Chapter 5

Atmospheric Scattering; AerosolMin

The Pierre Auger Project measures the fluorescence light emitted by extensive air showers to determine the properties of ultra high-energy cosmic rays (UHECR). As such, it is necessary to know the local light attenuation properties of the atmosphere when an air shower occurs. Since the attenuation effect of air molecules can be determined from the atmospheric density, it remains to calculate the concentration and attenuation effects of aerosols, tiny particles suspended in the air. The transmission factor, T_a of a light path traveling through aerosols between the heights h_1 and h_2 is described in Chapter 2 Section 5.2 as,

$$T_a = \exp\left[\frac{h_a}{\Lambda_a(\lambda)\sin\alpha}\left(\exp\frac{-h_1}{h_a} - \exp\frac{-h_2}{h_a}\right)\right] \tag{5.1}$$

h_a is the aerosol vertical scale height and $\Lambda_a(\lambda)$ is the aerosol horizontal attenuation length. This transmission factor is for the single layer, constant temperature description of atmospheric aerosol density and does not include the effects of multiple scattering. For a description of the effect multiple scattering has on the attenuation effect of aerosols on a light path traveling through the atmosphere see Roberts (2004) [51].

The optical depth OD of a path through a scattering medium describes the total amount of scatter caused by all the particles present within that path. The optical depth is related to the transmission factor T through,

$$T = \exp(-OD) \tag{5.2}$$

If we take the path through the atmosphere to be the vertical distance from a reference height, $h_2 = 0$, to the end of the atmosphere, $h_1 = \infty$, then the vertical aerosol optical depth, $VAOD$, is described by,

$$VAOD = \frac{h_a}{\Lambda_a(\lambda)} \tag{5.3}$$

This reference height, h_2, can be defined anywhere in the atmosphere but for this thesis is defined from either sea level or the altitude of the detector.

The aerosol concentration of the atmosphere is measured at the site in regular intervals using a central laser facility. This facility fires a vertical laser pulse into the atmosphere to produce scattered light that the fluorescence detectors can measure. We can then use the fluorescence detector data to calculate the amount of scatter suffered by the laser pulse from the amount of light that reaches a detector [59]. This method is an accurate way to determine the concentration of aerosols in the atmosphere. The laser data may be complemented for rare events at the highest energies by using the measurement of a shower from two detectors (called stereo viewing) to reconstruct the original aerosol attenuation of the atmosphere at the time of the shower. If the aerosol scattering correction applied to the data is larger than the actual aerosol concentration of the atmosphere, the more distant detector will reconstruct an unrealistically brighter shower than the closer detector, because the light measured by the further detector will have traveled past more aerosol particles. For an incorrect, lower, aerosol concentration, the further detector will reconstruct a dimmer shower for the same reasons. We note that if the distance to the shower is the same for both detectors the brightness of the shower will always be reconstructed the same between the two detector data chains regardless of how different the assumed atmospheric aerosol concentration is to the actual value.

This concept has been used to create a program called AerosolMin, which compares the profiles of fluorescence light generated along an air shower track and then adjusts the aerosol concentration used in the reconstruction procedure until these profiles agree. I wrote two versions of AerosolMin that were compatible with the two reconstruction programs used by the Pierre Auger

Project. The first version was written in 2003 and used the data generated by the Flores reconstruction program. This version was run after the reconstruction software, because Flores was not able to concurrently reconstruct the data collected by two or more detectors. It was tested on vertical air showers simulated with the FDSim software and showed that the point where an air shower hits the ground needs to fall within a certain area on the surface array for AerosolMin to be be sensitive to changes in the aerosol concentration. The analysis of these simulated air showers also showed that the usefulness of AerosolMin was sensitive to the energy that a cosmic ray possesses. The second version was written in 2005 and used the Offline v1r2 software which allows multiple detector events to be analysed together. I used this version on all the real stereo events that had occurred between January 2004 and October 2005. However only two events were of high enough energy to be able to find a reasonable reconstruction of the $VAOD$.

1 Flores Version

1.1 A Description of the Code

To find the original aerosol concentration of the atmosphere at the time of a shower we need a program that will analyse the light measured by a detector. Flores (the Fluorescence detector Offline REconstruction System) reconstructs the properties of an air shower, including the light at the air shower track, the intrinsic brightness of an air shower. AerosolMin is then used to solve for the aerosol concentration. If the distances from each detector to the shower are significantly different, then for an incorrect atmosphere the profiles of the fluorescence photons reconstructed on the air shower track will not be the same. AerosolMin takes the calculated photon numbers emitted at the track and performs a χ^2 fit to the two profiles by adjusting the vertical aerosol optical depth until the difference between the two profiles is minimised. This returns a value of the $VAOD$, effectively measuring the aerosol concentration of the atmosphere at the time of the shower.

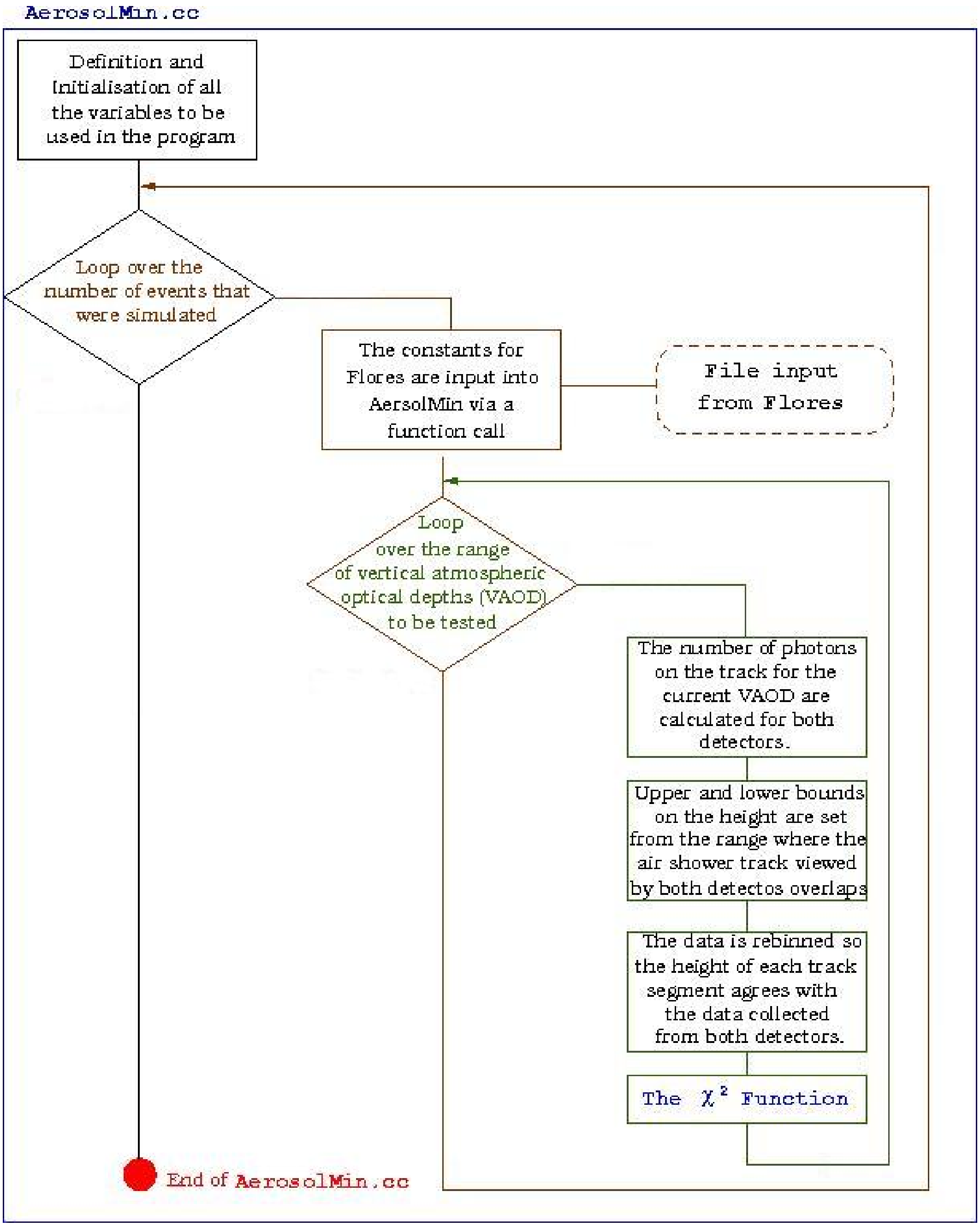


Figure 5.1: A Flow diagram of the AerosolMin function that is compatible with the Flores software. Blue text signifies a function call.

Input stage

The information necessary to define the number of photons emitted by the air shower track for different aerosol concentrations is input from a file as can be seen in Figure 5.1. Flores generates these data as it runs through its reconstruction procedure. Ideally, AerosolMin would be contained within the reconstruction chain itself. However, since Flores was unable to process multiple eye events, it was necessary to perform the minimisation after Flores had run.

Height Re-binning

AerosolMin is primarily concerned with calculating a χ^2 function between the profiles of the photon numbers on the shower track, as derived from two independent detectors. However, there is a technical problem with the data that needs to be addressed before this comparison can be performed. The data output by Flores is in the form of lists, where the list increment is a 100 ns time slice across the detector as light is being collected. Now, since each detector has a field of view ranging from 2° to 30° in elevation, it is obvious that two detectors viewing a shower at different distances will record the same height segment of the shower into different time bins. Hence we must find the common height range viewed by both detectors and re-bin the data such that the χ^2 will be calculated using the same segments of track. The χ^2 function is defined in a function call to the main program as seen in the flow diagram in Figure 5.1.

The χ^2 function

A χ^2 fit is a statistical test to fit a set of data to an error-less model by determining the weighted sum of the squares of the differences between a data point to the model at position x_i for the entire set, N, of data values by using the equation,

$$\chi^2 = \sum_{i}^{N} \left(\frac{y_i - y\left(x_i; a_j\right)}{\sigma_i} \right)^2 \tag{5.4}$$

Here (y_i, x_i) are the data set, $y(x_i; a_j)$ is the model, σ_i is the expected error on the y_i and the a_j are the variable parameters of the model. The a_j

are adjusted to make the χ^2 per degree of freedom ≈ 1. The χ^2 fit can be modified to relate two sets of data to each other, by changing the equation above to,

$$\chi^2 = \sum_i^N \left(\frac{y_{1i} - y_{2i}}{\sigma_i} \right)^2 \tag{5.5}$$

However since both sets of data contain intrinsic errors the σ_i must also be adjusted to be,

$$\sigma_i = \sqrt{\sigma_{1i}^2 + \sigma_{2i}^2} \tag{5.6}$$

Here σ_{1i} is the error in the first data set y_{1i} and σ_{2i} is the error in the second data set y_{2i}. In this case, the y_{1i} and y_{2i} are the profiles of the amount of fluorescence light produced by an air shower. This fit is performed on the lists of reconstructed light at the shower track for different atmospheric aerosol concentrations and used to determine the original $VAOD$.

Output stage

AerosolMin sequentially inputs a range of aerosol concentration values and calculates a χ^2 between the two data sets recorded for each detector. These χ^2 values are examined to find the value of the χ^2 function that is closest to one. These values can then be output for analysis.

1.2 The Simulated Events

To judge the effectiveness of AerosolMin at finding the atmospheric aerosol concentration at the time of a shower, the Auger shower simulation program FDSim, was used to generate 144 events at different core positions, initial cosmic ray energies and atmospheric aerosol concentrations. Figure 5.2 displays the core locations of the simulated showers with respect to the rest of the detector. Sixteen core locations were simulated between the Los Leones and Coihueco fluorescence detectors, starting at the center point (5060, 17680) of the line drawn between the two detectors, and then one event was simulated at every kilometer along that line from the center point toward the Los Leones detector. Each event was a vertical shower and was simulated in FDSim using a Gaisser-Hillas profile to define the number of particles present in the shower

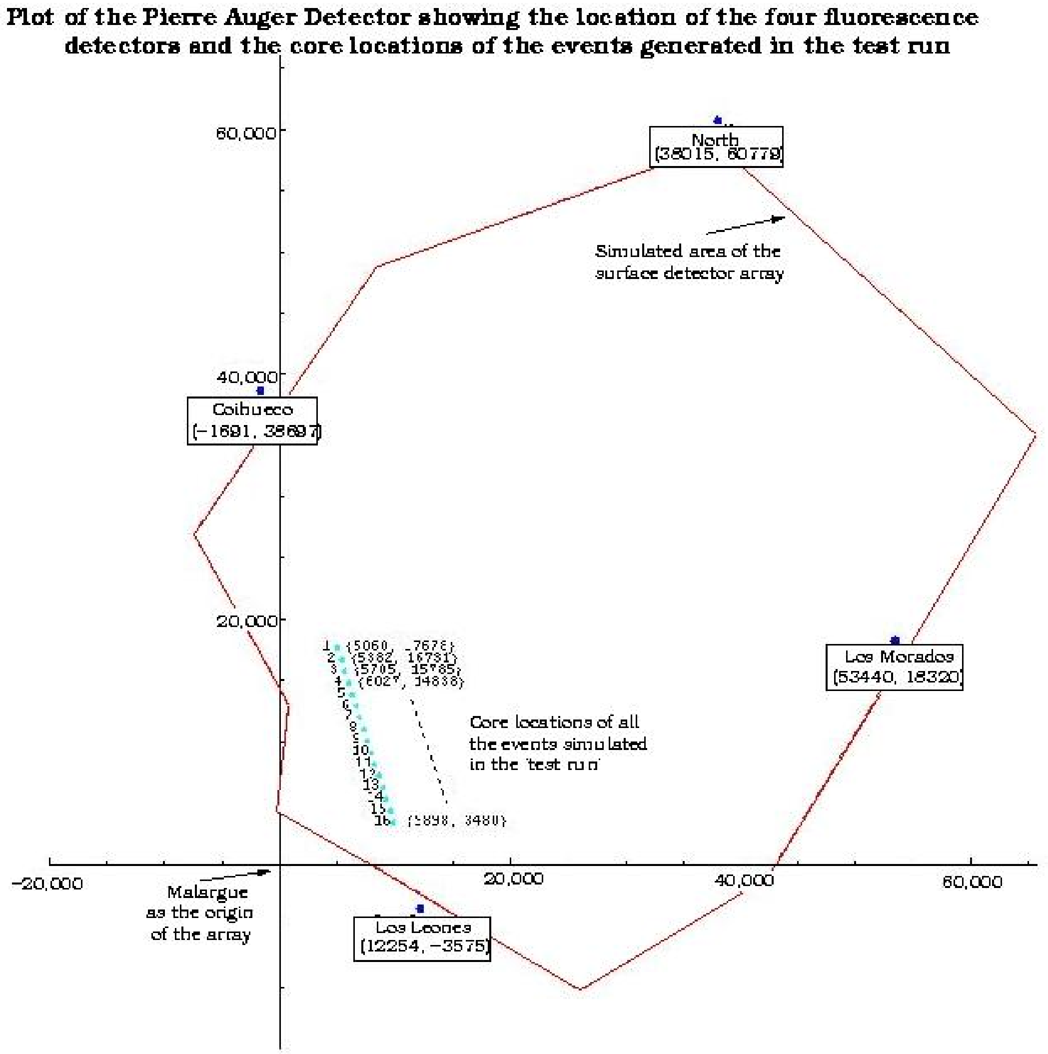


Figure 5.2: A plot showing the 16 core locations used by the FDSim software. Different initial cosmic ray energies and atmospheric aerosol concentrations were applied to each event position to simulate nine vertical air showers.

at any time. The 16 core locations were used nine times each, with different initial energies and atmospheric aerosol concentrations applied to the data. The effect of different air shower zenith angles was not studied in this test.

1.3 Limitations on the EAS core position

The events simulated in FDSim for the test run were spaced at regular 1 km intervals from each other and used the same physical models to describe the air shower and fluorescence detectors. The similarities between the events allowed me to determine some limit on the distance an air shower may fall from a detector within which AerosolMin will still effectively reconstruct the $VAOD$. For the event positions 13, 14, 15 and 16 the normalised χ^2 found by the AerosolMin program was greater than one when the event energies were 10^{20} eV. Since the only difference between the events simulated at these event positions and the events simulated at the event positions 2-12 are their distance to each detector, we conclude there is a distance cut that must be placed on the accurate reconstruction of the $VAOD$. When the distance between a detector to the event exceeds 34 km, for the events with an energy of 10^{20} eV, we find that AerosolMin cannot reconstruct the original $VAOD$ due to the decreased signal to noise ratio observed in the further detector. In addition, when the distances from the air shower core to a triggered detector are close to identical for vertical showers, the χ^2 value cannot be believed, because the light from the air shower will have been attenuated by the same amount of aerosols as it travels to either detector. As can be seen in Figure 5.3 the area that is bounded by these restrictions covers a significant proportion of the array site.

1.4 Limitations on the UHECR energy

Table 5.1 shows the statistics of the reconstructed $VAOD$s of the sixteen events for each combination of simulated $VAOD$, which ranged from 0.040 to 0.100 as defined from the height of the detector, and initial cosmic ray energy, which ranged from 10^{19} eV to 10^{20} eV. The values of the $VAOD$ are taken from the height of the detector as that is the nomenclature used by the Flores program. Of the sixteen core locations simulated only the 10 locations from positions 2 to 12 were used to calculated the average value of the reconstructed $VAOD$ seen in Table 5.1 because at position 1 the distance from the air shower to each

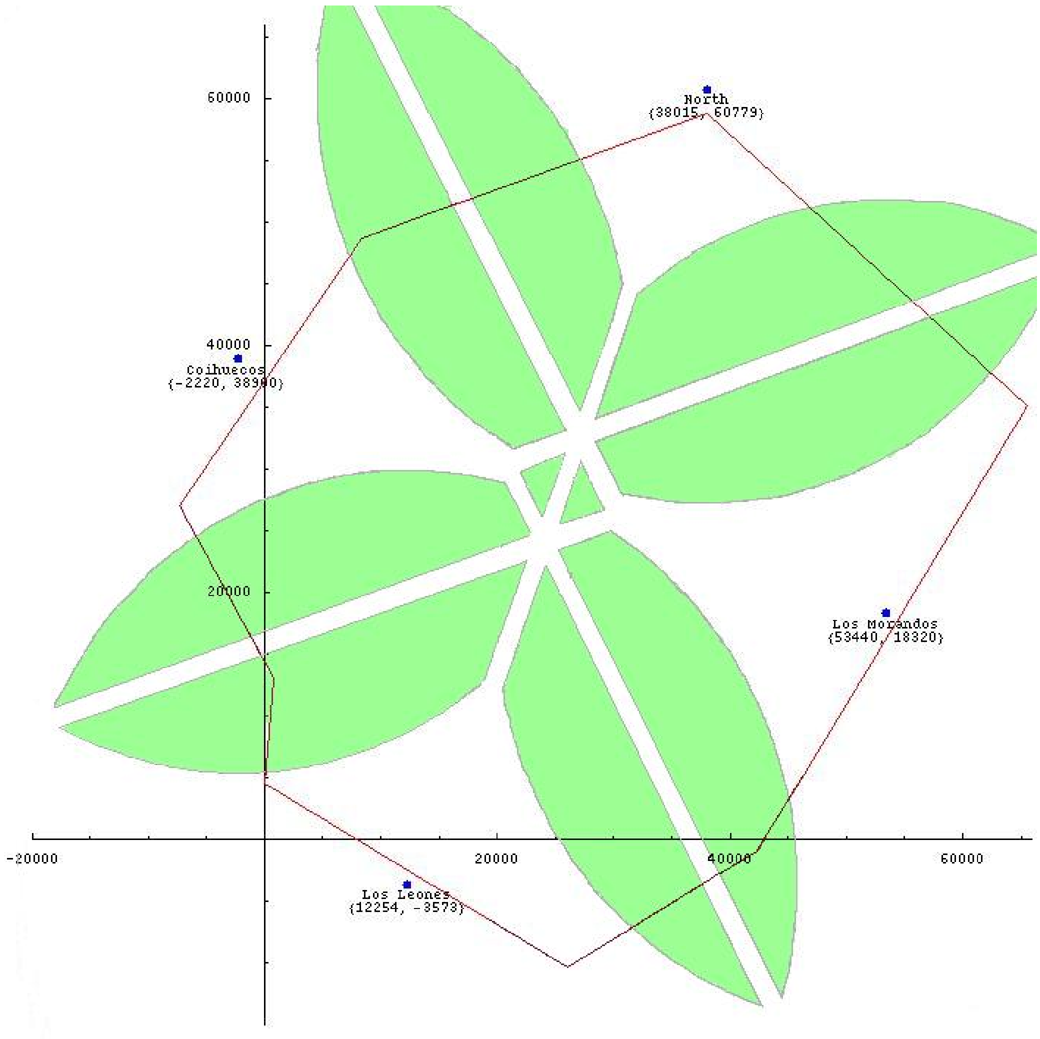


Figure 5.3: A plot showing the acceptable region where the core of a vertical air shower must fall within for the AerosolMin technique to be able to reconstruct a believable value of the $VAOD$ when the energy of an air shower exceeds 10^{20} eV.

detector was identical and at the positions greater than 13 the AerosolMin function was observed to be ineffective as discussed in the previous section. It must be noted that this average value is taken from a number of events all at different distances to the detectors, with resulting different signal intensities. Since both background noise and Poisson fluctuations are programmed into the signal, events that are far away from a detector will contain relatively more noise than events which are close to a detector. Hence these average values of the reconstructed $VAOD$ are only an approximation of how well AerosolMin has determined the atmospheric aerosol concentration.

For the events with energies below 10^{20} eV the average values determined for the $VAOD$ do not correspond to the simulated value within one standard deviation, so it must be concluded that for these energies this technique is not feasible. This is because the Auger detectors measure the fluorescence light emitted by a shower with photomultiplier tubes, i.e. by counting the number of photons arriving on the detector for a certain time interval. To make the simulation program FDSim as realistic as possible Poisson fluctuations along with a realistic value of the background noise are simulated. Hence the smaller the signal measured by a detector, the larger these effects will be. This is why the lower energy events have such poor reconstruction. For all of the 10^{20} eV showers, the original atmospheric aerosol concentration can be found to a precision of less than 20%.

2 Offline version

2.1 A Description of the Code

The Offline compatible version of AerosolMin has been written in two sections to incorporate the Cherenkov subtraction function of the Offline program. This is so we can first account for the amount of Cherenkov light produced by an air shower and then calculate the amount of Cherenkov light scattered towards a detector from that air shower. The first section of AerosolMin, SetVAOD, defines the value of the $VAOD$ to be used in the reconstruction chain and the second section, VAODChiSquared, runs the main body of AerosolMin. Both of these have been written as processing modules to be executed from the RunController of the Offline program (see Chapter 4 Section 2.2) and the loop over the various atmospheric aerosol concentrations is handled within the

	Energy (eV)	10^{19}	$10^{19.5}$	10^{20}
VAOD	Average	0.06	0.06	0.036
	Standard Deviation	0.03	0.01	0.006
	Relative Deviation	0.50	0.24	0.18
0.040	Maximum Value	0.09	0.08	0.044
	Minimum Value	0.03	0.03	0.030
	First Event Num.	2	2	2
	Last Event Num.	4	12	12
	Average	0.13	0.10	0.076
	Standard Deviation	0.09	0.02	0.007
	Relative Deviation	0.66	0.21	0.09
0.070	Maximum Value	0.24	0.15	0.086
	Minimum Value	0.03	0.08	0.067
	First Event Num.	3	2	2
	Last Event Num.	6	9	12
	Average	0.05	0.18	0.114
	Standard Deviation	0.03	0.04	0.013
	Relative Deviation	0.47	0.23	0.11
0.100	Maximum Value	0.08	0.24	0.133
	Minimum Value	0.03	0.13	0.092
	First Event Num.	3	2	2
	Last Event Num.	5	6	12

Table 5.1: The values of the average ($\bar{x}$), standard deviation (σ) and relative deviation ($\frac{\sigma}{\bar{x}}$) apply to the events simulated at the stated first and last event positions for the energy and simulated $VAOD$ values input into FDSim. The maximum and minimum reconstructed $VAOD$ for these events are recorded. All the reconstructed values of the $VAOD$ can be found in Appendix A. The values of $VAOD$ are defined from the height of the detector.

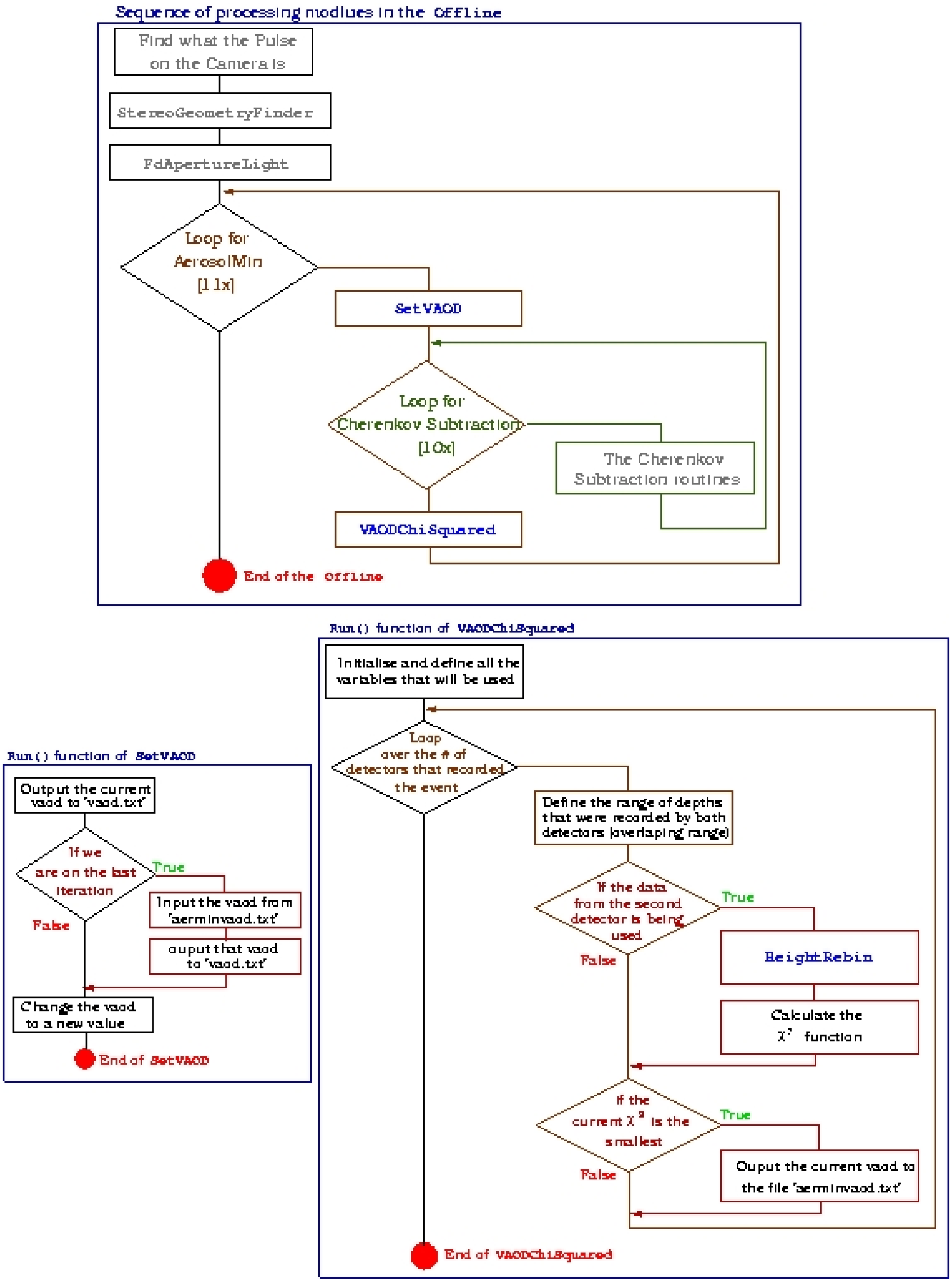


Figure 5.4: A Flow diagram of the AerosolMin function that is compatible with the Offline software. Blue text signifies a function call.

sequencing module of the Offline framework. This Offline compatible version of AerosolMin was run for all the stereo events recorded by the detector between the 14th of January 2004 to the 31st of October 2005 whose energies exceeded 2×10^{19} eV and whose relative difference in the distance from each detector to the core of the event was significant. Of the 104 stereo events recorded in this time frame, 14 matched these conditions but only two events were found to be energetic enough for the AerosolMin technique to be useful. However, one of these events was highly contaminated by direct Cherenkov light. This event occurred at the GPS second of 772256331. The other event is discussed in Section 2.2 in detail. These two events were the only events where it was possible to reconstruct the original aerosol concentration on the night of the event because all the other events possessed low signal to noise ratios. Only these two events had energies above 6×10^{19} eV and fell within the region specified by the test run. This energy is less than that predicted by the test run but the showers are slanted and the light profiles recorded by both detectors were well above the predicted error margin.

SetVAOD

The first part of the new AerosolMin function is a very simple program, where the $VAOD$ is set and output to an external file '*vaod.txt*' where the Offline program can access the values as it runs. The $VAOD$ values used were; 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.08, 0.1, 0.15, as defined from the height of the detector and these values encompass a range of aerosol concentrations from very clear (0.01) to quite dirty (0.15). The vertical aerosol scale height was fixed at $h_a = 1$ km, and the aerosol attenuation lengths were calculated from the $VAOD$ and the fixed h_a values as the Offline program cannot use the $VAOD$ value itself to calculate the atmospheric scattering due to aerosols. The aerosol attenuation length is then scaled to be defined from sea level, the nomenclature of the Offline, by using the formula,

$$\Lambda_a(\lambda)_{sea\ level} = \Lambda_a(\lambda)_{detector} \exp \frac{-h}{h_a} \tag{5.7}$$

where h is the height of the detector and can be approximated to be 1.4 km.

When the Offline is on the 11th AerosolMin function loop (see Figure 5.4), the last time the program is run, the $VAOD$ associated with the χ^2 value that is closest to one is recalled from another external file, '*aerminvaod.txt*' where it was output by VAODChiSquared.

VAODChiSquared : Initialisation

The inception of the Run() function of VAODChiSquared is where all the variables that will be used in the minimisation process are defined. The loop to run over all the detector data chains that have recorded information about the event is defined and within that loop the HeightRebin function is called and the χ^2 function is calculated.

VAODChiSquared : HeightRebin

The Offline software stores data profiles such that one datum bin corresponds to the amount of light recorded by the detector in a 100 ns time interval as the signal traveled across the detector. These bins correspond to various height ranges on the air shower track and the ranges defined by each detector will be different. The Offline software does not use the height of a track segment to define the position of a point on the air shower, but the atmospheric depth. So, for the AerosolMin function to be used on the data recorded for an event, the atmospheric depths at which the EAS are recorded must be identical between two detector data chains. I programmed this in the Offline by defining the range of atmospheric depths recorded by the data chain of one detector (data chain A) to be the range used by the data chain of the other detector (data chain B). This range of atmospheric depths was then used to interpolate the fluorescence light profile along the air shower track in data chain B at the ranges of atmospheric depths recorded by data chain A. The Offline software contains a definition of an interpolation function that can be used on data sets to allow a one dimensional interpolation to be performed on the fluorescence light profile for any atmospheric depth within the range of depths where light was recorded by a detector.

VAODChiSquared : χ^2 function

This section of the function loops over all the concurrent data points collected for two detectors and calculates the χ^2 function as described in Equation 5.5. The value of the χ^2 per degree of freedom is tested to see if it is the closest value to one as calculated for this event and, if so, it is saved to an external file, '*aerominvaod.txt*' where the corresponding value of $VAOD$ is also stored. At the current point in time the Offline v1r2 software cannot access the aerosol concentration parameters within the reconstruction chain without using external files to save the values, but newer versions are expected to have this capability.

2.2 The event which occurred at the GPS second of 799137161

This event occurred on the 3rd of May 2005 at 06:32 UTC time and was recorded by the Los Leones and Coihueco fluorescence detectors. The initial energy of the cascade inducing cosmic ray was reconstructed to be 5.2×10^{19} eV in the Coihueco data chain and 3.9×10^{19} eV in the Los Leones data chain. Figure 5.5 shows the amount of fluorescence radiation emitted along the air shower track deduced from the data recorded by both detectors for the nine values of $VAOD$ and indicates the amount of difference in the reconstruction of this profile from the two detector views. These profiles do not agree and the value of the χ^2 from Equation 5.5 never drops below 5.0. If we break the profiles into two, before and after 700 g/cm^2, we notice the profiles appear to agree before 700 g/cm^2 when the $VAOD = 0.08$. However, at this $VAOD$, after 700 g/cm^2 there seems to be too much scatter present in the profile reconstructed by the Los Leones data chain which is causing the χ^2 function to be so high. To check the effect of changing the aerosol concentration on the reconstruction of the amount of fluorescence radiation produced by an air shower, I have plotted the Gaisser-Hillas function reconstructed for each detector in Figure 5.6. The Gaisser-Hillas function is a parameterisation of the longitudinal profile which is directly related to the fluorescence light by the model of fluorescence yield used in the Offline software. Figure 5.6 shows that at a $VAOD$ of 0.08 the Gaisser-Hillas functions agree in size between the two data chains. At larger aerosol concentrations the Los Leones Gaisser-Hillas function is larger than the Coihueco Gaisser-Hillas function, and at smaller concentrations it is smaller. Since the Gaisser-Hillas function is constrained by its shape it is not affected by the scatter present in the data reconstructed by the Los Leones data chain at deeper atmospheric depths.

The weather station 1460 m above sea level positioned at the Los Leones

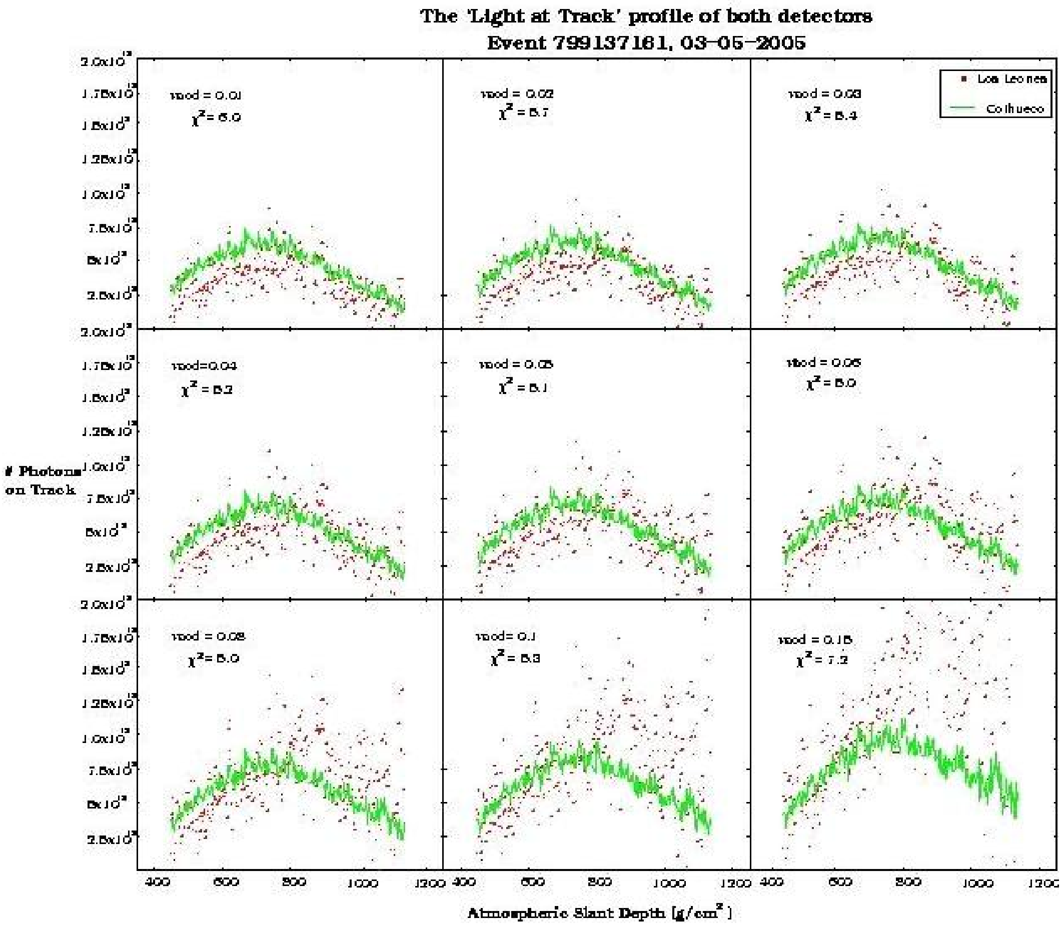


Figure 5.5: The fluorescence light at track profiles from each detector plotted against each other for the nine values of $VAOD$ applied to the reconstruction procedure. The $VAOD$s are defined from the height of the detector.

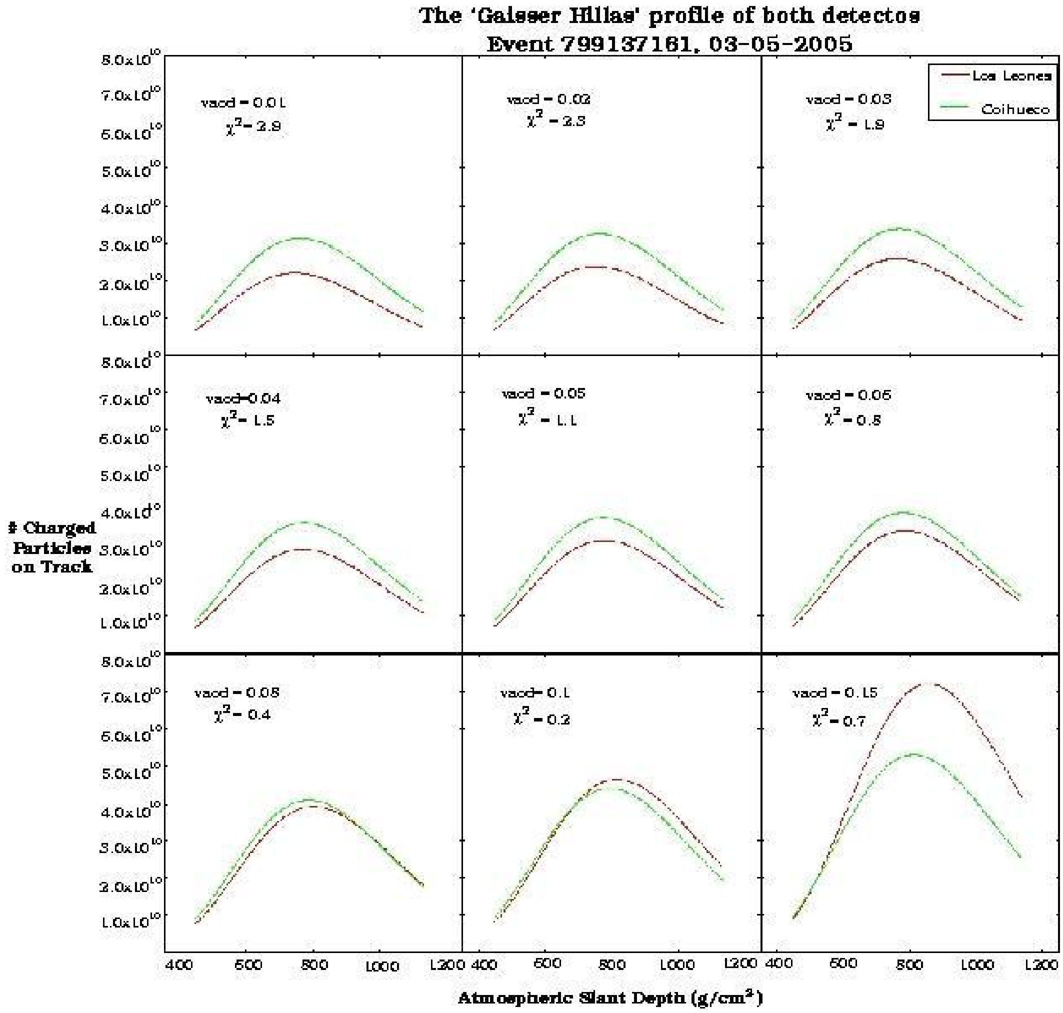


Figure 5.6: The Gaisser-Hillas profiles from each detector plotted against each other for the nine values of $VAOD$ applied to the reconstruction procedure. The $VAOD$s are defined from the height of the detector.

detector recorded the relative humidity at the time of the event to be 64.8%. The IR cloud camera (Figure 5.7) shows low lying cloud structure close to the ground near the Los Leones detector where the base of the tower is obscured. Hence it is likely that there was an inversion layer of fog lying between the Los Leones detector and the air shower. The Offline v1r2 software only applies a single layer aerosol concentration profile in the reconstruction chain, so it cannot accurately reconstruct a fluorescence light profile when there are multiple layers of aerosol concentration present on the night of an event. Hence, this is probably what is causing the scatter present in the Los Leones fluorescence light profile at deeper depths when larger $VAOD$s are applied to the reconstruction procedure. AerosolMin works by assuming that the average aerosol concentration of the atmosphere is constant over the entire array. This can been seen in the raw data collected by Michael Roberts where consistency in the $VAOD$s collected at both the Los Leones and Coihueco sites exists. However, this does not account for more complicated structures such as low lying fog, which may occur as Los Leones lies lower in the atmosphere than Coihueco. We conclude that on the night of the event which occurred at a GPS second of 799137161 the aerosol concentration was high, at a $VAOD \approx 0.08$ as defined from the height of the detector and that lying between the Los Leones detector and the event was a region of fog.

3 Chapter Summary

The AerosolMin program has been written to be compatible with both the Flores and Offline reconstruction programs that have been used by the Pierre Auger Project. The first version of AerosolMin was tested on events simulated in FDSim and it was found that only very energetic events that fell within a specified location were able to use this technique. The technique is a valid cross check on the laser measurements of atmospheric aerosol concentration that can be used on the most energetic events recorded by the observatory. The second version of the program was used on event 799137161, and showed that there was a layer of fog lying between the Los Leones detector and the event, as was observed by the IR camera positioned at the Los Leones detector.

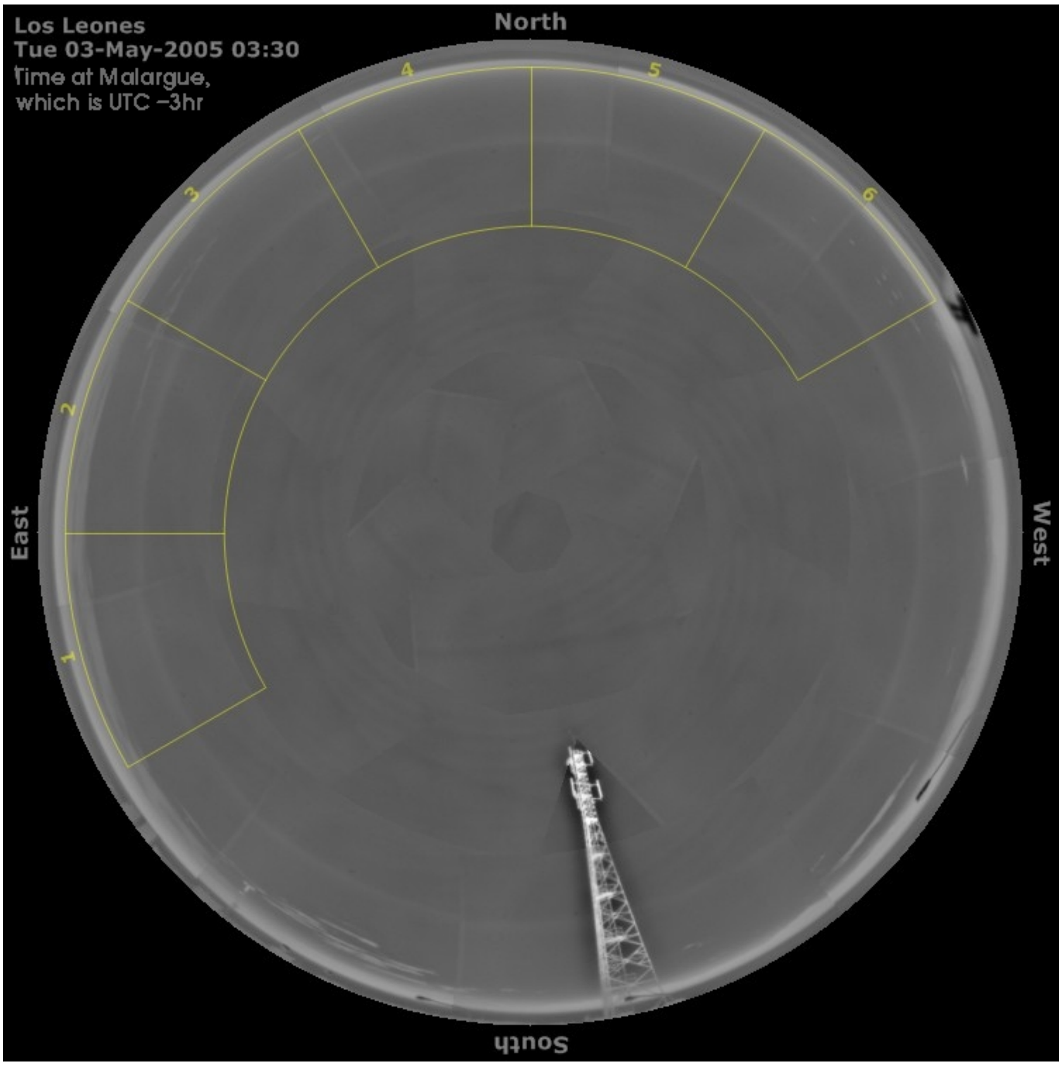


Figure 5.7: An infra-red image of the night sky taken at the Los Leones detector at the time the event at a GPS second of 799137161 occurred, which was 06:32 UTC time, or 03:32 local time at Malargue.

Chapter 6

FdCherenkovReplacer.cc and the Cherenkov radiation from an EAS

An extensive air shower creates two types of light producing phenomena to occur throughout the atmosphere. Of these two processes it is the fluorescence light that is of significance to the Pierre Auger Observatory. However, the production of Cherenkov light cannot be ignored completely, as an air shower generates both fluorescence and Cherenkov light within the same wavelength band. To account for this, the reconstruction software of the Pierre Auger project calculates the amount of Cherenkov light seen by a detector from a profile of the number of charged particles present in an air shower. The calculation of this profile is based on an initial assumption that all the light recorded by the detector was due to air shower fluorescence. The software then refines that profile over ten iterations by removing the calculated amount of Cherenkov light present in the signal. The main practical difference between the fluorescence light, and the Cherenkov light produced by an air shower is that the fluorescence light is directed isotropically, while the Cherenkov light is forward pointing. This means that, in general, a detector will only measure a very small proportion of Cherenkov light with respect to the amount of fluorescence light recorded. Hence, as long as the shower track geometry is well defined, a good estimate of the amount of Cherenkov light that is recorded by a detector can be made. This estimate of the Cherenkov light is recorded as a profile of the amount of Cherenkov light that would be produced by the shower as a function of atmospheric slant depth. When the shower is not properly defined, or too much Cherenkov light is present in a signal, this

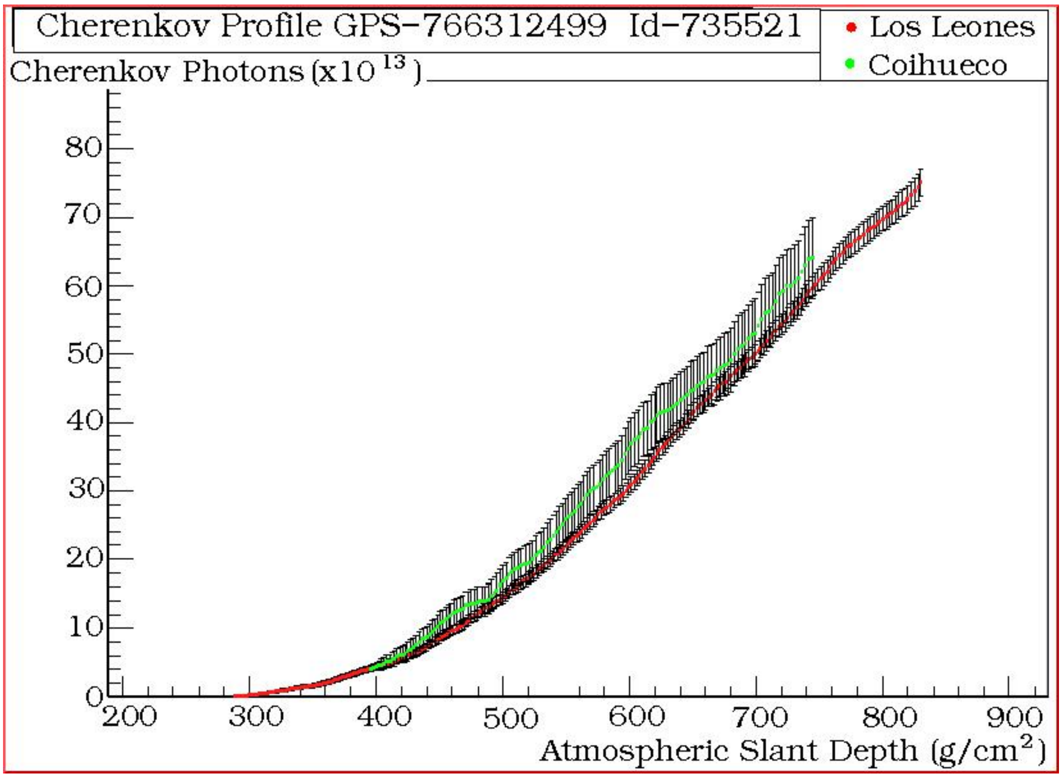


Figure 6.1: The Cherenkov profile on the air shower track for the event at the GPS second of 766312499. This event fits all the quality cuts used within FdCherenkovReplacer and the profiles calculated for both detectors agree.

iterative process causes the Cherenkov profile to be incorrectly accounted for.

For all the events that are viewed in stereo, there is a chance that while the Cherenkov iteration procedure has failed in the reconstruction chain of one detector, it will have worked in another detector's reconstruction chain. During the reconstruction process, the Offline software calculates the Cherenkov light that is produced along the track, and this profile should be consistent between both detectors as seen in Figure 6.1. When it is not, we know that one of the reconstruction procedures, say for detector A, has failed, and we can substitute the Cherenkov profile calculated by detector B into the reconstruction procedure for detector A. Thus we replace the failed Cherenkov profile for a Cherenkov profile that has been correctly calculated.

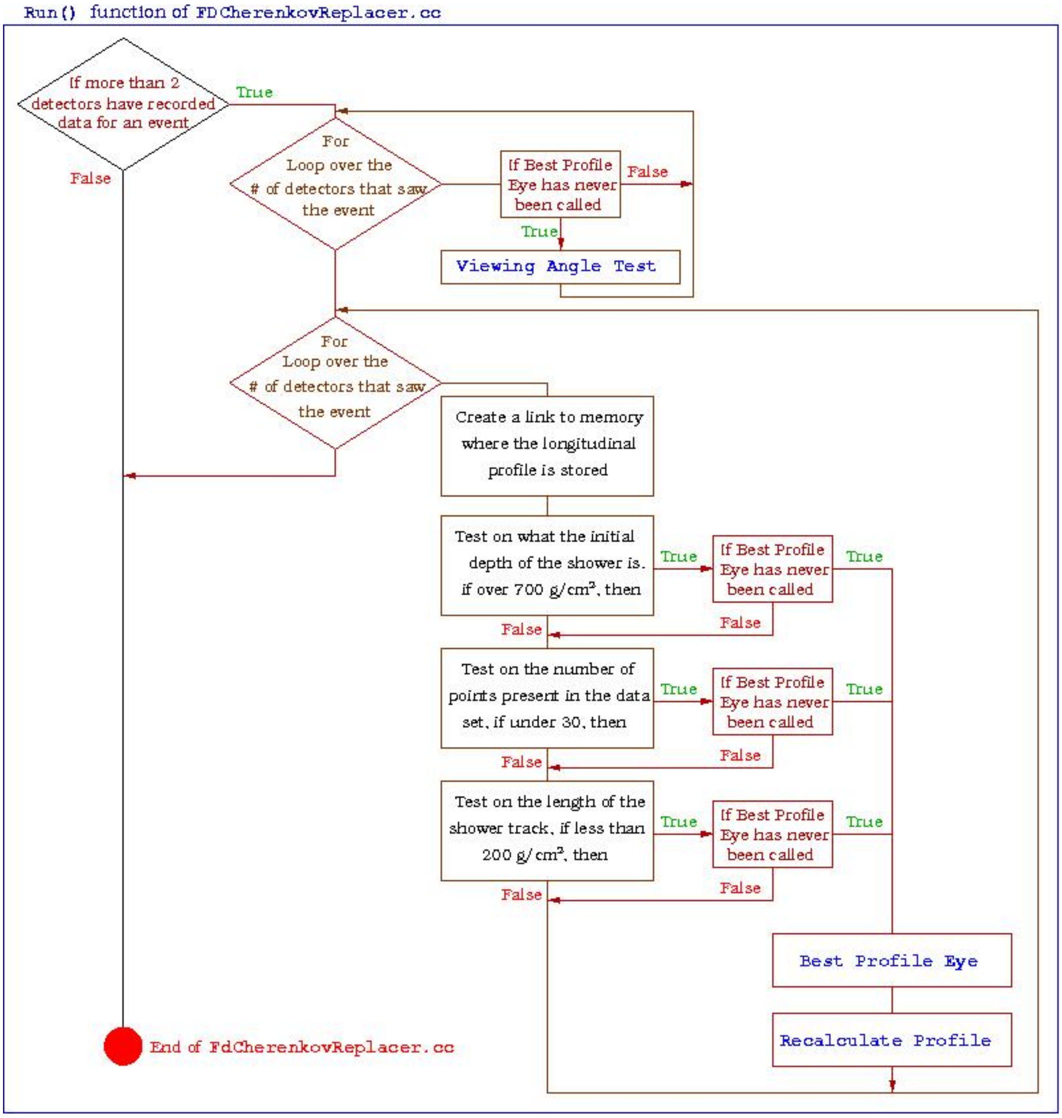


Figure 6.2: A Flow diagram of the Run function in FdCherenkovReplacer.cc. Blue text refers to a function call.

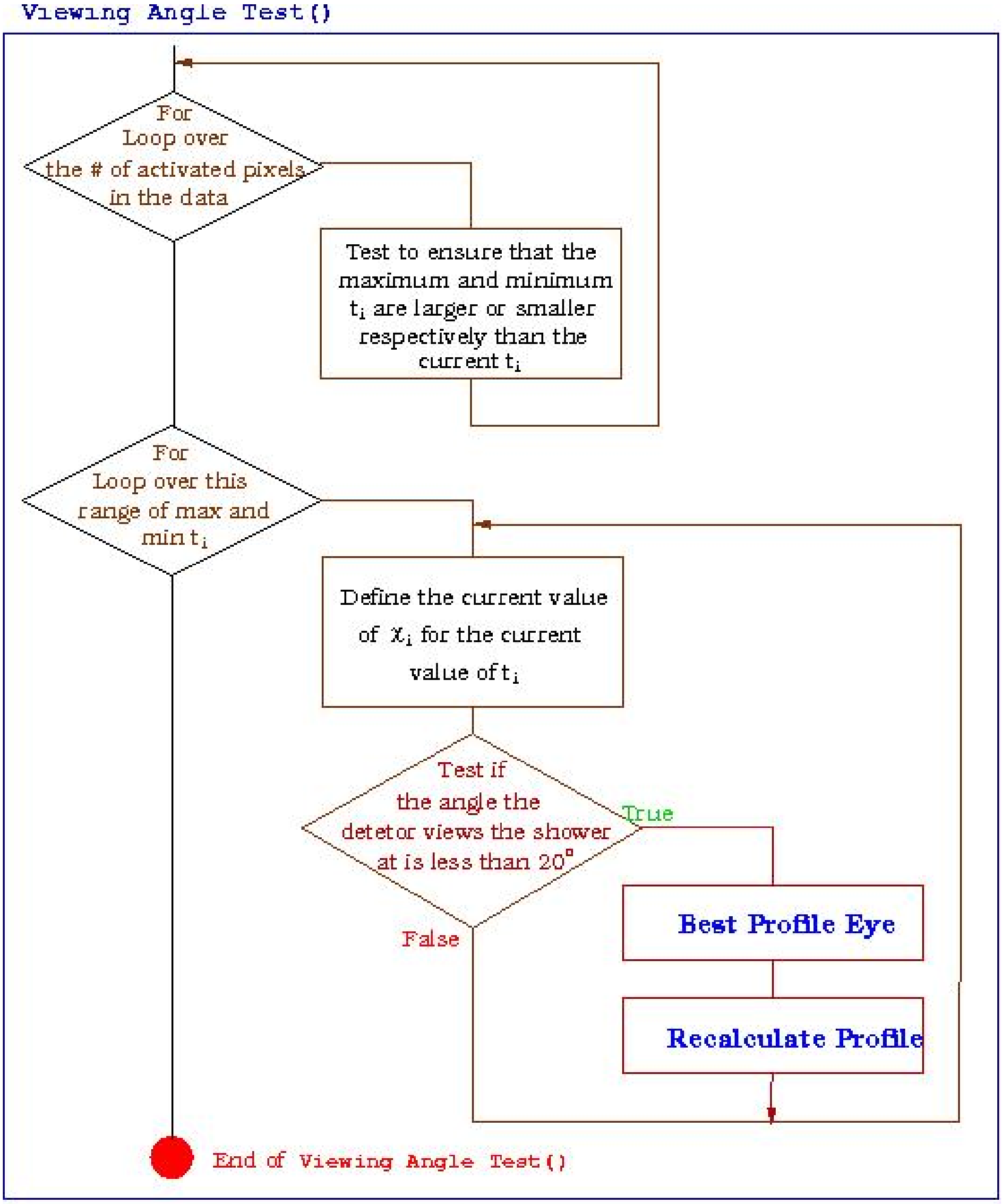
1 A Description of FdCherenkovReplacer

The main function of FdCherenkovReplacer is to see if the reconstruction from the data recorded by a detector has calculated a 'bad' Cherenkov profile on the track and, if so, to then replace that profile with a 'good' Cherenkov profile calculated by another detector. I found that a detector data chain was said to have calculated a 'bad' Cherenkov profile when at least one of four tests was satisfied. These tests are, (a) when the shower geometry points towards a detector and the recorded light signal is swamped with direct Cherenkov light, (b) when the number of data points collected by a detector is less than 30 (ie. the event duration is $< 3\mu s$), (c) when the initial depth a detector records a shower at is greater than 700 g/cm^2 or (d) when the measured air shower track length is less than 200 g/cm^2. I derived these tests after analysing the data output by the Offline software for all the stereo events that occurred from the 14th of January 2004 to the 31st of October 2005 as detailed in Section 2.

The program FdCherenkovReplacer has been written as a 'processing module' [57] so it can be easily inserted into the framework of the Offline, see Chapter 4. This means that the program has a Run function which is shown in Figure 6.2 and is called by the RunController as specified by a sequencing macro. The Run function for FdCherenkovReplacer can be roughly broken up into three sections, the initialisation, the Viewing Angle Test and the Quality Control Tests. Each of the quality control tests and the Viewing Angle Test call the function Recalculate Profile which recalculates the Cherenkov profile of the air shower and how much Cherenkov light will be seen by a detector. The initialisation is simply the inception of the Run function, where we initialise the variables that will be used throughout the function and test to ensure we are running a multi-detector event. It must be noted that this is separate from the initialisation that happens at the start of the Offline, where all the Initial functions of each processing module are called.

1.1 Viewing Angle Test

The vectorial direction of an air shower particle will not always be directly aligned with the geometrical center of the axis of an air shower. The direction of movement of any air shower particle will diverge from the central shower axis by some random angle determined from Coulomb scattering principles. Hence



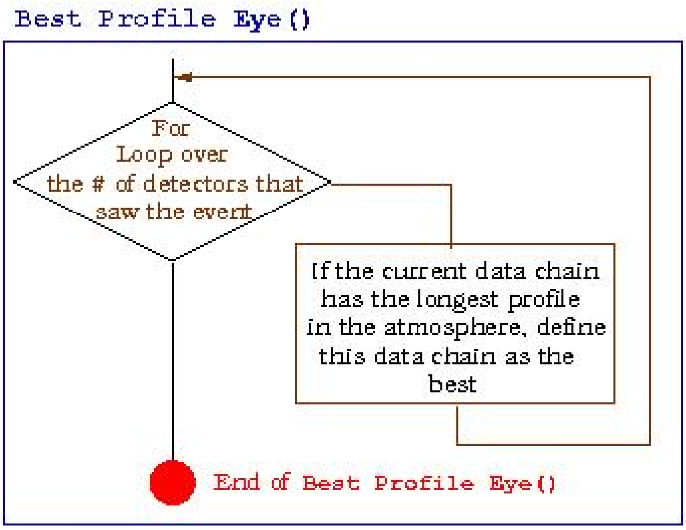


Figure 6.3: A flow diagram of the Viewing Angle Test function in FdCherenkovReplacer.cc. Blue text refers to a function call.

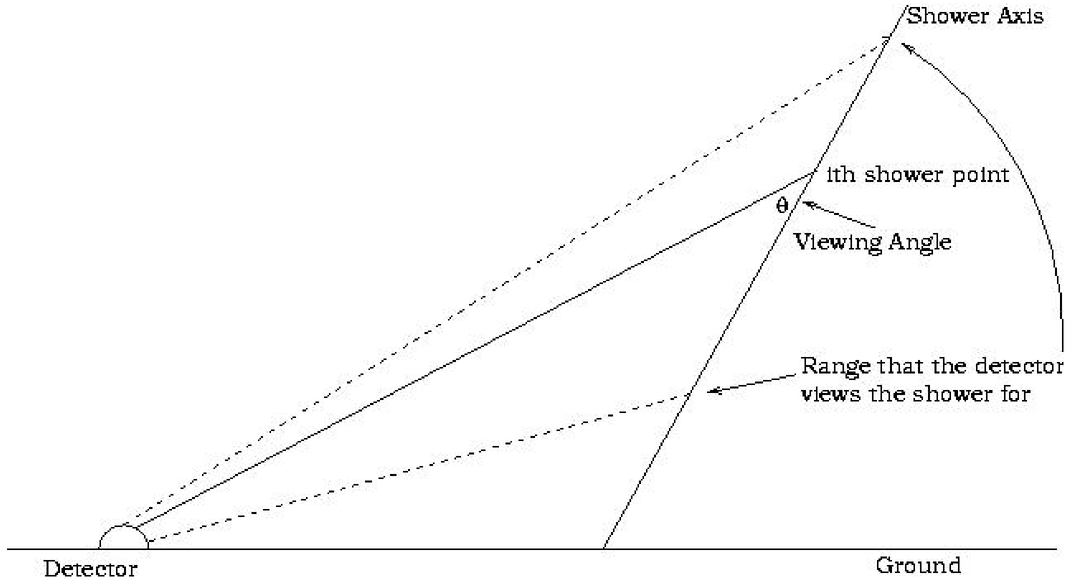


Figure 6.4: The definition of the air shower viewing angle.

the angle from the central shower axis at which you will see direct Cherenkov light will be greater than the angular size of the cone of radiation produced by the Cherenkov phenomenon[73]. If a detector views an air shower at an angle less than 20° from the central axis of the air shower a significant proportion of Cherenkov light will be recorded by the detector.

The Viewing Angle Test function determines whether a signal has been swamped with direct Cherenkov light by testing to see if the angle a detector views a shower is less than 20°. We run the Viewing Angle Test first as it is the most crucial test we can make. Viewing Angle Test (see Figure 6.3) begins by defining the range of time over which there is a signal present in the triggered pixels. The function then loops over that time range and identifies the angle between the air shower axis and the line from a point on the air shower axis to the detector as shown in Figure 6.4. If that angle is below 20° then we call Best Profile Eye to determine which of the other detectors that recorded this event has calculated the best Cherenkov profile. Finally Recalculate Profile is called to recalculate the amount of Cherenkov light recorded by the 'swamped' detector using the data stored by the detector with the better profile reconstruction.

1.2 Quality Control Tests

In order to reconstruct an accurate profile of the amount of Cherenkov light produced by an EAS, we assume that the data are of good quality. To determine the degree of quality of a Cherenkov profile and decide whether FdCherenkovReplacer must be used in the reconstruction chain, FdCherenkovReplacer tests three requirements (see Figure 6.2). These are: the initial depth at which a detector first records a shower is below 700 g/cm^2, the length of the air shower track recorded by a detector is above 200 g/cm^2 and the number of data points collected by a detector is above 30. When one or more of these tests fail we call Best Profile Eye, which simply uses the longest recorded air shower track length of the remaining detectors, to determine which detector has measured the best Cherenkov profile. Then Recalculate Profile is called which replaces the poor Cherenkov profile with the profile calculated by another detector data chain.

1.3 Recalculate Profile

The Recalculate Profile function in Figure 6.5 is where the FdCherenkovReplacer program changes the Cherenkov profile for a detector data chain that has originally calculated a poor Cherenkov profile. This function cannot directly access data objects stored in different detector data chains as the Offline software has been designed to protect the objects stored in different detector reconstruction chains. So the function is a little convoluted, to enable us to access the Gaisser-Hillas function and the longitudinal profile of the data chain that has calculated the better Cherenkov profile (data chain A), at the atmospheric depths of the data chain with the Cherenkov profile that needs to be replaced (data chain B). After defining these data access routes, Recalculate Profile calls the function Cherenkov Finder At Aperture which handles the actual calculation of the Cherenkov profile at the track and the amount of Cherenkov light that will be recorded by a detector.

Initial Cherenkov

Before the Cherenkov profile can be defined, the amount of Cherenkov light that exists in the shower before it is recorded by a detector must be calculated. This 'initial Cherenkov' profile is calculated from a function called

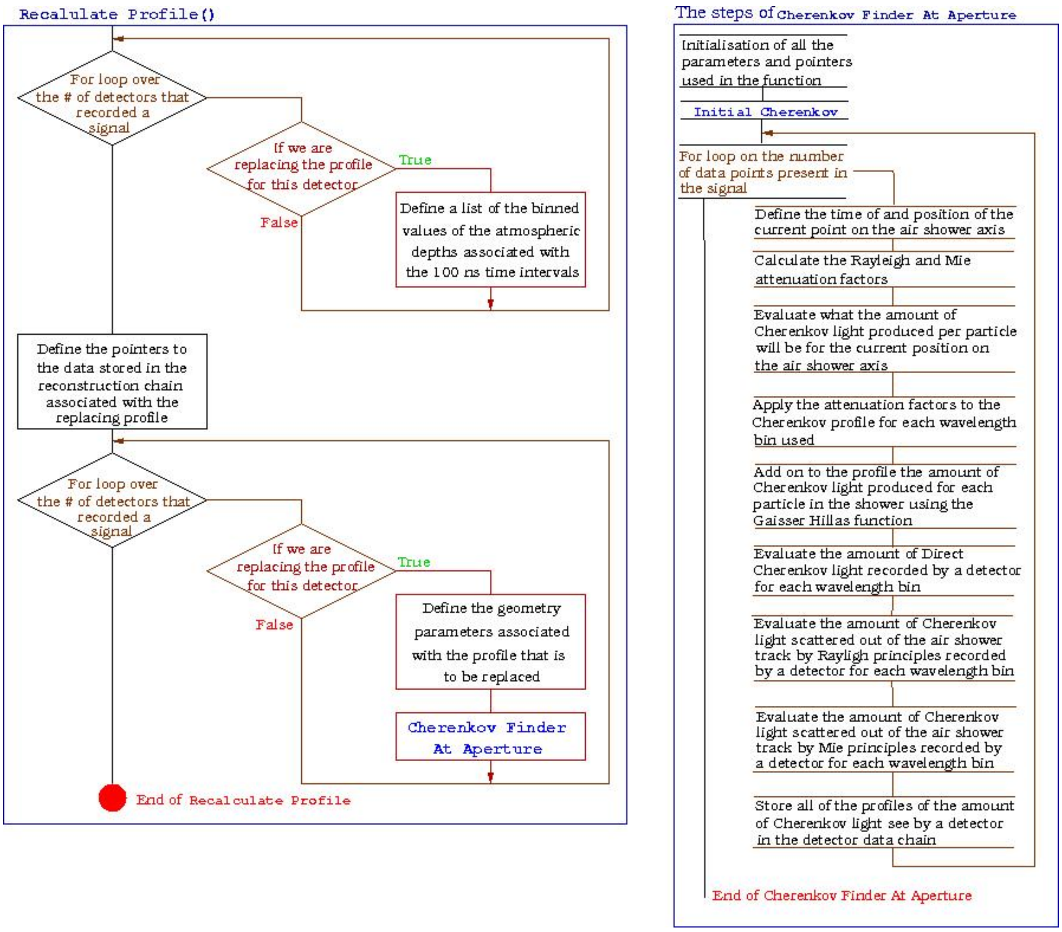


Figure 6.5: A Flow diagram of the Run function in FdCherenkovReplacer.cc. Blue text refers to a function call. The steps of Cherenkov Finder At Aperture are the same as those used by the current version of FdCherenkovFinder, the function used by the Offline software to calculate the amount of Cherenkov light a detector sees, but it has been modified so that the longitudinal profile and Gaisser Hillas function calculated for the 'good' detector will be used.

Initial Cherenkov. The Initial Cherenkov function is a revised form of another function with the same name currently used in the Offline software which is called at an earlier point in the reconstruction chain, before the Gaisser-Hillas function is calculated. This earlier form of Initial Cherenkov calculates an 'Initial Cherenkov' profile from some initial guess of what the longitudinal profile might be in the region above that actually measured by the detector. The FdCherenkovReplacer version of the Initial Cherenkov function calculates an 'Initial Cherenkov' profile by determining what the Cherenkov profile would be from the Gaisser-Hillas function found by data chain A for a range of atmospheric depths above the initial depth of the shower recorded in data chain B. In FdCherenkovReplacer we do not have to guess what the size of the shower will be because the Gaisser-Hillas function in the detector data chain that calculated the better Cherenkov profile will always have been defined prior to the start of FdCherenkovReplacer.

Cherenkov Finder At Aperture

The first step of Cherenkov Finder At Aperture is to call Initial Cherenkov which calculates how much Cherenkov light was present in the air shower before it was bright enough to be recorded by a detector. This must be done because the Cherenkov profile is cumulative and cannot be accurately defined if the very start of the profile is not calculated. The basic steps of Cherenkov Finder At Aperture are outlined in Figure 6.5. After calling Initial Cherenkov the function calculates the accumulated Cherenkov profile at each atmospheric depth for which the shower is recorded while taking the effect of atmospheric scattering into account. This profile is calculated from the two definitions of shower development stored by the Offline software, the Gaisser-Hillas function and the longitudinal profile. If the range of atmospheric depths recorded by data chain B (with the 'bad' Cherenkov profile) is within the range of atmospheric depths recorded by data chain A (with the 'good' Cherenkov profile), then the longitudinal profile of data chain A is interpolated to calculate the Cherenkov profile of data chain B. If the range of atmospheric depths recorded by the data chain B is outside the range recorded by data chain A (see Figure 6.6) then the Cherenkov profile is calculated from the Gaisser-Hillas function as found for data chain A. This is to preserve the fluctuations that might be present in the longitudinal profile, as the Cherenkov profile is cumulative and is sensitive

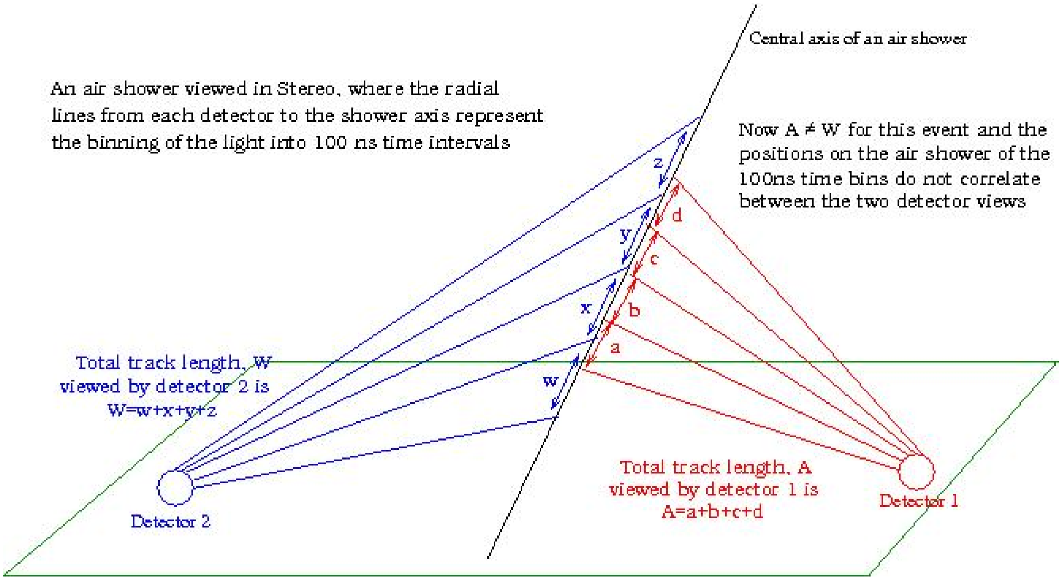


Figure 6.6: Each detector records an air shower by breaking the event time duration into 100 ns bins which correlate to different sections along the shower axis. The starting and ending points recorded by each detector correspond to different atmospheric depths. This inhibits any direct correlation between the two data chains for a specific atmospheric depth as required by FdCherenkovReplacer.

to the presence of these fluctuations. Then at every atmospheric depth the amount of Cherenkov light 'seen' by detector B is calculated and saved in data chain B for the direct, Rayleigh scattered and Mie scattered components.

1.4 Using the Gaisser Hillas Profile

In FdCherenkovReplacer we cannot simply switch the Cherenkov profile calculated from the data recorded by one detector to the other detector's reconstruction chain, as separate detector's view an air shower at different depths within the atmosphere (see Figure 6.6). Now, the calculation of the amount of Cherenkov light produced by an EAS is based on the profile of the number of charged particles present in the cascade. This profile is stored by the Offline software in two ways, the actual reconstruction of the number of charged particles present in the air shower as a function of atmospheric depth called the longitudinal profile, and a fitted Gaisser-Hillas function that parametrises the longitudinal profile. FdCherenkovReplacer is not always able to use an interpolation of the longitudinal profile to recalculate the Cherenkov beam strength

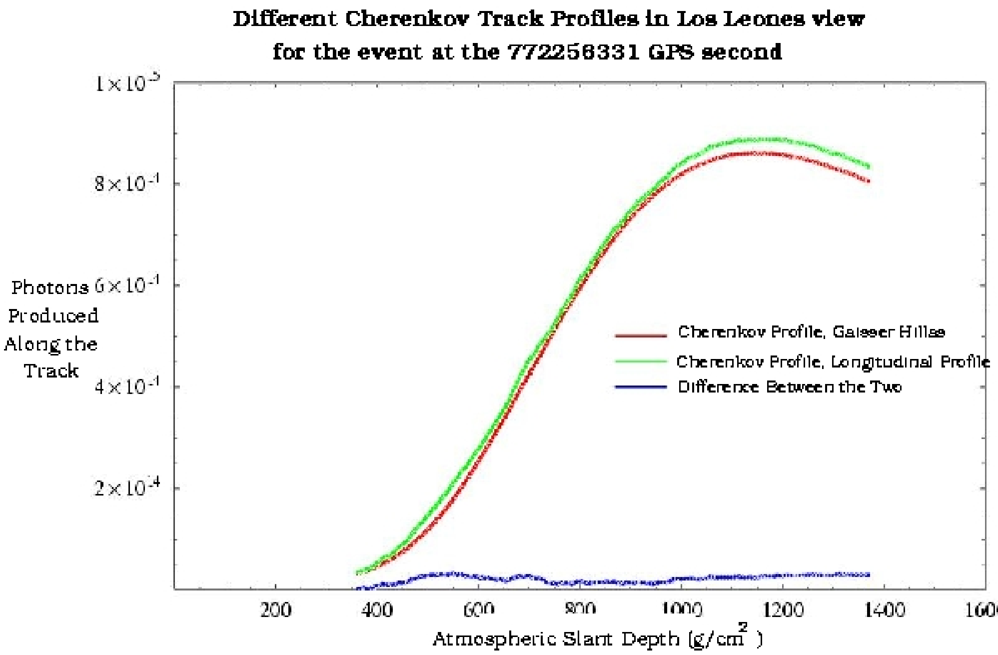


Figure 6.7: The Cherenkov profile on the air shower track calculated for the two ways the Offline software stores the number of particles present in an air shower, the Gaisser-Hillas function and the Longitudinal Profile. As can be seen there is very little difference in the calculation of the Cherenkov profile when the different shower size profiles are used.

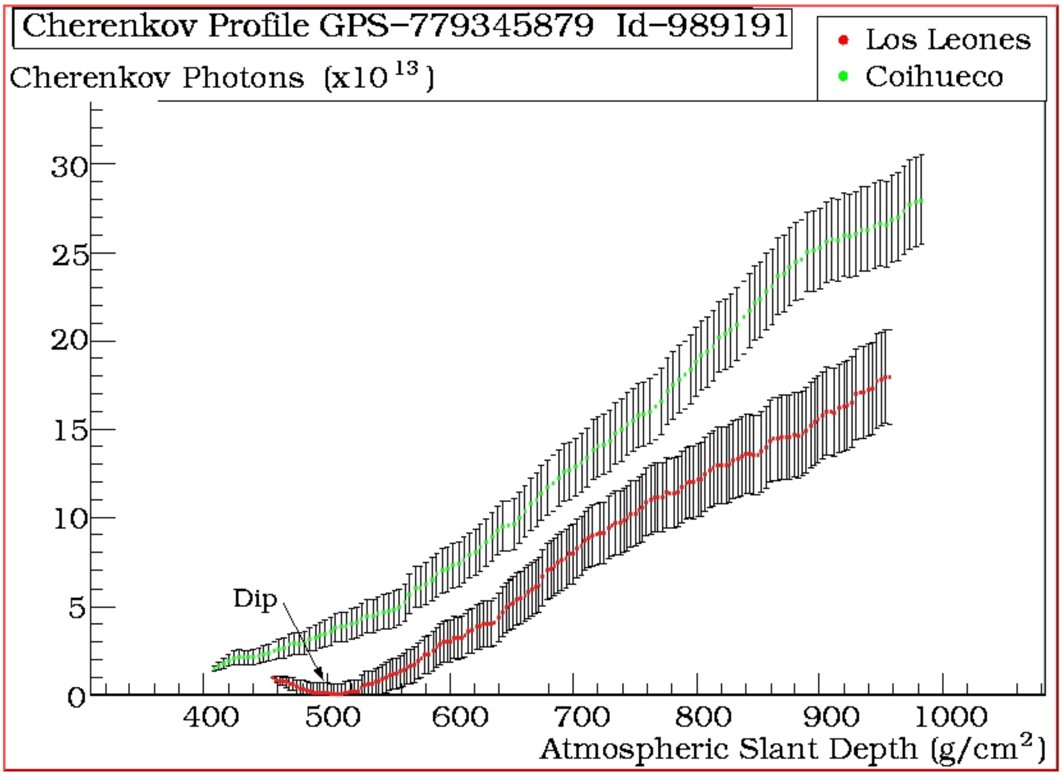


Figure 6.8: The points before the 'dip' have been reconstructed as having a negative amount of Cherenkov photons produced by the air shower. However, since the modulus of the amount of Cherenkov radiation produced by an air shower is plotted, a 'dip' like structure is seen.

as the entire length of the shower as recorded by each detector will generally begin and end at different atmospheric depths, as shown in Figure 6.6. Hence we must use the fitted model, the Gaisser-Hillas function, instead to find the Cherenkov profile on the air shower track. The Cherenkov profile on the air shower track was calculated for the event at a GPS second of 772256331 in the Los Leones detector from the two ways the Offline stores the profile of the number of charged particles present in an EAS, the longitudinal profile and the Gaisser-Hillas function. As can be seen in Figure 6.7 this has made little difference to the calculation of the amount of Cherenkov radiation produced by the air shower.

2 The Stereo Cherenkov profiles from 2004 to 2005

The Offline reconstruction software was run on the 104 events that were recorded by two detectors between the 14th of January 2004 to the 31st of October 2005 when FdCherenkovReplacer was not used. The Cherenkov profiles agreed for 69 of those events, and disagreed for 35. Of those 35 events, the three quality cuts stipulated above were placed on the data and accounted for the Cherenkov profiles disagreeing for 23 of the events. The disagreement between the other 12 events were due to,

- For two events at GPS seconds of 802597549 and 772256331, the amount of direct Cherenkov light recorded by one of the detectors that 'saw' the event made up over 40% of the light collected by that detector. Hence the iterative calculation failed to reconstruct the correct amount of Cherenkov light emitted by the air shower for the detector swamped with the direct Cherenkov signal.

- An average value of the aerosol concentration was used in the reconstruction of all the events which was $VAOD = 0.020$ as defined from the height of the detector. The aerosol concentrations on the nights of the events at the GPS seconds of 782010616 and 800238829 were $VAOD =$ 0.004 and 0.160 as defined from the height of the detector, respectively. Since these values are so different from the average value it is not surprising that the reconstructed Cherenkov profiles on the air shower track have not been found to be the same between the two reconstruction chains for each of these events.

- Three events at GPS seconds of 779345879, 787471951 and 801991626 have very strange Cherenkov track profiles as seen in the example in Figure 6.8. For these three events the 'Initial Cherenkov' profile calculated by one of the data chains is negative, an obvious physical impossibility. Since the modulus of the Cherenkov profile is plotted in Figure 6.8, no negative numbers are present in the plots. However the Cherenkov profile in the Los Leones detector was negative in the region before the 'dip' seen in Figure 6.8. The longitudinal profile for this event has recorded a negative number of particles present in the shower at the start of the profile, probably due to the night sky background being darker than expected. Since the 'Initial Cherenkov' profile is very dependent on the start of the longitudinal profile, this may be the cause of the structure seen in the Cherenkov track profiles for these three events.

- The remaining five events that occur at the GPS seconds of 758261109, 77935204, 804223217, 804500772 and 807342756 are anomalous, but the disagreement between the calculation of the Cherenkov profile on the air shower track may be due to flatness in the longitudinal profile reconstructed by both detectors. For these events the longitudinal profiles are relatively flat in the data recorded by each detector and may be causing the calculation of the Cherenkov profile to be incorrect, although other events with flatter profiles, eg. the event recorded at the GPS second of 779005589, were seen to have good agreement between the Cherenkov profile on the air shower calculated from both reconstruction chains. Whatever causes the disagreement, it is not a variable that can be tested. Thankfully only 5 out of the 35 events with disagreeing Cherenkov track profiles between the two detector data chains were found to have no known reason for their failure.

It must be noted that of the 69 events where the Cherenkov profiles agreed, 11 of the events failed one of the three cuts. So, even though the data are of poor quality, good agreement has been found between the Cherenkov profiles reconstructed for the two detectors. This is probably due to these events recording the air shower around the light production maximum, where a good reconstruction of the longitudinal profile can normally be accomplished. Hence the Cherenkov profile on the track may still be correctly accounted for in a small percentage of poor quality events, as long as the air shower maximum has been adequately observed.

3 The four requirements for FdCherenkovReplacer

The plots seen in Figures 6.1, 6.8 - 6.12 all show the beam strength along the shower axis of the Cherenkov light produced by a cosmic ray induced cascade when the event has been viewed in stereo. The y-axis displays the modulus of the number of Cherenkov photons produced by an EAS along the showers development in the atmosphere ($C(X)$) against the atmospheric depth (X) in g/cm^2. This profile is the accumulation of all the Cherenkov photons present in the beam that have not been attenuated out by scattering and is found through the Cherenkov yield function ($C_y(x)$) and air shower longitudinal profile ($N_e(X)$),

$$C(X) = \sum_{x=1}^{X} R(x)M(x)C_y(x)N_e(x) \tag{6.1}$$

$R(x)$ and $M(x)$ are the attenuation due to Rayleigh and Mie scattering suffered by the beam at depth x, respectively. The error bars in Figures 6.8 - 6.12 associated with each data point were calculated from the errors associated with the longitudinal profile that are calculated by the Offline, so,

$$\Delta C(X) = \sqrt{\sum_{x=1}^{X} \left[R(x)M(x)C_y(x)\right]^2 \Delta N_e(x)^2} \tag{6.2}$$

The error in the Cherenkov profile is only dependent on the error in the longitudinal profile, $\Delta N_e(X)$, and assumes there is no significant error present in any of the other variables used to calculate the Cherenkov profile.

If the Offline software has correctly accounted for the amount of Cherenkov light present within an air shower then the two profiles calculated for each detectors data chain should be identical, as they are in Figure 6.1. However, this is not always the case. The iterative Cherenkov removal procedure relies on having a good profile of the shower track and having a minimal amount of direct Cherenkov light present in the detector's view. We define a good profile as being one that has many data points (over 30), a long track length, (over 200 g/cm^2) and that the detector has recorded a profile early into the showers development (before 700 g/cm^2). Another crucial requirement is that the amount of direct Cherenkov light seen by the detector is less than approximately 40% of the total light viewed by the detector. When one of these criteria fail, we use FdCherenkovReplacer as shown in the next four examples.

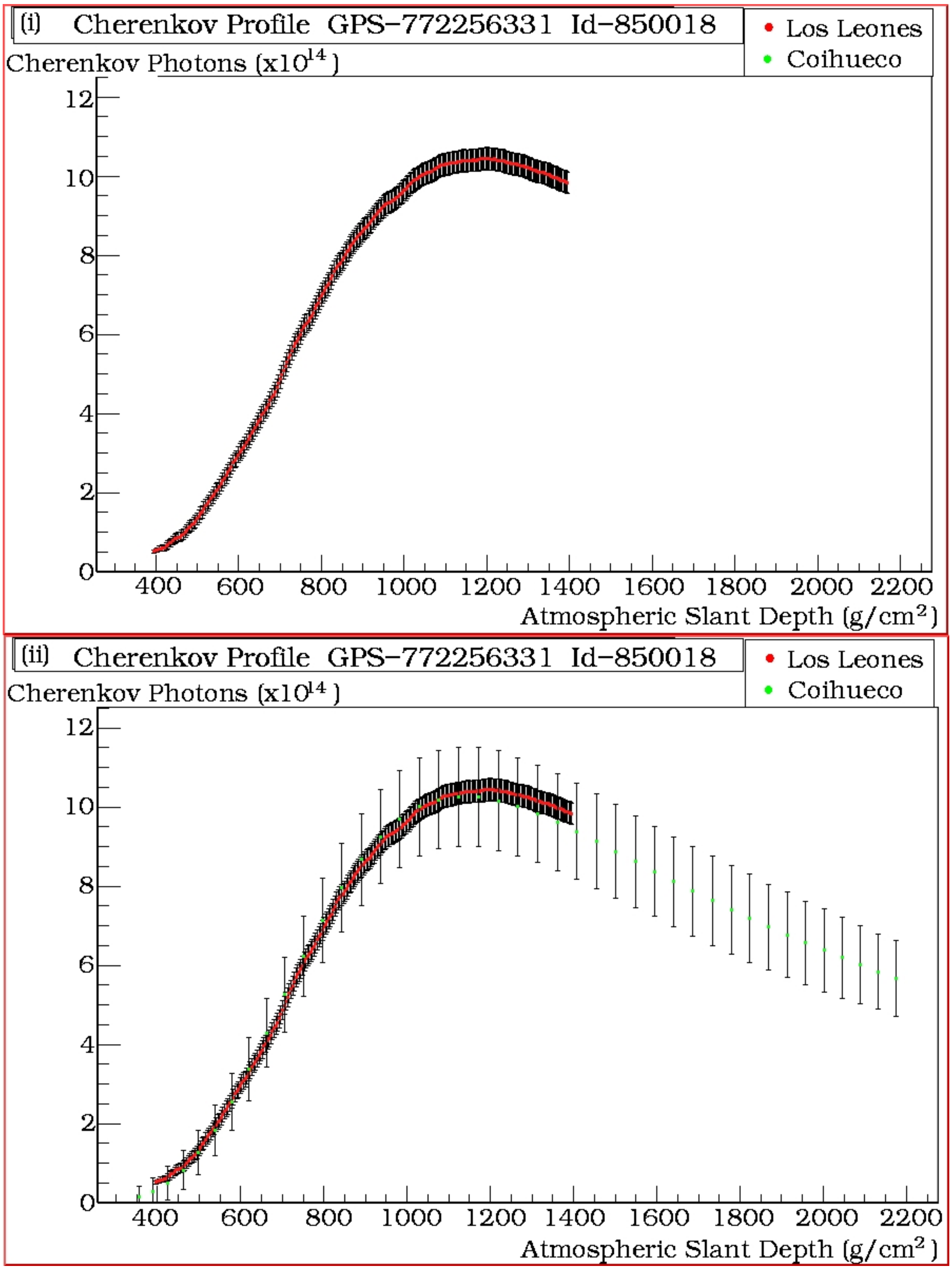


Figure 6.9: The Cherenkov profile on the air shower track for the event at the GPS second of 772256331 when FdCherenkovReplacer is not used (i) and is used (ii) in the Offline reconstruction chain.

3.1 Shower pointed towards detector

The event which occurred at a GPS second of 772265331 was recorded by the Los Leones and Coihueco fluorescence detectors on the 13th June 2004 (UTC time). The geometry of the air shower track was such that the shower was aimed towards Coihueco with a minimum viewing angle of 10.3°, which is less than 20°. Hence the amount of direct Cherenkov light observed by the Coihueco detector is as large as the amount of fluorescence light measured by the detector. The iterative procedure that removes the Cherenkov light from a signal works best when the amount of Cherenkov light recorded by a detector is less than 40%. When this is not the case the program will assume too much of the light that was produced by the air shower was due to fluorescence and so will calculate a longitudinal profile that is too large. Hence, the iterative procedure is divergent, and the program will not be able to accurately calculate what the Cherenkov profile should be. For this event the Cherenkov profile in the Coihueco detector has failed completely, as we can see it does not exist in Figure 6.9 (i) and the Gaisser-Hillas parameters have not been properly calculated as can be seen in Table 6.1.

Shower pointed towards the detector, 772256331 GPS sec

	Los Leones	Coihueco With FdCherenkovReplacer	Coihueco Without FdCherenkovReplacer
X_{max} (g/cm^2)	754	830	nan
N_{max} $(particles)$	3.81×10^{10}	7.16×10^{10}	nan
Energy (eV)	6.11×10^{19}	1.20×10^{20}	nan

Table 6.1: The values of the Gaisser-Hillas parameters and the initial cosmic ray energy for the event that occurred at a GPS second of 772256331. The reconstruction of the event in the Coihueco data chain was incorrect and so FdCherenkovReplacer was used.

Using FdCherenkovReplacer has meant that the calculation of the Cherenkov light profile in the Coihueco data chain has not failed and has caused the calculation of the Gaisser-Hillas parameters and the initial energy of the cosmic ray to be properly defined. In this case the relative difference in the calculation of N_{max} and the cosmic ray energy between the two detector data chains is 50 %, and the calculation of X_{max} is outside the expected error of $20g/cm^2$, which implies that either the atmospheric parameters or the calibration constants applied to the data are incorrect. If the calibration constants have a systematic error, this may explain the error in N_{max} and the initial energy and if the constants associated with a few pixels are wrong then they may be artifically moving X_{max}.

3.2 Late detection of shower

The event which occurred at a GPS second of 802594783 was recorded by the Los Leones and Los Morados fluorescence detectors on the 12th of June 2005 (UTC time). The Los Leones detector first recorded the event at an atmospheric depth of 730 g/cm^2 which fails the first of our three quality control cuts. This initial depth is very close to the position of X_{max} and so the calculation of the 'Initial Cherenkov' profile is crucial to the correct calculation of the Cherenkov profile. The FdCherenkovReplacer version of Initial Cherenkov calculates this 'Initial Cherenkov' profile from the Gaisser-Hillas function calculated by the detector data chain with the better Cherenkov profile, hence a more accurate 'Initial Cherenkov' profile is found. However, the Gaisser Hillas function is only an approximation of the longitudinal profile and does not contain any of the fluctuations present in the actual data. Since the Cherenkov profile is cumulative, small fluctuations in the longitudinal profile can add up to large differences in the Cherenkov profile, as can be seen in Figure 6.10, although the profiles do agree better than they did before FdCherenkovReplacer was used.

Late detection of shower, 802594783 GPS sec

	Los Morados	Los Leones With FdCherenkovReplacer	Los Leones Without FdCherenkovReplacer
X_{max} (g/cm^2)	775	787	794
N_{max} $(particles)$	4.02×10^9	5.00×10^9	5.36×10^9
Energy (eV)	6.62×10^{18}	8.27×10^{18}	8.90×10^{18}

Table 6.2: The values of the Gaisser Hillas parameters and the initial cosmic ray energy for the event that occurred at a GPS second of 802594783. The reconstruction of the event in the Los Leones data chain was incorrect and so FdCherenkovReplacer was used.

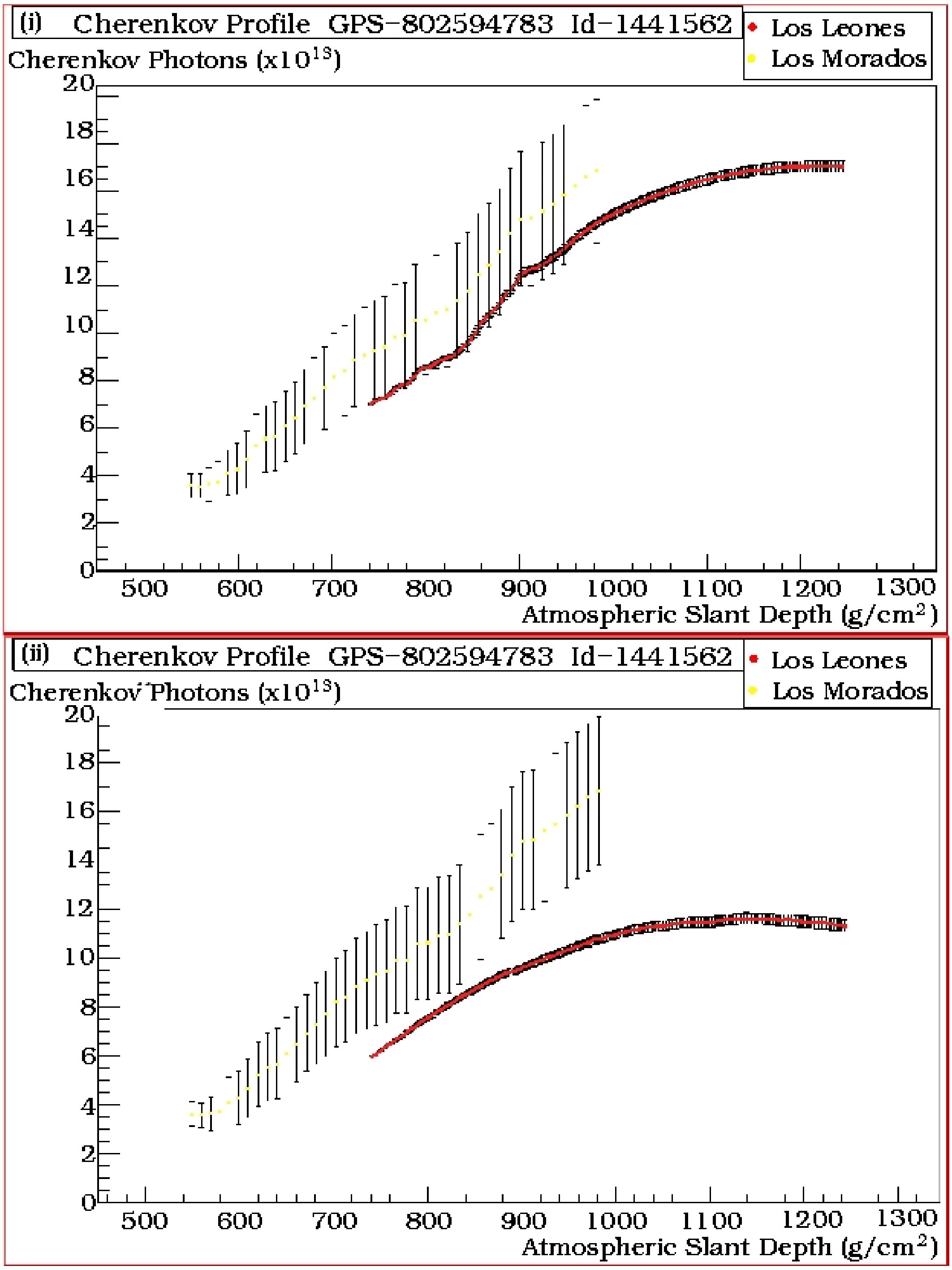


Figure 6.10: The Cherenkov profile on the air shower track for the event at the GPS second of 802594783 when FdCherenkovReplacer is not used (i) and is used (ii) in the Offline reconstruction chain.

Table 6.2 shows the calculation of the Gaisser Hillas parameters and the initial cosmic ray energy for the detectors that recorded the event. As can be seen, FdCherenkovReplacer has not improved the calculation of these parameters much, because the Gaisser Hillas function and ultimately the cosmic ray energy reconstruction are more dependent on the maximum of the air shower being recorded by a detector than on the size of the Cherenkov profile.

3.3 Short track length of shower recorded

The event which occurred at a GPS second of 802570479 was recorded by the Los Leones and Coihueco fluorescence detectors on the 12th of June 2005 (UTC time). The length of the air shower track recorded by the Coihueco detector was 177 g/cm^2 which fails the second of our three quality control cuts. The main reason why a short track length fails is because the cumulative nature of the Cherenkov profile means that if a significant proportion of the shower track is missing, we have a much higher chance of incorrectly calculating the Cherenkov profile on the track. In addition, measuring a shorter track length will generate a higher error on the reconstruction of the track orientation. These errors in the shower geometry will filter down into our reconstruction of the Cherenkov profile and may cause the profile to be incorrectly calculated.

Short track length of shower, 802570479 GPS sec

	Los Leones	Coihueco With FdCherenkovReplacer	Coihueco Without FdCherenkovReplacer
X_{max} (g/cm^2)	682	928	933
N_{max} $(particles)$	5.93×10^9	1.02×10^{10}	1.04×10^{10}
Energy (eV)	9.15×10^{18}	1.83×10^{18}	1.87×10^{18}

Table 6.3: The values of the Gaisser Hillas parameters and the initial cosmic ray energy for the event that occurred at a GPS second of 802570479. The reconstruction of the event in the Coihueco data chain was incorrect and so FdCherenkovReplacer was used.

Table 6.3 shows that when FdCherenkovReplacer is used it has very little effect on the reconstruction of the Gaisser Hillas parameters and the energy of the cosmic ray. The difference in the reconstruction of these parameters is

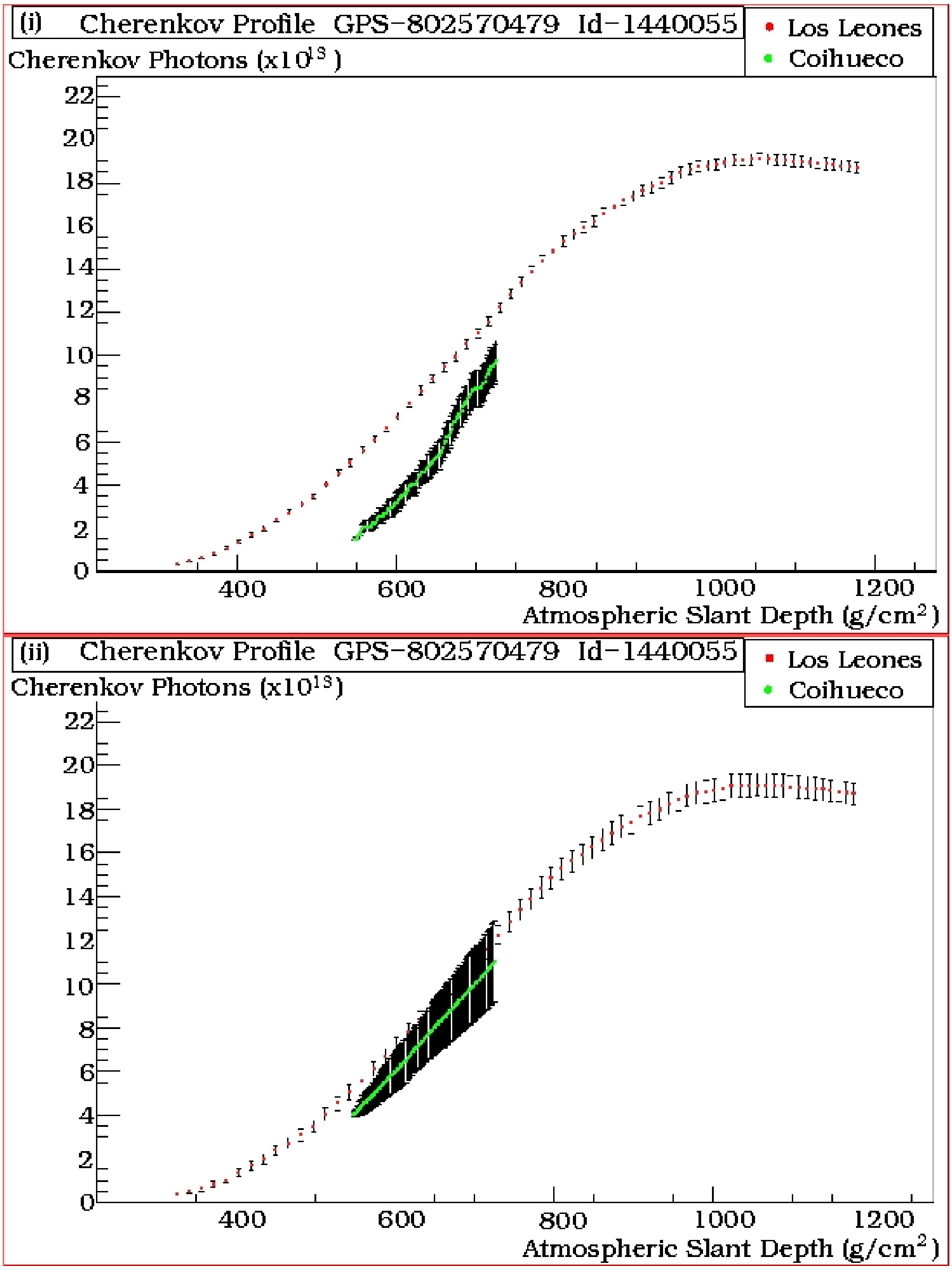


Figure 6.11: The Cherenkov profile on the air shower track for the event at the GPS second of 802570479 when FdCherenkovReplacer is not used (i) and is used (ii) in the Offline reconstruction chain.

outside the expected error of 20 g/cm^2 on X_{max} and $\sim 10\%$ on N_{max} and the energy. As with the case when the shower is detected late by a detector, the recording of the air shower maximum is more important in the calculation of these parameters than the Cherenkov profile.

3.4 Small number of data points

The event which occurred at a GPS second of 804404923 was recorded by the Los Leones and Coihueco fluorescence detectors on the 3rd of July 2005 (UTC time). The number of data points collected by the Coihueco detector was 25 which fails the third of our three quality control cuts. A small number of data points means the reconstruction of the longitudinal profile is more susceptible to any errors or fluctuations present in the data. Another reason why a small number of data points can cause the Cherenkov profiles calculated for two detectors to disagree, is that it indicates that the shower traveled across the the detector very quickly as happens when the shower is traveling towards the detector. Hence the detector may record a large amount of direct Cherenkov radiation even though the signal was not swamped with Cherenkov light. Figure 6.12 shows the Cherenkov profiles on the air shower track for the event at the 804404923 GPS second, where a small number of data points were collected by the Coihueco detector.

Small number of data points, 804404923 GPS sec

	Los Leones	Coihueco With FdCherenkovReplacer	Coihueco Without FdCherenkovReplacer
X_{max} (g/cm^2)	797	667	703
N_{max} $(particles)$	4.52×10^9	4.04×10^9	3.76×10^9
Energy (eV)	7.53×10^{18}	6.18×10^{18}	5.89×10^{18}

Table 6.4: The values of the Gaisser Hillas parameters and the initial cosmic ray energy for the event that occurred at a GPS second of 804404923. The reconstruction of the event in the Coihueco data chain was incorrect and so FdCherenkovReplacer was used.

When we examine the effect FdCherenkovReplacer has on the reconstruction of the Gaisser Hillas parameters and the initial energy of the cosmic ray

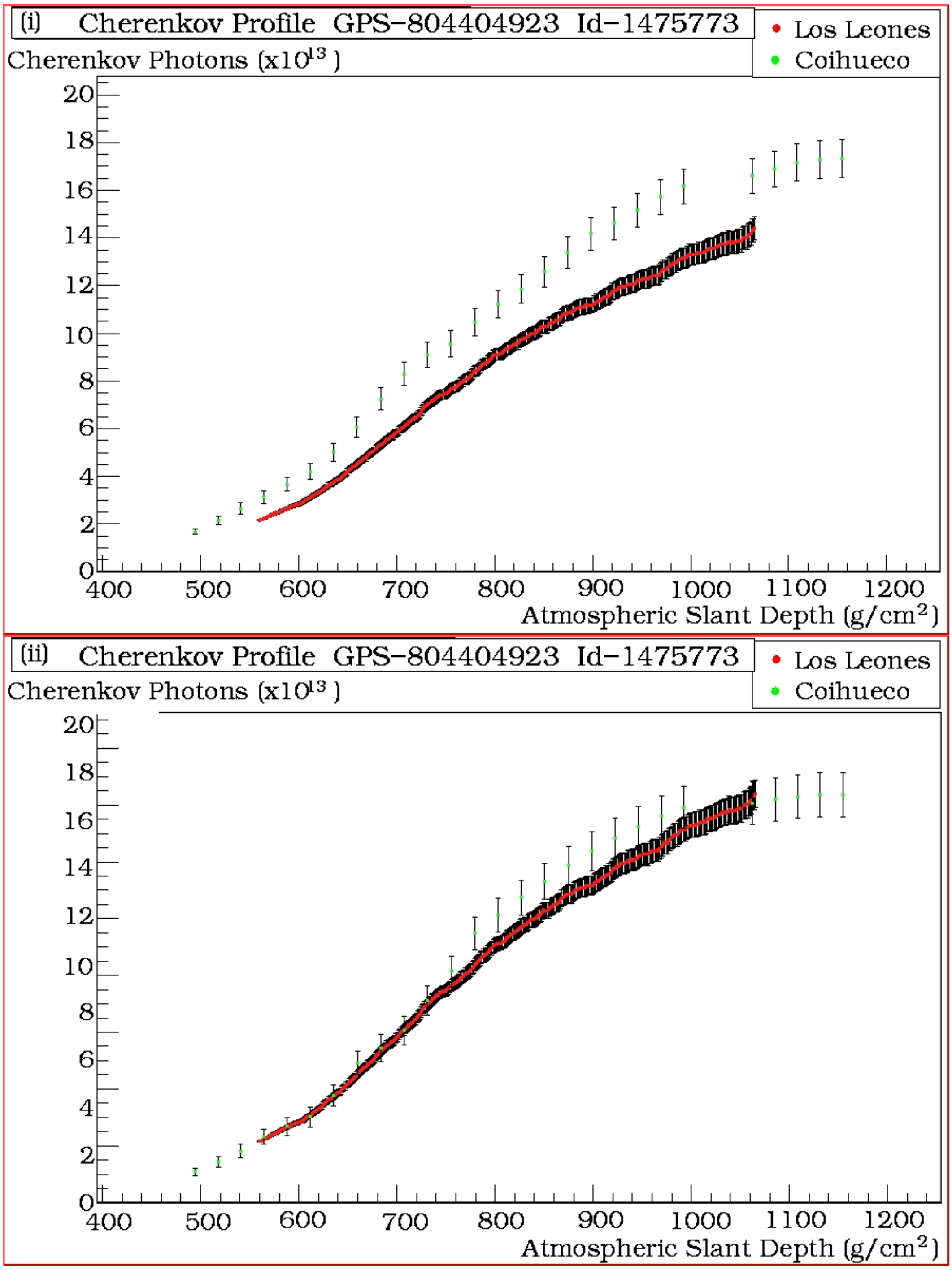


Figure 6.12: The Cherenkov profile on the air shower track for the event at the GPS second of 804404923 when FdCherenkovReplacer is not used (i) and is used (ii) in the Offline reconstruction chain.

in Table 6.4, we see that the energy parameters are reconstructed to a better accuracy when this function is used but the reconstruction of X_{max} has worsened. The size of the Cherenkov profile is significant for this event and has affected the calculation of the energy parameters, but it is now throwing the calculation of X_{max} off, because the fluctuations present in the light profile recorded by the Los Leones detector do not match those recorded by the Coihueco detector, and this artificially moves the placement of X_{max}.

4 Chapter Summary

The FdCherenkovReplacer function is a useful addition to the Offline software as it enables us to reconstruct stereo events that had calculated a 'bad' Cherenkov profile to a higher degree of accuracy. The four aspects of poor quality FdCherenkovReplacer has been written to process are; (a) when the shower geometry points towards a detector and is swamped with direct Cherenkov light, (b) when the number of data points collected by a detector is less than 30, (c) when the initial depth a detector records a shower at is greater than 700 g/cm^2 and (d) when the measured air shower track is less than 200 g/cm^2. The use of FdCherenkovReplacer gave better agreement between the calculation of the amount of Cherenkov radiation produced by an air shower in two detector data chains when the Cherenkov profile on the air shower track was likely to have been incorrectly calculated by one of the data chains. However, the agreement between the Gaisser Hillas parameters and the initial energy of the cosmic ray were only improved when the shower was pointed towards the detector and a small number of data points was recorded by a detector. In these two cases the amount of Cherenkov light recorded by a detector was large, otherwise the calculation of these parameters is more dependent on the detector 'seeing' the air shower maximum in the longitudinal profile.