# FD Atmospheric Absorption Corrections: Overview and Issues

Auger Event Reconstruction Workshop
University of Chicago

**John A.J. Matthews**
New Mexico Center for Particle Physics
University of New Mexico

October 2 ~ 5, 2002

# Atmospheric Corrections...

## ~ ordered by importance

1) Clouds:
   - Cloud monitors: steerable IR cameras
   - Shoot-the-shower: " LIDARs

2) Transmission corrections:
   - aerosols: steerable LIDAR's
     (HAMs, star monitor)
     [vertical laser beams ... proposed]
   - molecular: weather stations
     radiosondes ... new Karlsruhe initiativ
   - ozone: ——

3) Air Cherenkov correction:
   - to the above add: APF light source(s)

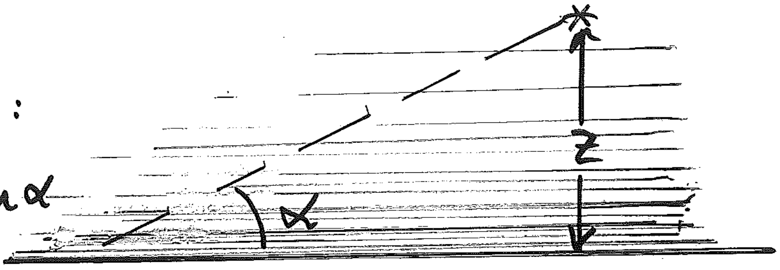
4) Multiple scattered light, consistency check, ...
   Probably need at least one, steerable, "5mJ/pulse"
   UV laser sited <u>away</u> from <u>FD</u>'s.

5) Other atmospheric effects, issues, ...
   - fluorescence effeciency $(\rho, T)$
   - "Where is the grammage?"

# "Transmission 101"

For 1-D atmospheres:

$$T(z,\alpha) = e^{-\tau(z)/\sin\alpha}$$



$$\tau(z) \equiv \int_0^z \frac{dz}{\Lambda(z)} \leftarrow \text{"local" attenuation length}$$

molecular: $\Lambda(z,\lambda) = \frac{2974\,\text{gm/cm}^2}{\rho_{air}(z)} \cdot \left(\frac{\lambda}{400\text{nm}}\right)^4 \approx 18.4\ \text{km}$ @ 360nm and $z=0$

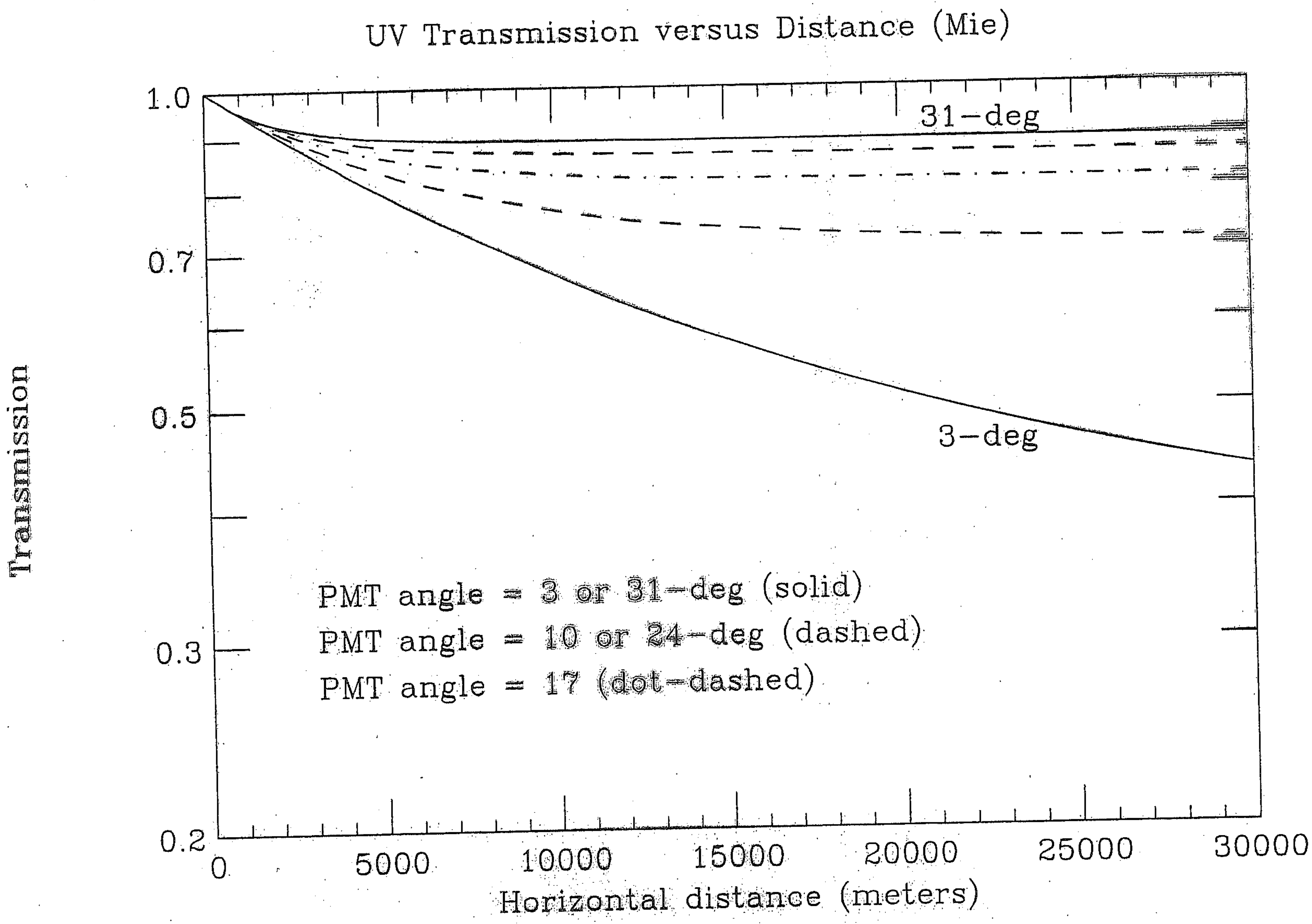
aerosol (model): $\Lambda(z) = \begin{cases} \Lambda(0) & z \leq h_m \leftarrow \text{mixing height} \\ \Lambda(0)\, e^{(z-h_m)/h_a} \leftarrow \text{scale height} & \end{cases}$

$\Lambda(0)$ ← horizontal extinction length

$$\tau(z \gg h_m, h_a) = \frac{h_m + h_a}{\Lambda(0)}$$

$$\doteq \frac{1\,\text{km}}{25\,\text{km}} = 0.04 \quad (\text{HiRes-Utah})$$

$$\boxed{\therefore \text{ for much of the shower: } \quad T^a \doteq e^{-\tau(\infty)/\sin\alpha}}$$



Typical desert atmosphere model:

Lambda_ex = 20000m, h_m = 0m, h_a = 1200m

TRANS_20KM-0-1200_VS_DIST.TDR

# How well do we know the corrections?

Quite well IF the atmosphere is the same as in our Monte Carlo

Not so well based ONLY on our atmosphere measurements.

EXAMPLE... B.O.E. estimate of $\frac{\Delta E}{E} = \frac{\Delta T^{source}}{T^{source}} = \frac{\Delta T}{T}$ :

molecular: use $T(z,\alpha) = T(z,90^\circ)^{1/\sin\alpha}$

then: $\frac{\Delta T}{T} = \frac{1}{\sin\alpha} \frac{\Delta T(z,90^\circ)}{T(z,90^\circ)}$

$$\therefore \underline{\underline{\frac{\Delta T(z,90^\circ)}{T(z,90^\circ)}}} \lesssim \underset{\substack{\uparrow \\ .1\sim.2}}{\sin\alpha} \times \underset{\substack{\uparrow \\ \lesssim 0.05 \text{ goal}}}{\frac{\Delta T}{T}} \approx \underline{\underline{.005\sim.01}} \ (\ldots\text{OK?})$$

aerosol: $\frac{\Delta T}{T} = \frac{1}{\sin\alpha} \Delta\tau$

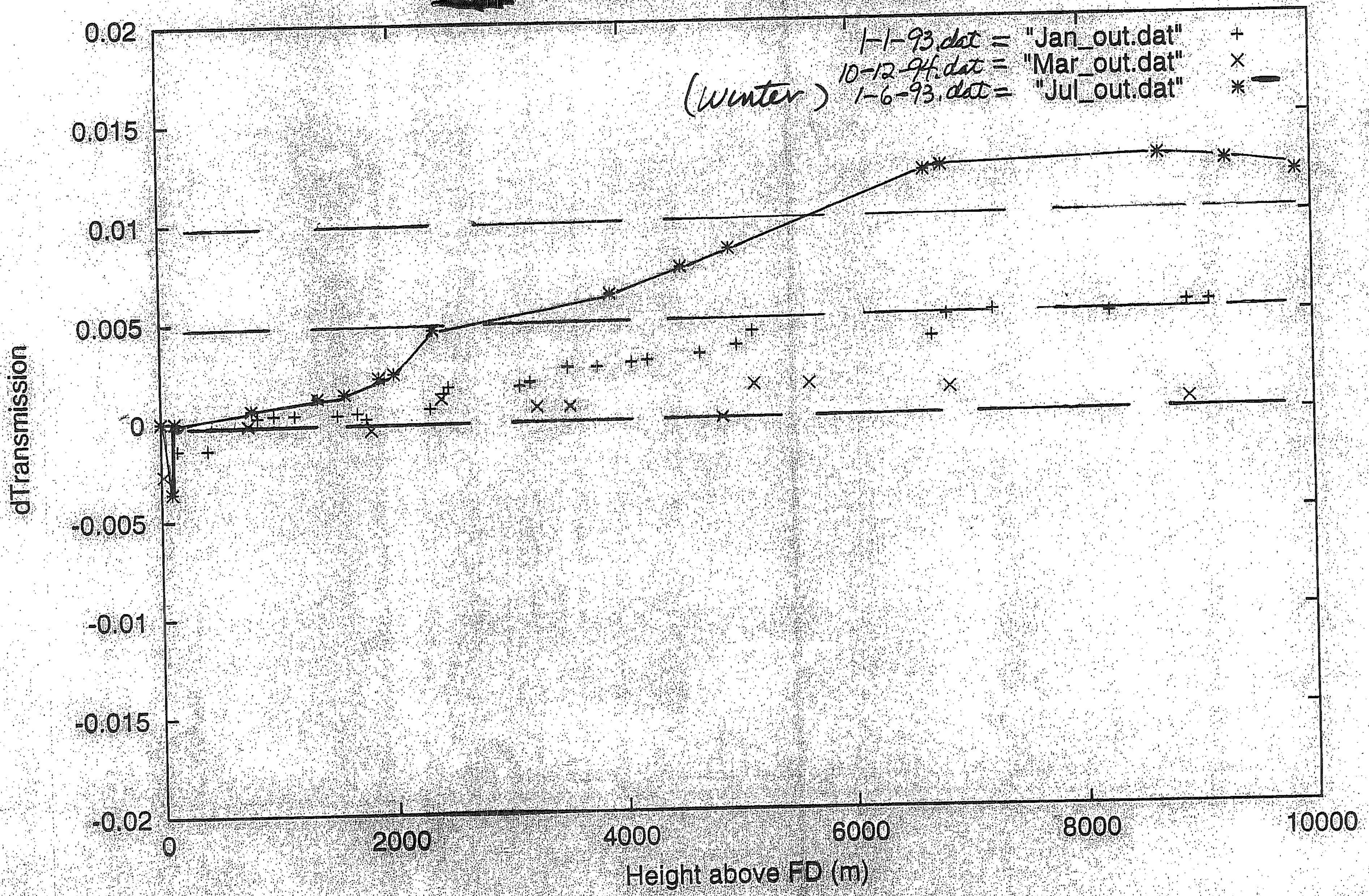
① For Auger we do not know $\Delta\tau$! (... maybe soon!)

② For $\frac{\Delta T}{T} < 0.1$ then $\Delta\tau < \underset{\substack{\uparrow \\ .1\sim.2}}{\sin\alpha} \underset{\substack{\uparrow \\ <.1 \text{ goal}}}{\frac{\Delta T}{T}} \approx .01\sim.02^{\dagger}$

† NB: $\underset{\substack{\uparrow \\ \text{a model}}}{\tau^{(\infty)}_{HiRes\,1999}} - \underset{\substack{\uparrow \\ \text{measurements}}}{\tau^{(\infty)}_{HiRes\,2002}} \approx 0.05$

RADIOSOUDE

Mendoza Rayleigh Transmission VS Adiabatic Model



# A "not unreasonible" estimate of $\frac{\Delta T^a}{T^a}$:

IF the (exponential) scale height of the "Malargue" atmosphere is $h_a = 1 \pm 0.5$ km, then:

$$\delta\tau^a(\infty) = \frac{0.5\,\mathrm{km}}{\Lambda^a_{HAM}} \lesssim 0.025 \quad \text{for } \Lambda^a_{HAM} > 20\,\mathrm{km}$$

or: $$\frac{\Delta T^a}{T^a} \lesssim \frac{0.025}{0.1 \sim 0.2} = 13 \sim 25\%^{\dagger}$$

Caveats:

1) $\Lambda^a_{HAM}$ needs to be calibrated

2) Until we analyze the LIDAR data (or vertical laser data) we do not know $h_a$.

† Consestent w/ studies done by B. Dawson "re"-analyzing E.A. events w/ different atmospheres.

# AVOD $(\equiv \tau^a(z))$ Light Sources (M. Roberts)

- ✓ simple geometry and analysis
- ✓ variety of F.D. crosschecks "for free"

Dominant uncertainties:

① $\frac{\delta I^{laser}}{I^{laser}} \lesssim 0.1$

② $\frac{\delta \varepsilon^{FD}}{\varepsilon^{FD}} \lesssim 0.1$

③ $\frac{\delta \rho^m}{\rho^m} \oplus \frac{\delta \left( \frac{1}{\sigma}\frac{d\sigma}{d\Omega}\Big|_R + \frac{\Lambda^m}{\Lambda^a}\frac{1}{\sigma}\frac{d\sigma}{d\Omega}\Big|_M \right)}{\left( \qquad " \qquad \right)} \lesssim 0.1$

④ $\delta \tau^m(z) \lesssim 0.005$

Then:

| $z$ (km) | $\delta\tau^a(z)$ |
|---|---|
| 1 | .007 |
| 2 | .011 |
| 3 | .015 |
| 4 | .019 |

} for laser at 34km from (each) F.D.

↑ estimated measurement precision / F.D.

consistent with

$\delta\tau^a(z) \leq 0.01 \sim 0.02$

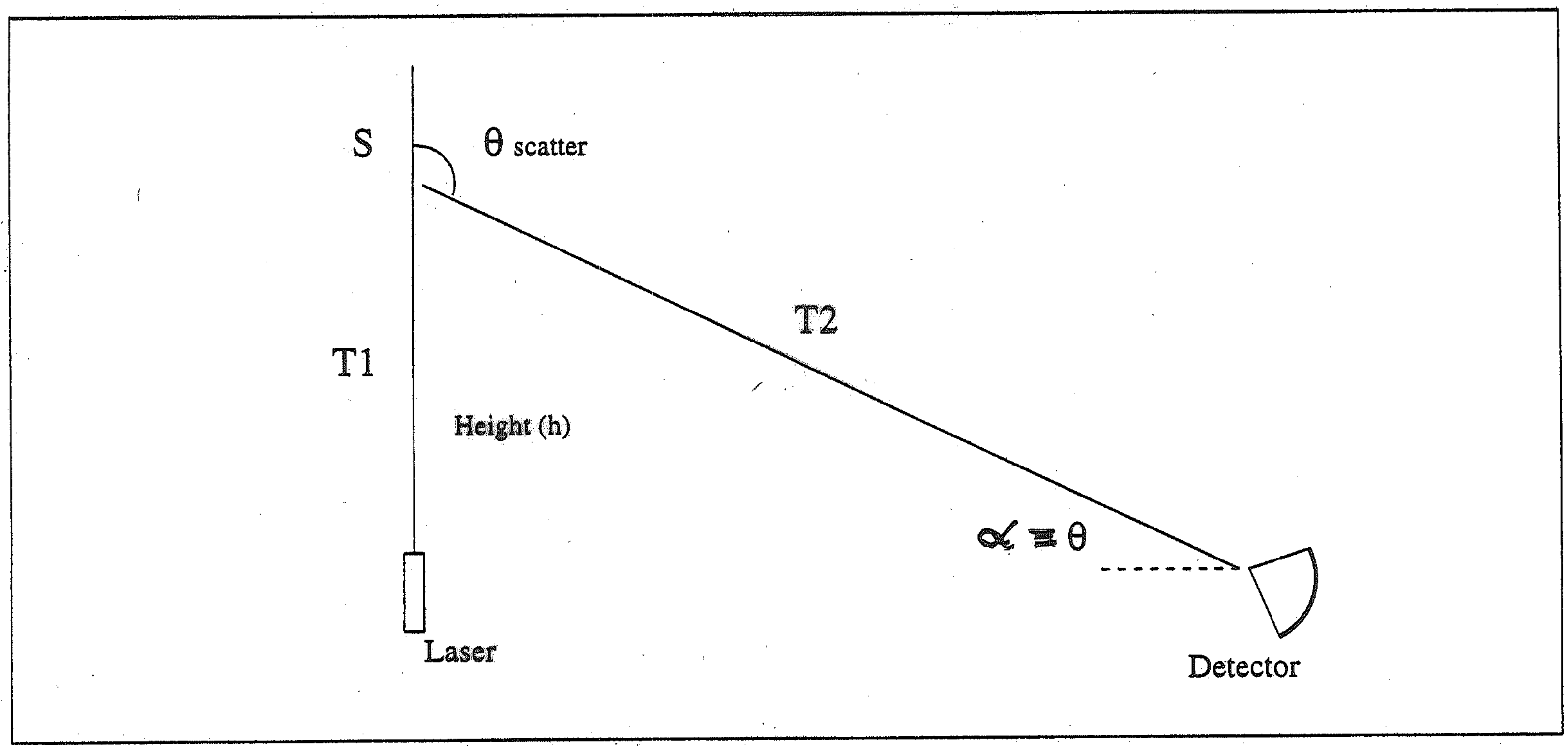
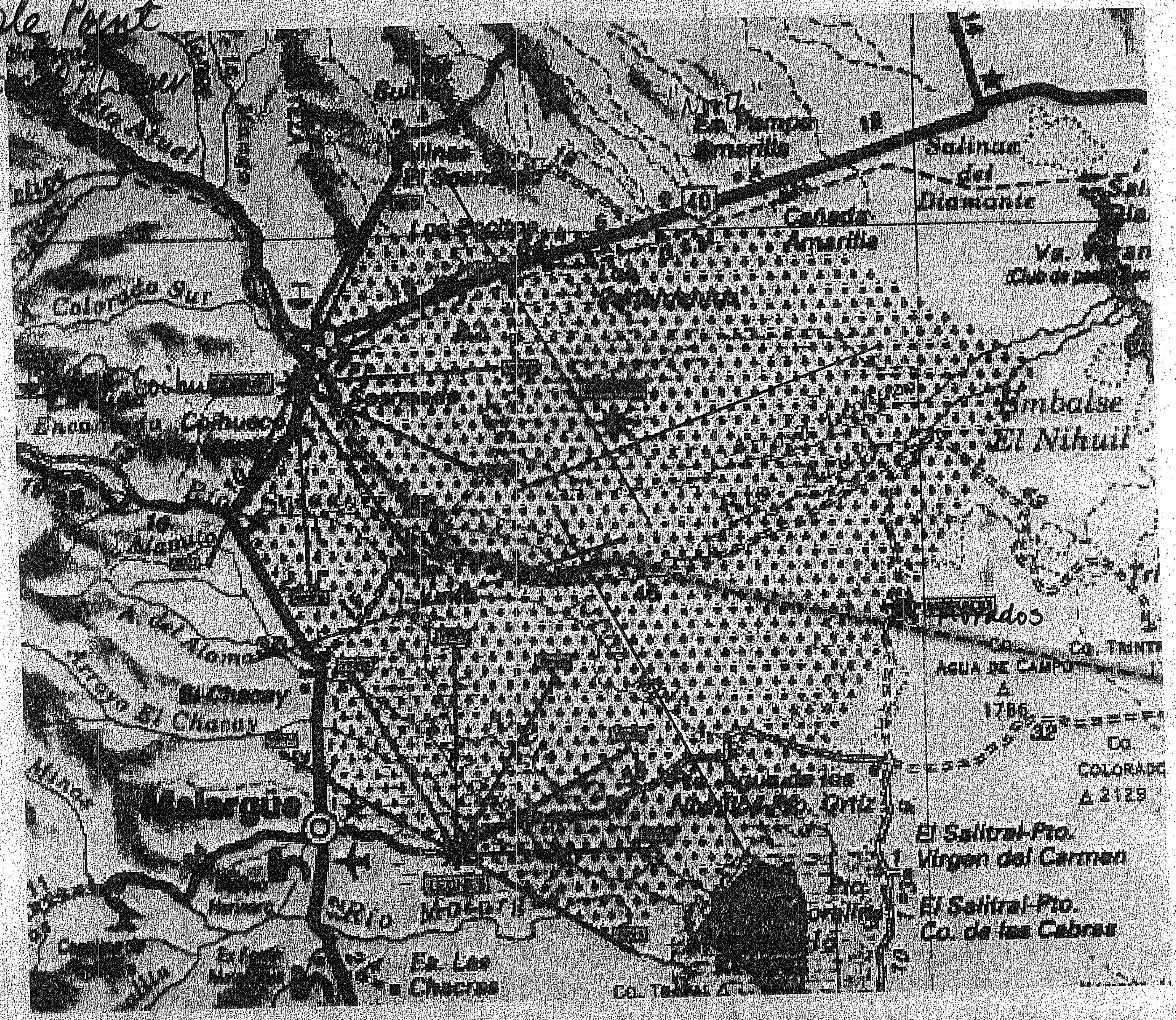
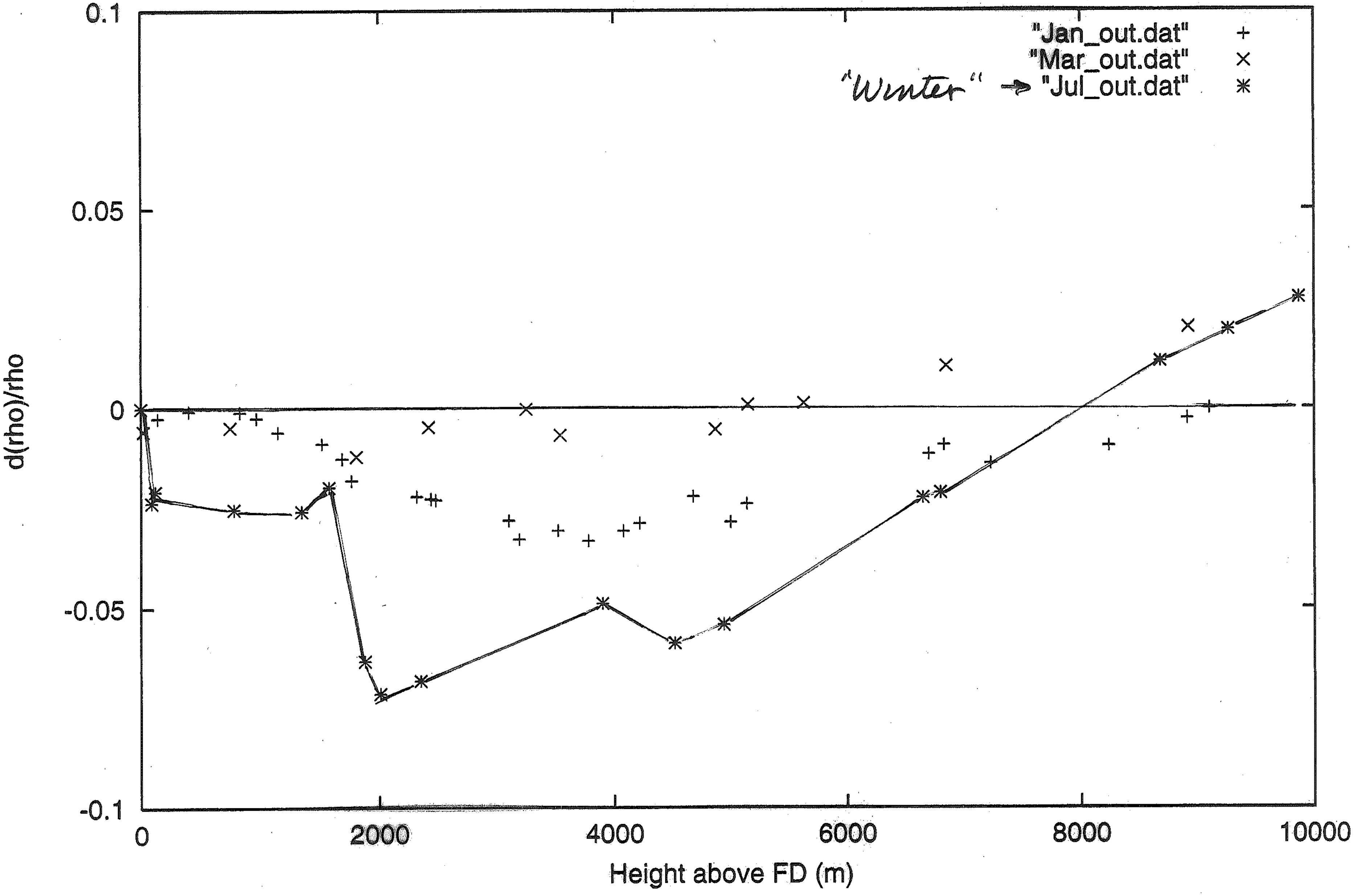


Figure 3: Measurement of aerosol optical depth with vertical laser beams. The amount of light measured at the detector at height h is determined by the vertical transmission (T1)to h, the scattering (S) at h and the transmission (T2) back to the detector.

"Triple Point" Vert[illegible]

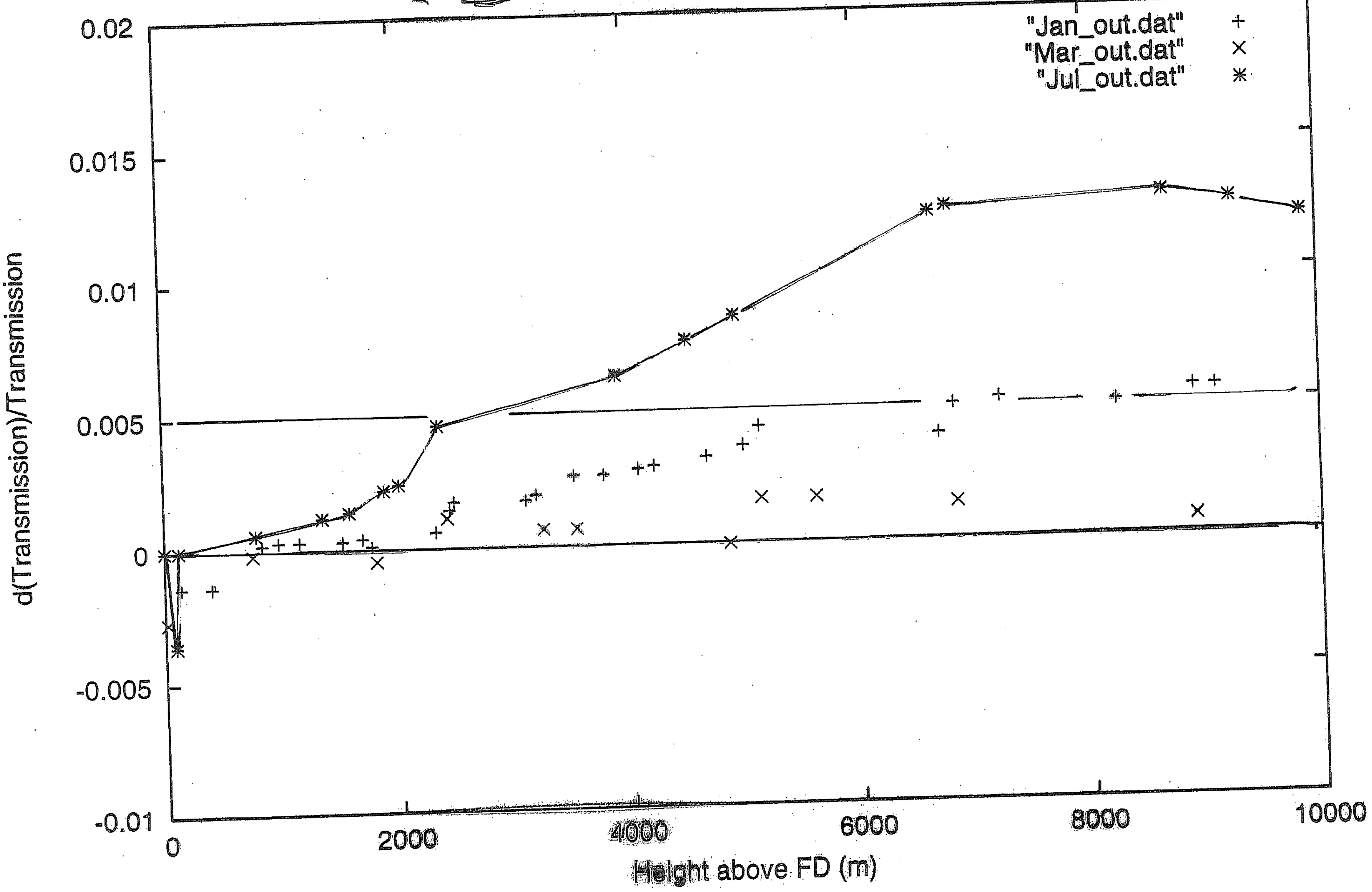




(RADIOSONDE Mendoza Rayleigh Air Density) VS (Adiabatic Model)

Radiosonde

(Mendoza Rayleigh Transmission) VS (Adiabatic Model)



# The basics (... what happens in detail):

- Fluorescence Detector (FD) telescopes observe $\gamma^{OBS-FD}_{i,j}$ photons in telescope "i", pixel "j"

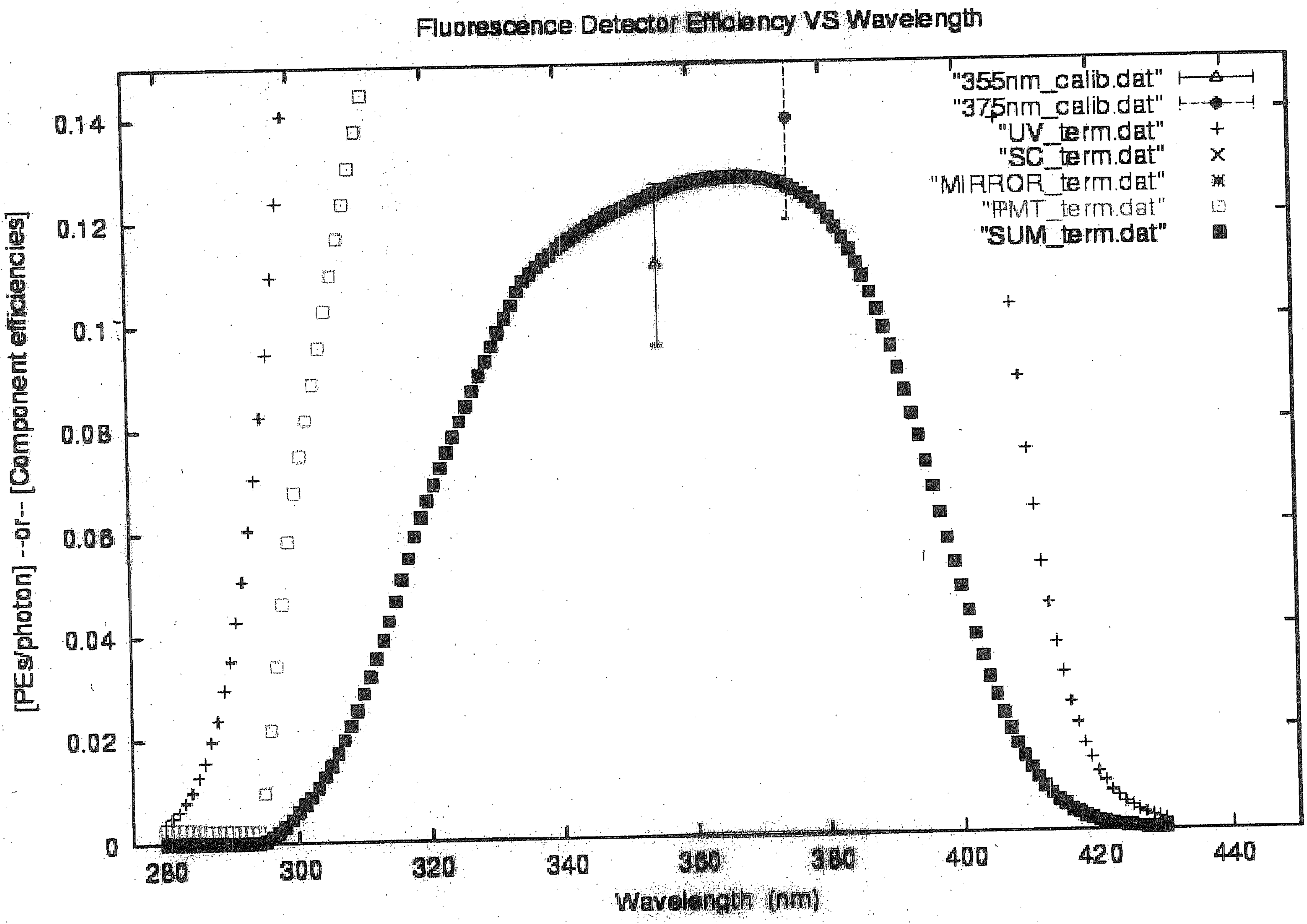
- Once the shower geometry is reconstructed then we can correct $\gamma^{OBS-FD}_{i,j}$ to $\gamma^{OBS-SOURCE}(z_{i,j})$ at the shower:

$$\gamma^{OBS-SOURCE}(z_{i,j}) \propto \frac{\gamma^{OBS-FD}_{i,j}}{\sum_{k} T^{a}(\lambda_k)\, T^{m}(\lambda_k)\, T^{o}(\lambda_k)\, \varepsilon_{i,j}(\lambda_k)\, f(\lambda_k)}$$

where: ① $T^{a}, T^{m}, T^{o}$ are aerosol, molecular, and ozone transmissions,

② $\varepsilon_{i,j}(\lambda_k)$ is the telescope efficiency,

③ $f(\lambda_k)$ is the fraction of light (at the source) in each wave length "bin".


Fluorescence Detector Efficiency VS Wavelength
[PEs/photon] --or-- [Component efficiencies]
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
280
300
320
340
360
380
400
420
440
Wavelength (nm)
"355nm_calib.dat"
"375nm_calib.dat"
"UV_term.dat"
"SC_term.dat"
"MIRROR_term.dat"
"PMT_term.dat"
"SUM_term.dat"

Comments:

a) $T^{a}(\lambda) \sim$ constant with wavelength;
$T^{m}(\lambda)$ and $T^{o}(\lambda)$ are smallest at "short" wavelengths, $\lambda \sim 300$nm, thus "skewing" the FD wavelength acceptance to "longer" wavelengths.

b) $f(\lambda_k)$ are evaluated "itteratively" as the amount of air Cherenkov light is estimated at each depth in the ~~shower.~~

... and your point is?

- many details that must not become "lost with time"
  - ✓ notes discussing/documenting each "piece"
  - ✓ data-bases (to track each "piece" with time)

T. Abu Zayyad, May 2000

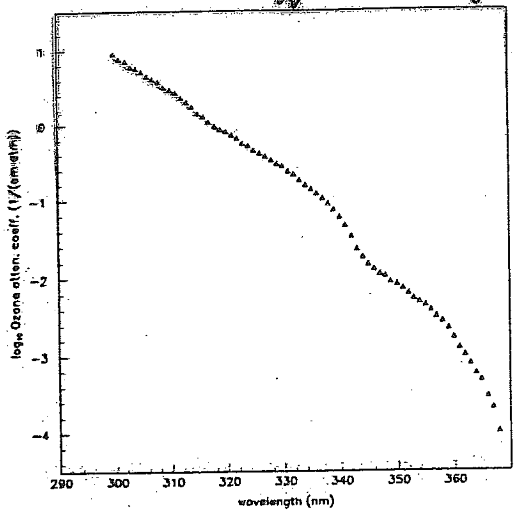


Figure 6.4. The Ozone attenuation coefficient as a function of wavelength.

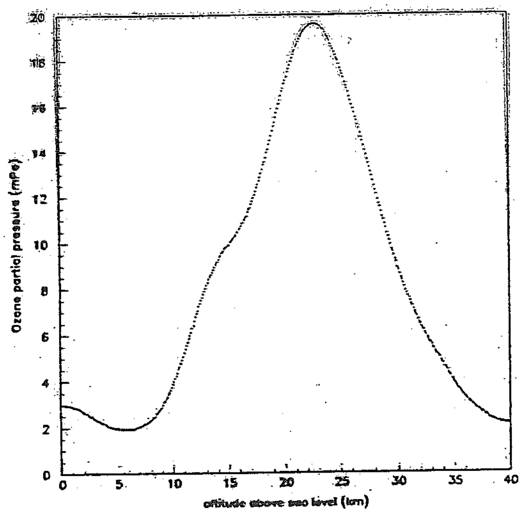


Figure 6.5. Ozone concentration as function of altitude.

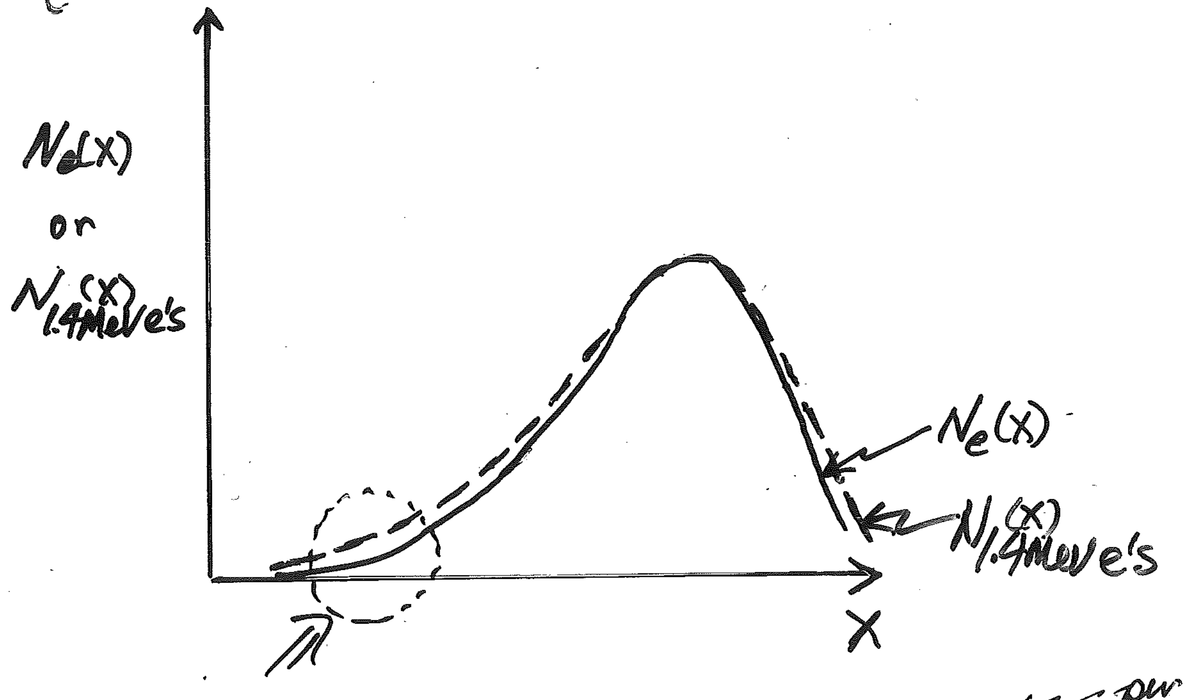
... the devil is in the details ...

Given the number of "RECONSTRUCTED" UV photons, $\gamma^{\text{OBS-SOURCE}}(\gamma/m)$, at the shower, then:

$$N^{(X)}_{1.4\text{MeV}\ e\text{'s}} \equiv \frac{\gamma^{\text{obs-source}}_{(X)}\ (\text{photons}/m\ )}{\gamma^{1.4\text{MeV}\ e^-}_{(\text{local}\ \rho,\ T)}\ \ (\text{photons}/m/1.4\text{MeV}\ e^-)}$$

Atmospheric fluorescence effeciency (ie the "calebration")

(FOR THE SAME WAVELENGTH RANGE USED IN THE ANALYSIS!)



$$\text{Scale factor} = \frac{\left\langle \frac{dE}{dx}(S(X))\ \text{MeV}/\text{gm}/\text{cm}^2 \right\rangle_{\text{showers}}}{(\text{collisional})\ \left.\frac{dE}{dx}\right|_{1.4\text{MeV}\ e\text{'s}}\ \text{MeV}/\text{gm}/\text{cm}^2}$$

← per shower "electron"

Thus: $$N_e(X) = N_{1.4\,MeV\,e^-'s}^{(X)} * \frac{\left.\frac{dE}{dX}\right|_{1.4\,MeV\,e^-'s}}{\left\langle \frac{dE}{dX}(S(X)) \right\rangle_{showers}}$$

Yes but "what do we mean by $N_e(x)$"?

- Is it the number of $e^{+/-}$ above the simulation cutoff (eg 0.1 MeV in C. Song et al)?
- Is it an optimal quantity to fit with the Gaisser-Hillas parameterization?
- Is it the optimal estimator for air Cherenkov flux (ie $N_e(x)$ above air Cherenkov threshold)?

• • •

Thus input needed from simulations including:

① TOTAL collisional energy loss: $\frac{\Delta E}{\Delta X}(S(X))$ MeV/gm/cm²

② EFFECTIVE $e^{\pm}$ flux above air Cherenkov threshold: $N_e^{\check{C}}(S(X))$

③ ...

Then eg $$\left\langle \frac{dE}{dx}(S(X)) \right\rangle_{showers}^{\check{C}} \equiv \frac{\Delta E/\Delta X\,(S(X))}{N_e^{\check{C}}(S(X))}$$

is available for analyzing the fluorescence data.

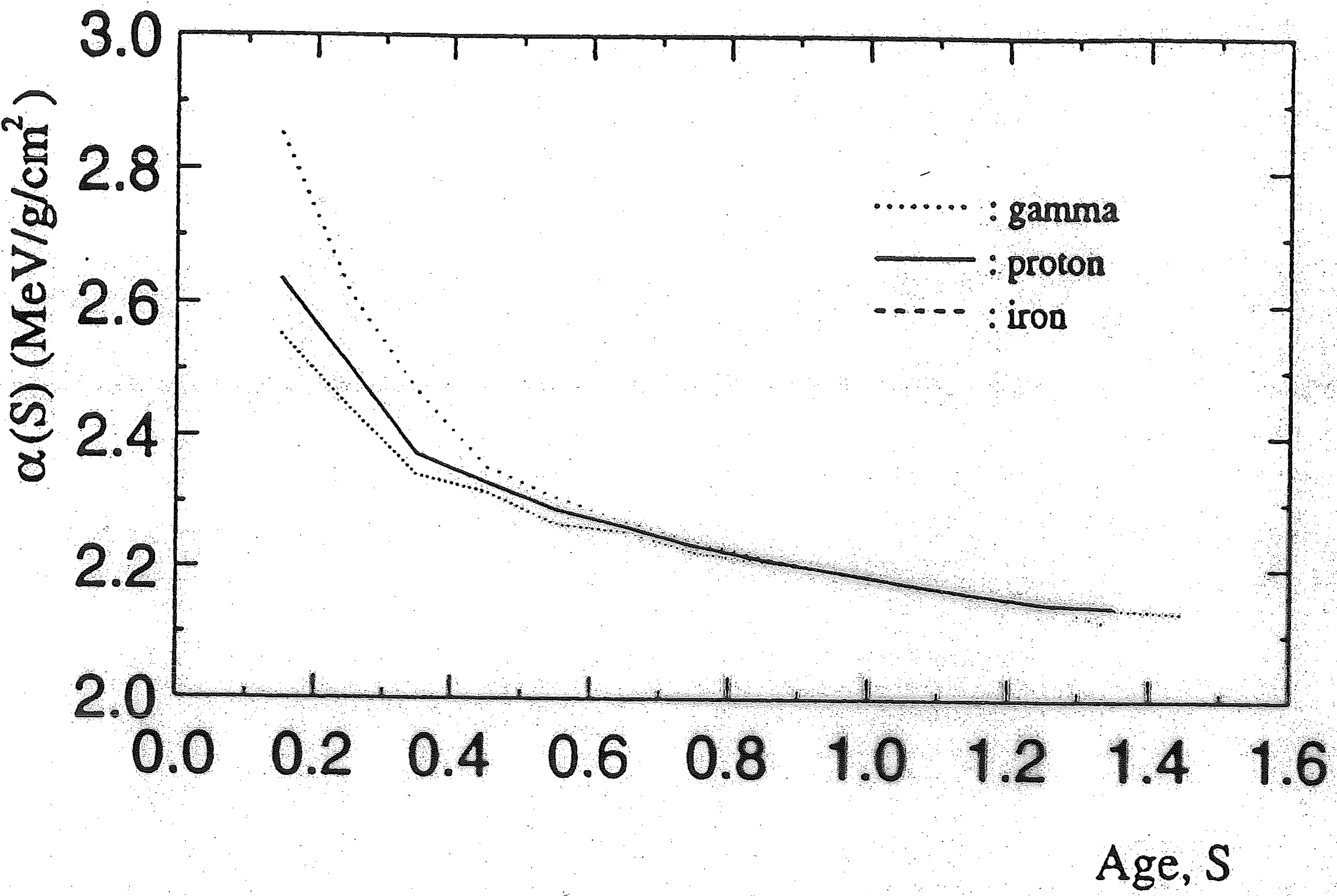


Fig. 2. The mean ionization loss rate $dE/dX$ as function of $S$ for γ-ray, proton, and iron-induced showers at $10^{17}$ eV.

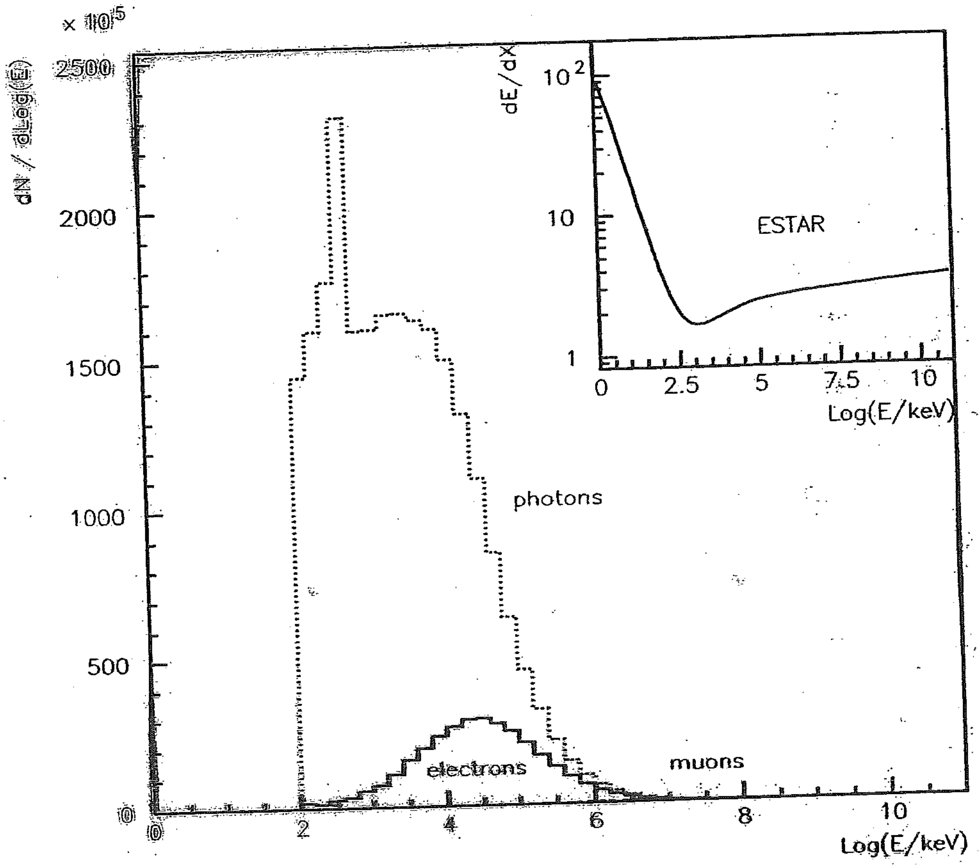


Figure 1: The mean energy spectra of photons, electrons and muons at $S = 1$ for 200 proton showers at $10^{17}$ eV. The spike in the photon spectrum corresponds to electron-positron annihilation. The inset shows the energy loss rate (in MeV/g/cm$^2$) by ionization of electrons in dry air over the same energy range as the main figure. The ESTAR code produced by US National Institute of Science and Technology (NIST) was used below 10 GeV[10] and this curve is extrapolated into the region above 10 GeV.

|  | With $\mu^+\mu$ & $\gamma N$ |  |  | Without $\mu^+\mu$ & $\gamma N$ |  |  |
|---|---|---|---|---|---|---|
| $E_0$, eV | $E_{cal}/E_0$ | $N_\mu$ | $N_{max}$ | $E_{cal}/E_0$ | $N_\mu$ | $N_{max}$ |
| $10^{16}$ | $0.888 \pm 0.004$ | $(2.146 \pm 0.795)10^3$ | $(8.324 \pm 0.392)10^6$ | $0.897 \pm 0.003$ | $0.000 \pm 0.000$ | $(8.448 \pm 0.413)10^6$ |
| $10^{17}$ | $0.888 \pm 0.005$ | $(2.823 \pm 1.369)10^4$ | $(7.881 \pm 0.339)10^7$ | $0.898 \pm 0.004$ | $0.000 \pm 0.000$ | $(7.967 \pm 0.392)10^7$ |
| $10^{18}$ | $0.889 \pm 0.004$ | $(3.185 \pm 0.916)10^5$ | $(7.439 \pm 0.271)10^8$ | $0.898 \pm 0.003$ | $0.000 \pm 0.000$ | $(7.558 \pm 0.281)10^8$ |

Table 1: Results of CORSIKA simulations of gamma-ray induced air showers at three primary energies. The right-hand half of the table shows results from simulations where photo-nuclear and muon pair production processes have been switched off. The uncertainties shown are root mean squared errors.

| $E_0$, eV | $E_{loss}/E_0$ | $E_e(<0.1$ MeV$)/E_0$ | $E_\gamma(<0.1$ MeV$)/E_0$ | $E_{cal}/E_0$ |
|---|---|---|---|---|
| $10^{16}$ | $0.888 \pm 0.003$ | $0.090 \pm 0.001$ | $0.010 \pm 0.001$ | $0.888 \pm 0.004$ |
| $10^{17}$ | $0.884 \pm 0.005$ | $0.090 \pm 0.001$ | $0.012 \pm 0.003$ | $0.888 \pm 0.005$ |
| $10^{18}$ | $0.876 \pm 0.007$ | $0.092 \pm 0.002$ | $0.018 \pm 0.005$ | $0.889 \pm 0.004$ |

Table 2: Results from a study of energy conservation within CORSIKA. Gamma-ray showers were simulated at three primary energies $E_0$. $E_{loss}$ refers to the energy lost to the atmosphere through ionization by charged particles with energies above 0.1 MeV. The fraction of the primary energy carried by sub-0.1 $MeV$ electrons and photons is shown in the next two columns. The fraction of primary energy determined by the calorimetric equation (final column) is consistent with $E_{loss}/E_0$. Again, all uncertainties are r.m.s.

Then when we evaluate the shower energy:

$$E_{shower} = \frac{\int N_e^{fit}(X) \left\langle \frac{dE}{dX}(S(X)) \right\rangle_{showers} dX}{\mathcal{E}_{vis}}$$

eg from Gaisser-Hillas profile with air Cherenkov "subtracted"

$\mathcal{E}_{vis}$ ← ~0.9 to correct for lost $\mu^{\pm}$, ν's, n's

To go back to our "roots" substitute:

$$N_e^{fit}(X) \left\langle \frac{dE}{dX}(S(X)) \right\rangle_{shower} \equiv N^{fit\,(X)}_{1.4MeV\,e's} \left.\frac{dE}{dX}\right|_{1.4MeV\,e's}$$

Then: $$E_{shower} = \left.\frac{dE}{dX}\right|_{1.4MeV\,e's} \frac{\int N^{fit}_{1.4MeV\,e's}(X)\, dX}{\mathcal{E}_{vis}}$$

THIS can come outside the integral as it is a constant.

Where: $$N^{fit\,(X)}_{1.4MeV\,e's} = \frac{\gamma^{obs-corrected}(X)}{\gamma^{1.4MeV}(\rho,T)}$$

← "corrected" observed signal

← fluorescence efficiency

our "roots"

I urge we use this "presentation" as it makes the connection between what we observe, the calibration, and what we determine ($E_{shower}$) most transparent.

C. Song, et al., astro-ph/9910195

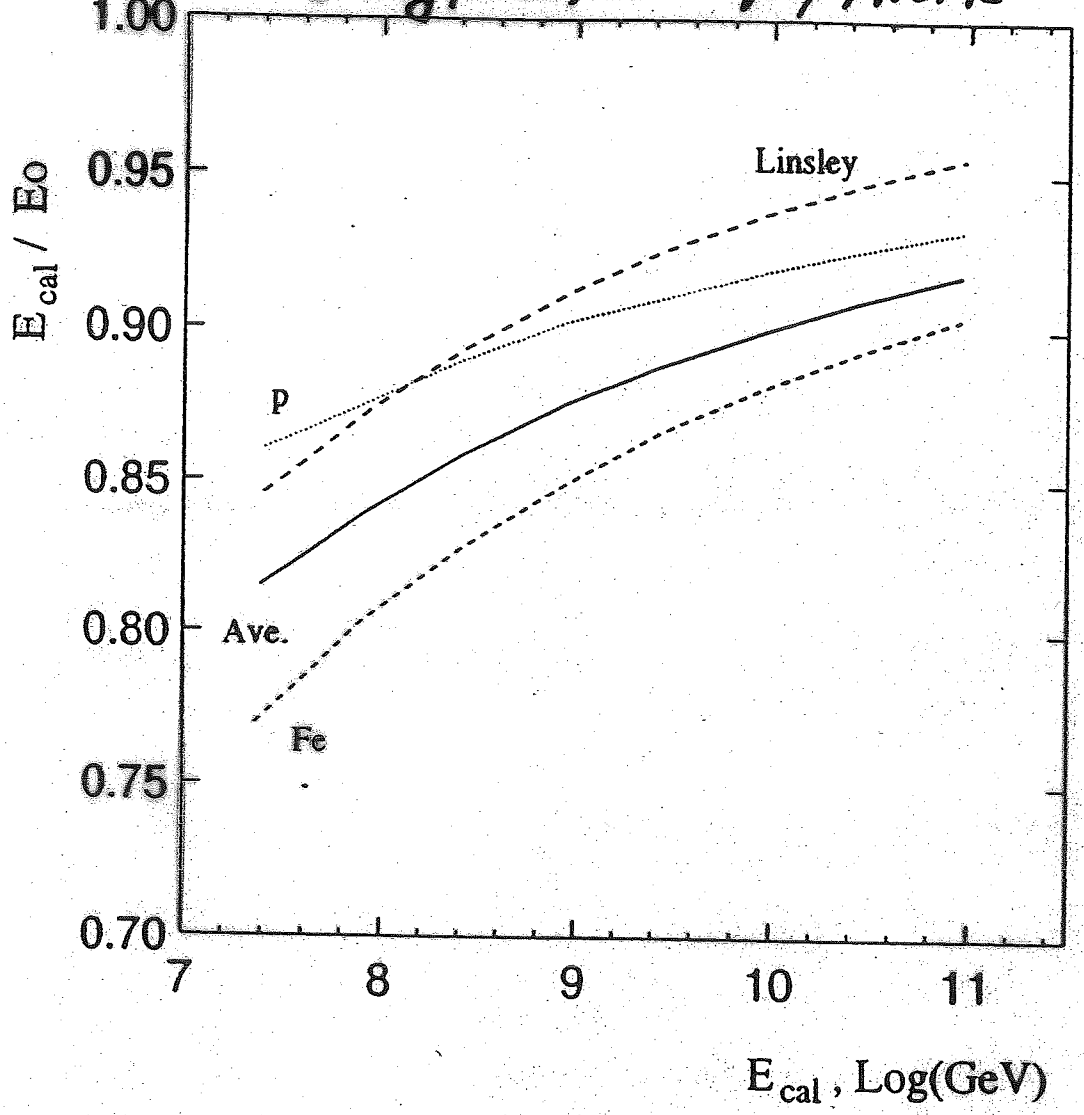


Figure 4: The functions for correcting the calorimetric energy to the primary energy, as a function of calorimetric energy. Shown are the corrections for proton showers (dotted line) and iron showers (short dashed line) and an average of the two(solid line). For comparison, Linsley's function is also shown.

## Summary:

1) We do not know the aerosol transmission corrections for the E.A. data.

- ✓ A not unreasonible model would estimate the $\delta T^a$ uncertainty to the shower energy to 13~25%.

- ✓ Why?
  Too few dedecated, focused people involved ... this needs to change!

2) There are many details in the fluorescence analysis ... that impact studies in areas other than atmospheric monitoring:

   - ✓ next generation air fluorescence efficiency measurements

   - ✓ shower simulations must be able to simulate "air fluorescence signal"

↗ These need to be clearly documented so all the pieces "fit".