Chapter 7

Analysis of the Stereo Event recorded on the 26th of June 2004

On the 26th of June 2004 at 03:38 (UTC) an event was recorded by the Los Leones and Coihueco detectors that had a shower axis geometry of 72° zenith, -57° azimuth as can be seen in Figure 7.1. The initial energy of the cosmic ray was found to be 6.2 x 10^{19} eV, as calculated from the data collected by the Los Leones detector. The event recorded at the GPS second of 772256331 has a special geometry because the Coihueco detector views the shower head on. The amount of direct Cherenkov light recorded by that detector is comparable to the amount of fluorescence light recorded by the detector and cannot be accurately accounted for with the iterative procedure used by the Offline software. FdCherenkovReplacer was used to gain a more accurate measurement of the amount of Cherenkov light present in the signal recorded by the Coihueco detector.

When an event has been recorded in stereo the reconstruction of the shower size profile between two detectors will be in good agreement if the values of the atmospheric profile, air shower geometry and detector calibration that were applied to the data were correct. The Offline software is expected to have an accuracy between two reconstruction chains of 20 g/cm^2 for X_{max}, and 10% for N_{max} and the inital energy of the cosmic ray. For the event at the 772256331 GPS second the shower size profiles do not agree within this margin of error when FdCherenkovReplacer is used, so the calculated geometry

Event recorded on the 26th of June at 03:38 (UTC)
Shower Zenith 72°
Shower Azimuth −57°

	Distance from detector to X_{max}	Distance from detector to Core
Los Leones detector	40 880 m	23 000 m
Coihueco detector	68 130 m	36 120 m

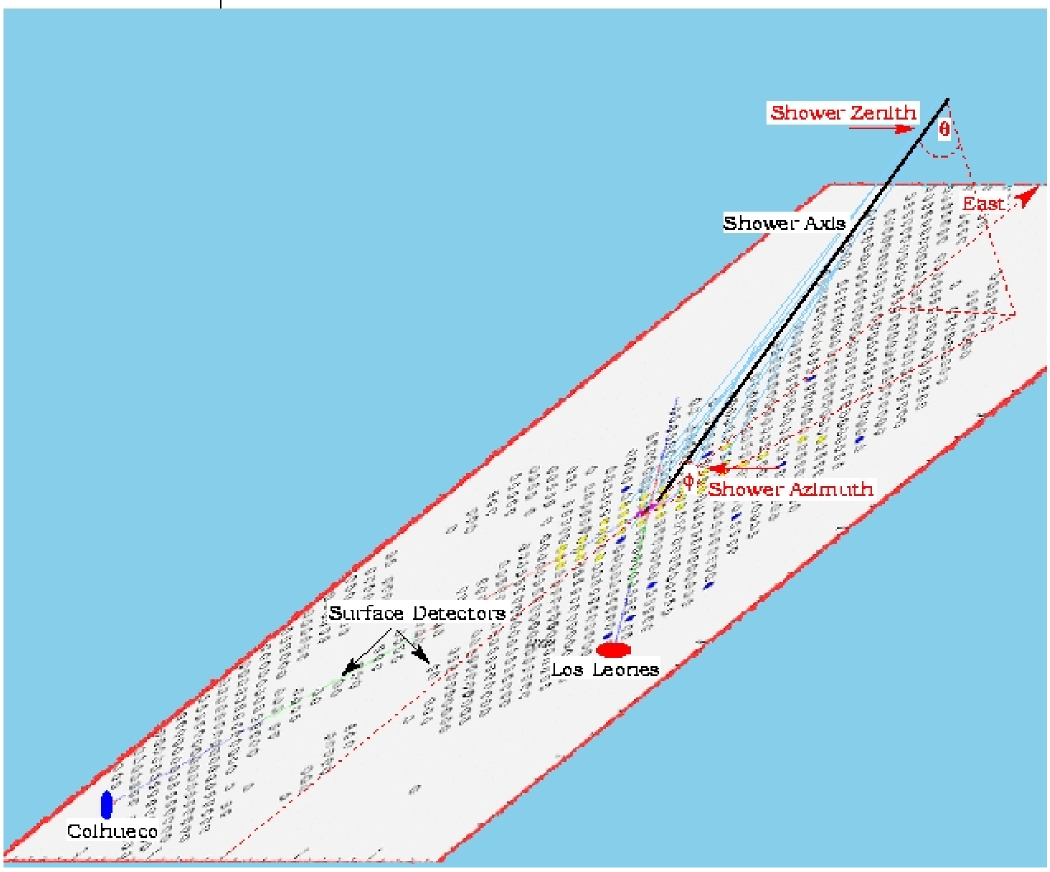

Figure 7.1: A schematic diagram of the event that shows how the shower is directed at the Coihueco detector, thereby causing the signal recorded by the Coihueco detector to be swamped with direct Cherenkov light. The shower geometry angles, θ and ϕ are also shown.

and assumed atmospheric scattering parameters are both suspect. The event analysis was run for a range of atmospheric aerosol concentrations and the geometry was adjusted through a range of values. Within the shower detector plane, (see Chapter 2) the angle χ_0 describes the tilt or angle of the shower axis. The amount of Cherenkov light contamination recorded by a detector will be most sensitive to the χ_0 parameter, rather than the tilt of the SDP itself. This parameter was adjusted by a value $\Delta\chi_0$ in the data reconstructed by the Coihueco detector to account for error present in the calculation of the air shower axis geometry within the SDP. The expected error in χ_0 has a typical upper limit of $\sim 0.5°$ [74] and the geometry of the air shower within the Coihueco SDP was varied by twice this amount. These adjustments were performed on the event for two Cherenkov parameterisations, the Hillas Model and the Nerling Model as described below. The effect the two different types of Cherenkov parameterisations have on the reconstruction of the event at the 772256331 GPS when the shower axis is adjusted and the aerosol scattering parameters are changed is described in Section 3.

1 Different Cherenkov Models of the Offline

The Cherenkov models used in the Offline reconstruction software of the Pierre Auger Project describe the angular distribution and energy spectrum of the charged particles present in a cascade. Once the angular distribution of charged air shower particles is known the angular distribution of the Cherenkov light generated by an air shower can be found from the known angular size of the Cherenkov cone of light [45]. The charged particle energy spectrum will define the fraction of shower particles above the Cherenkov threshold energy, and allow the calculation of the light flux. To generate a parameterisation of Cherenkov light, Hillas used a Monte Carlo simulation to study the particle density profile of an EAS, and to complement his study the Offline software uses the data recorded by the Fly's Eye detector to calculate the electron angular distribution. Nerling parameterised the Cherenkov spectrum from the data produced by the CORSIKA code to generate both the angular dependence and particle energy spectrum.

1.1 The Hillas Model

In 1982 Hillas [47] [48] performed a Monte Carlo simulation to study the development of electron-photon cascades in air including the energy spectrum of the shower particles. He examined the relationship between a cascade and the Cherenkov radiation it produces. This was performed for different shower ages and for various primary cosmic ray energies. Hillas modeled the interactions of the particles until their energy fell below 1 MeV, although since the purpose of the study was to determine the properties of air shower induced Cherenkov light, only particles with an energy exceeding 20 MeV were of interest. Nuclear and atomic scattering were treated separately and the parameterisation was through the shower age, s, not the initial energy of the cosmic ray. The normalised integral energy spectrum of the charged air shower particles can be described as the ratio of the total track length of all the charged particles in the shower with a kinetic energy above, E, to the total vertical component of the track length of all the charged particles in the shower. This can be parameterised, and is used by Auger, with,

$$T\left(E\right) = \left(\frac{0.89E_0 - 1.2}{E_0 + E}\right)^s \left(1 + 10^{-4}sE\right)^{-2} \tag{7.1}$$

$E_0 = 44 - 17(s - 1.46)^2$ if $s \geq 0.4$ or $E_0 = 26$ if $s < 0.4$. Then the total track length, TT(E), of all particles, N_e, with energy greater than, E, within a vertical thickness of dx can be defined as,

$$TT(E) = N_e T(E) dx \tag{7.2}$$

This parameterisation describes the energy spectrum of the charged particles present in an air shower in a way that is independent of atmospheric depth.

Hillas then proposed fits to the angular distribution of charged particles in an extensive air shower, however, the results used by the Offline are those which were found experimentally by Baltrusaitis et al. (1987) [75] after studying the stereo events measured with the Fly's Eye detector. The distribution was based on the threshold energy of Cherenkov radiation E_{thr} which is dependent on the refractive index of the medium,

$$\frac{dn}{d\theta} = \frac{1}{0.83E_{thr}^{-0.67}} \exp\left(\frac{-\theta}{0.83E_{thr}^{-0.67}}\right) \tag{7.3}$$

1.2 The Nerling Model

Nerling et. al. [46] generated a new parameterisation that described the number of Cherenkov photons, dN_γ, produced per slant depth, dX in an air shower at an atmospheric depth of X through the integral,

$$\frac{dN_\gamma}{dX}(X) = \int_{\ln E_t}^{\infty} N(X)\, y_\gamma(h,E)\, f(X,E)\; d(\ln E) \tag{7.4}$$

Where,

- $N(X)$ is the number of charged particles present in the shower as a function of atmospheric depth and was taken from the profile produced by CORSIKA.
- $y_\gamma(h,E)$ is the yield of the number of Cherenkov photons produced by a single charged particle with energy E at an altitude h.
- E_t is the local Cherenkov energy threshold, below which Cherenkov radiation will not be produced. This energy depends on the refractive index of air at the height of the air shower.
- and, $f(X,E)$ is the normalised differential electron energy spectrum at an atmospheric depth of X,

$$f(X,E) = \frac{dN}{(N\, d\ln E)} \tag{7.5}$$

Nerling compared the electron energy spectrum produced by CORSIKA with the parameterisation calculated by Hillas [47] and found the Hillas parameterisation of Cherenkov light production was larger than the CORSIKA Cherenkov profile by ∼5%. He then generated a new electron energy parameterisation that fit the longitudinal Cherenkov profile generated by CORSIKA to within 1-2%. The new parameterisation of the electron energy spectrum was,

$$f_{para}(s,E) = a_0 \frac{E}{(E+a_1)(E+a_2)^s} \tag{7.6}$$

s is the shower age parameter, and a_1 = 6.879 - 2.029·s, a_2 = 122.0 when E is in MeV.

Nerling [76] found that the angular distribution of air shower particles was dependent on two separate parameters, the shower age, s, and the refractive index of air which is itself dependent on height. The parameterisation based on the shower age was found to be described by some third order polynomials $A(s)$ and $B(s)$ which were fitted to spectra output by CORSIKA. The height dependence of the angular distribution was found to be described by two exponential factors, θ_{cc} and the Cherenkov angle θ_c (see Equation 2.5), which are parameterisations of the energy threshold, E_{thr} of Cherenkov radiation. The energy threshold of Cherenkov radiation is dependent on the refractive index of the medium containing the emitting particle. Since this is the atmosphere, the refractive index of air, and hence θ_c and θ_{cc} are dependent on the height of the emitting radiation. The parameterisation of θ_c and θ_{cc} which best fit the data generated by CORSIKA were,

$$\theta_c(h) = 0.627\, E_{thr}^{-0.606} \tag{7.7}$$

$$\theta_{cc}(h) = 10.509 - 4.964\, \theta_c(h) \cdot s \tag{7.8}$$

Together the shower age factors and the height dependent factors describe the angular distribution of Cherenkov light in an air shower, $\frac{dN_\gamma}{d\theta}$, to be

$$\frac{dN_\gamma}{d\theta} = \frac{A(s)}{\theta_c} \exp\left(-\frac{\theta}{\theta_c}\right) + \frac{B(s)}{\theta_{cc}} \exp\left(-\frac{\theta}{\theta_{cc}}\right) \tag{7.9}$$

2 The Light Profile in the Coihueco Detector

We now study the analysis of the event shown in Figure 7.1. The plots shown in Figure 7.2 show the number of photons, per unit telescope diaphragm area, that have been recorded by the Coihueco detector for the event that occurred at a GPS second of 772256331 as a function of time. This total light is further broken down into the different components of light the Offline software has calculated, which are the total fluorescence light, the direct Cherenkov light and the amount of Cherenkov light scattered toward the detector due to Rayleigh and Mie scattering. The time on the x-axis refers to the number of nanoseconds that have passed since an arbitrary trigger time. In Figure 7.2 (i) you can see that the amount of Cherenkov light calculated by the Offline software from the light collected by the Coihueco detector is incorrect, as this plot indicates that the amount of direct Cherenkov light measured by the Coihueco detector is negative. In the next plot, Figure 7.2 (ii) FdCherenkovReplacer has been

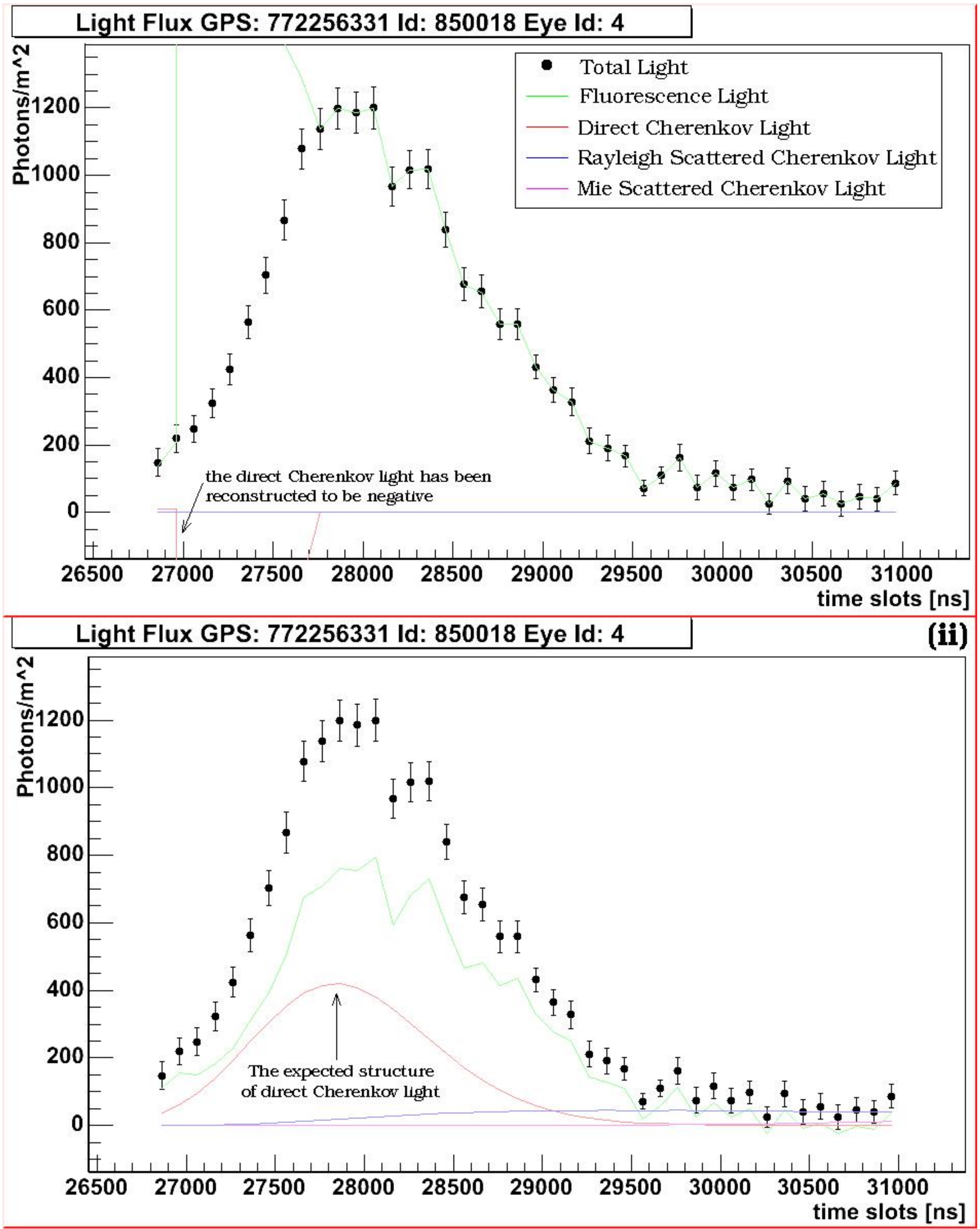

Figure 7.2: The light profiles of the event at the 772256331 GPS second without FdCherenkovReplacer (i) and with FdCherenkovReplacer (ii). Showing all the different Cherenkov profiles recorded by the detector.

used to generate the amount of Cherenkov light collected by the Coihueco detector. In this plot the direct Cherenkov light has the expected structure and is comparable to the amount of fluorescence light collected by the detector.

3 Reconstruction of the Energy Parameters

The event recorded at the 772256331 GPS second was reconstructed using the FdCherenkovReplacer function for the two different Cherenkov parameterisations, when the geometry of the event within the Coihueco SDP was varied and the assumed atmospheric aerosol concentrations were adjusted. The geometry of the axis calculated by the Coihueco detector was adjusted around the nominal χ_0 by a range of $\Delta\chi_0$ values, because the direct Cherenkov light seen by the Coihueco detector is very bright and is tightly contained around the air shower axis, so it will be very sensitive to small changes in the shower axis geometry. So if the calculation of the geometry of the shower axis within the SDP of the Coihueco data chain was incorrect by even a small amount, the reconstruction of X_{max}, N_{max} and energy will be noticeably affected. At the same time the aerosol concentrations were varied from very 'dirty' to very 'clear' by keeping the vertical aerosol scale height constant at 1 km and changing the horizontal aerosol attenuation length, which are the natural parameters used by the Offline. This accounted for that fact that no measurement of the aerosol concentration of the atmosphere was taken by the laser or LIDAR monitoring systems on the night of the shower. Figures 7.3 - 7.8 present density plots which show the difference in the reconstruction of the Gaisser Hillas parameters and the energy of the cosmic ray, between the Los Leones and Coihueco data chains for the various geometry adjustments and aerosol concentrations. It has been found that the Offline reconstruction software is accurate to around 20 g/cm^2 in the reconstruction of X_{max} and within 10% of the reconstruction of N_{max} and the initial energy of the cosmic ray between two detector data chains.

3.1 Reconstruction of X_{max}

The parameter X_{max} describes the slant depth in g/cm^2 where the maximum number of charged particles occurred during the development of an air shower. This parameter is defined when fitting the Gaisser-Hillas function (see Chapter

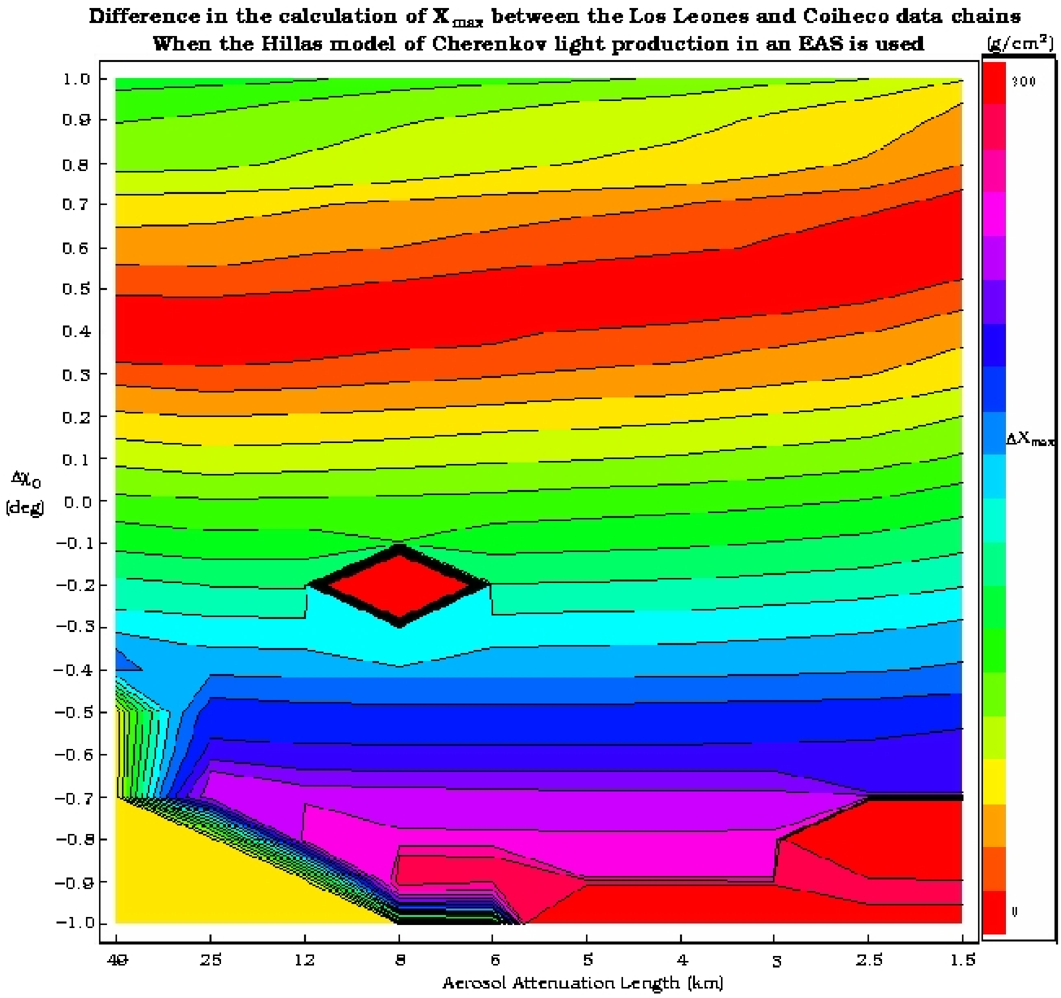

Figure 7.3: Plots of the difference in the reconstruction in X_{max} between the data collected by the Los Leones and Coihueco detectors for the combinations of the variations of aerosol concentration and geometry that have been placed on the shower reconstruction. The Hillas model of Cherenkov production was used. The shower geometry within the Coihueco SDP was varied by $-1.0° < \Delta\chi_0 < 1.0°$ and the aerosol concentration was varied through 1.5 km $< \Lambda_a(\lambda) <$ 49 km as defined at sea level.

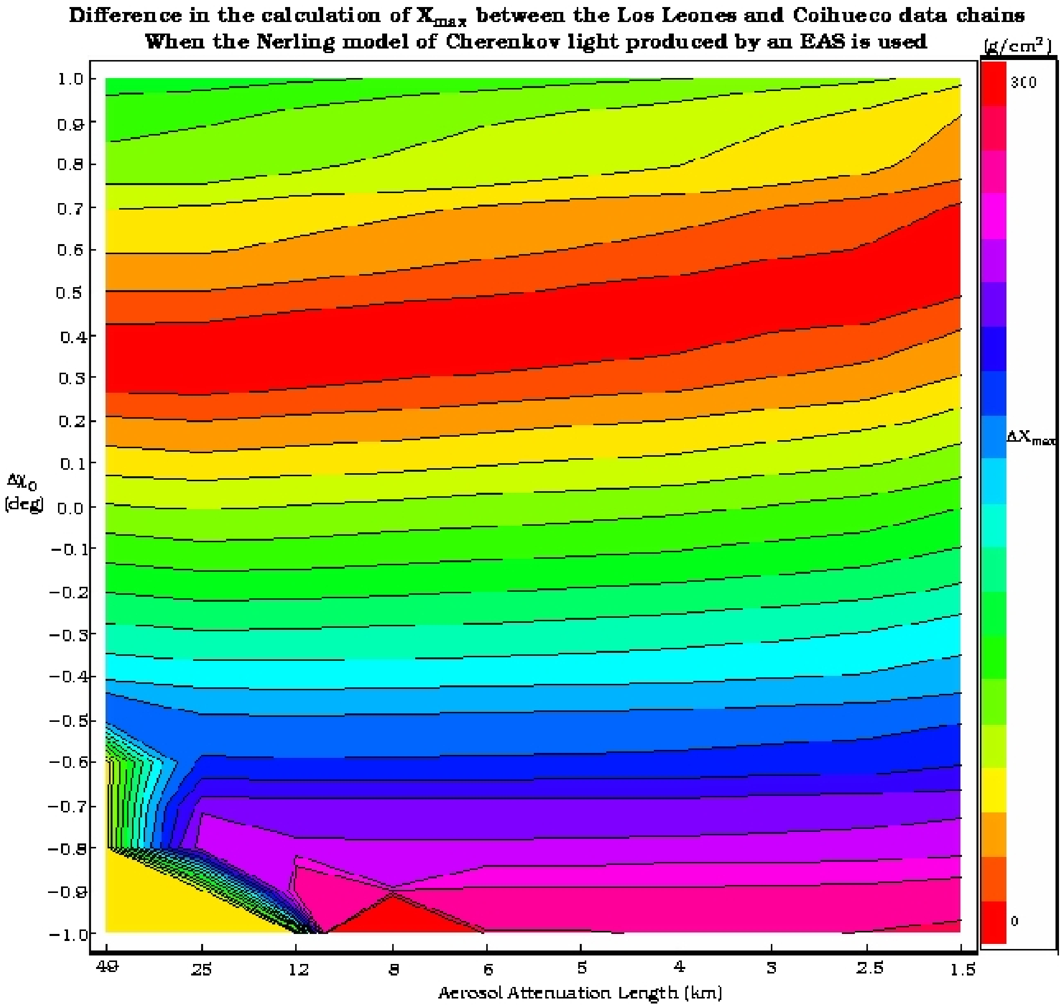

Figure 7.4: Plots of the difference in the reconstruction in X_{max} between the data collected by the Los Leones and Coihueco detectors for the combinations of the variations of aerosol concentration and geometry that have been placed on the shower reconstruction. The Nerling model of Cherenkov production was used. The shower geometry within the Coihueco SDP was varied by $-1.0° < \Delta\chi_0 < 1.0°$ and the aerosol concentration was varied through 1.5 km $< \Lambda_a(\lambda) < 49$ km as defined at sea level.

Aerosol Attenuation Length (km)	X_{max} (g/cm^2)	N_{max} (particles)	Energy (eV)
49	753	3.6×10^{10}	5.8×10^{19}
25	752	3.6×10^{10}	5.7×10^{19}
12	751	3.6×10^{10}	5.8×10^{19}
8	751	3.7×10^{10}	5.9×10^{19}
6	751	3.8×10^{10}	6.0×10^{19}
5	751	3.9×10^{10}	6.2×10^{19}
4	751	4.0×10^{10}	6.4×10^{19}
3	752	4.2×10^{10}	6.8×10^{19}
2.5	754	4.5×10^{10}	7.2×10^{19}
1.5	757	5.3×10^{10}	8.5×10^{19}

Table 7.1: This table documents the X_{max}, N_{max} and Energy values found by the Los Leones data chain for the event that occurred at the GPS second of 772256331 for the 10 values of the horizontal aerosol attenuation length simulated in the test. These values were the same when either parameterisation of Cherenkov light production was used. The $\Lambda_a(\lambda)$ are defined at sea level.

2) and it provides information on the composition of the primary cosmic ray. The values of X_{max} as found from the Los Leones reconstruction chain for the various horizontal aerosol attenuation lengths are quoted in Table 7.1. An error of $20g/cm^2$ on X_{max} can be assumed to be the error on all the values of X_{max} quoted in this Chapter.

The plots shown in Figures 7.3 and 7.4 display the modulus of the difference in the calculation of X_{max} by the Los Leones reconstruction chain (X_{maxLL} in Table 7.1) and that found by the Coihueco reconstruction chain (X_{maxCo} in Appendix C).

$$\Delta X_{max} = \mid X_{maxCo} - X_{maxLL} \mid \tag{7.10}$$

These values are for variations in the horizontal aerosol attenuation length of $\Lambda_a(\lambda)$ = 1.5 km to $\Lambda_a(\lambda)$ = 49 km as defined at sea level, when the scale height was fixed to 1 km and when the shower axis geometry within the SDP, as has been calculated by the Coihueco data chain, was varied around the parameter χ_0 by -1.0° < $\Delta\chi_0$ < 1.0°. See Appendix B for the conversion to the $VAOD$ defined from the height of the detector. Above $\Delta\chi_0$ = 0.4° the values of X_{max} reconstructed by the Los Leones data chain were larger than those calculated by the Coihueco data chain, but the modulus of the difference in the reconstruction of X_{max} are plotted in Figures 7.3 and 7.4 to emphasize any minimuma around $\Delta\chi_0 = 0$.

Using the Hillas Model to describe the amount of Cherenkov light produced by an air shower (Figure 7.3) I found,

- A minimum at $\Delta\chi_0 = 0.4°$ for all values of horizontal aerosol attenuation length.
- The difference in the calculation of X_{max} between the two detector data chains has very little dependence on the aerosol concentration, especially at low concentrations.
- At the point $\Lambda_a(\lambda) = 8$ km, $\Delta\chi_0 = -0.2°$, a failure occurred in the calculation of X_{max} by the Coihueco data chain.
- When $\Delta\chi_0 < -0.8°$ and the aerosol concentrations are large ($\Lambda_a(\lambda) < 5$ km) the calculation of X_{max} by the Coihueco data chain tends to fail. This indicates that this adjustment of the geometry of the air shower is too far away from the true air shower geometry within the SDP.
- A secondary minimum occurs at $\Delta\chi_0 < -0.8°$ and $\Lambda_a(\lambda) > 5$ km, but this adjustment of χ_0 caused the calculation of X_{max} to fail in the Coihueco detector when $\Lambda_a(\lambda) < 5$ km, and so this minimum is questionable.

Using the Nerling Model that describes the amount of Cherenkov light produced by an air shower (Figure 7.4) I found,

- A minimum for all values of the horizontal aerosol attenuation length at the same place as that found when the Hillas model of Cherenkov light production is used, when $\Delta\chi_0 \sim 0.4°$.
- The same lack of dependence on $\Lambda_a(\lambda)$ as was seen when the Hillas model was used.
- At the point $\Lambda_a(\lambda) = 8$ km, $\Delta\chi_0 = -1.0°$, a failure occurred in the calculation of X_{max} by the Coihueco data chain.
- A minimum at $\Delta\chi_0 < -0.8°$ and $\Lambda_a(\lambda) > 12$ km, as was found when the Hillas model was used.

The difference in the calculations of X_{max} between the two detector data chains shows very little dependence on the type of Cherenkov model used to determine the amount of Cherenkov light produced by an air shower. The only difference is that when using the Nerling model, we have more values where the calculation of X_{max} has not failed in the Coihueco data chain. The minimum at $\Delta\chi_0 = 0.4°$ of $\Delta X_{max} \sim 1\ g/cm^2$ (see Appendix C and Table 7.1) indicates that the geometry within the SDP was incorrectly calculated by the Coihueco data chain by 0.4°. A secondary minimum that exists when $\Delta\chi_0 < -0.8$ and the aerosol concentration is low, is questionable due to the fact, that at this adjustment of the geometry within the SDP, the reconstruction of X_{max} by the Coihueco data chain tends to fail for large aerosol concentrations.

When different aerosol parameters are applied to the data, no large effect is observed in the difference in the calculation of X_{max} between the two detector data chains. Now, if the aerosol concentration applied to the reconstruction chain is changed, the light profile recorded by a detector will become skewed, due to the vertical non-uniformity of atmospheric aerosol density. For two detectors that view an event, the degree of skewness will be in the same direction, but with different magnitudes. However, this effect will only be pronounced when the event-detector distance is significantly different, or the aerosol concentration is very high, hence Figures 7.3-7.4 show a very slight dependence on the horizontal aerosol attenuation length at high aerosol concentrations.

3.2 Reconstruction of N_{max}

N_{max} describes the maximum number of charged particles that occurred during the development of an air shower. As with the parameter X_{max}, N_{max} is defined by the Gaisser-Hillas function and gives a rough estimation of the size of an air shower. The values of N_{max} calculated by the Los Leones data chain for the various horizontal aerosol attenuation lengths are in Table 7.1. The error on N_{max} of 10% is the error on all the quoted values of N_{max} in this Chapter.

Shown in Figures 7.5 and 7.6 are the relative values of the modulus of the difference in the reconstruction of N_{max} between the data recorded by the Los Leones detector (shown in Table 7.1) and that recorded by the Coihueco detector (see Appendix C) and are found through,

$$\frac{\Delta N_{max}}{N_{max}} = \frac{\mid N_{maxCo} - N_{maxLL} \mid}{N_{maxCo}} \tag{7.11}$$

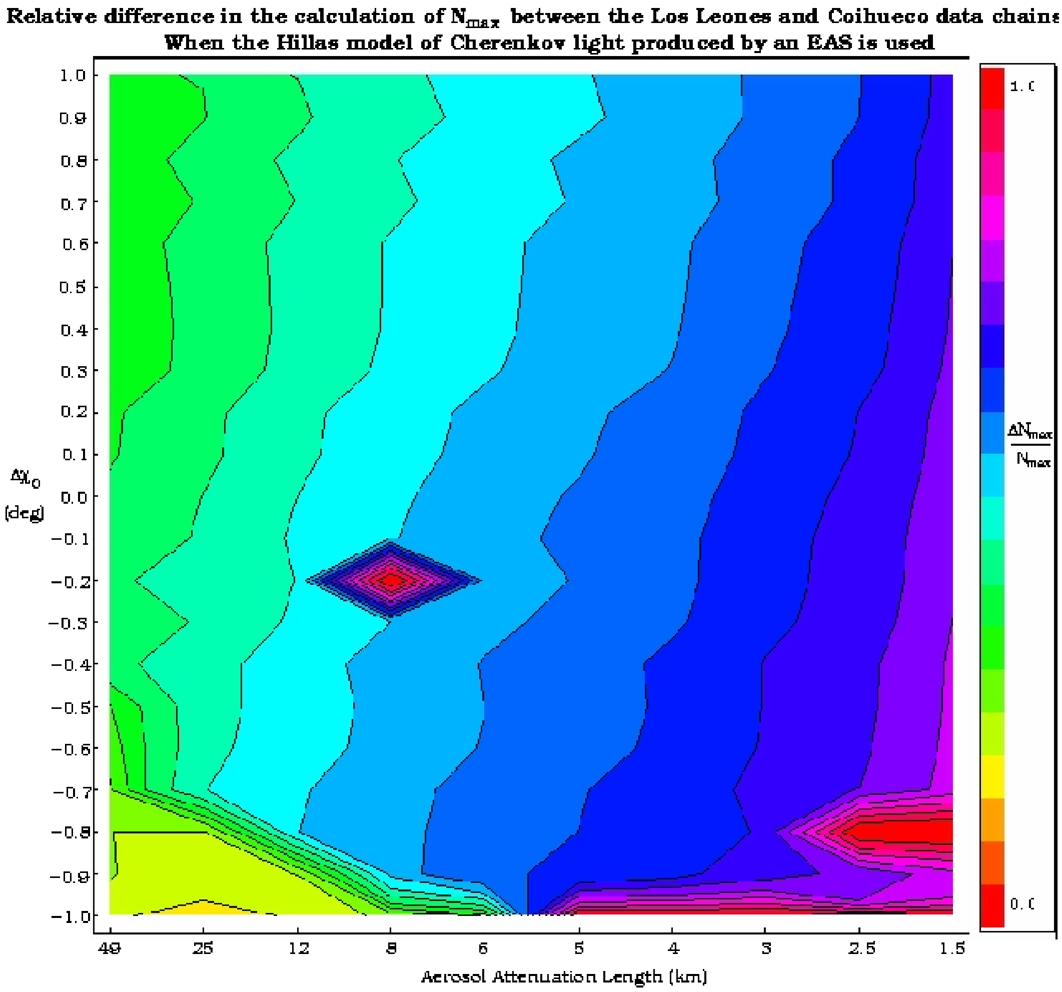

Figure 7.5: Plots of the difference in the reconstruction in N_{max} between the data collected by the Los Leones and Coihueco detectors for the combinations of the variations of aerosol concentration and geometry that have been placed on the shower reconstruction. The Hillas model of Cherenkov production was used. The shower geometry within the Coihueco SDP was varied by $-1.0° < \Delta\chi_0 < 1.0°$ and the aerosol concentration was varied through 1.5 km $< \Lambda_a(\lambda) <$ 49 km as defined at sea level.

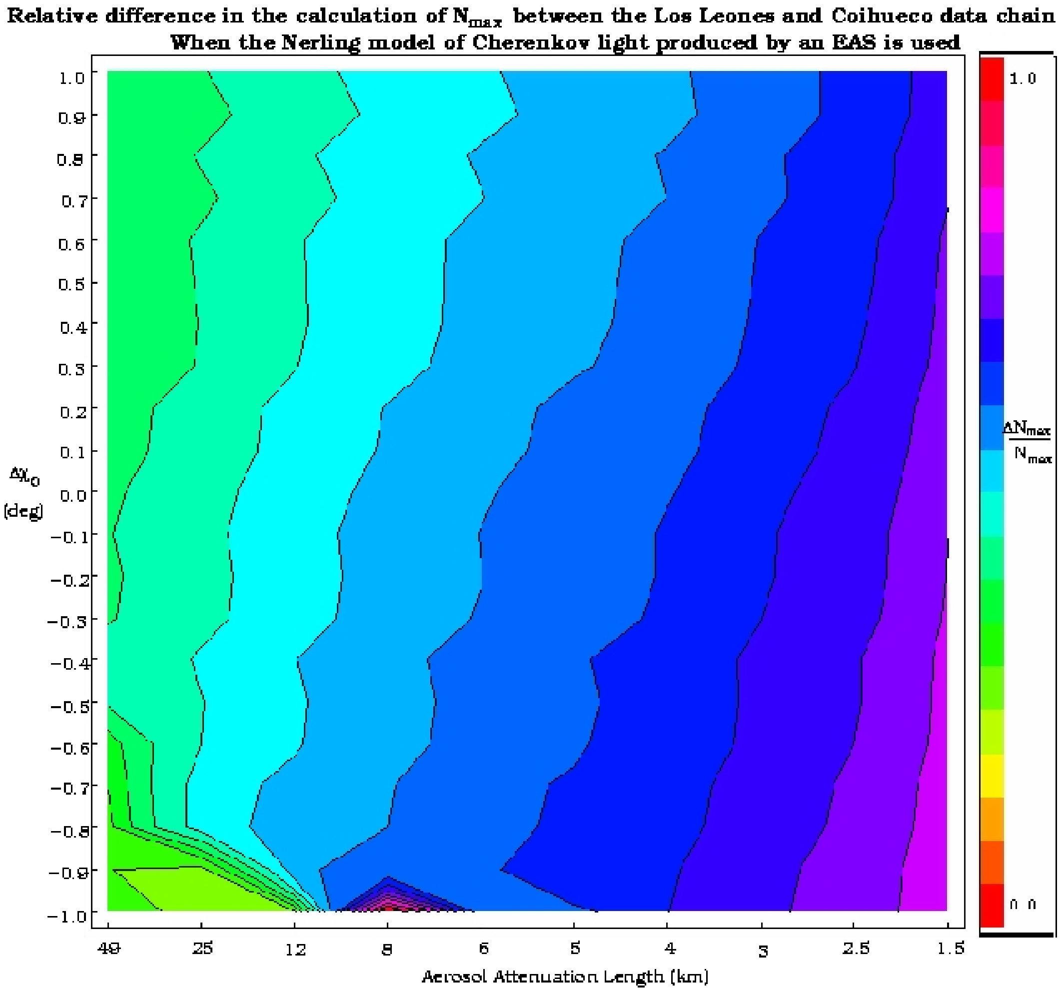

Figure 7.6: Plots of the difference in the reconstruction in N_{max} between the data collected by the Los Leones and Coihueco detectors for the combinations of the variations of aerosol concentration and geometry that have been placed on the shower reconstruction. The Nerling model of Cherenkov production was used. The shower geometry within the Coihueco SDP was varied by $-1.0° < \Delta\chi_0 < 1.0°$ and the aerosol concentration was varied through 1.5 km $< \Lambda_a(\lambda) <$ 49 km as defined at sea level.

N_{maxCo} is the value of N_{max} calculated from the data recorded by the Coihueco data chain and is always larger than the value of N_{maxLL} calculated by the Los Leones data chain. These values are for aerosol concentrations that have been varied through $\Lambda_a(\lambda) = 1.5$ km (dirty) to $\Lambda_a(\lambda) = 49$ km (clear) as defined at sea level, when the scale height was fixed to 1 km. See Appendix B for the conversion to the $VAOD$ defined from the height of the detector. The shower axis geometry within the SDP, as has been calculated by the Coihueco data chain, was varied around the parameter χ_0 by -1.0° < $\Delta\chi_0$ < 1.0°.

Using the Hillas Model that describes what the amount of Cherenkov radiation produced by an air shower will be (Figure 7.5) I found,

- The density plot of the relative difference in the calculation of N_{max} lies between 0.16 and 0.80, see Appendix C and Table 7.1, these values are outside the degree of accuracy expected for the reconstruction software.
- If we exclude values where the calculation of N_{max} by the Coihueco data chain have failed then, when $\Delta\chi_0 > 0.2°$ and the horizontal aerosol attenuation length is 49 km a minimum is observed.
- There is only a very small dependence on $\Delta\chi_0$, in the difference in the calculation of N_{max}.
- A failure occurred in the calculation of N_{max} by the Coihueco data chain at the point $\Lambda_a(\lambda) = 8$ km, $\Delta\chi_0 = -0.2°$.
- The calculation of N_{max} by the Coihueco detector tends to fail when $\Delta\chi_0 < -1.0°$ and the aerosol concentrations are very large ($\Lambda_a(\lambda) < 5$ km). This implies this adjustment of the geometry of the air shower was too far away from what the actual geometry of the air shower was within the Coihueco SDP.

Using the Nerling Model that describes the amount of Cherenkov light that will be produced by an air shower (Figure 7.6) I found,

- As for the Hillas model, the range of values of the relative difference in the calculation of N_{max} between the two data chains are outside the degree of accuracy expected for the reconstruction software and are between 0.24 to 0.80 (see Appendix C and Table 7.1).

- Again, only a slight dependence in $\Delta\chi_0$ is observed.

- When $\Delta\chi_0 > -0.2°$ the same minimum is found as when the Hillas model of Cherenkov light production is used, when the horizontal aerosol attenuation length is 49 km.

- At the point $\Lambda_a(\lambda) = 8$ km, $\Delta\chi_0 = -1.0°$, a failure occurred in the calculation of N_{max} by the Coihueco data chain.

The difference in the calculations of N_{max} between the two detector data chains shows very little dependence on the type of Cherenkov model used to determine the amount of Cherenkov light produced by an air shower as was seen for the parameter X_{max}. Using the Nerling model the Offline software reconstructs less failed values of N_{max} from the Coihueco data chain. There is a very small effect on the difference in the calculation of N_{max} between the two detector data chains when the geometry is adjusted in the Coihueco detector data chain. When we adjust the geometry of the air shower within the SDP of the Coihueco data chain the position of the direct Cherenkov profile shifts in depth but changes in size only slightly. So the effect of changing the geometry of the air shower has less effect on the calculation of N_{max} than changes in the atmospheric scattering profile and so Figures 7.5-7.6 are more sensitive to changes in the horizontal aerosol attenuation length.

At the position of $\Delta\chi_0 = -1.0°, \Lambda_a(\lambda) > 12km$ a minimum is found. This minimum exists for both the Nerling and the Hillas parameterisations and is in the same spot as was found for X_{max}. For the same reason as this minimum was discounted in the plots of X_{max}, it is discounted here. The reason being that the geometry is too far away from whatever the correct air shower orientation within the Coihueco SDP was, hence the lowest value of the relative difference in the calculation of N_{max} is at $\Delta\chi_0 = 0.9°, \Lambda_a(\lambda) = 49$ km and is 0.34 for the Hillas Cherenkov model and about 0.39 for the Nerling model. These values are outside the expected error margin of the fluorescence detectors at the Pierre Auger Observatory. Thus either the calibration of the detector has been incorrectly applied or it is possible that the Cherenkov models used in the Offline software have underestimated the amount of direct Cherenkov light that was produced by this air shower.

3.3 Reconstruction of Initial Energy

The calculation of the initial energy of a cosmic ray is the final purpose of the Offline software. It is through the analysis of the energy spectrum of cosmic rays that the problem of cosmic rays will be solved. So it is crucial that the Pierre Auger Project can rely on the values of cosmic ray energy that are reconstructed by the Offline software. In this case the initial energy found by the Los Leones data chain are in Table 7.1 for the nine values of horizontal aerosol attenuation length, an assumed error of 10% lies on all the values of energy quoted in this Chapter.

Figures 7.7 and 7.8 show all the values of the modulus of the relative difference in the reconstruction of the cosmic ray's energy between the data recorded by the Los Leones detector, $Energy_{LL}$, to the reconstruction from the data recorded by the Coihueco detector, $Energy_{Co}$, so the plotted values were found from,

$$\frac{\Delta Energy}{Energy} = \frac{\mid Energy_{Co} - Energy_{LL} \mid}{Energy_{Co}} \tag{7.12}$$

The reconstruction of the initial cosmic ray energy was always larger when calculated by the Coihueco data chain. This is for aerosol concentrations that have been varied through the horizontal attenuation length by values of $\Lambda_a(\lambda)$ = 1.5 km to 49 km as defined at sea level, when the scale height was fixed at 1 km. See Appendix B for the conversion to the $VAOD$ defined from the height of the detector. χ_0 was varied through -1.0° $< \Delta\chi_0 <$ 1.0° in the Coihueco detector data chain.

The density plots generated for the difference in the calculation of the initial energy of a cosmic ray between the two detector data chains were very similar to those found for the N_{max} parameter, but the plots have more dependence on the variations in χ_0. This is because the calculation of the energy of a cosmic ray is very closely related to the N_{max} and the X_{max} parameters. The initial energy is found by integrating the shower size profile found for an event and this profile is fitted with a Gaisser-Hillas function, where the maximum number of particles present in an air shower is represented by N_{max} at the depth, X_{max}. However, all of the features seen in the density plots created for the N_{max} parameter are seen in the density plots created for the initial energy of a cosmic ray and the same conclusions can be drawn. As with the Gaisser

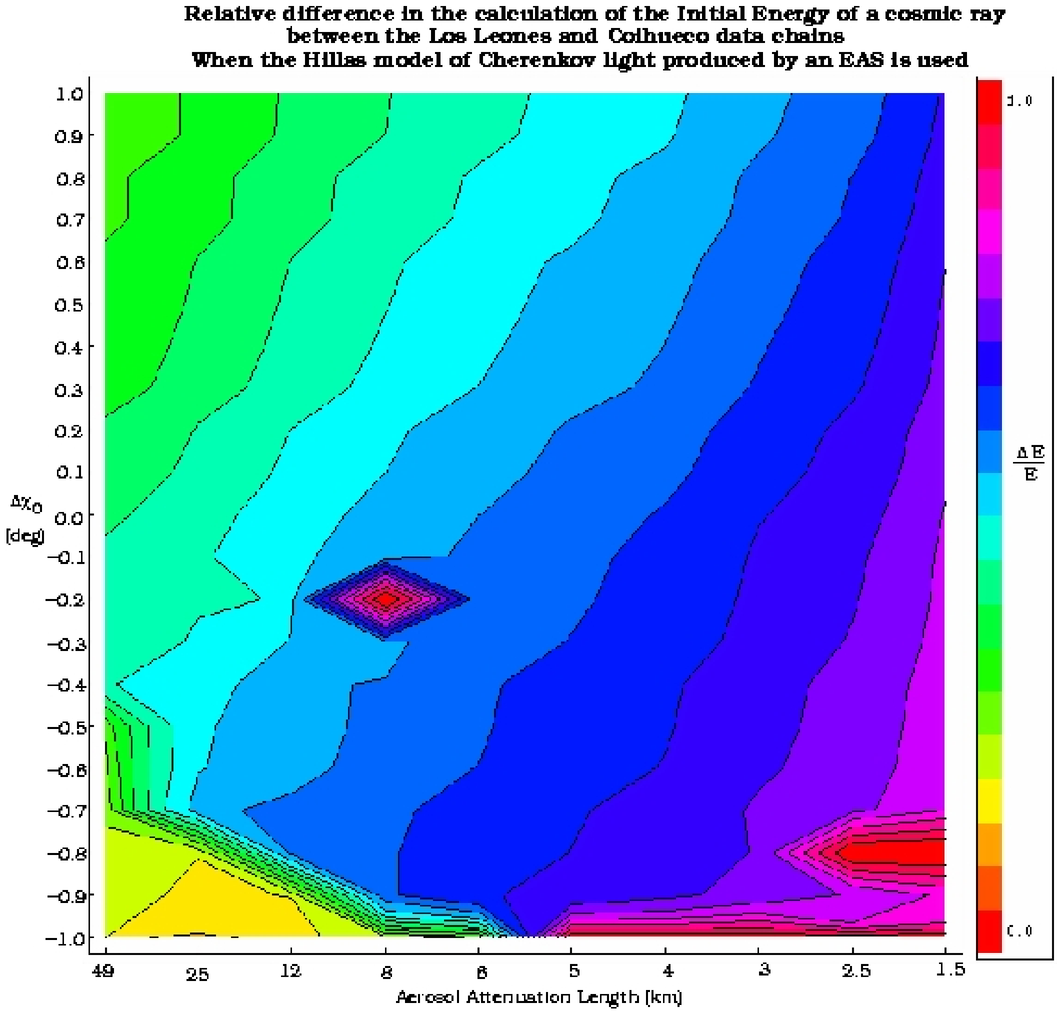

Figure 7.7: Plots of the difference in the reconstruction of the initial cosmic ray energy between the data collected by the Los Leones and Coihueco detectors for the combinations of the variations of aerosol concentration and geometry that have been placed on the shower reconstruction. The Hillas model of Cherenkov production was used. The shower geometry within the Coihueco SDP was varied by $-1.0° < \Delta\chi_0 < 1.0°$ and the aerosol concentration was varied through 1.5 km $< \Lambda_a(\lambda) <$ 49 km as defined at sea level.

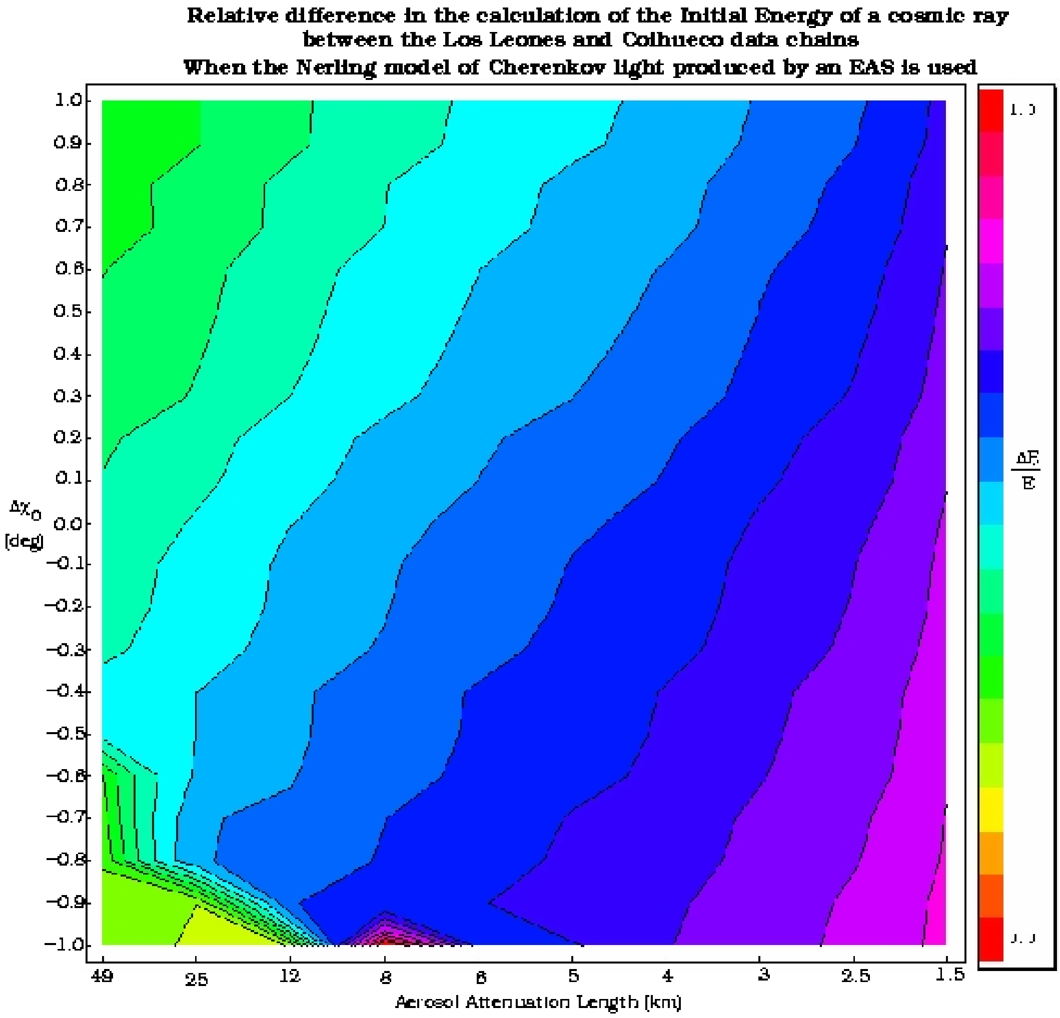

Figure 7.8: Plots of the difference in the reconstruction of the initial cosmic ray energy between the data collected by the Los Leones and Coihueco detectors for the combinations of the variations of aerosol concentration and geometry that have been placed on the shower reconstruction. The Nerling model of Cherenkov production was used. The shower geometry within the Coihueco SDP was varied by $-1.0° < \Delta\chi_0 < 1.0°$ and the aerosol concentration was varied through 1.5 km $< \Lambda_a(\lambda) <$ 49 km as defined at sea level.

Hillas parameters, the minimum at the point where $\Delta\chi_0 = -1.0°, \Lambda_a(\lambda) > 12$ km, is suspicious because this adjustment of the air shower geometry within the SDP of the Coihueco data chain is probably too different to whatever the correct air shower geometry was. The difference in the calculation of the initial energy of a cosmic ray between the two detector data chains has a minimum at 0.34 when the Nerling model is used and 0.30 when the Hillas model is used (see Appendix C and Table 7.1) which is not within the accuracy expected. It is possible that the Cherenkov models used are underestimating the amount of direct Cherenkov light that will be measured by a detector.

4 Other Events with a Large Direct Cherenkov Contamination

Aerosol concentrations are measured nightly using the project's Central Laser Facility (CLF). However, no measurement of the atmospheric aerosol concentration was taken on the night of event that occurred at a GPS second of 772256331. As a cross check on the Cherenkov reconstruction for events with a large amount of direct Cherenkov contamination, FdCherenkovReplacer was used on two other events. For these events the amount of direct Cherenkov light recorded by a detector is large, but a measurement of the atmospheric aerosol concentration had been taken on the night.

4.1 Event at the GPS second of 799040826

This event occurred on the 2nd of May 2005 at 03:46 (UTC). The air shower track was pointed towards the Los Leones detector and across the Coihueco detector, but was very far away from the Coihueco detector. The light profile recorded by the Coihueco detector was not of good quality as shown in Appendix D. The horizontal aerosol attenuation length was fixed at 19 km with a scale height of 1 km as defined at sea level, where this corresponds to a VAOD of 0.013 from the height of the detector. The reconstruction differences between the detectors are recorded in Appendix D where they are plotted against $\Delta\chi_0$. The smallest difference in the reconstruction of the energy parameters found by the data collected from the two detectors for both models of Cherenkov production are;

- X_{max}: using the Hillas model, the smallest difference was 10 g/cm^2 at $\Delta\chi_0 = 2.0°$ and using the Nerling model the smallest difference was 2.0 g/cm^2 at $\Delta\chi_0 > 1.9°$.

- N_{max}: using the Hillas model, the relative difference hovers at 0.45 before slowly ascending to 1.0 when $\Delta\chi_0 > 1.0°$. Using the Nerling model there is a minimum of 0.03 at $\Delta\chi_0 = 1.0°$ and above 1.4° the difference equals 1.0.

- Initial energy: using the Hillas model, the relative difference hovers at 0.45 before slowly ascending to 1.0 when $\Delta\chi_0 > 1.0°$. Using the Nerling model there is a minimum of 0.05 at $\Delta\chi_0 = 1.0°$ and above 1.4° the difference equals 1.0.

The light profile recorded by the Coihueco detector is of poor quality, hence the reconstruction of the Gaisser Hillas parameters and the initial cosmic ray energy for the Coihueco detector are not very reliable. The difference in the reconstruction of X_{max} between the two detectors indicates that the geometry of the air shower within the SDP may have been incorrectly calculated by the Los Leones detector by $\sim 2°$, but it may also mean that the reconstruction of X_{max} in the Coihueco detector is incorrect. Either way, this is quite a large adjustment to make to the calculation of the air shower geometry within the SDP and explains why the reconstruction of the energy parameters failed in the Los Leones detector for large adjustments of $\Delta\chi_0$. This still supports the results found for the event that occurred at the 772256331 GPS second as the difference in the reconstruction of X_{max} between the two detectors seems to highlight a miscalculation of the geometry of an air shower for the detector that recorded a large Cherenkov contamination.

4.2 Event at the GPS second of 770961669

This event occurred on the 11th of June 2004 at 04:00 (UTC). The air shower track was pointed towards the Coihueco detector, but away from the Los Leones detector. Hence the light profile recored by the Los Leones detector was not of good quality as can be seen in Appendix D, where the graphs of the difference in the reconstruction of the three parameters are also displayed. The horizontal aerosol attenuation length was fixed at 22km with a scale height of 1 km as defined at sea level, where this corresponds to a VAOD of 0.011 from the height of the detector. The smallest difference in the reconstruction of the energy parameters found by the data collected from the two detectors for both models of Cherenkov production are;

- X_{max}: using the Hillas model, the smallest difference was 8 g/cm^2 at $\Delta\chi_0 = 0.8°$ and using the Nerling model the smallest difference was 2 g/cm^2 at $\Delta\chi_0 = 0.7°$.
- N_{max}: using the Hillas model, the profile is incredibly flat at about 50% and using the Nerling model the profile is flat at around 50%.
- Initial energy: using the Hillas model, the profile is flat at a value of $\sim$0.50 and using the Nerling model the profile is flat at about 0.50.

There is very little that can be determined from this event because the reconstruction of the air shower light profile was so poor for the Los Leones detector. However, the structure seen in the plots of the difference in X_{max} does seem to confirm that seen for the event at the GPS second 772256331. The reconstruction of X_{max} is very dependent on the geometry of the air shower within the SDP, so when the size of χ_0 is adjusted in the Coihueco data chain by $\Delta\chi_0$ there is a very noticeable change in the difference in the reconstruction of X_{max} between the two data chains. However, the difference in the reconstruction of N_{max} and initial energy of the cosmic ray is always about twice as big in the Coihueco data chain compared to the Los Leones data chain, implying that the reconstruction of these parameters calculated for both detectors was incorrect.

5 Chapter Summary

For the event at the 772256331 GPS second the reconstruction of X_{max} has a very good agreement as found by the data collected from the detectors Los Leones and Coihueco when the geometry within the SDP had been adjusted around χ_0 in the Coihueco data chain by 0.4°. However, the relative difference in the reconstruction of N_{max} and the cosmic rays initial energy never fell below the expected error margin of 10% for every combination of $\Delta\chi_0$ and $\Lambda_a(\lambda)$ that was applied to the reconstruction chain.

The two events that were similarly contaminated by direct Cherenkov light showed similar results. The difference in the reconstruction of X_{max} was highly dependent on the calculation of the geometry of the air shower within the SDP and at a specific value, good agreement between the two data chains was reached. For N_{max} and the initial cosmic ray energy, there was always a disagreement between the two data chains that was greater than the expected accuracy of the detectors. However, for these events, the light profiles recorded by the detectors not swamped with direct Cherenkov light were of very poor quality and the reconstruction of the Gaisser Hillas parameters and the initial cosmic ray energy calculated from these light profiles may not be reliable.

Chapter 8

Conclusion

The question of the origin of cosmic rays has been pondered for almost 100 years. The only aspect of this question that has changed in this time is the energy of the particles in question. As the mystery of cosmic rays at lower energies was solved, new detection methods have been discovered that have pushed the energy at which astronomical objects must be able to accelerate particles to, up to the current limit of 10^{20} eV. This is the macroscopic energy a baseball has when pitched at $\sim$50 km/hr, all contained by one subatomic particle.

To solve this mystery about the origin of cosmic rays we require detailed knowledge of their anisotropy, composition and energy spectrum. The popular origin of ultra high energy cosmic rays is within the lobes of a radio galaxy, gigantic structures, thrown up by the accretion disk of a rotating massive black hole. Other origin theories favor black holes themselves as the source of cosmic rays and some theories support the decay of relics of the big bang, massive particles trapped in space and time. The Pierre Auger Observatory that has been built in Argentina will be able to collect the largest body of high energy events ever recorded by one cosmic ray detector. This increase in the statistics is expected to further the knowledge of the three aspects of cosmic rays and provide the answer to their origin.

The Pierre Auger Observatory uses the cascade of particles initiated by the collision of a cosmic ray with an atmospheric nucleus to detect the primary cosmic ray. This air shower generates an enormous number of charged particles that traverse the atmosphere creating secondary effects as they pass. Atmospheric nitrogen is excited by the passage of this 'extensive air shower' and will fluoresce in the UV. Muons and electrons that survive the atmosphere slam into the Earth as a thin front of the air shower reaches the ground. The fluorescence detectors of the Pierre Auger project can record the brief flash of UV light generated by the air shower and an array of detectors spread over the surface of the Earth record the front of the air shower itself.

Reconstructing the arrival direction, composition and energy of a primary cosmic ray from the data recorded by a fluorescence detector relies on the accurate knowledge of the geometry of the air shower axis, the scattering properties of the atmosphere and the amount of Cherenkov light that is also created by the particle beam. When a cosmic ray has an energy that exceeds 10^{19} eV it may be recorded in stereo, by two of the fluorescence detectors of the project. This stereo recording intrinsically contains the atmospheric scattering properties of the atmosphere and the amount of Cherenkov light produced by an air shower.

To reduce the error on the calculation of the initial properties of a cosmic ray when the scattering properties of the atmosphere are not known, the program AerosolMin was written. This program compared the reconstruction of the light emitted at the air shower as calculated from two detectors as these profiles should be the same. When the profiles differ in magnitude, the atmospheric aerosol concentration parameters can be changed to find the value of these parameters where the profiles do agree. The first version of AerosolMin was written to be compatible with the Flores reconstruction software and was used on a series of simulated events and determined that only the highest energy events that fell within 34 km of a detector had signal to noise ratios that were high enough for this technique to be used. An updated version of AerosolMin was used on all the stereo events that occurred from January 2004 to October 2005, but only two were of a high enough energy to be able to use this technique, and one of those events was highly contaminated with Cherenkov light On the night of the event that occurred at a GPS second of 799137161 it was found that a layer of fog lay between the Los Leones detector and the event that the simplistic model of aerosol production currently used by the Offline software was unable to describe.

The Cherenkov profiles emitted by an air shower should be consistently reconstructed between the detector reconstruction chains that record an event. When they are not, for stereo events it is most likely that only one of the detector data chains will have reconstructed the profile incorrectly. In this case the Cherenkov profile that was incorrectly reconstructed can be replaced by the Cherenkov profile calculated by another detector by using a program called FdCherenkovReplacer. Cherenkov profiles were found to be incorrectly calculated; when the air shower pointed towards a detector with an angle $< 20°$, when an shower was first recorded at a depth beyond 700 g/cm^2, when the length of an air shower track was below 200 g/cm^2 and when the number of data points calculated by a detector is below 30. These criteria for when FdCherenkovReplacer needed to be used, were created after all the stereo events that occurred from January 2004 to October 2005 were analysed. The Gaisser Hillas parameters were found to only be reconstructed more accurately when a large amount of direct Cherenkov light was recorded by a detector.

The record by the Coihueco detector of the event that occurred at the GPS second of 772256331 was highly contaminated with direct Cherenkov light. To account for this FdCherenkovReplacer was used on the event so a more correct Cherenkov profile was calculated by the Coihueco data chain. The aerosol concentration parameters on the night of the event were unknown, so a range of values were run and it was found that low values of the aerosol concentration generated the best agreement between the energy parameters. The geometry of the event was adjusted around χ_0 in the Coihueco data chain within 1° and was found to have been incorrectly calculated by 0.4°. Two other events had recorded a large direct Cherenkov profile in one detector, but on the night of these events a measurement of the atmospheric aerosol concentration had been made. These events were found to validate the results found for the event at the 772256331 GPS second.

The highest energy events recorded by the Pierre Auger Observatory will benefit from the extra analytical techniques that can be applied to the data when an event has been viewed in stereo. These events need the most accurate reconstruction as they occur so infrequently. The aerosol concentration on the night of an event can be independently checked with AerosolMin and if a high energy event contains a large amount of direct Cherenkov light, it can be accounted for with FdCherenkovReplacer.