Time Variation of the Vertical Profile of the Atmosphere for Air Fluorescence Measurements

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Abstract

The next generation air fluorescence experiments studying cosmic rays near 10^{20} eV require significantly better atmospheric monitoring than the original Fly's Eye experiment in order to reconstruct accurately the energy of the cosmic rays. In this paper we study the time variation of the vertical profile of the atmosphere. For the study we use the twice daily radiosonde data from the Salt Lake City (SLC) airport. The relevance of the atmospheric time variations on the transmission correction for fluorescence signals is summarized.

1 Introduction:

The atmospheric corrections to data from the High Resolution Fly's Eye (HiRes) experiment (Sokolsky, 1999) are of two forms. The first is the correction for the finite transmission of light from the extensive air shower to the fluorescence telescopes. Thus the observed light intensity, I, is related to the light intensity at the source, I_0, as follows:

$$I \sim I_0 \cdot T^m \cdot T^a$$

where T^m is the transmission based on Rayleigh scattering (on the molecular atmosphere) and T^a is the transmission based on Mie scattering (on aerosols in the atmosphere). Both T^m and T^a must be known and are collectively called the *transmission* correction. The measurement of T^a is discussed in Matthews, 1999; T^m is discussed in this paper.

In practice the observed signal includes both air fluorescence plus some scattered air Cherenkov light from the air shower. The latter must be subtracted as part of the shower reconstruction/analysis and constitutes the second (*air Cherenkov*) correction to the fluorescence data. This is discussed in Tessier, 1999.

In this paper we review the transmission correction, and in particular uncertainties in the transmission correction, from Rayleigh scattering in the (molecular) atmosphere. The transmission corrections depend on the total number of scatterers between the source and the fluorescence detector and on the total scattering cross sections. For Rayleigh scattering the cross section is known. It is the vertical profile of the density of the atmosphere that varies with time. Twice daily radiosonde data from the nearby SLC airport are used to provide information on the time variation of the atmosphere for the HiRes experiment.

2 Radiosonde Data:

The radiosonde data are collected by a special weather balloon sent up from the weather station at the SLC airport. The data are continually transfered during the ascent, a process which takes approximately 90 minutes. These large balloons carry the radiosonde equipment generally to a maximum height of 100,000 ft. The balloon then simply pops and the radiosonde equipment deploys a parachute and descends slowly. The data are stored in banks accessible through the web (http://raob.fsl.noaa.gov/). The data used in this analysis were taken during 1996.

3 Atmospheric (Molecular) Transmission Correction:

The molecular atmosphere is essentially 1-dimensional. Thus the transmission, T^m, depends on the height of the light source above the fluorescence detector *eye*, z, the viewing angle (*e.g.* from the horizontal) of the i^{th} photo-tube, α_i, and the wavelength of the light, λ:

$$T^m \equiv T^m(z, \alpha_i, \lambda) = e^{-\int_0^z \frac{\rho(z)dz}{\Lambda^m(\lambda)} \cdot \frac{1}{sin(\alpha_i)}} \quad (1)$$

where $\rho(z)$ is the air density versus height and $\Lambda^m(\lambda) = 2970 \cdot (\frac{\lambda}{400nm})^4$ gm/cm^2 is the reciprocal of the Rayleigh cross section. For HiRes this corresponds to $\Lambda^m(\lambda) \sim 16.61 \cdot (\frac{\lambda}{350nm})^4$ km at the elevation of the fluorescence eyes.

The integral of the air density to height, z, can be re-expressed as:

$$\int_0^z \rho(z)dz \approx \frac{\delta P(z)(mbar) \cdot 10}{g(m/s^2)} \approx \delta P(z) \;\; gm/cm^2$$

where g is the acceleration of gravity and $\delta P(z) = P(0) - P(z)$ is the pressure difference (in mbar) between $z = 0$, the height of the fluorescence detector eyes, and the height of the light source, z. Thus the fractional uncertainty in T^m is:

$$\frac{\Delta T^m}{T^m} \approx (\frac{1}{sin(\alpha_i)}) \cdot \frac{\Delta(\delta P(z)) \;\; gm/cm^2}{\Lambda^m(\lambda)} \tag{2}$$

where $\Delta(\delta P(z))$ is the uncertainty in the pressure difference between the ground and height z (in mbar). If we require $\frac{\Delta T^m}{T^m} < n$% at 350nm, near the center of the HiRes wavelength acceptance, then:

$$\Delta(\delta P) \leq n(\%) \cdot \frac{17 \; mbar}{(1/sin(\alpha_i))} \tag{3}$$

Fortunately δP must be known most precisely at small viewing angles, *i.e.* near the ground. As an example with $n = 3$(%) and $\alpha_i = 9°$ (middle of HiRes ring one mirrors) then we require that $\Delta(\delta P) \sim 8$ mbar (or less).

4 Uncertainties in the Transmission Correction:

As noted above, the relevant quantity for estimating the molecular transmission corrections are the pressure difference(s), $\delta P(z)$ (mbar), *versus* height above the fluorescence eye(s). The issue for fluorescence experiments is whether simple models estimate $\delta P(z)$ to sufficient precision so that the resulting errors in the molecular transmission estimation, Eqn. 1, are within the acceptable error budget: $\Delta T^m / T^m$ of a few percent.

For this study we take the SLC airport radiosonde pressure data, $\delta P_{data}(z) \equiv P_{radiosonde}(0) - P_{radiosonde}(z)$, *versus* height to represent reality. We then use two different models for the atmosphere: the standard adiabatic atmosphere (CRC 1991) <u>or</u> a monthly average atmosphere. The adiabatic model allows a simple determination of the pressure *versus* height using the ground level temperature and pressure and a fixed lapse rate of -6.5°C/1000m; this is denoted $\delta P_{adiabatic}(z)$. In the monthly average model the SLC airport radiosonde pressure data *versus* height are summed for a given month to derive an average pressure difference, $\delta P_{average}(z)$, profile. Finally, the fractional error in the molecular transmission correction, see Eqn. 2, is proportional to: $\Delta(\delta P(z)) = \delta P_{data}(z) - \delta P_{model}(z)$.

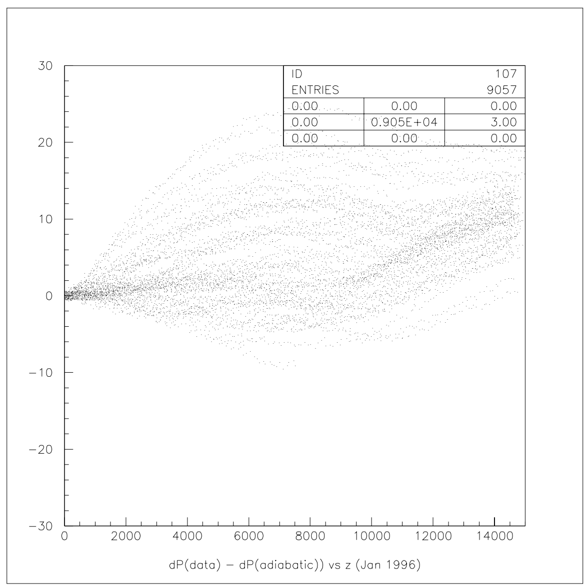

Figure 1: SLC airport radiosonde $\delta P_{data}(z)$ minus $\delta P_{adabatic}(z)$, in mbar, *versus* height, in meters, for the month of January 1996.

An example of $\delta P_{data}(z) - \delta P_{model}(z)$ for the month of January is shown in Fig. 1 for the adiabatic model and in Fig. 2 for the average atmosphere model. Data with major storms, with often significant changes with ground level pressure and temperature, are included. Thus model comparisons are conservative (*i.e.* worst case).
The Fig. 1 and 2 examples show that the scatter in $\delta P_{data}(z) - \delta P_{model}(z)$ for both models is similar; the adiabatic model shows in addition a systematic difference with height from the radiosonde data. The advantage of the average model is that the average value of $\delta P_{data}(z) - \delta P_{model}(z)$ is zero (by construction). It is significant that the majority of the values of $\delta P_{data}(z) - \delta P_{average}(z)$ are < 10 mbar. Thus the $\delta P_{average}(z)$ model is consistent with Eqn. 3 and the desire to keep the uncertainties in the Rayleigh transmission correction at the level of a few percent.
For distant showers the largest transmission corrections are at viewing angles near the horizon, *i.e.* α_i of a few degrees. This corresponds to small values for $sin(\alpha_i)$ in Eqns. 2 and 3 and results in the most stringent constraints on $\delta P(z)$. Fortunately this corresponds to heights of less than a few kilometers where both models provide the best estimates for $\delta P(z)$.

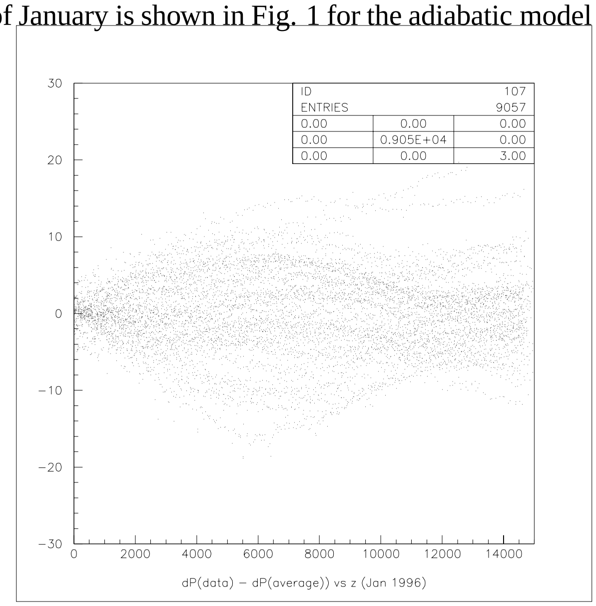

Figure 2: Same as Fig.1 but using the average atmosphere model.

The comparisons in Fig. 1 and 2 show how well the adiabatic or average atmosphere model duplicate the daily atmosphere for one month of 1996; furthermore Eqn. 2 shows how deviations contribute to the fractional uncertainty in the Rayleigh transmission, T^m. To show the variation over the entire year, we plot in Fig. 3 (adiabatic model) and Fig. 4 (average atmosphere model) the estimated value of $\Delta T^m/T^m$ for four fluorescence detector viewing angles, α_i: $4°$, $8°$, $12°$, and $16°$ to the horizontal. To relate the detector viewing angles to the light source height we assume a uniform distribution of sources (*i.e.* extensive air showers) out to a maximum viewing distance of 40km from the fluorescence eye. The sources are assumed to be viewed equally on each day of the month. As with the data in Fig. 1 and 2, the SLC radiosonde data are taken as the true atmosphere and the adiabatic and average atmosphere models are taken to model the atmosphere; then $\Delta T^m/T^m = T^m_{data}/T^m_{model} - 1$.

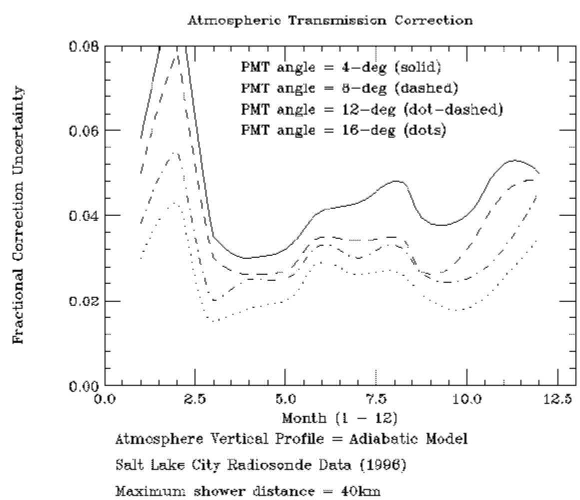

Figure 3: $\Delta T/T$ *versus* month (during 1996) for the adiabatic model.

Comparisons of the radiosonde data to the two models during each one month time interval provide a measure of the *rms* random scatter in $\Delta T^m/T^m$ from the two atmosphere models. The estimate for $\Delta T^m/T^m$ plotted for the adiabatic model, Fig. 3, includes both the systematic offset uncertainty in the adiabatic model estimate for $\delta P(z)$ as well as the (maximum) *rms* random error in the model estimate. The systematic offset error occurs when then average estimate for $\delta P(z)$ from the model differs from the average value of the radiosonde data; such an offset is visible in the January 1996 data, Fig. 1. As the *rms* errors are rather stable in time, the winter and summer months when the adiabatic model systematically under or over estimates $\delta P(z)$ show up as increased values for $\Delta T^m/T^m$ in Fig. 3. While our estimate of the combined systematic and *rms* random errors are approximate, it is clear that systematic errors are a problem with a simple adiabatic model estimate such as used in this analysis.

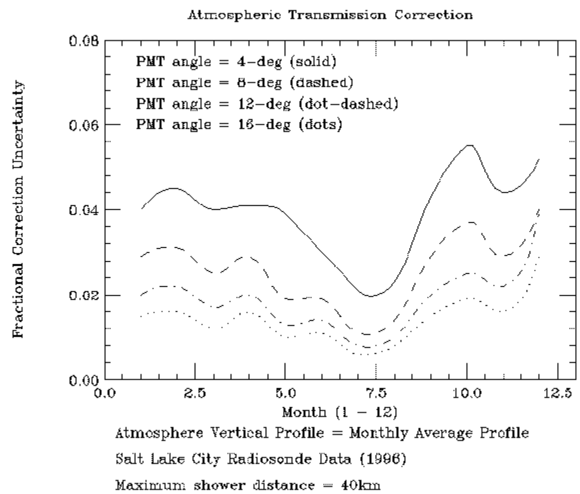

Figure 4: $\Delta T/T$ *versus* month (during 1996) for the average atmosphere model.

The estimate for $\Delta T^m/T^m$ plotted for the average atmosphere model, Fig. 4, shows the (maximum) value of the *rms* random error. By construction the systematic offset error is zero. Months with an essentially constant vertical profile, $\delta P(z)$, *e.g.* June through August, show the smallest values of $\Delta T^m/T^m$. The success of the average atmosphere model suggests that a month by month parameterization of the radiosonde data may provide a useful time dependent model for the atmosphere above the HiRes experiment.

5 Conclusions:

This paper summarizes the time variation of the vertical profile of the atmosphere near the HiRes experiment. Radiosonde data from the SLC airport were used to estimate errors in the transmission correction for fluorescence experiments. The estimated uncertainty in the Rayleigh transmission correction $\Delta T^m/T^m \approx 3\%$ based on using the monthly average of radiosonde data to model the atmosphere.

6 Acknowledgments

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