Chapter 7

Fluorescence Detector Design

The primary role of the fluorescence detector is to measure the longitudinal development profiles of air showers in the atmosphere. The longitudinal profile gives a direct measure of the electromagnetic shower energy, and, for a given total energy, the depth of maximum shower size is correlated with the mass of the primary. The set of showers measured by the combination of both the surface array and the fluorescence detector (hybrid showers) will be the basis for the most reliable energy spectrum and composition determination. It is important to maximize the fraction of the surface array showers which are measured also by the fluorescence detector. The Fly's Eye experience demonstrates that operating the detector in clear, moonless conditions limits the duty cycle to 10%. To ensure that the hybrid shower set is not an even smaller subset of the surface array showers, it is essential that the fluorescence detector measure every shower accepted by the surface array. It is therefore required that its aperture include the entire aperture of the surface array.

The design of the fluorescence detector is guided by this aperture requirement together with specifications for the quality of longitudinal profile measurements. At any fixed energy, the expected depths of maximum span a range of approximately 100 g/cm^2 as the nuclear mass varies from proton to iron. A resolution of 20 g/cm^2 in the depth of maximum X_{max} is achievable and highly desirable for analyzing the primary mass distribution. Energy resolution of 10% is achieved by signal-to-noise requirements which have been shown previously (cf. 4.4.3) to lead to a 20 g/cm^2 X_{max} resolution.

These aperture and sensitivity requirements have been used to develop the reference design. Essential design parameters include the number of eyes, the elevation angle coverage, the pixel angular size, the light collecting area, the waveform time resolution, and the trigger conditions. The arguments for the chosen design parameters have been given in technical notes and will only be summarized briefly here. The design is based upon proven principles implemented in the High Resolution Fly's Eye (HiRes)[120].

Detailed simulation of the reference design has been done, and the results are summarized in chapter 5. Further details can be found in [137]. The reference design has been shown to meet the aperture and sensitivity requirements.

7.1 The site layout

At each of the two Auger Observatory sites there will be multiple separate optical detector stations or "eyes". A layout with just a single eye, though capable in principle of achieving good shower reconstruction, suffers from the fact that it must be able to detect showers out to the edge of the array (31 km distant). This is approximately 3 horizontal attenuation lengths. Although adequate light signals could be collected with large enough mirrors, inferring the shower size from the small fraction of remaining light is subject to uncertainty due to uncertainty in the attenuation. Because of the exponential attenuation, the fractional uncertainty in the shower size is given by the fractional uncertainty in the atmospheric attenuation length *times the distance to the shower measured in attenuation lengths.* It has not been demonstrated that the aerosol density distribution can be monitored with sufficient precision to allow profiles to be measured with our required accuracy at a distance of 30 km. To ensure a robust design, it is worth a small additional cost to build multiple eyes and reduce the typical viewing distance. The hardware costs are not significantly greater for 3 moderate eyes than for a single far-sighted eye with smaller pixels and larger mirrors.

The specific arrangement of the eyes has not been definitively determined and may be based partly on land topology at the chosen sites. There is an advantage in building the eyes on elevated terrain so that they look up through less of the aerosol mixing layer. Two suitable arrangements are shown in Figure 7.1 and in Figure 7.2. The "Superman" configuration has 3 identical eyes, each viewing 360 degrees in azimuth. The "filled hexagon" configuration would use the same set of telescopes as the Superman configuration, but two of the eyes would be divided into 3 segments, each of 120 degrees azimuth coverage. The six partial eyes would be placed at the vertices of a regular hexagon, looking inward. One full (360-degree) eye would be at the hexagon's center. The filled hexagon option offers more redundant coverage of the Auger array area [140]. Compared to the Superman configuration, there are more showers measured by 2 eyes, 3 eyes, etc. The highest energy showers might be measured by all 7 eyes. With this configuration, the fluorescence detector wastes very little aperture on showers landing outside the surface array, and even at threshold shower energies there is a significant multi-ocular viewing aperture. The Superman configuration, on the other hand, obtains some stereo fluorescence aperture for showers outside the periphery of the surface array [141]. It therefore extends the total aperture for well reconstructed fluorescence events. It also requires less site preparation and operation than the filled hexagon arrangement.

In either case, the telescopes will be arranged to cover an elevation angle range from $2°$ to $30°$. This is adequate for measuring the longitudinal profiles of showers with cores distant enough so that the scintillation light is not dominated by direct Čerenkov light. A 360-degree eye will be made up of 45 telescopes, 23 viewing a low elevation altitude ring and 22 an upper elevation ring. Each mirror unit will have a field of view of $16° \times 14°$.

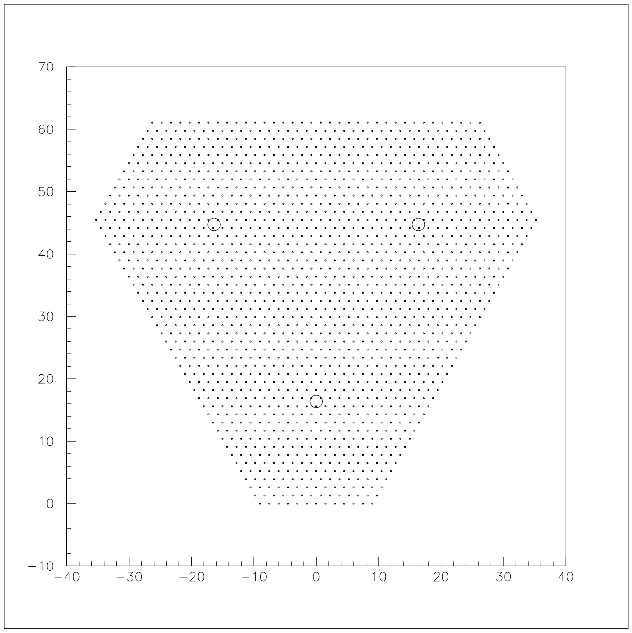

Figure 7.1: Superman layout. The long edge is 52.5 km, the short edge 18 km. There are 1596 ground stations enclosing an area of 2970 km^2. The three eyes (circles, not to scale) are separated by 32.74 km. Each eye is expected to measure showers at least to a distance of 17.8 km.

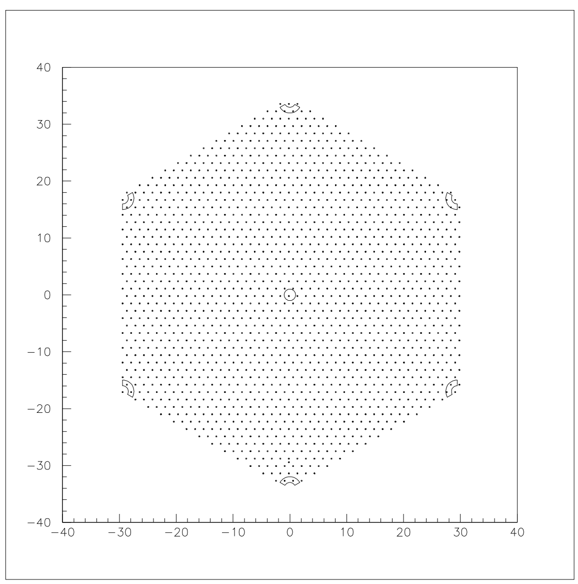

Figure 7.2: Filled Hex layout. The edges are 33.9 km in length. The central detector views a full 360° of azimuth. The detectors at the vertices each view 120° azimuthal regions centered on the central detector.

7.2 The telescope design

Primary design parameters for the telescope are the mirror area and the pixel solid angle. To achieve the S/N sensitivity imposed by the longitudinal profile resolution criteria, it is possible to trade one against the other, since

$$S/N \sim \frac{\text{mirror diameter}}{\text{pixel angular diameter}}.$$

A fundamental constraint is that the pixel size should not exceed a 1.5-degree diameter. Otherwise the angular resolution (finding the shower-detector plane) is insufficient for converting the measured light flux from the different parts of the shower into a longitudinal profile of the required accuracy. The simulations reported in chapter 5 demonstrate that 1.5-degree pixels are adequate.

There are good reasons to make the pixel size as large as the geometric reconstruction allows. A major reason is cost. Over the range of interest, it is less expensive to increase S/N with larger mirrors than by increasing the number of pixels. Even if cost were not a consideration, however, big pixels are desirable. As long as the shower axis geometry is known, the fluorescence light flux measured as a function of time gives the shower size as a function of atmospheric depth. It is advantageous to minimize detector complications in recording the light flux as a function of time. If the focused spot of light remains within the active region of a single PMT for an extended time, that is better than constantly crossing PMT boundaries. These considerations have led to the pixel size of 1.5 degree diameter.

With 1.5-degree pixels, the longitudinal profile resolution requires mirrors of 1.5 m diameter. Each is to be a spherical concave $f/1$ mirror with an associated camera at its focus. The camera will house a hexagonally packed array of 121 (11×11) pixels. Each hex-shaped pixel will have the equivalent area of a 1.5° diameter circular pixel. This will be accomplished with phototubes of the prescribed size and shape or with smaller phototubes augmented with Winston cones or Fabry lenses. Optical filters, chosen to remove most of the light outside the nitrogen fluorescence bands, will be placed ahead of the phototube faces.

Each pixel element will be attached to integrating flash ADC electronics which will digitally measure its signal every 100 ns. This time slice is smaller than the light pulses in individual PMTs, which can vary from about 100 ns for nearby showers approaching the eye to about 4 μs for the most distant showers going away from the eye (cf. Sec.4.4.3). In most cases, this time slicing will provide measurements of the pulse duration and pulse shape which are useful for the timing information used in the geometric reconstruction as well as augmenting the amplitude information in fitting the shower detector plane. To achieve good trigger sensitivity to the low amplitude distant showers, a running sum of perhaps 2 μs duration will be used to discriminate pixel "hits." For at least some part of almost any track, the pixel pulse duration will be less than 2 μs. The system will be designed to recognize, in real time, the temporal and spatial patterns of phototube hits characteristic of real cosmic ray showers. It should also be noted that a shower traverses less than 4 g/cm^2 of atmosphere in 100 ns, yielding a very fine segmentation of the longitudinal profile (if the S/N is high enough to take advantage of such fine segmentation).

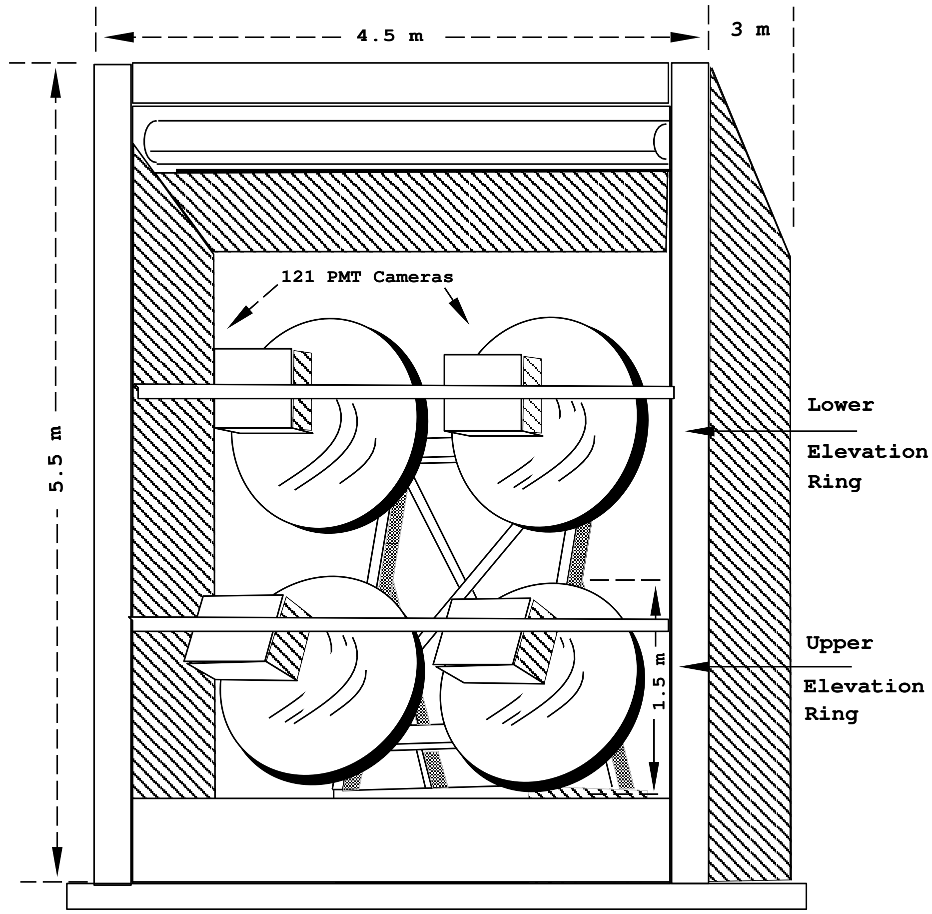

Figure 7.3: Possible Optical detector enclosure. Such a configuration contains four mirror units, two with a high altitude view, two with a low altitude view.

Several trigger levels will be implemented in each eye. The simplest, a sequence of hit phototubes in a linear pattern, will cause the associated data to be held locally for a time long enough to be available if trigger information comes either from the surface array or from another eye. The next level trigger, which utilizes the results of a rudimentary trajectory fit, will result in the information being broadcast to the other eyes and the surface array for possible confirmation. If still stronger criteria are satisfied, the data will be saved as a probable track, even in the absence of corroborating information.

At each 360-degree eye there will be 12 mirror buildings or enclosures and a central triggering and communication facility. 11 of the mirror buildings will house mutually mounted sets of 4 mirror units. One building will house a single mirror unit. The combined mirrors in each mirror building will observe both the upper and lower elevations for two side-by-side 16° azimuthal intervals. A conceptual drawing of a possible building is shown in Figure 7.3. Such structures with automatic roll doors have been successfully implemented by the High Resolution Fly's Eye (HiRes) project.

A sophisticated atmospheric monitoring system will be an integral part of the fluorescence detector system. In order to adequately characterize the volume of atmosphere above the surface array one must make periodic measurements of both the particulate distribution and cloud cover. This system will include multiple steerable LIDAR stations, an array of vertical Xenon flashers and several high-powered steerable UV lasers.

7.3 Alternative Designs

The reference design described above is based on techniques which have been well tested by the Fly's Eye and the HiRes prototype detectors. It is a conservative design which is certain to produce the required resolution. Some variations on this technology have been proposed for the Auger fluorescence detector but are not part of the reference design because they have not yet been demonstrated in practice. The modifications may offer better performance at reduced cost.

7.3.1 The Dual Mirror Concept

A novel detection scheme presently being studied is the *dual-mirror* system[138]. In this scheme, instead of a single telescope viewing any portion of the sky, there are two telescopes with almost identical fields of view. If each telescope has 2.5-degree wide pixels, say, then their fields of view would be offset from each other by 1.25° in elevation and 1.25° in azimuth. The overlapping views of the two mirrors A and B are illustrated in Figure 7.4. The instantaneous image of a shower will be seen in each mirror in one of its 2.5-degree pixels, but the overlap of the two pixels will isolate the position of the shower spot to a $1.25° \times 1.25°$ region of the sky at that instant. Such a system has been proposed because it provides 1.25° resolution with only 72 pixels instead of the 144 which would be needed with a single telescope. The cost is significantly reduced. Enhanced trigger efficiency is also expected since the mirrors, operating in coincidence, automatically reject most noise triggers. This method of suppressing noise triggers has been exploited extensively in atmospheric Čerenkov astronomy. In addition, an important advantage of this technique is that the spot of light from the shower front is almost always cleanly contained within some physical pixel's field of view, and the light flux is measured by each PMT for a longer duration. Pixel boundaries are less problematic in obtaining a reliable light flux as a function of time.

7.3.2 Wide angle Schmidt telescopes

The number of buildings and supporting equipment for the telescopes can be reduced if the field of view of each mirror is extended from approximately 15x15 degrees to 30x30 degrees. For a simple spherical reflector, such wide angle observations have unacceptably large coma aberration. A way to eliminate the coma is to use a diaphragm at the mirror's center of curvature[139]. The area of the diaphragm is then the light collecting area. The mirror must be much larger than the diaphragm to receive all the light which comes through the

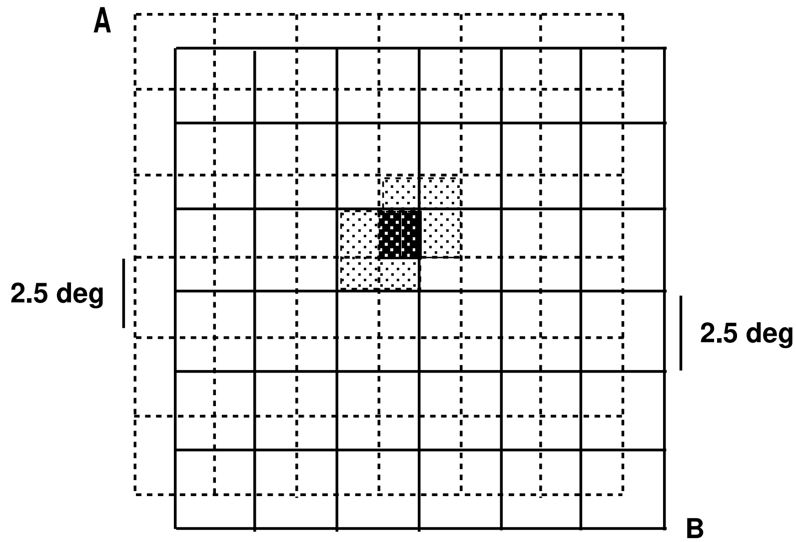

Figure 7.4: The fields of view for dual mirrors A and B. Each mirror has 72 pixels in its focal surface, each pixel having a 2.5° width. The fields of view are displaced from each other by 1.25° in azimuth and 1.25 ° in elevation. The signal can be localized to a 1.25° square by the intersection of a pixel in mirror A with a pixel in mirror B.

diaphragm over the large range of arrival directions. The focal surface must be part of a sphere which is concentric with the mirror at approximately half the radius. This method offers several important advantages: (1) Coma aberration is eliminated, and the spot is almost uniform even over the larger field of view. (2) The reduction in the number of buildings, electronics crates, calibration devices, etc., can reduce the cost of each eye. (3) The opening to the outside is only the diaphragm, so the building doors can be smaller and therefore less expensive and more reliable. (4) By covering the diaphragm with UV transparent material (like thin mylar), it may be possible to keep dust and dirt out of the telescopes and maintain them at nearly constant temperature, thereby eliminating important causes of sensitivity variation.