High Resolution Fly's Eye Note: HiRes-98-XXX
D R A F T

Proposed Atmospheric Monitoring for HiRes Experiment

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Abstract

The atmosphere is the *calorimeter* for HiRes; it is also an essential part of the HiRes *readout system*. The monitoring of the atmosphere falls into two broad categories: the detailed characterization of the atmosphere as needed for accurate reconstruction of the fluorescence light signal, and the detection and tracking of clouds, *i.e.* opaque or *dead* regions in the HiRes calorimeter. These monitoring tasks are made more challenging and important as we propose to view showers at greater and greater distances from the fluorescence eyes. Furthermore this monitoring must be done over the entire HiRes aperture. In this note we propose a minimum set of measurements to characterize the atmosphere.

1. Introduction:

The atmospheric corrections to the High Resolution Fly's Eye, HiRes, experiment [1] data 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). The fractional uncertainty in the reconstructed shower energy is:

$$\frac{\Delta E}{E} = \frac{\Delta I_0}{I_0} = \frac{\Delta T}{T}$$

Thus a *e.g.* 10% uncertainty in transmission correction results in a 10% uncertainty in shower energy. In practice the observed signal includes contributions from air fluorescence plus some scattered air Cherenkov light. The latter must be subtracted as part of the shower reconstruction/analysis and constitutes the second correction to the fluorescence data.

The transmission corrections depend on the total number of scatterers between the source and the fluorescence detector and on the total scattering cross sections ... *i.e.* integral quantities. The correction for the scattering of air Cherenkov light (which is initially approximately collinear with the air shower) into the acceptance of the fluorescence telescopes depends on the local density of scatterers and on the differential scattering cross sections ... *i.e.* differentials of the quantities in the transmission corrections!

Thus various properties of the atmosphere must be known to allow the correction of the observed fluorescence plus scattered air Cherenkov light signal back to the source fluorescence signal at the air shower:

a) the vertical profile of the atmosphere: density, $\rho(z)$, and temperature, $T(z)$, as a function of the height, z, above the fluorescence detector eyes. To first order this is well represented by values at the ground, $z = 0$, combined with the U.S. Standard Atmosphere model [2].

b) the vertical profile of aerosols, also as a function of the height above the fluorescence detector eyes. This varies significantly with time. As a guide, a common parameterization for the the normalized density of aerosols *versus* elevation, $\tilde{\rho}^a(z) = \rho^a(z)/\rho^a(0)$, is given by:

- $\tilde{\rho}^a(z) = 1.$ for $z \leq h_m$, the height of the mixing layer, and

- $\tilde{\rho}^a(z) \;=\; e^{-(z-h_m)/h_a}$ for $z > h_m$, with an aerosol scale height h_a.

c) the Rayleigh scattering total and differential cross section as a function of wavelength (which are known).

d) the aerosol Mie scattering total and differential cross sections as a function of wavelength in the range: $310nm \leq \lambda \leq 410nm$. One prediction of the normalized aerosol Mie scattering differential cross section (for desert locations such as HiRes) is shown in Fig. 1 [3]. In practice the aerosol differential cross section needs to be measured for scattering angles: $10° \leq \theta \leq 160°$.

Transmission losses from Rayleigh scattering on the (molecular) atmosphere are shown in Fig. 2a, and from (predicted) Mie scattering on aerosols [3,4] in the atmosphere in Fig. 2b. For distances of a few kilometers, and in the case of aerosols for large viewing angles from the horizontal, the transmission factors are near one. This was the situation for the Fly's Eye experiment [5]. However for the HiRes experiment we need to view showers to distances of 10s of kilometers. Furthermore the HiRes telescope viewing angles are near the horizontal, $3° \sim 31°$, as shown in Fig. 2. Thus the transmission losses are significant and the transmission corrections must be known at the $\sim 10\%$ level. This places a premium on our detailed knowledge of the aerosol transmission. For example Fig. 3 shows the aerosol transmission with the same (horizontal) attenuation length as Fig. 2b but with a different aerosol vertical scale height.

At present the HiRes experiment includes several pulsed, collimated light sources: a system of broad band emission xenon flashers [6] and two, steerable, frequency tripled YAG lasers operating at 355nm [7]. The laser and xenon data provide both good night to night comparison of atmospheric conditions as well as comparisons with simulated desert aerosol models [8,9,10]. Existing monitoring techniques provide a separation of *good* nights with little aerosol scattering and *poor* nights with obvious aerosol light scattering.

What is now needed are a set of atmospheric measurements that provide quantitative transmission corrections with a precision of $\frac{\Delta T}{T} \sim 10\%$. To accomplish this we propose to measure the transmission, $T^m \cdot T^a$, at one wavelength near the middle of the wavelength acceptance of HiRes. The aerosol transmission, T^a, is obtained by dividing by the comparatively well known molecular transmission, T^m. The measurements of T^a with light sources at fixed elevations, z, viewed at different angles from the horizontal, will provide a direct measurement of the aerosol optical depth, $\tau^a(z)$, versus height above HiRes; see Appendix I. We will use scattered light from frequency tripled YAG lasers at 355nm. This measurement will also provide information on the vertical profile of aerosols; see Sect. 2.b.2. To make corrections over the full wavelength acceptance of HiRes, $310nm < \lambda < 410nm$, we will measure the wavelength dependence of the aerosol attenuation length at the level of the HiRes eyes, $z = 0$. Finally to make corrections for the scattering of air Cherenkov light into the fluorescence telescopes we will measure the aerosol differential cross section, at least near the middle of the wavelength acceptance of HiRes, also at ground level.

2. Proposed measurements:

Our goal is to make the minimum number of measurements that will allow us to correct HiRes data for atmospheric transmission losses and for backgrounds from air Cherenkov light scattered into the air fluorescence signal. To proceed we use a 1-dimensional model, *i.e.* variation only with height, for the atmosphere and for the aerosols. This is a very good model for the molecular atmosphere and it is also good first approximation for aerosols on the horizontal scale of the present HiRes experiment. Ultimately this model can be tested by measuring the horizontal variation of the aerosols *e.g.* by repeating the proposed aerosol measurements at widely different locations in the HiRes aperture.

In the 1-dimensional approximation, the molecular and aerosol transmissions depend on the height of the light source above the eye, z, the viewing angle (*e.g.* from the horizontal) of the i^{th} phototube, α_i, and the wavelength of the light, λ.

2.a Rayleigh scattering in the molecular atmosphere

Rayleigh scattering of light results in an exponential decrease of the light intensity of a light beam passing through the atmosphere. The multiplicative *molecular transmission* is given by:

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

where $\rho(z)$ is the air density versus height and $\Lambda^m(\lambda) = 2970 \cdot (\frac{\lambda}{400nm})^4$ gm/cm^2 is the Rayleigh attenuation length[1]. This can be re-expressed in terms of the *molecular optical depth*, $\tau^m(z,\lambda) = \int_0^z \frac{\rho(z)dz}{\Lambda^m(\lambda)}$ and the slant factor, $\frac{1}{sin(\alpha_i)}$:

$$T^m(z, \alpha_i, \lambda) = e^{-\tau^m(z,\lambda) \cdot \frac{1}{sin(\alpha_i)}} \tag{1}$$

The integral of the density to height, z, can be re-expressed in terms of the pressure difference, δP in millibar, between the light source and the fluorescence eye:

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

and g is the acceleration of gravity. Thus the fractional uncertainty in T^m is:

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

[1] For HiRes this corresponds to $\Lambda^m(\lambda) \sim 16.61 \cdot (\frac{\lambda}{350nm})^4$ km.

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

$$\Delta(\delta P) \quad \leq \quad n(\%) \cdot \frac{15 \; mbar}{(1/sin(\alpha_i))}$$

Fortunately δP must be known most precisely at small viewing angles, *i.e.* near the ground. As an example with $n = 2(\%)$ and $\alpha_i = 6°$ then we require that $\Delta(\delta P) \sim 3$ mbar (or less).

We propose to monitor the molecular atmosphere using several weather stations to provide the local pressure and temperature through out the HiRes aperture. The vertical profile is then obtained using a combination of the time dependent US Standard Atmosphere model and twice daily radiosonde profiles from Salt Lake City airport. This should be sufficient to limit $\Delta(\delta P) \sim$ a few mbar [11].

2.b Mie scattering on aerosols in the atmosphere

2.b.1 Aerosol Transmission Correction

Mie scattering of light on aerosols in the atmosphere results in an additional exponential decrease of the light intensity of a light beam passing through the atmosphere. The multiplicative *aerosol transmission* is given by:

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

where $\tilde{\rho}^a(z) = \rho^a(z)/\rho^a(0)$ is the normalized density of aerosols *versus* elevation and $\Lambda^a(\lambda)$ is the aerosol attenuation length (*e.g.* in meters) at $z = 0$ as a function of wavelength. As with the molecular transmission, the aerosol transmission can be re-expressed in terms of the *aerosol optical depth*, $\tau^a(z, \lambda) = \int_0^z \frac{\tilde{\rho}^a(z)dz}{\Lambda^a(\lambda)}$ and the slant factor:

$$T^a(z, \alpha_i, \lambda) \quad = \quad e^{-\tau^a(z,\lambda) \cdot \frac{1}{sin(\alpha_i)}} \tag{2}$$

With this functional form for the aerosol optical depth we make three assumptions about the aerosols in the atmosphere:

- the vertical dependence is much more important than horizontal variations, *i.e.* we use a 1-dimensional model for the aerosols (as noted above);
- the aerosol vertical profile is the same at all wavelengths for the wavelength interval of interest, $310nm \sim \lambda \sim 410nm$. That is we assume that to first order the wavelength dependence is only in the attenuation length, $\Lambda^a(\lambda)$.

- the aerosol total cross section, or equivalently the aerosol attenuation length, does not change with height, z, for the wavelength interval of interest, $310nm \sim \lambda \sim 410nm$. That is we assume that to first order the height dependence is only in the normalized aerosol density, $\tilde{\rho}^a(z)$.

Thus if $T^a(z, \alpha_i, \lambda)$ is known at 355nm, then:

$$T^a(z, \alpha_i, \lambda) \;=\; (T^a(z, \alpha_i, 355nm))^{\frac{\Lambda^a(355nm)}{\Lambda^a(\lambda)}} \;=\; (T^a(z, \alpha_i, 355nm))^{R(\lambda)} \qquad (3)$$

The exponent, $R(\lambda)$, is expected to vary with time; typical values for a desert atmosphere are predicted in the range: $1.14 \sim 0.91$ [3].

We propose to monitor the aerosols using both point and collimated beam light sources at a variety of wavelengths in the $310nm \sim 410nm$ acceptance of the HiRes optics. The specific proposed measurements related to the aerosol transmission factor are:

a) *aerosol optical depth versus height, z, at 355nm* - this will be measured at 355nm using a steerable laser at least at ONE of the HiRes eyes plus the fluorescence telescopes at the SECOND HiRes eye to read out the scattered light. The concept is to use the scattered light from the laser, with controlled geometries, to place known intensity light sources at various discrete elevations in the atmosphere and at various distances from the read out eye. Measurements at different slant factors, $\frac{1}{sin(\alpha_i)}$, combined with knowledge of the vertical profile of the molecular atmosphere, allow a direct determination of the aerosol optical depth *versus* height, z, and thus of the aerosol transmission, $T^a(z, \alpha_i, 355nm)$ (Eqn. 2), at 355nm. For additional details on extracting the aerosol optical depth *versus* height see Appendix I.

b) *(horizontal) aerosol attenuation length versus wavelength* - this will be measured using pairs of Hg(Xe) point light sources: one near the receiver and one $20km \sim 40km$ far from the receiver. Measurements will be done at several wavelengths between $300nm \leq \lambda \leq 580nm$. Denoting d_{far} the distance to the far light, I^{1m}_{far} the intensity at say 1m from the far light, I^{obs}_{far} the observed intensity of the far light at the receiver and with similar definitions for the near light, then the attenuation length is given by ratios of measured quantities:

$$\Lambda^{tot} \;=\; \frac{(d_{far} - d_{near})}{ln\left(\frac{I^{obs}_{near}}{I^{obs}_{far}} \cdot \frac{I^{1m}_{far}}{I^{1m}_{near}} \cdot \left(\frac{r_{near}}{r_{far}}\right)^2 \right)}$$

Individual wavelengths will be selected using narrow band filters matched to the prominent mercury spectral lines. A bialkali photocathode PMT, with UV transparent window, will be used for the detector. This provides good efficiency even below

300nm and has a natural cutoff above $\sim$ 670nm thus precluding the need for additional IR blocking filters. These measurements, combined with the local temperature and pressure which determine $\Lambda^m(\lambda)$, will determine $\Lambda^a(\lambda)$ using the relation:

$$\frac{1}{\Lambda^{tot}} = \frac{1}{\Lambda^m} + \frac{1}{\Lambda^a}$$

Finally the wavelength correction is given by $R(\lambda) = \frac{\Lambda^a(355nm)}{\Lambda^a(\lambda)}$. The wavelength correction is used to provide the wavelength dependence for the aerosol transmission correction; see Eqn. 3.

2.b.2 Correction for Air Cherenkov Scattering on Aerosols

The correction for air Cherenkov light scattered into the fluorescence telescopes involves several elements. Furthermore the correction differs greatly from shower to shower as showers directed *towards* a fluorescence telescope have the potential for the largest correction(s). To make the correction we need to know the density of scatterers *versus* height and the differential scattering cross sections for both Rayleigh (molecular) and Mie (aerosol) scattering. The Rayleigh scattering component depends on the vertical density profile of the air and on the known Rayleigh differential cross section. Furthermore the vertical density profile of the air is well modelled (US Standard Atmosphere), frequently measured (radiosonde data) and we can measure the density at ground level, $z = 0$, easily. In contrast the Mie scattering component requires several sophisticated measurements: the vertical normalized density profile of aerosols, $\tilde{\rho}^a(z)$, the aerosol attenuation length versus wavelength, $\Lambda^a(\lambda)$, and the Mie scattering differential cross section (possibly versus wavelength) for scattering angles in the range: $10° \sim 160°$.

The measurement of $T^a(z, \alpha_i, 355nm)$ and separately $\Lambda^a(355nm)$ discussed in Sect. 2.b.1 provides a measurement of an *effective aerosol thickness*, $t^a_{eff}(z)$, as a function of height above the fluorescence detectors:

$$t^a_{eff}(z) = \Lambda^a(355nm) \cdot \int_0^z \frac{\tilde{\rho}(z)dz}{\Lambda^a(355nm)} = \Lambda^a(355nm) \cdot \tau^a(z, 355nm) \qquad (4)$$

Thus the vertical profile of the normalized aerosol density can be extracted by differentiating $t^a_{eff}(z)$ [2]. In practice this may be done parametrically using *e.g.* the two parameter aerosol model (given above) where h_m is the height of the aerosol mixing layer and h_a is the

[2] This is true only as long as the aerosol attenuation length is independent of height. If both the aerosol density and attenuation length vary with height the transmission correction, Sect 2.b.1 is unaffected, however the effective aerosol thickness will include information on both the height dependence of the density of aerosols and the aerosol attenuation length.

aerosol scale height. The parameters h_m and h_a are obtained from a fit to the $t^a_{eff}(z)$ measurements[3].

The fraction of air Cherenkov light, $f^a(\lambda)$, scattered by aerosols through an angle, β, (from the original air Cherenkov light direction toward the fluorescence telescope), in a vertical distance, dz, is then:

$$f^a(\lambda) \;=\; \frac{\tilde{\rho}^a(z)}{\Lambda^a(\lambda)} \;\cdot\; \frac{dz}{sin(\tilde{\alpha})} \;\cdot\; \left(\frac{\frac{d\sigma(cos(\beta),\lambda)}{d\Omega}}{\sigma}\right) \;\cdot\; \Delta\Omega \tag{5}$$

where $\tilde{\alpha}$ is the direction of the air Cherenkov light with respect to the horizontal and $\Delta\Omega$ is the angular acceptance of the entrance aperture of a given fluorescence telescope. To a good approximation $\tilde{\alpha}$ is the direction of the air shower with respect to the horizontal. The ratio of aerosol cross sections, $\frac{\frac{d\sigma(cos(\beta),\lambda)}{d\Omega}}{\sigma}$, is called the *aerosol phase function.* The dependence on the wavelength of the light is through the attenuation length, $\Lambda^a(\lambda)$, and through the aerosol phase function.

The aerosol phase function in the angular range $10° \leq \beta \leq 90°$ is most relevant to the scattering of air Cherenkov light into the fluorescence telescopes. The aerosol phase function in the angular range $90° \leq \beta \leq 160°$ is most relevant to the (aerosol) scattering of HiRes laser (monitoring) light beams into the fluorescence telescopes (Appendix I). Thus the aerosol phase function must be measured through most of the range of scattering angles.

We propose to measure the aerosol phase function using a collimated (*e.g.* horizontal) light beam located very near ONE of the HiRes eyes. The combined geometry of the light beam and the acceptance of the fluorescence eye will allow for monitoring the intensity of the scattered light *versus* scattering angle for light scattering angles in the range of interest: $10° \sim 160°$ with respect to the light beam. In this geometry there is almost no attenuation correction for the light. The measurement will be done at several wavelengths in the range $310nm \leq \lambda \leq 410nm$ to measure changes in the the aerosol phase function with wavelength. As the scattered light includes both Mie (aerosol) and Rayleigh (molecular) contributions, a potential byproduct of the aerosol measurement is a check on the absolute *end to end* calibration, *i.e.* photons to ADC values, of the fluorescence telescopes based on the known differential scattering cross section for Rayleigh scattering. Thus the absolute intensity of each light beam pulse must be measured. Furthermore it may be profitable to linearly polarize the light as Rayleigh scattering near 90° is particularly sensitive to the plane of polarization[4]. If the absolute Rayleigh calibration is successful, then we would propose to locate one of these monitors at each eye.

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[3]Note, for small heights above the fluorescence eyes, $z \approx 0$, then $t^a_{eff}(z) = z$ and for heights well above the aerosols, $z >> h_m + h_a$, then $t^a_{eff}(z) = h_m + h_a$.

[4]For linearly polarized light with electric field vector *normal* to the plane of scattering the Rayleigh

3. Summary

The atmospheric corrections needed for the HiRes experiment were reviewed. Based on these corrections we propose four distinct measurements:

1. the ground level temperature and pressure
2. the atmospheric transmission, $T^m \cdot T^a$, at 355nm versus source height and observing angle (with respect to the fluorescence eye(s))
3. the (horizontal) attenuation length versus wavelength in the interval: $300nm \leq \lambda \leq 580nm$ and
4. the aerosol Mie scattering differential cross section.

At this point in our understanding of the aerosol component of the atmosphere, these measurements constitute a minimum set of atmospheric monitoring measurements.

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differential cross section is *flat* in scattering angle, θ. For linearly polarized light with electric field vector *in* the plane of scattering the Rayleigh differential cross section is $\propto cos^2(\theta)$.

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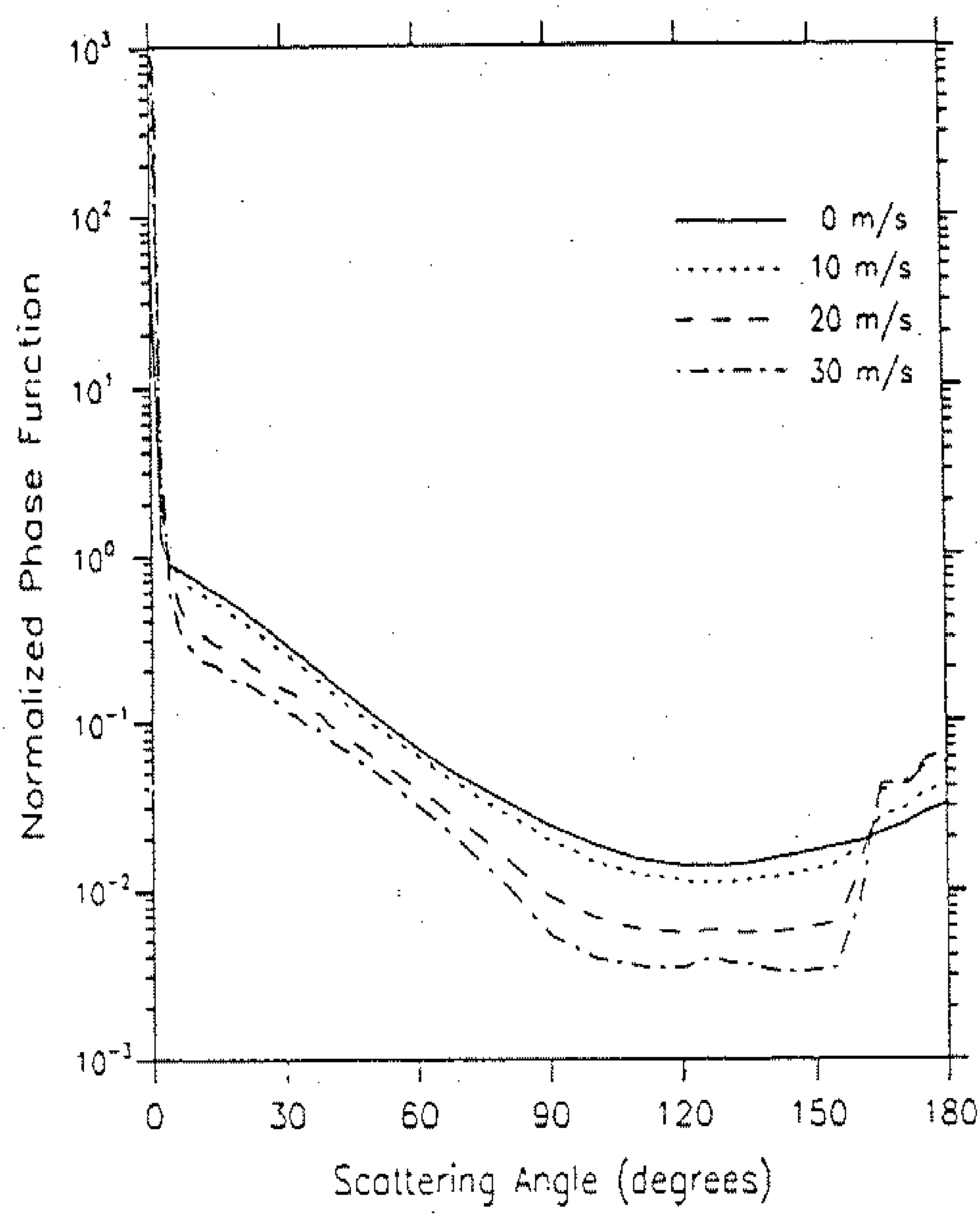

Fig. 1: The ratio of aerosol cross sections, $\frac{\frac{d\sigma(cos(\beta),\lambda)}{d\Omega}}{\sigma}$, or *aerosol phase function*, is shown *versus* scattering angle at a wavelength of 550nm. The curves are from a simulation of aerosols in a desert environment [3].

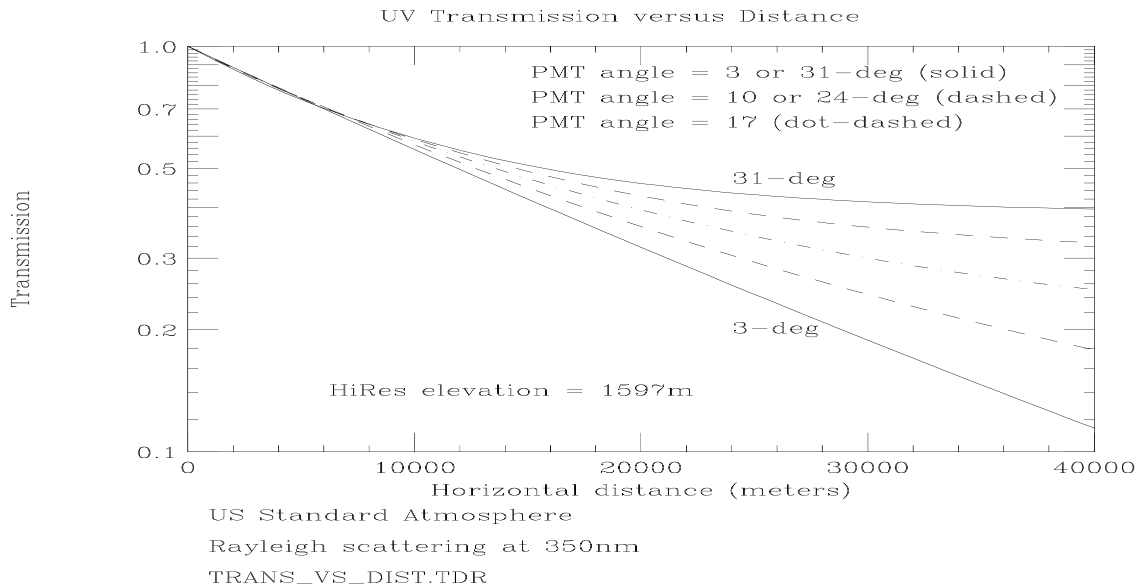

Fig. 2a: Transmission factor, T^m, for Rayleigh scattering in the (molecular) atmosphere. Curves are shown for HiRes viewing angles from $3° \sim 31°$ to the horizon.

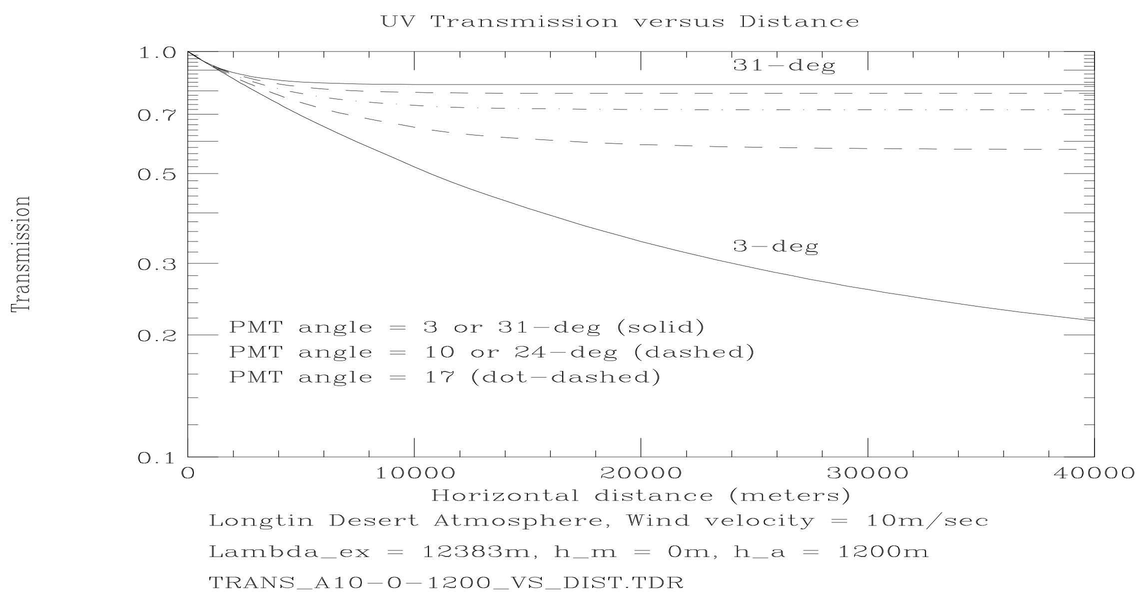

Fig. 2b: Transmission factor, T^a, for Mie scattering on the aerosols in the atmosphere. The aerosols are described by a (horizontal) attenuation length $\Lambda^a(350nm) = 12,383$m and an exponential scale height, $h_a = 1200$m [3,4]. Curves are shown for HiRes viewing angles from $3° \sim 31°$ to the horizon.

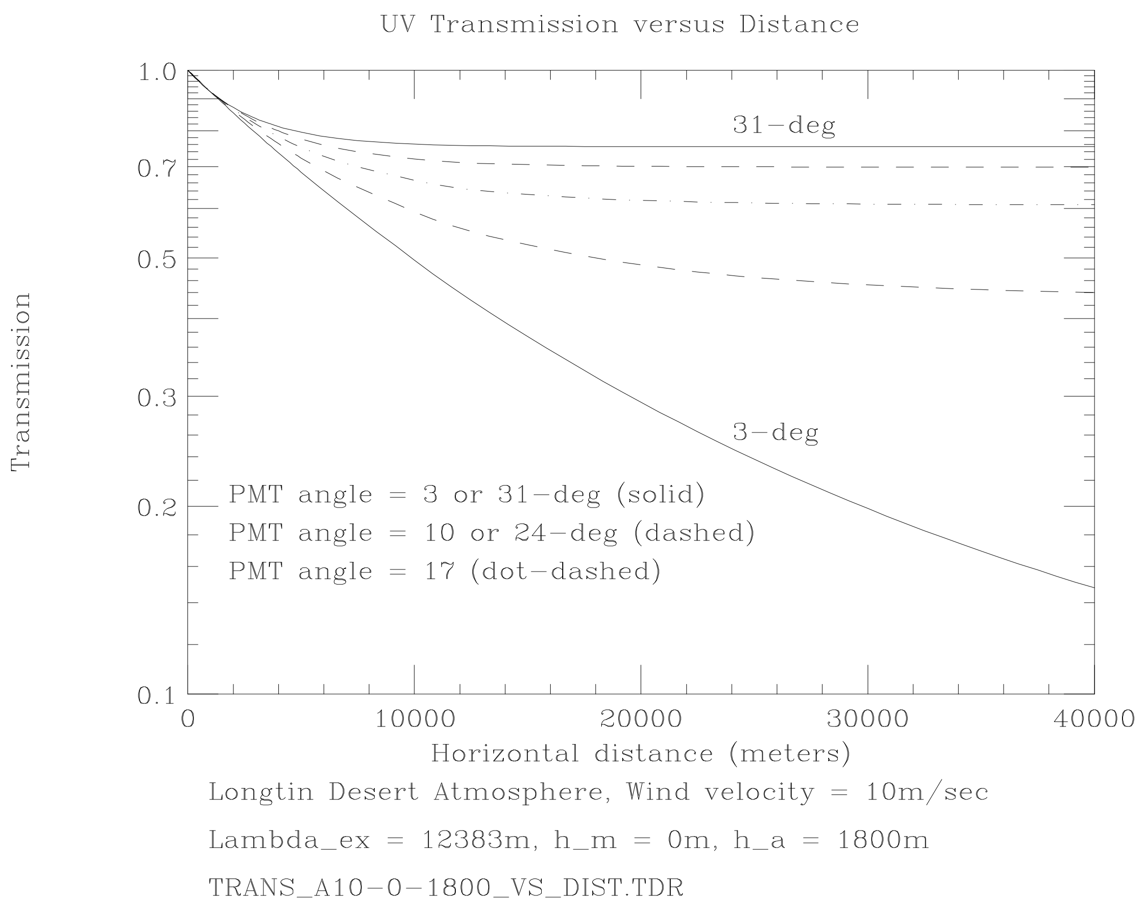

Fig. 3: Transmission factor, T^a, for Mie scattering on the aerosols in the atmosphere. The aerosols are described by a (horizontal) attenuation length $\Lambda^a(350nm) = 12,383$m and an exponential scale height, $h_a = 1800$m [3]. Curves are shown for HiRes viewing angles from $3^\circ \sim 31^\circ$ to the horizon.

Appendix I: Measurement of the Aerosol Optical Depth

The *aerosol optical depth*:

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

and the slant factor, $\frac{1}{sin(\alpha_i)}$, are defined in Sect. 2.b.1. At a given wavelength and with our 1-dimensional model for the aerosols, the aerosol optical depth depends only on the light source height, z, above the fluorescence telescope(s). Thus the aerosol optical depth for light from <u>all</u> light sources at the <u>same</u> height z above the fluorescence eye(s) is the <u>same</u>! Furthermore for our 1-dimensional aerosol model the aerosol transmission factorizes into z-dependent and into α_i-dependent parts:

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

Thus if we place light sources of known intensity, I_0, at the same height, z, above a fluorescence eye but at different horizontal distances from the eye these will be viewed with different slant factors and will have different observed intensities. If we denote the observed intensities, corrected for simple geometrical effects (*e.g.* the r^{-1} dependence with distance (r) for *line* light sources) and for Rayleigh scattering, by $\tilde{I}_{obs}(\alpha_i)$ then:

$$\tilde{I}_{obs}(z,\alpha_i) \;=\; I_0 \;\cdot\; e^{-\tau^a(z)\;\cdot\;\frac{1}{sin(\alpha_i)}}$$

The natural logarithm of $\tilde{I}_{obs}(\alpha_i)$ is then:

$$ln(\;\tilde{I}_{obs}(z,\alpha_i)\;) \;=\; ln(\;I_0\;) \;-\; \tau^a(z) \;\cdot\; \frac{1}{sin(\alpha_i)}$$

The slope of $ln(\;\tilde{I}_{obs}(z,\alpha_i)\;)$ *versus* $\frac{-1}{sin(\alpha_i)}$ gives the aerosol optical depth, $\tau^a(z)$. Alternatively for two measurements with very different values of $\frac{1}{sin(\alpha_i)}$ we obtain:

$$ln(\;\frac{\tilde{I}_{obs}(z,\alpha_{large})}{\tilde{I}_{obs}(z,\alpha_{small})}\;) \;=\; \tau^a(z) \;\cdot\; (\frac{1}{sin(\alpha_{small})} \;-\; \frac{1}{sin(\alpha_{large})})$$

where α_{small} is a small angle to the horizontal and corresponds to light from a very distant source, and α_{large} is a large angle to the horizontal and corresponds to light from a nearby source. **This relation provides a direct measurement of $\tau^a(z)$.**

With our above definition of $\tilde{I}_{obs}(z, \alpha_i)$, then:

$$\frac{\tilde{I}_{obs}(z,\alpha_i)}{I_0} \;=\; e^{-\tau^a(z,\lambda)\,\cdot\,\frac{1}{sin(\alpha_i)}} \;=\; T^a(z,\alpha_i)$$

Plots of $T^a(z, \alpha_i)$ *versus* $\frac{1}{sin(\alpha_i)}$ are shown in Fig. A1a and A1b for two different aerosol vertical profiles. The different aerosol vertical density profiles are apparent if one compares the slopes of the transmission factors from fixed height sources. For aerosol vertical distribution with the <u>same</u> value of $h_m + h_a$, then for light sources well above the aerosols the slopes should be the same ... and they are. This can be seen more clearly in Fig. A2 which shows the effective aerosol thickness, $t^a_{eff}(z)$ (Eqn. 4), for the two aerosol vertical distributions.

Thus to measure $\tau^a(z)$ we need known intensity, pulsed, UV light sources placed more or less throughout the atmosphere above the HiRes aperture. For the light sources we propose to use *scattered* light from frequency tripled YAG laser beams. The relative brightness of each source will be known based on monitoring the intensity of each laser pulse <u>and</u> by making a (small) correction for variations in the scattering probability versus laser light scattering angle (*i.e.* the angle between the initial laser beam direction and the final direction toward the monitoring fluorescence telescope). Two possible geometries for the lasers are given by:

1. <u>Fixed Radius Multi-source Geometry</u>:
   In this geometry we would place vertically directed light sources at a **fixed radius** around **one** FD eye. This eye is the *monitor* eye and provides the measurement of the relative shot to shot laser intensity – only azimuthal symmetry need be assumed. A second, *attenuation*, eye views these at different distances. Thus for a given z the attenuation eye views these at different values of $\frac{1}{sin(\alpha_i)}$ as required. This is sketched in Fig. A3a.

2. <u>Fixed Radius Single-source Geometry</u>:
   In this geometry we would locate a <u>single</u> steerable laser at some (large) distance from the attenuation eye. The shot to shot intensity of the laser is monitored <u>and</u> provides the measurement of the relative shot to shot laser intensity for points along the laser (beam) at **fixed radius** from the laser – only azimuthal symmetry need be assumed. A range of z and $\frac{1}{sin(\alpha_i)}$ is obtained by directing the laser beam at various azimuth and elevation angles. This is shown in Fig. A3b and corresponds to the present HiRes plan to locate steerable YAG lasers at each of the eyes.

For the two geometries in Fig. A3, the scattering angle of the laser light is in the range: $90° \sim 120°$ for the *fixed radius multi-source* geometry and in the approximate range: $100° \sim 160°$ for the *fixed radius single-source* geometry. The normalized Rayleigh and predicted Mie scattering differential cross sections [3,4] are shown in Fig. A5a. The fraction of laser light that undergoes Mie scattering on aerosols in the atmosphere is given by Eqn. 5 in Sect. 2.b.2. A similar expression applies to the fraction of the laser light that undergoes Rayleigh scattering in the atmosphere. In both cases a small fraction of the laser light scatters from the original laser beam direction toward the monitoring fluorescence telescope (the *attenuation eye*) ... this defines the scattering angle, β, in Eqn. 5.

At 355nm the relative attenuation lengths for aerosol and molecular scattering at the HiRes experiment are predicted to be approximately equal [3]; see Fig. A4. In practice the HiRes experience is that the typical aerosol attenuation length at the HiRes experiment, Dugway Utah, is about $1.4\times$ longer than the Longtin [3] prediction [12]. To first order the effective scattering cross section is approximately the sum of the Rayleigh and Mie distribution in Fig. A5a. In Fig. A5b we show the sum of Rayleigh plus Mie scattering cross sections normalized to the Rayleigh cross section for three cases:

- Rayleigh attenuation length is twice the Mie attenuation length ... this corresponds to a night with much larger than expected levels of aerosols,
- Rayleigh attenuation length equals the Mie attenuation length and
- Rayleigh attenuation length is one-half the Mie attenuation length ... this corresponds to a typical night with low levels of aerosols.

Except for nights with much larger than expected levels of aerosols the total Rayleigh plus Mie cross section (normalized to the Rayleigh cross section) is quite constant over the angular scattering range: $100° \sim 160°$. Thus we anticipate that only small corrections will be needed to *normalize* the scattered light intensities at the different values of $\frac{1}{sin(\alpha_i)}$ for each fixed value of z. Furthermore, the corrections become smaller, *i.e.* the ratio in Fig. A5b approaches 1.0, as the height of the sources increases. This is because the typical scale height for aerosols, $h_a \sim 1.2$km, is much less than the scale height, ~ 7.5km, for atmospheric air density.

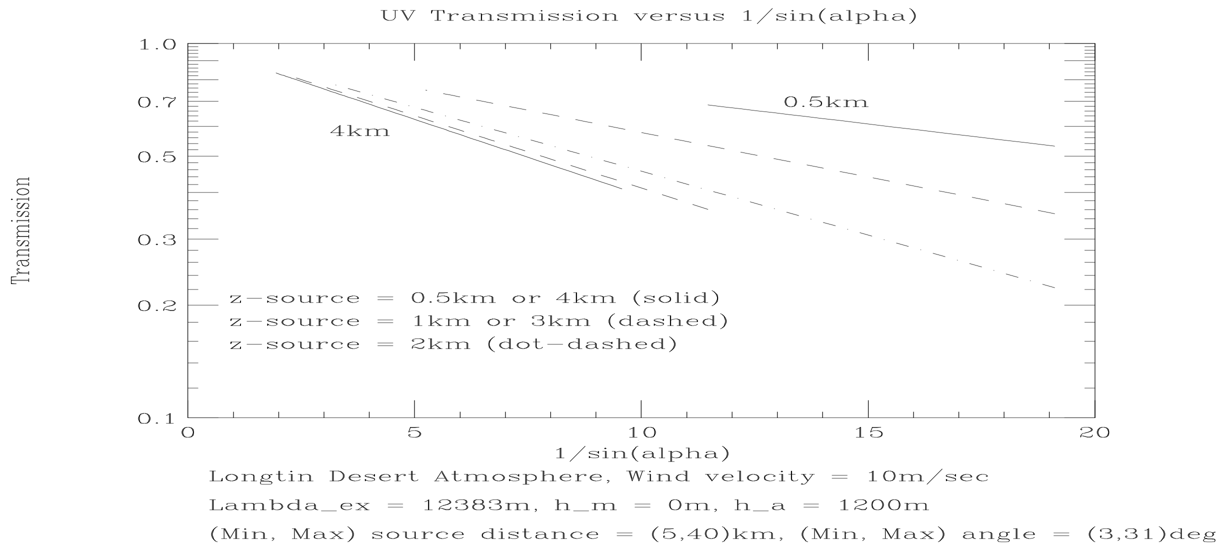

Fig. A1a: Transmission factor for sources at fixed heights observed at different values of $\frac{1}{sin(\alpha_i)}$. The normalized density of aerosols *versus* elevation, $\tilde{\rho}^a(z) = \rho^a(z)/\rho^a(0)$, is modelled by $h_m = 0$m and $h_a = 1200$m. The (horizontal) attenuation length for light at 350nm is $\Lambda^a = 12383$m [3].

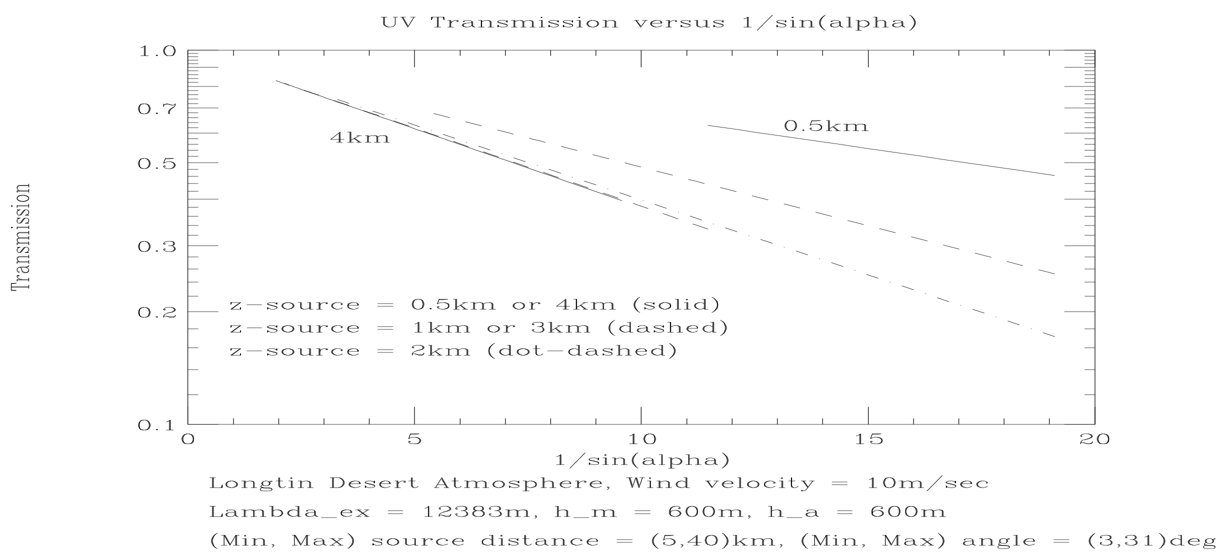

Fig. A1b: Transmission factor for sources at fixed heights observed at different values of $\frac{1}{sin(\alpha_i)}$. The normalized density of aerosols *versus* elevation, $\tilde{\rho}^a(z) = \rho^a(z)/\rho^a(0)$, is modelled by $h_m = 600$m and $h_a = 600$m.

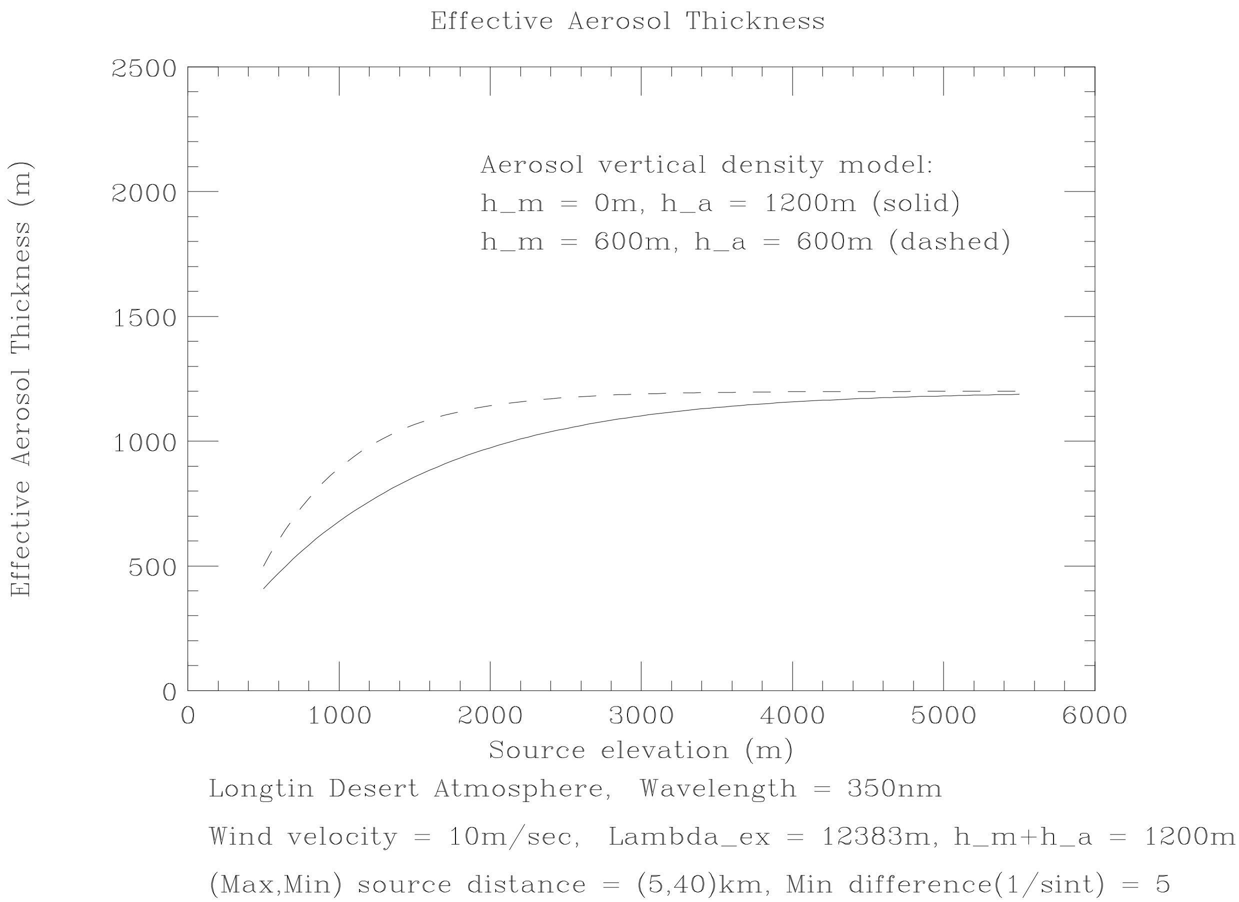

Fig. A2: The effective aerosol thickness, $t^a_{eff}(z)$ (Eqn. 4), for two different vertical distributions having the same $h_m + h_a$.

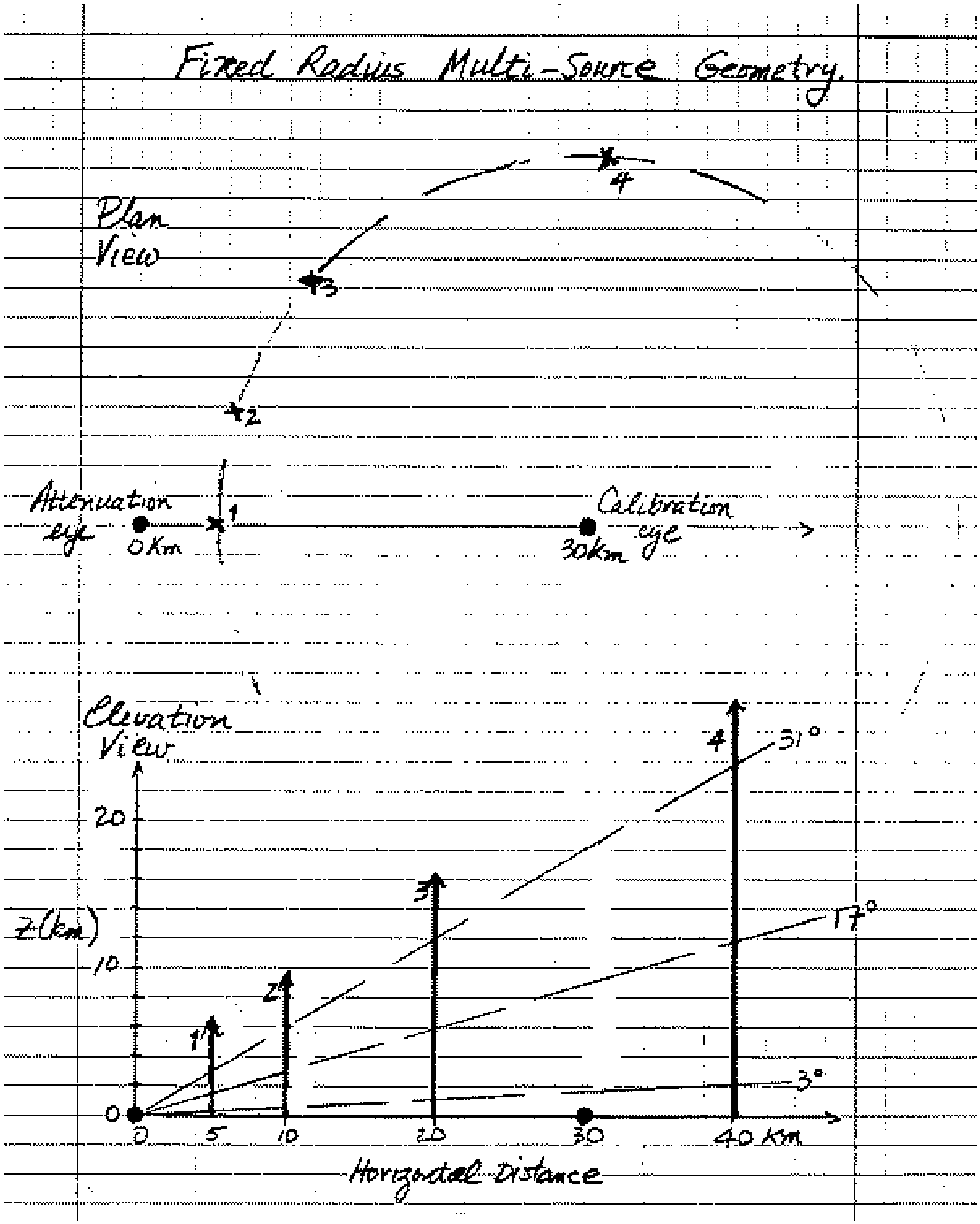

Fig. A3a: Sketch of *fixed radius multi-source* laser geometry for aerosol monitoring. The intensity of each laser is monitored by the *monitor* ≡ *calibration* eye.

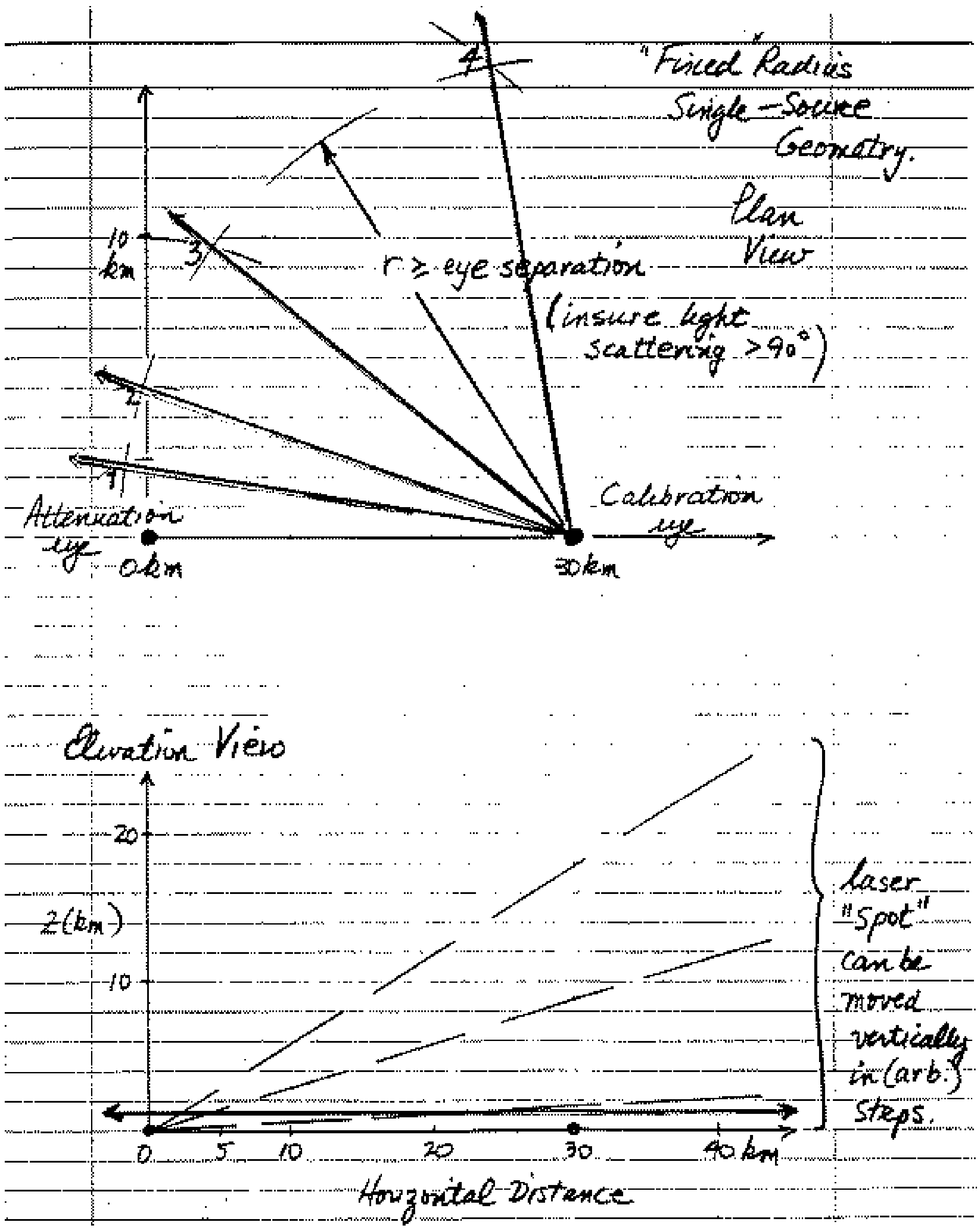

Fig. A3b: Sketch of *fixed radius single-source* laser geometry for aerosol monitoring. The steerable laser is located at the *monitor* ≡ *calibration* eye. This is the geometry that will be used initially by HiRes.

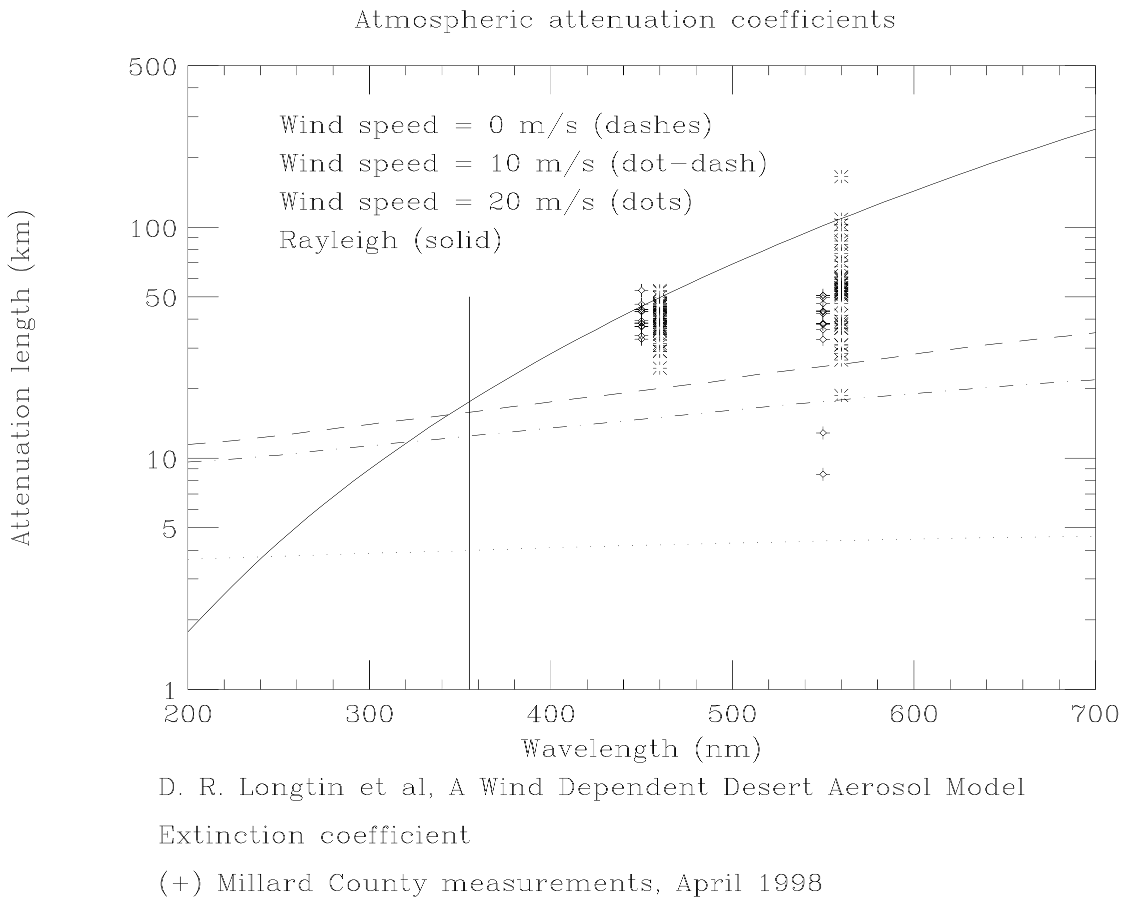

Fig. A4: Rayleigh and predicted Mie [3] scattering attenuation lengths at the HiRes experiment, Dugway, Utah. The vertical line is at 355nm.

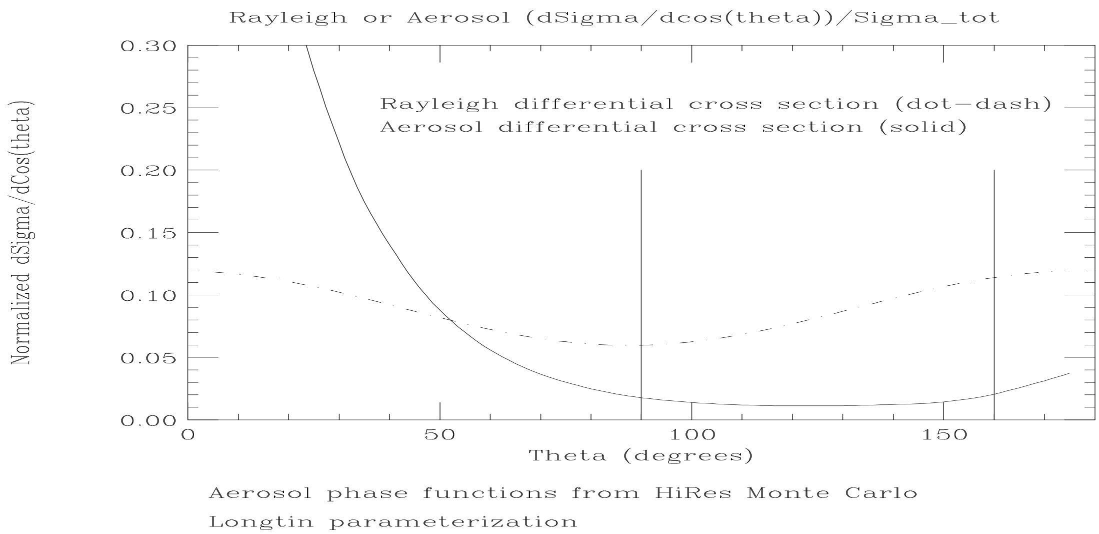

Fig. A5a: Normalized Rayleigh and Mie [3,4] scattering differential cross sections plotted versus scattering angle. For the aerosol monitoring geometries in Fig. A3 the typical scattering angles are in the range: $90° \sim 160°$ (vertical lines).

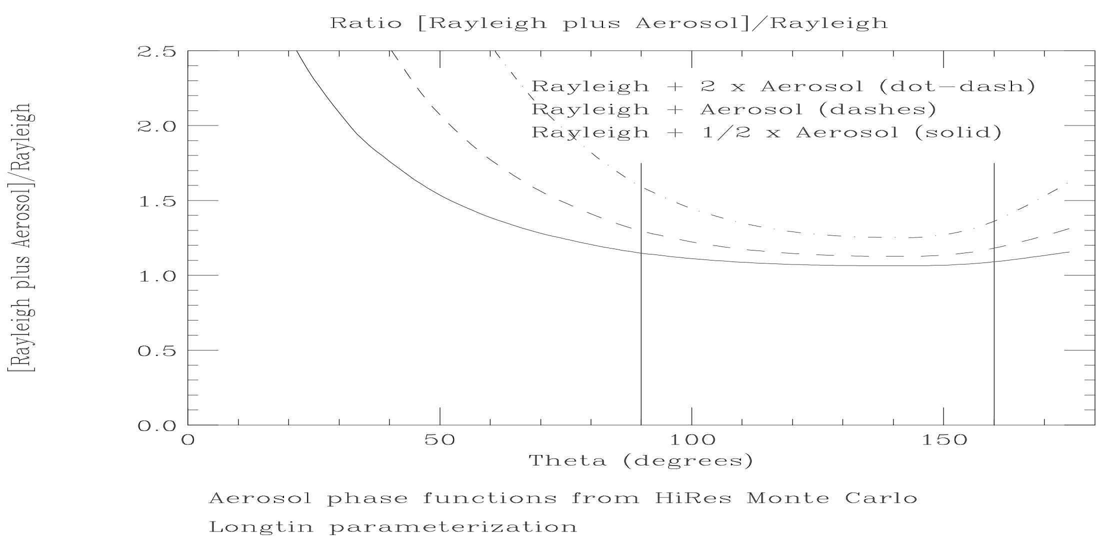

Fig. A5b: The sum of Rayleigh plus Mie scattering differential cross sections normalized to the Rayleigh cross section for three cases; see text. The case with the Rayleigh attenuation length equal to, or one-half, the Mie attenuation length (shown as the dashed and solid curves) corresponds to a typical night with low levels of aerosols. For the aerosol monitoring geometries in Fig. A3 the typical scattering angles are in the range: $90° \sim 160°$ (vertical lines).