ATMOSPHERIC EFFECTS
ON EVENTS MEASURED BY THE
PIERRE AUGER OBSERVATORY SURFACE DETECTOR

A Dissertation in
Physics
by
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Abstract

The nature of ultra high energy cosmic rays, nuclear particles from outer space with energies greater than $10^{18}$ eV, is one of the big mysteries of physics due to the low flux of events that reach earth. This small flux necessitates the use of detectors with large collecting areas and excludes using satellite and balloon borne experiments which could detect cosmic rays directly. Instead, we must study the extensive air shower (EAS) caused by a primary cosmic ray as it traverses the atmosphere.

When a cosmic ray enters the earth’s atmosphere it interacts to produce pions. The pions continue to interact until the energy per particle falls below a critical threshold, roughly 2000 MeV. While the charged pions produce muons and neutrinos, the neutral pions produce electromagnetic cascades of electrons, positrons, and gamma rays. This collection of particles is known as an EAS.

The Pierre Auger Observatory was built to study these rare cosmic rays and answer fundamental questions about them, such as their origin and composition. Located in Argentina, the Pierre Auger Observatory detects the EASs created by primary cosmic rays. Since the development of EASs is affected by the atmosphere, it is important to understand these effects so that we can more accurately reconstruct the events. An accurate determination of the primary cosmic ray energy leads to the ability to make more sensitive anisotropy studies, for example.

To this end, rate variations over annual and diurnal cycles are studied. We look at rate variations in comparison with atmospheric temperature and pressure. Using a modified Rayleigh analysis we show that the rate lags behind the temperature in both cases. A lag of 2 weeks is seen in the annual case; in the diurnal case a lag of 2 hours is visible. Both effects are seen at greater than a $3\sigma$ level using events with zenith angles less than 45 degrees. From the modified Rayleigh analysis, we also obtain coefficients which are used to normalize the atmospheric parameters to the rate. Since these coefficients measure the strength of the effect on the rate caused
by that parameter, they can be used to remove the atmospheric effects. Using these atmospheric correction coefficients and phase lags, we correct the event energies. These corrections remove the spurious sinusoidal variations seen in the raw data. Redoing the analysis with the atmospheric corrected data, we find that the annual and diurnal rates are flat within uncertainties.

This improves the upper limits on cosmic ray anisotropy in right ascension. No evidence of anisotropy is found in either the first or second harmonic over 5 differential energy bins. Anisotropy amplitudes of 1-3% are seen in the $4 \leq E < 8$ EeV and $8 \leq E$ energy ranges for both the first and second harmonic; the significances are less than $1.5\sigma$ in all cases though. At lower energies, the anisotropy amplitudes are generally even lower. The significances of detections are still below $3\sigma$. 
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I do not feel obliged to believe that the same God who has endowed us with sense, reason, and intellect has intended us to forego their use.

—Galileo Galilei

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The heavens declare the glory of God,
and the sky above proclaims his handiwork.
Day to day pours out speech,
and night to night reveals knowledge.

—Psalm 19:1-2
Chapter 1

Introduction

Happy is he who gets to know the reason for things.

–Virgil

Every minute the earth is bombarded with nuclear particles from outer space known as cosmic rays. Since their discovery by Victor Hess in 1912 much has been learned about them, but even more remains a mystery. The composition of the highest energy cosmic rays is still unknown. Likewise, we do not know how cosmic rays attain such high energies, the energy of a fast-ball in some cases.

One of the reasons for this lack of knowledge is the small flux of events reaching earth. In order to compensate, detectors must have large collecting areas. This precludes using satellite and balloon borne experiments which could travel high in the atmosphere and detect the cosmic rays directly. Instead we detect the extensive air shower (EAS) caused by a primary cosmic ray. When a cosmic ray enters the earth’s atmosphere it interacts to produce pions. The pions continue to interact until the energy per particle falls below a critical threshold, roughly 2000 MeV. The neutral pions produce electromagnetic cascades of electrons, positrons, and gamma rays. The charged pions produce muons and neutrinos. The shape of an EAS is well defined and scales longitudinally with radiation length and laterally with Moliere length. The radiation length of air is approximately 37 g/cm$^2$ and is the mean path length for gamma ray pair production and for bremsstrahlung by an electron. The Moliere length is a characteristic length scale related to the
radiation length and is approximately 9.5 g/cm$^2$ in air [1].

Comprised of 1600 water Cherenkov detectors, 4 fluorescence detector sites, and covering an area the size of Rhode Island, the Pierre Auger Observatory measures the energies and arrival directions of the highest energy cosmic rays, particles with energies greater than $10^{18}$ eV (1 EeV), and attempts to answer fundamental questions about their properties, such as origin and composition. Since we detect the extensive air showers at ground level, rather than the primary particles themselves, it is important to understand how air shower development is influenced by the atmosphere. To this end, there are several weather stations throughout the array. The work presented here relies on the CLF (Central Laser Facility) weather station, which is located in the middle of the array and has the best temporal coverage.

Since the water Cherenkov detectors are located on a triangular grid, the lateral distribution of an EAS is only measured at discrete points. Therefore, the lateral distribution function (LDF), which describes how the signal decreases with increasing distance from the shower core, must be determined from the signal at a limited number of points. Errors in functional fit or fluctuations in EAS development can cause corresponding uncertainties in the reconstructed position of the shower core and of the total integrated signal in the LDF, which is related to the total number of particles and thus to the shower energy. However, using the signal at a fixed distance from the core minimizes the effect of uncertainties in the LDF. Also, shower to shower fluctuations in charged particle density far from the shower core are small although the total number of charged particles per shower can fluctuate greatly. The distance from the core that minimizes uncertainties and fluctuations depends on the grid geometry and spacing. In the case of the Pierre Auger Observatory, the best distance is 1000 meters from the core [2].

As the air temperature rises, the air density decreases. This increases the Moliere length, as measured in meters, which in turn affects the ground level air shower charged particle density seen a certain distance from the core. When the air density is low and the Moliere length increases, the charged particle density at 1000 meters from the core increases and can become comparable to that seen closer to the core when the air density is higher. This means that the signal at 1000 meters from the shower core increases. This causes a shower of a certain primary
energy to have a higher signal at 1000 meters from the core, and thus a higher reconstructed energy, in warmer air. Therefore, for a certain energy cut there will be more events detected when it is warmer, as lower energy events appear more energetic due to an increased signal at 1000 meters from the core.

The higher the air pressure, the greater the atmospheric over-burden a shower has to traverse. Because we generally measure showers after they have reached their maximum densities, the greater the atmospheric overburden, the less energetic a shower will appear. Conversely, the lower the air pressure, the more energetic the event will appear. So higher rates of events are expected with lower air pressures.

Quantifying atmospheric effects on the energies measured is important for anisotropy studies, where more accurate energy assignments allow for more accurate searches. Temperature variations are cyclic over the period of one year and over the period of one day. Beating of spurious sinusoidal variations caused by atmospherically varying energy assignments can induce an apparent rate variation in sidereal time which is not due to cosmic ray anisotropy.

Because of the linear relation between the atmospheric parameters and rate, the first method of studying these effects involved binning the rate by temperature or pressure and performing a linear fit. However, this method suffered from several problems. First, this method was unable to easily take phase offsets between the rate and atmosphere into account. This turns out to be an important effect. Second, only one temperature or pressure coefficient was determined, rather than allowing for separate annual and diurnal coefficients. Third, while the variations present in the rate decreased after the corrections were applied, there were still significant variations present.

Therefore a modified Rayleigh analysis was performed on the difference of the rate and normalized temperature. This method yields coefficients for both the annual and diurnal case, as well as phase lags between the rate and ground level temperature. While the ground temperature can be used for energy and rate corrections, the relevant altitude is not ground level, but rather two radiation lengths above ground level [3]. This corresponds to a height of roughly 800 - 900 meters above ground level at the Pierre Auger Observatory. Direct evidence for this is the fact that, on average, the changes in event rates lag behind changes in ground temperature, and changes in temperature at the relevant height above the
surface lag behind changes at the ground by the same amount of time.

In the seasonal case, an offset of 14 days is seen between the CLF (Central Laser Facility) ground level temperature and rate for events above 1.5 EeV. To determine if the temperature at a higher altitude tracks the rate without a phase lag, we used data from the Global Data Assimilation System (GDAS), a global atmospheric model produced by the National Centers for Environmental Predicion (NCEP). Data are given at 23 pressure levels on a 1 degree latitude and longitude grid with 3 hour time resolution [4]. Performing the same analysis using data taken from various pressure levels of GDAS shows that the 750 hPa level tracks the annual rate curve with no phase lag. Therefore, the temperature approximately 100 hPa above the surface of the array is used to remove seasonal weather corrections.

In the diurnal case, the 3 hour time offset seen between the CLF temperature and rate for events above 1.5 EeV is not as easily explained using GDAS data. This is in part due to the temporal sampling rate of GDAS (3 hours for GDAS versus 5 minutes for the CLF) and in part due to heavy model dependence of the GDAS data over those time scales. This does not mean that the ground level is the relevant altitude; it simply means that we should look beyond GDAS to explain the diurnal shifts.

This combination of time lagged ground level data from the CLF and instantaneous 750 hPa GDAS data is used to perform both seasonal and diurnal atmospheric corrections. These corrections remove the first harmonic annual and diurnal atmospheric effects, produce an annual and diurnal rate that is flat within statistical uncertainties, and increase the sensitivity of our anisotropy studies. After applying the corrections, no evidence for low energy anisotropy is seen using either a harmonic analysis in right ascension or a harmonic analysis in sidereal time.
Chapter 2

The Science of Cosmic Rays and the Atmosphere

Coming out of space and incident on the high atmosphere, there is a thin rain of charged particles known as primary cosmic rays.

–C. F. Powell

2.1 Introduction to Cosmic Rays

For many thousands of years people have been staring up at the sky, seeking to understand the nature of the universe around us. Much has been learned in this time, but even more remains a mystery. It wasn’t until 1912 that Victor Hess discovered the existence of what are now known as cosmic rays [5].

Around the turn of the twentieth century, knowledge of radioactivity was increasing. Electrosopes were used to measure the intensity of radiation through the time needed to dissipate an electric charge. However, it was noted that even in the absence of radioactive sources, the charge would slowly leak off a well insulated electroscope. This led to attempts to determine the cause of the leakage. Electrosopes were taken to tops of buildings and high above the earth in balloons. Father Thomas Wulf, who carried an electroscope to the top of the Eiffel Tower, noted a decrease in the leakage rate, but not as much as expected if it all came from the ground. He theorized that radiation was coming through the atmosphere, in addition to from the ground. Victor Hess then flew 17,500 feet above the earth
in a hydrogen balloon [6]. He discovered that at first the radiation decreased as he ascended, but by 5,000 feet the radiation level was higher than at ground level. The intensity continued to increase the higher he went. This led him to conclude that the source was non-terrestrial. Later, another physicist, Robert Millikan, made similar measurements and introduced the term "cosmic rays". [5]

Since then, this area of study has been fraught with puzzles but much has been learned. The cosmic rays that Victor Hess detected are now known to be galactic in origin. They are 85% protons, 12% helium, 2% heavier elements, and 1% electrons [6]. Their energy spectrum is a power law with different spectral coefficients on either side of $10^{15}$ eV, creating a feature known as the knee. Below $10^{15}$ eV the spectral index is 2.7; above this energy the spectral index is 3.3 [7] [8]. Supernova remnants are good candidates for the origin of these cosmic rays as Fermi acceleration of particles crossing the shock front gives rise to a power law spectrum [9].

Ultra high energy cosmic rays (UHECRs) must be extragalactic though as the magnetic field of the galaxy is not high enough to contain these particles and there is no model for galactic sources to produce cosmic rays at such high energies. Indeed, the nature of UHECRs is one of the great mysteries in physics today. We do not know where they come from or how they are accelerated to such high energies [10]. We do not even know what they are, whether they are protons, iron, or some other nuclei. Another mystery, the fact that we see such high energy cosmic rays at all, is detailed in Subsec. 2.1.1. Subsec. 2.1.2 explains how the flux of cosmic rays changes with energy.

### 2.1.1 GZK Cut-off

In 1966, Greisen, Zatsepin, and Kuzmin calculated that cosmic rays with energies greater than $5 \times 10^{19}$ eV (8 J) should interact with the photons of the cosmic microwave background (CMB) via the delta resonance, resulting in photoproduction of pions according to Eqn. 2.1 [11] [7]. Each interaction carries away $\sim 20\%$ of the nucleon’s energy. Based on the interaction length, cosmic rays from farther than $\sim 200$ Mpc should not be observed. This expected cut-off of the cosmic ray spectrum is known as the GZK (Greisen-Zatsepin-Kuzmin) limit.
\[ p + \gamma \rightarrow \Delta^* \rightarrow p + \pi^0 \]
\[ p + \gamma \rightarrow \Delta^* \rightarrow n + \pi^+ \] (2.1)

It is therefore surprising that cosmic rays with energies greater than 50 EeV are observed. They cannot be confined to the galaxy by magnetic fields above energies of 3 EeV [7]. Given this, and the fact that there appears to be no correlation of arrival direction with the galactic plane, it appears that cosmic rays with energies above \( 10^{18.65} \) eV are extragalactic in origin. [7]

The highest energy cosmic ray ever recorded was measured October 15, 1991 by the Fly’s Eye detector in Utah [11]. The energy of this event was reconstructed to be 51 J \((3.2 \pm 0.9 \times 10^{20} \) eV). The Pierre Auger Observatory has also measured several events of comparable energy. The detection of these events and the absence of a strong correlation with nearby sources is therefore a mystery.

2.1.2 Flux

One of the difficulties in studying UHECRs is the low density of events per year. The cosmic ray flux decreases rapidly with increasing energy. Cosmic rays with energies greater than \( 10^{19} \) eV arrive at a rate of approximately 1 particle per km\(^2\) per year. Cosmic rays with energies greater than \( 10^{20} \) eV arrive at a rate of approximately 1 particle per km\(^2\) per century.

The cosmic ray spectrum is shown in Fig. 2.1. The spectrum follows a power law, which means that the flux, \( \frac{dJ}{dE} \), is inversely proportional to the energy, E, raised to the spectral index, \( \gamma \).

\[ \frac{dJ}{dE} \propto E^{-\gamma} \] (2.2)

The spectral index is not constant over all energies. However, within different energy regions the spectrum is well approximated by power laws using different spectral indices. Below \( 10^{15} \) eV, the index is 2.7 [7]. Between this energy and \( 10^{18.65} \) eV \( \gamma \) steepens to \( 3.28 \pm 0.07 \) [8]. Above \( 10^{18.65} \) eV, the spectrum flattens out again and \( \gamma = 2.65 \pm 0.14 \) [8]. These critical energies where the spectrum changes are known as the knee and the ankle respectively. It is theorized that
Figure 2.1: The cosmic ray spectrum, showing the differential flux as a function of total particle kinetic energy. The dotted line shows the spectrum $\times E^{-3}$ as a guide to the eye. Figure from [12].
Figure 2.2: Energy spectrum scaled by $E^3$. The ankle is clearly visible at $10^{18.65}$ eV. The arrows indicate the uncertainty of the Auger flux scaled by $E^3$ due to a 22% systematic energy uncertainty. Differences between the HiRes and Auger spectra could be accounted for by a shift within the systematic uncertainty of the energy scales of one or both experiments [14]. Figure from [8].

the knee is caused by decreasing efficiency of galactic accelerators beyond $10^{15}$ eV, coupled with likely energy-dependent escape from the galaxy; the ankle is likely caused by a transition from galactic sources to extragalactic sources [13].

Fig. 2.2 shows the cosmic ray flux scaled by a factor of $E^3$. This allows for better visualization of changes in the spectral index. The ankle is clearly visible at $10^{18.65}$ eV. Around $10^{19.5}$ eV one can see what is sometimes known as the toe. This is the suppression of the flux due to the GZK limit.

2.2 Extensive Air Showers

Since the column depth of the atmosphere at sea level is roughly 1000 g/cm$^2$ and the interaction length of hadrons in air is 70 g/cm$^2$, primary cosmic rays
will interact before reaching sea level [13]. These interactions lead to extensive air showers (EASs). By studying the properties of these EASs, we can infer the energies, arrival directions, and mass composition of the highest energy cosmic rays. Here we describe the development of extensive air showers and detection methods.

2.2.1 Development

Composed mainly of atomic nuclei, UHECRs come flying out of space and smack into atoms of the atmosphere. In more technical, but less exciting terms, an UHECR interacts with an atomic nucleus, most likely nitrogen, in the atmosphere. This starts the extensive air shower cascade, which comprises two parts: a hadronic cascade and an electromagnetic cascade. Composed mostly of pions, the hadronic cascade continues until the energy per pion falls below a critical threshold, 2000 MeV [15]. This threshold is the energy where the charged pions are likely to decay before colliding.

An extensive air shower can be thought of in terms of generations, where at each generation, all the particles interact. In each generation, a third of the energy goes into neutral pions which immediately decay into gamma ray pairs. These gamma rays then develop electromagnetic subcascades by decaying into $e^\pm$ pairs. This means that after N generations, $(2/3)^N$ of the initial energy remains in the hadronic cascade.

The charged pions produce muons and neutrinos when they decay, the number being dependent on the fraction of energy left in the hadronic cascade when the threshold for decaying instead of colliding is reached. Showers that reach this critical energy in few generations produce many muons. Showers that require many generations to reach critical energy produce few muons.

The $e^\pm$ pairs created in the electromagnetic cascade create gamma rays through bremsstrahlung. This process of $e^\pm$ pair production and bremsstrahlung continues until the energy per particle falls below the critical energy. The radiation length, $X_0$, is the mean path length for gamma ray pair production or bremsstrahlung by an electron. In air, $X_0 = 37 \text{ g/cm}^2$. Since the ionization energy loss is $\sim 2.2 \text{ MeV g/cm}^2$, the critical energy is 81 MeV. [16]
Showers caused by iron primaries develop differently than those caused by proton primaries. A cascade caused by iron develops like a superposition of 56 proton showers, each with 1/56 the initial energy. This means than an iron shower develops in fewer generations than a proton shower of the same primary energy. Therefore, iron showers have a larger muonic component than proton showers with the same initial energy. In addition, iron showers reach their maximum number of particles higher in the atmosphere than proton showers. That is, they have a lower $X_{\text{max}}$. [16]

2.2.2 Methods of Detection

There are two main types of extensive air shower detectors, those that measure the flux of secondary particles at ground level and those that measure the shower front as it descends through the atmosphere. The Pierre Auger Observatory uses both of these methods to study air showers through an array of water Cherenkov detectors and 27 fluorescence detector telescopes. A brief description of each method is given here; more details about the specifics of the Auger instruments are given in Sec. 3.1.

2.2.2.1 Water Cherenkov Detectors

A water Cherenkov detector performs a measurement of the electromagnetic energy density at its location. The amplitudes measured by the tanks are fit to a lateral distribution function from which we obtain the signal at 1000 m from the core, $S(1000)$. Since $S(1000)$ is proportional to energy for any fixed zenith angle, this determines the energy of an event. The ratio of $S(1000)$ to $E^{0.95}$ varies by roughly a factor of 4 between 0° and 60° zenith angle, with low zenith angles having a higher ratio [17]. Differences in arrival times of signals at tanks are used to reconstruct the arrival directions. Two time differences between three non co-linear tanks determine the arrival direction uniquely [16]. For the Pierre Auger Observatory, angular resolutions of 2.2° are possible for events with signals in 3 tanks. Events with signals in 6 or more tanks, corresponding to energies greater than $\sim 10$ EeV, can be reconstructed to better than 1.0° [18]. More details about event reconstruction accuracies are given in Subsec. 3.3.3.
2.2.2.2 Air Fluorescence Detectors

Fluorescence detector sites, also called eyes, measure the longitudinal profile of air showers as they develop. As shower particles collide with air molecules, primarily nitrogen, light is emitted in the 300-400 nm wavelength. Large mirrors collect these UV fluorescence photons onto an array of photomultiplier tubes, forming a movie of the shower front moving down through the atmosphere. With one eye, the track of the shower can be reconstructed to a plane, called the shower detector plane. If two eyes record an event, the shower axis is the intersection of the two planes (stereo reconstruction) [16].

Alternatively, one can combine the arrival time of signals at ground stations with the signal of a fluorescence detector eye to determine the shower axis. Using the time versus angle information from the fluorescence detector eyes, if one can fix the distance to the shower and time at one point (i.e. by using data from a surface detector) then one can determine the shower axis. This method is known as hybrid reconstruction.

Because the signal measured is affected by various atmospheric properties, including aerosol content and clouds, it is important to monitor these parameters. Clouds can block EAS light from reaching a fluorescence detector eye, leading to artificially small signals unless their presence is taken into account. The location of clouds can be determined from cloud cameras or satellite data. Two types of scattering occur in the atmosphere: Rayleigh and Mie scattering. Rayleigh scattering describes scattering in a molecular atmosphere while Mie scattering describes the scattering of light by aerosols. For Rayleigh scattering, temperature and pressure corrections are well determined. Corrections for Mie scattering are not known a priori. However, they can be measured with the use of lidars. [19]

2.3 Planetary Boundary Layer

Although the prior part of the chapter dealt with cosmic rays directly, we now turn our attention to the earth’s atmosphere. Because we detect the EAS, and not the primary cosmic ray, the atmosphere forms part of our detector. Therefore, we need to understand the atmosphere and how it can influence the development of
EASs. Since air showers reach their maximum after traversing 700 - 850 g/cm$^2$, the lower atmosphere is of particular interest. Here we describe the planetary boundary layer.

To place later discussions in a broader context, we first mention the overall nature of the atmosphere. Earth’s atmosphere is composed of four main layers: the troposphere, the stratosphere, the mesosphere, and the thermosphere. The approximate altitude and temperature of each layer are shown in Fig. 2.3. The temperature inversions in the stratosphere and thermosphere, where temperature increases with height, are due to solar excitations of ozone (oxygen) in the stratosphere (thermosphere) [20].

Air showers measured by the Pierre Auger Observatory generally reach their maximal extent after traversing 700-850 g/cm$^2$ integrated density [22] [23]. Since pressure decreases exponentially with height, this corresponds to an altitude a few kilometers above ground level for vertical showers with energies greater than approximately 1 EeV at the location of the Pierre Auger Observatory (1400 meters above sea level). Showers with large zenith angles can reach their maximal extent much higher in the atmosphere. However, the troposphere is the atmospheric layer that changes on time scales of days [21].

Therefore, we concern ourselves with the planetary boundary layer (PBL). This is the part of the troposphere that is directly influenced by the earth’s surface. The height varies with season. As the PBL is generally thinner in high pressure regions than in low pressure regions, the top is lower in winter than in summer [20]. This seasonal height difference is also due to different amounts of incoming radiation over course of the year. While 3 km is a typical height in summer, 500 m is a typical height in the winter. Fig. 2.4 shows the parts of the PBL and its variation over the course of a day. The PBL is composed of three main parts: a mixed layer, a residual layer, and a stable boundary layer. The structure evolves over diurnal cycles.

The mixed layer is driven by convective turbulence. Growth is driven by solar heating of the ground on days that are initially clear, as most days at the Pierre Auger Observatory are. The mixed layer starts to grow approximately half an hour after sunrise, reaching its maximal extent late in the afternoon. Thermals of warm air rising from the ground cause turbulence, which causes the height of the layer
Figure 2.3: The four main layers of the atmosphere: troposphere, stratosphere, mesosphere, and thermosphere. The planetary boundary layer is denoted by slashed lines, below about 2 km. The red line traces the mean temperature at each altitude. Figure from [21].

to grow by mixing in air from above. This process is known as entraining. [20]

The stable layer at the top of the mixed layer is called the entrainment zone, since this is where entrainment takes place. If the temperature of this region increases with height, this layer is known as a capping inversion. [20]

The thermals of warm air rising from the ground cease roughly half an hour
Figure 2.4: The planetary boundary layer is composed of three main parts: a turbulent mixed layer, a residual layer which contains air formerly part of the mixed layer, and a stable nocturnal boundary layer. The height scale is typically lower in the winter and higher in the summer, although the temporal pattern remains the same. Figure from [20].

before sunset. This causes the turbulence formerly present to decay and the mixed layer to become the residual layer. This residual layer is less affected by the ground since no active mixing is occurring [20]. The stable boundary layer forms at ground level and increases in height into the residual layer throughout the night. Unlike the mixed layer, this stable layer has a poorly defined upper boundary. [20]

As will be seen in later chapters, the rate of events has a well defined diurnal and seasonal pattern. The diurnal and seasonal variations of the lower atmosphere, specifically the planetary boundary layer, are largely responsible for this. Therefore, an understanding of the cause of atmospheric variations is useful for understanding the physical processes involved and the indirect causes of rate variations.
Chapter 3

The Pierre Auger Observatory

If your experiment needs statistics, then you ought to have done a better experiment.

–Ernest Rutherford

The Pierre Auger Observatory is located in western Argentina in Mendoza Province. It covers 3000 km$^2$, an area roughly the size of Rhode Island, and is located approximately 1400 meters above sea level, although the actual heights range from 1300 - 1700 meters above sea level [4]. Headquarters are in Malargue (-35.463331° latitude, -69.584975° longitude) and the array is located northeast of the town.

We first present an overview of the hardware of the Pierre Auger Observatory, paying special attention to the surface detector and weather station used in analyses presented here. Then we discuss how the exposure of the surface detector is calculated. Finally we discuss event triggers, reconstruction procedures and accuracies, and quality cuts applied to the data.

3.1 Parts of the Detector

We now give a brief overview of the components of the Pierre Auger Observatory. Since the research presented here relies on data from the surface detector and from the weather station at the central laser facility, these parts are covered in greater detail in sections 3.1.2 and 3.1.3.
3.1.1 General Overview

The Pierre Auger Observatory is composed of a surface detector (SD), a fluorescence detector (FD), 4 lidars, 6 ground-based weather stations, 2 laser facilities, and a balloon launch station (BLS). The FD is composed of four sites, or eyes, each with six telescopes. The SD is composed of 1600 water Cherenkov detectors. The locations of the FD eyes and SD water tanks are shown in Fig. 3.1. In addition, a host of other instruments are now being built and operated to detect cosmic rays using non-optical methods.

The fluorescence detector eyes bound the array and measure the profile of air showers as they develop in the atmosphere [25]. They measure the fluorescence light emitted by charged shower particles interacting with atmospheric molecules, primarily nitrogen. Since the FD only operates on clear, moonless nights it has a duty cycle of $\sim 10\%$. The site of each eye also hosts a lidar, used for measuring clouds and aerosols. The building of each eye houses the six telescopes, each
with a 30° azimuth by 28.6° elevation field of view [26]. The six telescopes at each site give a combined 180° lateral field of view from 1.7°-30.3° elevation [26]. Each telescope consists of a $3.5 \times 3.5$ m spherical mirror with a 3.4 m radius of curvature that reflect lights onto an array of 440 one inch PMTs sensitive to 300-400 nm wavelengths. A schematic is shown in Fig. 3.2. Located at Coihueco, HEAT is atiltable 3 bay eye capable of measuring profiles 30° - 60° above the horizon. For further technical details, see [25] [27].

While the maximum distance a shower can be seen is energy dependent, there are events in the Auger data set that have been recorded by all 4 fluorescence detector sites. The angular uncertainty is 0.3° for hybrid events, events that are recorded by both the FD and the SD and therefore use the time versus angle information from a fluorescence detector eye and the distance to the shower and time at one point from the surface detector to determine the shower axis [10]. There is a 22% systematic uncertainty in the energy scale due to uncertainty in the fluorescence yield, the amount of light emitted by nitrogen due to EAS charged particle energy loss [28].

The BLS is located in the western central portion of the array. From March 2009 through December 2010, weather balloons were launched from there after showers with energies of 20 EeV or greater, in order to obtain atmospheric profiles [29]. Each balloon contained a DFM-09 probe, manufactured by GRAW, which measured temperature, pressure, humidity, and windspeed, generally up to an altitude of 25 km [30] [31]. These data were used to provide more accurate shower reconstruction parameters. This program has since been discontinued and GDAS data substituted [4]. The BLS data were used to validate the use of GDAS data.

Two laser facilities, the central laser facility (CLF) and the extreme laser facility (XLF), are located near the center of the array and are used for aerosol measurements with the fluorescence eyes measuring the attenuation of scattered light propagating from the beam. The CLF is visible from all FD eyes except Loma Amarilla. The XLF is visible from all FD eyes except Los Leones.
3.1.2 Surface Detector

The ground array of the Pierre Auger Observatory consists of 1600 water Cherenkov detectors on a triangular grid of 1.5 km spacing [32] [25]. Together these individual detectors are known as the surface array or surface detector (SD). Each detector, or tank, consists of several parts: a polyethylene shell, a Tyvek liner, 12,000 liters of ultrapure water, 3 photomultiplier tubes (PMTs), a solar panel, two batteries,
a radio, and various electronics.

Requirements for the surface detector include that the tanks be able to survive in all weather conditions for at least 20 years and be opaque to light. The tanks have diameters of 3.6 m, which corresponds to a surface area of 10 m$^2$ and are capable of being filled to a height of 1.2 m with water while still leaving room for the PMTs and electronics. The total height is less than 1.6 m due to shipping restrictions. Since steel tanks would rust in the local environment, polyethylene tanks are used. The tanks are rotomolded in two layers: a beige outer layer and a black inner layer. The outer layer is beige to blend in with the environment; the inner layer is black, having been mixed with carbon black pigment to provide opacity to the walls and some protection against UV damage. A UV stabilizer is also included in the plastic to provide more resistance to UV damage. [33]

To further block external light, as well as to provide a barrier between the water and the electronics and act as a diffuser of Cherenkov light, a Tyvek liner is inserted into the tank [33]. This liner is cylindrical in shape, 1.2 m high and 3.6 m in diameter. Three transparent windows are spaced 120° apart on the top at a radius of 1.2 m from the center and house the PMTs. Since the PMTs are situated on the top of the detector and face downward, the distribution of light hitting them is uniform [25]. Caps are also present so that the liners can be filled with water and then sealed. [33]

The water of the SD should not need to be replaced over the lifetime of the experiment and therefore must remain transparent. This requires chemical and biological activity to be minimized. By using plastic tanks and liners, rust is eliminated. To inhibit bacterial growth, special precautions are taken while handling the bags to insure they are not contaminated with dirt or other materials. In addition, the tanks are filled with ultrapure water, water with greater than 15 MΩ-cm resistivity and less than 10 ppb organic carbon residues [33]. Because of the large quantity of water needed, a water purification plant was built on-site at the Auger Central Building in Malargue. The water is then transported via tanker truck to the tanks in the field. Fig. 3.3 shows the tanker truck along with a tank.

Since each tank is solar powered, power consumption is limited to 10 W [27]. The electronics of each tank consist of three 20 cm diameter Photonis PMTs, frontend electronics, a station controller, a slow control module, and a Global
Figure 3.3: A tank and the tanker used to fill it with water. The solar panel and communications antenna are clearly seen on the upper right of the tank. The battery enclosure is located at the lower left of the tank. The electronics are housed in the domed hatch cover.

Positioning Satellite (GPS) system for timing [32]. The bases of the PMTs are supplied with 12 V DC, which is converted to high voltage, with a maximum voltage of 2 kV and a maximum power of 500 mW. The high voltage is adjustable for each individual PMT. Each PMT has its own gain and is read out on a different channel. The slow control module is used to monitor various parameters of the tanks, such as the water temperature and voltage of the PMTs.

The GPS is set to position hold mode to achieve maximum timing resolution. Using this mode, GPS signals are only used for timing, the fixed positions of the tanks having been previously determined using a differential GPS. Using position hold mode, timing resolution increases from 13 ns to 8 ns. [34]

The communication system is composed of communication towers located at
the FD eyes and visitors center and of communication electronics at the SD tanks. The tanks relay information to one of the communication towers via the 2400-2483 MHz ISM band. Each tank is required to have 10 sec worth of buffering due to the maximum delay between sending and receiving of data requests. [35]

In addition, the tanks must be calibrated. The purposes of calibration are three-fold: to match the high gains of the PMTs so that they produce the same output signal, to obtain the value needed to convert between FADC signal and vertical equivalent muons, and to measure the ratio of the attenuation of the low gain to that of the high gain [32].

To match the high gain channels of the PMTs, the high voltage of PMT 1 is adjusted so that the gain is the average of the gain of PMT 2 and 3. Then PMTs 2 and 3 are adjusted so that they have the same gain as PMT 1 [32].

Absolute calibration occurs through the use and measurement of the atmospheric muon background to determine the signal caused by one vertical equivalent muon (VEM). One VEM is the average energy that is deposited by a vertical muon passing through the center of the tank [36]. This method uses a simple threshold cut and is based on the signal generated by muons which cross the tank. In practice, muons arrive from all directions; however, the location of the peak in the charge distribution can be used to infer the charge of a VEM. A peak occurs in the counts versus charge plot at $\sim 2.5 \times 10^7$ eV. Since the background rate is roughly 2 kHz, this calibration can be done rather quickly. [32]

The relative calibration of low to high gain channels is obtained by comparing responses from the two channels in regions where both have signals and neither is saturated, in the region of 20 - 50 VEM [32].

### 3.1.3 CLF Weather Station

Because the atmosphere forms part of our detector, we monitor various atmospheric parameters through the use of six ground level weather stations. These are located at the four eyes of the fluorescence detector, the BLS, and the CLF. Each contains a barometer, a temperature and humidity probe, an anemometer, and a solar monitor, all of which are manufactured by Campbell Scientific. The model numbers of each probe are listed in Tab. 3.1.
<table>
<thead>
<tr>
<th>Instrument</th>
<th>Model Number</th>
<th>Model Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature and Humidity probe</td>
<td>CS500-LC</td>
<td>Vaisala 50Y Temperature RH Probe-Metdata1</td>
</tr>
<tr>
<td>Barometer</td>
<td>CS105MD</td>
<td>Vaisala Barometer (600-1060 HPA) for Metdata1</td>
</tr>
<tr>
<td>Anemometer</td>
<td>05103-LC</td>
<td>RM YOUNG Wind Monitor-Metdata1</td>
</tr>
<tr>
<td>Solar Monitor</td>
<td>LI200X-LC</td>
<td>LI-COR SOLAR (Fixed Calib.) Metdata1</td>
</tr>
</tbody>
</table>

Table 3.1: Instrument, model number, and model name for the instruments composing the Auger weather stations. [37]

The reading frequency is set using a program running at the local weather station. The CLF and Coihueco weather stations read the pressure on an hourly basis, although the temperature is read every 5 minutes [37]. In September 2009, the Los Leones weather station was changed to read the pressure every 5 minutes. There are plans to change the other stations [37].

Although each eye, as well as the BLS and CLF, has a weather station, we choose to use data from the CLF for two reasons. First, as the CLF is centrally located in the array, this should provide a representative measurement of the temperature over the majority of the array. Second, the CLF weather station has the best temporal coverage as shown in Fig. 3.4. Only the station at Los Leones can compare with the CLF. However, the Los Leones station is missing data from a large part of 2007, early 2008, and 2009.

3.2 Exposure Calculation

The aperture of the SD is the area that is currently operating at any given time integrated over solid angle. Considering only zenith angles between 0° and 60°, the integral over solid angle is $3\pi/4$. While this may seem like a straightforward definition of the aperture, there are several ways this area could have been defined [38]. However, a purely geometrical method was adopted. In this method, a hexagonal unit cell is defined as the Brillouin zone of a tank, that is the area in which a point is closer to that tank than any neighboring tank [39]. See Fig. 3.5 for a pictorial representation. The aperture is then the aperture of a working hexagon multiplied by the number of working hexagons. The area of a hexagonal unit is 1.9485 km², one third the area of a large hexagon, which is defined as a hexagon with tank at each vertex. Alternatively, the area can be calculated as follows. Think of the small hexagon as composed of 6 equilateral triangles each
Figure 3.4: Time coverage of the weather stations located at the CLF, BLS, and FD eyes from January 1, 2004 - October 20, 2011. The temperature values have been shifted 20° C between each station to clearly show temporal coverage.

...with side length L. The height of a triangle is 0.75 km (1.5 km/2). L is then (0.75 km)/cos(30°). The area of the hexagon is

\[ 6 \times \frac{1}{2} \times L \times \frac{L}{\cos(30°)} = 3L^2 \frac{1}{\cos(30°)} = 3(0.75)^2 \frac{1}{\cos(30°)} = 1.9485 \text{ km}^2 \quad (3.1) \]

The aperture is then

\[ 1.9485 \text{ km}^2 \times \frac{3\pi}{4} \text{ sr} = 4.5910 \text{ km}^2 \text{sr} \quad (3.2) \]

The exposure is the time integrated aperture and is calculated from the num-
ber of working hexagons each minute. For example, an aperture of 7000 km$^2$sr operating for a year and an aperture of 3500 km$^2$sr operating for two years both have an exposure of 7000 km$^2$sr·yr. Files listing the GPS second and number of working hexagons each minute are available at http://ipnweb.in2p3.fr/ auger/AugerProtected/AcceptHexagons.html.

Throughout this work we give the exposure in units of area-time, that is without integrating over solid angle. To convert to units of area-time-sr, multiply the exposure by the integral over the solid angle for the range of zenith angles considered, that is by $\int_{\theta_1}^{\theta_2} \cos(\theta)2\pi \sin(\theta)d\theta$.

Using this geometrical method of calculating the exposure requires the concept of a 6T5 trigger. T5 denotes the fifth trigger or condition that events must pass, the other triggers being labeled T1, T2, T3, and T4. These are discussed in detail in Sec. 3.3.1. The 6T5 trigger means that the hottest tank - the tank with the highest signal - of an air shower event must be surrounded by six working tanks [40]. That is, the hottest tank must be at the center of a working hexagon. However, it is sometimes desirable to use a less restrictive definition. This leads to a slightly different method of calculating the exposure, although it is still a purely geometrical approach. Instead of requiring all six neighboring tanks to be working, we only require five working neighboring tanks and that the core of the reconstructed shower be located in the working area. This is known as a 5T5 trigger and leads to a working area that is 2/3 the size of a hexagonal unit, as shown in Fig. 3.5 [40]. However, the base unit is defined as 1/4 the working area. Therefore, the exposure of the array if using a 5T5 trigger is the number of unit cells times the area of a unit cell. Since a unit cell is 1/6 of a hexagonal unit, they have an area of 0.3247 km$^2$.

The above approaches are predicated on the assumption that the core position of a shower will be inside the hexagon of the tank with the highest signal. However, this is not always the case, particularly for showers with large zenith angles, as shown in [39]. For showers coming from the north, the Brillouin zones in the shower plane for showers of 45 and 60 degree zenith angle are shown on the left of Fig. 3.6. Converting to the ground plane, one sees the deformation from the usual hexagonal shape. The exact shape depends strongly on the azimuth angle of the shower, due to geometric effects of the array.
Figure 3.5: Left: The definition of a working hexagon for purposes of a 6T5 (or strict T5) trigger. All six tanks surrounding the central tank are functional. Right: For a 5T5 trigger, 5 tanks surrounding the central tank must be working and the reconstructed shower core must be located in the working area. The working area is shown in blue. [41]

However, the exposure calculation is not affected, as the total area in which the shower core position falls does not change, only the shape. Fig. 3.7 shows how the shape and density of shower core position relative to the hottest tank changes with zenith angle. Density here refers to the fraction of showers, with a uniform azimuthal distribution, that cause the central tank to have the highest signal. As zenith angle increases, the traditional hexagonal shape is distorted. The central tank may have the highest signal even though the shower core is closer to another tank. The array still has full acceptance everywhere as the areas overlap.
Figure 3.6: Left: The Brillouin zone drawn in the shower plane for events with zenith angle 45 degrees (top) and 60 degrees (bottom). Right: The Brillouin zone projected onto the ground plane. At 45 degrees, the standard hexagon is deformed. At 60 degrees, it is a rhombus. Figure from [39].
Figure 3.7: Distribution of shower core position and density relative to the hottest tank for events with zenith angles of 0, 15, 30, 45, 60, and 75 degrees and uniform azimuthal distribution. The colors correspond to the density of shower core positions for events with uniform azimuthal distribution that cause the central tank to have the highest signal. Figure from [39].
3.3 Event Reconstruction and Quality Cuts

Having given an overview of the hardware of the detector in Sec. 3.1, we now discuss various data quality issues that must be dealt with in order to perform accurate analyses. Since only data from the SD are used throughout this work, we restrict ourselves to discussing those issues pertaining to the SD data.

3.3.1 Quality Cuts

In every experiment, the differentiation of signal from noise is an important problem. In the Auger Observatory, this is handled by requiring any possible signals to pass five different quality cuts or triggers before being labeled an event. The first two are local triggers, in that they are carried out by the tanks themselves. The first trigger, T1, identifies a signal in a tank [35]. This can happen one of two ways. The first method is a simple threshold trigger which requires a signal in all three PMTs greater than 1.75 times the pulse height produced by a vertical equivalent muon (VEM). The second method requires at least 325 ns out of a 3 µs sliding time window to be above 0.2 times the pulse height produced by a VEM in at least 2 of the 3 PMTs [42]. The T2 trigger identifies signals that could be part of an air shower and forms a time stamp and integrated pulse height which are then transmitted to the central data acquisition system (CDAS). To pass the T2 trigger, T1 triggers from the first method are required to pass a threshold of 3.2 times the pulse height produced by a VEM in coincidence among all three PMTs. All T1 triggers from the second method are automatically promoted to T2 triggers. The T1 rate is \( \sim 100 \) Hz. The T2 rate is \( \sim 20 \) Hz [35] [42]. The T3 trigger is carried out by CDAS and identifies coincidences between signals of 3 or more tanks that might be part of an air shower. Because it is very permissive, we have the ability to detect many different types of events.

However, this also means that the majority of T3 events are not real air shower events [35]. Therefore, a physics cut is imposed. It is designed to exclude chance coincidence events, events caused by the accidental coincidence of signals in nearby tanks [38] [43]. This T4 trigger selects coincidences which could be part of an actual physical event by requiring 3 localized stations in a triangular pattern (equilateral or isosceles) with time delays consistent with the speed of light [44] [35]. The T3
trigger rate is 0.05 Hz; the T4 trigger rate for the fully deployed array is 0.02 Hz, or roughly 1800 events per day [45] [46].

The last trigger, the T5 trigger, is a quality trigger which ensures that all the events are certain to be reconstructed reliably [38]. As mentioned in section 3.2 this is based solely on geometry. A strict T5, or 6T5, trigger is met if the tank with the largest signal is surrounded by six working stations. A less restrictive 5T5 trigger is met if the tank with the largest signal is bordered by five working tanks and the reconstructed shower core is inside a working triangle. The T5 trigger rate is comparable to, though slightly less than, the T4 trigger rate.

Unless explicitly stated otherwise, for purposes of the analyses carried out for this dissertation a strict T5 trigger is imposed, as well as requiring more than 3 tanks with signals in an event. Since the T5 trigger is based solely on geometry, while the T4 trigger utilizes signal information from the tanks, these two triggers are independent.

### 3.3.2 Bad Periods

Although the surface detector is capable of running continuously, there are periods where operation is not possible for various reasons, such as CDAS or the communications systems being down. The bad periods (official term) are determined by looking at the time interval between consecutive events in the raw data files. Since the arrival time between successive T5 events follows a Poisson distribution, a time interval is marked as bad if the chance probability of it occurring is less than a certain threshold, determined from the average time interval between events, and also from the number of events [47].

It is important to exclude these periods from analysis otherwise results obtained will be inaccurate. A list of the bad periods for the SD is found at the acceptance webpage [48]. The bad periods are listed in a text file with each bad period listed on a separate line. The UTC time, GPS time, day, month, year, hour, minute, and second are given for the starting time and ending time of each period. While events at the start or end of a bad period can be used, data within a bad period should not be [48].
3.3.3 Event Reconstruction

The calculation of the energy, arrival direction, shower core location, and other EAS parameters from the timing and signal information of individual tanks is accomplished by the Auger Observer, a server which automatically reconstructs the events and is based on the latest Offline release [49]. Offline provides a framework of how to reconstruct events from measured parameters [50]. As Offline is updated and new versions are released, new versions of the Observer data files are produced. Old versions are archived and compared to new versions to ensure data quality. Technical details can be found at [49] and [50].

The angular resolution of the SD depends on the tank multiplicity of an event, that is on the number of tanks which record a signal and are therefore used in event reconstruction. Fig. 3.8 shows the angular resolution as a function of zenith angle for different tank multiplicities. As the zenith angle and multiplicity increase, the angular uncertainty decreases. Vertical events which trigger 3 tanks have an angular resolution of 2.7°; vertical events which trigger more than 5 tanks have an angular resolution of 1.0° [51].

The uncertainty in S(1000) is less than 12% for events with at least one saturated station, a station where the PMT signal is saturated at its maximum value. The uncertainty in S(1000) is less than 8% for events with no saturated stations [52]. The energy uncertainty is ∼10% and is independent of energy and zenith angle [52].

3.3.4 24 Hour Data Gaps

In addition to the bad periods described in subsection 3.3.2, there are several 24 hour periods where the data are missing due to problems processing the raw data files [53]. These data version dependent gaps are caused by crashes during the reconstruction process which cause the data from a file (a 24 hour period that runs from noon to noon UTC) to disappear [53] [54]. These problems are currently being addressed and should not exist for the surface detector data in the next release of the Observer data [54].

However, as the exposure is calculated independently of whether the raw data can be reconstructed, these gaps must be taken into account when calculating the
rate of events. Otherwise for a particular time window one would calculate a large exposure and low counts, leading to an artificially low rate. Therefore, I construct a second bad period file that excludes the time periods of these unreconstructed days from the exposure and event counts calculation. Unless otherwise noted, periods of missing data have been excluded in all analyses described throughout this dissertation.

More details about the specific dates of these gaps and their properties can be found in App. C.

### 3.4 Weather File Construction

The hardware of the weather station at the CLF is described in Sec. 3.1.3. Here we note the location and format of the data file used throughout this dissertation when ground level weather data is needed. A detailed description can be found in
The weather file used is downloaded from http://fisica.cab.cnea.gov.ar/particulas/experiments/auger/private/monit/. This is the new repository for the weather files, as the link in [55] is no longer active.

Each line of the text file contains 9 variables: UTC second, air temperature (°C), relative humidity (%), windspeed (km/hr), average windspeed (km/hr), maximum windspeed (km/hr), wind direction (north = 0 deg, east = 90 deg, etc.), barometric pressure (hPa), and a flag for the record origin. Throughout this work, we deal only with the air temperature and pressure measurements. The uncertainty in temperature is less than 1° C between -20° C and 60° C, the exact values being temperature dependent as seen in Fig. 3.9 [56]. The uncertainty in pressure is ±2 hPa between 0° C and 20° C and ±4 hPa between -20° C and 45° C [57]. Times in the raw weather files are cross checked with CDAS to ensure the correct time stamp in production of the files. The origin flag is set to 0 if the source is the original data file. In the case of time gaps less than 2 hours long, the temperature, pressure, and humidity values are interpolated and the origin flag is set to 1 since these variable change slowly. For other variables, the value is frozen at the last available measurement and the origin flag is set to 1 due to possibility of fast fluctuations. There are other versions of the weather files where longer gaps are filled using data from other weather stations or else interpolated over longer time scales. We do not use these versions here. We restrict ourselves to using the file wclf_CLF.dat.
Temperature Accuracy:

Figure 3.9: The accuracy of the CLF temperature probe varies with the temperature. It is less than 1° C between -20° C and 60° C. Figure from [56].
Expected Weather Effects

In theory there is no difference between theory and practice, in practice there is.

–Unknown

4.1 Motivation

As previously discussed, the detector is composed of two main elements, a surface detector and a fluorescence detector. Neither directly detects the primary cosmic rays; instead, they detect the extensive air showers caused by the primary particles interacting with the atmosphere and the subsequent particle interactions. Since these interactions occur throughout the atmosphere, it behooves us to understand if the changing conditions of the atmosphere can affect our measurements, and if so, by how much.

4.2 Why do we expect an effect?

In this section we use the Greisen formula, the Nishimura-Kamata-Greisen (NKG) function, and the ideal gas law to derive the relationship between a change in air temperature and pressure and the change in charged particle density. However, a qualitative argument is also instructive and thus also presented.
4.2.1 Qualitative Argument

As discussed in Ch. 1, the Moliere length is a characteristic EAS lateral length scale, generally given in units of integrated density, g/cm² for example. To determine the Moliere length in units of length, one divides by the air density. While the Moliere length in units of integrated density is independent of air density, the Moliere length as measured in units of length is not.

As the air temperature rises, the air density decreases, assuming other parameters stay constant. When the air density decreases, the Moliere length, as measured in meters, increases and the charged particle density 1000 meters from the core increases to that seen closer to the core when the air density is higher. This means that the signal 1000 meters from the shower core increases, resulting in a shower of a certain energy appearing more energetic in warmer air. Therefore, for a certain energy cut there will be more events detected when it is warmer, as lower energy events appear more energetic. The reverse is true for low temperatures; fewer events will be detected, resulting in a lower rate for a given energy cut.

The higher the air pressure, the greater the atmospheric over-burden a shower has to traverse. Because we generally measure showers after they have reached their maximum densities, a shower will appear less energetic the greater the atmospheric overburden. Conversely, the lower the air pressure, the more energetic the event will appear. So higher rates of events are expected with lower air pressures.

Therefore one expects a higher rate of events with higher temperatures and lower air pressures. The magnitude of the temperature and pressure effects are explored in Sec. 4.3 as well as the importance of the effects relative to each other.

4.2.2 Quantitative Argument

This derivation depends on three main equations - the Greisen formula, the NKG function, and the ideal gas law. Due to the number of variables, we define them here before listing the above formulas.

Notation and definitions:

\[ \rho = \text{charged particle density (units of particles per area)} \]

\[ \eta = \text{air density} \]
\( T = \) temperature
\( P = \) pressure
\( V = \) volume
\( N = \) number of particles in a gas
\( k_b = \) Boltzmann’s constant \( = 1.3806488(13) \times 10^{23} \text{ J/K} \)
\( \theta = \) zenith angle
\( X_0 = \) radiation length \( ( \approx 37 \text{ g/cm}^2 \) in air) 
\( t = \frac{X}{X_0} = \) atmospheric slant depth in radiation lengths 
\( t_v = \frac{X_v}{X_0} = \) vertical atmospheric depth in radiation lengths 
\( t_{max} = \ln \left( \frac{E}{E_c} \right) = \) atmospheric slant depth of shower maximum in radiation lengths 
\( s = \frac{3t}{t + 2T_{max}} = \) shower age 
\( E = \) energy of shower 
\( E_c = 2.2 \text{ MeV cm}^2/\text{g} \) \( X_0 \approx 81 \text{ MeV} = \) critical energy 
\( E_s = \sqrt{\frac{4\pi}{\alpha}} m_e c^2 \approx 21 \text{ MeV} = \) scale energy 
\( R_M = X_0 \frac{E_s}{E_c} \approx \frac{21}{2.2} \approx 9.5 \text{ g/cm}^2 = \) Moliere unit 
\( r_m = \) distance measured in meters 
\( r_M = \frac{r(m)\eta}{R_M} = \) distance measured in Moliere units 
\( g = \) acceleration due to gravity 
\( \Gamma(x) = \) Gamma function \( = \int_0^\infty e^{-t}t^{x-1}dt \) 
\( \Psi(x) = \) Digamma function \( = \frac{d}{dx} \ln \Gamma(x) = \frac{\Gamma'(x)}{\Gamma(x)} \) 
\( B(x,y) = \) Beta function \( = \frac{\Gamma(x)\Gamma(y)}{\Gamma(x+y)} \) 

\[ (4.1) \]

The Greisen formula gives the number of charged particles as a function of
atmospheric depth [16].

\[ N(s, t) = \frac{0.31}{\sqrt{t_{\text{max}}}} e^{t_s \frac{\eta}{R_M^2}} \]  

(4.2)

The NKG function gives the charged particle density as a function of distance with dependence on the age of the shower [16]. Note that \( r \) here denotes \( r_M \), a dimensionless quantity.

\[ \rho = \frac{N(s)\eta^2}{R_M^2} \frac{r^{s-2}(1 + r)^{s-4.5}}{2\pi B(s, 4.5 - 2s)} \]  

(4.3)

The ideal gas law is

\[ PV = Nk_b T \]  

(4.4)

We start by writing the change in charged particle density as a function of change in shower age and distance. Then we will solve for and plug in the derivatives.

\[ \Delta \rho = \frac{\delta \rho}{\delta r} \left( \frac{\delta r}{\delta T} \Delta T + \frac{\delta r}{\delta P} \Delta P \right) + \frac{\delta \rho}{\delta \eta} \left( \frac{\delta \eta}{\delta T} \Delta T + \frac{\delta \eta}{\delta P} \Delta P \right) + \frac{\delta \rho}{\delta s} \left( \frac{\delta s}{\delta T} \Delta T + \frac{\delta s}{\delta P} \Delta P \right) \]  

(4.5)

First, use geometry to simplify \( \Delta t \), remembering that \( \theta \) is measured from the vertical:

\[ \cos \theta = \frac{t_v}{t} \Rightarrow \Delta t = \frac{\Delta t_v}{\cos \theta} = \sec \theta \Delta t_v \]  

(4.6)

Now we have

\[ \Delta \rho = \frac{\delta \rho}{\delta r} \left( \frac{\delta r}{\delta T} \Delta T + \frac{\delta r}{\delta P} \Delta P \right) + \frac{\delta \rho}{\delta \eta} \left( \frac{\delta \eta}{\delta T} \Delta T + \frac{\delta \eta}{\delta P} \Delta P \right) + \frac{\delta \rho}{\delta s} \frac{\delta s}{\delta t} \sec \theta \Delta t_v \]  

(4.7)

Note that the \( \rho \) we want is \( \rho \) at 1000 m. Therefore, \( \frac{\delta r}{\delta T} \) and \( \frac{\delta r}{\delta P} \) denote the derivatives at \( r = 1000 \) m. Calculate \( \frac{\delta \rho}{\delta r} \) using Eqn. 4.3.

\[ \frac{\delta}{\delta r} \rho = \frac{\delta}{\delta r} \left[ \frac{N(s)\eta^2}{R_M^2} \frac{r^{s-2}(1 + r)^{s-4.5}}{2\pi B(s, 4.5 - 2s)} \right] \]
\[
N(s)\eta^2 \frac{1}{R_M^2} 2\pi B(s, 4.5 - 2s) \left[ (s - 2) r^{s-3} (1 + r)^{s-4.5} + r^{s-2} (s - 4.5)(1 + r)^{s-5.5} \right] = \frac{N(s)\eta^2}{R_M^2} \frac{r^{s-2} (1 + r)^{s-4.5}}{2\pi B(s, 4.5 - 2s)} \left[ (s - 2) \frac{1}{r} + (s - 4.5) \frac{1}{1 + r} \right] = \rho \left[ \frac{s - 2}{r} + \frac{s - 4.5}{1 + r} \right] = \rho \left[ \frac{(s - 2)(1 + r) + (s - 4.5)r}{r(1 + r)} \right] = \rho \frac{1}{r(1 + r)} \left[ s + sr - 2 - 2r + sr - 4.5r \right] = \frac{\rho}{r(1 + r)} \left[ s + 2sr - 2 - 6.5r \right]
\] (4.8)

Now find \( \delta r / \delta T \). Rearranging Eqn. 4.4 we have

\[
\frac{N}{V} = \frac{P}{k_b T} = \eta
\] (4.9)

Using this and the relation between \( r_M \) and \( r_m \) we have

\[
r_M = r_m \frac{\eta}{R_M} = r_m \frac{P}{k_b T R_M} \frac{1}{R_M}
\] (4.10)

Taking the derivative

\[
\frac{\delta r_M}{\delta T} = -r_m \frac{1}{k_b T^2} \frac{P}{R_M} = -r_m \frac{1}{T} \frac{1}{R_M} = -\frac{r_M}{T}
\] (4.11)

Next find \( \delta r / \delta P \). Taking the derivative of Eqn. 4.10 with respect to \( P \) we have

\[
\frac{\delta r_M}{\delta P} = r_m \frac{1}{k_b T} \frac{1}{R_M} = r_m \frac{1}{P} \frac{1}{R_M} = \frac{r_M}{P}
\] (4.12)

Now calculate \( \delta \rho / \delta \eta \). From Eqn. 4.3

\[
\frac{\delta}{\delta \eta} \rho = \frac{\delta}{\delta \eta} \left[ \frac{N(s)\eta^2}{R_M^2} \frac{r^{s-2} (1 + r)^{s-4.5}}{2\pi B(s, 4.5 - 2s)} \right]
\]
\[
\frac{\delta \eta}{\delta T} = \frac{-1}{k_B} \frac{P}{T^2} = -\frac{\eta}{T} \tag{4.15}
\]

and
\[
\frac{\delta \eta}{\delta P} = \frac{1}{k_B} \frac{1}{T} = \frac{\eta}{P} \tag{4.16}
\]

Next calculate \(\frac{\delta \rho}{\delta s}\) using Eqn. 4.3.
\[
\frac{\delta \rho}{\delta s} = \frac{\delta}{\delta s} \left[ N(s) \eta^2 \frac{r^{s-2} (1 + r)^{s-4.5}}{R_M^2 \pi B(s, 4.5 - 2s)} \right]
\]
\[
= \frac{\eta^2}{2\pi R_M^2} \frac{\delta}{\delta s} \left[ N(s) \frac{r^{s-2} (1 + r)^{s-4.5}}{B(s, 4.5 - 2s)} \right]
\]
\[
= \frac{\eta^2}{2\pi R_M^2} \frac{\delta}{\delta s} [AC] \text{ where } A = \frac{N(s)}{B(s, 4.5 - 2s)} \text{ and } C = r^{s-2} (1 + r)^{s-4.5}
\]
\[
= \frac{\eta^2}{2\pi R_M^2} [AC' + A'C]
\]
\[
= \frac{\eta^2}{2\pi R_M^2} \left[ \frac{N(s)}{B(s, 4.5 - 2s)} \frac{r^{s-2} \ln (1 + r) + r^{s-2} (1 + r)^{s-4.5} \ln (1 + r) + r^{s-2} (1 + r)^{s-4.5}}{B(s, 4.5 - 2s)^2} \right]
\]
using \(\frac{d}{dx} a^x = a^x \ln x\)
\[
= \frac{\eta^2}{2\pi R_M^2} \frac{N(s)}{B(s, 4.5 - 2s)} r^{s-2} (1 + r)^{s-4.5} \times
\]
\[
\ln r + \ln (1 + r) - \frac{B'(s, 4.5 - 2s)}{B(s, 4.5 - 2s)} \frac{N'(s)}{N(s)} = \rho \left[ \ln r + \ln (1 + r) - \frac{1}{B(s, 4.5 - 2s)} \frac{dB(s, 4.5 - 2s)}{ds} + \frac{1}{N(s)} \frac{dN(s)}{ds} \right]
\]

(4.17)

Now evaluate \( \frac{d}{ds} B(s, 4.5 - 2s) \) using the fact that

\[
\frac{d}{dx} B(x, y) = B(x, y)[\Psi(x) - \Psi(x + y)]
\]

(4.18)

where \( \Psi(x) \) is the digamma function.

\[
\frac{d}{ds} B(s, 4.5 - 2s) = B(s, 4.5 - 2s)[\Psi(s) - \Psi(4.5 - s)] + B(s, 4.5 - 2s)[\Psi(4.5 - 2s) - \Psi(4.5 - s)](-2)
= B(s, 4.5 - 2s)[\Psi(s) + \Psi(4.5 - s) - 2\Psi(4.5 - 2s)]
\]

(4.19)

Next rewrite \( N(s,t) \) from Eqn. 4.2 in terms of \( s \) only. From the definition of \( s \),

\[
\begin{align*}
  s & \equiv \frac{3t}{t + 2t_{\text{max}}} \\
  (t + 2t_{\text{max}})s &= 3t \\
  3t - st &= 2t_{\text{max}}s \\
  t(3 - s) &= 2t_{\text{max}}s \\
  t &= \frac{2st_{\text{max}}}{3 - s}
\end{align*}
\]

(4.20)

Therefore,

\[
N(s) = \frac{0.31}{\sqrt{t_{\text{max}}}} e^{\frac{2st_{\min}}{3 - s}} s^{-3st_{\min}}
\]

(4.21)

Next find \( \frac{d}{dx} x^{f(x)} \).

\[
\frac{d}{dx} \ln x^{f(x)} = \frac{d}{dx} (f(x) \ln x) = \frac{f(x)}{x} + f'(x) \ln x
\]
So \( \frac{d}{dx} x^f(x) = x^f(x) \left( \frac{f(x)}{x} + f'(x) \ln x \right) \) 

(4.22)

Use Eqns. 4.21 and 4.22 to evaluate \( \frac{dN(s)}{ds} \).

\[
\frac{d}{ds} N(s) = \frac{d}{ds} \left( \frac{0.31}{\sqrt{\tau_{\text{max}}}} e^{\frac{2 \tau_{\text{max}} t_{\text{max}}}{3-s} s^{-3 s \tau_{\text{max}}}} \right) \\
= \frac{0.31}{\sqrt{\tau_{\text{max}}}} \left[ e^{\frac{2 \tau_{\text{max}} t_{\text{max}}}{3-s} \left( \frac{2 t_{\text{max}}}{3-s} + \frac{2 s t_{\text{max}}}{(3-s)^2} \right)} s^{-3 s \tau_{\text{max}}} \right. \\
\left. + e^{\frac{2 \tau_{\text{max}} t_{\text{max}}}{3-s} s^{-3 s \tau_{\text{max}}}} \left( \frac{1-3 s t_{\text{max}}}{s} \ln s \left( \frac{-3 t_{\text{max}}}{3-s} \right) \right) \right] \\
= \frac{0.31}{\sqrt{\tau_{\text{max}}}} e^{\frac{2 \tau_{\text{max}} t_{\text{max}}}{3-s} s^{-3 s \tau_{\text{max}}}} \times \\
\left[ \frac{2 t_{\text{max}}}{3-s} + \frac{2 s t_{\text{max}}}{(3-s)^2} - \frac{3 t_{\text{max}} \ln s}{3-s} - \frac{3 s t_{\text{max}} \ln s}{(3-s)^2} \right] \\
= N(s) \frac{t_{\text{max}}}{(3-s)^2} \left[ 6 - 2 s + 2 s - 9 s - 9 \ln s + 3 \ln s - 3 \ln s \right] \\
= N(s) \frac{t_{\text{max}}}{(3-s)^2} \left[ 3 s - 3 - 9 \ln s \right] \\
= \frac{dN(s)}{ds} \\
(4.23)

Now plug Eqns. 4.19 and 4.23 back into Eqn. 4.17.

\[
\frac{\delta \rho}{\delta s} = \rho \left[ \ln r + \ln \left( 1 + r \right) - \Psi(s) - \Psi(4.5 - s) + 2 \Psi(4.5 - 2s) + \frac{t_{\text{max}}}{(3-s)^2} (3s - 3 - 9 \ln s) \right] \\
= \frac{3}{t + 2 t_{\text{max}}} - \frac{3 t}{(t + 2 t_{\text{max}})^2} \\
= \frac{3 t + 6 t_{\text{max}} - 3 t}{(t + 2 t_{\text{max}})^2} \\
(4.24)

Next calculate \( \frac{\delta s}{\delta t} \).

\[
\frac{\delta s}{\delta t} = \frac{3}{t + 2 t_{\text{max}}} \left( t + 6 t_{\text{max}} - 3 t \right) \\
= \frac{t + 6 t_{\text{max}} - 3 t}{(t + 2 t_{\text{max}})^2} \\
42
Now look at the third term of Eqn. 4.7 and find $\Delta t_v$ for a change in $P$, $\Delta P$.

\[
t_v = \frac{X_v}{\chi_0} = \frac{P}{g\chi_0}
\]
\[
dt_v\bigg|_{dP} = \frac{1}{g\chi_0}
\]
\[
dt_v = \frac{1}{g\chi_0} dP
\]
\[
\Delta t_v = \frac{\Delta P}{g\chi_0}
\]

(4.26)

Insert Eqns. 4.8 and 4.11 into the first term of Eqn. 4.7; Eqns. 4.8 and 4.12 into the second term; Eqns. 4.13 and 4.15 into the third term, Eqns. 4.13 and 4.16 into the fourth term, and Eqns. 4.24, 4.25, and 4.26 into the fifth term.

\[
\Delta \rho = \frac{\partial \rho}{\partial r} \left( \frac{\partial r}{\partial T} \Delta T + \frac{\partial r}{\partial P} \Delta P \right) + \frac{\partial \rho}{\partial \eta} \left( \frac{\partial \eta}{\partial T} \Delta T + \frac{\partial \eta}{\partial P} \Delta P \right) + \frac{\partial \rho}{\partial s} \frac{\partial s}{\partial t} \sec \theta \Delta t_v
\]
\[
= \frac{\rho}{r_M (1 + r_M)} \left[ s + 2sr_M - 2 - 6.5r_M \right] \left( -r_M \frac{\Delta T}{T} + r_M \frac{\Delta P}{P} \right) + 2 \rho \left( -\frac{\Delta T}{T} + \frac{\Delta P}{P} \right)
\]
\[
+ \rho \ln r_M + \ln (1 + r_M) - \Psi(s) - \Psi(4.5 - s) + 2\Psi(4.5 - 2s) + \frac{t_{\text{max}}}{(3 - s)^2} (3s - 3 - 9 \ln s) \frac{6t_{\text{max}}}{(t + 2t_{\text{max}})^2} \sec \theta \frac{\Delta P}{g\chi_0}
\]

(4.27)

\[
\Delta \rho \rho = \frac{1}{1 + r_M} \left[ s + 2sr_M - 2 - 6.5r_M \right] \left( -\frac{\Delta T}{T} + \frac{\Delta P}{P} \right) + 2 \left( -\frac{\Delta T}{T} + \frac{\Delta P}{P} \right)
\]
\[
+ \frac{6t_{\text{max}} \sec \theta}{(t + 2t_{\text{max}})^2} \ln r_M + \ln (1 + r_M) - \Psi(s) - \Psi(4.5 - s) + 2\Psi(4.5 - 2s) + \frac{t_{\text{max}}}{(3 - s)^2} (3s - 3 - 9 \ln s) \frac{\Delta P}{g\chi_0}
\]
\[
= \frac{1}{1 + r_M} \left[ s + 2sr_M - 2 - 6.5r_M + 2(1 + r_M) \right] \left( -\frac{\Delta T}{T} + \frac{\Delta P}{P} \right)
\]
\[
+ \frac{6t_{\text{max}} \sec \theta}{(t + 2t_{\text{max}})^2} \ln r_M + \ln (1 + r_M) - \Psi(s) - \Psi(4.5 - s) + 2\Psi(4.5 - 2s)
\]
\[
\frac{\Delta \rho}{\rho} = \frac{1}{1 + r_M} [s + 2sr_M - 4.5r_M] \left( \frac{-\Delta T}{T} + \frac{\Delta P}{P} \right) \\
+ \frac{6t_{max} \sec \theta}{(t + 2t_{max})^2} [\ln r_M + \ln (1 + r_M) - \Psi(s) - \Psi(4.5 - s) + 2\Psi(4.5 - 2s)] \\
+ \frac{t_{max}}{(3 - s)^2} (3s - 3 - 9 \ln s)] \Delta t_v
\]

(4.28)

Therefore the final result for the fractional charged particle density change given a temperature and pressure change is

\[
\frac{\Delta \rho}{\rho} = \frac{1}{1 + r_M} [s + 2sr_M - 4.5r_M] \left( \frac{-\Delta T}{T} + \frac{\Delta P}{P} \right) \\
+ \frac{6t_{max} \sec \theta}{(t + 2t_{max})^2} [\ln r_M + \ln (1 + r_M) - \Psi(s) - \Psi(4.5 - s) + 2\Psi(4.5 - 2s)] \\
+ \frac{t_{max}}{(3 - s)^2} (3s - 3 - 9 \ln s)] \Delta t_v
\]

(4.28)

4.3 How much of an effect do we expect?

Having shown that an effect is expected, we now attempt to quantify the magnitude. Changes are calculated for five different angular values (sec \( \theta \) equal to 1.0, 1.2, 1.4, 1.6, and 1.8) and four different values of \( X_{max} \) (700, 750, 800, and 850 g/cm\(^2\)). The fractional change in charged particle density is listed in Tab. 4.1 for a 1 K increase in temperature about a reference temperature of 284 K and for a 1 hPa increase about a reference pressure of 862 hPa.

The charged particle density is expected to change by approximately 0.7% per
Table 4.1: The expected fractional change in charged particle density based on a 1 K temperature change and a 1 hPa pressure change for a purely electromagnetic shower.

<table>
<thead>
<tr>
<th>sec $\theta$</th>
<th>1.000</th>
<th>1.200</th>
<th>1.400</th>
<th>1.600</th>
<th>1.800</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta$</td>
<td>0.000</td>
<td>33.557</td>
<td>44.415</td>
<td>51.318</td>
<td>56.251</td>
</tr>
<tr>
<td>$X_{max} = 700.0 \frac{g}{cm^2}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dT term</td>
<td>6.812E-3</td>
<td>5.921E-3</td>
<td>5.149E-3</td>
<td>4.472E-3</td>
<td>3.876E-3</td>
</tr>
<tr>
<td>dP terms</td>
<td>-2.168E-3</td>
<td>-2.291E-3</td>
<td>-2.467E-3</td>
<td>-2.681E-3</td>
<td>-2.925E-3</td>
</tr>
<tr>
<td>$X_{max} = 750.0 \frac{g}{cm^2}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dT term</td>
<td>7.140E-3</td>
<td>6.262E-3</td>
<td>5.496E-3</td>
<td>4.822E-3</td>
<td>4.225E-3</td>
</tr>
<tr>
<td>dP terms</td>
<td>-2.159E-3</td>
<td>-2.278E-3</td>
<td>-2.449E-3</td>
<td>-2.660E-3</td>
<td>-2.899E-3</td>
</tr>
<tr>
<td>$X_{max} = 800.0 \frac{g}{cm^2}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dT term</td>
<td>7.441E-3</td>
<td>6.577E-3</td>
<td>5.818E-3</td>
<td>5.149E-3</td>
<td>4.552E-3</td>
</tr>
<tr>
<td>dP terms</td>
<td>-2.146E-3</td>
<td>-2.260E-3</td>
<td>-2.427E-3</td>
<td>-2.634E-3</td>
<td>-2.870E-3</td>
</tr>
<tr>
<td>$X_{max} = 850.0 \frac{g}{cm^2}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dT term</td>
<td>7.719E-3</td>
<td>6.868E-3</td>
<td>6.119E-3</td>
<td>5.454E-3</td>
<td>4.860E-3</td>
</tr>
<tr>
<td>dP terms</td>
<td>-2.128E-3</td>
<td>-2.237E-3</td>
<td>-2.401E-3</td>
<td>-2.604E-3</td>
<td>-2.837E-3</td>
</tr>
</tbody>
</table>

degree K at small zenith angles. This effect should decrease to roughly 0.4% at large zenith angles. A 1 hPa increase in pressure should decrease the rate by approximately 0.2 - 0.3% depending on the zenith angle, events with larger angles being more affected. Although in some cases the pressure coefficients have a larger magnitude than the temperature coefficients, the effect of pressure variations are expected to be less than the effects of temperature variation by roughly an order of magnitude. Over the course of a year, the pressure varies by approximately 10 hPa while the temperature can vary by over 45 K. These calculated coefficients are comparable to those empirically derived in [58] and [59]. Those derived in [58] are possibly more relevant as they relate directly to the Pierre Auger Observatory data and are determined for the event energies studied here.

Note that the previous calculation assumes a 100% electromagnetic shower, one with no hadronic component. In fact, the Auger water tanks have a strong response to muons in a shower, in addition to the electromagnetic part of the shower. The muonic component of a shower is not expected to be affected by atmospheric effects since muons, once created, are not sensitive to changes in the
air density. Thus the actual expected effect of temperature and pressure is

\[
\left( \frac{\Delta \rho}{\rho} \right)_{\text{exp}} = f_{\text{em}} \left( \frac{\Delta \rho}{\rho} \right)_{\text{calc}}
\]

(4.29)

where \( f_{\text{em}} \) is the fraction of the shower that is electromagnetic, \( (\Delta \rho/\rho)_{\text{calc}} \) is the change calculated above, and \( (\Delta \rho/\rho)_{\text{exp}} \) is the actual expected change. Note that one could solve for \( f_{\text{em}} \) given the values of the table above and a measurement of the actual change, thus providing a rudimentary composition analysis.

### 4.4 Calculation of Electromagnetic Fraction

Alternatively, one can calculate the fraction of the shower that is electromagnetic as a function of zenith angle and then compare the measured parameters to the calculated ones. We present the calculation here.

Let \( \kappa \) denote the ratio of the electromagnetic signal at angle \( \theta \) to the vertical (0°) electromagnetic signal.

\[
\kappa = \frac{S_{\text{em}}(\theta)}{S_{\text{em}}(0)} = \frac{e^{t S - \frac{\theta}{2}}}{e^{t_v S - \frac{\theta}{2}}}
\]

(4.30)

If we assume that \( t_v = t_{\text{max}} \) and note that the shower maximum occurs at \( s = 1 \), then

\[
\kappa = \frac{e^{t S - \frac{3 \theta}{2}}}{e^{t_{\text{max}} S - \frac{3 \theta}{2}}}
\]

(4.31)

Noting that \( t = t_v \sec \theta \) and defining \( y = \sec \theta - 1 \) we write

\[
\kappa = e^{t_{\text{max}} \sec \theta - t_{\text{max}} S \cdot \frac{3 \theta}{2}} = e^{t_{\text{max}} y S \cdot \frac{3 \theta}{2} + y (y + 1)}
\]

(4.32)

From the definitions of \( s, t, \) and \( y, \)

\[
s = \frac{3t}{t + 2t_{\text{max}}} = \frac{3t_{\text{max}} \sec \theta}{t_{\text{max}} \sec \theta + 2t_{\text{max}}} = \frac{3t_{\text{max}} y + 3}{t_{\text{max}} y + 3} = \frac{3y + 3}{y + 3}
\]

(4.33)

Then

\[
\kappa = e^{t_{\text{max}} y \left( \frac{3y + 3}{y + 3} \right)^{-\frac{3}{2} t_{\text{max}} (y + 1)}}
\]

(4.34)
The fraction of the shower that is electromagnetic, $f_{em}$, is

$$f_{em} = \frac{S_{em}}{S_{total}} = \frac{S_{em}}{S_{em} + S_{\mu}} = \frac{S_{em}(\theta)}{S_{em}(0)} + \frac{S_{\mu}(\theta)}{S_{em}(0)} = \frac{\kappa}{\kappa + 1} = 1 - \frac{1}{\kappa + 1} \quad (4.35)$$

where $S_{total}$ is the total signal, $S_{\mu}(\theta)$ is the muonic signal, and we assume $S_{em}(0) = S_{\mu}(\theta) = \text{constant}$.

Plotting the above function using $t_{max} = 25$ yields the curve shown in Fig. 4.1. One can see that the electromagnetic fraction decreases from 0.5 for vertical showers to 0.1 for showers at an angle of $51^\circ$ degrees. This agrees well with other calculations of $f_{em}$ as a function of zenith angle, for example, as shown in [58].
4.5 Relation Between Atmospheric Coefficients

In the preceding sections we derived a relation between the change in charged particle density at ground level and a change in temperature and pressure. Since we desire to correct the energies and rates of events we now calculate how they relate to a change in charged particle density. Throughout this section \( Y_o \) denotes the value of variable \( Y \) at reference atmospheric parameters.

For simplicity we denote a change in atmospheric parameters as \( (x - x_o) \), the charged particle density at ground level as \( \rho \), and the charged particle density correction coefficient as \( A \). Then

\[
-\frac{\Delta \rho}{\rho} = \frac{\rho_o - \rho}{\rho} = A(x - x_o) \Rightarrow \rho_o = \rho + \Delta \rho = \rho + A(x - x_o) \rho = \rho(1 + A(x - x_o)) \\
\]

However, \( A \) assumes purely electromagnetic showers. Since this is not the case we define \( \alpha = f_{em}A \) where \( f_{em} \) is the electromagnetic fraction of the signal 1000 m from the core. Since the signal measured at 1000 m from the core, \( S(1000) \), is proportional to \( \rho \) we write

\[
S(1000)_o = S(1000)[1 + \alpha(x - x_o)]
\]

The reconstructed energy, \( E_r \), is proportional to \( S(1000)^B \) where B comes from calibrating the SD energy using the FD energy measurement [58]. The corrected energy, \( E_o \), is then

\[
E_o = CS(1000)^B_o = CS(1000)^[1 + \alpha(x - x_o)]^B = E_r[1 + \alpha(x - x_o)]^B \]

where \( C \) is the proportionality constant. We now work out how the rate changes. The rate \( R \) of events per unit time above a signal \( S_{min} \) is given by

\[
R \propto G \int_{S_{min}} dS \frac{dJ}{dS} \]

where \( G \) is the geometric aperture and \( J \) is the cosmic ray flux [58]. We neglect
any trigger effects here. Assume that the cosmic ray spectrum is a pure power law

\[
\frac{dJ}{dE_o} \propto E_o^{-\gamma}
\]  

(4.40)

Then

\[
\frac{dJ}{dS} = \frac{dJ}{dE_o} \frac{dE_o}{dS} = E_o^{-\gamma} \frac{dE_o}{dS} = \frac{dE_o}{dS} \cdot [S(1000)^B(1 + \alpha(x - x_o))^B]^{-\gamma} BS(1000)^{B-1}[1 + \alpha(x - x_o)]^B
\]

\[
\propto S(1000)^{-B\gamma+B-1}[1 + \alpha(x - x_o)]^{-B\gamma}[1 + \alpha(x - x_o)]^B
\]

\[
\propto S(1000)^{-B\gamma+B-1}[1 + \alpha(x - x_o)]^{-B\gamma+B} \alpha(x - x_o)
\]

\[
\propto S(1000)^{-B\gamma+B-1}[1 + (-B\gamma + B)\alpha(x - x_o)]
\]

\[
\propto S(1000)^{-B\gamma+B-1}[1 - (B\gamma - B)\alpha(x - x_o)]
\]

(4.41)

where \(a = B(\gamma - 1)\alpha\). Plugging the result into Eqn. 4.39 we obtain

\[
R \propto \left[1 - a(x - x_o)\right] G \int_{S_{\min}} dSS^{-B\gamma+B-1}
\]

\[
R = R_o - \Delta R
\]

\[
R_o = R + \Delta R = [1 + a(x - x_o)]R
\]

(4.42)

So

\[
a = B(\gamma - 1)\alpha = B(\gamma - 1)f_{em}A
\]

(4.43)

where \(A\), \(\alpha\), and \(a\) are the correction coefficients for the charged particle density, electromagnetic fraction of \(S(1000)\), and rate. \(B\) comes from SD energy calibration using the FD and \(\gamma\) is the spectral index.
4.6 Conclusion

In this chapter we presented both a qualitative and a quantitative argument for how the atmosphere affects the development of extensive air showers. We expect to observe higher rates of events with higher temperatures and lower air pressures due to showers appearing more energetic when the temperature is higher and when the air pressure is lower.

The magnitudes of these effects were calculated and are shown in Tab. 4.1. We expect approximately a 0.6% increase in the charged particle density per 1°C increase in temperature. We expect approximately a 0.2% decrease in the charged particle density per 1 hPa increase in pressure.

Lastly, we determined the relation between the atmospheric coefficients for charged particle density, energy, and rate. The relation is given by Eqn. 4.43.
Chapter 5

Weather Effects Observed Using Direct Binning

Errors using inadequate data are much less than those using no data at all.

–Charles Babbage

Having calculated the expected effect of atmospheric variations on the rate, we now turn to the data to see what effect is observed. Since the expected relation is linear, to determine how the rate is affected by atmospheric parameters, we bin the exposure and events by the atmospheric parameter we want to study, calculate the rate, convert to the fractional rate, and fit a line through the resulting points. The method is described in Sec. 5.1. Results using temperature are presented in Sec. 5.2; those using pressure are presented in Sec. 5.3. Sec. 5.4 discusses the effect of changing the count threshold for including a bin in the linear fit. Sec. 5.5 discusses the effect of different seasonal definitions. Possible effects of temperature inversions and time offsets are discussed in Sec. 5.6. Finally, the result of applying the corrections is checked in Sec. 5.7. It is found that the corrections do not fully remove the atmospheric variations; therefore, another method of determining the coefficients is needed. Such a method will be described in Ch. 6. The coefficients are compared to the expected values in Sec. 5.8. Concluding remarks are found in Sec. 5.9.
5.1 Method

To study temperature effects, we use 5°C temperature bins centered on 0°C. The exposure in each temperature bin is calculated. We then count the number of events in each temperature bin. Dividing the two yields the rate.

\[ R_i = \frac{C_i}{E_i} \]  \hspace{1cm} (5.1)

where \( R_i \) is the rate, \( C_i \) is the number of events, and \( E_i \) is the exposure in bin \( i \).

The fractional rate is then found using

\[ R_i^{frac} = \frac{R_i - \langle R \rangle}{\langle R \rangle} \]  \hspace{1cm} (5.2)

where \( R_i^{frac} \) is the fractional rate in bin \( i \), \( R_i \) is the rate in bin \( i \), and \( \langle R \rangle \) is the average rate. \( \langle R \rangle \) is obtained by averaging the rate over all bins that have more than 12 events. In the case of specific cuts - seasonal, angular, etc - we use the specific average rate to obtain the fractional rate. For example, the fractional rate in summer is found using the average rate in summer, not the average rate across all seasons.

The uncertainty in the rate, \( \sigma_i \), is equal to the square root of the number of counts, \( C_i \), divided by the exposure, \( E_i \), in bin \( i \).

\[ \sigma_i = \frac{\sqrt{C_i}}{E_i} \]  \hspace{1cm} (5.3)

The uncertainty in the fractional rate, \( \sigma_i^{frac} \), is

\[ \sigma_i^{frac} = \frac{\sigma_i}{\langle R \rangle} \]  \hspace{1cm} (5.4)

where \( \sigma_i \) is the rate uncertainty in bin \( i \), and \( \langle R \rangle \) is the average rate.

A weighted least squares fit is performed to calculate the linear fit. All bins with more than 12 events are used. The slope of the fit is equal to the fractional rate change coefficient. To study pressure effects, we use 1 hPa bins centered on the hPa. The method is identical otherwise. Throughout this analysis we use Observer v2r5p6 data from 2005 - 2008. Energy, angle, season, and diurnal cuts
are described as they are presented below.

## 5.2 Results Using Temperature

We first present the results of studying the rate dependence on temperature. Using all events with zenith angles less than 60° we obtain the graph shown in Fig. 5.1. The fractional rate and temperature are linearly related with a slope of $0.00611 \pm 0.00033$.

To study the zenith angle dependence, we use five equal bins in $\sin^2(\theta)$ that cover the range from 0.00 to 0.75. Results are shown in Fig. 5.2 for three energy ranges: $E < 2$ EeV, $E \geq 2$ EeV, and $E \geq 0$ EeV. The all energy case and the low energy case are very similar due to the large overlap of events. However, the $E < 2$ EeV and $E \geq 2$ EeV case, which do not share events, are also consistent within uncertainties. The exception is the $0.30 \leq \sin^2(\theta) < 0.45$ case. Yet even there the difference is of marginal significance. A clear trend of decreasing temperature dependence with increasing zenith angle is seen as predicted in Ch. 4. A detailed comparison of the calculated and observed coefficients is presented later in Sec. 5.8.
Figure 5.1: Fractional rate versus temperature (°C) using all data from 2005-2008 with zenith angles less than 60 degrees.
Figure 5.2: Temperature fractional rate change coefficients found for 5 equal bins in $\sin^2(\theta)$ using events with $E < 2$ EeV (blue), $E \geq 2$ EeV (red), and $E \geq 0$ EeV (green). Note that the blue points are nearly overlaid by the green ones.
5.2.1 Seasonal Dependence

Next we study how the temperature coefficient varies with season. Seasons are defined as quarter year periods with summer centered on the summer solstice. Figs. 5.3 and 5.4 show the $0^\circ \leq \theta < 60^\circ$ zenith angle case for energies greater and less than 2 EeV. The slopes and uncertainties are listed in Tab. 5.1. The linearity is still evident.

Fig. 5.5 and 5.6 show the slopes versus zenith angle by season for $E \geq 2$ EeV and $E < 2$ EeV. The coefficients in the high energy case are consistent with no zenith angle or seasonal dependence. The low energy case has smaller uncertainties and shows a decreasing coefficient with increasing zenith angle. This is qualitatively the same pattern as derived in the preceding chapter. A closer comparison is done in Sec. 5.8. Summer has the smallest coefficient across zenith angles. Interestingly, spring, not winter, generally has the highest seasonal coefficient. The reason for this is unknown.

<table>
<thead>
<tr>
<th>Season</th>
<th>$E &lt; 2$ EeV</th>
<th>$E \geq 2$ EeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>0.00316 ± 0.00039</td>
<td>0.0049 ± 0.0014</td>
</tr>
<tr>
<td>Fall</td>
<td>0.00478 ± 0.00046</td>
<td>0.0033 ± 0.0012</td>
</tr>
<tr>
<td>Winter</td>
<td>0.00499 ± 0.00054</td>
<td>0.0045 ± 0.0013</td>
</tr>
<tr>
<td>Spring</td>
<td>0.00549 ± 0.00047</td>
<td>0.0047 ± 0.0011</td>
</tr>
<tr>
<td>All</td>
<td>0.00620 ± 0.00034</td>
<td>0.0052 ± 0.0006</td>
</tr>
</tbody>
</table>

Table 5.1: Slope of linear fit to fractional rate versus temperature line by season using data from 2005-2008 and $\theta \leq 60^\circ$ degrees.
Figure 5.3: Fractional rate versus temperature (° C) by season using data from 2005-2008, $E \geq 2$ EeV, and $\theta \leq 60^\circ$ degrees.
Figure 5.4: Fractional rate versus temperature (° C) by season using data from 2005-2008, $E < 2$ EeV, and $\theta \leq 60^\circ$ degrees.
Figure 5.5: Fractional rate change coefficients found by season for 5 equal bins in $\sin^2(\theta)$ using events with $E \geq 2$ EeV.
Figure 5.6: Temperature fractional rate change coefficients found by season for 5 equal bins in $\sin^2(\theta)$ using events with $E < 2$ EeV.
5.2.2 Day and Night Dependence

Now we determine whether the temperature coefficient varies over the course of the day by dividing the day into day and night periods. We define the transitions at 10:00 and 22:00 UTC, or 7:00 am and 7:00 pm local time. The $E \geq 2$ EeV and $E < 2$ EeV cases for zenith angles less than $60^\circ$ are shown in Figs. 5.7 and 5.8 respectively.

To see if the slopes are significantly different we look at the slope versus season graphs for the two energy cases, as shown in Fig. 5.9 and 5.10. In the high energy case, the coefficients are consistent across seasons and time of day. In the low

Figure 5.7: Fractional rate versus temperature (° C) for day and night using data from 2005-2008, $E \geq 2$ EeV, and $\theta \leq 60^\circ$ degrees.
Figure 5.8: Fractional rate versus temperature (°C) for day and night using data from 2005-2008, $E < 2$ EeV, and $\theta \leq 60°$ degrees.

energy case, with better statistics, we see a generally increasing coefficient from summer to spring. More significantly, the nighttime coefficient is higher than the daytime coefficient. The exact cause is unknown.
Figure 5.9: Temperature fractional rate change coefficients found by season using events with $E \geq 2$ EeV for day (blue), night (red), and all (green).
Figure 5.10: Temperature fractional rate change coefficients found by season using events with $E < 2$ EeV for day (blue), night (red), and all (green).
5.3 Results Using Pressure

We now turn from temperature effects to pressure effects. Using all events with zenith angles less than 60° we obtain the graph shown in Fig. 5.11. As in the temperature case, a strong correlation is seen, with some of the range of pressures yielding a linear rate change dependence. In particular, the rate appears to plateau at the lowest pressures. This might be due to a correlation between pressure and temperature. If the lowest pressures occur during the lowest temperatures in winter, the low temperatures could pull the rate down. Excluding this segment below 860 hPa, the best fit line would then fit the highest pressure points better. The slope of the fit shown by the solid blue line, which uses all bins with more than 12 counts, is \(-0.01021 \pm 0.00030\). The slope of the green line, utilizing only the points in the region above 860 hPa, where linearity is more evident, is \(-0.01406 \pm 0.00064\).

To study the zenith angle dependence we use five equal bins in \(\sin^2(\theta)\) that cover the range from 0.00 to 0.75. Results are shown in Fig. 5.12 for three energy ranges: \(E < 2\) EeV, \(E \geq 2\) EeV, and \(E \geq 0\) EeV. As in the temperature case, the low and all energy cases are very similar due to the large overlap of events. The coefficients of the \(E \geq 2\) EeV energy case are systematically higher than the coefficients of the \(E < 2\) EeV case.
Figure 5.11: Fractional rate versus pressure (hPa) using all data from 2005-2008 with zenith angles less than 60 degrees. The blue line is fit to all points with more than 12 counts per bin and has a slope of \(-0.01021 \pm 0.00030\). The green line has a slope of \(-0.01406 \pm 0.00064\) and utilizes the region above 860 hPa.
Figure 5.12: Fractional rate change coefficients found for 5 equal bins in $\sin^2(\theta)$ using events with $E < 2$ EeV (blue), $E \geq 2$ EeV (red), and $E \geq 0$ EeV (green). Note that the blue points are nearly overlaid by the green ones.
5.3.1 Seasonal Dependence

Next we study how the pressure coefficient varies with season. The $E \geq 2$ EeV and $E < 2$ EeV cases for zenith angles less than 60° are shown in figs. 5.13 and 5.14 respectively. The slopes and uncertainties are listed in Table 5.2. One immediately notes that the points overlay each other much more than in the temperature case. In the temperature case the points and fits shift along the y-axis with season. No such behavior is seen here.

Figs. 5.15 and 5.16 show the slopes versus zenith angle by season for $E \geq 2$ EeV and $E < 2$ EeV respectively. In both energy ranges the slopes are consistent across zenith angles and seasons. In the low energy case, summer has a marginally lower coefficient in the $0.00 \leq \sin^2(\theta) < 0.15$ and $0.45 \leq \sin^2(\theta) < 0.60$ cases.

<table>
<thead>
<tr>
<th>Season</th>
<th>$E &lt; 2$ EeV</th>
<th>$E \geq 2$ EeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>-0.01178 ± 0.00071</td>
<td>-0.0081 ± 0.0026</td>
</tr>
<tr>
<td>Fall</td>
<td>-0.00922 ± 0.00059</td>
<td>-0.0061 ± 0.0025</td>
</tr>
<tr>
<td>Winter</td>
<td>-0.00864 ± 0.00049</td>
<td>-0.0084 ± 0.0019</td>
</tr>
<tr>
<td>Spring</td>
<td>-0.00931 ± 0.00044</td>
<td>-0.0054 ± 0.0018</td>
</tr>
<tr>
<td>All</td>
<td>-0.01036 ± 0.00031</td>
<td>-0.0076 ± 0.0011</td>
</tr>
</tbody>
</table>

Table 5.2: Slope of linear fit to fractional rate versus pressure by season using data from 2005-2008 and $\theta \leq 60^\circ$. 

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Figure 5.13: Fractional rate versus pressure (hPa) by season using data from 2005-2008, $E \geq 2$ EeV, and $\theta \leq 60^\circ$. 
Figure 5.14: Fractional rate versus pressure (hPa) by season using data from 2005-2008, $E < 2$ EeV, and $\theta \leq 60^\circ$. 
Figure 5.15: Pressure fractional rate change coefficients found by season for 5 equal bins in $\sin^2(\theta)$ using events with $E \geq 2$ EeV.
Figure 5.16: Pressure fractional rate change coefficients found by season for 5 equal bins in $\sin^2(\theta)$ using events with $E < 2$ EeV.
5.3.2 Day and Night Dependence

To determine whether the pressure coefficient varies over the course of the day, the day is divided into day and night as before. The $E \geq 2$ EeV and $E < 2$ EeV cases for zenith angles less than $60^\circ$ are shown in Figs. 5.17 and 5.18 respectively. As in the seasonal cases, the points overlay each other. This is also true of the day and night temperature case.

Figs. 5.19 and 5.20 show the slope versus season by time of day for the two energy cases. In the $E \geq 2$ EeV case, the coefficients are consistent between day and night and across all seasons. In the $E < 2$ EeV case, the day and night coefficients are consistent although some seasonal variation is seen.

![Figure 5.17: Fractional rate versus pressure (hPa) for day and night using data from 2005-2008, $E \geq 2$ EeV, and $\theta \leq 60^\circ$.](image-url)
Figure 5.18: Fractional rate versus pressure (hPa) for day and night using data from 2005-2008, $E < 2$ EeV, and $\theta \leq 60^\circ$. 
Figure 5.19: Fractional rate change coefficients found by season using events with $E \geq 2$ EeV for day (blue), night (red), and all (green).
Figure 5.20: Fractional rate change coefficients found by season using events with $E < 2$ EeV for day (blue), night (red), and all (green).
5.4 Effects of Count Threshold

In the linear fits, all bins with more than 12 events are used. This threshold is chosen as this is where a Poisson distribution starts to resemble a gaussian. However, it is worthwhile to study the effects of different thresholds on the linear fits. To this end, thresholds of 12, 25, 50, 100, 150, and 200 are applied to the temperature-rate linear fits and the resulting slopes are compared.

Figure 5.21 shows the slopes found using all events with energies greater than 2 EeV. The slopes are consistent across all thresholds. The same is true for the low energy counterpart, shown in figure 5.22. The story is identical when we break the

![Figure 5.21: The slope of the fractional rate as a function of temperature using events with energies ≥ 2 EeV and all seasons.](image)
data into seasons. In all cases, the slopes are consistent within error bars. Since the threshold does not affect the slope found, we continue to use a threshold of 12 counts as this provides the highest statistics per bin.

5.5 Effects of Seasonal Definitions

Fig. 5.23 shows the exposure as a function of temperature. In this figure the seasons are defined as quarter year bins with the first bin centered on January 1. Two odd features are visible. First, winter has a significantly higher integrated exposure than the other seasons. Second, spring is almost as cold as winter. Specifically
Figure 5.23: Exposure (km$^2$ day) per 5 degree C temperature bins for the range January 1, 2005 - September 1, 2008. Seasons are defined by quarter year bins centered on January 1.

looking at the lowest temperatures reached, both winter and spring have data at -20$^\circ$ C.

To study the cause of the low temperatures across seasons, the seasonal boundaries were changed to the solstices and equinoxes. That is, summer runs from December 21 - March 20, fall from March 20 to June 21, winter from June 21 to September 23, and spring from September 23 to December 21. Fig. 5.24 shows the result of making this change. The spring temperatures shift up and the fall temperatures shift down. Summer and winter temperatures do not shift visibly.
Figure 5.24: Exposure (km$^2$ day) per 5 degree C temperature bins for the range January 1, 2005 - September 1, 2008. Seasons start and end at the equinoxes and solstices.

To quantitatively study how the seasonal definitions change the seasonal temperatures, the average, high, low, 10%, and 90% temperatures of each season are calculated. Results are shown in Table 5.3. 'All' denotes data from all seasons. The temperature where 10% of the measurements are colder is denoted by '10%'. The temperature where 10% of the measurements are warmer is denoted by '90%'. These two measurements have a resolution of 2.5° C due to the histogram bin width. Average, highest, and lowest temperature are self explanatory. The average temperature is computed by summing all the temperature measurements and
Seasons defined by quarter year bins with the first bin centered on January 1

<table>
<thead>
<tr>
<th>Season</th>
<th>Summer</th>
<th>Fall</th>
<th>Winter</th>
<th>Spring</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>average temperature</td>
<td>19.0 ± 0.8</td>
<td>12.4 ± 0.8</td>
<td>4.7 ± 0.8</td>
<td>8.7 ± 0.8</td>
<td>10.7 ± 0.8</td>
</tr>
<tr>
<td>10%</td>
<td>7.5 ± 2.5</td>
<td>0.0 ± 2.5</td>
<td>-7.5 ± 2.5</td>
<td>-5.0 ± 2.5</td>
<td>-5.0 ± 2.5</td>
</tr>
<tr>
<td>90%</td>
<td>25.0 ± 2.5</td>
<td>20.0 ± 2.5</td>
<td>10.0 ± 2.5</td>
<td>17.5 ± 2.5</td>
<td>22.5 ± 2.5</td>
</tr>
<tr>
<td>lowest temperature</td>
<td>0.0 ± 2.5</td>
<td>-10.0 ± 2.5</td>
<td>-22.5 ± 2.5</td>
<td>-20.0 ± 2.5</td>
<td>-22.5 ± 2.5</td>
</tr>
<tr>
<td>highest temperature</td>
<td>37.5 ± 2.5</td>
<td>35.0 ± 2.5</td>
<td>25.0 ± 2.5</td>
<td>32.5 ± 2.5</td>
<td>37.5 ± 2.5</td>
</tr>
</tbody>
</table>

Seasons defined as the periods between solstices and equinoxes

<table>
<thead>
<tr>
<th>Season</th>
<th>Summer</th>
<th>Fall</th>
<th>Winter</th>
<th>Spring</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>average temperature</td>
<td>18.7 ± 0.8</td>
<td>7.7 ± 0.8</td>
<td>4.2 ± 0.8</td>
<td>14.6 ± 0.8</td>
<td>10.7 ± 0.8</td>
</tr>
<tr>
<td>10%</td>
<td>7.5 ± 2.5</td>
<td>-5.0 ± 2.5</td>
<td>-7.5 ± 2.5</td>
<td>2.5 ± 2.5</td>
<td>-5.0 ± 2.5</td>
</tr>
<tr>
<td>90%</td>
<td>25.0 ± 2.5</td>
<td>15.0 ± 2.5</td>
<td>12.5 ± 2.5</td>
<td>22.5 ± 2.5</td>
<td>22.5 ± 2.5</td>
</tr>
<tr>
<td>lowest temperature</td>
<td>-2.5 ± 2.5</td>
<td>-15.0 ± 2.5</td>
<td>-22.5 ± 2.5</td>
<td>-10.0 ± 2.5</td>
<td>-22.5 ± 2.5</td>
</tr>
<tr>
<td>highest temperature</td>
<td>37.5 ± 2.5</td>
<td>32.5 ± 2.5</td>
<td>30.0 ± 2.5</td>
<td>35.0 ± 2.5</td>
<td>37.5 ± 2.5</td>
</tr>
</tbody>
</table>

Table 5.3: The temperature distributions in degrees C for two different seasonal definitions using data from January 1, 2005 - September 1, 2008.

dividing by the number of measurements; therefore, its accuracy is given as the instrumental uncertainty, 0.8° C.

From Tab. 5.3 we learn that the seasonal binning method has a minimal effect on summer and winter. Spring and fall are more similar using the quarter year binning. Using the solstice and equinox seasonal definitions, fall becomes more winter-like and spring becomes more summer-like. The -20° C measurements in spring noted earlier are caused by a short cold period in early spring 2007.

Having determined the behavior of the temperature distributions, we now turn our attention to the winter exposure question. Using quarter year bins, winter has the most exposure, while the other seasons have roughly equal exposure. When using solstice/equinox seasonal definitions, winter still has the highest exposure, but the other seasons are no longer roughly equal. Summer has the lowest exposure followed by spring and fall. The following tests are performed using the solstice and equinox seasonal definition.

First, bad periods were included to test if there were fewer bad periods in winter and this was causing the difference. A slight increase in the exposure of each season is observed as expected. However, the overall exposure differences between seasons do not change.

Next, the effect of using a non-integer number of years was tested. The data range was changed to cover four integer years starting January 1, 2005. The exposure still varies by season with winter having the highest exposure, then fall, spring, and summer. To test if starting and ending in the middle of a season could have an effect, the data range was set to March 20, 2005 - March 20, 2008. Winter has the most exposure; the rest of the seasons are roughly equal. This
is unexpected since the exposure was increasing throughout this time period as the array was growing. Therefore, one expects fall to have the lowest exposure, followed by winter, spring, and summer.

A Monte Carlo simulation was developed to mimic the growth of the array. Using a linearly increasing exposure with no bad periods and a large growth rate (the exposure grows from 0 - 150 arbitrary units over the course of a year), one obtains the expected result of higher exposure in later seasons. Including bad periods and using growth rates of 3 - 5% per year does not yield this result.

At this point, the number of days in each season was calculated. That is, the number of days between the solstices and equinoxes was determined. Summer has 89 days, fall has 93, winter has 94, and spring has 89. This explains why winter and fall have the highest exposure in the above tests. When the exposure increases slowly in time, the difference of season length is the dominant factor in determining total seasonal exposure. Only when the exposure increases rapidly does the temporal increase of exposure become the main factor. Then the seasonal exposure values cycle with starting season.

However, Fig. 5.25 uses equal length seasons, yet has unequal seasonal exposure values. This is explained by a combination of the non-integer number of months, the fact that a linearly increasing exposure is only a rough approximation, and the fact that there are missing data periods. Fig. 5.25 shows the actual exposure every day in km² days as a function of time.
Figure 5.25: The exposure every day in km² days as a function of time. The start of each year is marked by a colored vertical line. The points where the exposure is unusually low are due to only a subset of the array working, or to bad periods in the data.
5.6 Effects of Temperature Inversions and Phase Offsets

Next we look for evidence of temperature inversions by comparing the slopes of the linear fits found using day and night data. This is done by season for the two energy ranges. Events with zenith angles less than 60 degrees are used. Seasons are defined as quarter year intervals with the first bin centered on the summer solstice. Day is defined as 10 am - 10 pm UTC or 7 am - 7 pm local time.

Figs. 5.9 and 5.10 show the results using events with energies greater and less than 2 EeV. For the higher energy case the day and night slopes are consistent with each other, with the exception of fall. This exception might be due to statistic fluctuations, as the difference is not highly significant. For the less than 2 EeV case, the day and night slopes are inconsistent in all cases. The results do not change when using a seasonally variable definition of day and night corresponding to the actual daylight hours.

However, one calculates that temperature inversions do not affect the slopes of the linear fits. Assume that the rate is linearly correlated with the temperature at some height, H, above the ground, where H could be zero. If the temperature profile is constant in time, changing the height of temperature used will merely shift the rate-temperature line; it will not change its slope.

If the temperature decreases with height during the day and increases with height at night, and H > 0, then the rate - ground temperature graphs will be straight lines where the line using inverted night data is shifted to the left of the line using non-inverted data. This is because at night the ground temperature is higher than the actual temperature at the altitude that matters. During the day the ground temperature is warmer than the relevant temperature. So the same rate, caused by the same temperature aloft, will correspond to a higher ground temperature during the day and a lower one at night.

This simple description neglects possible effects of the temperature profile during inversion formation and dissipation. However, we do not have a way to model these processes and thus cannot speculate on their effects.

Since temperature inversions alone do not cause different slopes something else must. What this phenomenon is cannot be determined from linear fits and simple
models. When plotting the average diurnal and annual rate, a phase offset with the diurnal and annual average temperature is visible by eye. However, the linear fit method is not well adapted to take possible phase offsets between the rate and temperature into account. The different day and night slopes could possibly be due to these phase offsets or a combination of phase offsets and temperature inversions, although no direct evidence for this connection is seen using this method. Phase offsets will be explored more thoroughly in later chapters using more sensitive methods.

5.7 Check of Atmospheric Corrections

We now correct the energies using the coefficients found above and the relationship between rate and energy correction coefficients derived in Sec. 4.5. The corrected rate, \( R_c \), has the form

\[
R_c = R[1 - a_T(T - <T>) - a_P(P - <P>)]
\] (5.5)

where \( R \) is the uncorrected rate, \( T \) is the instantaneous temperature, \( P \) is the instantaneous pressure, \( < T > \) is the average temperature (11.4° C), and \( < P > \) is the average pressure (862 hPa). All atmospheric values are from the CLF. Instantaneous means a measurement within 5 minutes of the event time.

Transforming Eqn. 5.5 into an energy correction yields

\[
E_0 = E_r[1 - \alpha_T(T - < T >) - \alpha_P(P - < P >)]^B
\] (5.6)

where \( E_0 \) is the corrected energy, \( \alpha_T = B(\gamma - 1)a_T \), and \( \alpha_P = B(\gamma - 1)a_P \), \( B = 1.08 \), and \( \gamma = 3.3 \). The other variables are the same as in Eqn. 5.5.

All events which have CLF atmospheric measurements within 5 minutes of the event time are corrected using the above formula.

Figs. 5.26 and 5.27 show the average annual and diurnal plots, respectively, for the corrected and uncorrected rates using events with energies greater than 1.5 EeV and zenith angles less than 45°. In the annual case, a clear seasonal variation is still observed using the corrected events. However, the amplitude is smaller than in the uncorrected case. The story is less clear in the diurnal case; neither
the uncorrected case nor the corrected case appear flat.

To quantify the effect of the corrections, the first harmonic power, $R$, of each case is calculated using

$$R = \sqrt{x^2 + y^2}$$

$$x = \sum_{i=1}^{N} R_i \cos\left(\frac{2\pi i}{N}\right)$$

$$y = \sum_{i=1}^{N} R_i \sin\left(\frac{2\pi i}{N}\right)$$

(5.7)

where $R_i$ is the mean-subtracted rate in bin $i$ and $N$ is the total number of bins. The normalization coefficient, $K$, is

$$K = \frac{R_R}{R_T} \frac{1}{\langle R \rangle}$$

(5.8)

where $R_R$ is the harmonic power of the rate, $R_T$ is the harmonic power of the temperature, and $\langle R \rangle$ is the average rate. For a flat rate, $K$ will be zero. $K$ increases the more sinusoidal the rate is.

Tab. 5.4 shows the results. One can see that in the seasonal case the corrections remove slightly over half of the amplitude. While the atmospheric corrections help, they only remove half of the variation present in the seasonal rate. In the diurnal case, the amplitude increases by a factor of two indicating that the corrections actually make the rate variations greater. Clearly, the usefulness of these corrections is limited. Because the corrections described in this chapter cannot remove all of the atmospheric variations seen in the rate, probably due to the inability to take separate seasonal and diurnal variations, time lags, or temperature inversions into account, we look for other ways to study rate and atmospheric relations. This other method is detailed in Ch. 6.
<table>
<thead>
<tr>
<th>Correction Method</th>
<th>$K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>uncorrected annual</td>
<td>0.00951 ± 0.00057</td>
</tr>
<tr>
<td>corrected annual</td>
<td>0.00437 ± 0.00057</td>
</tr>
<tr>
<td>uncorrected diurnal</td>
<td>0.00231 ± 0.00064</td>
</tr>
<tr>
<td>corrected diurnal</td>
<td>0.00485 ± 0.00065</td>
</tr>
</tbody>
</table>

Table 5.4: Check of weather correction methods using events with $E > 1.5$ EeV and zenith angle $< 45$ degrees. $K$ equal to 0 indicates a flat rate, one with no atmospheric variation. The higher $K$ is, the more sinusoidal the rate. The atmospheric corrections remove half the observed variation in the annual case, but actually increase the variation seen in the diurnal case.

Figure 5.26: Uncorrected (blue) and corrected (red) annual rate.
Figure 5.27: Uncorrected (blue) and corrected (red) diurnal rate.
5.8 Comparison with Calculated Coefficients

We now compare the atmospheric coefficient values found using events with energies greater than 2 EeV with those calculated in Ch. 4. The comparison for temperature is shown in Tab. 5.5. The pressure comparison is shown in Tab. 5.6. The calculated values for $X_{\text{max}} = 800$ g/cm$^2$ are used.

As shown in Sec. 4.4 the expression for the electromagnetic fraction of a shower is

$$f_{\text{em}} = \frac{\kappa}{\kappa + 1} = 1 - \frac{1}{\kappa + 1}$$

(5.9)

where

$$\kappa = e^{t_{\text{max}}y(3y + 3) - \frac{3}{2} t_{\text{max}}(y+1)}$$

(5.10)

and $y = \sec \theta - 1$.

Using $t_{\text{max}} = 25$, we calculate the expected $f_{\text{em}}$. These values are listed as the expected $f_{\text{em}}$ in Tabs. 5.5 and 5.6. Inspecting the values obtained from the temperature coefficients, we see that the calculated $f_{\text{em}}$ does not show a clear pattern. The same is true in the pressure case, although the situation is worse. In three cases, $f_{\text{em}}$ is greater than 1, a physical impossibility. Clearly, the story is more complex than a simple time independent linear relation between the rate and atmospheric ground parameters.
<table>
<thead>
<tr>
<th>$\sec \theta$</th>
<th>1.000</th>
<th>1.200</th>
<th>1.400</th>
<th>1.600</th>
<th>1.800</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta$</td>
<td>0.000</td>
<td>33.557</td>
<td>44.415</td>
<td>51.318</td>
<td>56.251</td>
</tr>
<tr>
<td>calculated charged density coefficient</td>
<td>7.441E-03</td>
<td>6.577E-03</td>
<td>5.818E-03</td>
<td>5.149E-03</td>
<td>4.552E-03</td>
</tr>
<tr>
<td>calculated rate change coefficient</td>
<td>1.848E-02</td>
<td>1.634E-02</td>
<td>1.445E-02</td>
<td>1.279E-02</td>
<td>1.131E-02</td>
</tr>
<tr>
<td>observed rate change coefficient</td>
<td>7.25 ± 0.94 E-03</td>
<td>4.26 ± 0.97 E-03</td>
<td>4.6 ± 1.0 E-03</td>
<td>5.1 ± 1.5 E-03</td>
<td>2.3 ± 1.7 E-03</td>
</tr>
<tr>
<td>calculated $f_{em}$</td>
<td>0.39 ± 0.05</td>
<td>0.26 ± 0.06</td>
<td>0.32 ± 0.07</td>
<td>0.40 ± 0.11</td>
<td>0.21 ± 0.15</td>
</tr>
<tr>
<td>expected $f_{em}$</td>
<td>0.50</td>
<td>0.43</td>
<td>0.25</td>
<td>0.09</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 5.5: Comparison between the expected temperature coefficients at $X_{max} = 800 \text{ g/cm}^2$ and those found using the linear fit method with energies $\geq 2 \text{ EeV}$. $f_{em}$ is calculated by dividing the observed change by the calculated change.
<table>
<thead>
<tr>
<th>sec $\theta$</th>
<th>1.000</th>
<th>1.200</th>
<th>1.400</th>
<th>1.600</th>
<th>1.800</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta$</td>
<td>0.000</td>
<td>33.557</td>
<td>44.415</td>
<td>51.318</td>
<td>56.251</td>
</tr>
<tr>
<td>calculated charged density coefficient</td>
<td>-2.146E-3</td>
<td>-2.260E-3</td>
<td>-2.427E-3</td>
<td>-2.634E-3</td>
<td>-2.870E-3</td>
</tr>
<tr>
<td>calculated rate change coefficient</td>
<td>-5.331E-3</td>
<td>-5.614E-3</td>
<td>-6.029E-3</td>
<td>-6.543E-3</td>
<td>-7.129E-3</td>
</tr>
<tr>
<td>observed rate change coefficient</td>
<td>$-8.2 \pm 1.7 \ E-03$</td>
<td>$-9.5 \pm 2.1 \ E-03$</td>
<td>$-4.9 \pm 2.6 \ E-03$</td>
<td>$-8.5 \pm 3.3 \ E-03$</td>
<td>$-0.9 \pm 3.6 \ E-03$</td>
</tr>
<tr>
<td>calculated $f_{em}$</td>
<td>1.53 ± 0.32</td>
<td>1.69 ± 0.37</td>
<td>0.82 ± 0.43</td>
<td>1.29 ± 0.50</td>
<td>0.12 ± 0.50</td>
</tr>
<tr>
<td>expected $f_{em}$</td>
<td>0.50</td>
<td>0.43</td>
<td>0.25</td>
<td>0.09</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 5.6: Comparison between the expected pressure coefficients at $X_{max} = 800 \ g/cm^2$ and those found using the linear fit method with energies $\geq 2 \ EeV$. $f_{em}$ is calculated by dividing the observed change by the calculated change.
5.9 Conclusion

When trying to determine a relation between two variables, the first method thought of might be to plot one variable versus the other. In this chapter, we binned the exposure and events by temperature and pressure. Dividing the number of counts in each temperature or pressure bin by the exposure of each temperature or pressure bin yielded a rate. The rate was then converted to a fractional rate by subtracting the mean rate and then dividing the result by the mean rate. Bins with more than 12 events were used to fit a straight line through the points. Uncertainties based on Poisson statistics were taken into account.

A linear relation between the fractional rate and temperature was found with a slope of $0.00611 \pm 0.00033$. In this case, events with zenith angles less than 60 degrees were used and no energy cut was applied. While a definite relation between rate and pressure was seen, the linearity was not as strong as in the temperature case. The slope of a fit using all bins with more than 12 events was $-0.01020 \pm 0.00030$. Excluding regions of non-linearity, fitting only above 860 hPa, a slope of $-0.01406 \pm 0.00064$ is seen. Again, events with zenith angles less than 60 degrees were used and no energy cut was applied in this case. While the magnitudes of the fractional rate correction coefficients are comparable, the pressure effect is less than the temperature effect due to the average range of each variable. While the temperature varies linearly over 55° C, the pressure varies linearly over 15 hPa.

The energies of events were corrected using the slopes obtained from the linear fits. The effect of the corrections was determined by observing the first harmonic power over annual and diurnal cycles using events with energies $E > 1.5$ EeV. In the annual case, rate variations decreased by a factor of two after applying atmospheric corrections. However, in the diurnal case, rate variations increased by a factor of two. Therefore, these atmospheric corrections are incapable of removing the variations observed and can actually introduce more variation. Another way of determining the effect of atmospheric parameters on the rate is needed. In Ch. 6 we describe a second method, which proves capable of fully removing the atmospheric variations.
Chapter 6

Time Offset Between the Rate and Temperature Curves

In any experiment, the timing will always be off.

—Anonymous

As seen in the previous chapter, the behavior of the rate is more complicated than an instantaneous dependence on temperature and pressure. Looking at the rate and temperature curves over a diurnal or annual cycle, the rate appears to lag the temperature. A modified Rayleigh analysis is used to quantify this lag and determine its significance. Sec. 6.1 discusses some subtleties of normalizing the two curves, while Sec. 6.2 describes the overall process. Results are presented in Sec. 6.3. Possible physical explanations are given in Sec. 6.4. Sec. 6.5 compares the coefficients found with those calculated in Ch. 4. Conclusions are presented in Sec. 6.6.

6.1 Temperature Curve Normalization

In order to study possible phase lags between the rate and temperature, it is necessary to normalize the latter to the former. This normalization can be thought of as transforming the temperature into an expected rate. The actual rate is then compared with an expected rate based on the instantaneous temperature. The magnitude of the curves should be well matched so that any differences between the two can be attributed to differences in phase rather than amplitude. Also, since the
temperature normalization coefficient provides one measure of the rate correction coefficient, the normalization should be as accurate as possible. Therefore, it is worth discussing various methods of normalization.

While the annual and diurnal temperature curves are smooth, the rate curves are noisy due to statistical limitations. We would like a way of normalizing the temperature curve to the underlying rate curve that is insensitive to statistical fluctuations.

Four different normalization methods are compared in this section: peak amplitude matching, variance matching, matching the mean absolute deviation from the mean, and matching the power in the first harmonic. Eqns. 6.1 - 6.4 show the formulas used in each case. Throughout the chapter both the temperature and the rate are mean subtracted. $R_{exp}$ is the normalized temperature, i.e. the expected rate based on the instantaneous temperature. $T$ and $R$ denote the temperature and rate respectively. The subscript $i$ denotes the $i^{th}$ bin of $N$ bins.

Amplitude matching:

$$R_{exp} = \frac{\maxval(|R|)}{\maxval(|T|)} T$$  \hspace{1cm} (6.1)

Variance matching:

$$R_{exp} = \frac{\sigma_R}{\sigma_T} T$$

$$\sigma_R^2 = \frac{1}{N-1} \sum_{i=1}^{N} R_i^2$$

$$\sigma_T^2 = \frac{1}{N-1} \sum_{i=1}^{N} T_i^2$$  \hspace{1cm} (6.2)

Matching the mean absolute deviation from the mean:

$$R_{exp} = \frac{a_R}{a_T} T$$

$$a_R = \frac{1}{N} \sum_{i=1}^{N} |R_i|$$

$$a_T = \frac{1}{N} \sum_{i=1}^{N} |T_i|$$  \hspace{1cm} (6.3)
Matching the power in the first harmonic:

\[
R_{\text{exp}} = \frac{P_R}{P_T}
\]

\[
P_R = \sqrt{P_{Rx}^2 + P_{Ry}^2}
\]

\[
P_{Rx} = \sum_{i=1}^{N} R_i \cos \frac{2\pi i}{N}
\]

\[
P_{Ry} = \sum_{i=1}^{N} R_i \sin \frac{2\pi i}{N}
\]

\[
P_T = \sqrt{P_{Tx}^2 + P_{Ty}^2}
\]

\[
P_{Tx} = \sum_{i=1}^{N} T_i \cos \frac{2\pi i}{N}
\]

\[
P_{Ty} = \sum_{i=1}^{N} T_i \sin \frac{2\pi i}{N}
\] (6.4)

To compare these methods a model consisting of two superimposed cosine waves is used. For purposes of this study, the base sinusoid has unit frequency and the noise part has a frequency of 6 Hz. The ratio of the amplitudes is varied, as is the number of bins. Fig. 6.1 shows a schematic of the 24 bin case with a noise to base amplitude ratio of 0.5. The base sinusoid (black) can be seen as well as the sum of the base and noise sinusoids (cyan). The base sinusoid is what we would like to fit; the sum of the base and noise sinusoids are the data we have. The best fit curves using the four methods previously discussed are also shown in Fig. 6.1. The results are examined in more detail below; here we note that the amplitude matching (blue) is the furthest from the base sinusoid while matching the power in the first harmonic (purple) exactly replicates the base sinusoid.

For a more systematic study, the noise to base amplitude ratio is varied from 0.0 to 0.5 in steps of 0.005. To measure the accuracy of each normalization method, the ratio of the variance of the fitted curve to the variance of the underlying base curve is calculated. Results are shown in Fig. 6.2. Amplitude matching is the least accurate of the methods. At a signal to noise ratio of 10%, the deviation of the fitted variance to the actual variance is 20%. This deviation increases linearly as the noise increases. However, matching the power in the first harmonic
Figure 6.1: Model of sinusoidal data with sinusoidal noise superimposed: Black - base sinusoid, Cyan - base sinusoid with sinusoidal noise superimposed, Green - fit to the model based on matching the absolute deviation from the mean, Red - fit to the model based on matching the variances, Blue - fit to the model based on matching the amplitudes, Purple - fit to the model based on matching the power in the first harmonic. The black curve is covered by the purple curve.

exactly replicates the variance of the original curve for all noise levels. Both of these results are expected, as amplitude matching is directly affected by the fluctuations, and as the frequency of the noise is orthogonal to the underlying frequency in the case of power matching. The structure of the two other methods is more complicated. Below a certain noise threshold, which is dependent on bin number, variance matching is more accurate than matching the absolute deviation from the mean. This behavior is caused by the non-linear decrease in accuracy with increasing noise of the variance matching method and the linear response of abso-
Figure 6.2: Comparison of 4 methods of normalizing a sinusoidal curve to the sinusoidal model data with sinusoidal noise superimposed: Matching the power in the first harmonic reconstructs the underlying model sinusoid perfectly for all noise values. The accuracy of amplitude matching decreases rapidly with increasing noise levels. Matching the variances or absolute deviations from the mean are comparable in accuracy up to large noise levels, with variance matching being more accurate for low noise levels. The transition point depends on the number of bins.

As the number of bins is increased, the threshold below which variance matching is more accurate decreases. The exact cause of this has not been studied, as only the most accurate method is desired. Varying the number of bins from 12 to 72 in steps of 12 has no effect on the results of amplitude and power matching.

However, the fluctuations in the actual data are statistical in nature, not si-
Figure 6.3: Model of sinusoidal data with Poisson noise superimposed: Black - base sinusoid, Cyan - base sinusoid with Poisson fluctuations superimposed, Green - fit to the model based on matching the absolute deviation from the mean, Red - fit to the model based on matching the variances, Blue - fit to the model based on matching the amplitudes, Purple - fit to the model based on matching the power in the first harmonic.

Therefore another model was developed that fluctuated the rate based on Poisson counting statistics. Fig. 6.3 shows a sample case with 24 bins and a noise to signal ratio of 0.3. The base sinusoid (black) can be seen as well as the fluctuated curve (cyan). Again, the best fit curves using the four methods are also shown. As before, the amplitude matching (blue) is the furthest from the base sinusoid, while matching the power in the first harmonic (purple) is closest. However, unlike in the previous model, power matching does not exactly replicate the base curve.
Figure 6.4: Comparison of 4 methods of normalizing a sinusoidal curve to the sinusoidal model data with Poisson fluctuations: Matching the power in the first harmonic reconstructs the underlying model sinusoid best for all noise values. Deviations from the true curve only occur at high noise levels. The accuracy of amplitude matching decreases rapidly with increasing noise levels. Matching the variances or absolute deviations from the mean are comparable in accuracy up to large noise levels, with variance matching being more accurate for low noise levels. The transition point again depends in the number of bins.

As before, a systematic study is conducted where the noise to base amplitude ratio is varied and studied. The ratio of the variance of the fitted curve to the variance of the underlying curve is calculated. Results are shown in Fig. 6.4. Amplitude matching is the least accurate of the methods. At a noise to signal ratio of 10%, the deviation of the fitted variance to the actual variance is greater than 20%. Again, this deviation increases linearly with the fluctuations. The behavior
of variance and absolute deviation matching is the same as in the previous case. However, the behavior seen at higher bins in the sin model is seen at lower bins in the fluctuated model. Once again, matching the power in the first harmonic most closely replicates the original curve. Unlike the previous model, it does not exactly replicate the base sinusoid at high noise levels. This is due to the possibility of the fluctuations having some power in the first harmonic. However, the error in the variances is less than 5% at a noise to signal ratio of 0.5.

6.2 Method

For two sinusoidal curves of the same amplitude, $A$, and frequency, $\nu$, but different phases, $\phi_A$ and $\phi_B$, the difference between them is a sinusoid whose phase and amplitude depend on the phase difference between the original curves. This is schematically shown in Fig. 6.5. The amplitude of the difference is equal to $A \sin((\phi_A + \phi_B)/2)$ and will be a maximum when the two curves are 180 degrees out of phase. When the two curves are in phase the amplitude of the difference will be zero. The phase of the difference is given by $\alpha = (\pi - \phi_A - \phi_B)/2$.

Given a discrete sinusoid, $D$, a Rayleigh vector, $R$, is defined as $(R_x, R_y)$ where

$$R_x = \sum_{i=1}^{N} D_i \cos\left(\frac{2\pi i}{N}\right)$$

$$R_y = \sum_{i=1}^{N} D_i \sin\left(\frac{2\pi i}{N}\right)$$

(6.5)

Here $N$ is the number of bins and $D_i$ denotes the difference of the rate and expected rate in the $i^{th}$ bin. Fig. 6.6 shows $R_{xi}$ and $R_{yi}$ as well as $R$ for the example shown in Fig. 6.5. The phase lag between the two sinusoids, $\phi_D$, is $\phi_R - \phi_{R_{\text{exp}}}$, where $\phi_R$ is the phase calculated from the Rayleigh analysis of the rate and $\phi_{R_{\text{exp}}}$ is the phase from the Rayleigh analysis of the expected rate. The uncertainty of $\phi_D$ is determined from 1,000,000 Monte Carlo simulations of the rate Poisson fluctuated based on the number of counts in each bin. The result is a Gaussian distribution in $\phi$. The standard deviation is given as the uncertainty.

As discussed in the previous section, the temperature is transformed into an
expected rate by setting the first harmonic power equal to that of the actual rate. This is the rate expected if the rate depends on the instantaneous temperature measured at ground level. To determine whether a phase offset exists the expected rate is subtracted from the rate and a modified Rayleigh analysis as described above is performed.

A Monte Carlo analysis consisting of 1,000,000 simulations is done to determine the significance of the results. A phase shift between the rate and temperature results in a non-zero Rayleigh amplitude of the difference curve. The Monte Carlos
Figure 6.6: Rayleigh analysis of an idealized sinusoidal rate (red), temperature (blue), and their difference (black). The x and y components of each point’s contribution to the Rayleigh vector is plotted. The vector sum of the black points yields the Rayleigh vector shown in green. The magnitude and phase of the Rayleigh vector can be used to determine the phase difference of the original sinusoids.

allow us to calculate the probability of the difference curve having a greater amplitude due to Poisson fluctuations in rate measurements that are in phase with the temperature. For each Monte Carlo simulation the expected rate is Poisson fluctuated according to the number of counts in the actual rate. That is
\[ C_i = \text{poidev} \left[ \frac{R_i^{\text{exp}}}{\sum_{j=1}^{M} R_j^{\text{exp}}} K \right] \]

\[ S_i = \frac{C_i}{K} \sum_{j=1}^{M} R_j^{\text{exp}} \]  \hspace{1cm} (6.6)

where \( C_i \) is the fluctuated expected counts in the \( i^{th} \) bin, \( R_i^{\text{exp}} \) is the expected rate in the \( i^{th} \) bin, \( K \) is the total number of counts, and \( S_i \) is the fluctuated expected rate in the \( i^{th} \) bin. A Rayleigh analysis is then performed on the difference of \( S \) and \( R^{\text{exp}} \) and a Rayleigh distribution of the form \( R_{\text{dist}}(x) = \frac{x}{b^2} e^{-x^2/(2b^2)} \) is fit using the Rayleigh amplitudes found. As this distribution already has unit area, the probability of getting a Rayleigh amplitude greater than \( R \) by chance is

\[ \int_{0}^{R} \frac{x}{b^2} e^{-\frac{x^2}{2b^2}} \, dx = \left. e^{-\frac{R^2}{2b^2}} \right|_0^R = e^{-\frac{R^2}{2b^2}} \]  \hspace{1cm} (6.7)

The two dimensional sigma level for the Rayleigh amplitude seen is defined as \( \sigma_R = R/b \) where \( R \) and \( b \) are defined above.

### 6.3 Results

Results are summarized below. Two time periods were analyzed (before and after the communications crisis) as well as two different energy ranges (greater and less than 1.5 EeV) and zenith angle ranges (0 - 45 degrees and 45 - 60 degrees).

From April 15, 2009 - November 16, 2009 there was a problem with the communications system of the surface detector where the tanks would frequently disconnect from CDAS. In the SD there are 28 base-stations, each of which receives communications from approximately 60 tanks. The ARQ (Automatic Repeat re-Quest) system of the SD is designed to ensure the transmission of data packets over noisy radio links. It inspects the packets received by the base-stations and requests that imperfect packets be resent in one of six timeslots allocated for re-requests.
These timeslots are organized into two pairs of triplets. The system is designed to handle a 10% average packet error rate before any data are permanently lost. If all retry slots are full in a certain second, the requests are stored and resent for up to 7 seconds, at which point the requests are stopped and data are irretrievably lost. [60]

However, a bug present in the code rendered the last two slots of each triplet unusable for any tank not addressed in the first slot. This reduced the maximum packet error rate that the ARQ system could handle from 10% to 2-3%. This bug was not found in testing. Since the radio environment of Malargue was quieter during construction and early operation of the SD than it has been since 2009, the bug was not discovered throughout early array operations either. When error rates would spike above 2-3% on short time scales the signature of this bug was identical to a tank disconnecting and reconnecting, a common occurrence for some tanks with poor radio links. When the radio interference around the array increased in 2009, the ARQ rate increased. Since four of six slots were not functioning as expected, this led to even more ARQ requests, which led to a cascade of requests and data transmission failures. Once the bug was discovered, the code was fixed, and updates were sent to the tanks. The cause of the increased radio background around Malargue is still unknown, but the ARQ system is able to handle the current packet error rate now that the bug in the code has been fixed. [60]

This bug caused a 7-20% loss of events. The frequent instabilities of the tanks invalidated the use of the traditional exposure calculation, which uses the number of tanks active at the start of an event [61]. While there are procedures to recover events from the later half of the communications crisis, for the purposes of this analysis we exclude the period entirely [61]. This period provides a natural point at which to divide the data into two sections. The wisdom of studying each period separately will be seen as the two periods have different results.

### 6.3.1 Before the Communications Crisis

#### 6.3.1.1 Annual Case

Tab. 6.1 summarizes the results for the two energy ranges for zenith angles less than 45 degrees. For each energy range, the fractional change coefficient for the
Table 6.1: Annual phase offsets using events with zenith angles < 45 degrees before the comms crisis. While the phase lag is slightly longer for events with energies > 1.5 EeV (14.7 vs 9.3 days), the fractional change coefficients are comparable.

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>Fractional Coefficient</th>
<th>Phase (days)</th>
<th>P(R)</th>
<th>σ</th>
<th>shifted</th>
<th>R_{exp}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 ≤ E &lt; 1.5</td>
<td>(9.67 ± 0.17)E-03</td>
<td>9.3 ± 1.0</td>
<td>7.16E-18</td>
<td>8.88</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>1.5 ≤ E</td>
<td>(9.51 ± 0.57)E-03</td>
<td>14.7 ± 3.5</td>
<td>1.16E-04</td>
<td>4.26</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>0 ≤ E &lt; 1.5</td>
<td>(9.63 ± 0.17)E-03</td>
<td>0.4 ± 1.0</td>
<td>9.25E-01</td>
<td>0.40</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>1.5 ≤ E</td>
<td>(9.45 ± 0.56)E-03</td>
<td>0.2 ± 3.5</td>
<td>9.98E-01</td>
<td>0.07</td>
<td>yes</td>
<td></td>
</tr>
</tbody>
</table>

rate is given, as well as the phase lag in days, the chance probability of the offset, and the sigma level of the offset. The first two lines of the table show the result using the CLF temperature. The next two lines use the CLF temperature shifted by the amount found in the previous lines. This is to verify that artificially shifting the temperature removes the phase lag between the rate and temperature. This is indeed the case.

One can see that the fractional coefficient is comparable for lower and higher energies, at approximately 0.95% rate increase per degree C increase. However, the phase lags are different. In the case of events with energies less that 1.5 EeV, there is an offset of 9.3 days. Events with energies greater than 1.5 EeV are offset from the temperature by 14.7 days. The phase lags are significant at greater than a 4σ level.

Figs. 6.7 and 6.8 show the rate curves and contour plot respectively for the E < 1.5 EeV case using zenith angles less than 45 degrees. No time shifts have been imposed. This is the result shown in the first line of Tab. 6.1. The phase lag between the rate and temperature is clearly visible, as is the significance of the offset found, as evidenced by the Monte Carlo simulations.

Figs. 6.9 and 6.10 show the rate curves and contour plot respectively for the E < 1.5 EeV case using zenith angles less than 45 degrees after the temperature has been shifted by 9.3 days. This is the result shown in the third line of Tab. 6.1. No phase lag between the rate and shifted temperature is seen.

Tab. 6.2 summarizes the results for the two energy ranges for zenith angles between 45 and 60 degrees. One can see that the fractional coefficients are comparable for lower and higher energies, at approximately 0.17% rate increase per degree C increase. This is a fifth of that seen at lower zenith angles. At large
zenith angles, the electromagnetic fraction at ground level is greatly reduced relative to the muons, which are largely insensitive to low-altitude air density. Again, the phase lags are different. In the case of events with energies less than 1.5 EeV, there is an offset of 1.5 days; however, this is not significant. Events with energies greater than 1.5 EeV are offset from the temperature by 14.1 days with marginal significance.
Figure 6.8: January 1, 2005 - April 15, 2009: E < 1.5 EeV, 0-45 degrees: The Rayleigh vector of the difference between the rate and non time shifted expected rate is shown by the blue '+'. Contour lines show the results of 1,000,000 Monte Carlo simulations.
Figure 6.9: January 1, 2005 - April 15, 2009: $E < 1.5$ EeV, 0-45 degrees: Temperature shifted by 9.25 days: Annual rate (red) and time shifted temperature (blue) curves, along with their difference (black).

Table 6.2: Annual phase offsets using events with zenith angles, $45 \leq \theta < 60$ degrees before the comms crisis: The phase lags are not statistically significant. Unlike the lower zenith angle case, the fractional coefficient for the higher energy case is roughly twice that of the lower energy range.
Figure 6.10: January 1, 2005 - April 15, 2009: E < 1.5 EeV, 0-45 degrees: Temperature shifted by 9.25 days: The Rayleigh vector of the difference between the rate and time shifted expected rate is shown by the blue '+'. Contour lines show the results of 1,000,000 Monte Carlo simulations.
6.3.1.2 Diurnal Case

Tab. 6.3 shows the diurnal Rayleigh analysis results for events with zenith angles less than 45 degrees. For the two energy ranges, the fractional change coefficients are identical within error bars and are equal to a 0.2% rate change per degree C temperature change. Again, the phases are different, as the lower energy range shows a 1.8 hour offset between the temperature and rate, while the higher energy range yields a 3.3 hour offset. Both of these results are statistically significant; the first at the 4.3σ level, the second at the 3.0σ level. Shifting the temperature curves by the offsets found and redoing the analysis shows that the rate and expected rate are then identical, as the phase lag decreases to zero and the change probability increases to 1, indicating the curves are matched in amplitude and phase.

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>Fractional Coefficient</th>
<th>Phase (hours)</th>
<th>P(R)</th>
<th>σ</th>
<th>shifted R_{exp}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 ≤ E &lt; 1.5</td>
<td>(2.50 ± 0.20)E-03</td>
<td>1.8 ± 0.3</td>
<td>2.22E-05</td>
<td>4.34</td>
<td>no</td>
</tr>
<tr>
<td>1.5 ≤ E</td>
<td>(2.31 ± 0.65)E-03</td>
<td>3.3 ± 1.1</td>
<td>1.10E-02</td>
<td>3.00</td>
<td>no</td>
</tr>
<tr>
<td>0 ≤ E &lt; 1.5</td>
<td>(2.50 ± 0.20)E-03</td>
<td>0.0 ± 0.3</td>
<td>1.00E-01</td>
<td>0.02</td>
<td>yes</td>
</tr>
<tr>
<td>1.5 ≤ E</td>
<td>(2.31 ± 0.64)E-03</td>
<td>0.0 ± 1.1</td>
<td>1.00E+00</td>
<td>0.00</td>
<td>yes</td>
</tr>
</tbody>
</table>

Table 6.3: Diurnal phase offsets using events with zenith angles < 45 degrees before the comms crisis: While the phase lag is slightly longer for events with energies ≥ 1.5 EeV (3.3 vs 1.8 hours), the fractional change coefficients are comparable.

Figs. 6.11 and 6.12 show the rate curves and contour plot respectively for the E < 1.5 EeV case using zenith angles less than 45 degrees. No time shifts have been imposed. This is the result shown in the first line of Tab. 6.3. The phase lag between the rate and temperature is clearly visible, as is the significance of the offset found, as evidenced by the Monte Carlo simulations.

Figs. 6.13 and 6.14 show the rate curves and contour plot respectively for the E < 1.5 EeV case using zenith angles less than 45 degrees after the temperature has been shifted by 1.8 hours. This is the result shown in the third line of Tab. 6.3. No phase lag between the rate and shifted temperature is seen.

Table 6.4 shows the diurnal Rayleigh analysis results for events with zenith angles between 45 and 60 degrees. The fractional change coefficient in the higher energy case is twice that in the lower energy case and half that in the 0 ≤ θ < 45 degree case. So events with large zenith angles are not as sensitive to temperature variations as low zenith angle events. A 3.1 hour phase offset is seen at the 4σ
level in the low energy case. In the other case, the lag seen is not significant. This high energy case has a poorly defined rate due to very limited statistics so this is not surprising.
Figure 6.12: January 1, 2005 - April 15, 2009: $E < 1.5$ EeV, 0-45 degrees: The Rayleigh vector of the difference between the rate and non time shifted expected rate is shown by the blue '+' . Contour lines show the results of 1,000,000 Monte Carlo simulations.
Figure 6.13: January 1, 2005 - April 15, 2009: $E < 1.5$ EeV, 0-45 degrees: Temperature shifted by 1.84 hours: Diurnal rate (red) and time shifted temperature (blue) curves, along with their difference (black).

Table 6.4: Diurnal phase offsets using events with zenith angles, $45 \leq \theta < 60$ degrees before the comms crisis: Due to the limited statistics, the phase lag is not statistically significant in the $> 1.5$ EeV case. The fractional change coefficients are roughly an order of magnitude less than in the previous cases, possibly due to the lack of events.
Figure 6.14: January 1, 2005 - April 15, 2009: E < 1.5 EeV, 0-45 degrees: Temperature shifted by 1.84 hours: The Rayleigh vector of the difference between the rate and time shifted expected rate is shown by the blue ‘+’. Contour lines show the results of 1,000,000 Monte Carlo simulations.
6.3.2 After the Communications Crisis

We now show the results for the period between November 15, 2009 and October 1, 2011. While the fractional rate change coefficients are generally comparable, the phase offsets found are significantly different than those in the previous case. While the exact cause of this change is unknown and should be investigated further, it is not due to a change in the behavior of the atmosphere. No differences are found when comparing the temperature curves from the two time periods. However, a difference in phase is seen when comparing the rates of the two time periods.

6.3.2.1 Annual Case

Due to the large offsets seen in the low zenith angle, annual case, the significances seen are very high. For the same statistics, a large phase lag will be more significant than a smaller one since we are analyzing the difference between two curves. A 38 day lag is seen in the $0 \leq E < 1.5$ EeV case, while a 44 day lag is seen in the $1.5 E \geq$ E case. The coefficients are the same within error bars, both between energy ranges and between time periods. The results are given in Table 6.5.

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>Fractional Coefficient</th>
<th>Phase (days)</th>
<th>P(R)</th>
<th>σ</th>
<th>shifted $R_{exp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0 \leq E &lt; 1.5$</td>
<td>(11.43 ± 0.22)E-03</td>
<td>38.4 ± 1.5</td>
<td>1.32E-265</td>
<td>34.90</td>
<td>no</td>
</tr>
<tr>
<td>$1.5 \leq E$</td>
<td>(7.77 ± 0.65)E-03</td>
<td>43.8 ± 7.3</td>
<td>4.00E-18</td>
<td>8.94</td>
<td>no</td>
</tr>
<tr>
<td>$0 \leq E &lt; 1.5$</td>
<td>(11.51 ± 0.22)E-03</td>
<td>-0.3 ± 1.5</td>
<td>9.74E-01</td>
<td>0.23</td>
<td>yes</td>
</tr>
<tr>
<td>$1.5 \leq E$</td>
<td>(7.80 ± 0.65)E-03</td>
<td>-0.9 ± 7.3</td>
<td>9.81E-01</td>
<td>0.20</td>
<td>yes</td>
</tr>
</tbody>
</table>

Table 6.5: Annual phase offsets using events with zenith angles < 45 degrees after the comms crisis: The phase offset seen increases to 38 (44) days compared with the 9 (14) days seen in the pre comms crisis period.

Tab. 6.6 shows the annual results for the large zenith angle case. Once again, the coefficients are comparable to those in the pre comms crisis period. In the high energy case, the coefficients are the same within error bars. In the low energy case, the pre comms crisis period coefficient is lower by $\sim 5\%$. The phase lags are once again very different from the pre comms crisis phase lags. However, the low energy lag of 39 days is comparable to the 38 day lag seen in the low zenith angle range after comms crisis period. The high energy cases are different. Here a 75 day lag is seen, while the low zenith angle case found a 44 day lag.
6.3.2.2 Diurnal Case

The results of the diurnal Rayleigh analysis for the low zenith angle range in the after comms crisis period are shown in Tab. 6.7. Once again, the coefficients in the high energy range are within error bars of those in the pre comms crisis period. In the low energy range, the coefficients are \( \sim 50\% \) lower than those in the pre comms crisis period. No significant lag is seen in the low energy range. A marginally significant lag of 10 hours is seen in the high energy range. Note that after shifting the temperatures and rerunning the analysis, the significance increases, although the lag becomes zero. This behavior is due to the shape of the diurnal rate curve, which is more complicated than a single sinusoid. Since this analysis is predicated on the assumption that the rate and temperature curves have the same shape, an assumption that is true in all other cases, it is expected that the phases found will not be valid if the shapes are too dissimilar.

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>Fractional Coefficient</th>
<th>Phase (days)</th>
<th>( P(R) )</th>
<th>( \sigma )</th>
<th>shifted ( R_{exp} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 ( \leq ) E ( &lt; 1.5 )</td>
<td>((2.50 \pm 0.11)E-03)</td>
<td>(-0.4 \pm 3.5)</td>
<td>9.88E-01</td>
<td>0.16</td>
<td>yes</td>
</tr>
<tr>
<td>1.5 ( \leq ) E</td>
<td>((2.92 \pm 0.49)E-03)</td>
<td>(-1.0 \pm 32.0)</td>
<td>9.95E-01</td>
<td>0.10</td>
<td>yes</td>
</tr>
</tbody>
</table>

Table 6.6: Annual phase offsets using events with zenith angles, 45 \( \leq \theta \) \(< 60\) degrees after the comms crisis: The phase offsets seen are comparable to those of the post comms crisis, low zenith angle case.

The results of the diurnal Rayleigh analysis for the high zenith angle range are shown in Tab. 6.8. The coefficient in the high energy range is \( \sim 2.5 \) times that in the low energy range. Both are approximately half what was observed in the pre comms crisis period. However, the error bars in this period are large.

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>Fractional Coefficient</th>
<th>Phase (hours)</th>
<th>( P(R) )</th>
<th>( \sigma )</th>
<th>shifted ( R_{exp} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 ( \leq ) E ( &lt; 1.5 )</td>
<td>((2.50 \pm 0.11)E-03)</td>
<td>0.0 \pm 0.6</td>
<td>9.99E-01</td>
<td>0.05</td>
<td>no</td>
</tr>
<tr>
<td>1.5 ( \leq ) E</td>
<td>((2.94 \pm 0.70)E-03)</td>
<td>9.9 \pm 1.0</td>
<td>7.09E-02</td>
<td>2.30</td>
<td>no</td>
</tr>
</tbody>
</table>

Table 6.7: Diurnal phase offsets using events with zenith angles < 45 degrees after the comms crisis: The phase offsets found in the low and high energy cases are not compatible, unlike in the pre comms crisis period.

The results of the diurnal Rayleigh analysis for the high zenith angle range are shown in Tab. 6.8. The coefficient in the high energy range is \( \sim 2.5 \) times that in the low energy range. Both are approximately half what was observed in the pre comms crisis period. However, the error bars in this period are large.
due to limited statistics. Offsets found are of marginal significance, again due to statistical fluctuations.

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>Fractional Coefficient</th>
<th>Phase (hours)</th>
<th>P(R)</th>
<th>σ</th>
<th>shifted</th>
<th>$R_{exp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0 \leq E &lt; 1.5$</td>
<td>$(2.0 \pm 1.2)E-04$</td>
<td>$10.1 \pm 4.5$</td>
<td>$7.05E-01$</td>
<td>0.84</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>$1.5 \leq E$</td>
<td>$(5.3 \pm 5.3)E-04$</td>
<td>$-0.7 \pm 5.5$</td>
<td>$1.35E-01$</td>
<td>2.00</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>$0 \leq E &lt; 1.5$</td>
<td>$(2.0 \pm 1.2)E-04$</td>
<td>$0.0 \pm 4.5$</td>
<td>$4.14E-03$</td>
<td>3.31</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>$1.5 \leq E$</td>
<td>$(5.3 \pm 5.3)E-04$</td>
<td>$0.0 \pm 5.5$</td>
<td>$1.32E-01$</td>
<td>2.01</td>
<td>yes</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.8: Diurnal phase offsets using events with zenith angles, $45 \leq \theta < 60$ degrees after the comms crisis: The phase offsets seen are incompatible with those of the post comms crisis, low zenith angle case.

## 6.4 Explanation

### 6.4.1 Seasonal Case

The above results were obtained using the ground level temperatures from the CLF. While the surface detector detects signals at ground level, the lower atmosphere influences the development of extensive air showers, and thus the signal measured at ground and the rate of events detected. It is therefore plausible that the relevant quantity is not the instantaneous temperature at ground level, but the instantaneous temperature a certain altitude above ground level. The temperature at a certain altitude above ground level is expected to lag the ground level temperature on time scales of days to a couple of weeks due to radiation from the ground.

To study this for the seasonal cycle we used the Global Data Assimilation System (GDAS), a global atmospheric model produced by the National Centers for Environmental Prediction (NCEP). Standard atmospheric variables are given in a 1 degree grid with 3 hour time resolution over the world [4]. Twenty three pressure levels varying from 1000 hPa to 20 hPa are included for each entry as well as ground level information [62]. Since ground level in the array is 1400 meters above sea level, the first 5 pressure levels are below ground level. Therefore, we restrict ourselves to looking at pressure levels of 850 hPa and less here.

Fig. 6.15 shows the annual temperature for the CLF and the first 5 GDAS pressure levels above ground level. Qualitatively, one can see that the amplitude
of the variation in GDAS is less than that from the CLF and that there appears to be a phase offset between the GDAS and CLF temperatures. This offset is not due to different data sources, as there is no phase lag between the ground level GDAS data and the ground level CLF data, and since the phase lag increases with altitude, as expected. For a quantitative analysis, the analysis of the previous section was repeated using GDAS temperatures at different pressure levels and the event data. The 750 hPa GDAS level is found to have the smallest offset with the event data. The rate curves and contour plot are shown in Figs. 6.16 and 6.17.
As can be seen, the 750 hPa GDAS level matches the event rate with no phase offset. We have used the $1.5 \text{ EeV} \leq E$ energy range here since the end goal is to correct the energies. As such, we focus on the energy range where trigger effects are less important. The rate change coefficient is higher than in the comparable case with CLF data. This is because the GDAS data has a smaller amplitude than the CLF data. Therefore, it must be scaled by a larger factor to match the variations seen in the rate. No offset is seen between the 750 hPa GDAS and event rate. Therefore, it appears that the temperature at 750 hPa is the temperature respectively. Numerical results are shown in Table 6.9.
Figure 6.17: January 1, 2005 - April 15, 2009: 1.5 EeV \leq E: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue ‘+’. Contour lines show the results of 1,000,000 Monte Carlo simulations.

that affects the event rate the most.
<table>
<thead>
<tr>
<th>Energy Range</th>
<th>Fractional Coefficient</th>
<th>Phase (days)</th>
<th>P(R)</th>
<th>σ</th>
<th>shifted</th>
<th>( R_{exp} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 1.5 \leq E )</td>
<td>0.01461 ± 0.00084</td>
<td>-0.6 ± 3.3</td>
<td>0.9819</td>
<td>0.19</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>( 1.5 \leq E )</td>
<td>0.01460 ± 0.00084</td>
<td>-0.1 ± 3.3</td>
<td>0.9999</td>
<td>0.02</td>
<td>yes</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.9: Annual phase offsets using events with zenith angles, \( 0 \leq \theta < 45 \) degrees before the comms crisis and 750 hPa GDAS data: No significant offset is seen.

### 6.4.2 Diurnal Case

However, the above procedure cannot be repeated for the diurnal case. As mentioned previously, GDAS provides data points every three hours. This gives 8 points over the course of a day. Measuring the first harmonic power only determines the phase to between 2 and 6 hours, the exact number depending on the month analyzed. For the CLF, the phase can be determined to within 20 - 40 minutes.

In addition, the diurnal CLF behavior over the course of a year mirrors the diurnal rate behavior more closely than the GDAS data does. Fig. 6.18 shows how the diurnal CLF temperature varies with the month of the year. Fig. 6.19 shows how the diurnal 750 hPa GDAS temperature varies with the month of the year. The pattern is similar for other levels. For lower pressure levels, the variations are smaller. For higher pressure levels, the variations are slightly higher.

The diurnal rate variation in winter is roughly 0.66 of that in summer. Therefore we would expect the relevant temperatures to exhibit similar behavior. The winter to summer diurnal amplitude ratio of the CLF is 0.77. For the GDAS data it is 0.29 for the 800 hPa level, 0.23 for the 750 hPa level, and 0.13 for the 700 hPa level. The CLF is clearly the best fit.

This does not imply that the relevant temperature is the ground level temperature. This merely says that GDAS data does not have the ability to shed light on the relevant height. Over diurnal scales, models rather than observations tend to drive the values. Between this and the coarse time scale, something else is needed to determine the relevant height and rate-temperature relation. Details of a project designed to study this are given in App. A. Unfortunately, this project experienced several technical difficulties and no conclusive results were obtained. Therefore, we are restricted to using time lagged CLF temperature data to perform diurnal corrections.
Figure 6.18: The average diurnal CLF temperature curves over the months of a year. Hours are UTC time.
Figure 6.19: The average diurnal 750 hPa GDAS temperature curves over the months of a year. Hours are UTC time.
6.5 Comparison of Calculated and Expected Coefficient Values

We now compare the coefficient values found here with those calculated in Ch. 4. The comparison is shown in Tab. 6.10. The calculated values for $X_{\text{max}} = 800 \, \text{g/cm}^2$ are used here. The value at $\sec(\theta) = 1.2$ ($\theta = 33.557^\circ$) is used in the 0 - 45 degree case; the average of $\sec(\theta) = 1.4$ and $\sec(\theta) = 1.6$ ($\theta = 51.318^\circ$ and $44.415^\circ$) is used in the 45 - 60 degree case. We use the coefficients obtained from events with $E \geq 1.5 \, \text{EeV}$ before the communications crisis since the coefficients are comparable across energy ranges.

As shown in Sec. 4.4 the expression for the electromagnetic fraction of a shower is

$$f_{em} = \frac{\kappa}{\kappa + 1} = 1 - \frac{1}{\kappa + 1} \quad (6.8)$$

where

$$\kappa = e^{t_{\text{max}}y} \left( \frac{3y + 3}{y + 3} \right) - \frac{3t_{\text{max}}(y+1)}{2} \quad (6.9)$$

and $y = \sec \theta - 1$.

Using $t_{\text{max}} = 25$, we obtain $f_{em} = 0.43$ in the 0 - 45 degree case and $f_{em} = 0.17$. Again, the value at $\sec(\theta) = 1.2$ is used in the 0 - 45 degree case and the average of $\sec(\theta) = 1.4$ and $\sec(\theta) = 1.6$ is used in the 45 - 60 degree case. Comparing these values with those shown in Table 6.10, we see that the expected value is within uncertainties in the high zenith angle case, but not in the low zenith case. However, given the rough modeling implicit in Eqns. 6.8 and 6.9, we can say that the electromagnetic fractions observed agree acceptably well with the expected values.

<table>
<thead>
<tr>
<th>$\theta$ (degrees)</th>
<th>0 - 45</th>
<th>45 - 60</th>
</tr>
</thead>
<tbody>
<tr>
<td>calculated charged density coefficient</td>
<td>6.58E-03</td>
<td>5.48E-03</td>
</tr>
<tr>
<td>calculated rate change coefficient</td>
<td>16.34E-03</td>
<td>13.62E-03</td>
</tr>
<tr>
<td>observed rate change coefficient</td>
<td>$(9.51 \pm 0.57) , \text{E-03}$</td>
<td>$(2.17 \pm 0.43) , \text{E-03}$</td>
</tr>
<tr>
<td>inferred $f_{em}$</td>
<td>$0.58 \pm 0.04$</td>
<td>$0.16 \pm 0.03$</td>
</tr>
</tbody>
</table>

Table 6.10: Comparison between the expected atmospheric coefficients and those found using the seasonal Rayleigh analysis with $1.5 \, \text{EeV} \leq E$ events. $f_{em}$ is calculated by dividing the observed change by the calculated change.
6.6 Conclusion

A modified Rayleigh analysis provides a way to study seasonal and diurnal atmospheric rate variations separately. By matching the first harmonic powers of the rate and temperature, rate correction coefficients can be obtained. In the pre comms crisis, low energy and zenith angle case, the annual coefficient is 0.00967 ± 0.00017 and the diurnal coefficient is 0.00250 ± 0.00020. In the \( E \geq 1.5 \) EeV case, the coefficients are the same within uncertainties. By comparing the coefficients found at low and high zenith angles, the electromagnetic fraction, \( f_{em} \), can be calculated. Results agree with the expected values derived in Sec. 4.4.

A phase offset between the rate and temperature is seen in both the annual and diurnal cases. The magnitude is approximately two weeks and two hours respectively. By performing the analysis on data from various GDAS pressure levels, we find that no seasonal offset is present when using data from the 750 hPa GDAS level. Since air showers are expected to be influenced by the atmospheric parameters two radiation lengths above ground level, this makes sense [3]. Two radiation lengths above the SD corresponds to a height of \( \sim 800-900 \) m. The 750 hPa GDAS level (\( \sim 1 \) km) is the closest in height to this value. The phase lag is caused by the time it takes for the ground level temperature to propagate up through the atmosphere. While the GDAS data can be used to explain the seasonal offset, its temporal coverage and reliance on models precludes using it in the diurnal case.
Anisotropy Studies

You should never bet against anything in science at odds of more than about $10^{12}$ to 1.

—Ernest Rutherford

After finding the atmospheric correction parameters we use them to correct the energies of events and check that the annual and diurnal variations decrease. Sec. 7.1 explains the correction procedure while Sec. 7.2 checks that the atmospheric effects are removed. We then search for anisotropies at low energies. Methods and results are described in Secs. 7.5, 7.6, and 7.7. Definitions used throughout this chapter are presented in Sec. 7.3.

7.1 Applying Atmospheric Corrections

Two different sets of atmospheric corrections are applied, those presented in [58] and those derived in Ch. 6.

7.1.1 Weather Paper Corrections

In [58], the rate is calculated every hour using data from January 1, 2005 - August 31, 2008. While no energy cuts were applied, zenith angles were required to be less than 60 degrees. The rate is assumed to be of the form

$$R_0C_i = \frac{\nu_i}{A_i}$$
where $R_0$ is the average rate, $\nu_i$ is the expected number of events, and $A_i$ is the exposure in bin i. $P_0$ is the reference pressure at the array, 862 hPa; P is the pressure; $\eta$ is the air density; $\eta_d$ is the average air density over 24 hours; and $\eta_0$ is the reference air density at the array, 1.06 kg·m$^{-3}$. The coefficients of $C_i$ are determined through a maximum likelihood fit to the data.

The corrected energy, $E_0$, is related to the reconstructed energy, $E_r$, by

$$E_0 = E_r[1 - \alpha_P(P - P_0) - \alpha_\eta(\eta_d - \eta_0) - \beta_\eta(\eta - \eta_d)]^B$$

where $\alpha_P = B(\gamma - 1)\alpha_P$, $\alpha_\eta = B(\gamma - 1)\alpha_\eta$, and $\beta_\eta = B(\gamma - 1)\beta_\eta$. See Sec. 4.5 for details on converting between rate and energy correction coefficients. $B = 1.08 \pm 0.01$ (stat) $\pm 0.04$ (sys) and is derived from the calibration of the surface detector energy scale using the fluorescence detector energy measurement. $\gamma$ is the spectral index. Because we are looking at all energies, including those below which the array is fully efficient, $\gamma$ is taken to be 3.3. [58]

All events which have CLF atmospheric measurements within 5 minutes of the event time are corrected using the above formula. Although the CLF does not directly measure the air density, it is calculated from the temperature and pressure using

$$\eta = \frac{M_m P}{k_b T}$$

where $M_m$ is the molecular mass of air ($4.81056 \times 10^{-26}$ kg·molecule$^{-1}$) and $k_b$ is the Boltzmann constant ($1.3806503 \times 10^{-23}$ m$^2$kg s$^{-2}$K$^{-1}$).

### 7.1.2 Rayleigh Analysis Corrections

The rate correction coefficients and time offsets derived from a Rayleigh analysis are listed in Ch. 6. The seasonal rate correction coefficient is denoted by $a_S$ and utilizes measurements from the 750 hPa GDAS level. The diurnal rate correction coefficient is denoted by $a_D$ and utilizes data from the CLF. The corrected rate, $R_c$, has the form

$$R_c = R[1 - a_D(T_{CLF} - <T_{CLF} >_{24}) - a_S(<T_{GDAS} >_{24} - <T_{GDAS} >)]$$
where $R$ is the uncorrected rate, $T_{CLF}$ is the instantaneous time lagged temperature at the CLF, $< T_{CLF} >_{24}$ is the CLF temperature averaged over a 24 hour period centered on the time of the event minus the time lag, $< T_{GDAS} >_{24}$ is the 750 hPa level GDAS temperature averaged over a 24 hour period centered on the time of the event, and $< T_{GDAS} >$ is the mean GDAS temperature at 750 hPa. Instantaneous temperature means a temperature measurement within 5 minutes of the event time.

Transforming Eqn. 7.4 into an energy correction yields

$$E_0 = E_r[1 - \alpha_D(T_{CLF} - < T_{CLF} >_{24}) - \alpha_S(< T_{GDAS} >_{24} - < T_{GDAS} >)]^B \quad (7.5)$$

where $E_0$ is the corrected energy, $\alpha_D = B(\gamma - 1)a_D$, and $\alpha_S = B(\gamma - 1)a_S$. The other variables are the same as in Eqn. 7.4.

All events which have CLF atmospheric measurements within 5 minutes of the event time and GDAS measurements within 1.5 hours of the event time are corrected using the above formula.

### 7.2 Check of Atmospheric Corrections

To check that the corrections remove seasonal and diurnal variations, the same program used to find the coefficients is applied to the weather corrected events. Because of atmospheric trigger effects we only use events with energies greater than 1.5 EeV. That is, an event with energy $E_{th}$ that barely triggers the detector at reference atmospheric parameters will trigger the detector with reconstructed energy $E > E_{th}$ when the temperature is higher. When the temperature is lower that same event will not trigger the detector due to an apparent energy $E < E_{th}$. Since we cannot correct events that are not recorded, we apply an energy cut throughout.

The diurnal and seasonal rate curves using the uncorrected and corrected events are shown in Figs. 7.1 and 7.2. While one can clearly see the effect of the weather corrections in the seasonal case, the diurnal case is less clear. The mean subtracted rate, normalized temperature curve, and difference are shown for the annual and diurnal cases and the two correction methods in Figs. 7.3, 7.4, 7.5, and 7.6. Figs. 7.7,
7.8, 7.9, and 7.10 show the resulting contour plots.

In the seasonal case, a residual sinusoidal variation is clearly seen even after applying the weather paper corrections; however, the sinusoidal variation decreases compared to the uncorrected case. In the case of the Rayleigh analysis corrections, remaining variations are within statistical fluctuations. Tab. 7.1 summarizes these results.

The pattern is similar in the diurnal case. Due to noise, the chance probabilities may be lower than expected. However, the normalization coefficients provide a good measure of the remaining sinusoidal variation. A high coefficient means
Figure 7.2: January 1, 2005 - April 15, 2009 data: The average seasonal rate curves for uncorrected events (blue), weather paper corrected events (green), and Rayleigh analysis corrected events (red).

A large variation and a zero coefficient means no variation. The weather paper coefficient is \( \sim 80\% \) of the uncorrected coefficient. The Rayleigh analysis coefficient is an order of magnitude smaller and almost zero within error bars. Tab. 7.2 summarizes the results.
Figure 7.3: January 1, 2005 - April 15, 2009 data: The average annual rate curve (red), normalized temperature curve (blue) and difference (black) for weather paper corrected events.

<table>
<thead>
<tr>
<th>Correction Method</th>
<th>Fractional Coefficient</th>
<th>Phase (days)</th>
<th>P(R)</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>weather paper</td>
<td>0.00289 ± 0.00057</td>
<td>58 ± 12</td>
<td>5.92E-6</td>
<td>4.91</td>
</tr>
<tr>
<td>Rayleigh analysis</td>
<td>0.00032 ± 0.00060</td>
<td>76 ± 100</td>
<td>8.08E-1</td>
<td>0.65</td>
</tr>
</tbody>
</table>

Table 7.1: Check of seasonal rate variations using the two weather correction methods for events with E > 1.5 EeV and zenith angle < 45 degrees. A residual variation is found in the case of the weather paper corrections. Corrections using the Rayleigh analysis method are consistent with a flat rate.
Figure 7.4: January 1, 2005 - April 15, 2009 data: The average annual rate curve (red), normalized temperature curve (blue) and difference (black) for Rayleigh analysis events.

<table>
<thead>
<tr>
<th>Correction Method</th>
<th>Fractional Coefficient</th>
<th>Phase (hours)</th>
<th>P(R)</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>weather paper</td>
<td>0.00207 ± 0.00065</td>
<td>8.6 ± 1.3</td>
<td>7.46E-8</td>
<td>5.73</td>
</tr>
<tr>
<td>Rayleigh analysis</td>
<td>0.00070 ± 0.00069</td>
<td>-0.8 ± 2.2</td>
<td>1.29E-1</td>
<td>2.02</td>
</tr>
</tbody>
</table>

Table 7.2: Check of diurnal rate variations using the two weather correction methods for events with E > 1.5 EeV and zenith angle < 45 degrees.
Figure 7.5: January 1, 2005 - April 15, 2009 data: The average diurnal rate curve (red), normalized temperature curve (blue) and difference (black) for weather paper corrected events.
Figure 7.6: January 1, 2005 - April 15, 2009 data: The average diurnal rate curve (red), normalized temperature curve (blue) and difference (black) for Rayleigh analysis corrected events.
Figure 7.7: January 1, 2005 - April 15, 2009 data: Weather paper corrected events, annual case: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue "+". Contour lines show the results of 1,000,000 Monte Carlo simulations.
Figure 7.8: January 1, 2005 - April 15, 2009 data: Rayleigh analysis corrected events, annual case: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue '+'. Contour lines show the results of 1,000,000 Monte Carlo simulations.
Figure 7.9: January 1, 2005 - April 15, 2009 data: Weather paper corrected events, diurnal case: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue '+'. Contour lines show the results of 1,000,000 Monte Carlo simulations.
Figure 7.10: January 1, 2005 - April 15, 2009 data: Rayleigh analysis corrected events, diurnal case: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue '+' sign. Contour lines show the results of 1,000,000 Monte Carlo simulations.
7.3 Definitions

Right ascension measures the position of an object relative to the background stars and can be thought of as the celestial equivalent of longitude. It is the angle between the direction of the vernal equinox and a point measured eastward. A schematic is shown in Fig. 7.11.

A sidereal day is one rotation of earth relative to the background stars. This is different than a solar day, which is one rotation of earth relative to the sun. As such, a solar day is longer than a sidereal day. Sidereal time can be given in units of time or angle: midnight or 0 hours corresponds to 0 degrees, 12:00 corresponds to 180 degrees. Sidereal time is the right ascension directly overhead for an observer. As such, it depends on the observer’s longitude.

An anti-sidereal day is an artificial time scale not relative to any natural phenomena. As such, no real anisotropy is expected at this frequency, which corresponds to 364.25 days per year, one less than solar days per year [64]. Beating of residual seasonal and diurnal variations due to atmospheric effects can induce

![Figure 7.11: The right ascension, a, of a point is the angle measured eastward in the celestial plane from the vernal equinox, g, to the point [63].](image)
Figure 7.12: Two events with the same right ascension (blue) may have different sidereal times (red) due to the earth’s daily rotation.

anistropy in the sidereal and antisidereal frequencies. Performing anisotropy analyses in anti-sidereal time provides a check on results found in sidereal time.

Hour angle is the sidereal time minus the right ascension. Alternatively, right ascension is equal to the sidereal time minus the hour angle.

As shown in Fig. 7.12, it is possible for events with the same right ascension to have different sidereal times. Events may also have the same sidereal time but different right ascensions. The sidereal time of an event can be calculated from its time of arrival as described below.

7.4 Calculating Sidereal Time from Universal Time

The Julian date is another method of counting time and is the number of days and fraction of a day since 12:00 universal time on January 1, 4713 BC [65]. We first calculate the Julian date of an event from its universal time. The Julian date, JD,
of an event with universal time, UTC, is given by

\[ JD = JD_{2002} + \frac{UTC - UTC_{2002}}{86400}. \]  

(7.6)

where \( JD_{2002} = 2452275.5 \) is the Julian date at 00:00 UTC January 1, 2002 and \( UTC_{2002} \) is the universal time at 00:00 January 1, 2002.

The Julian time since 12:00 UTC January 1, 2000 is then calculated by subtracting 2,451,545 from JD.

\[ dT = JD - 2451545 \]  

(7.7)

Next we calculate the number of centuries since 2000, \( dY \).

\[ dY = \frac{dT}{36525} \]  

(7.8)

The sidereal time in degrees at 0 degrees longitude at universal time UTC is then [66]

\[ s_0(\theta) = 280.46061837 + 360.98564736629 \cdot dT + \left( 0.000387933 - \frac{dY}{38710000} \right) (dY)^2 \]  

(7.9)

where \( s_0(\theta) \) should be converted to a number from 0 - 360. That is, it is the remainder of division by 360.

The sidereal time in degrees at a location with longitude, \( L \), is then

\[ s_L(\theta) = s_0(\theta) + L \]  

(7.10)

Multiply by \( \pi/180 \) to convert to radians. The longitude of the Auger Observatory is taken to be that of the CLF, -69.33°.
7.5 Harmonic Analysis in Right Ascension

7.5.1 Method

Also known as a Rayleigh analysis, a m-th order harmonic analysis in right ascension fits a sine wave of period $2\pi/m$ to a distribution of N right ascensions, $\phi_{i...N}$ [67] [68]. Given N points, the first harmonic amplitude and phase of the Rayleigh vector are

$$r = \sqrt{a^2 + b^2}$$
$$\cos(\Phi) = \frac{a}{r}$$
$$\sin(\Phi) = \frac{b}{r}$$

(7.11)

where

$$a = \frac{2}{N} \sum_{i=1}^{N} \cos \phi_i$$
$$b = \frac{2}{N} \sum_{i=1}^{N} \sin \phi_i$$

(7.12)

The uncertainty in the phase, $\Delta \Phi$, is $1/\sqrt{2k}$ radians if $k \gg 1$ where $k = r^2/r_0^2 = N r^2/4$ since $r_0 = 2/\sqrt{N}$.

For the second harmonic, $\phi_i$ is replaced by $2\phi_i$ when computing the Rayleigh amplitude components. The phase is then half the phase of the resulting Rayleigh vector. It will range from 0 - $\pi$ radians. The phase uncertainty becomes $\Delta \Phi = 1/\sqrt{8k}$ radians.

The probability of observing a Rayleigh amplitude greater than $r$ by chance is given by

$$P(\geq r) = e^{-k}$$

(7.13)

This can be converted to a sigma level by noting the similarity of $P(\geq r)$ and
a Rayleigh distribution or two dimensional Gaussian. From this we can write

\[ k = \frac{r^2}{r_0^2} = \frac{2\sigma^2}{r_0^2} \Rightarrow \sigma = \frac{r_0}{\sqrt{2}} \quad (7.14) \]

The sigma level is then

\[ \sigma_r = \frac{r}{\sigma} = \frac{r\sqrt{2}}{r_0} = \sqrt{2}k \quad (7.15) \]

This sigma level pertains to a two dimensional Gaussian and will be used as a measure of statistical significance.

In addition, upper limits, \( r_{ul} \), on amplitudes at the 99\% confidence level are calculated using

\[ C.L. = \sqrt{\frac{N}{\pi}} \frac{1}{I_0\left(\frac{r^2N}{8}\right)} \int_0^{r_{ul}} I_0\left(\frac{r_sN}{2}\right) e^{-N\left(\sigma^2 + \frac{s^2}{2}\right)} ds \quad (7.16) \]

where \( I_0 \) is a modified bessel function of the first kind with order 0, \( r \) is the Rayleigh amplitude, and \( N \) is the number of events \[69\]. \( C.L. \) is the confidence level desired, 0.99 in this case.

However, the above formulation implicitly assumes that in the absence of any anisotropy, the arrival directions - that is the distribution of events in right ascension - will be uniform. If this is not the case, using the above will yield a result of anisotropy where none is present. Since the exposure of the SD changes over time due to tank construction, equipment failures, dead times, and other causes, we must take this into account in order to perform an accurate study.

We cannot calculate the exposure at any arbitrary point in the sky, i.e. at the arrival direction for every event. Therefore we divide the sky into 72 bins, each covering 5 degrees of sidereal time or right ascension. The exposure of each bin, \( A_i \), in sidereal time is calculated and a weight \( \omega_i \) is assigned to the bin as

\[ \omega_i = \frac{A_i}{< A >} \quad (7.17) \]

where \(< A >\) is the average exposure of a bin.
The components of the Rayleigh vector then become

\[
a = \frac{2}{N} \sum_{i=1}^{72} C_i \cos \frac{2\pi (i - 0.5)}{72}
\]

\[
b = \frac{2}{N} \sum_{i=1}^{72} C_i \sin \frac{2\pi (i - 0.5)}{72}
\]

(7.18)

where \( C_i \) is the weighted number of events in right ascension bin \( i \) and \( N \) is the total weighted number of events [70]. Each event is weighted by the exposure of its sidereal time. So an event is counted as \( 1/\omega_j \) instead of 1 where \( j \) is the sidereal time bin of an event and \( \omega_j \) was previously calculated.

### 7.5.2 Results

Tab. 7.3 shows the results from the harmonic analysis in right ascension for the first harmonic. With the exception of the \( 4.0 \leq E < 8.0 \text{ EeV} \) and \( 8.0 \text{ EeV} \leq E \) energy bins, the significance of the findings decreases after applying weather corrections. In four out of five differential energy ranges, the exception being \( 1.0 \leq E < 2.0 \text{ EeV} \), the anisotropy significance is less using the Rayleigh analysis corrections than using the weather paper corrections. Inspecting the results found using events with Rayleigh analysis corrections, we see a pattern of increasing anisotropy amplitude and decreasing significance as the energy range increases. This is probably due to a combination of residual trigger effects at low energies and the loss of statistics as energy increases. A graphical representation of the findings using the Rayleigh corrections is shown in Figs. 7.13 and 7.14.

Tab. 7.4 shows the results from the harmonic analysis in right ascension for the second harmonic. In all energy bins, the significance of the findings decreases after applying the Rayleigh analysis weather corrections. With the exception of the first two energy bins, the significance of the findings decreases after applying the weather paper corrections. Inspecting the results found using events with Rayleigh analysis corrections, we see anisotropy amplitudes of less than 1.0% and marginal significance. The exception is in the \( 8.0 \text{ EeV} \leq E \) energy bin where we see a 2.7% anisotropy amplitude, again with marginal significance. A graphical representation of the findings using the Rayleigh corrections is shown in Figs. 7.15 and 7.16.
<table>
<thead>
<tr>
<th>Energy Range (EeV)</th>
<th>R</th>
<th>Angle (degrees)</th>
<th>P(R)</th>
<th>σ</th>
<th>r_{ul}</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Uncorrected</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5 ≤ E &lt; 1.0</td>
<td>0.0079</td>
<td>313 ± 14</td>
<td>0.0006</td>
<td>3.864</td>
<td>0.0125</td>
</tr>
<tr>
<td>1.0 ≤ E &lt; 2.0</td>
<td>0.0095</td>
<td>19 ± 20</td>
<td>0.0182</td>
<td>2.831</td>
<td>0.0168</td>
</tr>
<tr>
<td>2.0 ≤ E &lt; 4.0</td>
<td>0.0185</td>
<td>328 ± 23</td>
<td>0.0401</td>
<td>2.537</td>
<td>0.0341</td>
</tr>
<tr>
<td>4.0 ≤ E &lt; 8.0</td>
<td>0.011</td>
<td>98 ± 77</td>
<td>0.759</td>
<td>0.74</td>
<td>0.044</td>
</tr>
<tr>
<td>8.0 ≤ E</td>
<td>0.029</td>
<td>125 ± 47</td>
<td>0.482</td>
<td>1.21</td>
<td>0.078</td>
</tr>
<tr>
<td>1.5 ≤ E</td>
<td>0.0083</td>
<td>359 ± 32</td>
<td>0.1928</td>
<td>1.814</td>
<td>0.0180</td>
</tr>
<tr>
<td><strong>Rayleigh Analysis Corrections</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5 ≤ E &lt; 1.0</td>
<td>0.0053</td>
<td>288 ± 24</td>
<td>0.0581</td>
<td>2.386</td>
<td>0.0101</td>
</tr>
<tr>
<td>1.0 ≤ E &lt; 2.0</td>
<td>0.0085</td>
<td>21 ± 24</td>
<td>0.0642</td>
<td>2.343</td>
<td>0.0162</td>
</tr>
<tr>
<td>2.0 ≤ E &lt; 4.0</td>
<td>0.0142</td>
<td>322 ± 32</td>
<td>0.1968</td>
<td>1.803</td>
<td>0.0307</td>
</tr>
<tr>
<td>4.0 ≤ E &lt; 8.0</td>
<td>0.014</td>
<td>129 ± 67</td>
<td>0.691</td>
<td>0.86</td>
<td>0.049</td>
</tr>
<tr>
<td>8.0 ≤ E</td>
<td>0.032</td>
<td>129 ± 46</td>
<td>0.455</td>
<td>1.26</td>
<td>0.086</td>
</tr>
<tr>
<td>1.5 ≤ E</td>
<td>0.0058</td>
<td>336 ± 49</td>
<td>0.5022</td>
<td>1.174</td>
<td>0.0162</td>
</tr>
<tr>
<td><strong>Weather Paper Corrections</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5 ≤ E &lt; 1.0</td>
<td>0.0053</td>
<td>310 ± 23</td>
<td>0.0467</td>
<td>2.476</td>
<td>0.0100</td>
</tr>
<tr>
<td>1.0 ≤ E &lt; 2.0</td>
<td>0.0081</td>
<td>23 ± 25</td>
<td>0.0733</td>
<td>2.286</td>
<td>0.0156</td>
</tr>
<tr>
<td>2.0 ≤ E &lt; 4.0</td>
<td>0.0152</td>
<td>314 ± 29</td>
<td>0.1411</td>
<td>1.979</td>
<td>0.0314</td>
</tr>
<tr>
<td>4.0 ≤ E &lt; 8.0</td>
<td>0.014</td>
<td>110 ± 65</td>
<td>0.676</td>
<td>0.89</td>
<td>0.048</td>
</tr>
<tr>
<td>8.0 ≤ E</td>
<td>0.040</td>
<td>150 ± 36</td>
<td>0.281</td>
<td>1.59</td>
<td>0.092</td>
</tr>
<tr>
<td>1.5 ≤ E</td>
<td>0.0067</td>
<td>346 ± 41</td>
<td>0.3846</td>
<td>1.382</td>
<td>0.0168</td>
</tr>
</tbody>
</table>

Table 7.3: January 1, 2005 - April 15, 2009: 0 ≤ θ < 45 degrees: Results of a Rayleigh analysis in right ascension for the first harmonic.
Figure 7.13: The first harmonic anisotropy amplitude and phase in right ascension.
Figure 7.14: The first harmonic significance in right ascension plotted as a function of phase angle.
<table>
<thead>
<tr>
<th>Energy Range (EeV)</th>
<th>R</th>
<th>Angle (degrees)</th>
<th>P(R)</th>
<th>σ</th>
<th>r_{ul}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Uncorrected</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5 ≤ E &lt; 1.0</td>
<td>0.0042</td>
<td>156 ± 10</td>
<td>0.1193</td>
<td>2.062</td>
<td>0.0086</td>
</tr>
<tr>
<td>1.0 ≤ E &lt; 2.0</td>
<td>0.0039</td>
<td>15 ± 16</td>
<td>0.5167</td>
<td>1.149</td>
<td>0.0109</td>
</tr>
<tr>
<td>2.0 ≤ E &lt; 4.0</td>
<td>0.0106</td>
<td>97 ± 13</td>
<td>0.3474</td>
<td>1.454</td>
<td>0.0258</td>
</tr>
<tr>
<td>4.0 ≤ E &lt; 8.0</td>
<td>0.011</td>
<td>139 ± 31</td>
<td>0.784</td>
<td>0.70</td>
<td>0.043</td>
</tr>
<tr>
<td>8.0 ≤ E</td>
<td>0.031</td>
<td>166 ± 27</td>
<td>0.418</td>
<td>1.32</td>
<td>0.081</td>
</tr>
<tr>
<td>1.5 ≤ E</td>
<td>0.0042</td>
<td>146 ± 9</td>
<td>0.6544</td>
<td>0.921</td>
<td>0.0139</td>
</tr>
<tr>
<td></td>
<td>Rayleigh Analysis Corrections</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5 ≤ E &lt; 1.0</td>
<td>0.0040</td>
<td>148 ± 11</td>
<td>0.2037</td>
<td>1.784</td>
<td>0.0086</td>
</tr>
<tr>
<td>1.0 ≤ E &lt; 2.0</td>
<td>0.0043</td>
<td>2 ± 17</td>
<td>0.4860</td>
<td>1.201</td>
<td>0.0119</td>
</tr>
<tr>
<td>2.0 ≤ E &lt; 4.0</td>
<td>0.0096</td>
<td>99 ± 16</td>
<td>0.4745</td>
<td>1.221</td>
<td>0.0260</td>
</tr>
<tr>
<td>4.0 ≤ E &lt; 8.0</td>
<td>0.007</td>
<td>169 ± 23</td>
<td>0.919</td>
<td>0.41</td>
<td>0.044</td>
</tr>
<tr>
<td>8.0 ≤ E</td>
<td>0.027</td>
<td>136 ± 53</td>
<td>0.567</td>
<td>1.07</td>
<td>0.081</td>
</tr>
<tr>
<td>1.5 ≤ E</td>
<td>0.0043</td>
<td>151 ± 13</td>
<td>0.6812</td>
<td>0.876</td>
<td>0.0148</td>
</tr>
<tr>
<td></td>
<td>Weather Paper Corrections</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5 ≤ E &lt; 1.0</td>
<td>0.0045</td>
<td>154 ± 10</td>
<td>0.1096</td>
<td>2.103</td>
<td>0.0091</td>
</tr>
<tr>
<td>1.0 ≤ E &lt; 2.0</td>
<td>0.0042</td>
<td>5 ± 18</td>
<td>0.5000</td>
<td>1.177</td>
<td>0.0115</td>
</tr>
<tr>
<td>2.0 ≤ E &lt; 4.0</td>
<td>0.0079</td>
<td>98 ± 16</td>
<td>0.5863</td>
<td>1.033</td>
<td>0.0240</td>
</tr>
<tr>
<td>4.0 ≤ E &lt; 8.0</td>
<td>0.002</td>
<td>49 ± 44</td>
<td>0.989</td>
<td>0.15</td>
<td>0.042</td>
</tr>
<tr>
<td>8.0 ≤ E</td>
<td>0.026</td>
<td>149 ± 50</td>
<td>0.591</td>
<td>1.03</td>
<td>0.078</td>
</tr>
<tr>
<td>1.5 ≤ E</td>
<td>0.0048</td>
<td>158 ± 11</td>
<td>0.6089</td>
<td>0.996</td>
<td>0.0150</td>
</tr>
</tbody>
</table>

Table 7.4: January 1, 2005 - April 15, 2009: $0 \leq \theta < 45$ degrees: Results of a Rayleigh analysis in right ascension for the second harmonic.
Figure 7.15: The second harmonic anisotropy amplitude and phase in right ascension.
Figure 7.16: The second harmonic significance in right ascension plotted as a function of phase angle.
7.6 Sidereal Analysis

7.6.1 Method

The method of the sidereal analysis is identical to that of the harmonic analysis in right ascension except that the events are binned by sidereal time rather than by right ascension.

7.6.2 Results

If there is anisotropy, less anisotropy is expected to be observed in sidereal time than in right ascension since events are binned by arrival time relative to the background stars rather than by arrival direction. The results are shown in Tab. 7.5 and are comparable to those found using right ascension, both in anisotropy amplitude and significance. With the exception of the $4.0 \leq E < 8.0$ EeV energy bin, applying weather corrections reduces the significance of anisotropies found. In the $4.0 \leq E < 8.0$ EeV energy bin the significance increases from $0.63\sigma$ to $1.09\sigma$. The anisotropy amplitude also increases from $0.9\%$ to $1.8\%$. A graphical representation of the findings using the Rayleigh corrections is shown in Figs. 7.17 and 7.18.

Using the results from events with the Rayleigh analysis weather corrections, the anisotropy amplitudes and significances of the second harmonic in sidereal time are similar to those of the second harmonic in right ascension with the exception of the $1.5$ EeV $\geq E$ energy bin. In right ascension a $0.4\%$ anisotropy amplitude was seen with $0.88\sigma$. Here a $1.1\%$ anisotropy amplitude is seen at a $2.2\sigma$ level in the second harmonic in sidereal time. While possibly suggestive, this is still not significant.
<table>
<thead>
<tr>
<th>Energy Range (E\text{eV})</th>
<th>R</th>
<th>Angle (degrees)</th>
<th>P(R)</th>
<th>$\sigma$</th>
<th>$r_{ul}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncorrected</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$0.5 \leq E &lt; 1.0$</td>
<td>0.0083</td>
<td>320 ± 14</td>
<td>0.0003</td>
<td>4.033</td>
<td>0.0129</td>
</tr>
<tr>
<td>$1.0 \leq E &lt; 2.0$</td>
<td>0.0105</td>
<td>18 ± 18</td>
<td>0.0074</td>
<td>3.133</td>
<td>0.0178</td>
</tr>
<tr>
<td>$2.0 \leq E &lt; 4.0$</td>
<td>0.0142</td>
<td>329 ± 29</td>
<td>0.1500</td>
<td>1.948</td>
<td>0.0295</td>
</tr>
<tr>
<td>$4.0 \leq E &lt; 8.0$</td>
<td>0.010</td>
<td>147 ± 91</td>
<td>0.820</td>
<td>0.63</td>
<td>0.043</td>
</tr>
<tr>
<td>$8.0 \leq E$</td>
<td>0.037</td>
<td>101 ± 37</td>
<td>0.300</td>
<td>1.56</td>
<td>0.087</td>
</tr>
<tr>
<td>$1.5 \leq E$</td>
<td>0.0071</td>
<td>358 ± 37</td>
<td>0.3031</td>
<td>1.545</td>
<td>0.0167</td>
</tr>
<tr>
<td>Rayleigh Analysis Corrections</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$0.5 \leq E &lt; 1.0$</td>
<td>0.0052</td>
<td>296 ± 25</td>
<td>0.0672</td>
<td>2.324</td>
<td>0.0099</td>
</tr>
<tr>
<td>$1.0 \leq E &lt; 2.0$</td>
<td>0.0092</td>
<td>11 ± 23</td>
<td>0.0402</td>
<td>2.536</td>
<td>0.0170</td>
</tr>
<tr>
<td>$2.0 \leq E &lt; 4.0$</td>
<td>0.0114</td>
<td>327 ± 40</td>
<td>0.3528</td>
<td>1.444</td>
<td>0.0278</td>
</tr>
<tr>
<td>$4.0 \leq E &lt; 8.0$</td>
<td>0.018</td>
<td>178 ± 52</td>
<td>0.549</td>
<td>1.10</td>
<td>0.053</td>
</tr>
<tr>
<td>$8.0 \leq E$</td>
<td>0.034</td>
<td>111 ± 43</td>
<td>0.405</td>
<td>1.35</td>
<td>0.088</td>
</tr>
<tr>
<td>$1.5 \leq E$</td>
<td>0.0049</td>
<td>317 ± 57</td>
<td>0.6081</td>
<td>0.998</td>
<td>0.0154</td>
</tr>
<tr>
<td>Weather Paper Corrections</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$0.5 \leq E &lt; 1.0$</td>
<td>0.0054</td>
<td>316 ± 23</td>
<td>0.0417</td>
<td>2.521</td>
<td>0.0101</td>
</tr>
<tr>
<td>$1.0 \leq E &lt; 2.0$</td>
<td>0.0081</td>
<td>17 ± 25</td>
<td>0.0708</td>
<td>2.301</td>
<td>0.0157</td>
</tr>
<tr>
<td>$2.0 \leq E &lt; 4.0$</td>
<td>0.0116</td>
<td>316 ± 38</td>
<td>0.3202</td>
<td>1.509</td>
<td>0.0276</td>
</tr>
<tr>
<td>$4.0 \leq E &lt; 8.0$</td>
<td>0.015</td>
<td>164 ± 61</td>
<td>0.644</td>
<td>0.94</td>
<td>0.049</td>
</tr>
<tr>
<td>$8.0 \leq E$</td>
<td>0.036</td>
<td>129 ± 40</td>
<td>0.355</td>
<td>1.44</td>
<td>0.088</td>
</tr>
<tr>
<td>$1.5 \leq E$</td>
<td>0.0044</td>
<td>333 ± 62</td>
<td>0.6542</td>
<td>0.921</td>
<td>0.0147</td>
</tr>
</tbody>
</table>

Table 7.5: January 1, 2005 - April 15, 2009: $0 \leq \theta < 45$ degrees: Results of the first harmonic sidereal analysis.

With the exception of the $4.0 \leq E < 8.0$ E\text{eV} energy bin, applying the Rayleigh analysis weather corrections reduces the significance of anisotropies found. In the $4.0 \leq E < 8.0$ E\text{eV} energy bin the significance increases from 0.92$\sigma$ to 1.23$\sigma$. The anisotropy amplitude also increases from 1.4% to 2.0%. With the exception of the $0.5 \leq E < 1.0$ E\text{eV} energy bin, applying the weather paper corrections reduces the significance of anisotropies found. In that case the significance increases from 2.74$\sigma$ to 2.85$\sigma$, a minor effect. The anisotropy amplitudes are consistent. A graphical representation of the findings using the Rayleigh corrections is shown in Figs. 7.19 and 7.20.
Figure 7.17: The first harmonic anisotropy amplitude and phase in sidereal time.
Figure 7.18: The first harmonic significance in sidereal time plotted as a function of phase angle.
<table>
<thead>
<tr>
<th>Energy Range (EeV)</th>
<th>R</th>
<th>Angle (degrees)</th>
<th>P(R)</th>
<th>σ</th>
<th>r_{ul}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uncorrected</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5 ≤ E &lt; 1.0</td>
<td>0.0056</td>
<td>170 ± 10</td>
<td>0.0232</td>
<td>2.744</td>
<td>0.0101</td>
</tr>
<tr>
<td>1.0 ≤ E &lt; 2.0</td>
<td>0.0059</td>
<td>140 ± 16</td>
<td>0.2069</td>
<td>1.775</td>
<td>0.0130</td>
</tr>
<tr>
<td>2.0 ≤ E &lt; 4.0</td>
<td>0.0159</td>
<td>99 ± 13</td>
<td>0.0909</td>
<td>2.190</td>
<td>0.0314</td>
</tr>
<tr>
<td>4.0 ≤ E &lt; 8.0</td>
<td>0.0144</td>
<td>151 ± 31</td>
<td>0.657</td>
<td>0.92</td>
<td>0.046</td>
</tr>
<tr>
<td>8.0 ≤ E</td>
<td>0.026</td>
<td>2 ± 27</td>
<td>0.558</td>
<td>1.08</td>
<td>0.076</td>
</tr>
<tr>
<td>1.5 ≤ E</td>
<td>0.0146</td>
<td>125 ± 9</td>
<td>0.0063</td>
<td>3.186</td>
<td>0.0246</td>
</tr>
<tr>
<td>Rayleigh Analysis Corrections</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>0.5 ≤ E &lt; 1.0</td>
<td>0.0060</td>
<td>163 ± 11</td>
<td>0.0249</td>
<td>2.717</td>
<td>0.0109</td>
</tr>
<tr>
<td>1.0 ≤ E &lt; 2.0</td>
<td>0.0060</td>
<td>146 ± 17</td>
<td>0.2522</td>
<td>1.660</td>
<td>0.0136</td>
</tr>
<tr>
<td>2.0 ≤ E &lt; 4.0</td>
<td>0.0142</td>
<td>95 ± 16</td>
<td>0.1970</td>
<td>1.802</td>
<td>0.0307</td>
</tr>
<tr>
<td>4.0 ≤ E &lt; 8.0</td>
<td>0.020</td>
<td>178 ± 23</td>
<td>0.468</td>
<td>1.23</td>
<td>0.055</td>
</tr>
<tr>
<td>8.0 ≤ E</td>
<td>0.014</td>
<td>168 ± 53</td>
<td>0.863</td>
<td>0.54</td>
<td>0.071</td>
</tr>
<tr>
<td>1.5 ≤ E</td>
<td>0.0107</td>
<td>124 ± 13</td>
<td>0.0954</td>
<td>2.168</td>
<td>0.0213</td>
</tr>
<tr>
<td>Weather Paper Corrections</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>0.5 ≤ E &lt; 1.0</td>
<td>0.0061</td>
<td>163 ± 10</td>
<td>0.0174</td>
<td>2.847</td>
<td>0.0108</td>
</tr>
<tr>
<td>1.0 ≤ E &lt; 2.0</td>
<td>0.0057</td>
<td>140 ± 18</td>
<td>0.2742</td>
<td>1.609</td>
<td>0.0131</td>
</tr>
<tr>
<td>2.0 ≤ E &lt; 4.0</td>
<td>0.0139</td>
<td>97 ± 16</td>
<td>0.1920</td>
<td>1.817</td>
<td>0.0301</td>
</tr>
<tr>
<td>4.0 ≤ E &lt; 8.0</td>
<td>0.010</td>
<td>161 ± 44</td>
<td>0.812</td>
<td>0.64</td>
<td>0.045</td>
</tr>
<tr>
<td>8.0 ≤ E</td>
<td>0.014</td>
<td>0 ± 50</td>
<td>0.851</td>
<td>0.55</td>
<td>0.069</td>
</tr>
<tr>
<td>1.5 ≤ E</td>
<td>0.0122</td>
<td>124 ± 11</td>
<td>0.0407</td>
<td>2.531</td>
<td>0.0226</td>
</tr>
</tbody>
</table>

Table 7.6: January 1, 2005 - April 15, 2009: 0 ≤ θ < 45 degrees: Results of the second harmonic sidereal analysis.
Figure 7.19: The second harmonic anisotropy amplitude and phase in sidereal time.
Figure 7.20: The second harmonic significance in sidereal time plotted as a function of phase angle.
7.7 Anti-sidereal Analysis

7.7.1 Method

The method of the anti-sidereal analysis is identical to that of the harmonic analysis in right ascension except that the events are binned by anti-sidereal time rather than by right ascension.

7.7.2 Results

No anisotropy is expected to be observed in anti-sidereal time as no known phenomena occur with this frequency. The results are shown in Tab. 7.7 and are consistent with this. With the exception of the $4.0 \leq E < 8.0$ EeV and $8.0 \leq E < 15.0$ EeV energy bin, applying weather corrections reduces the significance of anisotropies found. No significant anisotropy is seen. A graphical representation of the findings using the Rayleigh corrections is shown in Figs. 7.21 and 7.22.

Using the results from events with the Rayleigh analysis weather corrections, the anisotropy amplitudes and significances of the second harmonic in anti-sidereal time also do not show evidence of anisotropy. See Tab. 7.8 for the results. The anisotropy amplitudes are similar between the two correction methods and the uncorrected data. A graphical representation of the findings using the Rayleigh corrections is shown in Figs. 7.23 and 7.24.
<table>
<thead>
<tr>
<th>Energy Range (EeV)</th>
<th>R</th>
<th>Angle (degrees)</th>
<th>P(R)</th>
<th>σ</th>
<th>rвал</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Uncorrected</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5 ≤ E &lt; 1.0</td>
<td>0.0080</td>
<td>307 ± 15</td>
<td>0.0005</td>
<td>3.891</td>
<td>0.0126</td>
</tr>
<tr>
<td>1.0 ≤ E &lt; 2.0</td>
<td>0.0046</td>
<td>313 ± 41</td>
<td>0.3830</td>
<td>1.386</td>
<td>0.0116</td>
</tr>
<tr>
<td>2.0 ≤ E &lt; 4.0</td>
<td>0.0119</td>
<td>301 ± 35</td>
<td>0.2652</td>
<td>1.629</td>
<td>0.0271</td>
</tr>
<tr>
<td>4.0 ≤ E &lt; 8.0</td>
<td>0.017</td>
<td>143 ± 51</td>
<td>0.533</td>
<td>1.12</td>
<td>0.049</td>
</tr>
<tr>
<td>8.0 ≤ E</td>
<td>0.033</td>
<td>292 ± 41</td>
<td>0.383</td>
<td>1.39</td>
<td>0.083</td>
</tr>
<tr>
<td>1.5 ≤ E</td>
<td>0.0098</td>
<td>285 ± 27</td>
<td>0.1039</td>
<td>2.128</td>
<td>0.0195</td>
</tr>
<tr>
<td><strong>Rayleigh Analysis Corrections</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5 ≤ E &lt; 1.0</td>
<td>0.0062</td>
<td>310 ± 21</td>
<td>0.0214</td>
<td>2.772</td>
<td>0.0110</td>
</tr>
<tr>
<td>1.0 ≤ E &lt; 2.0</td>
<td>0.0001</td>
<td>253 ± 360</td>
<td>0.9997</td>
<td>0.025</td>
<td>0.0093</td>
</tr>
<tr>
<td>2.0 ≤ E &lt; 4.0</td>
<td>0.0102</td>
<td>267 ± 44</td>
<td>0.4326</td>
<td>1.295</td>
<td>0.0266</td>
</tr>
<tr>
<td>4.0 ≤ E &lt; 8.0</td>
<td>0.025</td>
<td>130 ± 38</td>
<td>0.319</td>
<td>1.51</td>
<td>0.059</td>
</tr>
<tr>
<td>8.0 ≤ E</td>
<td>0.051</td>
<td>285 ± 29</td>
<td>0.138</td>
<td>1.99</td>
<td>0.105</td>
</tr>
<tr>
<td>1.5 ≤ E</td>
<td>0.0067</td>
<td>240 ± 43</td>
<td>0.4046</td>
<td>1.345</td>
<td>0.0170</td>
</tr>
<tr>
<td><strong>Weather Paper Corrections</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5 ≤ E &lt; 1.0</td>
<td>0.0056</td>
<td>289.96 ± 22.30</td>
<td>0.0369</td>
<td>2.569</td>
<td>0.0102</td>
</tr>
<tr>
<td>1.0 ≤ E &lt; 2.0</td>
<td>0.0030</td>
<td>260.08 ± 67.57</td>
<td>0.6981</td>
<td>0.848</td>
<td>0.0105</td>
</tr>
<tr>
<td>2.0 ≤ E &lt; 4.0</td>
<td>0.0113</td>
<td>280.53 ± 38.97</td>
<td>0.3392</td>
<td>1.470</td>
<td>0.0273</td>
</tr>
<tr>
<td>4.0 ≤ E &lt; 8.0</td>
<td>0.029</td>
<td>119.45 ± 31.48</td>
<td>0.191</td>
<td>1.82</td>
<td>0.063</td>
</tr>
<tr>
<td>8.0 ≤ E</td>
<td>0.050</td>
<td>281.98 ± 28.62</td>
<td>0.135</td>
<td>2.00</td>
<td>0.103</td>
</tr>
<tr>
<td>1.5 ≤ E</td>
<td>0.0071</td>
<td>247.56 ± 38.86</td>
<td>0.3373</td>
<td>1.474</td>
<td>0.0172</td>
</tr>
</tbody>
</table>

Table 7.7: January 1, 2005 - April 15, 2009: 0 ≤ θ < 45 degrees: Results of the first harmonic anti-sidereal analysis.
Figure 7.21: The first harmonic anisotropy amplitude and phase in anti-sidereal time.
Figure 7.22: The first harmonic significance in anti-sidereal time plotted as a function of phase angle.
<table>
<thead>
<tr>
<th>Energy Range (EeV)</th>
<th>R</th>
<th>Angle (degrees)</th>
<th>P(R)</th>
<th>σ</th>
<th>r_{ul}</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Uncorrected</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5 ≤ E &lt; 1.0</td>
<td>0.0048</td>
<td>32 ± 12</td>
<td>0.0636</td>
<td>2.348</td>
<td>0.0092</td>
</tr>
<tr>
<td>1.0 ≤ E &lt; 2.0</td>
<td>0.0027</td>
<td>156 ± 35</td>
<td>0.7205</td>
<td>0.810</td>
<td>0.0099</td>
</tr>
<tr>
<td>2.0 ≤ E &lt; 4.0</td>
<td>0.0074</td>
<td>50 ± 28</td>
<td>0.5929</td>
<td>1.023</td>
<td>0.0227</td>
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<tr>
<td>4.0 ≤ E &lt; 8.0</td>
<td>0.011</td>
<td>115 ± 41</td>
<td>0.783</td>
<td>0.70</td>
<td>0.043</td>
</tr>
<tr>
<td>8.0 ≤ E</td>
<td>0.012</td>
<td>155 ± 59</td>
<td>0.888</td>
<td>0.49</td>
<td>0.065</td>
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<tr>
<td>1.5 ≤ E</td>
<td>0.0034</td>
<td>72 ± 38</td>
<td>0.7541</td>
<td>0.751</td>
<td>0.0133</td>
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<td><strong>Rayleigh Analysis Corrections</strong></td>
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</tr>
<tr>
<td>0.5 ≤ E &lt; 1.0</td>
<td>0.0042</td>
<td>22 ± 15</td>
<td>0.1610</td>
<td>1.911</td>
<td>0.0089</td>
</tr>
<tr>
<td>1.0 ≤ E &lt; 2.0</td>
<td>0.0038</td>
<td>160 ± 28</td>
<td>0.5820</td>
<td>1.040</td>
<td>0.0114</td>
</tr>
<tr>
<td>2.0 ≤ E &lt; 4.0</td>
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<tr>
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<td>101 ± 33</td>
<td>0.691</td>
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<td>23 ± 66</td>
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<td>23 ± 19</td>
<td>0.3082</td>
<td>1.534</td>
<td>0.0078</td>
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<td>153 ± 25</td>
<td>0.5228</td>
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<td>43 ± 26</td>
<td>0.5521</td>
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<td>0.0244</td>
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<tr>
<td>4.0 ≤ E &lt; 8.0</td>
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<td>104 ± 32</td>
<td>0.666</td>
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<td>0.049</td>
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<td>0.8696</td>
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Table 7.8: January 1, 2005 - April 15, 2009: 0 ≤ θ < 45 degrees: Results of the second harmonic anti-sidereal analysis.
Figure 7.23: The second harmonic anisotropy amplitude and phase in anti-sidereal time.
Figure 7.24: The second harmonic significance in anti-sidereal time plotted as a function of phase angle.
Summary and Conclusions

Results! Why man, I have gotten a lot of results, I know several thousand things that don’t work.

–Thomas Edison

The nature of high energy cosmic rays remains one of the great mysteries of physics. Their rarity requires detectors with large exposures and long operating times. One such detector is the Pierre Auger Observatory, which is comprised of 1600 water Cherenkov detectors, 4 fluorescence detector eyes, and covers an area the size of Rhode Island. We detect the extensive air showers at ground level, rather than the primary particles themselves, and thus need to understand how air shower development is influenced by the atmosphere. Quantifying atmospheric effects on the energies measured is important for anisotropy studies, where more accurate energy assignments allow for more accurate searches. Here we have presented research detailing the relation between rates, energies, and atmospheric parameters. We have studied not only the magnitude of the effects, but also temporal offsets between the rates and temperature.

In the seasonal case, an offset of 14 days is seen between the CLF temperature and rate for events above 1.5 EeV. Performing the same analysis using data taken from various pressure levels of GDAS shows that the 750 hPa level tracks the annual rate curve with no phase lag. Therefore, the temperature 100 hPa above the surface of the array is used to remove seasonal weather corrections.

In the diurnal case, the 3 hour time offset seen between the CLF temperature and rate for events above 1.5 EeV is not as easily explained using GDAS data. This
is in part due to the temporal sampling rate of GDAS (3 hours for GDAS versus 5 minutes for the CLF) and in part due to heavy model dependence over those time scales. This does not mean that the ground level is the relevant altitude; it simply means that we should look beyond GDAS to explain the diurnal shifts.

To further study this diurnal time offset, we developed a method to measure air temperature and pressure up to 1 kilometer above the ground. However, the oktokopter which was designed to carry the atmospheric sensor has not worked reliably. Therefore time lagged CLF data is used to correct the diurnal atmospheric effects and we still have no way to identify temperature inversions at the site.

This combination of time lagged ground level data from the CLF and instantaneous 750 hPa GDAS data is used to perform both seasonal and diurnal atmospheric corrections. These corrections remove the first harmonic annual and diurnal atmospheric effects, produce annual and diurnal rates that are flat within uncertainties, and increase the sensitivity of our anisotropy studies. Having removed atmospheric effects which can cause anisotropy signals where no cosmic ray anisotropy is present, we are only limited by statistics and should be able to detect a 1% cosmic ray anisotropy with 99% confidence. Despite the corrections, no evidence for low energy anisotropy is seen using either a harmonic analysis in right ascension or a harmonic analysis in sidereal time in the first or second harmonic.

In the future, it would be worthwhile to further study the diurnal rate. Precisely determining the relevant altitude at which the rate and temperature curves are in phase could provide useful information for more effective weather corrections as would determining the cause of early morning rate increases during the winter months, particularly June. The diurnal variation of the rate during winter is $\sim 5\%$ full scale. Since a second brief maximum appears where the minimum is expected in the rate (see Fig. A.2), but is not present in the CLF temperature, applying temperature corrections can lead to a systematic increase of already high rates in the early morning hours. Rather than decreasing the second maximum by 2.5%, the early morning rate variation will be doubled due to low temperatures at that time. This will result in generally flat rates throughout the day, as the temperature correction performs as expected, except in the early morning hours where the rate will be $\sim 5\%$ above the mean. Although this only pertains to early morning rates during winter, this effect is well worth understanding as it could introduce
systematic errors when looking at winter only time periods.

Although it is hypothesized that these rate increases are caused by temperature inversions, we were not able to make sufficient measurements to confirm this. Temporally dense lower atmospheric profiles are needed and would lead to a better understanding of how temperature propagates upwards and how temperature inversions form and dissipate. Possibly another attempt with the oktokopter would be successful, although this would require replacement of the Flight Control board and possibly other parts. Alternatively, instrumenting a nearby volcanic cone could provide easier measurements that would still be useful. The top of Cerro Diamante, a local small mountain, rises 1 km above the array so relative measurements between the CLF and the top of Cerro Diamante could signal temperature inversions. However, Cerro Diamante is located 30 km outside the array, leading to uncertainty if localized temperature effects are present. These effects could be decreased if the top and bottom of Cerro Diamante were instrumented and a study of systematic differences with the CLF was conducted.
Appendix A

MIRACLE:
MIkrokopter Roving AtmospheriC
Levitating Experiment

Never run out of altitude, airspeed, and ideas at the same time.
–Unknown

A.1 Motivation

While the atmospheric data from the CLF weather station have complete temporal coverage, the spatial coverage is lacking. Balloon data have excellent vertical coverage, but sparse time coverage due to manpower and cost restrictions [4]. Model and satellite data are useful several kilometers above ground level since models do not take the ground into account, and thus cannot show ground effects, and satellite data are affected by infrared radiation from the ground. Therefore, we are missing data with complete temporal coverage in the first few kilometers above the ground.

To rectify this situation, an oktokopter equipped with a temperature and pressure sensor was proposed. A weather sensor would be attached to the oktokopter, which would then be flown vertically upwards to a height of 1 kilometer from a central location inside the array. Various other methods of obtaining vertical profiles were considered, such as launching model rockets or smaller weather ballons more
frequently. However, all were deemed less ideal than an oktokopter. Both balloons and rockets would drift as they descend, making equipment retrieval difficult. Additionally, rockets posed the possibly insurmountable problem of transporting rocket fuel from the USA to Argentina over passenger airlines. A tethered balloon, in addition to the challenge of finding a cable long enough, would require calculating the height given various wind drifts. In comparison, the oktokopter has a slot for a microSD card which logs flight data for later correlation with the atmospheric sensor. Also, since the oktokopter is self powered, it can theoretically land at a spot of the operator’s choosing.

By conducting flights at different times of the day over the course of several weeks, it was hoped that an average daily profile of the lower atmosphere could be obtained, as well as a sense of how the temperature propagates though the atmosphere.

These data are desired for several reasons:

1. To see if the diurnal temperature curve at an altitude other than ground level has a maximum correlation with the diurnal rate curve with no time offset.

2. To see if the diurnal temperature curve at an altitude other than ground level has the same shape as the winter diurnal rate curve.

3. To see if the diurnal temperature curves at various altitudes have the same shape as at ground level or if the structure is more complex.

4. To see what fraction of days in winter have temperature inversions and to measure their length, strength, time of formation, and time of dissipation.

As explained in Ch. 6, a 1.9 hour offset between the diurnal rate and diurnal CLF temperature is seen. While GDAS data can be used to study the seasonal offsets, they are less effective for studying the diurnal case. It was hoped that the data from the oktokopter could be used to explain the diurnal offsets.

While the overall diurnal rate curve appears sinusoidal, the winter rate curve exhibits a second maximum (see Fig. A.2) where the minimum is in the all seasons case (see fig.A.1). Inspecting the diurnal rates on a month by month basis (see Figs. A.3, A.4, A.5) shows that this effect is predominantly due to the month of June. Thus June data were particularly desirable.
Figure A.1: The diurnal rate curve using 2005-2008 data. All events with zenith angles less than 60 ° were used.
Figure A.2: The diurnal rate curve for winter using data from 2005-2008. All events with zenith angles less than 60° were used.
Figure A.3: The diurnal rate curve for May using data from 2005-2008. All events with zenith angles less than 60° were used.
Figure A.4: The diurnal rate curve for June using data from 2005-2008. All events with zenith angles less than 60° were used.
Figure A.5: The diurnal rate curve for July using data from 2005-2008. All events with zenith angles less than 60° were used.
A.2 Assembly

The oktokopter was procured in May 2010. While a commercial product, it is a build-it-yourself project [71]. The website www.mikrokopter.de/ucwiki/en/MK-Okto and its links are a valuable reference when building an oktokopter. Surface mount components come soldered on; everything else requires soldering.

Electronic parts on the oktokopter consist of a flight control board (FlightCtrl), a navigational control board (NaviCtrl), 8 brushless control boards (BLCs), a tilt compensated compass (MK3MAG), a GPS receiver (MKGPS), and a power control board (PCB) [71]. The MKGPS, MK3MAG, NaviCtrl, and FlightCtrl form a central tower around which the PCB sits. The PCB holds each of the BLCs in a separate slot. While the FlightCtrl controls the general operation of the oktokopter, relaying signals from the transmitter to the motors and keeping the oktokopter stable, the NaviCtrl, MK3MAG, and MKGPS extend the abilities of the oktokopter. They allow the operator to set a position which the oktokopter maintains. These components also allow for logging of flight data to a microSD card. Additionally, a specially designed USB board (MK-USB) is used to connect the oktokopter to a computer in order to set and read out parameters.

The frame consists of a circular disk roughly 9 inches in diameter upon which the electronics and 4 "Y" shaped arms are mounted. Plastic and fiberglass landing gear provide clearance from the ground. See Fig. A.6 for a picture of the fully assembled oktokopter. While the mikrokopter wiki pages are useful, they do not provide the best method to assemble the frame. Since the motor wires need to be threaded through two sets of metal tubes, it is best to completely assemble the arms of the oktokopter before mounting them to the central hub. The tubes with three holes drilled in one end are the outer arms. Feed the wires of one motor through the innermost hole of a tube and out the far end. Although any hole will work, using the innermost one keeps the wires out of the way when attaching the motor. After the wires are threaded though the outer arms, the motor is attached using the two small screws that come with the motor.

After this, wires from two motors are threaded though an inner tube and exit through the large holes on two sides of the arm. It is important to keep track of which wires go to which motor, as this is crucial to proper motor function. Feeding
the wires from each motor through as a separate group is helpful. A loop of stiff wire to catch the motor wires and pull them through the hole is also useful, as is patience. After the wires are out, they should be knotted or taped together to prevent them from falling back inside. Further details are available on the mikrokopter wiki pages.

The propellers come in two orientations and it is important to match them with the motor directions. If they are incorrect, the oktokopter will rock back and forth as the throttle in increased rather than lift off. This problem is easily fixed by swapping the propellers.

The proof of concept flight occurred on May 30, 2010 at 1:40 pm local time in the field next to the Pennsylvania State University Law School in University Park, PA, USA. The oktokopter lifted off without problems. The first flights were confined to altitudes less than 2 m above ground due the skill of the pilot and the
Figure A.7: The pressure sensor of the MSR 145 is attached to the camera mounting plate of the oktokopter, while the temperature probe is mounted halfway down one of the landing legs. The data logger itself is taped to the top of the landing gear where it meets the circular frame.

desire to transport a working oktokopter to Argentina.

A MSR145 with external temperature and pressure sensors is used for the atmospheric measurements. The attachment of the sensors to the oktokopter can be seen in Fig. A.7. The pressure sensor is centrally located beneath the oktokopter to minimize the effects of propeller turbulence. The temperature sensor is located halfway down the landing gear legs to minimize the effect of heat from the electronics. Attachment is by means of electrical tape, as it is easier to remove than duct tape, is sufficiently strong, and does not become brittle in the cold.
A.3 Transport

As the oktokopter is a fragile piece of electrical equipment, and fragile electronic equipment does not fare well in checked baggage, it is desirable to transport the oktokopter and its accessories from the USA to Argentina via carry-on baggage.

The fully assembled oktokopter is 30 inches from wingtip to wingtip. Its accessories include:

- 1 transmitter (7 x 7 x 3 inches)
- 4 batteries (1 x 3 x 6 inches)
- 1 battery charger (3 x 6 x 8 inches)
- extra propellers, spare wires, cables, miscellaneous electronic parts
- tools for assembly

As of June 2010, American Airlines requires that carry-on bags weigh less than 40 lbs (18 kg) and have overall dimensions (length + width + height) of less than 45 inches, although the maximum measurement cannot exceed any of the following: 22 inches long, 14 inches wide, and 9 inches tall.

Batteries are allowed in carry-on luggage as long as the terminals are covered and certain size restrictions are met. Indeed, lithium batteries are only allowed in carry-on luggage. Lithium batteries less than 100 watt-hours are allowed in any quantity. Lithium batteries between 100 - 300 watt-hrs are allowed with one in the device and two spares. Lithium batteries greater than 300 watt-hrs are prohibited. A 4s/5000mAh LiPo battery has approximately 75 watt-hrs, so the quantity being transported is irrelevant.

Screwdrivers, wrenches, and pliers with an overall length of less than 7 inches are allowed in carry on luggage. However, drills, hammers, saws, crowbars, knives, and tools longer than 7 inches must be checked. Most tools for the oktokopter are longer than 7 inches and therefore must be transported in checked baggage.

To summarize, the tools must go in checked baggage, the batteries must go in carry on, and the rest is desirable to put in carry-on baggage. Although the fully assembled oktokopter is too large for carry on baggage, the legs can be disassembled
at the Y joint. They are still connected to the rest of the frame by the motor wires, but once unscrewed they are free to pivot. In this manner they may be folded into a square with one main brace at each corner. Once this is done, the minimum square of the oktokopter is 13 inches on a side, small enough to fit in carry-on. The landing gear also unbolts and disassembles. After this, the height of the oktokopter is approximately 5 inches.

However, the transport container should be strong enough to protect the oktokopter even if it has to be checked. The design and procurement of the container was outsourced to Dr. Thomas Criss of the Johns Hopkins University Applied Physics Laboratory due to his extensive field test experience. We decided to re-enforce a standard carry-on bag rather than construct a container for several reasons. First, a container constructed completely of plywood would be heavy and likely exceed the carry-on baggage weight. Second, a standard piece of luggage would attract less attention to the contents. Third, standard luggage would already have wheels and a handle for rolling, desirable features given the number of airports to be traversed and the weight of the oktokopter and its accessories.

After procuring the luggage container it needed to be re-enforced, since the top and bottom were less rigid than the sides. Half inch think plywood was cut to fit in the top and bottom of the suitcase as well as along the top and bottom sides. Right angle brackets were attached to the bottom piece and to the top and bottom side pieces, to form a U shape. The top piece was also equipped with right angle brackets that would fit inside the side pieces. This way the top piece will not shift. The plywood frame can be disassembled with a Philips head screwdriver, and needs a screwdriver in order to be completely removed from the suitcase due to the tight fit. While removal is unnecessary in the course of normal events, it could be required by either TSA or customs. For this reason, it is wise to carry a small screwdriver when traveling. Carrying the invoices for the equipment is also recommended in case explanations are needed.

After re-enforcing the container, the oktokopter was disassembled and padded with upholstery foam cut to fit using an electric knife. A general base layer was inserted in the bottom of the container, with a slot cut diagonally at one end for the camera mount of the oktokopter. This way the weight of the oktokopter is distributed over the circular frame instead of resting on the four screws of the
camera mount. This also allows the oktokopter to sit lower in the suitcase, giving more room for other components on top. The oktokopter is situated as far left (towards the top) of the suitcase as possible in order for the transmitter to fit on the right hand side. The extra electronics and wires were placed to the right of the oktokopter and next to the transmitter. The legs of the disassembled landing gear and the spare propellers fit around the oktokopter frame. The ”U” shaped landing gear pieces were placed around the cap of the oktokopter. The batteries were located in the inside pocket of the lid (outside of the plywood frame) after being protected by two layers of cardboard. The battery charger did not fit into the suitcase and was carried in a backpack. Fig. A.8 shows the oktokopter and its accessories packed for transport.

The oktokopter cleared security without issues. In Santiago it was checked as the flight was full. (Note: the batteries were still inside the suitcase and thus went over the Andes in the cargo hold. No harm resulted.) The oktokopter arrived safely in Mendoza and suffered no harm in the cargo area.

Customs can present problems for oktokopters. A brochure with pictures of the fully assembled and flying oktokopter is helpful in explaining what it is. Despite explanations, the oktokopter does not count as normal luggage, even if travelling in a suitcase, and customs paperwork is needed.

Assembling the oktokopter in Malargue took an hour and a half. This included unpacking the case, reinstalling the landing gear, rebolting the arms, and reattaching the propellers. Nothing was damaged in transit.

While travelling is not without problems, the transport worked perfectly. The oktokopter arrived safe, unharmed, and unbroken, even after having been checked for one flight segment.
A.4 MSR Calibration and Comparison

Since we would like to directly compare the atmospheric measurements of the MSR to those of the CLF, we need to understand any systematic differences between the two. From November 12 - 19, 2010 the MSR was stationed at the CLF and recorded data simultaneously. The CLF atmospheric files were copied off the local computer at the end of the time period. The MSR was taped to the top of the CONEX container next to the weather station as shown in Fig. A.9. It was located inside a triangular prism made of cardboard in an effort to remove the effects of solar radiance on the temperature probe. The ends were open to allow airflow across the sensors.

Since the CLF records a measurement every 5 minutes, and the MSR every
second, the MSR data were averaged over 5 minute intervals before comparison with the CLF. Results are shown in Figs. A.10 and A.11. The CLF and MSR probes track each other very well. A histogram of the differences was made to study systematic effects. Fig. A.12 shows that the MSR temperature is systematically higher than the CLF temperature by 0.38°C. This could be caused by remaining radiant heating effects on the MSR or mis-calibration of either the CLF or MSR. Testing of the MSR temperature calibration is shown later. Fig. A.13 shows that the CLF pressure is systematically higher than the MSR pressure by 1.55 hPa.

In order to study the cause of the slight temperature shift between the MSR and the CLF, the MSR was placed in a thermos of ice water, whose temperature was a constant 0°C, for several hours while recording data. The setup is shown in Fig. A.14. The temperature probe is submerged in the ice water; the pressure
Figure A.10: November 12-19, 2010: Temperature from the MSR (black) and CLF (red).

sensor is taped to the outside of the thermos and the data logger body is taped to the rim of the thermos. Inspection of the data, Fig. A.15, show that the MSR measured a temperature of 0\(^\circ\) C with fluctuations of less than 0.1\(^\circ\) C. Therefore the cause of the shift between the MSR and the CLF is not due to faulty calibration of the MSR.

The resolution of the temperature sensor of the MSR is given as \(\pm 0.5^\circ\) C by the manufacturer [72]. The temperature probe at the CLF, a CS500-LC from Campbell Scientific, has a resolution of less than \(\pm 1^\circ\) C between the -25\(^\circ\) C and 60\(^\circ\) C [56]. The actual resolution is temperature dependent as shown in Fig. A.16.
The systematic shift observed between the MSR and the CLF is within stated uncertainties. Therefore, we can directly compare the temperature measurements of the CLF and the MSR.

The same is true for the pressure measurements. The resolution of the pressure sensor of the MSR is given as $\pm 2.5$ hPa by the manufacturer [72]. The barometer at the CLF, a CS105MD from Campbell Scientific, has a resolution of $\pm 2$ hPa from $0^\circ$ C to $20^\circ$ C and $\pm 4$ hPa from $-20^\circ$ C to $45^\circ$ C [37] [57]. The systematic shift observed between the MSR and the CLF is within stated uncertainties. Therefore, we can directly compare the pressure measurements of the CLF and the MSR.
Figure A.12: November 12-19, 2010: Histogram of the difference between the CLF and MSR temperatures.
Figure A.13: November 12-19, 2010: Histogram of the difference between the CLF and MSR pressures.
Figure A.14: Although the MSR was precalibrated, the calibration was checked in August 2010 by placing the sensor in an ice bath and recording the temperature over a period of several hours.
Figure A.15: Results of placing the MSR in an ice bath: The temperature in degrees C is plotted as a function of time. The temperature fluctuated by less than 0.1° C over 8 hours.
Temperature Accuracy:

Figure A.16: The accuracy of the CLF temperature probe varies with the temperature. It is less than 1° C between -20° C and 60° C. Figure from [56].
A.5 Data Acquisition

After spending a week and a half learning how to fly the oktokopter in the field of the Auger Visitor’s Center, the first data acquisition flight occurred at the Balloon Launch Station (BLS) on June 16, 2010 in the afternoon, morning flights being canceled due to rain. The first flight reached an altitude of 150 m and the last flight reached an altitude of 450 m. These were the lowest and highest flights. The average maximum height was 280 m. Low clouds in the early afternoon limited the maximum height obtainable, as the oktokopter needed to be kept in visual sight and the electronics needed to stay dry. The clouds broke mid-afternoon allowing the height of the last flight to be unconstrained by clouds. Instead, the height was limited by the fact that real-time altitude observations were by visual inspection, the fact that the oktokopter is surprisingly hard to see against a bright blue sky, and the pilot’s reluctance to fly too high on the first day. Despite these limitations, there were several flights over the course of a few hours. The oktokopter returned safely from all of them, each time landing within 20 feet of where it took off. See Tab. A.1 for a list of altitudes and times of the first day’s flights.

<table>
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<tr>
<td>16:52</td>
<td>270</td>
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<td>17:06</td>
<td>236</td>
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<td>18:41</td>
<td>205</td>
</tr>
<tr>
<td>19:58</td>
<td>450</td>
</tr>
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</table>

Table A.1: Altitudes and times of the oktokopter data acquisition flights on June 16, 2010.

A.6 Technical Difficulties

June 17, 2010, the oktokopter was flown near the AERA site in the afternoon, morning flights having been precluded by transportation difficulties. At 1:26 pm, the oktokopter was hovering in preparation for a controlled descent when it tumbled
and fell. The point at which the oktokopter started an uncontrolled descent is clearly visible in the elevation profile, which is shown in Fig. A.17. The throttle was set at a reasonable level for non-accelerated flight throughout this period. However, the oktokopter did not respond to any controls. Takeoff occurred along the dirt road that runs by AERA. Impact occurred approximately 30 m further down the road, off the south side. Upon impact, the motors were switched off as a safety precaution, although they were likely already off. The oktokopter was found right side up, the motors off, the camera mount shorn off at the plastic screw heads, the battery dented, and the propellers cracked or broken. The MSR was still blinking, indicating that data was still being recorded. Further inspection revealed that the MSR suffered no damage.

An assessment of the oktokopter revealed that all but two of the motors no longer spun freely due to impacted dirt and gravel. Motors 1 and 8 were the stiffest, while 6 and 7 spun freely. This indicated that the oktokopter struck the ground at an angle on motors 1 and 8 and then rotated around on the motors before coming to an upright stationary position.

It was also noted that all the wires were still connected except for the gray wire on motor 7. It is impossible to say for certain when separation occurred. However, the oktokopter is designed to fly with up to 4 nonfunctioning motors; therefore, this connection is likely not the cause of the crash. Also, as hovering does not put a lot of stress on the wires, it is unlikely that the wire would have come loose during flight. The separation probably occurred during freefall and tumbling or else during impact.

The oktokopter continued to log data throughout the uncontrolled descent, allowing a study of the freefall properties of an oktokopter. Freefall started at 310 m above ground level and took around 30 seconds. A terminal velocity of 70 km/hr was reached in less than 20 seconds. It had been hoped that the structure of the oktokopter would provide stability so that the oktokopter would descend in an upright position, with the propellers helping to control any otherwise uncontrolled descent. Sadly, this is not the case, despite what the Flight Control Manual wiki pages claim [71].

Further analysis of the flight data did not reveal any clues to the cause of the crash. According to the mikrokopter forums, there is redundancy for propeller and
engine failures. However, there is no redundancy for BLC failures. If a BLC burns out or loses power, the I2C bus will lock up, the oktokopter will shut off, and fall [73]. While the oktokopter reported an I2C error upon connection to MKTools, this is likely the result, and not the cause, of the crash since the oktokopter recorded flight data during freefall indicating that it was still on. Therefore, the I2C error had not shutdown power before freefall; it only did so after impact. Comparison of parameters measured during the fatal flight with those measured during flights
the previous day showed no anomalies. The crash flight did not have the highest altitude, lowest voltage, coldest temperatures, highest battery capacity spent, etc. Even now, the exact cause of the crash remains unknown.

Powering up the oktokopter at the visitor’s center, the GPS and MK3MAG showed solid green LEDs. The NaviCtrl and FlightCtrl showed solid red and green LEDs. Connection via the MK-USB to MKTools showed that the FlightCtrl was reporting an I2C error. The NaviCtrl reported no errors. MKTools also reported that is was not able to find any of the BLCs. Numbers 1-4 showed no LEDs, while numbers 5-8 generally showed solid red and green, indicating they weren’t receiving any signals.

To test whether there was a problem with the BLCs or the PCB, BLC 8 was removed and placed in slot 1 of the PCB. BLC 8 did nothing when power was connected. When it was placed back in slot 8, it lit up again. So there was a problem with the PCB, likely a hairline crack as nothing appeared by visual inspection and this was an intermittent behavior. As this confirmed a problem with the PCB, but did not rule out dead BLCs, the BLCs were unsoldered from the PCB and tested in various slots of the PCB. BLCs 1-4 consistently showed no lights. BLCs 5-8 consistently showed both green and red LEDs. Thus it appeared that BLCs 1-4 were dead, while BLCs 5-8 would be functional given a new PCB.

A.7 Upgrades, Repairs, and Further Difficulties

After replacing the PCB and BLCs 1-4, the I2C error went away and BLCs 1-4 worked properly. However, BLCs 5-8 did not return to normal behavior. BLCs 5-8 were then replaced. At this time two wireless modules were also procured and built to allow for remote monitoring of oktokopter parameters, such as altitude, velocity, and battery voltage. These wireless modules (Wi232) have a range of more than 1 km with line-of-sight [74].

In January 2011, the oktokopter returned to Malargue for final debugging and more data acquisition. Flight parameters were checked and compared to the standard beginner settings and also to the Karlsruhe group’s settings. Test flights were uneventful. Then, on 2011 February 4, the oktokopter became unresponsive after a routine test flight. No parameters had been changed and the landings and
takeoffs had all been smooth. Using MKTools, it was determined that there was no FlightCtrl communication. The red LED was lit on the FlightCtrl.

The FlightCtrl was then directly connected with the MKUSB and the terminal on MKTools started. The FlightCtrl was then powered on and the firmware updated. Updating the FlightCtrl firmware required that the NaviCtrl firmware also be updated. After these updates and changing the receiver setting to ”spektrum” from ”jeti” under Mikrokopter > Settings > Channels in MKTools, all errors went away and the LEDs showed green. The MK3MAG was recalibrated. The motors would turn on after calibrating the gyros (left stick to upper left) each time the oktokopter was powered on.

After a short and uneventful test flight, the oktokopter stopped responding to the transmitter again and was not recognized in MKTools. No LEDs were lit on the FlightCtrl, the NaviCtrl showed red, while the MKGPS and BLCs showed green. No connection was found with MKTools. This behavior varied with time, as occasionally the FlightCtrl would show green LEDs, but would not recognize the NaviCtrl or other boards.

Finally, the FlightCtrl was swapped out for a new one in June 2011. Testing the oktokopter without the extended equipment (NaviCtrl, MK3MAG, and MKGPS) yielded good results. Motor response was as expected and no errors were present. However, when the other boards were attached, the NaviCtrl was showed only a red LED. The MKGPS showed green. Connection to MKTools via the NaviCtrl failed. The connections between the FlightCtrl and the NaviCtrl were tested, but no problems were found. Trying to reload or update the firmware failed. At this point, the most probable cause is a bad processor on the NaviCtrl. While the oktokopter can be flown without a NaviCtrl, the high altitudes desired require the use of the abilities granted by use of the NaviCtrl and subordinate boards.

It is interesting to note that upon comparison of relative handling abilities, the Karlsruhe oktokopter is much more stable than this oktokopter. This cannot be accounted for by the pilot’s skill, as the position hold function - which causes the oktokopter to automatically hold itself at a fixed location - holds the Karlsruhe oktokopter to within a fraction of a meter and this one to within a couple of meters.
Figure A.18: The diurnal temperature plot using oktokopter data obtained during June and July 2010. The colored lines represent height (in m) above ground level.

A.8 Results

Despite the setbacks mentioned above, the feasibility of oktokopters as a method of atmospheric measurement was demonstrated. This is due in large part to the Karlsruhe group, particularly Dr. Kai Daumiller, who flew the MSR on their oktokopter during flights to study the halo of the FDs during 2010 July 14, 17, 19, and 21. Temperature inversions of approximately 10° C were measured on the last two nights.
Figure A.19: The diurnal pressure plot using oktokopter data obtained during June and July 2010. The colored lines represent heights (in m) above ground level.

From these flights in June and July, rudimentary temperature and pressure curves can be constructed. These plots are shown in Figs. A.18 and A.19.

Fig. A.20 shows the temperature inversions more readily. Height versus temperature is plotted and the colored lines represent different hour bins centered on the half hour. Inversions are present from 4-7 am local time, with the strongest inversion occurring between 5 and 6 am.
Figure A.20: Height versus temperature profiles for different hours of the day in local time using oktokopter data from June and July 2010. The colored lines represent 1 hour bins in local time.
I have yet to see any problem, however complicated, which, when you looked at it the right way, did not become still more complicated.

–Paul Alderson

At the 2010 Auger Analysis meeting, Dr. Glennys Farrar noted that when she binned the surface detector data in 500 hour bins and calculated the $\chi^2$ per DOF, the resulting value was larger than expected (1.6 instead of 1.0) [75]. We had previously spent time looking at the Fourier transform of the data in reference to power over annual and diurnal cycles and had noticed a large amount of noise in the low frequency part of the spectrum. Therefore, we wondered if the two results could be related. It turns out that the larger $\chi^2$ per DOF seen by Dr. Farrar is part of a larger pattern of noise which is inversely proportional to frequency and present in bins with lengths greater than 250 hours.

B.1 Introduction

First discovered in vacuum tube experiments, $1/f$ noise has since been found in many natural and man-made systems, from heartbeats to semiconductors [76]. When a process has a power spectral density of the form

$$S(f) = \frac{\text{constant}}{f^\alpha} \quad \text{(B.1)}$$
where \( f \) is the frequency, that process is said to have \( 1/f \) noise \([77]\). This is different from the case of white noise, which has no dependence on frequency, and Brownian motion, which, while it has a \( 1/f^2 \) dependence, is well understood as similar to random walk processes. Although \( \alpha = 1 \) is the standard case, values of \( \alpha \) greater than 0, up to and including 3, are generally considered \( 1/f \) noise \([76]\).

There is no unified mathematical explanation or simple, linear differential equations for \( 1/f \) noise, although there are several possible formulations, some of which involve point processes that have high probabilities of clusters of points \([76]\).

### B.2 Method

To study possible \( 1/f \) noise, we use the Observer data from 2005 through 2008, exclude bad periods, apply T4 and T5 cuts, and require the zenith angle of the events to be less than 60 degrees. Energy cuts are done at 1.5, 2.5, and 3.5 EeV.

Frequencies ranging from 2 time bins per year to 500 time bins per year are used. Only frequencies which give an integer number of bins are used (i.e. 3 bins per year, but not 3.1415 bins per year) For each frequency, the exposure per bin is calculated as well as the number of events per bin. Dividing the two yields the rate. For each bin, we also require that the average rate multiplied by the exposure of that bin be greater than 5. That is, we required the expected number of counts to be greater than 5. The \( \chi^2 \) per degree of freedom (DOF) is then defined as

\[
\frac{\chi^2}{DOF} = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{R_{\text{obs}}(i) - R_{\text{avg}}}{R_{\text{err}}(i)} \right)^2
\]

where \( i \) runs over the number of bins, \( R_{\text{obs}} \) is the observed rate in bin \( i \), \( R_{\text{avg}} \) is the average rate, and \( R_{\text{err}} \) is the error in \( R_{\text{obs}} \).

Two different methods of calculating \( R_{\text{err}} \) are used. In the first method,

\[
R_{\text{err}}^1(i) = \frac{\sqrt{C_{\text{obs}}(i)}}{E(i)}
\]

where \( C_{\text{obs}}(i) \) is the number of counts in the \( i^{th} \) bin, and \( E(i) \) is the exposure of bin \( i \).

In the second method,
\[ R_{err}^2(i) = \frac{\sqrt{C_{exp}(i)}}{E(i)} = \frac{\sqrt{R_{avg} \cdot E(i)}}{E(i)} \] (B.4)

where \( C_{exp} \) is the expected number of counts in the \( i^{th} \) bin, based on the exposure and average rate.

Although the first method is perhaps the more standard way of defining the error in rate of a particular bin, it has the drawback of slightly under or over estimating the error in rate if the number of counts has fluctuated greatly. Using the expected number of counts based on the exposure of the bin removes this. As will be seen in the next section, results are similar for the two methods, only differing at higher frequencies.

After obtaining the \( \chi^2 \) per DOF for each frequency, the data are plotted on a log-log scale and fitted with a straight line using the frequencies below 30 bins per year. From this the coefficient \( \alpha \) can be determined, as it is the negative inverse of the slope.

### B.3 Results

Fig. B.1 shows the \( \chi^2 \) per DOF versus frequency for the non weather corrected data with an energy cut of 3.5 EeV. One can see that there is little difference between the two methods in this frequency range, although the points using \( R_{err}^1 \) are systematically higher. However, as one looks at higher frequencies the differences become more noticeable (Fig. B.2). Using \( R_{err}^1 \), the \( \chi^2 \) per DOF plateaus at 1.3, slightly higher than expected assuming only statistical noise. When \( R_{err}^2 \) is used, the \( \chi^2 \) per DOF stabilizes at 1.0, which is the value one would expect from only statistical fluctuations.

In Fig. B.3 the data are shown on a ln-ln scale. The transition from 1/\( f \) noise is clearly visible. It is interesting to see that the \( \chi^2 \) per DOF using \( R_{err}^1 \) stabilizes as soon as the 1/\( f \) noise ends while in the \( R_{err}^2 \) case there are two more distinct segments, one occurring from 50-150 bins/year, and the other occurring after that. The reason for this is unknown.

In Figs. B.4 and B.5 one can see the results with energy cuts of 1.5 EeV and 2.5 EeV respectively. As the energy threshold is lowered, the 1/\( f \) noise extends to
Figure B.1: $\chi^2 / \text{DOF}$ versus frequency. The red line is the best fit exponential decay to the green curve. The black line is the best fit exponential decay to the blue curve. One can see that there is very little difference between the two methods of calculating $R_{err}$ in this range.

Higher frequencies and the value of $\alpha$ decreases. Tab. B.1 summarizes the results and shows the slopes obtained from the linear fits, as well as the value of $\alpha$.

<table>
<thead>
<tr>
<th>$E_{\text{threshold}}$ (EeV)</th>
<th>slope with $R^2_{err}$</th>
<th>alpha with $R^2_{err}$</th>
<th>slope with $R^2_{err}$</th>
<th>alpha with $R^2_{err}$</th>
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</thead>
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<tr>
<td>1.5</td>
<td>-0.67 ± 0.03</td>
<td>1.49 - 0.07 + 0.08</td>
<td>-0.67 ± 0.03</td>
<td>1.49 - 0.07 + 0.08</td>
</tr>
<tr>
<td>2.5</td>
<td>-0.53 ± 0.03</td>
<td>1.90 - 0.10 + 0.12</td>
<td>-0.52 ± 0.03</td>
<td>1.91 - 0.17 + 0.12</td>
</tr>
<tr>
<td>3.5</td>
<td>-0.37 ± 0.03</td>
<td>2.73 - 0.20 + 0.23</td>
<td>-0.38 ± 0.03</td>
<td>2.63 - 0.19 + 0.22</td>
</tr>
</tbody>
</table>

Table B.1: Non weather corrected data with different energy thresholds.

Figs. B.6, B.7, and B.8, show the results using the weather corrected data. The weather correction coefficients were obtained from the atmospheric effects paper [58]. After the data were corrected on an event by event basis using the
Figure B.2: $\chi^2 / \text{DOF}$ versus frequency. One can see that as the frequency increases, the method using $R_{err}^1$ plateaus at 1.3, while the method using $R_{err}^2$ plateaus at 1.0.

CLF weather data files [55], an energy cut was applied and the above process was repeated. The results are summarized in Tab. B.2. Compared with Tab. B.1, one can see that the slopes uniformly decrease by approximately 10% after applying the weather corrections; however, the $1/f$ noise is still readily apparent. Thus, weather effects are not the predominant cause of $1/f$ noise in the data.

<table>
<thead>
<tr>
<th>$E_{\text{threshold}}$ (eV)</th>
<th>slope with $R_{err}^1$</th>
<th>alpha with $R_{err}^1$</th>
<th>slope with $R_{err}^2$</th>
<th>alpha with $R_{err}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>-0.62 ± 0.03</td>
<td>1.62 - 0.08 + 0.09</td>
<td>-0.62 ± 0.03</td>
<td>1.62 - 0.08 + 0.09</td>
</tr>
<tr>
<td>2.5</td>
<td>-0.49 ± 0.03</td>
<td>2.04 - 0.12 + 0.13</td>
<td>-0.49 ± 0.03</td>
<td>2.05 - 0.12 + 0.13</td>
</tr>
<tr>
<td>3.5</td>
<td>-0.33 ± 0.03</td>
<td>3.02 - 0.24 + 0.29</td>
<td>-0.35 ± 0.03</td>
<td>2.88 - 0.22 + 0.26</td>
</tr>
</tbody>
</table>

Table B.2: Weather corrected data with different energy thresholds.
Figure B.3: $\ln(\chi^2 / \text{DOF})$ versus $\ln(\text{frequency})$. One can see that the slope of the fitted region (up to 30 bins per year) is similar for both methods of calculating $R_{err}$. After the fitted region, the spectrum transitions to white noise in the case of $R_{err}^1$ (blue). Using $R_{err}^2$ (green), there is another region of frequency dependent spectra before the transition to white noise.
Figure B.4: Energy cut = 2.5 EeV. (a) $\chi^2$/DOF versus frequency. The exponential curve is proportional to $f^{-0.52}$, (b) ln($\chi^2$/DOF) versus ln(frequency).

Figure B.5: Energy cut = 1.5 EeV. (a) $\chi^2$/DOF versus frequency. The exponential curve is proportional to $f^{-0.67}$, (b) ln($\chi^2$/DOF) versus ln(frequency).
Figure B.6: Weather corrected data with an energy cut of 3.5 EeV: (a) $\chi^2 / \text{DOF}$ versus frequency, (b) $\ln(\chi^2 / \text{DOF})$ versus $\ln($frequency$)$.

Figure B.7: Weather corrected data with an energy cut of 2.5 EeV: (a) $\chi^2 / \text{DOF}$ versus frequency, (b) $\ln(\chi^2 / \text{DOF})$ versus $\ln($frequency$)$.
Figure B.8: Weather corrected data with an energy cut of 1.5 EeV:(a) $\chi^2 / \text{DOF}$ versus frequency, (b) $\ln(\chi^2 / \text{DOF})$ versus $\ln$ (frequency).
B.4 Simulations

Monte Carlo event sets were created to try and mimic the results of the real data. The sets contain the same number of events measured above 3.5 EeV. The first, and simplest, case involves simulating events with uniform exposure and no bad periods (i.e. points are randomly distributed uniformly in time over a period of 4 years). One thousand event sets are created and subsequently run through the programs described in Sec. B.2. A sample run is shown in Fig. B.9. The average $\chi^2$ per DOF was higher with $R_{err}^1$, as in the case of the real data. As shown in Fig. B.10, the $\chi^2$ per DOF plateaued at 1.121 with $R_{err}^1$ and at 0.999 with $R_{err}^2$. The slopes found in both methods were inconsistent with $1/f$ noise. Fig. B.11 shows the histogram of the slopes found in each of 1,000 Monte Carlo simulations using points with $ln(f) < 3.5$. Using $R_{err}^2$ the mean slope was 0.009, consistent with 0; using $R_{err}^1$ the mean slope was 0.075, which implies less noise at lower frequencies than at higher ones, not $1/f$ noise. Therefore, this simulation does not describe the actual data, in that no $1/f$ noise is present.

The next event set created was similar to the above, except that it excluded the same periods as the bad data periods in the actual data. Again, 1,000 Monte Carlo simulations were created containing the number of events above 3.5 EeV, uniform exposure, four years of time coverage, and excluding bad periods. The results are similar to the case with no bad periods. The average $\chi^2$ per DOF for all runs is 1.118 using $R_{err}^1$ and 0.992 using $R_{err}^2$. The average slope is 0.081 using $R_{err}^1$ and 0.015 using $R_{err}^2$, again consistent with 0.

After the sets with uniform event distributions in time failed to describe the data, 1,000 Monte Carlo sets with sinusoidal variations were created to mimic the sinusoidal variation of seasonal weather effects. The data sets were created by introducing a probability to accept a certain time point. A random number was picked, ranging from 0 to 1, while the threshold for accepting the time point was determined by a sinusoidal function with period of one year. If the random number was greater than the threshold, the point was discarded; if it was less than the threshold, the point was kept. Various amplitudes were tested. Again the total number of points simulated equalled the number of events above 3.5 EeV and 1,000 event sets were created for each case.
Figure B.9: A sample result from the simulated event set with uniform exposure, no bad periods, and 3.5 EeV energy cut. Blue - using $R^1_{err}$, Green - using $R^2_{err}$

The first case simulated an 80% variation. That is, the probability that a certain time point would be accepted varied from 20% to 100% and thus the variation in the number of counts per bin was 80% full scale. Fig. B.12 shows the histogram of slope distributions, while Fig. B.13 shows a sample run. As before, points with $ln(f) < 3.5$ are used to determine the slope. One can see that the $\chi^2$ per DOF never reaches a plateau as it does in the real data. However, $1/f$ noise is seen. The mean slope using $R^1_{err}$ was -0.804; using $R^2_{err}$, the mean slope was -0.898. While the amplitudes of these slopes are much larger than those seen in the actual data, this is to be expected as this system and its variations are highly non-physical. However, the main point is that sinusoidal variations are capable of causing $1/f$ noise as this variation is similar to the shot noise process described above.
Figure B.10: Simulated event set with uniform exposure, no bad periods, and 3.5 EeV energy cut. One can see that the $\chi^2 / \text{DOF}$ distribution is reasonably normal. Using $R_{\text{err}}^1$, the average $\chi^2 / \text{DOF}$ is 1.12. Using $R_{\text{err}}^2$, the average $\chi^2 / \text{DOF}$ is 1.00. (a) Histogram of the $\chi^2 / \text{DOF}$ using $R_{\text{err}}^1$ for 1,000 runs. (b) Histogram of the $\chi^2$ per DOF using $R_{\text{err}}^2$ for 1,000 runs.
Figure B.11: Simulated event set with uniform exposure, no bad periods, and 3.5 EeV energy cut. As evidenced by the mean slope of 0.08 using $R_{err}^1$ and of 0.01 using $R_{err}^2$, no $1/f$ noise is present in these simulations. (a) Histogram of the slopes using $R_{err}^1$ for 1000 runs. (b) Histogram of the slopes using $R_{err}^2$ for 1000 runs.
Figure B.12: Simulated event set with uniform exposure, no bad periods, 3.5 EeV energy cut, and 80% sinusoidal variation. As evidenced by the mean slope of -0.80 using $R_{err}^1$ and of -0.90 using $R_{err}^2$, $1/f$ noise is present in these simulations. However, the sinusoidal variations simulated are much greater than those present in the actual data. Thus, we cannot explain the noise in the data as only due to sinusoidal variations. (a) Histogram of the slope using $R_{err}^1$ for 1,000 runs. (b) Histogram of the slope using $R_{err}^2$ for 1,000 runs.
Figure B.13: Simulated event set with uniform exposure, no bad periods, 3.5 EeV energy cut, and 80% sinusoidal variation. One can see that there is evidence of $1/f$ noise. However, unlike in the actual data, the $\chi^2$ per DOF never reaches a plateau. Blue - $R_{err}^1$, Green - $R_{err}^2$

The second case simulated an 8% variation, which is more in line with the amplitude of the actual weather effects seen. The probability that a certain time point would be accepted varied from 92% to 100% and so the variation in the number of counts per bin was 8% full scale. Figs. B.14 and B.15 show the histograms of the average $\chi^2$ per DOF and slope for the 1,000 runs.

Although the $\chi^2$ per DOF value is similar to the value seen in the actual data, the slopes are incompatible. The average slope in these simulations is found to be -0.064 using $R_{err}^2$, approximately 6 times less than the amplitude seen in the real data. This also implies that the weather effects, which cause a sinusoidal signal in the data, are not the sole cause of the $1/f$ noise.
Figure B.14: Simulated event set with uniform exposure, no bad periods, 3.5 EeV energy cut, and 8% sinusoidal variation. One can see that the $\chi^2 / \text{DOF}$ distribution is reasonably normal. Using $R_{err}^1$, the average $\chi^2 / \text{DOF}$ is 1.17. Using $R_{err}^2$, the average $\chi^2 / \text{DOF}$ is 1.05. (a) Histogram of the $\chi^2$ per DOF using $R_{err}^1$ for 1,000 runs. (b) Histogram of the $\chi^2$ per DOF using $R_{err}^2$ for 1,000 runs.
Figure B.15: Simulated event set with uniform exposure, no bad periods, 3.5 EeV energy cut, and 8% sinusoidal variation. The mean slope using $R_{err}^1$ is 0.00. Using $R_{err}^2$, the mean slope is -0.06. Therefore, using realistic sinusoidal amplitudes does not replicate the $1/f$ noise seen in the actual data. (a) Histogram of the slope using $R_{err}^1$ for 1,000 runs. (b) Histogram of the slope using $R_{err}^2$ for 1,000 runs.
B.5 Conclusion

The surface detector event rate data is found to contain $1/f$ noise over a range of energies, with the amount of noise present increasing towards lower energies. The values of $\alpha$ range from 1.5 at an energy cut of 1.5 EeV to 2.6 at an energy cut of 3.5 EeV. Applying weather corrections to the data decreases the amount of noise present by $\sim 10\%$. At a threshold of 1.5 EeV $\alpha$ increases to 1.6; at a threshold of 3.5 EeV $\alpha$ increases to 2.9.

Monte Carlo simulations with 80% full scale sinusoidal variations are able to cause strong $1/f$ noise. However, Monte Carlo simulations with realistic sinusoidal amplitudes are unable to replicate the coefficients found in the actual data. Based on this and on the continued presence of $1/f$ noise in the data even after weather corrections, we surmise that there are additional causes of the $1/f$ noise. What this cause is remains unclear.
Mind the Gap: 24 Hour Periods of Missing Data in the Observer

Mind the gap.

–London subway announcement

The latest version of the Observer data (v7r3) contains gaps within which no events occur. These gaps, which have periods of an integer multiple of 24 hours, are seen in version v6r2, but not v2r5p6. The pattern of the gaps is consistent across data versions, although the actual time of the gaps varies. In v7r3 the longest gap is from March 25 - April 12, 2011. In v6r2 the longest gap occurs from October 10 - 27, 2010. This gap is not present in v7r3. These gaps are due to crashes in the reconstruction processing of the raw data files. The gaps run from noon to noon UTC as each raw data file covers a 24 hour period starting and ending at noon UTC [53]. If a crash occurs during the processing of a particular file, all data from that file are lost from the final Observer product. The issues that cause this problem are currently being addressed and should be fixed for the next Observer data release [54]. Here we describe how the gaps were found and their properties.

C.1 Method

Upon downloading and using version v6r2 of the Observer data it was noted that results from various analyses changed when compared to results using the previous version. Closer inspection led to the discovery of a 17 day period in October 2010
that contained no events. Deeper probing revealed several additional periods of a similar nature, although of shorter duration.

A program was written to cycle through the event files and determine the time between successive events. No cuts are imposed on the events. The exposure between events is also calculated. If a gap between events of duration greater than 2 hours is found, it is flagged if the following are true: the gap is not completely inside a bad period, the gap is not in the communications crisis period, and the exposure during the gap is greater than 1 km$^2$day. A complete list of the files used can be found in Secs. C.4 - C.6.

While all events should be present inside the data file, including data taken during bad periods, gaps completely within bad periods are excluded due to the possibility of CDAS being down as the cause of the bad period. In that case it would not be unreasonable to see large time gaps with no data. While ideally one does not expect gaps in the event files even during bad periods, it is not unreasonable to suppose they would be there.

For the purposes of this note, all gaps that occured between April 15, 2009, 00:00:00 UTC and November 16, 2009 00:00:00 UTC are excluded as belonging to the communications crisis period. While there are ways to recover events in part of this time segment, for simplicity and clarity we exclude the entire period.

The last requirement, that the exposure of the gap be greater than 1 km$^2$day, is imposed to exclude gaps that are likely natural and due to a small exposure.

### C.2 Results

#### C.2.1 Gaps found in v7r3

Table C.1 shows the gaps found in Observer data version v7r3. The first line of each triple line set lists the time of the last event before a gap, the time of the event that ends the gap, the duration of the gap in hours, the exposure per unit time during the gap (in units of km$^2$), and the total exposure during the gap (in units of km$^2$days). The second and third lines list the SD Id, Auger ID, GPS second, GPS nanosecond, date (in YYMMDD format), and time (in HHMMSS format) of the events that mark the start and end of the gap.
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<th>GPS nanosec</th>
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Table C.1: Periods of missing data found in the Observer version v7r3 data. The first line displays information about the gap, the second and third lines show detailed information about the events that mark the start and end of the gap.

From inspection of Tab. C.1 it appears that all the 24 hour gaps, or multiples thereof, run from just before noon UTC one day to just after noon UTC the next day(s). The only exception is the 45 hour gap from 2004 July 18 - 20, which starts at 15:00:26. The actual gaps run from noon to noon UTC, the differences of a few minutes before and after being due to the randomness of events. Second, the Auger Id numbers of the ending event all have low counts. The ID numbers of the form (YEARDOYcounter) always contain a low counter number.

### C.2.2 Gaps found in v6r2

Tab. C.2 shows the gaps found in Observer data version v6r2. The format is the same as in Tab. C.1. From inspection of Tab. C.2 it appears that all of the 24 hour gaps, or multiples thereof, follow the same pattern as those found in the v7r3 data.

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Table C.2: Periods of missing data found in the Observer version v6r2 data. The first line displays information about the gap, the second and third lines show more detailed information about the events that mark the start and end of the gap.

C.2.3 Comparison with previous version

The v7r3 and v6r2 Observer data are also compared to v2r5p6 Observer data. The same procedure described in Sec. C.1 is used. A summary of the gaps found in each of the three data versions is shown in Tab. C.3.

It appears that the gaps of duration 24n hours, where n is an integer, are new in the v7r3 and v6r2 data sets. Although the cause of the gaps is now known
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Table C.3: Summary of the gaps in three different Observer releases (v7r3, v6r2, and v2r5p6): The variables from left to right: GPS second of last event before gap, GPS second of event that ends gap, duration of gap in hours, average number of km² working per unit time, total exposure during time period (units of km²days).
to be crashes in the reconstruction procedure during processing, why these gaps have appeared is unknown [53]. If these gaps are not excluded similarly to official bad periods during analyses, artificially low rates could be obtained as the actual exposure of the array will differ from that calculated based on the number of hexagons, causing errors in results.

Regarding the gap present in v2r5p6, but not v6r2 or v7r3: A bad period starts 436 seconds after the gap starts and ends 1553 seconds before the gap ends, meaning only 33 minutes of the gap are not in a bad period. Thus this gap is not surprising. It is actually completely contained inside the 120 hour gap present in v6r2. In v7r3, an event is present at GPS time 764024505 that is not present in previous versions, probably due to small changes in event reconstruction.

As regards the gaps at GPS time 759180424-759187796 (v6r2 and v7r3) and 759180424-759187915 (v2r5p6): The gap is 2 minutes shorter in the newer versions. This is due to an event that is not present in v2r5p6. This is the event that ends the gap in the newer versions and is the only event before the ending event of the old version gap. The exact cause is unknown, although probably due to slight changes in reconstruction parameters and thresholds.

The roughly 2 hour gap present in v7r3 from 759292711-759300475 is not seen in previous versions owing to an event present in those versions that is not present in version v7r3. Again, this is probably caused by slight changes in the reconstruction. As the time duration is short and the exposure is low, this is not a cause for concern.

There are several 24n gaps in v6r2 that are not present in v7r3. Likewise, there are four gaps present in v7r3 that occur during the dates covered by v6r2 that are not present in v6r2. As for the other gaps not mentioned, the ones present in all versions of the data that are typically 2 - 5 hours in duration, it is possible that they arise naturally due to the timing of events and the exposure. They are not considered further here.

C.3 Conclusion

Three different versions of the Observer data were compared in search of periods of missing data. It was found that the latest releases (v7r3 and v6r2) contain gaps not found in the previous release (v2r5p6). The gaps present in v7r3 and v6r2
exhibit the same patterns, but do not occur at the same times, except in one case. These gaps have a duration of 24n hours, where n is an integer. In most cases the gaps are 24 hours, although there is a gap of 17 days in v6r2 and a gap of 18 days in v7r3. These gaps are caused by crashes in the reconstruction process of the raw data files and the subsequent loss of the data in that 24 hour file for the final data file. The issues that cause this problem are currently being addressed. A complete list of files that were unable to be reconstructed can be found by clicking on the "Bad Files" link at http://augerobserver.fzk.de/doku.php?id=datatree:root [54].

C.4 List of files used in the v2r5p6 analysis

Event files were downloaded July 7, 2009. The exposure and bad periods files were downloaded on March 22, 2011.

BadPeriods_010104_280211.txt

Exposure files:
HexagonsMn_2004.out
HexagonsMn_2005.out
HexagonsMn_2006.out
HexagonsMn_2007.out
HexagonsMn_2008.out
HexagonsMn_2009.out
Hexagons_2010.all
Hexagons_2011.2011_02_28

v2r5p6 ascii event files:
SDRec_2004.dat
SDRec_2005.dat
SDRec_2006.dat
SDRec_2007.dat
SDRec_2008.dat
SDRec_2009_01.dat

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C.5 List of files used in the v6r2 analysis

All files were downloaded on March 22, 2011.

BadPeriods_010104_280211.txt

Exposure files:
HexagonsMn_2004.out
HexagonsMn_2005.out
HexagonsMn_2006.out
HexagonsMn_2007.out
HexagonsMn_2008.out
HexagonsMn_2009.out
Hexagons_2010.all
Hexagons_2011.2011_02_28

v6r2 ascii event files:
SDRec_v6r2_2004_generated_2010-10-14.dat
SDRec_v6r2_2005_generated_2010-10-14.dat
SDRec_v6r2_2006_generated_2010-10-14.dat
SDRec_v6r2_2007_generated_2010-10-14.dat
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SDRec_v6r2_2008_03_generated_2010-10-14.dat
SDRec_v6r2_2008_04_generated_2010-10-14.dat
SDRec_v6r2_2008_05_generated_2010-10-14.dat
SDRec_v6r2_2008_06_generated_2010-10-14.dat
C.6 List of files used in the v7r3 analysis

Event files were downloaded on November 28, 2011. Other files were downloaded on November 23, 2011.

BadPeriods_010104_300911.txt

Exposure files:
HexagonsMn_2004.out
HexagonsMn_2005.out
HexagonsMn_2006.out
HexagonsMn_2007.out
HexagonsMn_2008.out
HexagonsMn_2009.out
Hexagons_2010.out
Hexagons_2011.out

v7r3 ascii event files:
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Appendix D

Graphs from Various Studies

What’s a tachyon?
A subatomic particle devoid of good taste.

—Unknown

It is not practical to show plots for all energy, time, and angle ranges in the previous chapters. However, these cases are informative and the graphs are worth including. Sec. D.1 shows the graphs from the study of the annual rate and temperature offsets while Sec. D.2 shows the graphs from the study of the diurnal rate and temperature offsets.

D.1 Annual rate - temperature time offset

D.1.1 Using Events with zenith angles of $0 \leq \theta < 45$ degrees

D.1.1.1 Before the communications crisis period
Figure D.1: January 1, 2005 - April 15, 2009: E < 1.5 EeV: Annual rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.2: January 1, 2005 - April 15, 2009: E < 1.5 EeV: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue ‘+’. Contour lines show the results of 1,000,000 Monte Carlo simulations.
Figure D.3: January 1, 2005 - April 15, 2009: E < 1.5 EeV: Temperature shifted by 9.25 days: Annual rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.4: January 1, 2005 - April 15, 2009: \( E < 1.5 \text{ EeV} \): Temperature shifted by 9.25 days: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue '+'. Contour lines show the results of 1,000,000 Monte Carlo simulations.
Figure D.5: January 1, 2005 - April 15, 2009: $E \geq 1.5$ EeV: Annual rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.6: January 1, 2005 - April 15, 2009: E ≥ 1.5 EeV: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue '+'. Contour lines show the results of 1,000,000 Monte Carlo simulations.
Figure D.7: January 1, 2005 - April 15, 2009: E ≥ 1.5 EeV: Temperature shifted by 14.71 days: Annual rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.8: January 1, 2005 - April 15, 2009: $E \geq 1.5$ EeV: Temperature shifted by 14.71 days: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue '+'. Contour lines show the results of 1,000,000 Monte Carlo simulations.
D.1.1.2 After the communications crisis period

Figure D.9: November 15, 2009 - October 1, 2011: $E < 1.5$ EeV: Annual rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.10: November 15, 2009 - October 1, 2011: $E < 1.5$ EeV: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue ’+’. Contour lines show the results of 1,000,000 Monte Carlo simulations.
Figure D.11: November 15, 2009 - October 1, 2011: E < 1.5 EeV: Temperature shifted by 38.44 days: Annual rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.12: November 15, 2009 - October 1, 2011: E < 1.5 EeV: Temperature shifted by 38.44 days: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue ‘+’. Contour lines show the results of 1,000,000 Monte Carlo simulations.
Figure D.13: November 15, 2009 - October 1, 2011: $E \geq 1.5$ EeV: Annual rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.14: November 15, 2009 - October 1, 2011: $E \geq 1.5$ EeV: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue '+' . Contour lines show the results of 1,000,000 Monte Carlo simulations.
Figure D.15: November 15, 2009 - October 1, 2011: $E \geq 1.5$ EeV: Temperature shifted by 43.84 days: Annual rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.16: November 15, 2009 - October 1, 2011: $E \geq 1.5$ EeV: Temperature shifted by 43.84 days: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue ‘+’. Contour lines show the results of 1,000,000 Monte Carlo simulations.
D.1.2 Using events with zenith angles of $45 \leq \theta < 60$ Degrees

D.1.2.1 Before the communications crisis period

Figure D.17: January 1, 2005 - April 15, 2009: $E < 1.5$ EeV: Annual rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.18: January 1, 2005 - April 15, 2009: E < 1.5 EeV: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue '+'.
Contour lines show the results of 1,000,000 Monte Carlo simulations.
Figure D.19: January 1, 2005 - April 15, 2009: E < 1.5 EeV: Temperature shifted by 1.51 days: Annual rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.20: January 1, 2005 - April 15, 2009: $E < 1.5$ EeV: Temperature shifted by 1.51 days: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue '+'. Contour lines show the results of 1,000,000 Monte Carlo simulations.
Figure D.21: January 1, 2005 - April 15, 2009: $E \geq 1.5$ EeV: Annual rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.22: January 1, 2005 - April 15, 2009: $E \geq 1.5$ EeV: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue '+'.
Contour lines show the results of 1,000,000 Monte Carlo simulations.
Figure D.23: January 1, 2005 - April 15, 2009: $E \geq 1.5$ EeV: Temperature shifted by 14.06 days: Annual rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.24: January 1, 2005 - April 15, 2009: $E \geq 1.5$ EeV: Temperature shifted by 14.06 days: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue '+'. Contour lines show the results of 1,000,000 Monte Carlo simulations.
D.1.2.2 After the communications crisis period

Figure D.25: November 15, 2009 - October 1, 2011: $E < 1.5$ EeV: Annual rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.26: November 15, 2009 - October 1, 2011: E < 1.5 EeV: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue '+'. Contour lines show the results of 1,000,000 Monte Carlo simulations.
Figure D.27: November 15, 2009 - October 1, 2011: $E < 1.5$ EeV: Temperature shifted by 39.45 days: Annual rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.28: November 15, 2009 - October 1, 2011: E < 1.5 EeV: Temperature shifted by 39.45 days: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue ’+'. Contour lines show the results of 1,000,000 Monte Carlo simulations.
Figure D.29: November 15, 2009 - October 1, 2011: $E \geq 1.5$ EeV: Annual rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.30: November 15, 2009 - October 1, 2011: $E \geq 1.5$ EeV: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue '+'. Contour lines show the results of 1,000,000 Monte Carlo simulations.
Figure D.31: November 15, 2009 - October 1, 2011: $E \geq 1.5$ EeV: Temperature shifted by 74.78 days: Annual rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.32: November 15, 2009 - October 1, 2011: $E \geq 1.5$ EeV: Temperature shifted by 74.78 days: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue '+'. Contour lines show the results of 1,000,000 Monte Carlo simulations.
D.2 Diurnal rate - temperature time offset

D.2.1 Using Events with zenith angles of $0 \leq \theta < 45$ degrees

D.2.1.1 Before the communications crisis period

Figure D.33: January 1, 2005 - April 15, 2009: $E < 1.5$ EeV: Diurnal rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.34: January 1, 2005 - April 15, 2009: $E < 1.5$ EeV: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue '+'.
Contour lines show the results of 1,000,000 Monte Carlo simulations.
Figure D.35: January 1, 2005 - April 15, 2009: E < 1.5 EeV: Temperature shifted by 1.84 hours: Diurnal rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.36: January 1, 2005 - April 15, 2009: E < 1.5 EeV: Temperature shifted by 1.84 hours: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue '+'. Contour lines show the results of 1,000,000 Monte Carlo simulations.
Figure D.37: January 1, 2005 - April 15, 2009: E ≥ 1.5 EeV: Diurnal rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.38: January 1, 2005 - April 15, 2009: $E \geq 1.5$ EeV: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue '+'.
Contour lines show the results of 1,000,000 Monte Carlo simulations.
Figure D.39: January 1, 2005 - April 15, 2009: $E \geq 1.5$ EeV: Temperature shifted by 3.31 hours: Diurnal rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.40: January 1, 2005 - April 15, 2009: $E \geq 1.5$ EeV: Temperature shifted by 3.31 hours: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue '+' symbol. Contour lines show the results of 1,000,000 Monte Carlo simulations.
D.2.1.2 After the communications crisis period

Figure D.41: November 15, 2009 - October 1, 2011: E < 1.5 EeV: Diurnal rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.42: November 15, 2009 - October 1, 2011: E < 1.5 EeV: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue '+' sign. Contour lines show the results of 1,000,000 Monte Carlo simulations.
Figure D.43: November 15, 2009 - October 1, 2011: E < 1.5 EeV: Temperature shifted by 0.04 hours: Diurnal rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.44: November 15, 2009 - October 1, 2011: $E < 1.5$ EeV: Temperature shifted by 0.04 hours: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue '+'.
Contour lines show the results of 1,000,000 Monte Carlo simulations.
Figure D.45: November 15, 2009 - October 1, 2011: $E \geq 1.5$ EeV: Diurnal rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.46: November 15, 2009 - October 1, 2011: $E \geq 1.5$ EeV: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue '+' symbol. Contour lines show the results of 1,000,000 Monte Carlo simulations.
Figure D.47: November 15, 2009 - October 1, 2011: $E \geq 1.5$ EeV: Temperature shifted by 9.87 hours: Diurnal rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.48: November 15, 2009 - October 1, 2011: $E \geq 1.5$ EeV: Temperature shifted by 9.87 hours: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue '+' . Contour lines show the results of 1,000,000 Monte Carlo simulations.
D.2.2 Using events with zenith angles of $45 \leq \theta < 60$ Degrees

D.2.2.1 Before the communications crisis period

Figure D.49: January 1, 2005 - April 15, 2009: $E < 1.5$ EeV: Diurnal rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.50: January 1, 2005 - April 15, 2009: $E < 1.5$ EeV: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue '+'.
Contour lines show the results of 1,000,000 Monte Carlo simulations.
Figure D.51: January 1, 2005 - April 15, 2009: $E < 1.5$ EeV: Temperature shifted by 3.11 hours: Diurnal rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.52: January 1, 2005 - April 15, 2009: E < 1.5 EeV: Temperature shifted by 3.11 hours: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue '+'. Contour lines show the results of 1,000,000 Monte Carlo simulations.
Figure D.53: January 1, 2005 - April 15, 2009: $E \geq 1.5$ EeV: Diurnal rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.54: January 1, 2005 - April 15, 2009: $E \geq 1.5$ EeV: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue '+'. Contour lines show the results of 1,000,000 Monte Carlo simulations.
Figure D.55: January 1, 2005 - April 15, 2009: E ≥ 1.5 EeV: Temperature shifted by -0.93 hours: Diurnal rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.56: January 1, 2005 - April 15, 2009: $E \geq 1.5$ EeV: Temperature shifted by -0.93 hours: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue '+' sign. Contour lines show the results of 1,000,000 Monte Carlo simulations.
D.2.2.2 After the communications crisis period

Figure D.57: November 15, 2009 - October 1, 2011: E < 1.5 EeV: Diurnal rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.58: November 15, 2009 - October 1, 2011: $E < 1.5$ EeV: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue '+'. Contour lines show the results of 1,000,000 Monte Carlo simulations.
Figure D.59: November 15, 2009 - October 1, 2011: $E < 1.5$ EeV: Temperature shifted by 10.05 hours: Diurnal rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.60: November 15, 2009 - October 1, 2011: $E < 1.5$ EeV: Temperature shifted by 10.05 hours: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue ‘+’. Contour lines show the results of 1,000,000 Monte Carlo simulations.
Figure D.61: November 15, 2009 - October 1, 2011: $E \geq 1.5$ EeV: Diurnal rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.62: November 15, 2009 - October 1, 2011: $E \geq 1.5 \text{ EeV}$: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue '+'.
Contour lines show the results of 1,000,000 Monte Carlo simulations.
Figure D.63: November 15, 2009 - October 1, 2011: $E \geq 1.5$ EeV: Temperature shifted by -0.73 hours: Diurnal rate (red) and temperature (blue) curves, along with their difference (black).
Figure D.64: November 15, 2009 - October 1, 2011: $E \geq 1.5$ EeV: Temperature shifted by -0.73 hours: The Rayleigh vector of the difference between the rate and expected rate is shown by the blue ‘+’. Contour lines show the results of 1,000,000 Monte Carlo simulations.
Coloring Book

A picture is worth a thousand words.

—Unknown

Throughout my stays in Argentina there were brief periods of free time. To amuse myself and to provide a useful product for the visitors center, I started drawing a Pierre Auger Observatory coloring book. Subjects range from buildings to lasers to forklifts. While the book has not yet been printed for distribution, three of the drawings were used as designs on the latest batch of childrens’ t-shirts. There are plans to distribute the coloring book to surrounding schools during visits from the local staff.
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Who never walks save where he sees men’s tracks makes no discoveries.

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Auger Observatory Internal Papers (GAP Notes):
R. Ulrich, S. Coutu, A. Criss, P. Sommers, ”Fitting the ankle” (2009-149)
S.-H. Cheng, S. Coutu, A. Criss, P. Sommers, R. Ulrich, ”Methods for Neutron Point
Source Upper Limits” (2010-112)
J. Brack, R. Cope, A. Dorofeev, B. Gookin, J. Harton, Y. Petrov, A. Rovero, R. Bruijn,
A. Criss, P. Sommers, A. Menshikov, G. La Rosa, ”Auger Fluorescence Detector Abso-
lute Calibration January and June 2010” (2010-118)

Presentations:
Auger US Analysis meetings, various locations
2011 Sept - Surface detector event rate - temperature offsets
2010 Oct - 1/f noise in the surface detector event data
2010 May - LAWS: Low Altitude Weather Station
2009 Oct - Work at Penn State
Auger Collaboration meetings, Malargue, Argentina
2012 Mar - Rate - Temperature phase lags before and after the comms crisis
2011 Mar - Relative FD calibration-C and drifting energy scale
2010 Nov - MIRACLE: Mikrokopter Roving Atmospheric Levitating Exp
2010 Mar - Update on recent absolute calibration work
2009 Nov - Unbinned analysis of spectral features
2008 Nov - Seasonal and diurnal effects of temperature on event rate
2009 May - Weather effects on the rate of events at the PAO
APS April Meeting, Denver, COs
2006 Fall - A.E. Criss et al, The diurnal tide as observed in TIMED/SABER tempera-
tures. 2006 fall AGU meeting, San Francisco, CA presented by coworker
2005 Fall - A.E. Criss et al, Seasonal and Interannual Variations of Migrating Diurnal
Tide in the Mesosphere as seen from the TIMED/SABER Temperature, 2005 fall AGU
meeting, San Francisco, CA presented by coworker
2004 June - A.E. Criss et al, Comparison of Derived Geostrophic Zonal Winds from
TIMED/SABER and TIMED/TIDI Winds in the Mesosphere and Lower Thermosphere,
2004 CEDAR conference, Santa Fe, NM
2002 Mar - A Technique for Passive Object Location Using Sound
Maryland Junior Science and Humanities Symposium