

**Proposal for a Remote Vertical Laser System
for the Auger Fluorescence Detector**

M. D. Roberts and J. A. J. Matthews

University of New Mexico
New Mexico Center for Particle Physics
Albuquerque, NM 87131

June 25, 2002

1 Introduction

Atmospheric monitoring of the variable aerosol component of the atmosphere will be done using inelastic backscatter LIDARs located at each of the four Auger fluorescence detector sites [1]. The job of the LIDARs is to measure, and thus monitor, the aerosol vertical optical depth, AVOD, as a function of height over the Auger ground array [1][2]. The AVOD needs to be known to a precision $\delta AVOD < 0.01$. This is a significant challenge.

One partial cross check of the backscatter LIDAR atmospheric monitoring is provided by the horizontal attenuation monitor system [1]. However there will be no cross check of the vertical distribution of atmospheric aerosols which are most directly related to the AVOD.

To address this need we propose two new, atmospheric-monitoring lasers to be located near the center of the Auger ground array. The lasers operate remotely and produce a pulsed, vertical light beam at 355nm (visible to the fluorescence detectors). Light scattered from the beams is measured by the four fluorescence detectors (located on the periphery of the Auger ground array). With laser pulses of known (monitored) intensity observed by calibrated fluorescence detectors, it is then straight forward to extract the vertical aerosol optical depth *versus* height. Additional motivation and a discussion of the principle of operation are discussed in the report attached to this proposal [2].

Vertical beam measurements have been made successfully at the HiRes fluorescence detector for a number of years [3]. Recent test measurements with a mobile laser system [4] have shown that similar measurements at the Auger observatory are also possible (see Fig. 1).

As part of this proposal we also recommend that the two lasers be positioned so that they are equidistant from two and ideally equidistant from three of the four Auger fluorescence detector sites. By choosing the *triple* equidistant sites the lasers permit a number of invaluable fluorescence detector monitoring tests at no additional cost. These include monitoring the relative timing of all of the FDs, the relative calibrations (photons to ADC values) of the FDs and the trigger efficiency of the FDs.

The details of laser positioning are discussed in the deployment section.

2 Requirements of the vertical laser system

The vertical laser system needs to provide a well aligned vertical, de-polarized beam that is intense enough to be seen by the fluorescence detectors at distances of up to 35km. The laser should fire at a low rate (typically 0.5Hz) and provide groups of 100-200 laser tracks 3 or 4 times per hour. The system needs to operate remotely with little maintenance for long periods of time. To reconstruct aerosol optical depth the absolute intensity of the laser beam must be monitored to an accuracy of better than 10%.

A prototype for this system has been constructed in co-operation with colleagues from the University of Utah (see Fig. 2). This system has operated successfully since the beginning of 2002. All of the requirements described above have been incorporated into this system. Thus we propose to copy the basic design of the system in Fig. 2 in the two Auger systems.

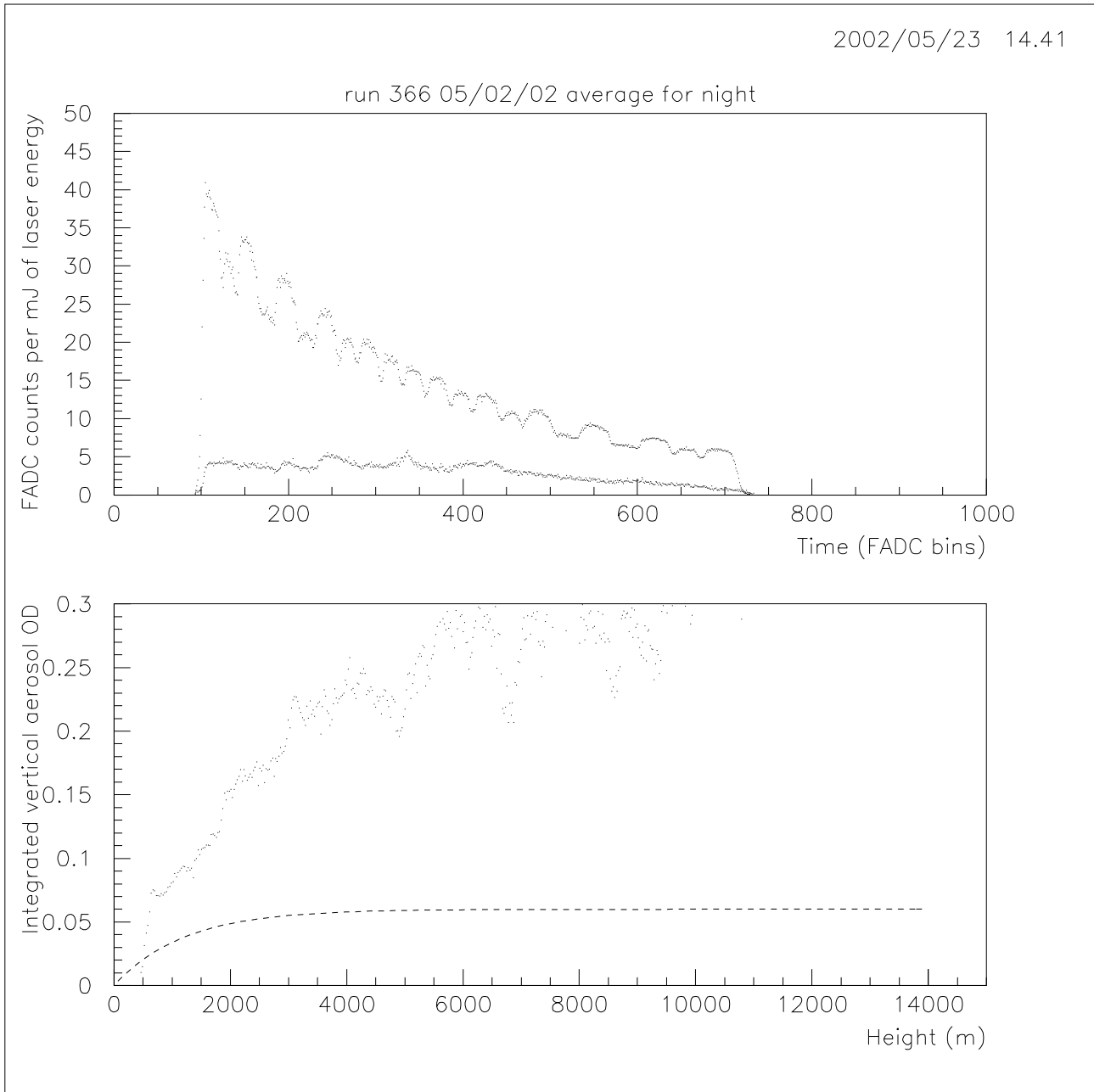


Figure 1: This plot shows a vertical laser beam measurement of vertical aerosol optical depth. This measurement was made on February 5 2002 with a laser located 26km from the Los Leones fluorescence detector. The top plot shows the measured FADC signal as a function of elapsed time since laser firing (100ns per FADC bin). The upper trace on this plot is a Monte Carlo prediction of the expected signal for a perfectly clear day, while the bottom trace shows the actual measurement. The bottom plot shows the optical depth, calculated by the method described in the attached report [2]. Also shown, with a dashed line, is optical depth for the HiRes standard desert atmosphere. The measured optical depth shows a uniform dense layer of aerosols extending up to around 4 km. This is typical of aerosol patterns which exist periodically during the summer months at the base of the Andes, when strong dry winds lift large amounts of dust up to the local height of the Andes.

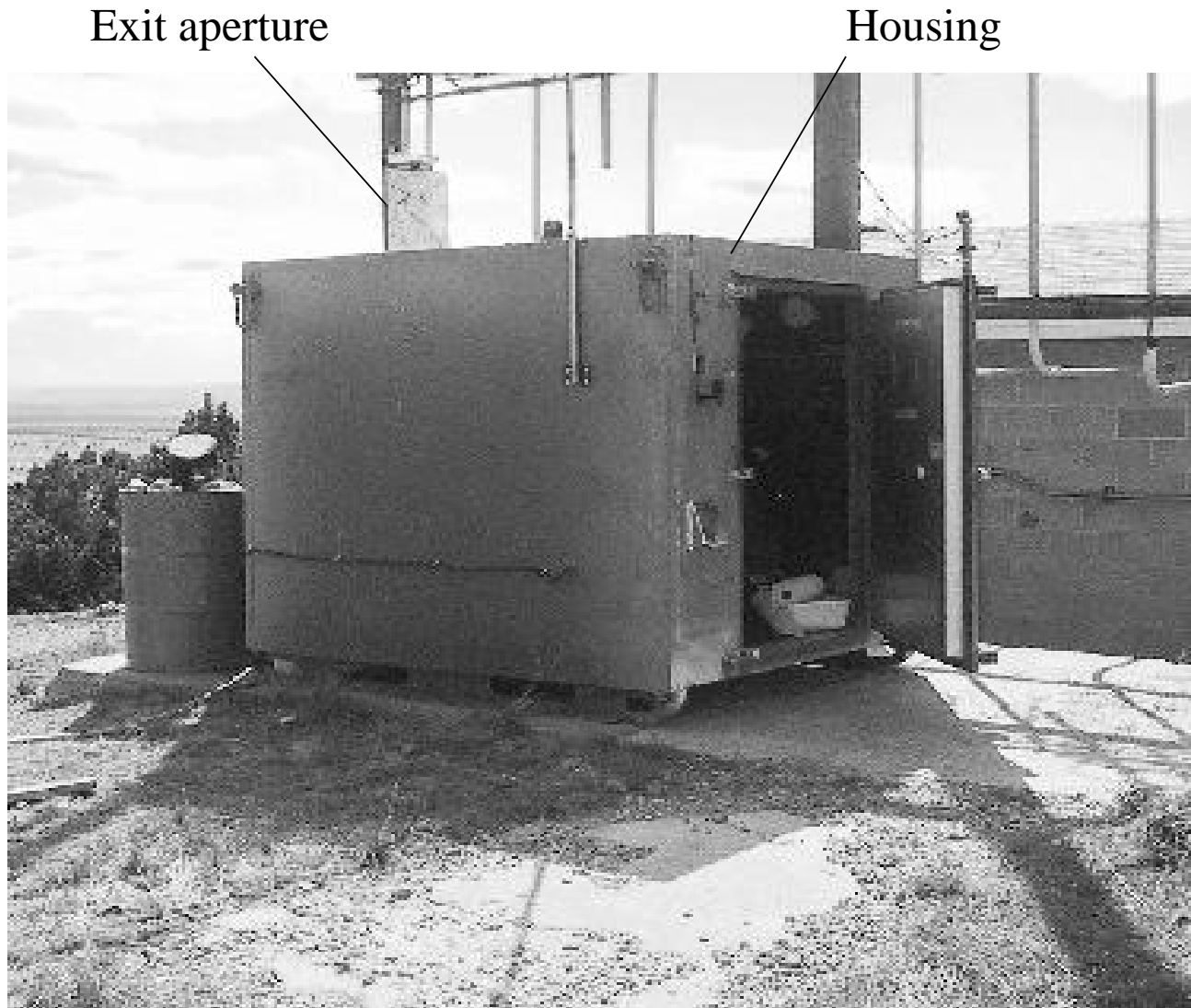


Figure 2: Photograph of a vertical remote-laser system under test and evaluation in Millard county Utah. Our New Mexico group is collaborating on this R&D with the HiRes collaboration. This system, operational since February 2002, is the prototype for the proposed Auger laser system. The Millard county system has all of the features that are required for the Auger system.

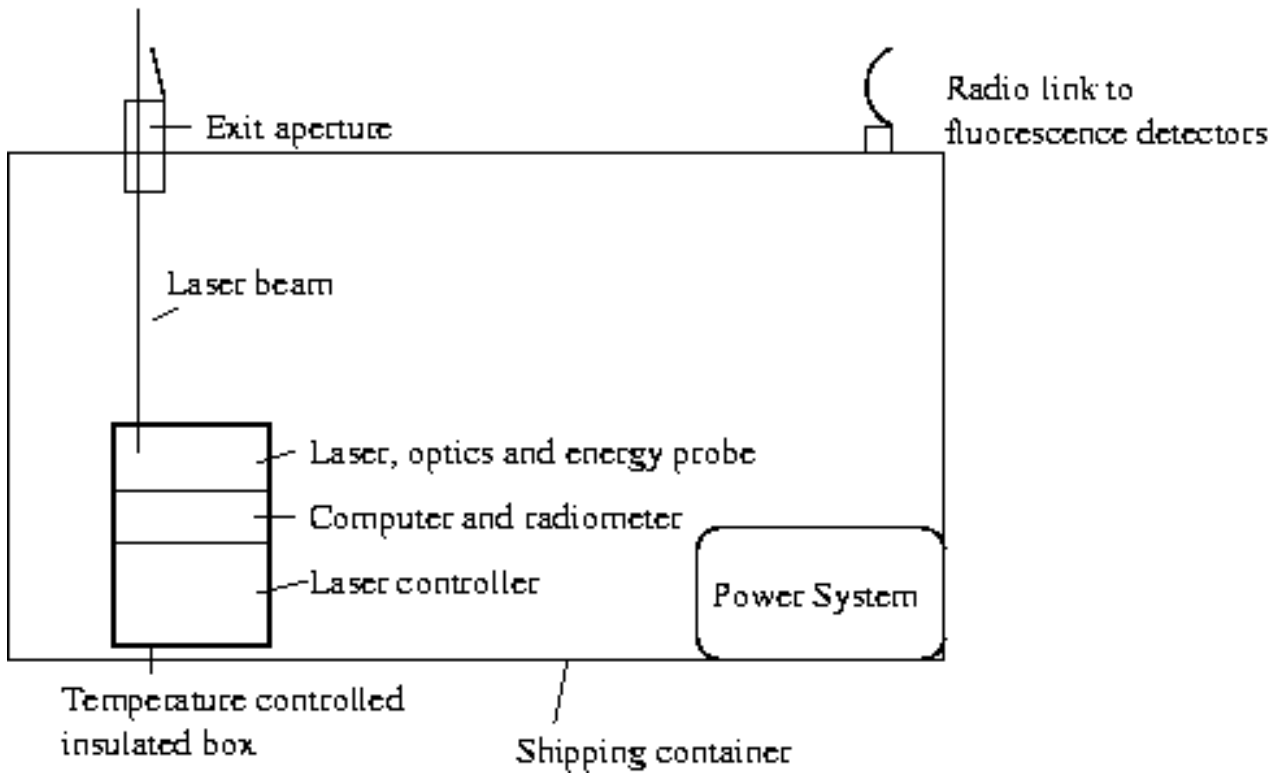


Figure 3: Arrangement of the laser, power and aperture systems in the shipping container

3 Design of the system

3.1 Housing

The overall design is shown in Fig. 3. The laser and power systems will be housed in a shipping container. These containers provide cheap, readily available and easily portable containment. The laser and power systems reside in the container, and an aperture system protects the laser optics from dust and weather. The laser system is controlled remotely from one of the fluorescence detector sites via radio Ethernet link.

3.2 Laser system

The laser system is based around a 5mJ BigSky 355nm frequency tripled YAG laser. We have used these lasers for various systems so we have considerable experience in deploying them. Beam steering mirrors clean non-355nm light from the beam and provide for accurate alignment. A fraction of the beam intensity is tapped and used to monitor pulse to pulse energy. To make the reconstruction of the scattering behavior simpler the beam is completely depolarized. The temperature of the laser system is controlled by keeping the entire system in an insulated box. Thermostatically controlled fans and heaters keep the temperature within the laser operating range (10 to 40 degrees centigrade).

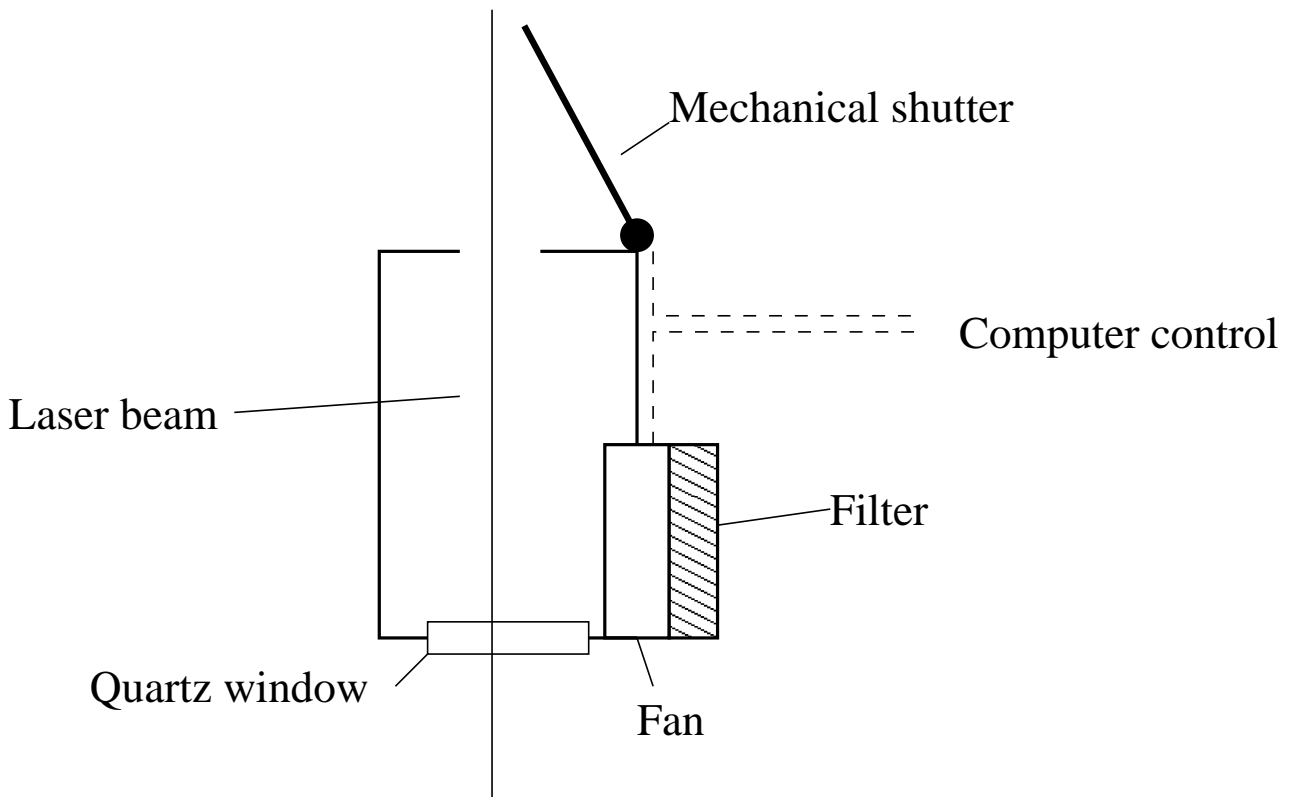


Figure 4: Schematic of the aperture system. During laser firing the mechanical shutter will open and the fan will turn on.

3.3 Aperture system

An aperture system (Fig.4) is needed to protect the laser optics from dust and other external contaminants. Only a small aperture (1 cm²) connects the inside of the aperture to the outside world. An electrically operated lid opens just before firing. A fan inside the aperture box keeps positive pressure to prevent dust, rain or snow from entering when the lid is opened.

3.4 Power system

During initial deployment the remote laser system will be connected to mains power. A site between the Los Leones and Coihueco fluorescence detectors with access to mains power has already been found. We are currently working on ways to reduce the power consumption so that it can be operated remotely from a solar panel/battery power system.

Table 1: **Vertical laser system cost breakdown**

Item	Cost(\$)	Contingency(\$)	Total(\$)
Shipping container (refurbished)	3000	1000	4000
Concrete pad for container	500	–	500
Insulated housing w/ control	1000	500	1500
Laser	18000	1000	19000
Radiometer and energy probes	2500	500	3000
Controller and communications	3000	500	3500
Optics	1000	500	1500
Aperture Box	500	–	500
Remote power system	3000	500	3500
Technician & shop time	2000	500	2500
Shipping	3000	1000	4000
Totals	37500	6000	43500

Ancillary costs

Spare laser and electronics	20000
Energy and polarization monitoring equipment	3000

Total for two sites 110000

4 Deployment plan

A sketch of the deployment plan with three potential laser sites (A,B,C) is shown in Fig. 5. The first vertical laser system would be deployed at site A. This site is 22km equidistant from the Los Leones and Coihueco FDs which are the first two FDs which will be completed. Site A has access to mains power and is accessible by a good quality road. It is a good site for final prototyping work and for the commissioning of the Los Leones and Coihueco FDs. After all FD sites are completed a second vertical laser system would be located at site B. This site would require a remote power source. The prototype, also modified to run without mains power, would then be moved to site C. The B site is 34km equidistant from the Los Leones, Coihueco and Morados FDs, while the C site is 34km equidistant from the Coihueco, Morados and Northern FDs. Sites which are equidistant from a number of FDs are attractive because as well as atmospheric monitoring data, the lasers can be used to monitor the relative timing and sensitivity of the FDs. A simulation of a set of 100 5mJ laser shots from a vertical laser at a distance of 34km from an FD is shown in Fig. 6. These simulations show that at a distance of 34km from an FD site, the proposed 5mJ laser has enough power to measure aerosol optical depth with sufficient accuracy.

5 Costs

The estimated cost for two vertical laser sites is given in Table 1. One set of instrumentation to monitor the absolute energy and polarization of the laser is included under ancillary costs. We have also included the additional cost of a *backup* laser (which would be used during times of factory servicing of one of the lasers) and one *backup* set of communications hardware (in case of a lightening strike on one of the containers).

References

- [1] J.A.J. Matthews, et al, *Atmospheric Monitoring for the Auger Fluorescence Detector*, Proc. of ICRC 2001, **2**, 745 (2001);
J.A.J. Matthews, et al, *Fluorescence Detector Optical Calibration and Atmospheric Monitoring for the Pierre Auger Experiment*, Auger note: GAP-2000-033 (2000) available at: http://www-hep.phys.unm.edu/~johnm/jpg_draft_v13.ps
- [2] M.D. Roberts, Auger note: GAP-2001-056 (2001).
- [3] M.D. Roberts et al, *Atmospheric Monitoring Techniques at HiRes* Proc. of ICRC 2001, **2**, 645 (2001).
- [4] The Auger *roving steerable laser* is similar to, and builds on, the R&D for the HiRes *roving steerable laser*; see:
M.D. Roberts et al, *Atmospheric Monitoring at HiRes - Hardware Systems I*, Proc. of ICRC 2001, **2**, 627 (2001).

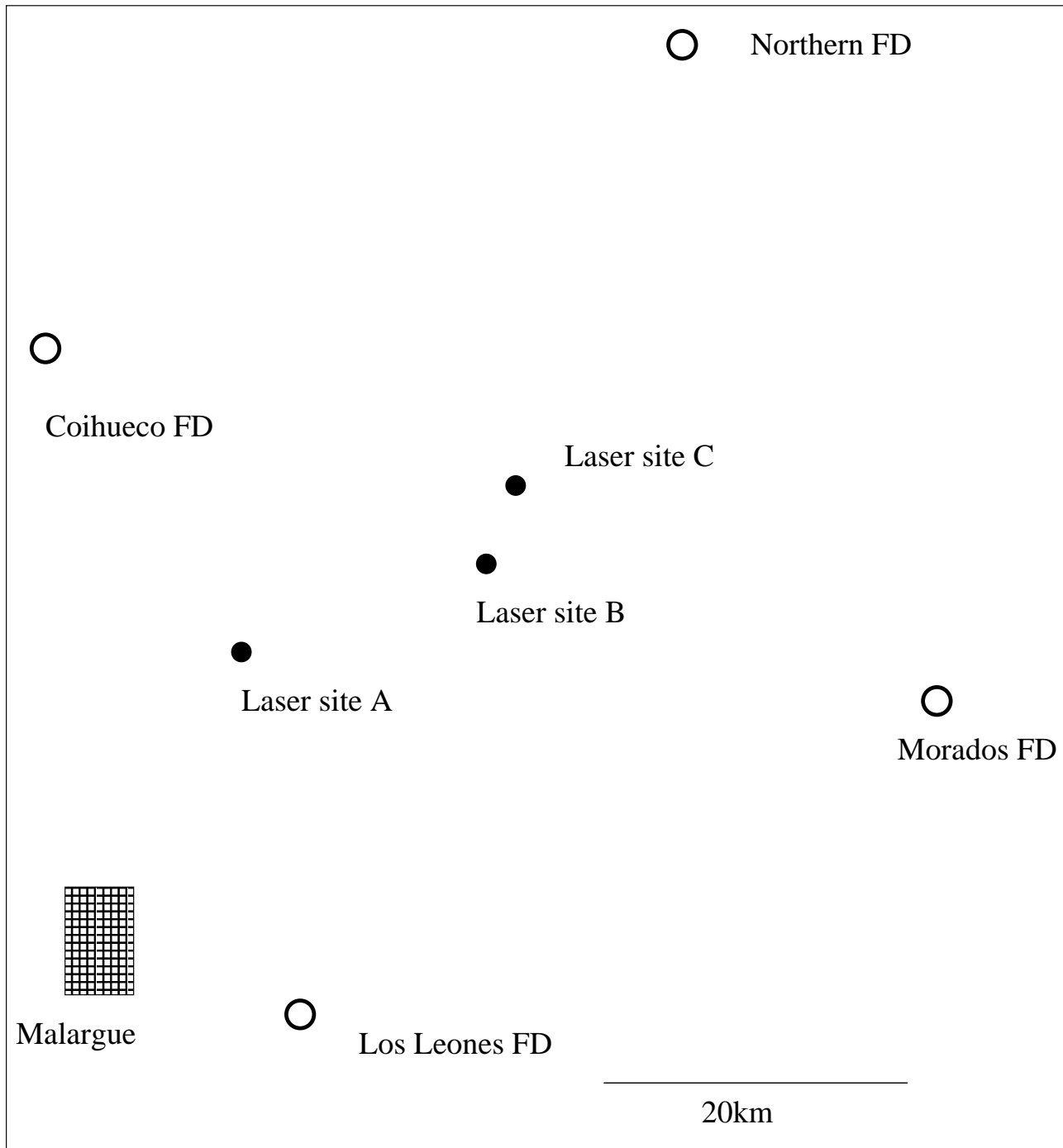


Figure 5: Sketch of the Auger aperture, with FD (fluorescence detector) and potential laser sites. Site “B” is equidistant from Los Leones, Coihueco and Morados FDs. Site “C” is equidistant from Coihueco, Northern and Morados FDs.

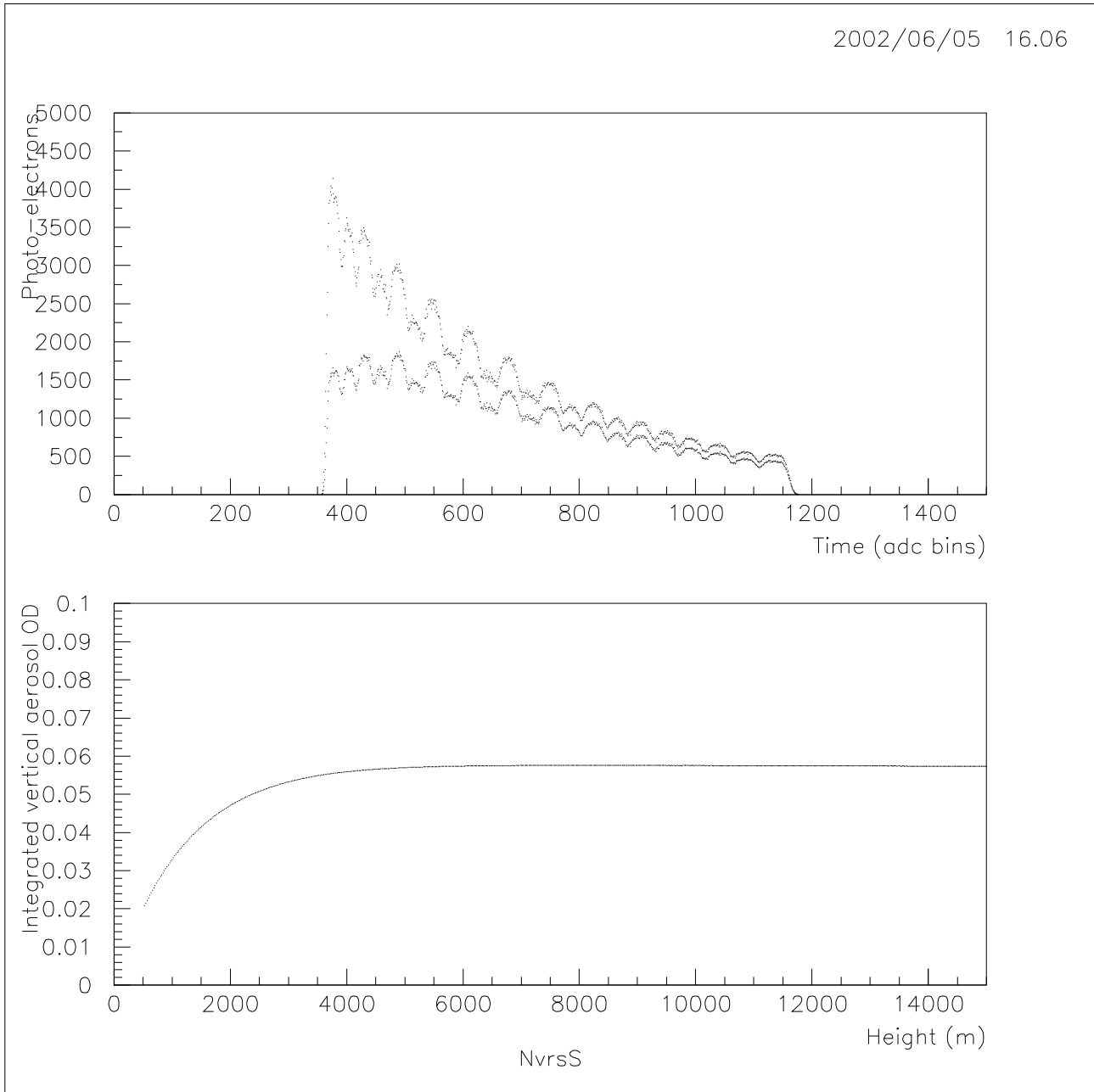


Figure 6: Monte Carlo simulation of the integrated FD signal for 100 5mJ laser shots with a vertical laser at a distance of 34km. The top trace of the top plot shows the number of photo-electrons per FADC bin (100ns per bin) for a perfectly clear day (no aerosols). The lower trace of the top plot shows the expected signal for a day with an average aerosol distribution. The bottom plot shows the integral aerosol optical depth as a function of height reconstructed from the data in the top plot. For the lower part of the atmosphere, which is where the aerosols are expected, the typical signal-strength limited uncertainty in reconstructed optical depth is less than 5%. The minimum height at which aerosol vertical structure can be measured, given the $\sim 2^\circ$ above horizontal minimum viewing angle of the FD, is ~ 1 km.

Atmospheric characterization for the Auger fluorescence detector using vertical laser beams

M. D. Roberts
University of New Mexico

1 Introduction

The primary source of atmospheric monitoring information for the Auger fluorescence detectors will be steerable backscatter LIDAR systems located at the eye sites. Being located at the sites, these systems will be able to probe directly the detector-shower atmospheric path. LIDAR systems are, however, known to have a number of weaknesses in determining atmospheric attenuation - particularly over an area as large as the Auger fluorescence aperture. We propose to augment the LIDAR based atmospheric monitoring with a number of simple vertical laser beams deployed in the fluorescence aperture. The fluorescence eyes will act as the receivers for the scattered light. Details will be given on how atmospheric parameters can be extracted from the vertical beam images.

A vertical beam LIDAR analysis is the main method used at the HiRes fluorescence detector for determining atmospheric attenuation corrections. Comparisons of energy balance for cosmic ray showers viewed in stereo has shown that this technique does predict the correct atmospheric aerosol attenuation (see figure 1).

Using the roving steerable laser systems developed by the universities of Utah, Chicago and New Mexico, we hope to demonstrate the usefulness of vertical laser beam atmospheric studies. The Auger budget already allows for the development and deployment of vertical flasher systems.

1.1 LIDAR measurements of attenuation

While the backscatter LIDARs are the most direct probe of the atmosphere between the detector and a cosmic ray track the ability of a simple backscatter LIDAR to determine atmospheric transmission for Auger may be limited by a number of factors:

Distance

Tracks may be seen at distances in excess of 30km. Given limited laser power and LIDAR mirror area it may be difficult to retrieve backscatter signals at these distances in a reasonable amount of time. The ability of the fluorescence eye to survive the very bright nearby backscatter signal of the laser tracks must also be taken into consideration when determining the maximum laser energy.

Dynamic range

The LIDAR equation has the form

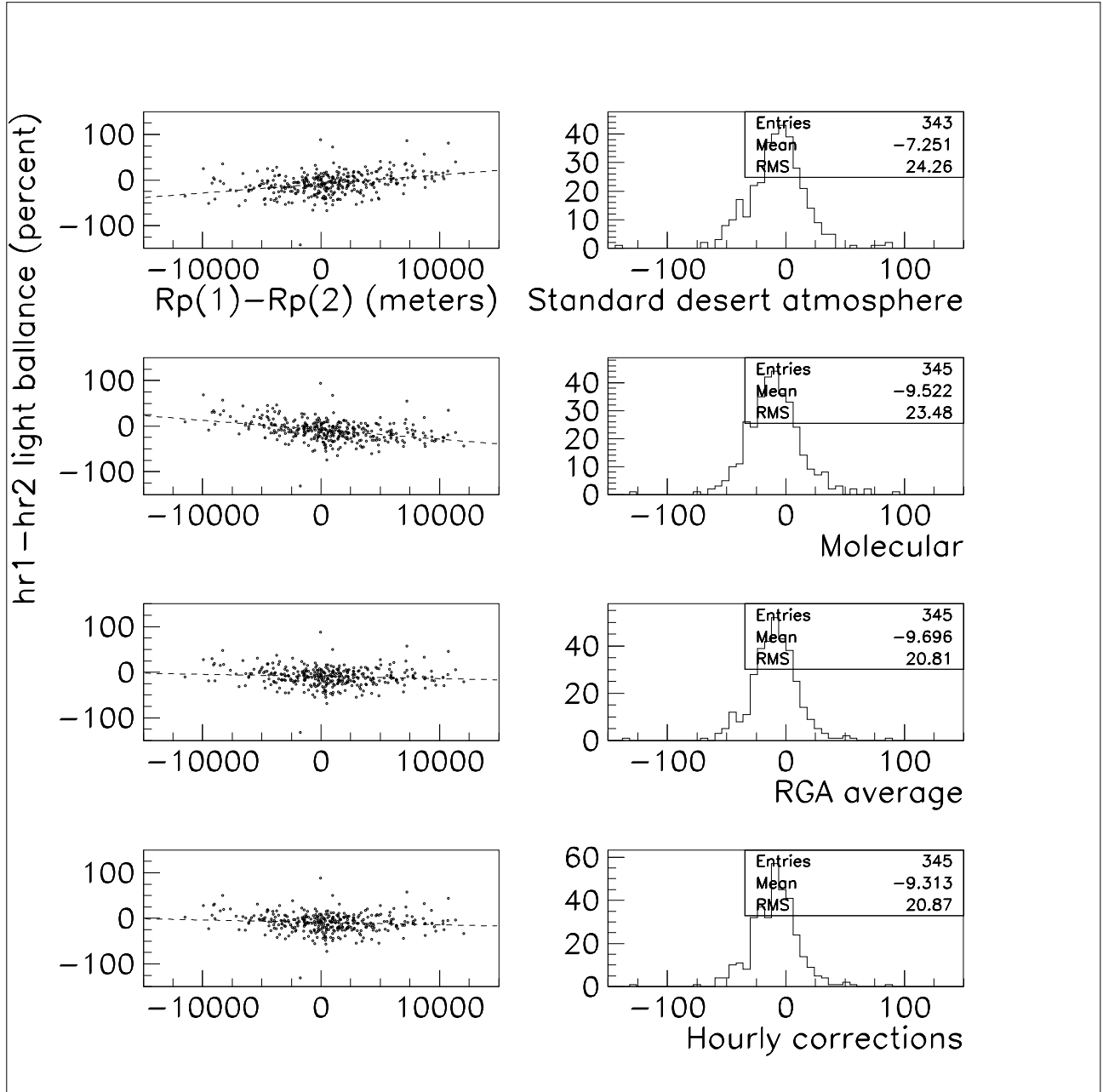


Figure 1: These plots show the predicted amount of light produced at cosmic ray tracks under different assumptions about the atmospheric attenuation. This light balance is plotted against the difference in distance from each detector to the shower. The top plot shows the light balance if the standard desert atmosphere is assumed. The second row shows the balance if it is assumed that there are no aerosols. The non-zero slopes of these plots indicate that both of these assumptions are incorrect. The bottom plots show the light balance for the measured atmosphere applied as an average correction (third row) and hourly correction (last row). The slope of the line (almost zero) indicates that these measurements are a good representation of the aerosol attenuation.

$$S(R) \propto \frac{1}{R^2} * e^{-2 \int_0^R \alpha(r) dr} \quad (1)$$

where S is the signal at distance R and α is the local scattering coefficient. The backscatter signal drops rapidly with distance. The further distant the point to be characterized the greater the dynamic range requirements of the light detector and DAQ system.

Solving the LIDAR equation for attenuation

The amount of light seen from each part of a LIDAR trace depends on two things: the attenuation of the laser beam to and from the point of scatter and the backscatter cross section at the point of scatter. With two unknowns the LIDAR equation cannot be solved unambiguously. The LIDAR equations for simple backscatter LIDAR are typically solved by assuming some functional relationship between aerosol density and aerosol backscatter cross section. In fact, it is known that the backscatter cross section is highly variable, and depends upon the composition (dielectric constant) and shape of the aerosols. Figure 2 shows some examples of the variability of the aerosol phase with particle size distribution under the assumption of purely spherical aerosol particles. For atmospheric physics research, Raman backscatter LIDAR are often used in preference to the ambiguities of simple backscatter measurements. The extremely small Raman backscatter cross-section (10^{-4} of the inelastic backscatter cross-section) make the implementation of Raman LIDAR impractical for probing large areas of the atmosphere.

Reliability

The experience at HiRes is that cosmic ray events cannot be reliably reconstructed without contemporaneous atmospheric monitoring information. It is conceivable that if the backscatter LIDAR at an eye breaks down, the cosmic ray data will not be analyzable until the system is fixed. The proposed backscatter systems, based on the EAS-TOP telescopes, are complicated systems with mechanical, electrical and optical sub-systems (the reliability of the steering system is discussed in [Cester et al. (2001)]). Simple vertical flasher systems, viewed by the fluorescence eyes will provide redundancy in atmospheric monitoring.

1.2 Vertical beam analysis

Atmospheric analysis of vertical laser beam images should complement the measurements made with the backscatter LIDARS. In particular the four weaknesses of backscatter LIDARS, listed above, can be addressed :

Distance

Tests at HiRes with a 5mJ 355 nm laser have shown that a vertical beam of this intensity can be seen in the HiRes detectors (similar in sensitivity to Auger detectors) at distances of 35km. The large area of fluorescence mirrors, and the fact that the light only travels once

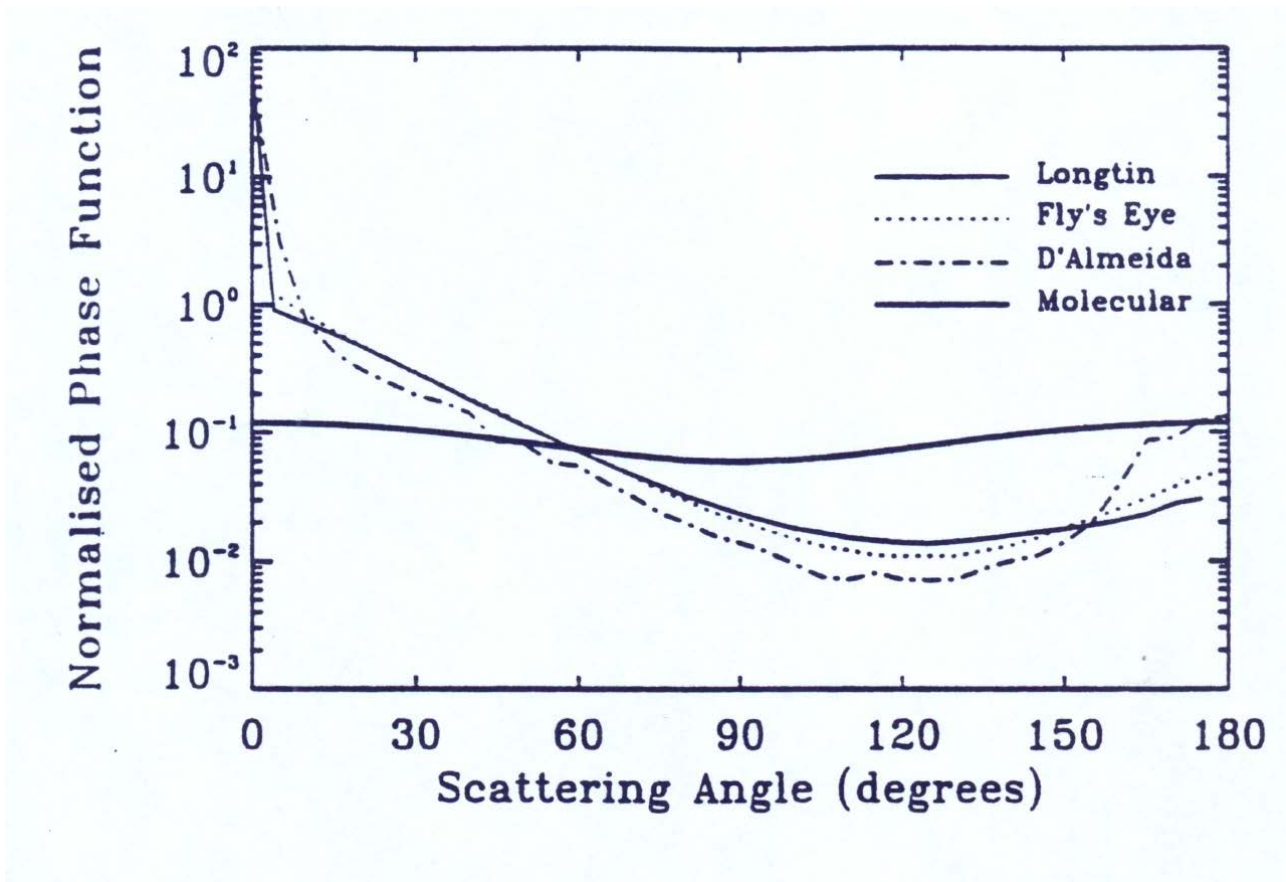


Figure 2: Examples of aerosol phase functions obtained with Mie theory (assumes all aerosol particles are spherical). Also shown is the Rayleigh (molecular) phase function. For typical aerosol densities the sideways scattering (90° to 120°) is dominated by well known Rayleigh scattering cross section.

through the atmospheric path being investigated accounts for this.

Dynamic Range

The change in intensity of light seen over the track image is less than an order of magnitude for vertical tracks. The flashers are located in the middle of the stereo aperture so there is no disturbance to the fluorescence eyes from local scattering.

Solving the LIDAR equation for attenuation

The scheme for determining optical depth as a function of height is shown in figure 3. The most important feature of solving the side scattered LIDAR equation in comparison to the backscatter equation is that only scattering angles near 90 degrees are viewed. At these scattering angles the aerosol phase function is minimized (figure 2). To a good approximation a vertical laser beam provides a predictable light source (“standard candle”) at each point

in the beam. The laser beam suffers little attenuation through the vertical atmosphere, and the sideways scattering is dominated by the well known Rayleigh cross section (corrections for the effects of vertical attenuation and the sideways Mie cross section can be estimated). The dominant effect on the light seen at the fluorescence eye is the atmospheric attenuation between the point of scatter and the detector. This measurement can be used to derive a vertical aerosol optical depth as shown in figure 3. If the transmission through the molecular atmosphere is well understood then the aerosol optical depth (AOD) at any point along the laser track can be calculated from

$$\text{AOD} = -\ln\left(\frac{\text{measured}}{\text{predicted}}\right) \quad (2)$$

where (measured) is the number of photons measured at each track point and (predicted) is the number of photons predicted if the atmosphere were molecular (no aerosols). Here the AOD is the total optical depth for the light from the laser, to the point of scatter to the detector. Assuming horizontal uniformity this can easily be converted to give the aerosol vertical optical depth (AVOD)

$$\text{AVOD} = \frac{\text{AOD}}{1 + \frac{1}{\sin(\theta)}} \quad (3)$$

using the nomenclature of figure 3. This analysis relies on the assumption that the aerosols are horizontally uniform - an assumption that can be tested with the backscatter LIDAR systems and by looking at the vertical beam with several different eyes.

The atmospheric parameterization obtained is most accurate for cosmic ray events falling in the region near the flasher. If the flasher is placed roughly equidistant between two fluorescence eyes then the parameterization obtained is most correct for cosmic ray events where the average atmospheric correction is greatest and where the large distances to the fluorescence eyes makes the use of the backscatter LIDARs most problematic.

In addition to providing atmospheric characterization, vertical laser beams can also be used as cosmic ray track simulations, to test the energy resolution due to atmospherics of the fluorescence detectors.

1.3 Accuracy of the attenuation determination

There are three major causes of uncertainty when applying the AVOD derived above to correct the atmospheric attenuation to cosmic ray tracks.

Measurement of absolute light flux from the laser beam

The AOD calculation relies on the measurement of absolute light flux. Errors in this measurement come from the absolute calibration of the fluorescence detector, and the calibration of the intensity and polarization of the laser beam. Experience at HiRes suggests that the absolute laser beam energy and polarization can be understood to $\sim 10\%$ (commercial total energy laser probes claim absolute accuracy of $\sim 5\%$). If it is assumed that the detector will be calibrated absolutely to $\sim 10\%$ then AOD could be measured to an accuracy of $\sim 15\%$.

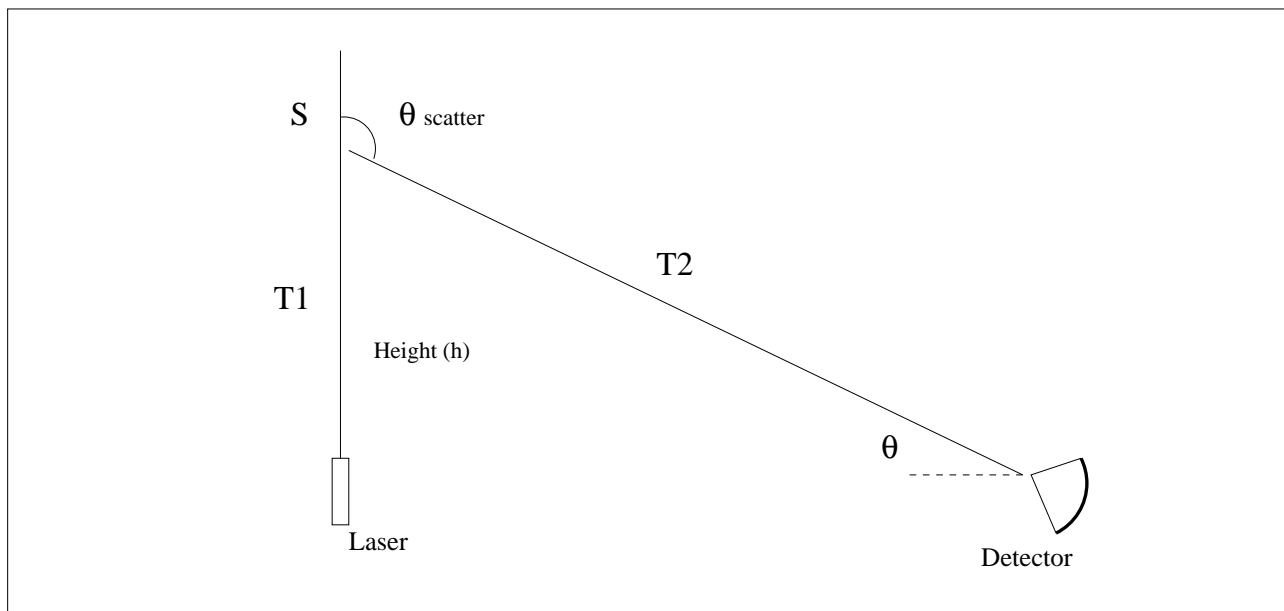


Figure 3: Measurement of aerosol optical depth with vertical laser beams. The amount of light measured at the detector at height h is determined by the vertical transmission (T1) to h , the scattering (S) at h and the transmission (T2) back to the detector.

Contribution to sideways scattering from Aerosols

Although the 90° to 120° scattering cross section of the aerosols is small and relatively invariant it will contribute some uncertainty to the determination of AOD. The contribution will depend upon the normalization of the aerosol phase function wrt to the Rayleigh phase function. If the scattering height above the laser is above the majority of the aerosols then the uncertainty will be negligible. In a typical worst case, where the local aerosol scattering length is equal to the Rayleigh scattering length the uncertainty in AOD (using the aerosol models in figure 2) would be $\sim 15\%$.

The two sources of uncertainty described above combine to give an uncertainty in AOD of $\sim 20\%$. If the vertical laser beam is deployed at a large distance then the error in determination of the aerosol vertical optical depth (AVOD) is reduced considerably by the slant depth correction to the AOD (under the assumption of atmospheric uniformity - which will be discussed later in detail). If the laser beam were placed at the typical maximum distance at which cosmic ray tracks were viewed then the maximum uncertainty in determining attenuation to these tracks would be similar to the error in determining AOD (20%). If the flasher were placed at a distance of 30km from the FD, then the AVOD would be determined to an accuracy of 0.01

Assumptions about horizontal uniformity

The determination and application of AVOD depends on the uniformity of the atmosphere. Measurements by HiRes of the Dugway atmosphere indicate that the AVOD is uniform on distance scales of $\sim 30\text{km}$ for a large fraction of observing time ($> 80\%$) to the accuracy that we can determine AVOD (± 0.02). Atmospheric uniformity is not measured at present around Malargue, but these measurements can be made with the LIDAR system to be installed at Los Leones (many of the suggested LIDAR based atmospheric analyses also rely on the horizontal uniformity of the aerosols). As stated previously, one advantage of the vertical laser beam analysis is that it provides a pseudo standard candle at typical maximum distances that cosmic ray tracks are seen. Even without strong uniformity the attenuation model that is derived should be useful for cosmic ray events that fall in the region near the laser (at distances where the maximum atmospheric corrections are being made). In contrast the measurements made by backscatter LIDAR near the eyes will be most accurate near the fluorescence eyes, where the smallest aerosol attenuation corrections are made.

1.4 Design and cost of vertical systems

The design of the vertical flasher is shown in figure 4. Here it is assumed that the laser is a BigSky 355nm 5mJ frequency tripled yag laser. The power consumption of the laser is 150-200 watts when firing. The laser energy is monitored with a local radiometer, and the recorded energies are transmitted out by radio or cell phone modem. A GPS module is used to fire the laser at a fixed offset wrt to the GPS second. The entire unit is solar powered. To conserve energy the laser and electronics are only turned on when the laser is to be fired (say 4 times per hour). The firing sequence and power switching of the electronics is handled by the local controller.

The laser and electronics are mounted on a rack, which is placed inside a tube that is partially buried in the ground. In this way the temperature of the laser can be stabilized. In particular the laser head, cooled by water, cannot be allowed to freeze.

1.5 Cost estimate

Laser	17000
Radiometer	5000
Controller and comms.	2000
Optics	1000
Solar panel + batteries	1000
Rack + containment tube	4000
Total	30000

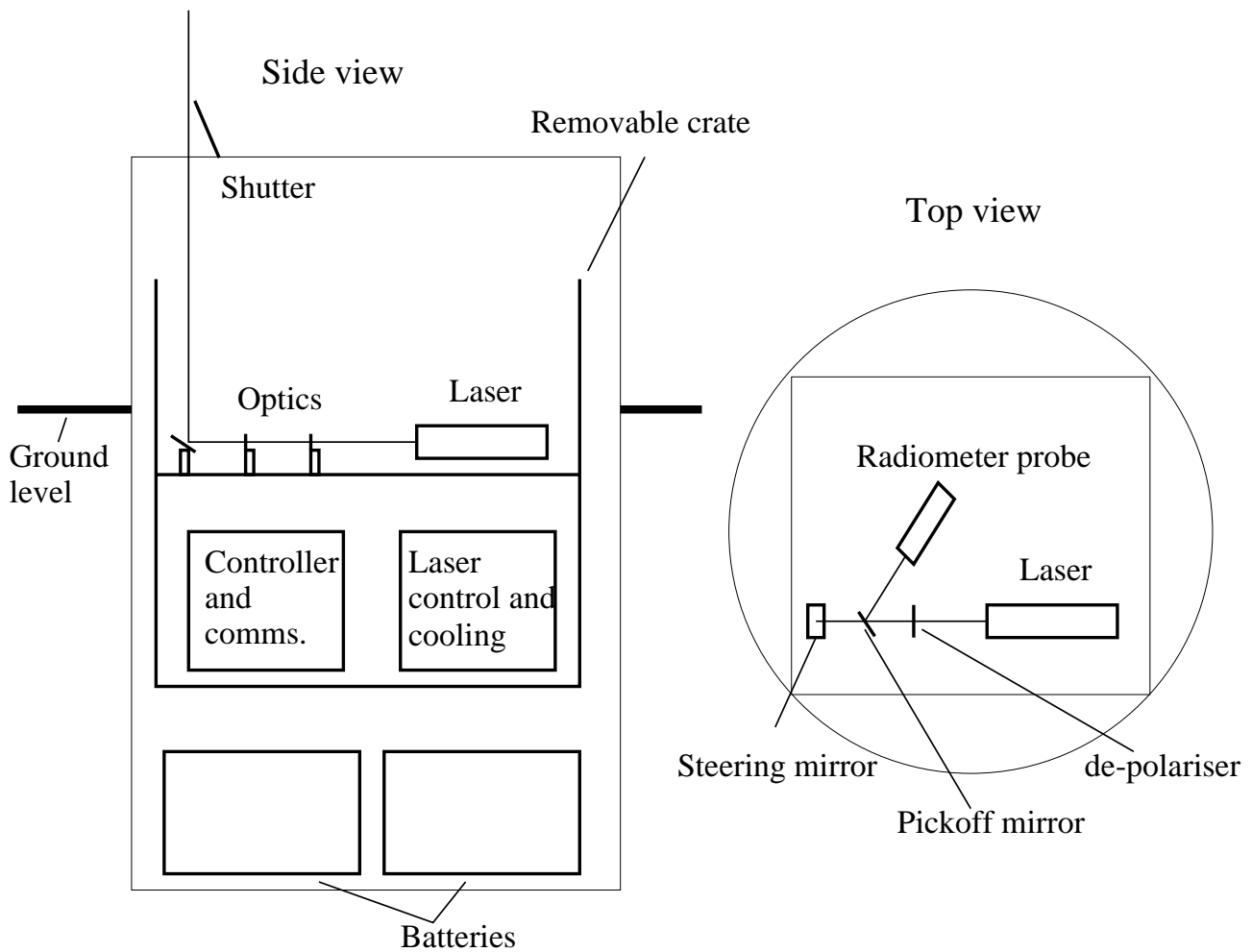


Figure 4: Schematic diagram of the layout of a remote vertical laser system.

References

[Cester et al. (2001)] R. Cester, M. Mostafa, R. Mussa, Auger GAP note, GAP-2001-052, 2001