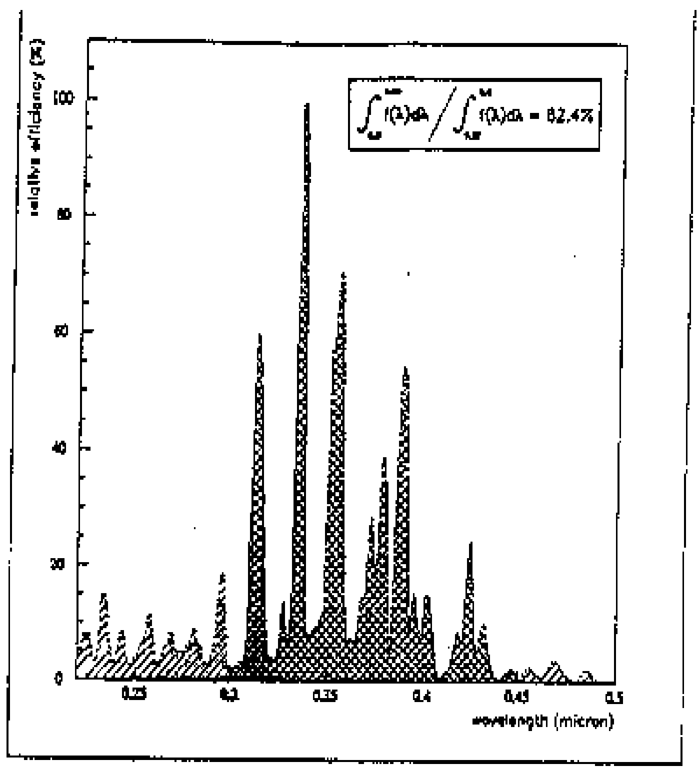
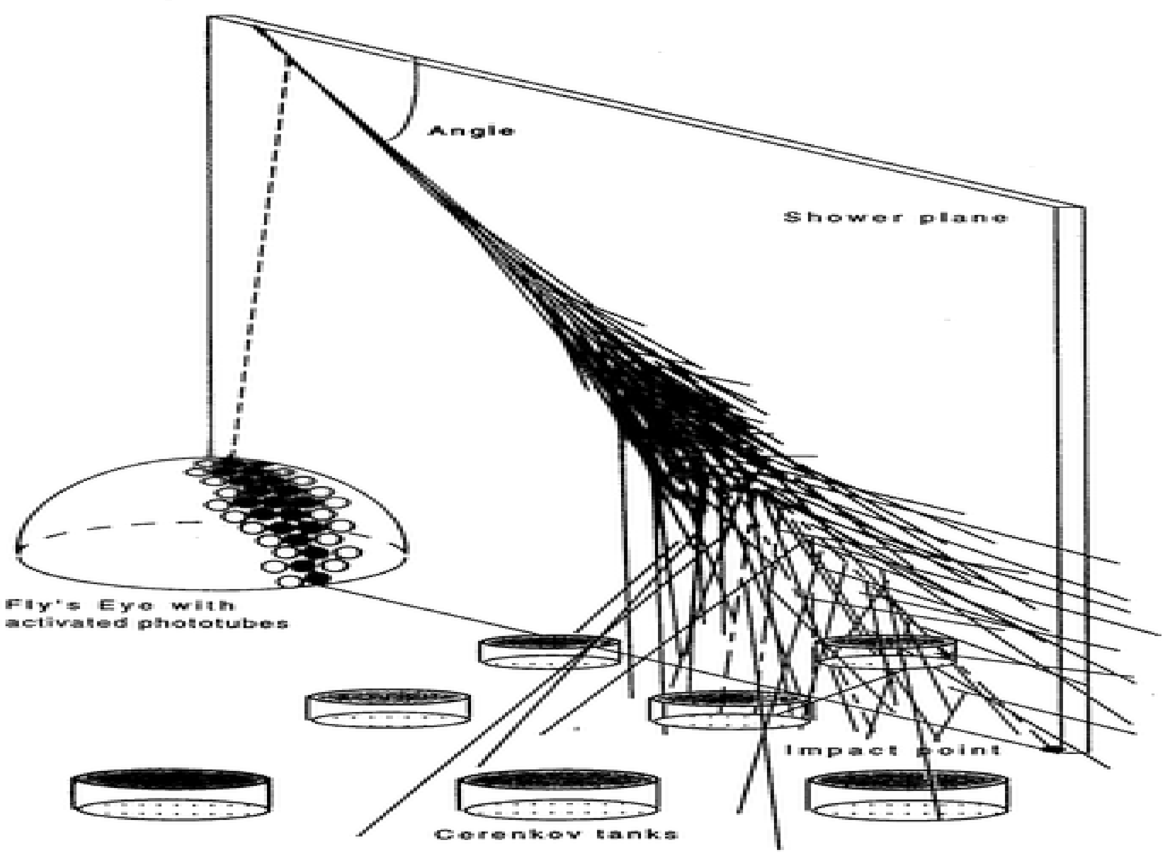


Figure 4.10: Emission spectrum of fluorescence light from the 2P band of molecular nitrogen and the 1N band of the N_2^+ molecular ion. Approximately 80% of the light is emitted between 300 and 450 nm.

Nitrogen fluorescence emission lines.

Air shower measurements by fluorescence detectors

- Auger is a hybrid experiment; a subset ($\sim 10\%$) of the events will be measured by both the Auger ground array and fluorescence detectors.
- The hybrid data provide a unique opportunity to monitor systematic errors in these two experimental techniques.



Sketch of hybrid detection concept.

Air shower measurements by fluorescence detectors

- The fluorescence energy measurements must be well understood. Our atmospheric monitoring goal is $\sim 10\%$ contribution to the energy measurement uncertainty.
- The dominant uncertainties come from:
  1. atmospheric transmission correction
  2. air Cherenkov subtraction
  3. light multiple scattering correction
  4. cloud corrections

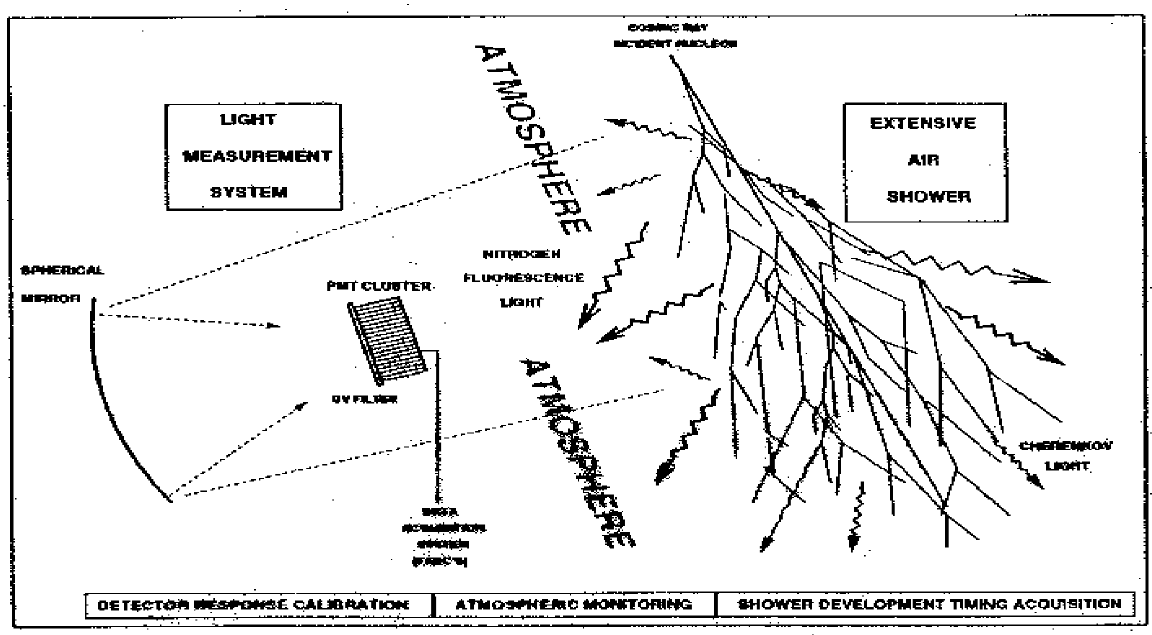


Figure 1.1. Air Fluorescence Technique.

Julián Girard, May 2000

Schematic of air fluorescence measurement issues.

Atmospheric characterization and corrections

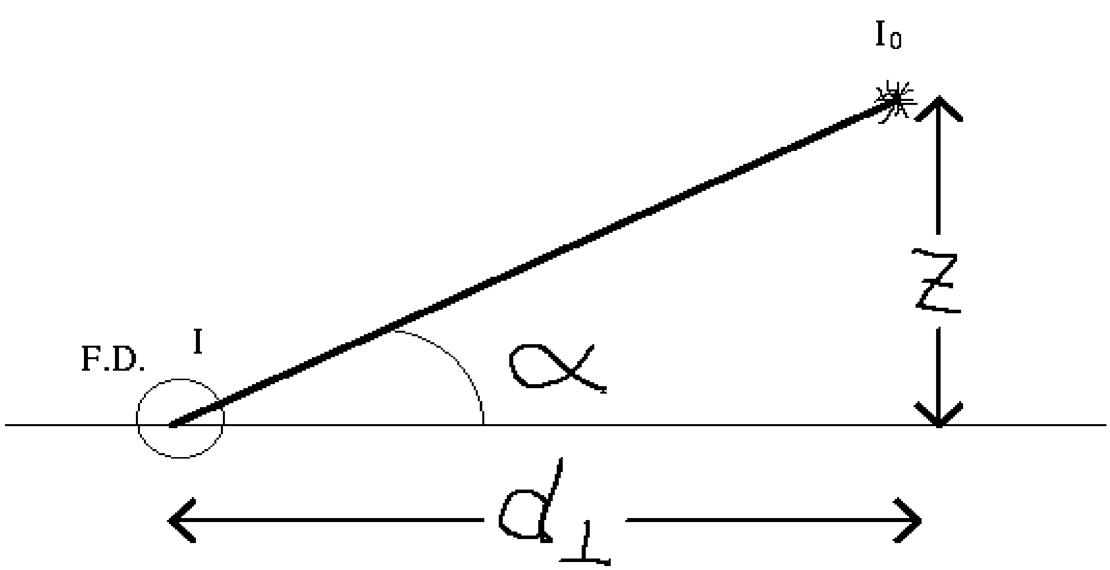
- The observed fluorescence light intensity, I, is related to the intensity of the (isotropic) source, I_0:

$$I \;=\; I_0 \cdot T^m \cdot T^a \cdot (1. \;+\; Mult.Scat.) \cdot \frac{d\Omega}{4\pi}$$

- T^m and T^a are the transmission factors for *molecular/Rayleigh* and *aerosol/Mie* scattering and $d\Omega$ is the solid angle of the observing telescope.

- In a 1-D model of the atmosphere:

$$T \;\equiv\; T(z,\alpha,\lambda) \;=\; e^{-\tau(z,\lambda) \,\cdot\, \frac{1}{sin(\alpha)}}$$



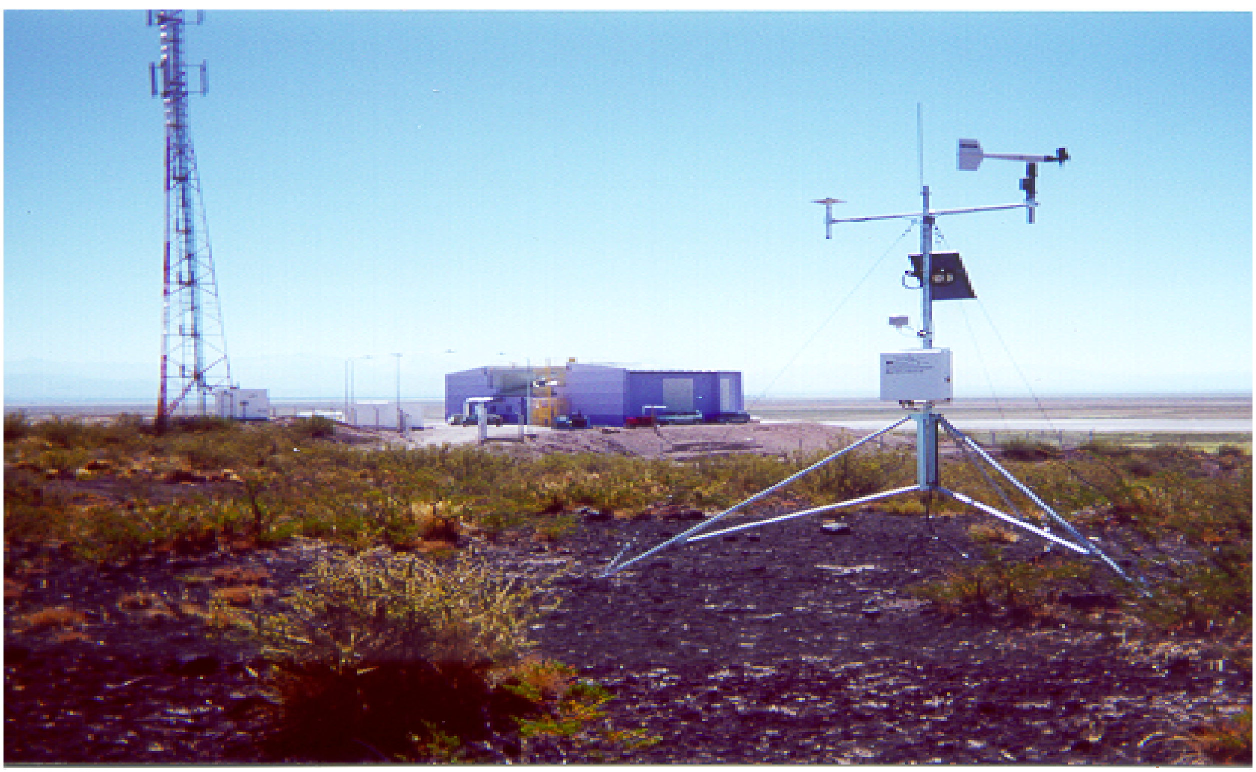
Atmospheric characterization and corrections

- The *molecular/Rayleigh* vertical optical depth:

$$\tau^m(z,\lambda) \;=\; \int_0^z \frac{\rho^m(z)dz}{\Lambda^m(\lambda)}$$

  depends on the air density, $\rho^m(z)$, and the known Rayleigh cross section, $\Lambda^m(\lambda) = 2974 \cdot (\frac{\lambda}{400nm})^4$ gm/cm^2.

- $\rho^m(z)$ is given by local temperature, T, and pressure, P, and the adiabatic model of the atmosphere.



High precision weather stations monitor T and P at each Auger fluorescence site.

Atmospheric characterization and corrections

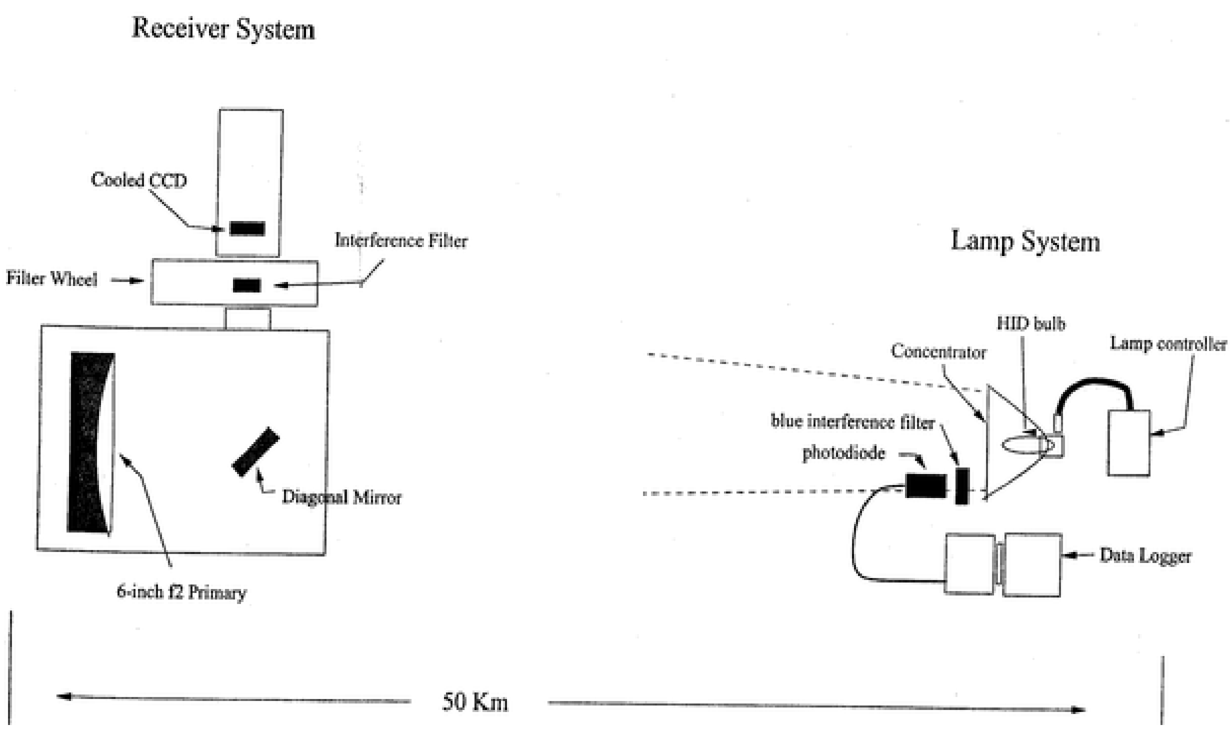
- The *aerosol/Mie* corrections, while typically less than the *molecular/Rayleigh* corrections, are *a priori* unknown.
- Thus most of Auger's atmospheric monitoring instrumentation is focused on the aerosol (Mie scattering) component.
- To minimize the *aerosol/Mie* uncertainties, Auger is located in a dry desert region with typically excellent visibility.
- Specific measurements/instrumentation include:
  1. $\Lambda^a(\lambda)$: horizontal extinction length monitors
  2. $\tau^a(z, 355nm)$: optical depth monitors
  3. $\tau^a(\infty, 550nm)$: star monitor
  4. $\frac{1}{\sigma^a}(\frac{d\sigma^a}{d\Omega})$: aerosol phase function monitors
- To monitor and to help minimize systematic uncertainties, all of the atmospheric monitoring measurements are made in at least two independent ways.

$\Lambda^a(\lambda)$: horizontal extinction length monitors

- The horizontal extinction length measurement determines the combined Rayleigh and Mie horizontal extinction length, $\Lambda(\lambda)$:

$$\frac{1}{\Lambda(\lambda)} = \frac{1}{\Lambda^m(\lambda)} + \frac{1}{\Lambda^a(\lambda)}$$

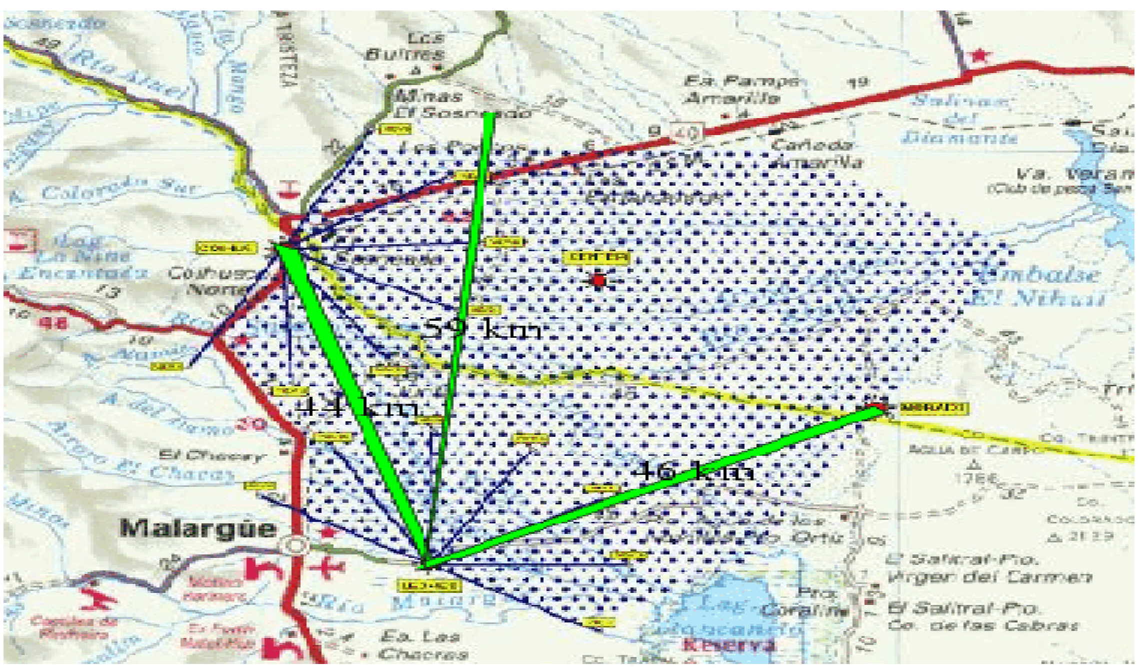
  at several wavelengths, λ =365nm, 405nm, 436nm and 546nm, in and near the wavelength acceptance of the fluorescence detectors.



Each system includes a stable (Hg) light source viewed by a stable (CCD) photometer.

$\Lambda^a(\lambda)$: horizontal extinction length monitors

- $\Lambda(\lambda)$ is determined using ratios of intensities at two distances, r_{near} and r_{far}, from the source.
- The photometer is normally positioned at r_{far}.
- The r_{near} measurement is made a few times each year.
- For $r_{far} - r_{near} >> \Lambda(\lambda)$, the fractional error, $\frac{\delta\Lambda(\lambda)}{\Lambda(\lambda)}$, is insensitive to small variations in the source intensity and/or photometer efficiency.



Light paths monitored by the three horizontal extinction length monitors.

$\tau^a(z, 355nm)$: optical depth monitors

- The optical depth *versus* height above the fluorescence detectors will be monitored using steerable, backscattered LIDARs.
- Horizontal measurements will provide a cross check of $\Lambda^a(355nm)$.
- LIDARs will be installed at each of the three fluorescence sites on the periphery of the Auger ground array.

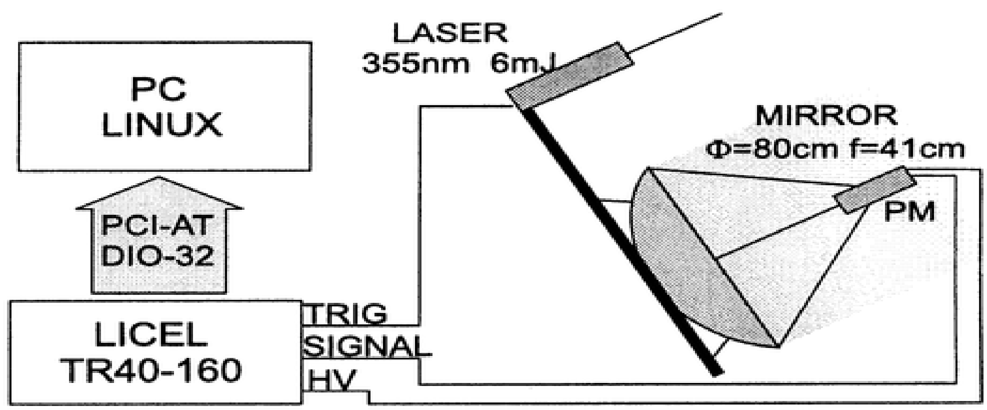


Fig. 1. Schematic view of the LIDAR system. Three mirrors of 80 cm diameter and UV-laser head are mounted on the EAS-TOP reused telescope. The LICEL TR40-160 receives the trigger from the laser and the signal from Hammamatsu R7400 phototube. The Linux-PC controls the LICEL digitizer through PCI-DIO-32HS Digital Input/Output card. The telescope motors are controlled through RS-323 port.

Each backscattered LIDAR consists of a pulsed, 355nm laser and up to 4 receiver telescopes.

$\tau^a(z, 355nm)$: optical depth monitors

- The EAS-TOP structures support up to 4 ($\sim$ 0.8m diameter) mirrors and provide full sky pointing with $0.05°$ resolution.
- The slew rate of $\sim 1.5°$/sec allows showers to be *shot* shortly after they are detected.
- Observation of the scattered (laser) light by the neighboring fluorescence site(s) provides an important cross check of $\tau^a(z, 355nm)$ and $\frac{1}{\sigma^a}(\frac{d\sigma^a}{d\Omega})$.

Prototype LIDAR testing at Pino Observatory near Torino.

$\tau^a(\infty, 550nm)$: star monitor

- A CONCAM photometer, CCD camera with $\sim 150°$ F.O.V. lens and Johnson-V filter, will monitor the overhead sky from one of the fluorescence sites.
- The goal is a measurement of $\tau^a(\infty, 550nm)$ to a precision of 10% (~ 0.005).
- The product of $\tau^a(\infty, 550nm) \cdot \Lambda^a(550nm) = h^a$ provides a monitor of the effective height, h^a, of the aerosols (for cross check of 355nm measurements).

CONCAM photometer (in weather-proof enclosure) with control computer.

$\frac{1}{\sigma^a}(\frac{d\sigma^a}{d\Omega})$: aerosol phase function monitors

- Through scattering in the air, some air Cherenkov light appears as a background in the fluorescence data.
- The observed light from an extensive air shower will also include a contribution of multiple-scattered light.
- To estimate the multiple-scattered and air Cherenkov light scattered on aerosols we need the aerosol extinction length, $\Lambda^a(z, 355nm) = (\frac{d\tau^a(z,355nm)}{dz})^{-1}$, and the aerosol phase function.

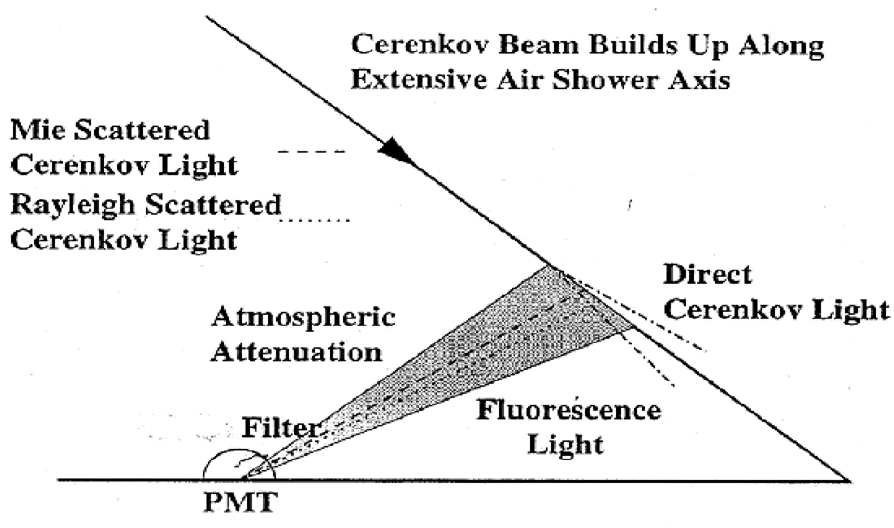
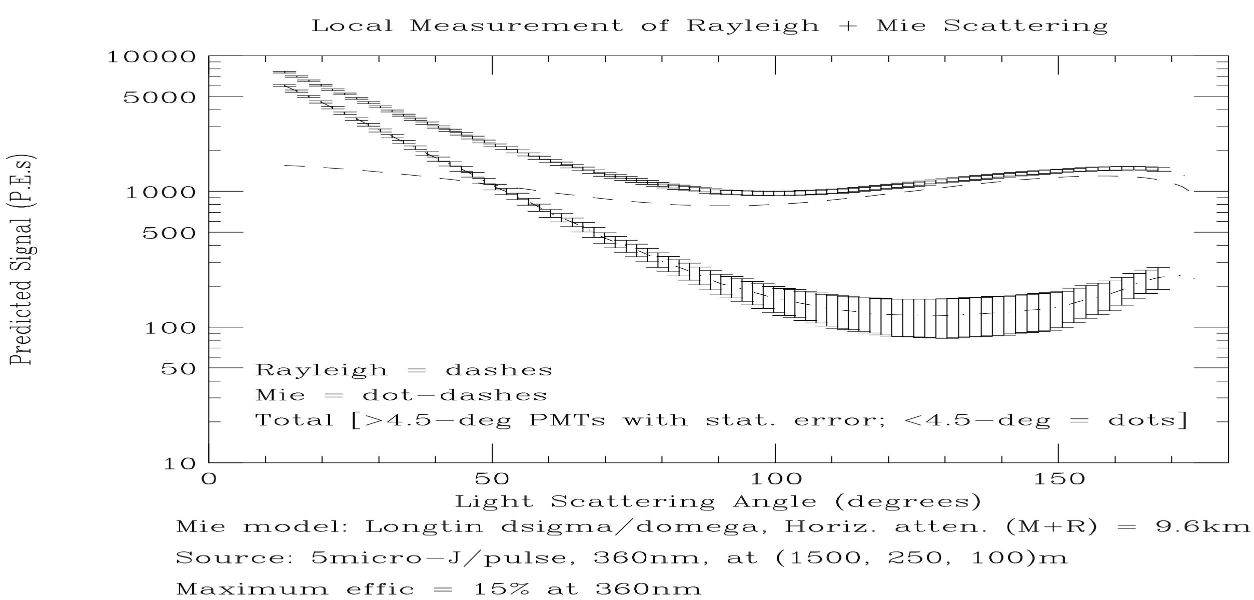


Figure 6.3: A summary of the factors that affect the light signal measured by the detector. Light is generated by the EAS and is attenuated as it travels to the detector. The actual signal measured will further depend upon detector parameters such as the transmission filter and PMT quantum efficiency. Note that most cases the light signal will be dominated by the fluorescence component.

$\frac{1}{\sigma^a}(\frac{d\sigma^a}{d\Omega})$: aerosol phase function monitors

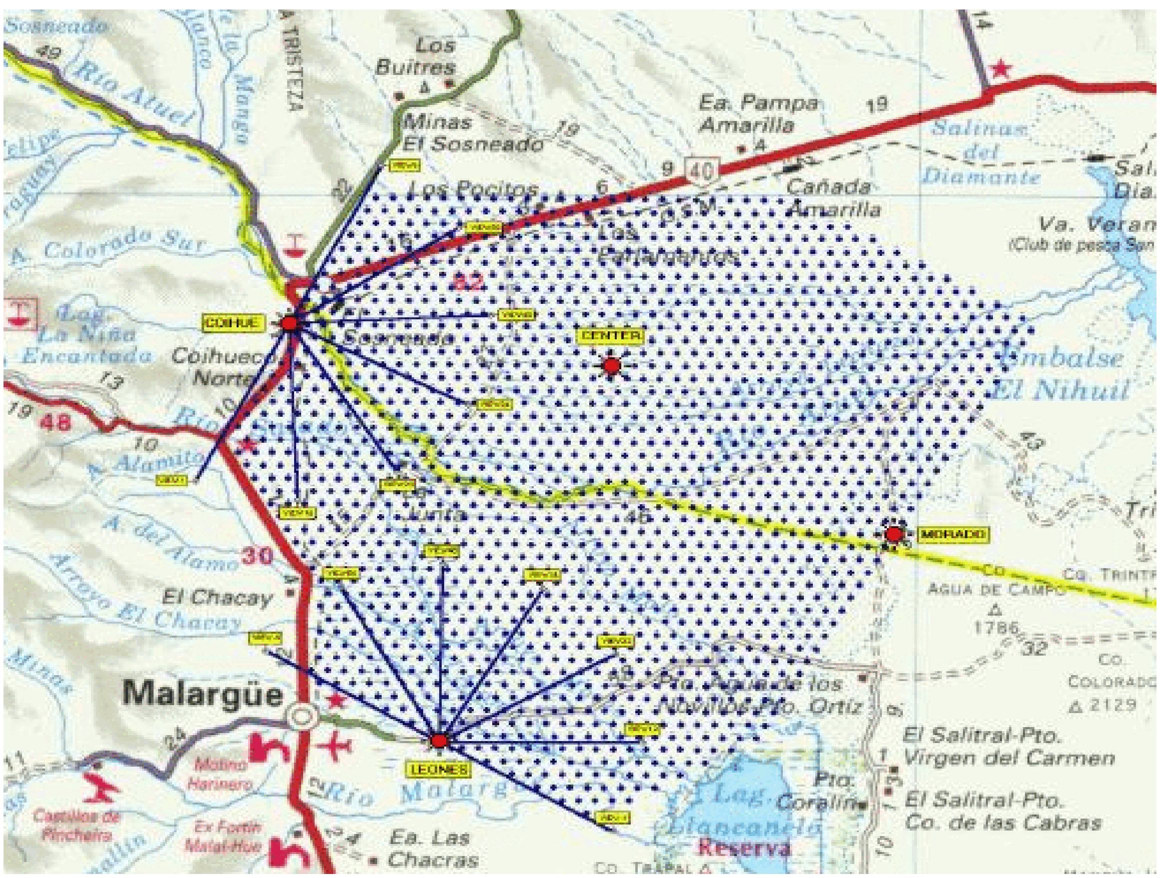
- The air Cherenkov and multiple-scattering corrections need best knowledge of the Mie phase function at forward scattering angles.
- As the fluorescence detectors view $\sim 180°$ in azimuth, even a fixed direction light beam crossing the fluorescence field of view allows $\frac{1}{\sigma^a}(\frac{d\sigma^a}{d\Omega})$ to be determined.
- Dedicated *aerosol phase function* light sources will be located near 2 fluorescence sites. In addition LIDAR beams, at near grazing incidence, provide a cross check and a measurement at the most forward angles.



Simulated $\frac{1}{\sigma^a}(\frac{d\sigma^a}{d\Omega})$ measurement using one of the nearby *aerosol phase function* light sources.

Cloud detection and monitoring

- The level of cloud cover is a factor in determining the collecting area available to the fluorescence detectors.
- Unlike smaller experiments, it is quite possible that parts of the atmospheric fiducial volume of the Auger Observatory will be usable while other parts are not.
- Additionally, the presence of small, or broken regions of cloud in an otherwise clear sky can lead to uncertainty in the interpretation of shower profiles.



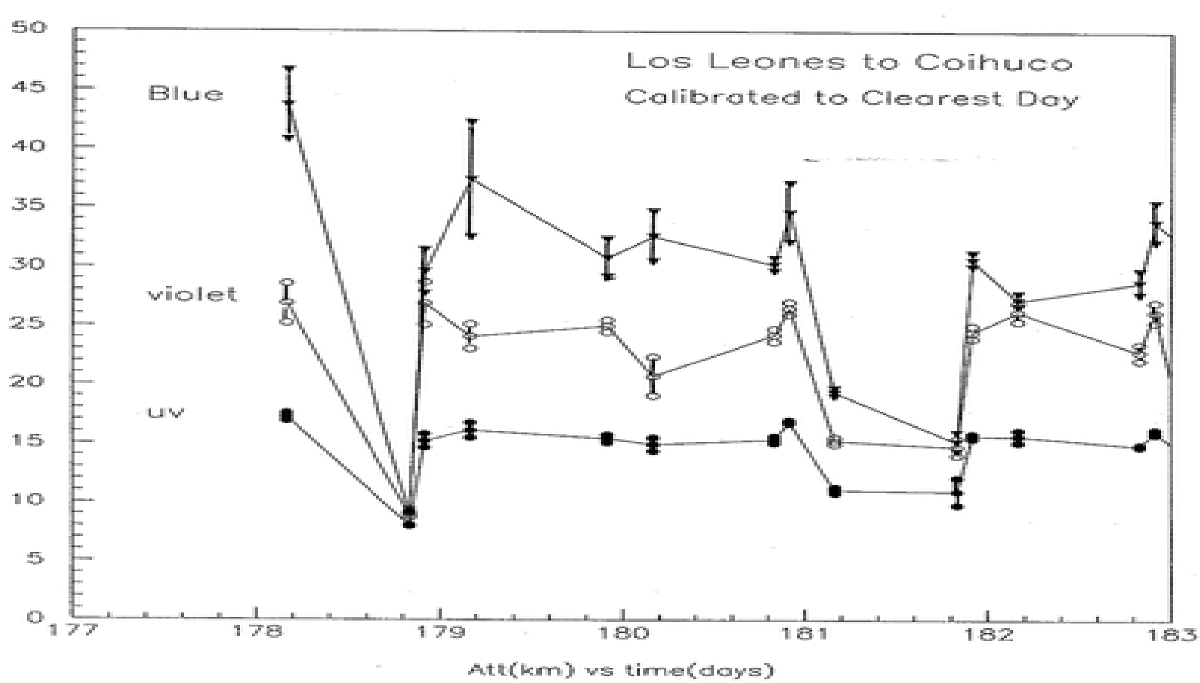
Cloud detection and monitoring

- Clouds radiate like a black body at wavelengths $\sim 10\mu$m; thus clouds can be detected by their strong infra-red emission against a weaker clear-sky background.
- We are examining the use of commercial infra-red imaging cameras to be sited at the three fluorescence sites on the periphery of the Auger ground array.
- Vertical-viewing, single-pixel radiometers will be placed on a subset of the ground array detectors.

IR camera view of clouds over Adelaide.

Summary

- The Pierre Auger Observatory atmospheric monitoring builds on the pioneering work of the High Resolution Fly's Eye (HiRes) collaboration.
- The Auger procedures have matured in collaboration with HiRes and Telescope Array collaborations.
- The Auger atmospheric monitoring goal is to limit the atmospheric contributions to the shower energy uncertainty to $\sim 10\%$.
- Field experience, combined with the explicit cross checks, are now needed!



Preliminary horizontal extinction data.