CHAPTER I

Introduction

The study of cosmic rays is one of the most active fields in astroparticle physics research. Their origin, acceleration, and transport to earth have been some of the unsolved problems in the astrophysics for nearly 100 years. To resolve these questions, a large detector which combined multiple detection techniques with higher duty cycles, are needed. We have investigated an alternative way to study cosmic rays: measuring the radio emission from cosmic ray air shower. It is unaffected by attenuation, has a high duty cycle promising to help solving the mystery of cosmic rays.

Radio pulses from cosmic ray air showers were first discovered by Jelley et al. in 1965 at 44MHz [Jelley65]. The results were soon verified and in the late 1960’s emission from 2MHz up to 520MHz were found. In the following years these activities ceased almost completely mostly due to difficulties with radio interference, uncertainty about the interpretation of the results and success of other methods.

Measuring the radio pulses from air shower has a number of advantages. If one can deal with radio frequency interference (RFI) it allows for round clock measurements, giving a much higher duty cycle than e.g. measuring fluorescence light. The signal is integrated over the whole air shower evolution, making it complementary to measuring the particles that reach the ground level. And because radio pulse is not quantized like the particle signal one can get better direction estimate for the air shower.

In the high frequency domain Geo-Synchrotron and Charge Separation are the responsible mechanisms for the radio emission from air shower. But in the low frequency (LF) as well as very low frequency (VLF) these two mechanisms fail to predict any observable radio emission from cosmic ray air shower. Only possible radio emission in the
LF/VLF region can be due to transition radiation mechanism. When the excess electrons of an EAS incident on the earth surface, due to the sudden change of the dielectric in the path of these electrons, transition radiation phenomenon occurs and LF/VLF radio emission take place.

After giving an introduction of cosmic rays, air shower and relevant experiment, I present the instrumentation and data acquisition method that were developed as part of this thesis, and discuss the results of the radio signal detection.

1.1 Cosmic Rays

The earth is continuously bombarded by highly energetic rays coming from outside the earth’s atmosphere. This cosmic radiation was discovered by Victor Hess in 1912 during balloon experiments. He found that the intensity of ionizing radiation above 1000m height rises with increasing height and accounted this to radiation from outside the earth atmosphere [Hess12]. Cosmic rays primarily consist of atomic nuclei with masses ranging from protons (hydrogen) to Uranium. Electrons and gamma-quanta make up less than 1% of the flux. The energy range of cosmic rays spans from some MeV to more than \(10^{20}\)eV. The arrival directions of the cosmic rays are distributed uniformly over the sky, only little anisotropy has been found at the highest energies.

Up to now there is no universally accepted theory for the origin of the primary particles at high energies, their acceleration, or their reactions in the interstellar medium during their transport to earth. Finding the sources of cosmic rays and understanding the mechanism that accelerates them to such a high energies is one of the unsolved mysteries of astronomy.

When a cosmic ray particle hits a nucleus of an atom of the earth atmosphere it undergoes a nuclear reaction and produce several secondary particles. These secondary particles can again react with atmospheric nuclei and produce more secondary particles. Together these secondary particles form an extensive air shower.

Cosmic rays are also of concern for the public. The secondary particles of air showers form a significant fraction of the natural radioactivity on earth. Neutrons in air showers
produce the radioactive $^{14}$C isotope that is used for archaeological age determination. It has been also proposed that cosmic rays affect the weather and thus can play a role in climate change [Shaviv05]. So the study of cosmic rays, their arrival directions, energy spectrum, and chemical composition is of interest for a number of branches of physics.

1.1.1 Energy Spectrum

Over a wide range of energy the primary cosmic ray flux follows a simple power law

$$\frac{dN}{dE} \propto E^{-\gamma}$$  \hspace{1cm} (1.1)

At $10^{11}$eV about one particle per second per square meter hits the earth, these changes to approximately one particle per year per square meter at $5 \times 10^{15}$eV, and above $10^{19}$eV only about one particle per century and per square kilometer hits the earth.

![Figure 1.1 Spectrum of the cosmic ray flux, taken from [Haungs04]. The flux has been multiplied by a factor of $E^{2.5}$. This emphasizes the so called knee at $\sim 5 \times 10^{15}$eV and ankle at $5 \times 10^{18}$eV in the spectrum.](image-url)
In the first approximation the power law index $\gamma$ in equation (1.1) is equal to 2.7. In detailed view of the figure 1.1 we see that $\gamma$ is not constant but changes slightly- the two most important regions of changes are named- knee at energy $5 \times 10^{15}\text{eV}$ and ankle at energy $2 \times 10^{19}\text{eV}$. At the knee position the spectrum become steeper, changes the value of power law index $\gamma$, going from $\gamma \approx 2.7$ to $\gamma \approx 3.1$. The probable cause for the knee is different acceleration mechanisms for energies below and above the knee. Effects during the transport through the interstellar medium and the fact that Protons can’t be confined by galactic magnetic field, causes decrease in flux.

At the highest energies above $10^{18}\text{eV}$ as shown in figure 1.1 the spectrum becomes flatter. This ankle could be caused by the transition from galactic to extragalactic components. Sharp decrease in flux at $5 \times 10^{19}\text{eV}$ is predicted by Greisen- Zatsepin-Kutz’min effect \cite{Greisen66, Zatsepin66}. This describes that high energy proton above $\sim 5 \times 10^{19}\text{eV}$ loose energy by producing pions in reactions with photons of the cosmic microwave background.

At energies below $10^{10}\text{eV}$ the flux and direction of cosmic rays is affected by the solar wind and the magnetic field of earth and sun. This part of the spectrum shows the 11-year variability in flux and is clearly associated with solar activity. At higher energies these affect can be neglected.

Observations of primary cosmic rays are carried above the Earth atmosphere and orbital probes, rockets and high-altitude balloons are used for the detection. Due to the very low flux, these techniques can’t be applied to detect primary cosmic rays beyond $10^{15}\text{eV}$. On the other hand measurements of cosmic ray induced air showers are possible starting at this energy range.
1.1.2 Chemical Composition

With direct measurement it is possible to make a detail analysis of the chemical composition of the cosmic radiation. Figure 1.2 shows the relative abundance of the different chemical elements for cosmic rays with less than 2GeV/nucleon compared to the composition in the solar system.

The composition of cosmic ray within this energy range and that of solar system agree to a large extent. This signifies to a common origin of the matter in the solar system and the matter in the cosmic radiation. Two discrepancies remain:

1. The light elements hydrogen and helium are less common in the cosmic radiation, than in the solar system. This is probably due to the high ionization energy of these elements that suppress the initial acceleration of those elements [Horneff1er06]
2. Lithium, beryllium, and boron as well as the elements from scandium to manganese are more common in the cosmic radiation. These elements are produced during the transport of the cosmic rays by spallation of nuclei from \( \text{C(C, Si, Ge, Sn& Pb)}, \text{N (N,P,As,Sb & Bi)}, \text{O(O, S, Se,Te & Po)} \) or the iron (Fe, Ru & Os) group.

At higher energies the chemical composition can only be deduced by comparing the results of air shower measurements to the results of simulations of air showers. As air showers have high statistical fluctuations and simulations have large uncertainty, the indirect determination has larger errors than the direct measurements.

At the highest energies the chemical composition is still largely unknown. It is due to the fact that determination of chemical composition is based on interpreting the air shower data with nuclear interaction model, which is to be extrapolated from low energy data. Thus it is still unclear whether highest energy cosmic rays are mainly protons or heavy nuclei [Watson06].

**Figure 1.3** Arrival directions of cosmic rays with energies above \( 4 \times 10^{19} \text{eV} \) as measured by AGASA experiment. Green circles represent events with \( E > 4 \times 10^{19} \text{eV} \), and red squares those with \( E > 10^{20} \text{eV} \). Shaded circles indicate event clustering within the angular resolution of \( 2.5^\circ \) [Takeda 99].
1.1.3 Anisotropy

The location or concentration of the arrival direction distribution of cosmic rays in a particular region of celestial sphere is defined by the term anisotropy. The cosmic rays are deflected by the Galactic magnetic fields which confine the particles in the Galaxy and homogenize their arrival directions. The spatial distribution of cosmic rays is almost isotropic. Only in the low energy region an excess is observed in the direction of the sun. Many analyses were done in the lower energy regions and summarized in [Watson92].

Some signs of slight anisotropy were observed in the energy region, where the Larmor radius is growing above the kilo-parsec order, above $10^{17}$eV. In the data from Havarah Park was found the amplitude with an excess of about 2% at the right ascension $212^\circ \pm 17^\circ$ in the energy region about $10^{17}$eV. 1.4 % excess at the very different right ascension $123^\circ$ in the energy region $3\times10^{16}-3\times10^{17}$ eV in Yakutsk data. Other interesting sign of anisotropy was found in the AGASA data between $8\times10^{17}-2\times10^{18}$ eV (4.3$\times10^4$ events), where the first harmonic amplitude of 4 % was found in the direction to the Galactic centre [Prouza01].

Stereo data collected by HiRes experiment over a six year period are examined for large scale anisotropy related to the inhomogeneous distribution of matter in the nearby universe. They found that HiRes data with threshold energies of 40 EeV and 57 EeV are incompatible with the matter tracer model at a 95% confidence level unless $\theta_s > 10^\circ$, where, $\theta_s$ is the typical deflection angle and are compatible with an isotropic flux. The data set above 10 EeV is compatible with both the matter tracer model and an isotropic flux [Abbasi10].

The analysis of the distribution of the arrival directions of the highest energy event collected by the Pierre Auger Observatory provided an evidence of anisotropy of UHECRs [PAC07]. In this work, it has been shown that there is a significant excess of cosmic rays with energy above $5.7 \times 10^{19}$eV within $\sim 3.2^\circ$ of the position of AGN of Veron-Cetty catalogue located at a distance smaller than 75Mpc from the earth [PAC07][Ryu09].
1.1.4 Origin, Acceleration and Propagation

The origin, acceleration mechanism and propagation of cosmic rays above $10^{14}$ eV could not been properly addressed till date. The great energy range and the features in the energy spectrum suggest that different kind of sources is responsible for the cosmic radiation at different energies. In the energy range between $10^9$eV up to near the knee region cosmic rays are of Galactic origin [Bhattacharjee00] and possibly emitted from supernovae remnant. Below the energy $\sim 10^9$eV the intensity of cosmic rays is temporally correlated with the solar activities, which confirms the solar origin at this energy level [Bhattacharjee00]. The possible sources of UHECRs can be addressed as follows.

The conventional scenario of theories of origin of UHECR is the so called bottom up acceleration [Bhattacharjee00], where charged particles are accelerated from lower energies to the highest energies in certain special astrophysical environments. The main difficulty in this bottom up scenario is that, distance of most favourable sources above $10^{20}$eV such as powerful radio galaxies are located at large distances($>>100$Mpc), beyond GZK cutoff distance. In an attempt to overcome these difficulties a different model known as top down model scenario has been postulated, where UHECR particles are the decay products of some supermassive X particles of mass $>>10^{20}$eV.

1.1.4.1 Bottom up Model

In the bottom–up models the acceleration is due to electromagnetic forces. This can be a direct acceleration that requires strong electromagnetic fields or a stochastic acceleration. The primary model for stochastic acceleration is the first order Fermi acceleration [Fermi49]. In this model a charged particle is scattered by magnetic fields and repeatedly traverses a shock front in the interstellar medium. On average it gains energy of $\frac{\Delta E}{E} \propto \beta$ (with $\beta = v/c$ the speed of the shock front) at each crossing. The second order Fermi-
acceleration is less effective. In this model a charged particle is scattered repeatedly at statistically distributed magnetic clouds and gains on average \( \frac{\Delta E}{E} \approx \beta^2 \) in every cycle.

The charged particles of the cosmic radiation are deflected by magnetic fields in the Milky Way. This confines cosmic rays with energies < \( 10^{18} \) eV to the Milky Way and its halo. From the relative abundances of radioactive isotopes one can infer the elapsed time since nucleosynthesis or spallation. With this, the average age of the cosmic rays is estimated to \( \sim 10^7 \) years. From the relative abundances of the spallation products one can estimate the traversed matter density of the cosmic rays to \( \sim 5 \) g/cm\(^2\). This entails that the cosmic rays stay mostly in the halo outside of the galactic disc.

**Origin in the vicinity of neutron stars in our Galaxy**

The nearest suitable UHECR sources should be represented by neutron stars. This source type is not consistent with the assumption of extragalactic origin of UHECRs and has to explain the observed isotropic distribution and no confinement with Galactic plane. According to the "Hillas plot" [Hillas84] the typical surface strength of magnetic field on young neutron stars is sufficient (\( \sim 10^{13} \)G) for the acceleration up to EHECR scale (\( 10^{20} \)eV for protons). However, the plasma that expands beyond the light cylinder is free from the main loss processes and may be accelerated to ultra-high energies. In particular, newly formed, rapidly rotating neutron stars may accelerate iron nuclei to ultra-high energies through relativistic magneto-hydrodynamic (MHD) winds [Blasi00]. These Galactic sources need enough efficient magnetic fields to isotropize the directions of UHECRs, because no observable correlation with Galactic plane was found.

**Origin in radio galaxy hot spots**

The hot spots are interpreted as a gigantic shock waves emanating from a central active galactic nucleus at relativistic speeds. Typical size of the hot spot is about few kilo-
parsec and the magnetic field within is several hundred μG. The maximum energy attainable is \((1-10) \times 10^{20}\) eV, dependent on actual parameters of the spot. The acceleration is classically due to first order Fermi acceleration.

**Origin in nearby galaxies**

It is generally agreed that our Galaxy is producing cosmic rays up to \(10^{18}\) eV, with luminosity \(10^{30}\) J.s\(^{-1}\) for a confinement time \(10^{11}\) s. It is possible that in more active galaxies [Takahara96], with higher rate of star formation, the magnetic field may be higher. The requirement for \(10^{20}\) eV protons exceeds \(3 \times 10^{15}\) G.m (magnetic field \(\times\) characteristic size). Acceleration to extremely high energies near the horizons of supermassive black holes in the galactic centers has also been suggested [Boldt99].

**Origin in gamma ray bursts**

According to some theories [Waxman95] origin of Gamma Ray Bursts (GRBs) may also be a source of ultra-high energy cosmic rays. Both phenomena have still unknown origins and also other similarities that may argue for a common source. UHECRs and GRBs are distributed isotropically, the average rate of γ-ray energy emitted by GRBs is comparable to the energy generation rate of UHECRs of energy \(> 10^{19}\) eV in a red shift independent cosmological distribution of sources, both have energy \(\sim 10^{37}\) J.Mpc\(^{-3}\).yr\(^{-1}\).

The general problem of all the processes described upto this point is that the generated particles have significant energy losses in the vicinity of all these discussed active environments. May be the most important loss channels are due to synchrotron radiation emissions and pair production in the dense surroundings of these objects.

1.1.4.2 Top down Model

**Origin in interactions with neutrinos**

The first “top-down” acceleration mechanism is represented by the neutrino--neutrino interactions. According to this scenario, the extreme energetic neutrino (~\(10^{22}\) eV) accelerated
in any cosmologically distant source interacts with background relic neutrino (with temperature about 1.9 K) and produces $Z^0$ boson. The resonance energy for this interaction is about $4 \times 10^{21}$ eV. This $Z$ boson decays and produces ~2 nucleons, ~20 $\gamma$-rays and ~50 neutrinos. "Z-bursts" are taking place in the relative vicinity (~ Mpc) to the Earth and we observe the arriving nucleons, which are products of $Z$ decay. Other possibility is that the cross-section of neutrino-nucleon interaction rises rapidly in the investigated energy region and these extreme energy neutrinos from the unknown cosmological sources are interacting directly with nucleons in the Earth's atmosphere [Stecker01].

**Decay of relic super heavy particles**

According to this theory cold dark matter in the galactic halo is supposed to contain a small admixture of long-lived super heavy particles with mass $> 10^{21}$ eV with a lifetime greater than the age of universe [Berezinsky01]. Such particles have to be created during reheating following the inflation or through the decay of hybrid topological defects. The decay products are nucleons, electrons and photons, which are arriving to the Earth and initiating showers with common properties.

**Origin in topological defects**

Topological defects as monopoles, cosmic strings, and superconducting strings should be also the sources of UHECRs [Berezinsky01]. These defects have to be left from the phase transitions in the early universe. The UHECRs are originated during the collapse, the annihilation or the crossings of such formations.

**New hadrons**

The suggestion has also been made that new neutral particles containing gluino could be producing the trans-GZK events [Farrar96]. This particle have to be stable and with lower cross-sections for the interactions during propagation. Such a particles are called "uhecrons".
Similarly vortons, superconducting cosmic strings stabilized by a current present a solution that is limited to the very highest energies.

**Magnetic monopoles**

The accelerated monopoles with mass $< 10^{10}$GeV should be the sources of UHECRs too [Porter60]. These monopoles should be accelerated in the Galactic magnetic field and then hit the Earth's atmosphere. But according to the simulations the produced showers then have to have special properties, which are not observed. Also the correlation with Galactic plane is not observed.

Violation of Lorentz symmetry presented idea of the possible departure from the strict Lorentz invariance [Coleman99]. The proposed departure is too small to be detected by the man-made accelerators, but large enough to affect the particle kinematics in ultra-high energy region and so to suppress or completely forbid the interactions of UHECRs with CMBR. Therefore the predicted cutoff in the spectrum is at least shifted by one order to higher energies and the origin of particles is possible also in the cosmological distances.

**1.2 Air Shower**

When a primary cosmic ray particle enters the earth's atmosphere it reacts strongly with an atomic nucleus of the air. The interaction point of the cosmic ray particle with the atmosphere is random and decided, on statistical basis, by its inelastic cross-section on the target nucleus. The inelastic cross-section, $\sigma_{\text{p-air}}$, of protons on an "air nucleus" (mean $Z=7.5$, mean $A=14.5$) is about 200mb corresponding to an interaction mean free path of $\sim 80$ g cm$^{-2}$ at an energy of $\sim 10^{14}$eV. So interaction occurs, on an average, at 80 g cm$^{-2}$ from the top of the atmosphere. In this reaction a multitude of secondary particles is formed, which in turn react with atoms in the air and produce more secondary particles. This is done not only by hadronic interactions but also by the electromagnetic interactions with atoms or electrons and by the decay of unstable particles. Eventually the cascade contains thousands of hundreds of
different particles which move towards the earth surface with a velocity close to the velocity of light - causing the phenomena of Extensive air shower.

The particles in an EAS form a disc with a few meters thickness and up to some kilometer lateral extent as they move through the atmosphere. This disc is not completely flat, but has more the form of cone with a very obtuse opening angle. In the centre the disc is thin but as we move away from the centre thickness increases with increasing distance (as shown in figure 1.4).

The energy lost by the primary particles is shared by the secondary particles. The total number of secondary particles, known as the multiplicity, slowly increases with the energy of interaction. In the beginning of the evolution of the shower the total number of particles rises due to the continuous production of secondary particles. After the average energy per particle drops below the threshold for the production of new particles the absorption of particle in the air starts to dominate and total number drops exponential
with the atmospheric depth (as shown in figure 1.5). However, muon component of EAS does not suffer significant attenuation after reaching maximum because muons lose energy only by ionization and small factions of them are lost by decay.

**Figure 1.5** Longitudinal and lateral particle distribution in an EAS. Average over 1000 simulation of an air shower induced by a $10^{15}$eV iron nucleus at a zenith angle of $22^\circ$[Glasstetter05][Horneffer06].

### 1.2.1 Components of an Air Shower

The particles in an EAS can be divided into three groups- electromagnetic, hadronic, and muonic component. Neutrinos are usually not taken into account as they do not produce further secondary particles and are too difficult to measure. Similarly radiation in the UV, optical and at radio wavelength is referred to as being emitted by and not as being part of the air shower.
1.2.1.1 Electromagnetic component

The electro-magnetic component of an EAS consists of electrons, positrons and photons. It is mainly due to the decay of neutral pions into gamma photons. Though photons interact with matter causing Photo electric effect, Compton Effect and Pair production, the first two have low reaction cross-section for high energy photons and can be neglected in the formation of electromagnetic cascade of EAS. The high energy electrons produced in the pair production in turn produces gamma photon and one low energy electron by the bremsstrahlung process. Thus the electromagnetic cascade is developed by the high energy particles in which they convert into each other by pair production and bremsstrahlung. The cascade starts with no average charge but it picks up atmospheric electrons and thus develops a negative charge excess. In crossing every radiation length each particle loses 1/e fraction of its average energy. Once the energy of the electrons or positrons drops below the critical energy (E_{c,air} = 84.2 MeV), they loose, on average, more energy by ionization than by bremsstrahlung. In this particular point the production of new photon ceases and the electromagnetic cascade dies out.

The electromagnetic cascades of hadrons initiated air shower consist of the superposition of many electromagnetic cascade whereas electron or photon initiated air shower consist of only one electromagnetic cascade.

1.2.1.2 Hadronic component

Every air shower that is initiated by atomic nuclei as primary particle starts from its hadronic component. The hadronic component consists of the strong interacting particles in the air shower, i.e. fragments of nuclei, single nucleons, mesons etc. In this process pions are the most common kind of particles. On average their transversal impulse is rather low compared to their total impulse. So, high energy hadrons are concentrated in a radius of only a few tens of meters around the shower axis. New hadrons are produced in high energy collisions of hadrons. When the energy of hadrons is too low for the production of pions it
looses energy through ionization until it decays or is stopped. At the high energies of the primary particles the nucleons of a nucleus can be considered as free particles. So an iron induced air shower can be considered as the superposition of 56 proton induced air showers each with the 56th part of the total energy. The proton–air cross section above 100GeV rises only logarithmic with energy, so the iron–air interaction length is about 4 times smaller than the proton–air interaction length [Geich-Gimbel89]. This makes iron induced air showers evolve earlier and faster in the atmosphere than proton induced ones.

The integral energy spectrum of hadrons can be expressed as a power law; the spectrum is flat at lower energies and become steeper as the hadrons energy increases.

1.2.1.3 Muonic component

The muons in an air shower are produced by the decay of charged pions and kaons. The muons themselves decay into electrons/positrons and neutrinos. Compared to pions their life time is about 100 times longer. Compared to electrons the scattering and bremsstrahlung is a factor of \((m_\mu/m_e)^2 \approx 4300\) smaller. Moreover the range of the muons in the laboratory rest frame is extended by relativistic time dilation.

Hence most muons reach the earth’s surface. The lateral distribution of the muons is mostly caused by the angular distribution and the height of their production. It can also be parameterized by the NKG-function [Kamata58][Greisen56]. However the latera distribution of the muons is flatter than the one of the electromagnetic component.

The energy spectrum of muons can be represented by a power law; it is flat at low energies because of increasing losses due to ionization and decay with decreasing muon energies. At higher energies the spectrum became steeper. The number of muon having energy \(> E_\mu\) can be related to the shower size \(N_e\) and primary mass \(A\) by the equations (1) and (2) respectively.

\[
N_\mu(> E_\mu) \propto N_e^{\alpha_\mu E_\mu}
\]
The exponent $\alpha(E^\mu)$ decreases with $E^\mu$ presumably because the decay probability of higher energy pions decreases as energy increases. The value of $\alpha(E^\mu)$ is 0.8-0.9 at $E^\mu \sim 1$GeV and decreases to about 0.7 at $E^\mu \sim 200$GeV.

1.2.2 Detection & Measurement Techniques

Earth atmosphere is acting as a large calorimeter on an incident cosmic ray and it has a vertical thickness of 26 radiation lengths and about 11 interaction lengths, which are acting in development of EAS. Based on the different phenomenon that happens to occur during its motion in the earth atmosphere and ground level, extensive air showers are detected by several different methods. Currently three differently, established methods in use to measure EAS, are as follows,

1.2.2.1 Air Čerenkov

When a fast particle moves through a medium at velocity v, greater than the phase velocity of light in that medium (so v>c/n; c is the speed of light, n is the refractive index of the given medium), it emits Čerenkov radiation. The physical principle of this effect rests in a polarization of medium by relativistically moving particle. A charged particle moving slowly through a transparent material will polarize the medium along its trajectory. The atoms around the particle are transformed into little dipoles. When the particle moves to another point, they relax to their normal state. Owing to complete symmetry of this effect no resulting field reaching larger distances is produced. However, the situation differs qualitatively along the path of flight and each element of the track is radiating. However, the elementary waves generally interfere destructively and there is then no visible effect at large distances. Only when the velocity of the particle is higher than the phase velocity of the light in the medium it will produced field detectable at distant point. Waves from the different points of the track combine constructively to form a plane wave front.
The wave fronts only add up to produce coherent radiation in a particular direction $\theta$ with respect to the velocity vectors of the particle, so the radiation should be observed only in a narrow cone along the track. The apex angle of this cone $\theta$ is given by the formula $\cos\theta = \frac{c}{vn}$. The intensity of radiation is given by [Longair92]

$$I(v) = \frac{vQ^2v}{4\pi\epsilon_0c^2} \left(1 - \frac{e^2}{n^2v^2}\right)$$

where $v$ is the frequency of the emitted radiation, $Q$ is the charge of a particle in coulombs and $\epsilon_0$ is the permittivity of vacuum.

In clear, moonless nights this light can be measured by optical telescopes with photomultiplier cameras. The image obtained with this telescope shows the track of the air shower. From this track the direction of the primary particle can be reconstructed. With two telescopes observing an air shower in stereo mode one can get angular resolution on a single air showers of less than 0.1°[Hinton04]. Since Čerenkov radiation is strongly beamed into forward direction, so the illuminated area on the ground is only few hundred meters wide. Examples are the Tunka array [Budnev05] and the AIROBICC array of the HEGRA experiment [Karle95]. The shape of the image of the air shower track is also useful to differentiate between hadron induced and photon induced air showers. Consequently this method is used for TeV-γ observatories like H.E.S.S experiment [Hinton04].

1.2.2.2 Air Fluorescence:

High energy shower particles excite and ionize the air molecules as they traverse down to the earth surface. The excited nitrogen molecules in turn emit fluorescence light mainly in the UV region (300-400nm). Most of the fluorescence light comes from 2P band system of molecular nitrogen (~80%) and 1N band system of the N$_2^+$ molecular ion (~20%). The emitted radiation is highly isotropic and can be detected at a large distance from the axis of the shower. By observing this light with optical telescopes one can image the track of the air shower in the atmosphere. For this reason, the whole observed sky is segmented, and each segment (typically~1°) is observed by its own photomultiplier. The
emission efficiency (ratio of emitted energy in fluorescence light to the deposited one) is poor (~1%), the detector sees the shower as a variable light bulb moving at the speed of light along the shower axis. Due to the low radiated power this method is only efficient for UHECRs. Like Čerenkov method this is only possible in clear, moonless night, i.e.-in about 10% of the time. Under favorable conditions UHECR showers should be detected at distances as large as 20km-at Fly's Eye of HiRes detectors. The fluorescence yield [Bertou00] is 4 photons per electron per meter at ground level.

The fluorescence technique is the most appropriate for energy measurements-atmosphere acts like large calorimeter and thus the emitted energy is proportional to a number of charged particles in shower.

In practice also several effects should be taken into account, which are complicating the evaluation and raising the uncertainty of result. These are, subtraction of the direct and diffused Čerenkov light, the wavelength-dependent Rayleigh and Mie scatterings and the dependence of the attenuation on the altitude.

1.2.2.3 Particle Detector Arrays

Pioneering research of Auger and his team showed that there is a relation between energy of primary particle and the size of the surface, where we are able to detect secondary particles. Primary energy above about $10^{14}$eV, a large number of air shower particles have enough energy to reach earth surface. These particles can then be measured with particle detectors. The detectors are distributed uniformly over the measurement area. The spacing between two adjacent detectors determines the low energy threshold of the experiment-e.g-KASCADE array: 13m, $\sim 10^{14.6}$eV, and Auger 1.5km, $\sim 10^{18.3}$eV. [Antoni03][Kampert04], and the size of the covered area determines the highest energy at which one has a reasonable count rate, e.g. KASCADE array: $4 \times 10^4 m^2$, $\sim 10^{17}$eV, and Auger: $3 \times 10^9 m^2$, $>10^{20}$eV. From the arrival times of the particles in the detectors one can determine the direction of the air shower, and from the energy measured with the detectors one can get the number of particles.
With suitable detectors it is possible to separately measure electron and muon numbers of an event shower.

### 3 Ultra High Energy Cosmic Rays (UHECRs)

Primary cosmic rays having energy above $10^{18}\text{eV}$ are known as UHECRs. Particles with this energy range have unique importance because of non-existence of suitable sources inside our galaxy for accelerating up to the observed highest energy. Furthermore, these extreme energies, about eight orders of magnitude lower than known methods of acceleration, require extreme intensity of magnetic fields or extreme sizes of acceleration regions. Such conditions are hardly available at any places in the universe; may be the most favorable are large radio lobes in active radio galaxies. But even these need to have all conditions finely tuned and only in such a case the theoretically derived maximum attainable energy is achieving $10^{21}\text{eV}$.

![Figure 1.6](image)

**Figure 1.6** Spectral deviation from $E^{-2.09}$ by Auger [PAC08](left); flux multiplied by $E^3$ by HiRes[HiRes08] and AGASA(right)
Although the first detection of UHECRs dates back to 1962 [Linsley63], it was only in the 1990s that an international effort began to address the mystery behind the UHECRs with the necessary large scale observatories. Akeno Giant Air Shower Array (AGASA) in Japan, High Resolution Fly's Eye (HiRes) at Utah, USA and the largest observatory ever constructed, the Pierre Auger Observatory in Argentina are some of the best observatories which are trying to explain the mystery of GZK cutoff, CMB etc.

In pursuing the journey to the highest energy end of UHECRs, AGASA reported an excess of flux while HiRes were closer to GZK prediction. The GZK effect is named after Greisen [Greisen66], Zatsepin, and Kuzmin [Zatsepin66] who predicted in 1966 a dramatic steepening of the spectrum above a few times $10^{19}$ eV caused by the interaction of UHECRs with cosmic microwave background (CMB) radiation as they propagate from extragalactic source to earth. In 2008 two observatories HiRes [HiRes08] and Pierre Auger Observatory [PAC08] published the GZK spectral feature as displayed in Fig-1.6.

This landmark measurement opens the way to astronomical searches for sources in the near by extragalactic universe using the distribution in arrival directions of trans-GZK cosmic rays. Above GZK threshold energy, sources contributing to the spectrum must lie within about 100 Mpc, the so called GZK horizon or GZK sphere. The Auger AGN correlation results argues that some sources can't be much further than about 100 Mpc, which rules out rare and distant sources, such as massive clusters of galaxies and most powerful radio galaxies. The Auger trans-GZK events also correlated with PSCz (Point sources Catalogue Redshift Survey) sources [Kashti08], with HI emitting galaxies [Ghiselini08], and Swift hard X-ray sources [George08].

Competing models of cosmic accelerators will be best tested once we can measure precisely the spectrum of individual sources. To do this the combination of large sky exposure and precise spectrum and composition measurements will be the best option for the cosmic ray observatories which is now feasible, limited only by the amount of exposure to each source.
1.4 Radio Emission from Extensive air Showers

Emission of Electromagnetic radiation at radio frequency due to the EAS of UHECRs has been theoretically and experimentally proved by different cosmic ray groups since 1965, when for the first time radio pulses associated with cosmic ray air showers were detected by Jelley and his co-workers in Harwell [Jelley65]. In the 1970ties the radio detection was overlooked due to the success of other methods and uncertainty about the interpretation of the radio results. The development of high resolution receiving system, new technologies as well as the advantages of this method, helped to revive its popularity among the theoretical and experimental cosmic ray groups.

Measuring the radio pulses from air showers has a number of advantages compared to the established techniques. With the RFI (radio frequency interference) suppression one can measure even in relatively radio loud environments, i.e. close to cities which are not possible with optical telescopes. It is not much affected by observing conditions. Except during thunderstorm conditions which seem to amplify the radio signal emitted by air showers [Buitink05][Buitink07] one can measure during day and night. This gives a much higher duty cycle than optical measurements.

The little attenuation of radio signals makes it possible to measure highly inclined air showers whose particle component has already, mostly died out at the ground level [Petrovic07]. This method can be used to study the air showers that are induced by high energy neutrinos, as it can help to distinguish between neutrino induced air showers and other air showers. Radio detectors can see air showers from any primary while particle detectors mainly detect those from neutrinos that had their first interaction close to the detectors [Falcke04].

The radio signal forms a continuous pulse front unlike the particle front that is quantized. This makes it possible to measure the relative arrival time of the shower front at different positions with high precision and thus get a better estimate for the arrival direction of the cosmic ray than with particle detector arrays.
1.4.1 Early Experimental Data

In 1962 Askaryan predicted that particle showers in matter should emit radio signals [Askaryan62]. He proposed that particle showers develop a negative charge excess so that the showers can coherently emit Čerenkov radiation at radio frequencies. In 1965 Jelley et al. discovered that extensive air showers indeed produced radio pulses at 44MHz [Jelley65]. In the following years emission from 2MHz up to 520MHz was found. Soon it was discovered that the signal strength in one polarization direction depends on the angle of the air shower to geomagnetic field, supporting theories that the radiation of air showers is caused by geomagnetic effects. Further studies showed that the polarization of the radio signal is consistent with geomagnetic emission process [Allan73].

The early experiments were limited by the existing technology. They restrained the observations in a relatively small band width of a few MHz. The received radio signal was integrated with a time constant of the order of hundred nanosecond to get the total receiving power. These systems hardly filter out transmitter stations that leak into the observed frequency band and thus one can’t distinguish air shower pulses from RFI pulses. Consequently measurement often done at night when commercial TV and radio stations were turned off and access to the site could be restricted.

1.4.2 Recent Experiments

The first effort trying to measure radio emission from air showers with the help of fast ADCs was done by Green et al. [Green03]. They set up one antenna near the CASA/MIA array [Borione94] in Utah. Due to limitations of the experiment and high levels of RFI they were not able to measure radio pulses from air showers. They found an upper limit for the emission strength of $34\mu V/m/\text{MHz}$ at primary particle energy of $\sim10^{17}\text{eV}$.

Another effort is the CODALEMA experiment [Ardouin07]. This uses several antennas of the Nancay decametric array, together with a small number of scintillation
detectors. The site is very radio quiet and the scintillation detectors are well shielded. With this they are able to measure radio pulses from air showers with field strength around from a few to 25μV/m/MHz [Ardouin07]. They also confirmed the limited footprint of the illuminated area on the ground of a few hundred meters and use it to distinguish between air shower pulses and RFI pulses. One limitation of this experiment is that it does not have access to a calibration of the air shower parameters and depends on incidental measurements, e.g. estimating the primary energy from the trigger rate.

The most interesting and challenging experiment on radio detection from cosmic ray air shower is the LOPES experiment in Germany. It consists of 30 single polarization antennas that are set up at the site of the KASCADE-Grande experiment, Germany [Falcke05]. It directly samples the radio signal in the frequency range from 40- to 80 MHz and stores 0.82ms of raw data every time it was triggered by KASCADE-Grande. For the analysis the data is offline correlated with the data from KASCADE-Grande array, radio interface is digitally filtered and a beam in the direction given by the KASCADE array is formed. With this they could reliably pick out radio pulses from air showers. They found that the height of the radio pulses have nearly linear dependence on the shower size (with power index slightly smaller than one), an exponential decline with the distance of the antennas to the shower axis, and a monotonic rise with the angle of the air shower to the geomagnetic field [Horneffer06].

1.4.3 Theories

The first postulated process for radio emission from air showers was Čerenkov radiation. The particles in the air shower travel faster than the speed of light in air so they emit Čerenkov radiation. The physical size of an air shower is smaller than the wavelength at radio frequencies so the emission is coherent. In a neutral shower with as many positrons as electrons the emission from positron and electron will cancel each other. Askaryan proposed that because the atmosphere or any other matter contains many electrons but no positron an air shower develops a negative charge excess [Askaryan65]. The net charge then allows an air shower to emit Čerenkov radiation at radio wavelengths.
Another emission mechanism is due to the deflection of charged particles (mostly electrons and positrons) in the earth's magnetic field. There are two ways to look at this, both are expected to be equivalent. One interprets it as a separation of charges in the air shower which leads to transverse currents in the air shower which in turn emit dipole radiation [Kahn66]. Falcke and Gorham [Falcke03] interpreted this as synchrotron radiation of particles gyrating in the geomagnetic field.

As the experimental data shows a clear dependence of the radio emission on the angle with the geomagnetic field, the geomagnetic emission process has to be the dominant one in air showers. The field strength rises nearly linearly with the primary particle energy, this means that the emitted power rises quadratically with the primary energy. This shows that the emission is nearly totally coherent as incoherent emission would only result in a linear rise of power with energy [Huege05]. Another result obtained so far is that the total electric field strength only weakly depends on the angle of the shower to the geomagnetic field. Of course the emission is purely linearly polarized in the direction perpendicular to the magnetic field and the air shower axis. Polarization angle is dependent on the geomagnetic field – emission is linearly polarized in the direction perpendicular to the magnetic field and the shower axis. Thus showers from due north or due south are both completely east-west polarized although they have different geomagnetic angles.

Based on transition radiation, another emission mechanism is forwarded by Nishimura in 1985 [Nishimura85]. When the excess negative charges from an EAS, hit the earth surface radio emission takes place due to the transition radiation mechanism. The emission is purely coherent in the low frequency region as the bunch length is very much less than the emitted wave length. The radiated field at VLF region is nearly 100 times greater than the field at LF/MF region [Dutta00][Hough73]. Of course the high frequency field strength spectrum given by transition radiation resembles with the field strength spectrum according to the geo-synchrotron mechanism.
1.5 Present work

1.5.1 Motivation

Radio measurements of EAS open an entirely new window for the observation of Cosmic Rays. The technique has a number of significant benefits. Similar to the optical fluorescence technique, it allows a much more direct view into the air shower cascade than particle measurement on ground, yielding information greatly simplifying the reconstruction of air shower parameters from the particle detectors. The radio technique mainly measures quantities integrated over full evolution of the air shower. A major benefit of the radio technique is that it is not hindered by need of superb observing conditions (clear sky, moonless night, far away from any light pollution) that limits the duty cycle of fluorescence detector typically to less than 10%.

1.5.2 Work Plan

This present work is continuation of detection of UHECRs by GU miniarray [Bezboruah99]. The importance of this present work is the development of new trigger circuit for the front end electronics of GU miniarray [Saikia05][Saikia08] and the detection and measurement of radio signal associated with UHECRs [Saikia07]. The thesis of this work is organized as follows:

In chapter II we discuss the idea and theory behind the miniarray method, working of GU miniarray and finally discuss the working of newly designed Trigger Circuit (TR) for the front end electronics of GU miniarray.

In Chapter III we present the theory of transition radiation at the interface between two surfaces of different dielectric properties following Doohar approach and finally calculate the magnetic field for vacuum to medium case.
In Chapter IV we discuss the principle of small loop antenna, its electrical properties and behavior of multiturn loop antenna. We then discuss the simulation of loop antenna using JtspiceIV and its results.

Chapter V consists of the construction, calibration and testing of receiving loop antenna. Then we discuss the calibration of scintillation detectors of miniarray and the calibration of discriminator circuits. We discuss the experimental setup for radio detection without miniarray and with miniarray.

Chapter VI comprises the discussion of model calculation of transition radiation using FORTRAN programming language. The geometry of shower acceptance and co-ordinate axes are inferred.

Chapter VII consists of the experimental results of LF/ VLF detection. Power spectral density, electric field and pulse height distribution of received radio signal has been discussed in this chapter.

Chapter VIII consists of the concluding remark and the future work plan.
References


[Horneffer06] A. Horneffer. in (Bonn, 2006).


