PARTICLE PRECIPITATION EFFECTS ON THE SOUTH AFRICAN IONOSPHERE

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Abstract

Particle precipitation involves the injection of energetic particles into the ionosphere which could increase the ionisation and conductivity of the upper atmosphere. The goal of this study was to examine the ionospheric response and changes due to particle precipitation in the region over South Africa, using a combination of ground-based and satellite instruments. Particle precipitation events were identified from satellite particle flux measurements of the Defence Meteorological Satellite Program (DMSP). Comprehensive studies were done on the events of 5 April, 2000 and 7 October, 2000. Analysis of the data from the satellite instruments indicates that no particle precipitation was observed over the South African region during these events and that it is unlikely to occur during other such events. To validate the data, methods and tools used in this study, precipitation in the South Atlantic anomaly (SAA) region is used. Satellite ion density measurements revealed that strong density enhancements occurred over the SAA region at satellite altitudes during the precipitation events, but this did not occur in the South African region. The measurements also revealed how the ionisation enhancements in the SAA region correlated with geomagnetic and solar activities. Particle precipitation and convective electric fields are two major magnetospheric energy sources to the upper atmosphere in the auroral and the SAA regions. These increase dramatically during geomagnetic storms and can disturb thermospheric circulation in the atmosphere and alter the rates of production and recombination of the ionised species. Ionosonde observations at Grahamstown, South Africa ($33.3^0S, 26.5^0E$), provided the data to build a picture of the response of the ionosphere over the South African region to particle precipitation during the precipitation events. This analysis showed that, within the confines of the available data, no direct connections between particle precipitation events and disturbances in the ionosphere over this region were revealed.

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Chapter 1

Introduction

The aim of this study is to investigate the effects of particle precipitation on the ionosphere over the South African region. This is achieved by tracking the response of the mid to low latitude ionosphere to particle precipitation, in order to obtain a picture of the sequence and relationship of ionospheric variations during particle precipitation events.

Firstly, the possible occurrence of direct particle precipitation over the South African ionosphere, a mid-latitude region, is investigated. Possible occurrences of Mid-latitude aurora and associated particle precipitation have been observed and discussed in the literature (e.g Rassoul and Hamid-Reza (1987), Rassoul *et al.* (1992), Rassoul *et al.* (1993), DeMajistre *et al.* (2005)). Ishimoto and Torr (1987) analysed and studied the spectral observations of the mid-latitude aurora that occurred on September 22, 1982. In their analysis, they used ground-based spectral observations of this event and found that the observed emissions were caused by either O(+) or H(+) energetic ions. The proximity of the South African region to the SAA region could lead to possible occurrences of particle precipitation in the South African region.

Secondly, events of particle precipitation in the SAA and the auroral regions are identified and the ionosphere over the South African region is examined for any variations and disturbances that could be linked to such events. Data from the Defence Meteorological Satellite Program (DMSP) are used to identify precipitation events, and ionosonde data from the Grahamstown ionospheric station, South Africa $(33.3^o S, 26.5^o E)$ are used to track and examine the ionospheric changes.

The Earth continuously receives radiation from the geospace environment in the following different forms:

- optical radiation as light,

- ionising electromagnetic radiation such as far ultra violet (FUV), gamma rays and X-rays and
- charged and energetic particles such as electrons, protons, alpha-particles and other heavier ions.

Particle precipitation involves the injection of the energetic particles into the ionosphere. The injected particles interact with the constituent particles of the Earth's upper atmosphere and cause the light emissions that are seen as aurora in the polar ionospheres. The precipitating particles also cause enhanced ionospheric ionisation (Galand, 2001; Galand and Richmond, 2001), compositional changes of the constituent particles of the atmosphere (Baker, 2004), enhanced ionospheric conductivity (Galand and Richmond, 2001) and temperature changes in the atmosphere (Gledhill, 1976). The intensity, and localisation of the precipitation are functions of solar and geomagnetic activity.

The sources of the precipitating particles are many and varied. The most important sources of the different radiation and high-energy particles include:

- The geomagnetically trapped particles in the Van Allen radiation belts. The Van Allen radiation belts are regions of high-energy particles, mainly protons and electrons, held captive by the magnetic influence of the Earth (see section 2.4.1). These particles comprise the diffuse and discrete auroral precipitation within the auroral zone, the energetic magnetospheric electrons extending from mid-latitudes throughout the auroral zone and the ring current particles precipitating at mid-latitudes.
- The solar energetic particles within the polar cap (protons, electrons, alpha particles and other heavy ions).
- Galactic cosmic-rays including interplanetary protons, electrons and heavy ions.

Particle precipitation represents a form of "space weather" which can have significant effects on technological systems, both ground-based and space-based. Changes in the ionosphere due to space weather effects are important in at least the following ways:

- They cause difficulties in radio communications, navigation, and use of Global Positioning Systems (GPS) due to increased radio scintillation (caused by increased density turbulence), and the creation of plasma density holes and enhancements in the ionosphere (which affects the propagation of signals) (Yizengaw *et al.*, 2005).

- They can cause difficulties in maintaining satellite orbits and orientations due to increased drag from the expanded and denser ionosphere.
- Increased auroral displays and particle precipitation affect the ionospheric density.
- The enhanced current and flow of the auroral electrojets leads to large, rapidly changing magnetic fields and associated induced currents on Earth.

This thesis presents an account of the investigation into the effects that particle precipitation has on the South African ionosphere. Chapter Two presents a detailed theoretical background to energetic particle precipitation, sources of these particles and how they interact with the Earth's magnetosphere and ionosphere. Chapter Three describes and explains in detail how the data sets used are collected and processed and how they can be accessed as well as the procedures undertaken in analysing the data. A qualitative comparison of ionospheric variation measurements by satellite and by ground based ionosondes for certain precipitation events is presented in Chapter Four. Chapter Five presents the discussions and the conclusions emerging from this study.

Chapter 2

Theory and Background

2.1 Introduction

This Chapter presents the detailed background theory on particle precipitation and the factors that lead to the occurrence of particle precipitation. It includes the discussion on the Sun's interaction with the Earth, and how this interaction drives different phenomena on Earth, including particle precipitation.

2.2 The Sun and solar activities

The Sun emits electromagnetic radiation and matter (most of which are protons and electrons, with a small percentage of alpha particles and some heavier nuclei) into interplanetary space as a consequence of the nuclear fusion process in its interior. This plasma outflow is known as the solar wind, and these particles travel in space at high speeds ranging between 200 km/s and 800 km/s (Lang, 1992).

The solar wind is responsible for fuelling magnetospheric storms, forming our planet's magnetosphere. It is the major driver of particle precipitation into the Earth's ionosphere causing auroral displays. It also contains a magnetic field that originates in the upper regions of the Sun's corona and is frozen into the solar wind particles, which therefore carries the interplanetary magnetic field into space as it flows outwards. The interaction of the Sun's frozen-in magnetic field with the Earth's magnetic field plays a key role in facilitating the transfer of energy from the solar wind into the ionosphere. One form of coupling between the Earth's magnetic field and the Sun's magnetic field is the existence of field lines in the polar regions of the Earth's magnetosphere, which are connected to interplanetary magnetic field lines. This coupling enables the direct transfer of energy from the solar wind into the magnetosphere.

At times, great eruptions, that vary in strength and frequency with the 11-year solar-activity cycle occur on the Sun. The solar eruptions cause disruptions of various magnitudes on Earth. Flares and Coronal Mass Ejections (CMEs) are two kinds of solar eruptions that can spew vast quantities of radiation and charged particles into space, potentially causing geomagnetic storms when they strike the Earth's magnetosphere.

Flares are strong transient outbursts of radiation, released near the solar surface, that extend tens or hundreds of thousands of kilometers into the outer solar atmosphere. They are highly localised on the Sun and typically last for a few minutes to a few hours, and emit radiation across most of the electromagnetic spectrum. Flares can disturb the F-region and very strong ones can increase ionisation of the E-region, thereby causing sudden increases in E-layer absorption. Most of a flare's energy is released as radiation in the corona, but some energy contributes to forcing electrons and ions through the outer solar atmosphere into the interplanetary solar wind.

A CME is an explosive ejection of a large amount of solar matter from the solar atmosphere into interplanetary space. High speed solar wind (about 600 km/s) can be associated with CMEs and the population of relativistic electrons is known to be closely related to the occurrence of high speed solar wind streams. The frequency of occurrence of CMEs varies in concert with the 11-year solar activity cycle.

The rate of solar particles incident on the Earth is strongly related to the level of activity of the Sun. When the Sun is actively producing solar flares, the particle fluxes reaching the Earth can be very high. The effects of the interaction of solar charged particles with Earth's magnetic field are referred to as space weather. Plasma from Solar Flares and CMEs carried in the solar wind can affect the ionisation and recombination processes in the ionosphere which may result in the thinning of the D-, E- and the F-Layers.

The daily solar activity is estimated by counting the number of individual spots and groups of spots called Sunspots on the face of the Sun. Sunspots are dark regions on the surface of the Sun, which represent large concentrations of strong magnetic flux associated with ultraviolet radiation. More Sunspots cause more ultraviolet radiation, increasing the F-Region ionisation.

2.3 Precipitating energetic particles

2.3.1 Causes of Particle precipitation

Various processes in interplanetary space and the magnetosphere can cause the precipitation of energetic charged particles into the ionosphere.

- Cyclotron wave-particle interaction causes precipitation of energetic particles from the radiation belt into the ionosphere (Yahnin *et al.*, 2003). This is due to the existence of a mechanism that provides pitch angle diffusion of the energetic electrons into the loss cone. In such a mechanism, pitch angle scattering will transport electrons from stably trapped orbits into the drift loss cone, and if the pitch angle becomes less than the local bounce loss cone, the electrons are lost to the atmosphere (Bob and Thorne, 1999). Pitch angle scattering by collisions or wave particle interaction is an important transport mechanism for energetic electrons in the magnetosphere, as energetic particles are sensitive to pitch angle scattering at low L-shells(Horne and Thorne, 2003). An example of this is the wave-particle interaction of VLF waves and electrons which has the cold plasma density as an important parameter (Østgaard *et al.*, 1999), for which the rate of pitch angle scattering is enhanced relative to the rate of injection associated with radial diffusion or convection by the relatively high plasma densities at low L-shell in the inner magnetosphere (Bob and Thorne, 1999). Søraas *et al.* (1974) observed close correspondences between the precipitation of relativistic electrons and the anisotropic proton precipitation, which suggests that the electrons are scattered into the loss cone by the electromagnetic ion cyclotron (EMIC) waves. This is in accordance with the theory by Thorne and Kennel (Thorne and Kennel, 1971), which suggests that ion cyclotron waves generated by the unstable proton population can precipitate relativistic electrons in the 1MeV range. Bob and Thorne (1999) examined the global pattern of the energetic particle precipitation. They applied a numerical model which simulates electron pitch angle scattering as a function of energy, L-shell and longitude to the Earth's inner radiation belt. They noted that the global morphology of electron precipitation is determined by the local rate of pitch angle scattering and the variation of loss cone size as electrons drift eastwards relative to the Earth along their gradient drift trajectories.

- The response of the magnetosphere to the interplanetary shocks or pressure pulses results in sudden injection of energetic particles into the inner magnetosphere (Li *et al.*, 2003). The interplanetary shock leads to changes in the magnetic and electric fields which are accompanied by the acceleration of energetic particles, thus leading to the injection of the particles into the inner magnetosphere. An example of this is the event of March 24, 1991 where higher fluxes of energetic particles were observed in the inner magnetosphere. Baker (2004) observed that a strong interplanetary shock struck the Earth's magnetosphere and generated high fluxes of very energetic electrons and protons observed in the inner magnetosphere.

- High-speed solar wind and a southward interplanetary magnetic field during magnetic storms generate large electrical forces which cause many high-energy charged particles to penetrate deeply into the inner magnetosphere. The intensity, spectrum, and localisation of the precipitation are functions of the solar and geomagnetic activity (Baker, 2004).

2.3.2 Electron Precipitation and Proton Precipitation

Both energetic electrons and protons play an important role in the transfer of energy within the Earth's magnetosphere and into the high latitude ionosphere. The energetic particles deposit their energy in the upper atmosphere and are a major source of enhanced ionisation in the ionosphere. Generally, electron precipitation carries most of the particle energy and is the major driver of auroral emissions in the high-latitude ionosphere. Auroral emissions result when the energetic electrons and protons collide with the atmospheric constituents.

Due to their small mass, electrons can be scattered through very large angles when they collide with the neutral particles in the atmosphere. If such deviations increase the pitch angle, it can lead to further penetration into the atmosphere causing the loss of more energy by collisions. On the other hand, if the deviations decrease the pitch angle, the electron is backscattered and will penetrate more on the other end of its bounce trajectory.

Protons, on the other hand, are heavier and therefore not significantly deviated from their spiral paths when they collide with the neutral particles in the atmosphere. Thus, electrons become the major driver of aeronomic effects in the high latitude regions.

At certain locations such as the equatorial edge of the auroral oval (Hardy *et al.*, 1989), and for certain times, proton precipitation can be the major source of ionisation and excitation and thus the primary contributor of auroral emissions (Galand *et al.*, 2002). Lilensten and Galand (1998) investigated the major source of ionisation over Trømso using satellite and ground-based European Incoherent SCATter (EISCAT) radar observations, and showed that protons are sometimes the major source of ionisation. This result was confirmed by Galand *et al.* (2001), who assessed the influence of proton precipitation on the Earth's auroral upper atmosphere using statistical patterns of both electron and ion characteristics. Fuselier *et al.* (2004) discovered a region of proton precipitation equator-ward of the nominal auroral oval from the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) spacecraft images. Senior (1991) found evidence of ionisation by energetic protons in the evening sector by comparing the height-integrated conductivities derived from EISCAT data with those obtained from precipitating electrons.

2.4 The Earth and it's Magnetic field

The Earth has a magnetic field whose major part resembles the field of a bar magnet. It appears to be generated in the Earth's core by a dynamo process associated with the circulation of liquid metal in the core and driven by internal heat sources. This magnetic field is surrounded in space by a region called the magnetosphere (Figure 2.1), which prevents most of the charged particles from the Sun, carried in the solar wind, from hitting the surface of Earth. The shape of Earth's magnetosphere is primarily determined by the distortion of the Earth's internal magnetic field, the solar wind plasma and the interplanetary magnetic field (IMF).

The Sun's solar wind significantly impacts the Earth's magnetic field. Instead of being a simple bar magnet, the Earth's magnetic field is compressed by the solar wind on the side facing the Sun and is stretched out on the opposite side called the magnetotail, which extends to tens of earth radii.

When the Earth's magnetic field is disrupted, the ionosphere is affected by changes in F-Region ionisation or recombination rates.

2.4.1 Trapping of charged particles

The solar wind particles flowing directly from the Sun towards the Earth encounter the magnetosphere. The charged particles do not readily travel across a magnetic field, but are deflected around the magnetosphere. Some solar wind particles travel along the Earth's magnetic field lines and leak into the Earth's magnetic field. A few of these particles can get captured within the magnetosphere in regions called the Van Allen radiation belts. However, most of the particles in these belts are not directly injected by the Solar wind, but come from the earth. Air particles are lifted into space from Earth and these particles become charged by the time they reach the Van Allen radiation belts.

The Van Allen radiation belts are two huge doughnut-shaped zones of trapped particles, electrons and protons, that encircle the Earth. They contain particles trapped in the Earth's magnetic field and are rotationally symmetric about the Earth's magnetic axis (Stern and Peredo, 1995). The Van Allen radiation belts protect the Earth from the damaging effects of radiation from the geospace environment.

The major constituent of the inner belt is high-energy protons, with a few million eV energies, produced when cosmic rays blast particles out of the upper atmosphere. The outer belt is populated mainly with high-energy electrons, with a few thousand eV energies, produced by cosmic rays and magnetospheric acceleration processes. During steady state conditions in the magnetosphere, particles neither enter nor escape these trapped orbits. During magnetospheric disturbances (explained below), accelerated particles may enter and leave the Van Allen belts.

The Earth's magnetic field cause particles to undergo three kinds of motions:

1. Spiral motion where protons and electrons spiral around magnetic field lines since they can't move across them easily.

2. Drift motion where particles drift around the earth relatively slowly. Protons drift westwards and electrons drift eastwards. This motion takes place on magnetic shells characterised by constant values of the McIlwain parameter L (Gledhill, 1976).

3. Bounce motion where particles bounce back and forth from one pole of the Earth to the other as they spiral around the field lines of the Earth's magnetic field. The bouncing of the particles is caused by crowded magnetic field lines near the poles (the mirror points). The bouncing motion brings the particles closer to the surface of the Earth as they move northward or southward away from the equator because of the curvature of the magnetic field lines.

Thus, the charged particles in the solar wind are either forced to move around the Earth by the Earth's magnetic field, or are captured within the Van Allen radiation belts.

Some particles from the solar wind gain access into the magnetosphere, entering at the funnels over the poles, called the polar cusps, or entering from the magnetotail

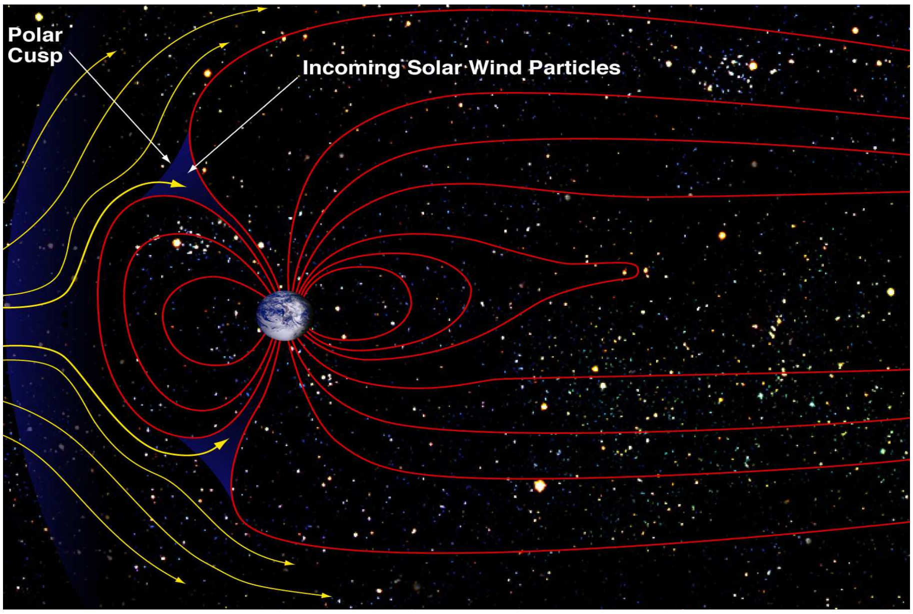


Figure 2.1: The figure shows the Earth's magnetosphere. Got from http:// ss-doo.gsfc.nasa.gov/education/lectures/magnetosphere/
.

and travelling towards the Earth. Charged particles ejected by the Sun are guided into the ionosphere along the Sun's frozen-in magnetic field lines which connect to the Earth's field lines and can impact the high latitude regions where the field lines enter the Earth's atmosphere to low altitudes.

2.4.2 Magnetic Storms and particle precipitation

Magnetic storms are planetary disturbances of the geomagnetic field driven by the interaction of the solar wind with the Earth's magnetic field. Two types of solar events, Solar Flares and CMEs, trigger geomagnetic disturbances in the Earth's environment. It must however be noted that not all solar flares result in geomagnetic storms and not all geomagnetic storms can be associated with solar flares.

Variations in the Earth's geomagnetic field can be measured by magnetometers and the results of such measurements are given interms of magnetic indices. Magnetic indices provide a measure of the perturbations of ground magnetometers which in turn can respond to electric fields induced by currents in the ionosphere and the magnetosphere. Storms are measured by the A-Index ('A' referring to amplitude), which is the overall geomagnetic condition of the ionosphere over a given 24 hour period, ranging typically from 1 to 100 but theoretically can go up to 400. It is derived by averaging the K-index, and is called Ap if averaged from the Kp-Index. The K-index is the overall geomagnetic condition of the ionosphere over the past 3 hours and ranges quasi-logarithmically from 0 to 9. It is directly related to the maximum amount of fluctuation (relative to a quiet day) in the geomagnetic field over a three-hour interval. The Kp-Index is an average of the eight 3-hour K-Indices averaged over the planet. The storms are classified as minor if the Ap is between 29 and 50, major for Ap between 50 and 100 and severe if Ap is over 100.

Magnetic storms can result in sudden injections of energetic particles into the ionosphere. Storm and substorm activities lead to the release of energy stored in the magnetotail during the magnetic reconnection process. Substorms are brief magnetospheric disturbances (lasting about 2 to 3 hours) that occur when the interplanetary magnetic field turns southward, permitting interplanetary and terrestrial magnetic field lines to merge at the dayside magnetopause and energy to be transferred from the solar wind to the magnetosphere.

During the storm and substorm activities, the Earth's magnetic field is dipolarised and the particles are accelerated towards the Earth. Substorm injected particles in general have peaked pitch angle distributions around 90^o. They can eventually reach lower altitudes in the high latitude regions by pitch angle scattering mechanisms that scatter particles to lower pitch angles and they thus can bounce to lower altitudes. The scattering is mainly due to wave-particle interactions with chorus waves. The precipitating particles then collide with the neutral particles of the upper atmosphere losing significant amounts of their energy. Such particle interactions cause Auroral displays and enhance ionospheric ionisation. Particle detectors on satellites like the precipitating particle spectrometer SSJ/4 sensors on the DMSP satellites monitor such particles as they are accelerated downwards towards the surface of the Earth.

During geomagnetic disturbances, energetic particles can precipitate into the ionosphere and the thermosphere. The precipitating particles increase the ionospheric ionisation significantly at high latitude regions. The ionised and neutral gasses are heated up considerably by the enhanced energy input leading to the uneven expansion of the thermosphere which produces pressure gradients that drive strong neutral winds (Buonsanto, 1999). The plasma moves up and down magnetic field lines and changes the rate of production and recombination of the ionised species. This changes the neutral composition, which is a very important factor in the depletion of ionisation reported by Yizengaw *et al.* (2005) who also observed that during storm periods the molecular concentration is increased and the atomic concentration is reduced, leading to the reduction of the atom to molecule ratio by a factor of about 20. Such molecularly enriched air can then be conveyed from high to low latitude regions by the equatorward storm induced winds (Danilov and Lastovicka, 2001).

2.5 Regions where particle precipitation is observed

2.5.1 Auroral regions

Energetic particles gain access into the Earth's upper atmosphere at high latitude regions, and this particle precipitation is seen in the spectacular auroral displays. The high energy charged particles and electric fields carrying energy, mass and momentum enter into the Earth's polar ionosphere from different magnetospheric regions. Solar wind particles enter through the polar cusps and follow the magnetic field lines towards Earth. The particles trapped in the Earth's magnetic field undergo bounce motion between two mirror points as they move northward or southward from the equator and their height above the Earth's surface reaches its minimum value at the mirror points in the polar regions. The mirror points occur at the same total magnetic field intensity at the north and the south ends of trajectory of a given particle (Gledhill, 1976).

Østgaard *et al.* (1999) compared the occurrence of lower energy precipitation observed in the UV imaging with the high energy precipitation observed in the X-ray imaging and noted that energetic electron precipitation concentrated at the poleward edge of the UV emission indicates higher energy precipitation in the polar regions.

2.5.2 Mid-latitude precipitation

At mid-latitudes, ions in the energy range 10-200 keV precipitate just inside the plasmapause from the ring current (Baker, 2004). The ions are anisotropic and have been observed down to an altitude of about 120 km (Foster *et al.*, 1997). The energy flux increases with magnetic activity from 10^{-7} to 10^{-5} J $m^{-2}s^{-1}$ (Foster and Rich, 1997). For disturbed conditions, the precipitating ions and neutrals are the primary source of nighttime ionisation at these altitudes and latitudes. Ring current ions interact with the outer edge of the plasmasphere, where they excite ion cyclotron waves. These waves lead to scattering of the ring current ions, which most likely produces the observed precipitation. Outside the plasmapause there is another region of ion precipitation, where the observed precipitating flux is more isotropic. The filled loss cone suggests that a mechanism for strong pitch angle diffusion exists in the outer magnetosphere.

There also exists some energetic magnetospheric electrons extending from mid-latitudes throughout the auroral zone (Baker, 2004).

Magnetic storms cause unusual magnetic depressions at equatorial latitudes and diffuse aurora moving toward low latitudes (Foster *et al.*, 1997). The diffuse aurora persist in the auroral latitudes almost continuously, but can be observed to be moving towards lower latitudes during the substorm periods.

Li *et al.* (2003) observed that magnetic and electric fields in the magnetotail can respond globally to the shock impact. This was shown by the fact that an enhancement in both the electrons and protons occurred almost simultaneously at satellites located at different local times, a phenomenon which suggested a global compression according to Li *et al.* (2003).

2.5.3 The South Atlantic Anomaly

At a certain location over the South Atlantic ocean, off the coast of Brazil, the shielding effect of the magnetosphere shows a dip. This is apparently the result of the eccentric displacement of the center of the Earth's magnetic field from the geographical center as well as the displacement between the Earth's magnetic and geographic axes (Sherrill, 1991; Haggard, 1994). The Van Allen radiation belts, which follow the magnetic field lines, are slightly off-center resulting in a weak surface magnetic field strength and hence reduced shielding effect of the magnetosphere over this region called the South Atlantic Anomaly (Sherrill, 1991). The Earth's magnetic and geographic axes are not aligned, and the magnetic and geographic equators are up to about 11 degrees apart. At Asian longitudes the magnetic equator is to the north of the geographic equator, whereas at American longitudes it is to the south.

The local bounce loss cone is strongest in this anomalous region (Benbrook *et al.*, 1983). This leads to the effect that the particles that are stably trapped outside the loss cone conserving the second adiabatic invariant tend to have lower mirror heights in this region, and hence can be more easily precipitated or lost. This results in significantly greater radiation intensity being encountered by Low Earth Orbit (LEO) satellites. Particles that the LEO satellites see outside the bounce loss cone in this region will mirror at high altitudes everywhere else on their drift trajectories, and thus can remain trapped for a long time. The extent of the South Atlantic anomaly increases with increasing altitude. The region of the South Atlantic anomaly is clearly indicated by the lowest magnetic field intensity over the South American continent and the South Atlantic ocean in Figure 2.2.

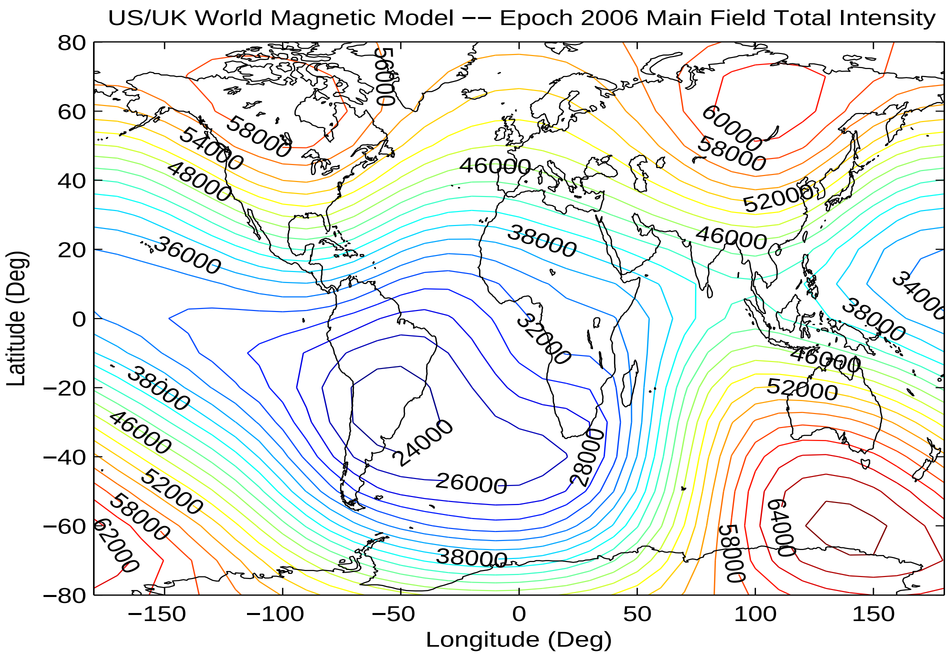


Figure 2.2: The geomagnetic field total intensity distribution represented by the iso-intensity lines over the globe. The lowest value of the total magnetic field intensity in nT defines the position of the center of the South Atlantic anomaly region over the coast of Brazil.

The trapped proton fluxes in the South Atlantic anomaly region are very penetrating and give rise to relatively high doses of radiation inside the spacecraft for low altitude spacecraft. The protons also contribute indirectly to single-event effects through proton-induced nuclear reactions (PINRs) (Holmes-Siedle and Adams, 2002). Bob and Thorne (1999) investigated the global pattern of the energetic particle precipitation. They found that precipitation fluxes are strongly correlated with variations in the loss cone boundary with localised maxima in the region of the South Atlantic anomaly. Vampola and Gorney (1983) observed a similar trend of electron precipitation using satellite data obtained at higher L-shells.

2.6 Observation of particle precipitation

2.6.1 Particle Precipitation Parameters

Particle precipitation is measured by observing enhancements in ionospheric electron density, conductivity, electron and ion temperatures and particle flux. Many observations show that the electron density and ion density values in the ionosphere are greater over the South Atlantic anomaly than at comparable places elsewhere, especially during magnetic disturbances (Galand, 2001). Higher ionospheric conductivities are also observed in this region (Galand and Richmond, 2001), which is attributed to observed particle precipitation. Electron and neutral temperatures are also higher than normal in this region (Gledhill, 1976).

The energy range of the measured particles is an important factor in particle precipitation observations. Particle detectors on satellites measure particles in specific energy ranges. The energy of the precipitating particles helps to determine the source of the particles and the region or layer of the ionosphere where the particles are likely to precipitate. The altitude of peak energy deposition is a function of energy with lower altitudes corresponding to higher energies. The average energy of the incident auroral flux is typically identified by means of an altitude-dependent loss mechanism. The altitude-dependent loss mechanism can translate into an energy-dependent loss mechanism since the altitude of peak energy deposition is a function of energy.

2.6.2 Instruments

Various kinds of instruments are used in particle precipitation observations and measurements. Many satellite and ground based missions are in place observing events of particle precipitation. These include the Polar Ionospheric X-ray Imaging Experiment (PIXIE) and the Ultraviolet Imager (UVI) aboard the NASA's POLAR satellite which were able to provide the first simultaneous global view of the patterns of electron precipitation (Østgaard *et al.*, 1999). The UVI responds to the total electron energy input and measures the lower energy UV emissions while PIXIE responds only to the high energy electron precipitation through the imaging of the high energy X-ray radiation.

The Polar Operational Environmental Satellite (POES), a polar-orbiting, Sun-synchronous, low-altitude satellite, has on-board the Medium Energy Proton and Electron Detector (MEPED) that monitors the intensities of charged particle radiation at higher energies extending up to cosmic rays (Galand and Evans, 2000).

The DMSP spacecraft are in polar Sun synchronous orbits (fixed in local time) sampling the ionospheric plasma at about 830 km. They have on-board sensors which include the SSJ4 precipitating ions and electrons monitor and the Special Sensor-Ions, Electrons, and Scintillation (SSIES) package used to monitor particle precipitation.

Ground-based instruments like Riometers measure the ionospheric absorption over a large field of view from which precipitation patterns can be derived, exploiting the fact that particle precipitation causes enhanced ionisation which leads to increased absorption of cosmic radio noise incident on the Earth (Wang *et al.*, 1994). A riometer is a set of highly sensitive, calibrated radio receivers which measure the signal strength of the weak radio signals received from the sky (Nashimo *et al.*, 1998). Observations can be made in various directions using an array of antenna elements.

Imaging riometers, usually placed in the polar regions, are used to visualise the spatial distribution of enhanced ionisation. Precipitating particles cause an increase in the ionospheric electron density and also generate enhanced auroral excitation, which eventually cause augmented absorption of cosmic radio noise incident on the Earth (Wang *et al.*, 1994). Although Riometer measurements can be used for monitoring particle precipitation, riometer data was not included in this work and, therefore, the reader is referred to the literature for more and detailed information (Detrick and Rosenberg (1990); Nishino *et al.* (2002); Wang *et al.* (1994) and http://www.spacenv.com/∼rice/riometer/USU/UnderstandingRiometers.htm).

The incoherent scatter radar can be used to detect the presence of particle precipitation although it cannot identify the type of the incoming particles (Galand *et al.*, 2003).

2.7 The Ionosphere

The ionosphere is the ionised region of the Earth's atmosphere lying between about 50 km and 1000 km. The ionosphere is coupled to both the magnetosphere and the neutral atmosphere, and it is of great practical importance due to its effect on radio waves. It is divided into two major sections, the bottomside (50-400 km) and the topside (above 400 km).

Ionisation characteristics appear at different ionospheric levels, producing layers or regions which may be identified by their interaction with radio waves. These layers are known as the D-, E-, and F-layers, and their locations are shown in Figure 2.3. These layers refract High Frequency (HF) radio waves, and are therefore important for HF propagation studies. The major source of ionisation is the electromagnetic radiation from the Sun (Baker, 2004). The processes of photoionisation and recombination break molecules apart resulting in the presence of electrons and molecules which have lost electrons. Electromagnetic radiation from the Sun at ultraviolet wavelengths (100 to 1000Å) ionises the F-region, which lies within the altitude range of about 150 km to about 400 km. The F-region can have two layers during the day; the F1 and the F2 layers. At night the two F-Layers combine into the F-region which refracts lower HF radio waves (10-15 MHz) not absorbed by the D- and E-Layers. The daytime F2-Layer lies between about 250 km and 400 km, and is the major ionisation layer for HF propagation. The F-region refracts much higher frequencies than the layers below it. The highest frequency refracted by the F-region is the maximum usable frequency (MUF).

The D-Layer is closest to the Earth's surface and lies between about 50 km and 90 km. It is ionised during the day, mostly at noon, and quickly deionises at night. It is ionised by hard X-ray radiation from the Sun at wavelengths (1 to 10Å). This lower layer absorbs lower frequencies (below 10MHz) and allows higher frequencies to pass to outer layers.

The E-Layer is ionised by soft X-rays with wavelengths in the range (10 to 100Å). It lies between about 90 and 150 km and is ionised only during the day like the D-layer. Photoionisation and recombination processes occur more slowly in the E-layer than in the D-Layer. Higher HF frequencies that would penetrate the D-Layer are refracted by the E-layer. For further background on the ionosphere, the reader is referred to (McNamara, 1991).

2.7.1 Ion density variations

The ionosphere can generally be considered as a series of horizontal layers that vary with time and geographical location. The real ionosphere however, does not always conform to this simple description, particularly in the equatorial and polar regions where some anomalies exist. To characterise its behaviour, the ionosphere can be divided into: the equatorial, the mid latitude and the polar regions, with the mid latitude region being the 'best behaved' and easier to study, while the polar and equatorial region ionospheres are both subject to a wider range of unexpected behaviour. The different zones of the ionosphere are characterised by different ionospheric conditions the major cause of this being the Sun. These variations in the

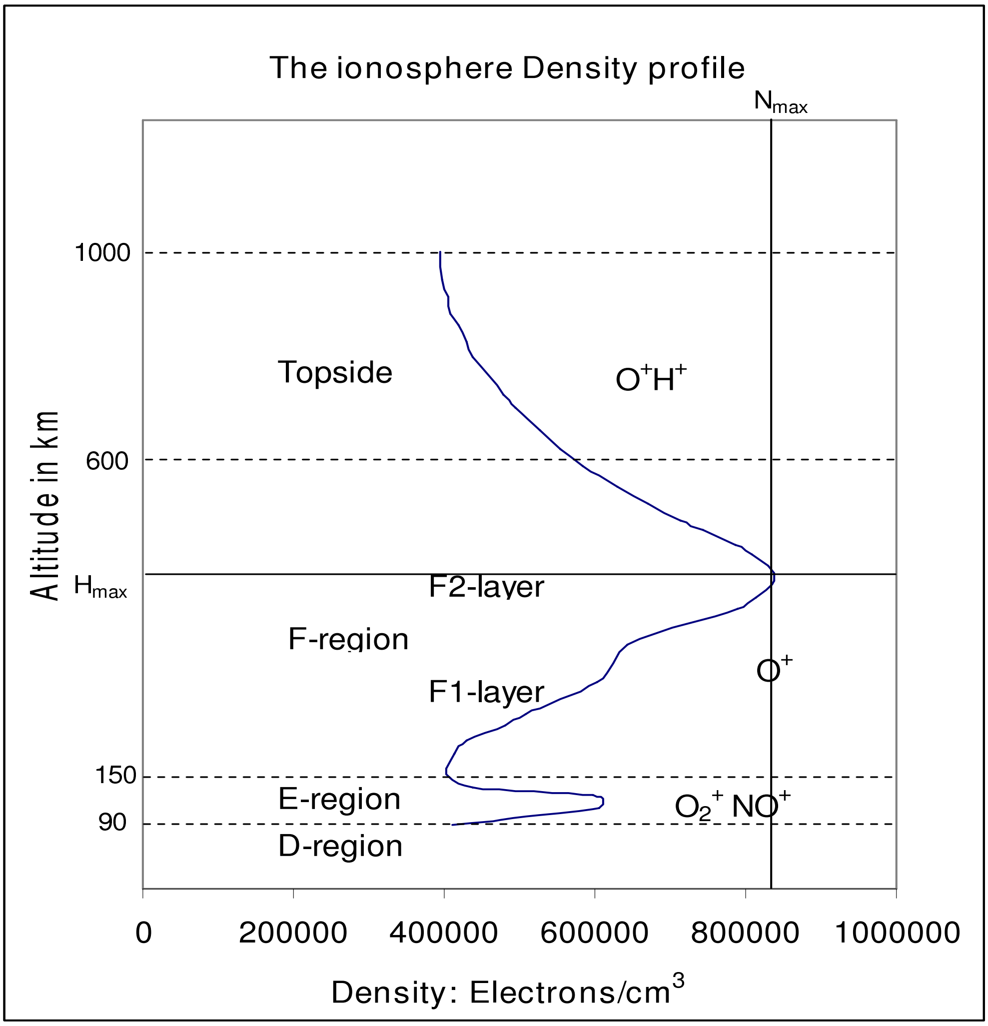


Figure 2.3: The ionosphere. A typical electron density altitude profile, the most important ions, and the various ionospheric layers. From http://www. dcs.lancs.ac.uk/ iono/ionosphere_intro/

ionosphere is a result of the fact that the Sun is directly overhead in the equatorial region with the incident Sun rays almost perpendicular to the surface of the Earth. Ionisation is higher in the equatorial region than in the mid-latitude and the polar regions, where the polar ionosphere is less dense due to higher zenith angle (Appleton, 1946; Balan and Bailey, 1995; Townsend, 1982; Kelly, 1989).

2.7.2 Enhanced ionisation

The structure and variability of the ionosphere are not only controlled by the solar radiation, but also by other solar dynamics (Callis *et al.*, 1991a) like the solar wind and its embedded magnetic field, and also by the Earth's magnetic field.

There are events of enhanced energy input and ionisation whose major source is the energetic particles from the Sun and the magnetosphere precipitating into the ionosphere. The particles trapped in the radiation belts interact with the neutral particles in the atmosphere. This is most prevalent near the mirror points in the polar regions where the trapped particles reach their closest approach to the surface of the Earth. Particles with energies that range from hundreds of eV to several thousand keV deposit energy flux into the ionosphere and the thermosphere. The particles lose some of their energy to the molecules producing such effects as excitation, ionisation, dissociation and subsequent emission of radiation and heating. The density of the neutral atmosphere is negligible at great heights but it increases as the altitude decreases. There is much more ionising radiation at great heights in the Earth's magnetosphere than at the Earth's surface but, there are much less neutral particles to ionise at great heights.

2.7.3 Coupling of neutral atmosphere, ionosphere and magnetosphere

The space around our atmosphere is alive and dynamic because the Earth's magnetic field reacts to changes in the solar wind. The interaction between the solar wind and the plasma of the magnetosphere acts like an electric generator, creating electric fields deep inside the magnetosphere. These fields in turn give rise to a general circulation of the plasma within the magnetosphere and accelerate some electrons and ions to higher energies.

The magnetosphere is coupled to the ionosphere via magnetic field lines. Magnetospheric electric fields map down to the ionosphere, creating plasma convection, frictional heating and plasma instabilities. The coupling is also important in driving neutral atmospheric waves that affect the state and the dynamics of the ionosphere significantly. The response of the ionosphere to the neutral atmospheric waves is driven by the Earth's magnetic field and the ionosphere, since the free electrons cannot be driven across the field lines (McNamara, 1991).

2.7.4 Ionospheric irregularities

Solar disturbances produce prompt and delayed effects at Earth (Buonsanto, 1999). The clouds of energetic particles ejected from the Sun and carried in the solar wind envelope the Earth's magnetosphere and can generate irregularities or increase the frequency of their occurrence in the ionosphere. Mangalev *et al.* (1994) found that energetic particles precipitating in the cusp region are able to influence the spatial distribution of the ionospheric parameters in the E and F regions. This section highlights some ionospheric irregularities that occur in the ionosphere.

F-region

The nighttime ionisation within the F-region does not always remain a uniform homogeneous sea of electrons. It is rather broken up into small bunches of electrons known as field-aligned irregularities, which are stretched out along the lines of force of the Earth's magnetic field as soon as they are created. The irregularities are stretched in this way because the electrons can only move freely up and down the lines of force and not across them. When these irregularities are present, a single pulse reflected from the ionosphere will be spread or stretched in time such that echoes arrive with time delays longer than those normally observed. Such scattered echoes can be observed in the F-region on ionograms and are termed spread-F (McNamara, 1991). Spread-F can be described either as range-spread if the echoes are stretched in range, which is equivalent to stretching in time, or frequency spread for broadening of the trace marking reflections from the ionosphere along the frequency axis. The spreading in the case of frequency spread is at the critical frequency such that the frequency is no longer a simple frequency but covers a range of frequencies. At mid and low latitudes, spread-F occurs mostly at night while at high latitudes it occurs even during day time.

E-region

The E-region is sometimes patched up with clouds of relatively high electron density that are a few kilometers thick and a few hundred kilometers across, occurring at altitudes between about 90 km and 130 km. These patches affect radio wave propagation significantly and they appear sporadically. They are named sporadic *E*-layers, denoted as Es. The Es-layers are characterised by two frequencies, foEs and fbEs. The foEs is the maximum frequency of radio waves reflected by the Es-layer, while fbEs is the blanketing frequency representing that frequency to which the Es-layer is not transparent for sounding radio waves, i.e.: the frequency to which the Es-layer screens the overlying ionosphere. The value of fbEs corresponds to the background ion density.

Es-layers can be classified into high latitude Es, mid latitude Es, low latitude Es and equatorial latitude Es depending on where they occur. The maximum electron density of Es varies with time of day and season, which is different at different latitudes. Mid latitude sporadic E-layers are essentially a daytime summer phenomenon (McNamara, 1991).

Occurrence of a sporadic E-layer prevents the high frequencies normally reflected in the F-layer from propagating to the F-region heights. The Es layers have a screening effect such that they reflect signals which would otherwise have gone up to the F-layer. To radio waves, they often look like good quality mirrors. Precipitating particles with energies between 2 keV and 40 keV can significantly enhance E-region ionisation and lead to increased occurrence of sporadic E-layers.

Thermospheric winds

The thermosphere is the region of the Earth's atmosphere lying above 100km in which the ionosphere is embedded. Winds blow in the thermosphere just like at sea level and as they blow, they attempt to drag the ionosphere with them. These winds have various effects on the dynamics of the ionosphere. The ionosphere at a specific location depends on the neutral winds which are blowing in the thermosphere at the time. Day to day changes in the winds at a particular time and place is one cause of diurnal variability of the ionospheric parameters, such as foF2 in the observed ionosphere.

During severe geomagnetic disturbances rapid influx of charged and energetic particles into the ionosphere occurs and the ionospheric irregularities can be enhanced in amplitude. Strong ionisation gradients and Travelling Ionospheric Disturbances (TIDs) are often correlated with the development of geomagnetic storms.

Enhanced energy inputs into the auroral region ionosphere such as during particle precipitation events can lead to the creation of TIDs in this region. The variable energy inputs due to the energetic particles precipitating in the auroral region cause substantial frictional heating in the E-region, where energy exchange between plasma and neutral particles maximises. This alters the lower thermospheric composition and neutral winds (Buonsanto, 1999). If the heating is impulsive, TIDs can be launched (Roble, 1992). TIDs are wave like motions of the ionosphere attributed to the passage of waves through the neutral atmosphere and coupling between the ionosphere and the neutral atmosphere. They lie within a class of waves called acoustic-gravity waves which are formed if the frequency of the wave motion is lowered towards the buoyancy frequency, such that the gravitational potential energy becomes as important as the compressional energy and the kinetic energy (McNamara, 1991). Particularly, and most important with the TIDs, is a branch within the acoustic gravity waves known as internal gravity waves which carry energy upwards from the lower atmosphere into regions of lower gas density. Since there are fewer molecules at higher heights, the waves oscillate with increasing amplitudes and carry their energy onwards, thus the waves grow larger and rise above the source (McNamara, 1991).

2.7.5 Importance of understanding the state of the ionosphere

As technology is advancing, the Earth is becoming more dependent upon systems that are vulnerable to damage from solar storms. Ionospheric activity, in a complex response to solar wind drivers, can lead to natural environments that are harmful to modern support systems.

Ionospheric storms may induce damaging currents into electric power grids causing electric blackouts. The high energy particles can also cause damage to satellites and increase the risk of radiation exposure to humans in high altitude spacecraft. In addition to operational interference, satellites can suffer physical damage from solar storms. The ability to predict major solar storms can give the concerned companies and organisations sufficient lead time to implement preventive measures. Although contingency strategies cannot disarm a major geomagnetic event, they can significantly lessen its impact. Advance warning of storms can also, in principle, allow communication companies to notify their customers that a lapse in service may be imminent and estimate how long the lapse might last.

Free electrons in the ionosphere alter the speed of electromagnetic waves propagating through it. Ionospheric propagation occurs when HF radio waves are refracted by the various layers of the Ionosphere and returned to Earth.

In satellite communications, it is important to understand which frequencies the different layers of the ionosphere absorb or refract, and which kind of radiation makes them absorb or refract various frequencies. Any irregularities in the ionosphere can cause variabilities in the reflectivity and refractivity of the ionosphere, which affects communication and navigation systems using radio signals transmitted to and from satellites.

Ionospheric irregularities also produce phase fluctuations that may cause a significant degradation of radio signals leading to the loss of signal lock that needs to be maintained for navigation signals (Basua *et al.*, 1999).

Chapter 3

Data description and analysis

3.1 Introduction

This chapter presents a description of the data used in this study. It also describes the procedures and methods undertaken to investigate the occurrence of particle precipitation in the South African region and to determine the influence that the energetic particles precipitating in other regions would have on the ionosphere over South Africa. Two data sets were employed in this investigation. The first data set used is from the F13 satellite of the Defence Meteorological Satellite Program (DMSP). The second data set consists of measurements made with the ionosonde at Grahamstown, South Africa ($33.3^o S, 26.5^o E$).

3.2 DMSP Data

The interest in the DMSP data in the context of this study lies in the energy of the particles that the detectors on these satellites are designed to monitor. Particles of different energy deposit most of their energies at different levels in the atmosphere. It is approximated that electrons with energy less than 2 keV lose most of their energy in the F-region, and those with energies between 2 keV and 40 keV lose their energy in the E-region, while those with energies greater than 40 keV deposit their energy in the D-region (Gledhill, 1976). Levels of maximum loss of energy for protons lies a little higher than for electrons of the same energy due to the larger cross-sections, although the differences are negligibly small. Investigating the effects and ionisation density changes in the E- and F-regions requires knowledge of the fluxes and energy of both electrons and protons with energies below about 40 keV. The DMSP satellite data provide a complete energy spectrum of low energy particles with energies in the range 30 eV-30 keV.

The particles monitored by the DMSP satellites include, among others:

- The low energy electrons (10-1000 eV) originating near the plasmasheet responsible for occurrences of low-latitude aurora, a storm time phenomena. These particles can enter the lower thermosphere and cause optical emissions at mid and low-latitudes (Robinson *et al.*, 1985). The low-latitude aurora can be seen in different forms which include; SAR arc, type d, type A, neutral atom and ion proton aurora (Rassoul *et al.*, 1993). The low energy electrons produce O(1D) (630.0 nm) oxygen emissions which are located at altitudes higher than 200 km to about 1000 km, within which the F-region lies. Type A red aurora is capable of ionising ionospheric plasma at about 400 km altitude and is produced by a burst of intense energy flux of low energy (about 30 eV) precipitating electrons lasting only about 5-10 minutes.

- Solar energetic particles (electrons and protons) trapped in the radiation belts precipitating in the auroral and South Atlantic anomaly regions. The precipitation of electrons originating from the magnetosheath near the cusp region results in the high latitude dayside aurora which also exhibit the 630 nm red emissions.

The DMSP satellite program also offers the advantage of global coverage by making near polar orbits roughly 14.1 times a day for each satellite. Since the number of orbits per day is not an integer, the sub orbital tracks do not repeat on a daily basis, although the local solar time of each satellite's passage is essentially unchanged for any latitude. The DMSP satellites are in different orbital orientations with the F12, F14 and F15 being nearly co-orbital in the general morning-evening meridional plane, while the F13 has a dawn-dusk orbit, and the orbit of F11 is in between these two planes (Boundouridis *et al.*, 2005). The orbit orientations allows them to monitor the occurrence of particle precipitation even at mid and low latitudes where South Africa lies, and gives a wide coverage of the polar regions.

Each satellite in the DMSP series carries a suite of instruments to measure several geophysical parameters of the Earth's atmosphere along the satellite's orbit, i.e. cloud cover, incoming solar protons, positive ions, electron-flux density, and the energy spectrum at the satellite altitude.

DMSP satellites are launched in a near polar, sun-synchronous orbit at a nominal altitude of about 830 km. They sample the ionospheric plasma at this altitude, monitoring the solar terrestrial environment, and provide global coverage. These satellites cover the entire polar region at least twice, and the equatorial region once a day (Ashrafi *et al.*, 2005). The F13 satellite orbit is approximately in the 05h45-17h45 local time (LT) orbital plane (Boundouridis *et al.*, 2005). The orbital period is around 101 minutes, which gives about 14.1 orbits a day, each separated in longitude by about 25 degrees (Venkatraman and Heelis, 1999).

The DMSP satellites carry instruments to measure several geophysical parameters along the satellite's orbit. The instruments include among others, the Special Sensor Ions, Electrons and Scintillation (SSIES) monitor (Venkatraman and Heelis, 1999) and the Special Sensor precipitating ions and electrons monitor (SSJ/4).

Most of the information in the following two sections was researched using the internet. Credit is given to the following websites:

http://www.ferzkopp.net/Personal/Thesis/node28.html

http://cindispace.utdallas.edu/DMSP/

http://www.ngdc.noaa.gov/ngdcinfo/onlineaccess.html

http://www.ngdc.noaa.gov/dmsp/sensors/ssj4.html

3.2.1 SSIES ion density

The SSIES package consists of four instruments: Langmuir Probe (LP), Retarding Potential Analyser (RPA), Ion Drift Meter (IDM) and Scintillation Meter (SM) (Heelis *et al.*, 1978). This package was built at the Centre for Space Sciences at the University of Texas in Dallas, and the data from this instrument is processed there.

The RPA and the IDM are variants of Faraday cups facing in the direction of the spacecraft, and are mounted on a metal plate which is held at the same potential as the ambient plasma.

The RPA measures the ion flux entering the instrument as a function of the retarding positive potential applied to the incoming ions. From this information, the RPA can measure the thermal ion flow speed in the direction of the spacecraft (Vx), the ion temperature (Ti) and the H+, He+ and O+ fractional composition of the plasma (fH+, fHe+, and fO+).

The IDM measures the cross-track horizontal ion flow (Vy) and vertical flow (Vz). These measurements are obtained by comparing the differences in the ion currents falling on the detectors. Since the geometry of the instrument is known, the arrival angles of the ions and hence the cross-track velocities of the plasma are deduced (Heelis *et al.*, 1978).

The scintillation meter (SM) measures the ion density of the plasma (Ni) by measuring the total ion current entering the Faraday cup, and this measurement serves as a check on the ion density measurements made by the RPA.

From the SSIES package, the following parameters were use in this study: the three components of the plasma bulk flow (Vx, Vy, Vz), the plasma density (Ni), the fractional composition of the plasma (i.e. percentages of H+, He+ and O+), the ion and electron temperatures (Ti and Te), as well as the time and location of the spacecraft in geographic and geomagnetic coordinates at a 4 second resolution.

The DMSP SSIES data simply produces, from the above mentioned parameters, a measure of the ion density in the ionosphere. This gives the level of ionisation of the ionosphere at the given time and location at the satellite's orbit. The main cause of ionisation is the far ultraviolet (FUV) radiation from the sun. The equatorial region receives the highest intensity of radiation compared to the polar regions due to the difference in the angle of incidence of the radiation, which is about 90^o around the equatorial region and is much smaller approaching 0^o in the polar regions.

3.2.2 SSJ/4 energetic particle flux

The SSJ/4 sensor, a precipitating Electron and Ion Spectrometer, was built by the United States Air Force (USAF) Research Lab and Space Vehicles Directorate. It was designed to measure the flux of charged particles as they enter the Earth's upper atmosphere from the near-Earth space environment. The DMSP satellites are three axis stabilised with particle detectors configured to point toward local zenith (Hardy *et al.*, 1985). The SSJ/4 detectors consist of four curved plate electrostatic analysers which measure the flux of charged particles with energies between 30 eV and 30 keV as they flow past the spacecraft towards Earth. The shape and orientation of the detectors allow precipitating electrons and ions to enter through an aperture with an 8^o field of view (Hardy *et al.*, 1984). Electrons and ions of the selected energy are deflected towards the target by an imposed electric field applied across the two plates. Two of the four electrostatic analysers are low energy (30 eV - 1 keV), and the other two are high energy (1 keV - 30 keV).

Each pair of high and low energy detectors consists of 10 logarithmically based energy channels which sample a portion of the energy range for a given time, such that in every second a complete spectrum over the entire energy range is produced (Hardy *et al.*, 1985).

The data from the SSJ/4 detector therefore consists of electron and ion fluxes between 30 eV and 30 keV recorded every second, giving a complete energy spectrum of the low energy particles that cause the aurora and other high latitude phenomena. The measured spectra are the average of the real spectra within the loss cone at the DMSP spacecraft altitude. Processing of the SSJ/4 archive data occurs onboard the satellite and at the National Geophysical Data Center (NGDC). The data is compressed for transmission purposes, i.e. from satellite to ground station, . At the NGDC the compressed data received from the Air Force Weather agency (AFWA) is decommutated, deinterleaved, edited, reordered and restructured. The resulting counts are converted into differential number flux in units of particles $cm^{-2}s^{-1}sr^{-1}eV^{-1}$. The differential number flux is the number of particles crossing a unit area from a unit solid angle per second at each energy level. The parameters relevant for this project are the number flux and the energy flux. The number flux (Nf) is derived by integrating the differential number flux across all energies. It is a measure of intensity and is independent of the energy, i.e. the number of particles crossing a unit area from a unit solid angle per second regardless of the energy.

Similarly, the differential energy flux is the amount of energy crossing the same unit area from a unit solid angle per second at each energy level, which when integrated across all energy levels, gives the energy flux (Ef). In other words, Ef is the total energy crossing a unit area from a unit solid angle per second. Dividing the energy flux by the number flux gives the average energy of the particles i.e. $< E >= \frac{Ef}{Nf}$.

3.3 Ionosonde data

The ionosonde observations provided the data to build a picture of how the ionosphere over the South African region would respond to particle precipitation.

Remote sensing by radio waves is a technique widely used to study the state and the structure of the ionosphere, which has provided much of today's knowledge of the ionosphere. Vertical sounding ionosondes use this technique for recording ionospheric behaviour.

An ionosonde is a pulsed radar device that sends a sweep frequency to the ionosphere and measures the time delay of the returning signal, which gives the virtual height of reflection of the signal within the ionosphere (Hunsucker, 1991). The ionosonde produces an ionogram, Figure 3.1 and Figure 3.2, which shows the variation of the virtual height of reflection with frequency for a vertical sounding. The virtual height is the height of reflection of the transmitted radio wave given that the wave travelled at the speed of light. The real height of reflection therefore would be less than the virtual height. At reflection the plasma frequency is equal to the vertically reflected radio frequency. An ionogram usually displays two traces, the

O- and the X-mode (Liu *et al.*, 2004). The greatest frequency on the O-mode trace is considered to be the penetration frequency of the ionospheric F2 region and is called foF2. In this study the ionograms, the foE and the foF2 recorded during the chosen events using the ionosonde at Grahamstown ($33.3^oS, 26.5^oE$), South Africa were examined.

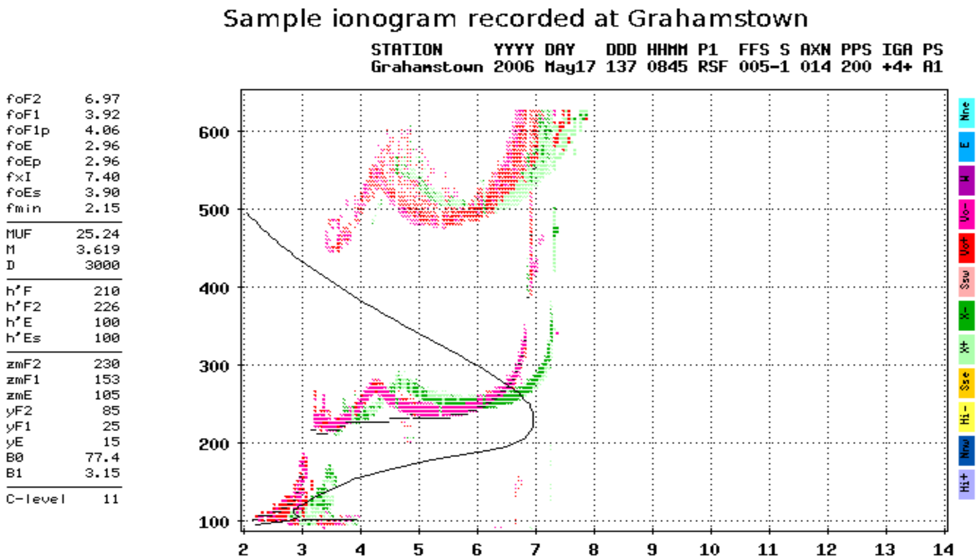


Figure 3.1: An ionogram, a graph of height of reflection of the transmitted signal against transmitted frequency. Each ionospheric layer shows up as an approximately smooth curve (upwardly curving sections).

The ionosonde data used in this study was downloaded from the Space Physics Interactive Data Resource (SPIDR) website;

http://spidr.ngdc.noaa.gov.

SPIDR is a distributed network of synchronous databases designed to allow solar terrestrial physics researchers and customers to access space physics data. It was developed by the National Geophysical Data Centre in Boulder (Conkright, 1999) to facilitate the archiving and exchange of reduced data.

3.4 Data analysis and procedure

3.4.1 Precipitation events

The first step undertaken in probing the effects of particle precipitation on the ionosphere over South Africa was to investigate the occurrence of particle precipitation

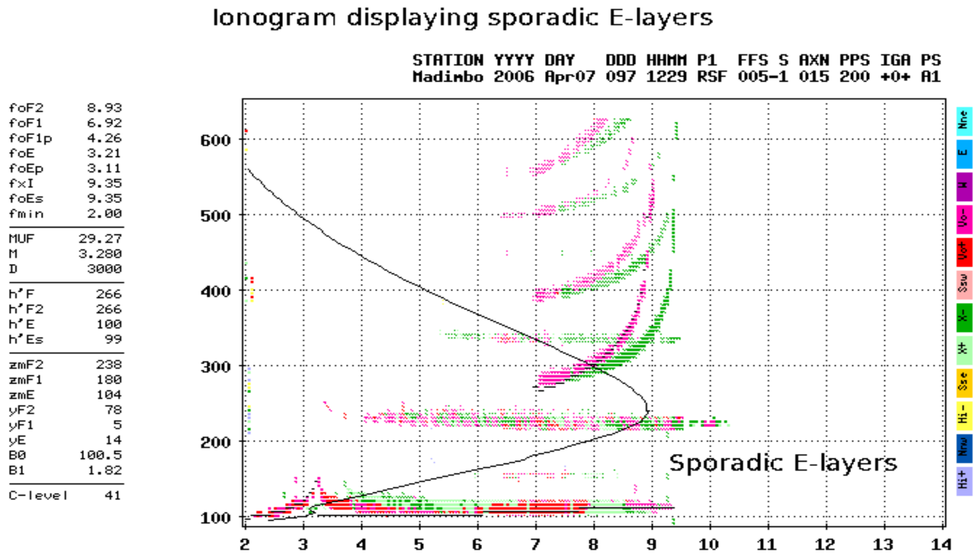


Figure 3.2: An ionogram recorded at Madimbo displaying sporadic E-layers irregularities

over this region. DMSP SSJ/4 particle flux measurements were used to identify and locate the regions visually where particle precipitation occurred.

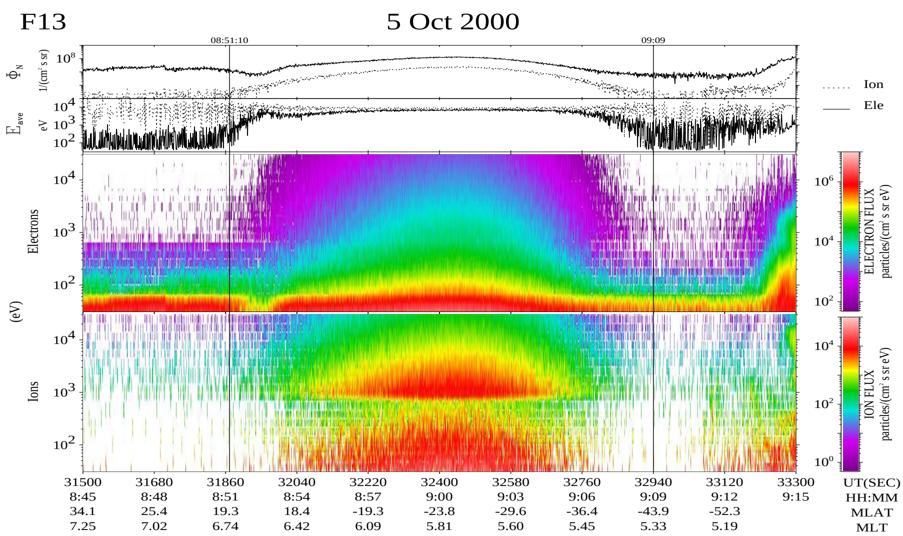


Figure 3.3: This is a typical plot of the DMSP particle flux measurements. It shows a region with higher radiation intensity of energetic particles bordered by the vertical lines.

Figure 3.3 presents an overview of the data from the particle spectrometer (SSJ/4) for the morning of October 5, 2000. The top panel is a plot of the number flux (y-axis) as a function of time (x-axis) for an interval of 30 minutes. The satellite flew between $34^o N$ and about $52^o S$ during this period. The dotted and the solid lines indicate the protons and the electrons respectively. The values for the line plots were obtained by integrating data across all energies. The second panel from the top is the average energy $< E >$ of the particles, dotted line for the protons and solid line for the electrons. The colour spectrogram (the two bottom panels) show the number flux from all the energy channels between 30 eV and 30 keV (y-axis) as a function of time (x-axis) for the electrons and protons as indicated on the figure.

The DMSP SSJ/4 particle flux data can be downloaded from the National Geophysical Data Centre, Solar Terrestrial Physics Division, Earth Observation Group (NGDC/STP/EOG) website:

ftp://ftp.ngdc.noaa.gov/STP/DMSP/data/purchase_1/. Data files from this website are in ASCII format. The NGDC/STP/EOG provides scientific stewardship and services for geophysical data from various satellite missions and projects. Similar data is also provided by Fredrick Rich, (Rich and Foster, 1998), on-line in plot format for selected events, and the complete data files are available upon request. The data for this study, was provided by Fredrick J. Rich.

Each data file contained unformatted binary data sampled at one second intervals from one satellite for all the approximately 14 orbits of a single day. The data files also provide the satellite ephemeris and magnetic coordinates where the precipitating particles are likely to be absorbed by the atmosphere. This data is compressed and unprocessed.

Most providers of satellite data do quality control on their data to ensure that it is refined, cleaned up and good for public use. F. J. Rich provided an IDL program with the data, which can also be found at the AFRL/VSB anonymous ftp site (Ridley, 1994). The program was developed by Aaron Ridley in 1994, additions and modifications were made to it by Jean H. James in 1995 and F. J. Rich from 1998 to 2004. The program reads the unformatted binary data files, computes the parameters described in section 3.2.2 and does the quality control. It outputs ASCII data files and plots such as the one given in Figure 3.3. The details of the program and how it can be used are given in Appendix A.

A comprehensive study was done on two events (April 7, 2000 and October 5, 2000). Particle precipitation is indicated by higher values of average energy and intensity of the detected particles. Although, strictly speaking just observing a particle flux at DMSP altitude (830 km) does not mean that there is necessarily precipitation. Precipitation only occurs where the local pitch angles of the particles are low enough such that the particles mirror far enough below the satellite altitude to reach the denser atmosphere. Pitch angle scattering mechanisms, mainly due to wave-particle interactions with chorus waves, can scatter particles to lower pitch angles, and the scattered particles can thus bounce to lower altitudes. Since often the pitch angle distribution goes up and down as a whole, by measuring locally mirroring particles and their increases, it is fairly safe to assume that in regions where the satellite encounters higher intensities of particles with higher average energies, the intensity of the precipitating ones increase too. Thus the assertion that the intensities and average energies of the measured particles in a region such as the one bordered by the vertical lines in Figure 3.3 indicate the presence of particle precipitation is based on this assumption.

The data was examined for any indication of particle precipitation over South Africa during the two events.

Particle precipitation observed in the polar and the South Atlantic anomaly regions could cause significant changes in the structure and dynamics of the South African ionosphere, since the two regions are nearby.The sections that follow, describe the procedures implemented to investgate connections that could exist between particle precipitation in the two regions and ionospheric changes in the South African region.

3.4.2 Ionisation effects

The DMSP SSIES ion density measurements indicated that the ionisation level at altitudes where the satellite orbits, in the South Atlantic anomaly region, was generally higher during the periods when there was particle precipitation, as shown in Figure 3.4. The strong density enhancements could be attributed to particle precipitation. These ionisation measurements were used to examine the correlations between particle precipitation (indicated by enhanced ionisation) and the geomagnetic and solar activities. The DMSP SSIES data is described in section 3.2.1 and can be downloaded from the following website:

http://cindispace.utdallas.edu/DMSP/dmsp_data_at_utdallas.html.

The on-line datasets provide what is called “level-1” and “level-2” data. “Level-1” data are the data with little or no checking or refining of the data. “Level-2” data have been cleaned up, checked, all the bad data either corrected or removed, and all the on-line data have been approved as valid and error free. Every four-second set of data is flagged with two quality flags (one for the RPA data and one for the IDM data) to provide the users with a guide on when to use and when to ignore the data. Each flag has one of four values:

1. means the data are good and can be used with high confidence

2. means the data are somewhat questionable and should be used with caution

3. means the data are bad and should not be used at all

4. means the quality could not be determined for these data and so should probably not be used or (depending on the circumstances) used with caution.

For this study, the data was received directly from the centre were it is processed and archived. The data files were received in Hierarchical Data Format (HDF) which can be read into Matlab. HDF is a data file format designed by the National Center for Supercomputing Applications (NCSA) to assist users in the storage and manipulation of scientific data across diverse operating systems and machines.

Each data file consisted of data points sampled at 4 second intervals for an entire orbit (northbound equatorial crossing to next northbound equatorial crossing). The files contained all three ion velocity components (Vx, Vy and Vz) and information about the densities of the various components (H+, He+, and O+) of the ionospheric plasma. They also contained temperature and data from the scintillation meter, (the

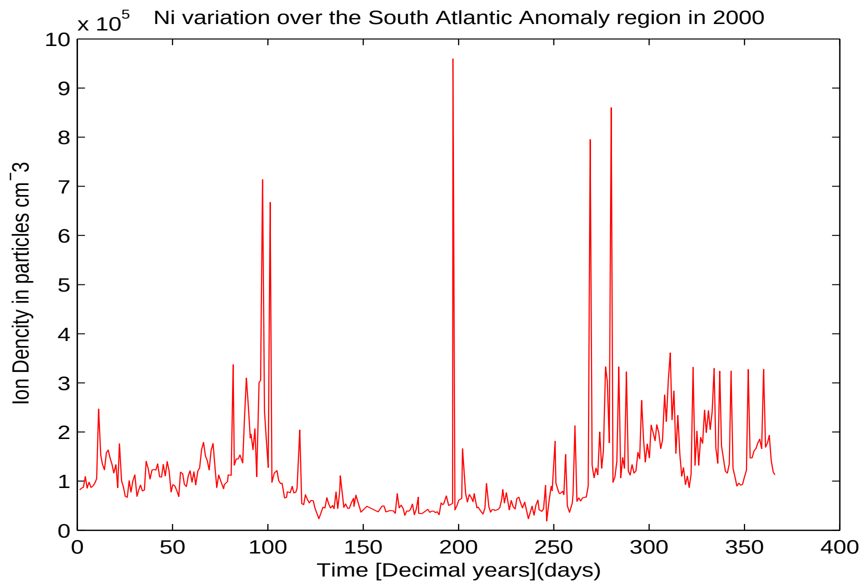


Figure 3.4: Ion density variation over the South Atlantic anomaly region during the year 2000. There are density enhancements during periods when there was particle precipitation in this region e.g. on day 200.

ion density), and also gave the satellite ephemeris in both geographic and magnetic coordinates.

During this study programs that perform different activities on the data were developed in Matlab. The first program reads the HDF data files and convert to Matlab or ASCII format. This program also generates quality flags similar to those given in the on-line data set. The quality flags are determined by considering the velocity components of the plasma and the ion and electron densities. Details of this procedure is provided in the program. The second program uses the Matlab or ASCII formatted data and plot the specified parameters. The user need to edit some lines in the program to specify the inputs i.e. location of the data, the parameters to plot and the region under investigation in terms of latitude and longitude. Depending on the format of the data, Matlab or ASCII, users must comment and uncomment appropriately as indicated and explained in the program.

Studying the condition and structure of the ionosphere and the changes that take place in a particular region or location using satellite measurements can be very complicated. The satellite is in motion and therefore does not observe the same region all the time. The satellite will only fly over a particular area within a short period of time, during which it is in view in that region. For example, the DMSP satellites fly across the South African region, (from about 21^S to 40^S latitude range), in approximately three minutes. The DMSP satellites, in sun synchronous orbits with an orbital period of approximately 101 minutes, monitor a particular region only twice per day, twelve hours apart, and each time the satellite may not fly over the exact longitude but will be shifted by a few degrees.

Data values for the South Atlantic anomaly region for each day are averaged to get the average ionisation over the region. Figure 3.4 shows the average ionisation over a period of one year i the South Atlantic anomaly. Similar analysis was done for the South African region and the results were compared.

3.4.3 Effects within the E and F-regions

Major effects of particle precipitation occur in the high latitude and the South Atlantic anomaly E- and F-regions of the ionosphere where particle precipitation is the main source of enhanced ionisation and conductivity. Spread-F and Sporadic E-layers are two kinds of irregularities that normally occur within the F- and E-region respectively. Particle precipitation increases their occurrence and magnitudes. These irregularities can be observed in ionosonde measurements given in ionogram form. Examples of these irregularities are given in Figure 3.1 and Figure

3.2.

Any significant correlations between these ionospheric irregularities in the South African ionosphere and particle precipitation observations in the South Atlantic anomaly and the auroral regions will indicate the effects that the particle precipitation in these two regions have on our region of interest.

Auroral precipitation is well known to produce traces of range spreading echoes of sporadic E-layers which can be observed even at mid latitudes (Abdu *et al.*, 2005). It is generally accepted, according to the shear-wind theory, that mid latitude sporadic E-layers are created when the thermospheric zonal wind interacts with the geomagnetic field ($\bar{u} \times \bar{B}$) (Whitehead, 1961) such that the vertical shear of the horizontal wind changes the vertical distribution of the ion (electron) density. This shear force acts in such a way that at the part of the electron density profile where the wind is in a West-East direction, the ions move upwards, and at the part where the wind has an East-West direction, they move downwards. Thus, a higher concentration of ions is found at the height where the zonal wind changes sign (Bencze *et al.*, 2004).

Particle precipitation in the South Atlantic anomaly can also result in the production of sporadic E-layers. Abdu *et al.* (2005) investigated the effects of the South Atlantic anomaly on the equatorial ionosphere. They observed that, during enhanced magnetic activity, sporadic E-layer frequencies, the top frequency backscattered by the layer, f_oEs, and the blanketing frequency, which indicates the plasma frequency of the reflecting layer, f_bEs, increase for events of a few hours duration, which suggested a corresponding increase in the E-layer ionisation. They noted oscillatory variations in the intensity of the sporadic E-layers. Their results are given in Figure 3.5, which suggests that particle precipitation in the E-region was the source of the enhanced ionisation responsible for the production of the sporadic E-layers.

Ionograms recorded at Grahamstown ($33.3^oS, 26.5^oE$), South Africa, were examined for any irregular variations of both the daytime and the nighttime foE (the penetration frequency of the E-region), in order check for an indication of any extra ionisation over South Africa which might be attributed to the particle precipitation observed in the South Atlantic anomaly and the auroral regions. Examination of the nighttime foE (E-region ionisation) was emphasised because the daytime E-layer peak is normally very high compared to nighttime ionisation, such that the response that may arise from particle precipitation effects may not be distinct enough to be observable.

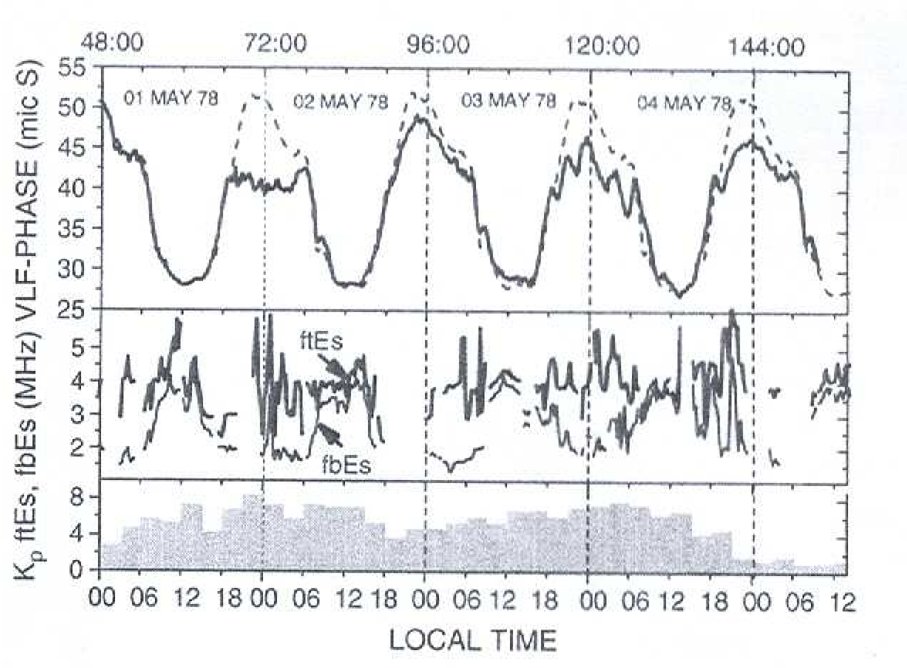


Figure 3.5: Taken from Abdu *et al.* (2005). Of interest, is the middle panel which shows the top frequency f_tEs reflected by the sporadic E-layer, whose plasma frequency is indicated by the blanketing frequency f_bEs. Oscillatory variations in the intensity of the Es are seen in the plot.

Evidence of extra ionisation due to particle precipitation in the South Atlantic anomaly region has been reported by Haggard (2004) and Abdu *et al.* (2005). Enhanced ionisation results in a corresponding enhancement of the ionospheric conductivity distribution pattern, which can then penetrate to low latitudes with magnetospheric electric fields. Solar wind pressure irregularities could aid penetration of zonal electric fields to low latitudes (Fejer and Emmert, 2003). When these disturbed zonal electric fields penetrate to low latitudes, under the presence of enhanced conductivities, they could affect the vertical plasma drift directly by causing the uplifting of the F-layer. If the F-layer uplift is in-phase with the normal vertical drift due to the pre-reversal electric field enhancement, this could help to trigger the development of spread-F irregularities during seasons when they do not normally occur, or can cause more intense spread-F during seasons of their normal occurrence (Abdu *et al.*, 2005). Bowman (1981) attributed the development and occurrence of spread-F to large scale travelling ionospheric disturbances that originate from the auroral region normally associated with particle precipitation.

The ionograms are examined to identify spread-F irregularities which may be due to the particle precipitation events. The electron density variation in the F-region during the selected events is examined in order to track the response of the ionosphere to the particle precipitation.

Chapter 4

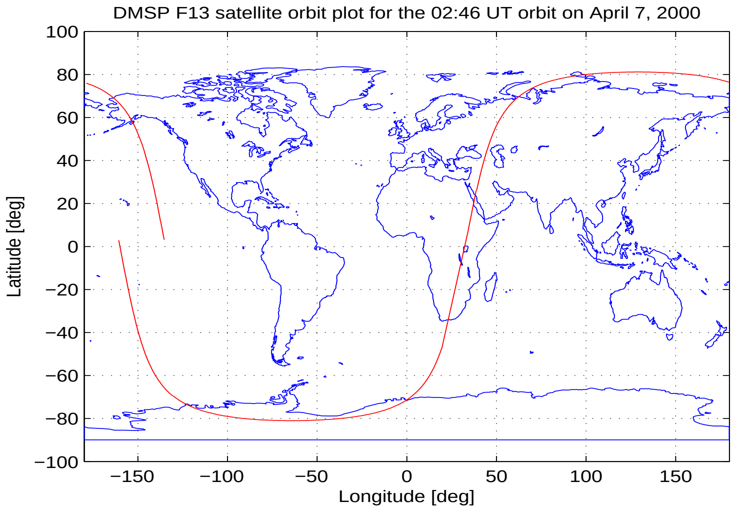
Results and Observations

This chapter presents the observations and the interpretations of the results that emerged from this investigation. First, the occurrence of particle precipitation over South Africa is investigated by comparing observations made in the South African region to those made in the South Atlantic anomaly region in order to determine if there is any evidence of particle precipitation over South Africa. Then the particle precipitation in the SAA and the Auroral regions is considered in order to investigate for any indirect effects such events would have in the South African region. Particle precipitation in the South Atlantic anomaly region is a well established phenomenon and the effects that the precipitating particles in this region have on the ionosphere within the region have been discussed in detail by the following authors: Haggard (1994); Gledhill (1976); Haggard (2004). Abdu *et al.* (2005) investigated the effects of particle precipitation in this region on the ionosphere in the low latitude regions.

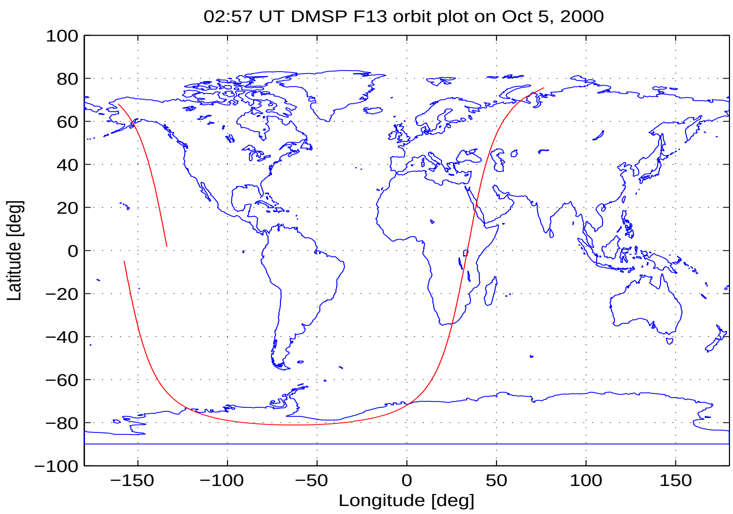
4.1 Particle precipitation over South Africa

Data from the DMSP SSJ/4 detector were used to investigate the occurrence of particle precipitation in the region over South Africa. Figures 4.1(a) and 4.1(b) are passes of the F13 satellite for which the satellite monitored the region over South Africa during the April 7 and the October 5 events respectively.

The number flux and the average energies of the electrons and the protons were plotted against time for the period of satellite flight over South Africa. Figures 4.2 and 4.3 corresponding to Figures 4.1(a) and 4.1(b) show plots of particle flux measurements for the identified events of April 7 and October 5, 2000 respectively. The figures indicate that the particle detectors on the F13 satellite did not encounter any energetic particles in the region over South Africa. As shown on the plots, there



(a) April 7, 02:46 UT F13 pass. Satellite monitored the South African region.



(b) October 5, 02:57 UT F13 pass. Satellite monitored the South African region.

Figure 4.1: DMSP F13 pass plots indicating that the satellite flew across the South African region during these passes. The time in UT in the titles indicate the first equatorial crossing time for the each pass.

is no indication of increases in intensity of particles and the average energies of the particles remained almost constant during the periods when the satellite was above the South African region. The periods of satellite overpass in the South African region are indicated by the vertical lines labeled "begin" and "end". The plots show that as the satellite went further south, it encountered particles with higher average energies, greater than $10^3 eV$, at magnetic latitudes above $56^0 S$ which indicate particle precipitation in the high latitude region. The plots show both colour spectrogram (the two bottom panels) and line plots (the two top panels). The spectrograms show the number flux from all the energy channels between 30 eV and 30 keV (y-axis) against time (x-axis) along the path of the satellite as it monitored the South African region through to the south pole. The line plots above the colour spectrogram are the ion and electron number flux, Φ_N (top panel), and average energy E_{ave} (2^{nd} panel from the top) (y-axis) against time (x-axis). The dotted and solid lines indicate the protons and electrons respectively. Also indicated on the plots are the magnetic local time (MLT) and the magnetic latitude (MLAT), which indicate the position of the satellite where the particle are sampled.

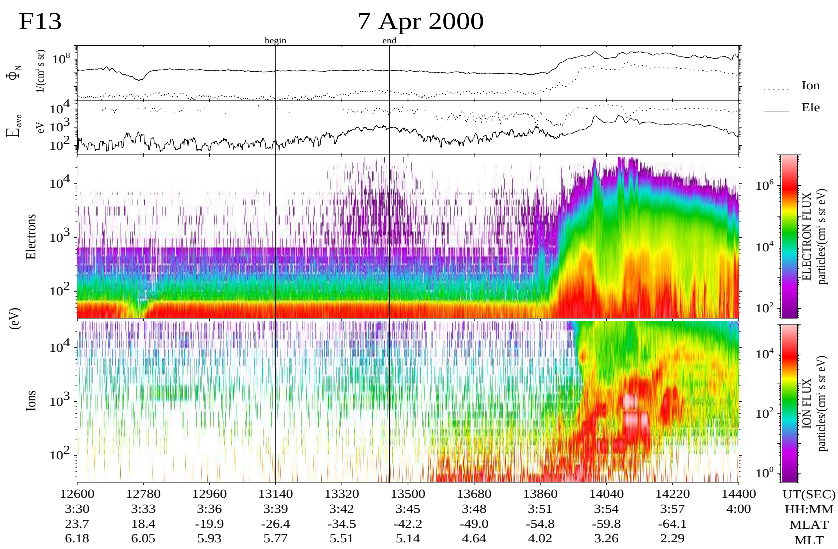


Figure 4.2: F13 DMSP satellite flew over South African region between 03:39 UT and 03:44 UT and monitored the auroral oval energetic particles at 03:51 UT, magnetic latitudes greater than 56

Figure 4.2 shows observations made during the April 7 event. Between 03:36 UT and 03:44 UT indicated by the vertical lines, the DMSP F13 satellite crossed South Africa. As the plot indicates, the SSJ/4 detector on the satellite did not detect any energetic particles during this period. The higher intensities of energetic particles were encountered starting at about 03:51 UT at magnetic latitude above $56^o S$ as it approached the equatorward edge of the auroral oval, a region where particle precipitation occurs with a predominance of energetic protons (Galand *et al.*, 2002).

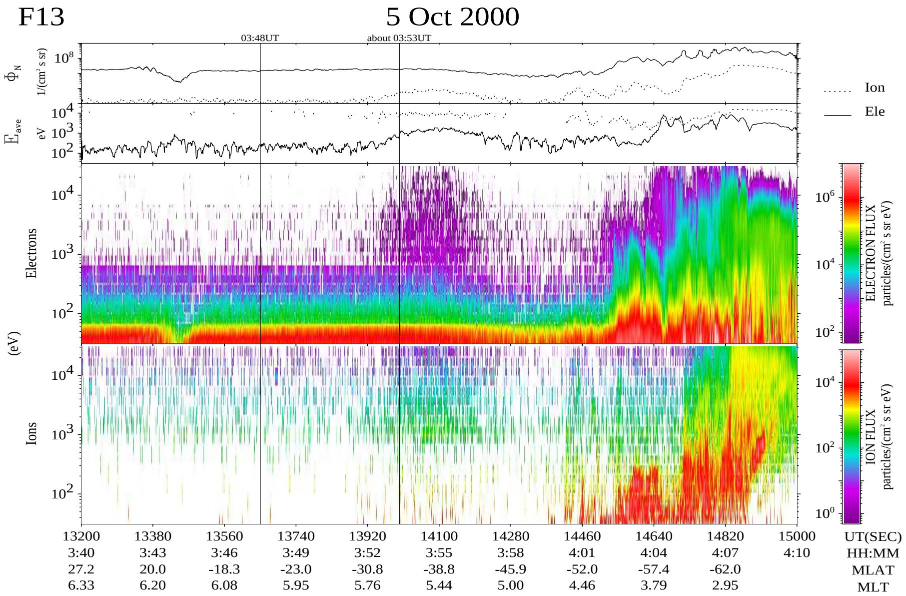
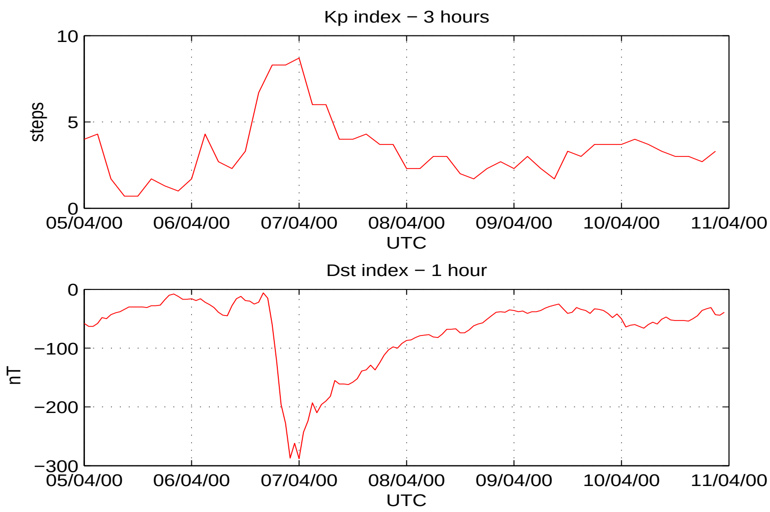


Figure 4.3: DMSP F13 SSJ/4 data showing the particle flux (top panel), the average energy of the electrons and of the protons (2^{nd} panel) and the colour spectrogram for electrons (3^{rd} panel) and ions (bottom panel) as a function of time in the x-axis for the event of October 5, 2000.

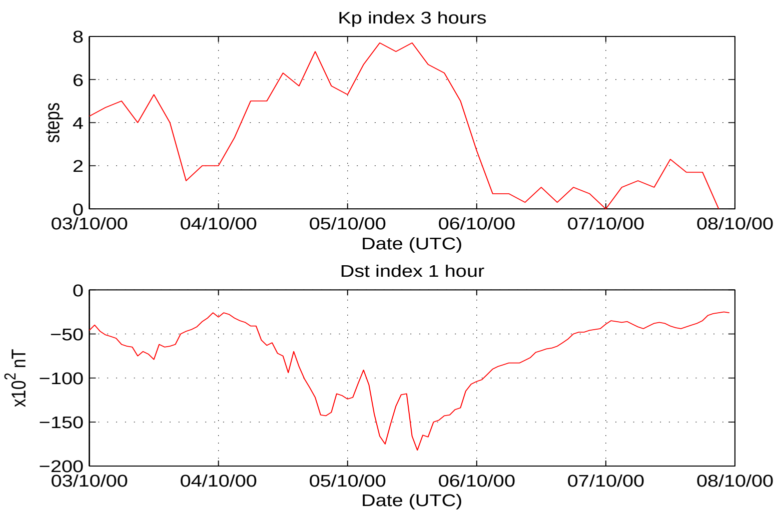
The vertical lines in Figure 4.3 indicate the period the F13 satellite flew over South Africa on October 5, 2000. During this period, the high latitude region was populated by energetic particles (protons and electrons) which the satellite encountered at latitudes greater than $56^0 S$.

The higher intensities of energetic particles observed during these events could be associated with solar wind disturbances which caused the high geomagnetic activities. The Dst and Kp indices shown in Figures 4.4(a) and 4.4(b) for the April 7 and October 5 events respectively indicate high magnetic activities during both events. On the April 7 event a magnetic storm which commenced during the last hour of 6 April occurred. The F13 satellite only flew near South Africa during the recovery period of this storm.

Similarly, October 5 was geomagnetically disturbed. Two successive magnetic storms occurred during the October 5 event within a 24 hour period. The first commenced on October 4 and the next commenced during the recovery period of the first one on October 5 at about noon UT.



(a) Dst and Kp indices from 5-10 April,2000



(b) Dst and Kp from 3-8 October, 2000

Figure 4.4: Dst and Kp indices indicating geomagnetic activity on April 7 (4.4(a)) and October 5 (4.4(b)) in 2000

These observations indicate that there were no energetic particles observed in the South African region during the these events. South Africa lies in the mid-latitudes region stretching to low latitudes where the surface magnetic field strength of the Earth is strong enough to prevent the trapped energetic particles and the incident solar particles carried in the solar wind from penetrating the magnetosphere to gain entry into the ionosphere. The magnetosphere effectively shields this region from most of the direct solar wind because charged particles do not readily travel across a magnetic field but are deflected at angles to the magnetic field.

4.1.1 The mechanism of energetic particle precipitation in the high latitude region

Although the magnetosphere shields the Earth from most of the direct solar wind, some solar wind plasma can travel along the Earth's magnetic field lines, leaking through the Earth's magnetic screen and follow the field lines toward the surface of the Earth (McNamara, 1991). The precipitating particles gain access into the Earth's ionosphere through the two funnel-like openings called the polar cusps which lie between the sunward magnetic field and the tailward magnetic field at the north and south poles (see figure 2.1). The leaking high-speed charged particles bombard the upper atmosphere and then interact with the neutral particles in the atmosphere, depositing significant amounts of their energy which cause various effects such as the observed auroral displays and enhanced ionospheric ionisation.

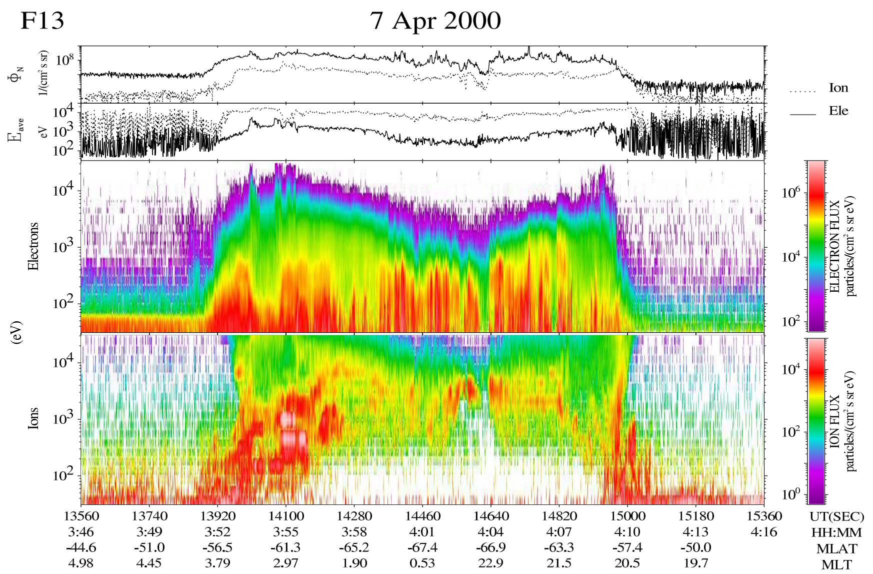


Figure 4.5: DMSP SSJ/4 Energetic particle flux along the path of the satellite as it crossed the Auroral zone at about 03:52 UT and encountered a sudden increase in intensity of energetic particles at magnetic latitudes above 56.5^oS

Figure 4.5 shows the high latitude region on April 7, 2000 indicating the higher flux, in the order of 10^4 particles $cm^{-3}sr^{-1}eV^{-1}$, of energetic protons and electrons with average energies greater than 10^3 eV in this region. This figure is a plot of particle flux along the orbit of the satellite for the time it crossed the Auroral region in the southern hemisphere. The plot starts at 03:46 UT when the satellite was at a magnetic latitude (MLAT) of 44.6^S and ends at 04:16 UT after travelling over the South pole. The magnetic local time (MLT) and universal time in hours and minutes are indicated on the plot.

The observed particle precipitation in this region could affect the dynamics of the ionosphere, and sometimes the effects could be global depending mostly on the magnitude of the energies being transferred from the solar wind into the ionosphere. The existence of field lines in the high latitude boundary layer of the Earth's magnetosphere, which do not close back on the Earth but are instead connected to interplanetary magnetic field lines referred to as "the open lines", is one form of coupling between the Earth's magnetic field and the Sun's magnetic field that enables the direct transfer of energy from the solar wind into the magnetosphere. Such energy transfers can probably drive the complex circulation of magnetospheric plasma and electric currents such as the ring current and field aligned currents. Enhanced energy input into the ionosphere can also lead to considerable rapid heating of the ionised and neutral gases resulting in uneven expansion of the atmosphere which drive strong neutral winds to low latitudes (Buonsanto, 1999). Thus, the direct effects of the particle precipitation in this region could be transported by the strong neutral winds to middle and low latitude regions.

4.1.2 Energetic particles in the South Atlantic Anomaly (SAA)

Particle precipitation is also observed in the SAA region. The trapped charged and energetic particles bouncing between hemispheres travel deeper down into the atmosphere over this region due to the low field intensity. Thus for a given altitude the radiation intensity is higher over this region than elsewhere at comparable latitudes. The precipitating particles interact with the dense atmosphere at low altitudes resulting in higher ionisation production rates. The precipitating particles also cause hazardous conditions for space operations around this region. Sometimes the particle flux is so high in this region that the detectors in satellites are shut off or at least placed in a "safe" mode to protect them from the radiation effects.

Figure 4.6 is a plot of four successive DMSP F13 satellite passes for which the satellite monitored particle precipitation in the SAA region and the polar region during the April 7 event. During pass 1, the satellite passed over South Africa and during the other three passes, it passed over the SAA region through to the polar region.

The plots in Figure 4.7 represent consecutive satellite passes over the SAA region

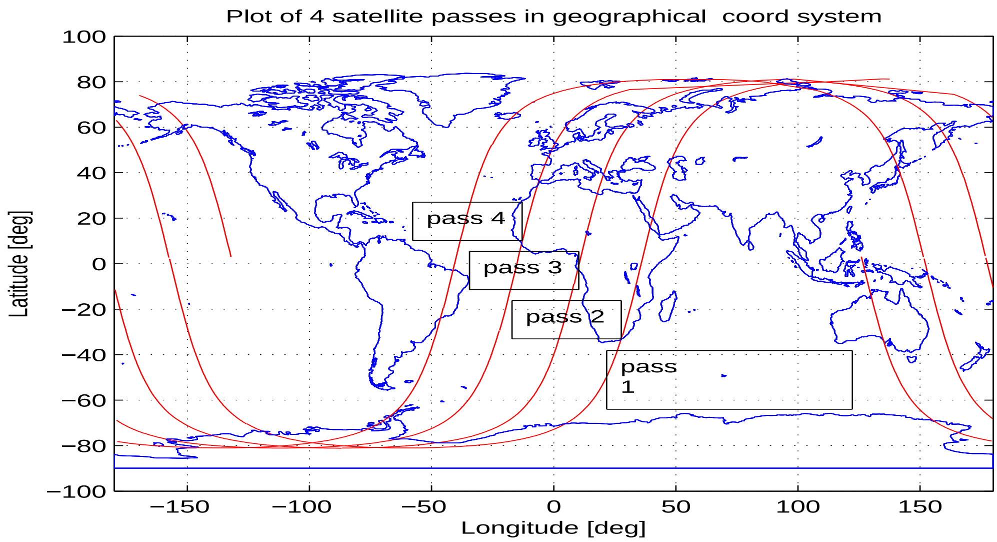
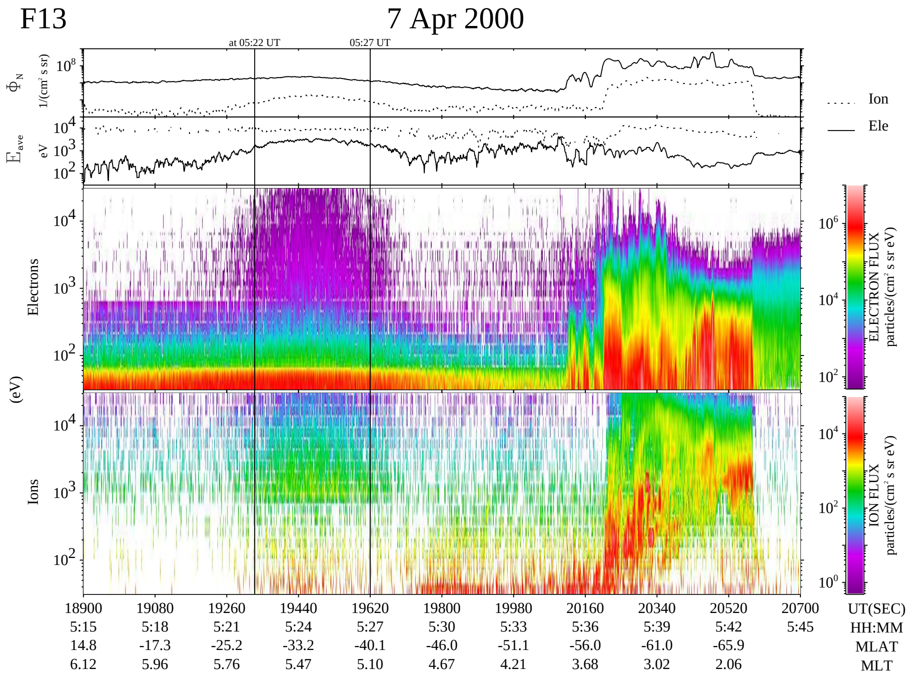


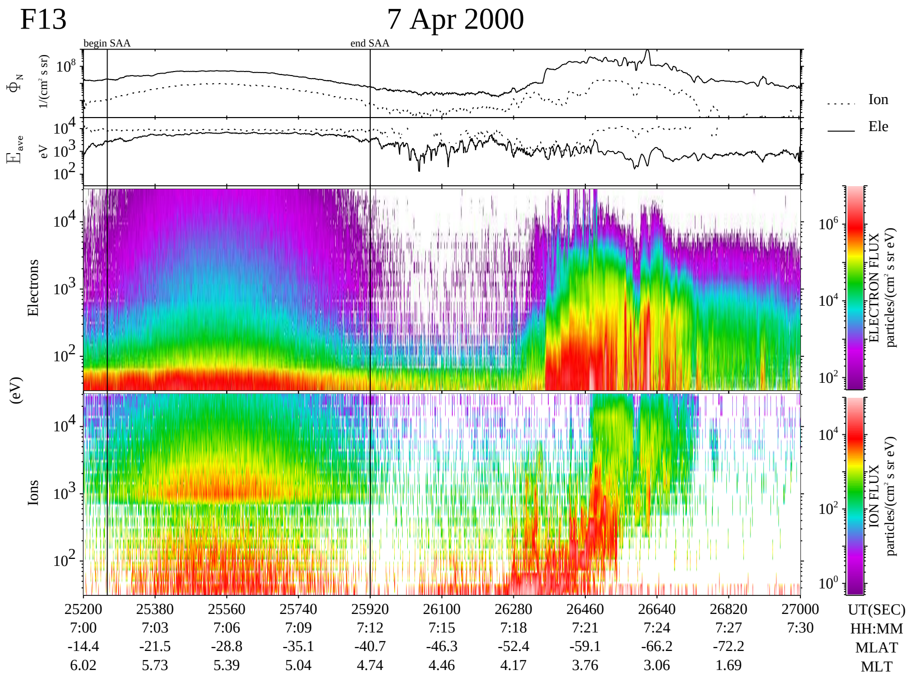
Figure 4.6: Plots of F13 satellite passes between 03:30UT and 10:00UT on April 7, 2000. The satellite passed across South Africa during pass 1 and monitored the SAA in the other indicated passes.

for the passes shown in Figure 4.6. The plots show evidence of high radiation intensity of energetic particles in the anomalous region. The size of the region and the order of magnitude of the particle flux increases from plots (a) through (b) to (c), Figure 4.7, which correspond to passes labeled pass 1, pass 2 and pass 3 on Figure 4.6 respectively. This indicates that higher particle flux values are observed around the eastern coast of Brazil than in the regions which lie closer to Africa. Figure 4.7(d) shows precipitation in the polar region.

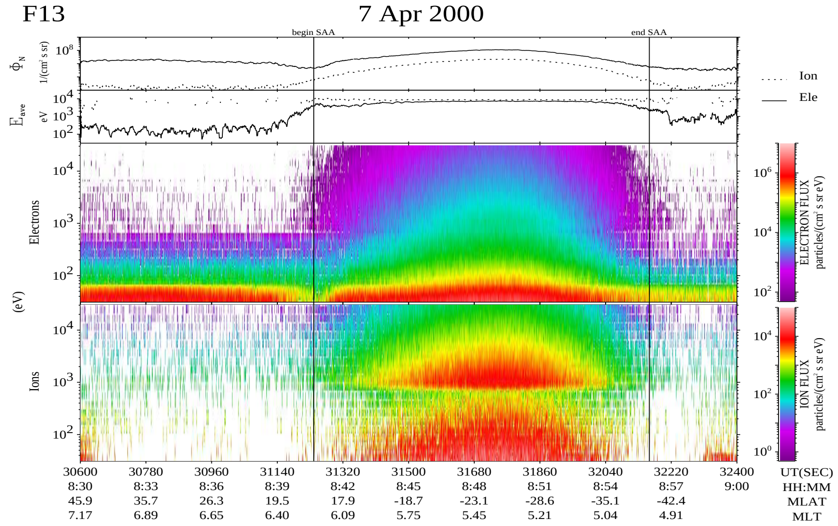
Figure 4.8 shows observations of the SAA region during the October 5 event. Four consecutive satellite passes over the region are shown. The SAA lies in the region indicated by the vertical lines on each plot. The plots also show how the



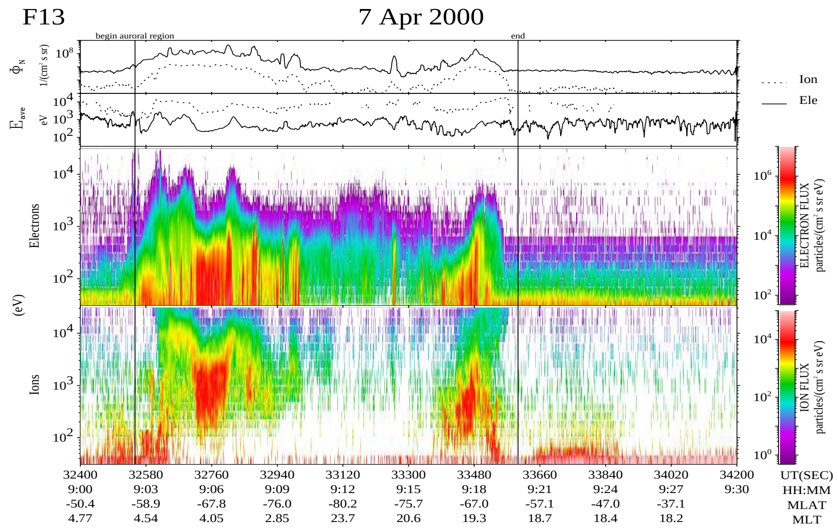
(a) First crossing of the SAA



(b) Second pass over the SAA region and monitored the auroral region



(c) Monitored the SAA region about 101 minutes after pass shown in Fig 4.7(b)

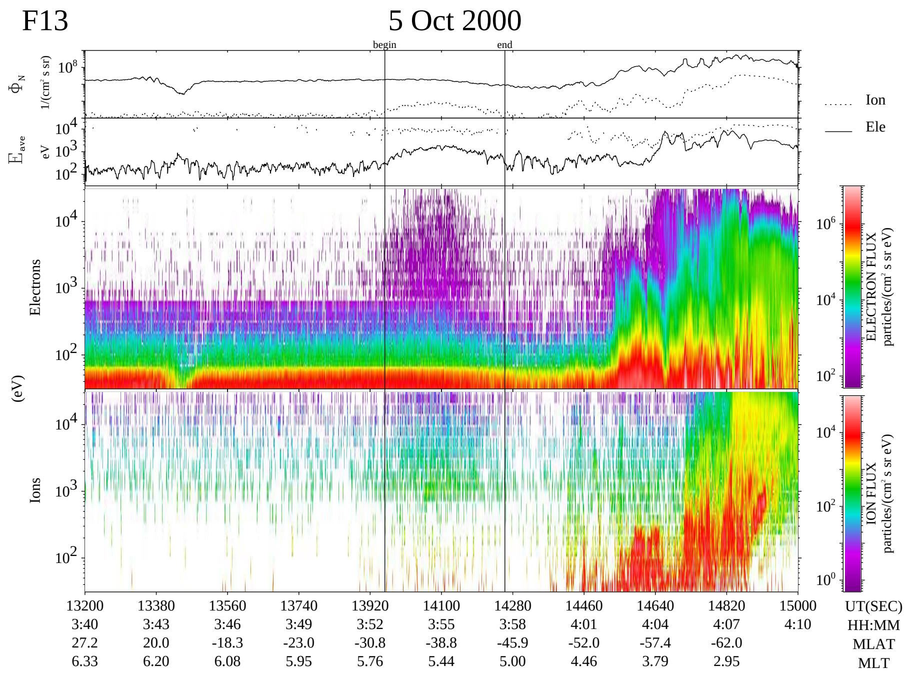


(d) Monitored the auroral region

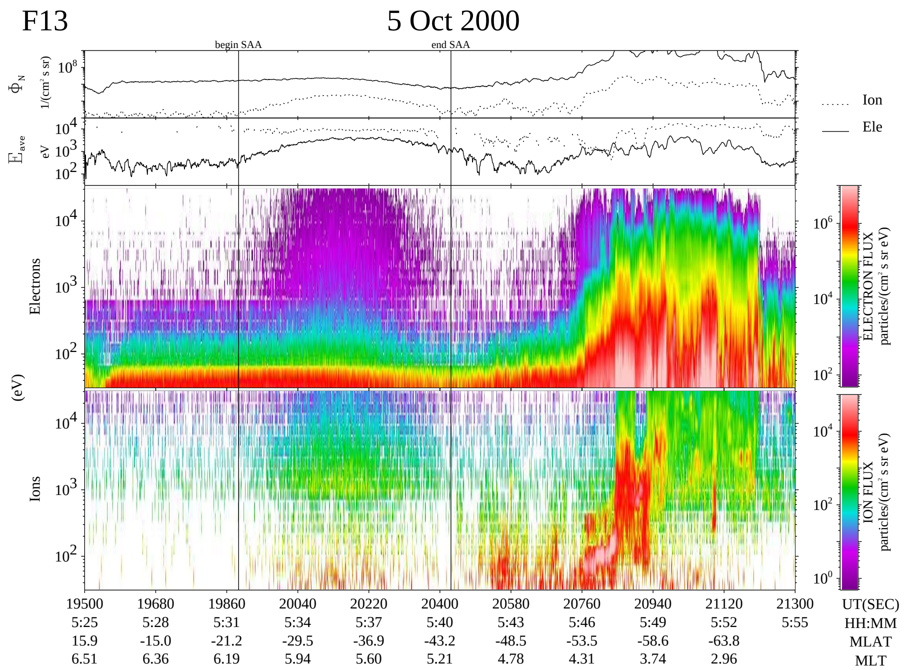
Figure 4.7: This figure shows three consecutive passes of the F13 satellite as it crossed the SAA region on 7 April, 2000 and also monitored the auroral region in Fig. 4.7(d). Vertical lines at magnetic latitudes below -50 degrees, boarder a region with higher intensities of energetic particles. This indicate the location of the SAA region.

region increases in size and the increase in radiation intensity moving from plot (a) to (d).

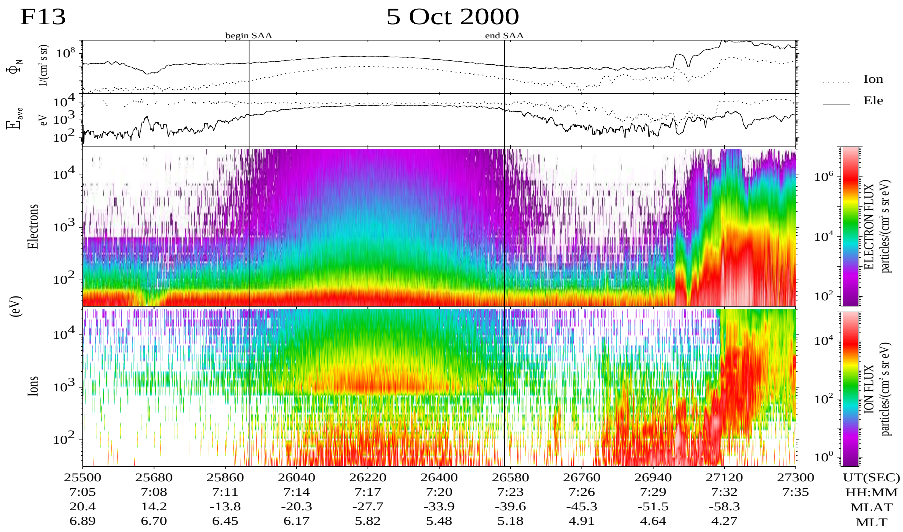
The effects of particle precipitation in this region have been investigated by many researchers. Haggard (2004) examined the effects of particle precipitation in this region on the daytime E-region and found evidence of a significant source of extra ionisation, in addition to solar ultraviolet and X-radiation. Gledhill (1976) investigated the aeronomic effects of this region and found evidence that both electron and neutral temperatures are higher in the anomalous region than elsewhere



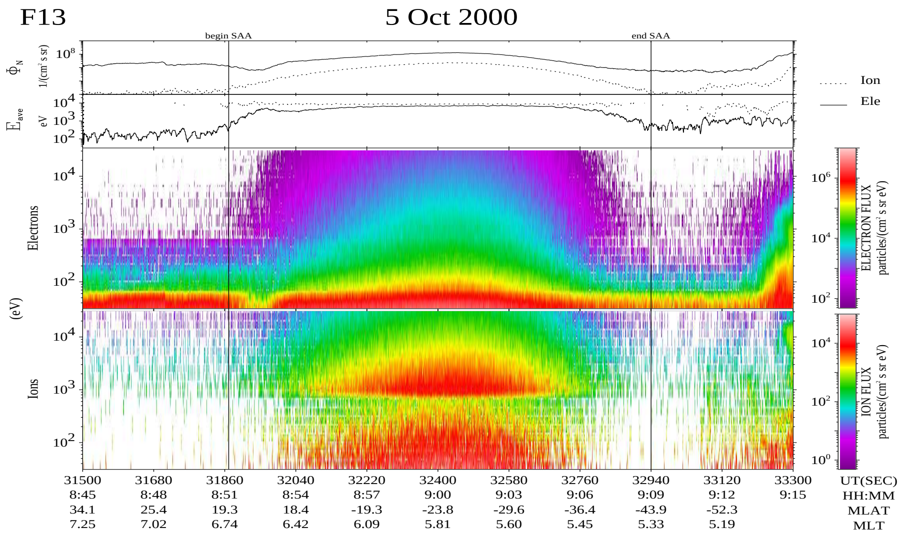
(a) Crossed South Africa



(b) 1st pass over the SAA



(c) 2nd pass over the SAA



(d) The SAA region

Figure 4.8: The SAA on October 5, 2000. The passes are at intervals of about 101 minutes, the orbital period of the satellite. The satellite monitored the high radiation of energetic particles in the anomaly region and the polar region.

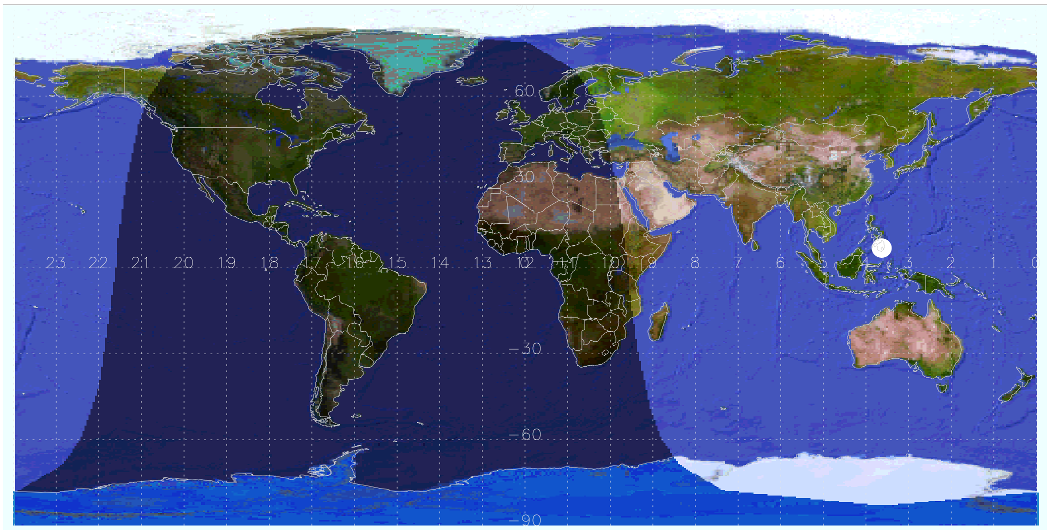
at comparable places. He also found a good correlation between trapped energetic electron fluxes and increases in ion concentration over the whole region, both during daytime and nighttime. Abdu *et al.* (1973) used antenna riometer measurements to study the great storm of August 1972 and obtained evidence of enhanced ionisation in the D-region over the SAA due to the precipitation of the inner radiation belt energetic particles drifting azimuthly eastward. Abdu *et al.* (2005) was able to verify the occurrence of significant ionisation enhancements in the D and E-regions of the ionosphere over this region using measurements of very low frequency phase (VLF) propagation in the Earth-ionospheres waveguide done by ground-based receivers and measurements by ionosondes (ionospheric vertical sounding radars). They also observed sporadic E-layers during night hours over Cachcoeira Paulista ($22.6^oS, 315^oE$ dip angle: 28^o) which according to their analysis revealed an extra source of ionisation that could be attributed to particle precipitation in the SAA.

Particle precipitation could be manifested in enhanced sporadic E-layer intensity (Nishino *et al.*, 2002). Sporadic E-layers being transient, localised patches of relatively high electron density in the E-region of the ionosphere which significantly affect radio wave propagation (Matthews, 1998). Their existence and presence in the ionosphere could cause disturbances and irregularities in the characterisation of ionospheric parameters such as the foF2.

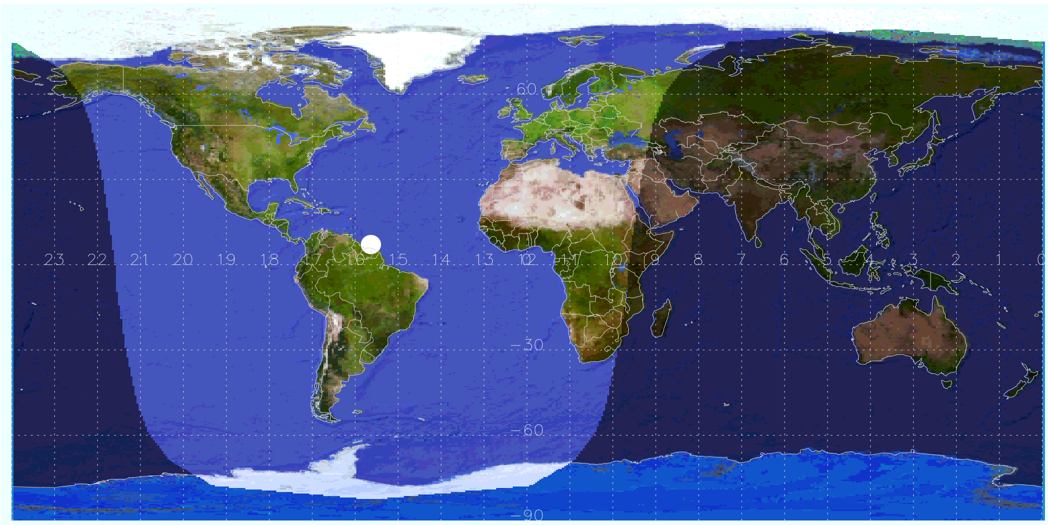
The particle induced ionisation in this region could result in a corresponding enhancement of the conductivity distribution pattern which could penetrate to low latitudes especially during periods of magnetic disturbances, thereby extending their effects.

4.1.3 Plasma density measurements by the DMSP

The Special Sensor - Ions, Electrons, and Scintillation (SSIES) package on the DMSP satellites provides measurement of the plasma velocities, temperatures, atomic composition, electrostatic potential, and ion and electron densities at an altitude of about 830 km. Each satellite with orbital period of approximately 101 minutes gives roughly 14 passes per day with data sampled at 4 second intervals. The ion density from this instrument was considered and data for the satellite passes for which the satellite monitored the SAA and the South African regions was selected. The satellite crosses the South African region at two local times per day - that is around 03:40 UT and around 15:50 UT. The two situations during the month of April are shown on Figure 4.9 which shows the position of the terminator at the two UT times during which the satellite monitors the South African region. As shown, the South African region lies entirely on the night side during the first pass (Figure 4.9(a)) and slightly to the dayside of the terminator line during the second pass (Figure 4.9(b)). Similar plots were done for the month of July and it was observed that the terminator line did not shift significantly.



(a) First pass at around 03:40 UT



(b) Second pass at around 15:50 UT

Figure 4.9: Figure showing the location of the terminator during the times in which the satellite passes over the South African region. (Fanning, 2006)

Bearing in mind that the distribution of radiation across the regions is not uniform, all the ion density values that fell within each region for each day were averaged respectively to get a rough estimate of the average ionisation for each day across each region. Figure 4.10 shows plots of the averaged ion densities against day of year over a period of one year (2000), for the SAA (top) and South Africa (bottom).

This shows in general terms how the ionisation in the two regions varies over a period of one year. Figure 4.10 indicates very high ionisation peaks in the SAA

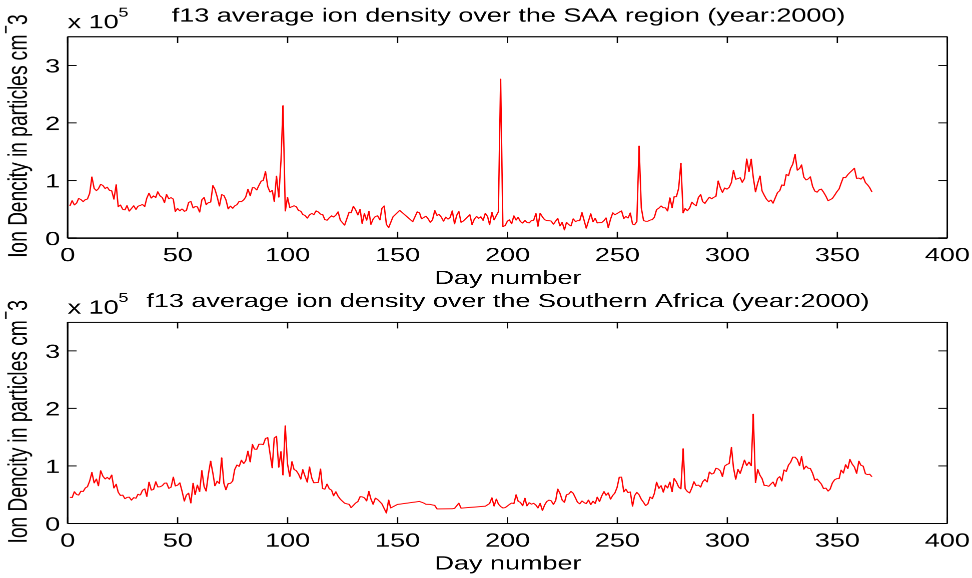


Figure 4.10: Averaged ion density in the South Atlantic Anomaly (top) and over South Africa (bottom) versus day of year during the year 2000.

region on some days in April, July and October. These sharp peaks are absent in the region over South Africa. The high ionisation peaks in the SAA could be attributed to particle precipitation during these periods. The variation for the South African region seems to follow the seasonal changes in the year, although some significantly high ionisation can be noted around the 100^{th} day, which seem to correlate with the sharp peaks observed in the SAA around the same time. The boundaries of the SAA region vary with altitude above the Earth. Its extent increases with increasing altitude, thus at altitudes where the satellites orbit, some parts of the South African ionosphere could lie much closer to, and sometimes could be overlapped by the anomalous region, and therefore the effects of precipitation in the SAA could extend to some parts of the South African region. The case is different at lower altitudes down to the F- and E-layers of the ionosphere where the size of the South Atlantic Anomaly is smaller and the intensity of radiation is not as high as at higher altitudes in the topside ionosphere where satellites orbit. The seasonal variation over South Africa is clearly visible with lower ionisation values recorded during the winter months than during the summer months. Effects of seasonal changes in this region are more significant due its geographical location in 'temperate' region where the solar effects become more significant. Although this seasonal effect could have been accentuated by the location of the terminator at the hours averaged, previous knowledge of the ionospheric behaviour at E and F region altitudes indicates that this seasonal effect can be believed.

4.1.4 Geomagnetic activity correlation

The geomagnetic condition of the ionosphere can be observed at a particular place and time, or the measurements can be averaged over time and over the whole planet. The K-Index, Kp-Index, A-Index, and Ap-Index achieve this.

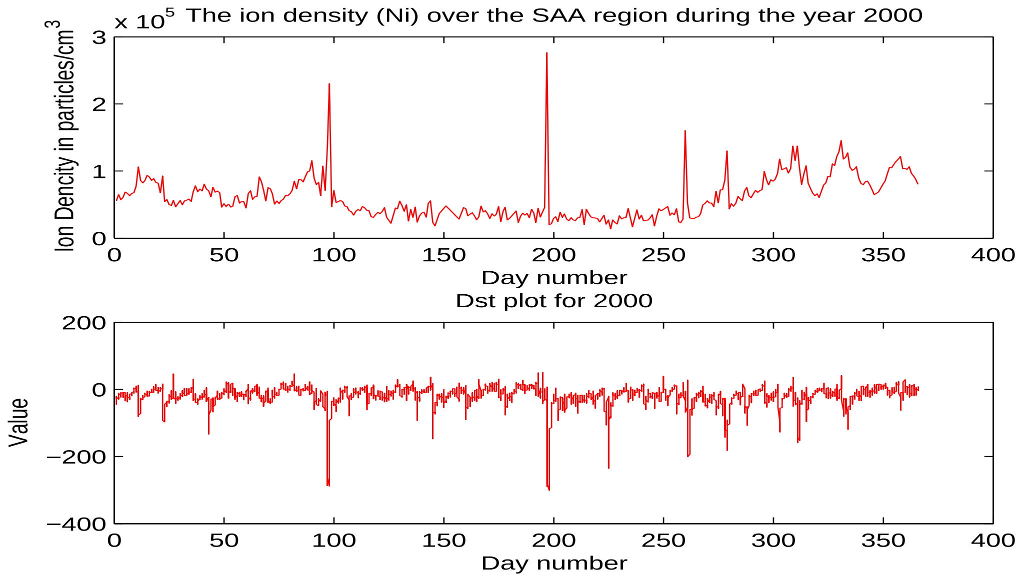


Figure 4.11: Top: Ion density over The SAA region during the year 2000. Bottom: The Dst plot for the year 2000

Figure 4.11 compares the averaged ion densities measured by the DMSP F13 satellite over the SAA region during the year 2000 with the geomagnetic activity indicated by the Disturbance storm time(Dst) index. The purpose of this comparison is to determine, visually, if there is any relationship between increased geomagnetic activity and enhanced ionisation in the SAA region. In general, how much particle precipitation occurs in the SAA region depends on many factors such as - the general level of the trapped particles in the radiation belts, and the presence or absence of mechanisms that scatter particles into the loss cone. For the general level of trapped particles in the radiation belts, the Dst index would be a good measure as it measures the strength of the ring current. The figure shows that there is significant enhancement in ionisation in the region during periods of high geomagnetic activity.

To get a measure of scattering processes is more difficult and complex. For example freshly injected particles such as substorms, can be indicated through the AE index. In this study, in order to investigate indirect effects that particle precipitation in the SAA and the auroral regions can have on the ionosphere over South Africa, the Ap-index is considered. The Ap index gives a measure of the general level of geomagnetic activity over the globe for a given (UT) day. It is derived from measurements at a number of stations world-wide of the variation of the geomagnetic field due to currents flowing in the Earth's ionosphere and, to a lesser extent, in the earth's magnetosphere.

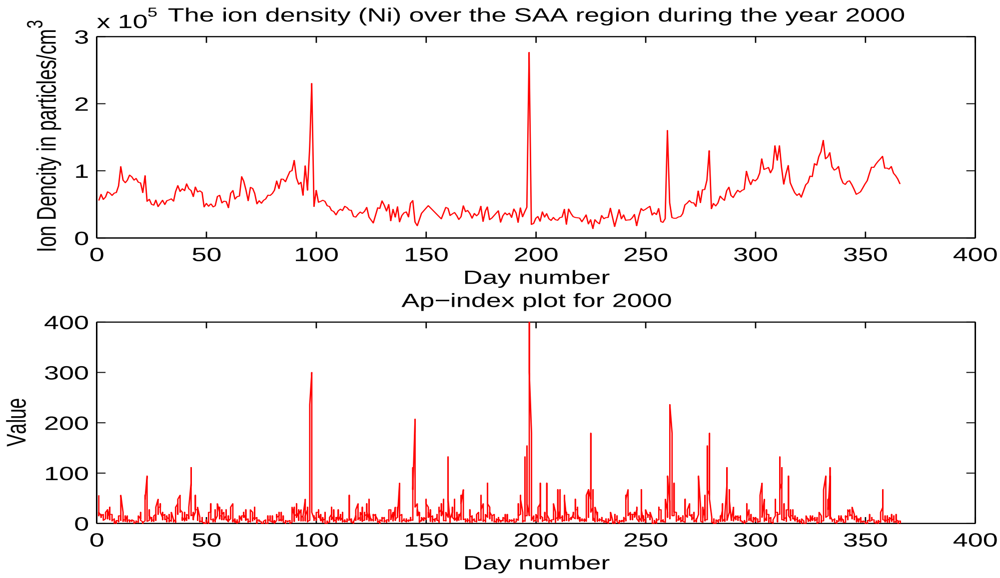


Figure 4.12: Top: DMSP F13 average ion density over the SAA region during the year 2000 (y-axis) versus day of the year (x-axis). Bottom: The Ap-index during the year 2000.

Figure 4.12 is a comparison of the averaged ion density measurements by the DMSP F13 satellite over the SAA during the year 2000 with the geomagnetic activity indicated by the Ap-index.

Both Figure 4.11 and Figure 4.12 indicate that, to a great extent, some correlations exist between geomagnetic activity and enhanced ionisation in the SAA region that could be due to particle precipitation. Particularly, the ionisation peaks around days 98, 199, 260 and 279 could be associated with high geomagnetic activities during these periods as indicated by both the Dst and the Ap indices. Geomagnetic activities are changes in the Earth's magnetic field resulting from the impact of strong solar wind particles of increased speed and/or density on the Earth's magnetosphere. The stronger solar wind being a result of CMEs which may have launched charged clouds or high speed streams of particles towards Earth. Thus, geomagnetic disturbances are associated with large energy inputs to the upper atmosphere in the form of enhanced electric fields, enhanced electric currents and energetic particle precipitation. However, there is an indication that for some cases where the Ap-index indicates high geomagnetic activity but there is no corresponding indication of enhanced ionisation. This could be attributed to the differences in magnitudes of the disturbances such that the moderate magnetic activities, Ap index less than 200, may not result in large enough energy inputs to cause significantly defined ionisation effects. Foster *et al.* (1997) observed that during geomagnetic disturbances, particle populations that characterise the Auroral region can expand equatorward extending their effects to the low and middle latitudes.

Comparison of average ionisation in the South African region and geomagnetic activity indicate that there isn't a well defined relationship between geomagnetic activity and the observed ionisation. There was no significant enhancements in ionisation observed during the geomagnetically disturbed periods as observed in the case of the SAA region. Although, as marked on Figure 4.13, there are some ionisation enhancements that seem to correlate with geomagnetic activities. But the times when these ionisation enhancements occur do not corespond with the periods of high geomagnetic activity which makes it difficult to relate them in the present study. The results of the SSJ/4 particle data, Figure 4.3 above, showed that no particle precipitation was observed in the region over South Africa.

In general, during geomagnetic storms:

- The solar wind is disturbed. During coronal mass ejections the eruption of solar material cause a shock wave on the average solar wind speed heading towards Earth, thus causing disturbances in the solar wind.

- The disturbed solar wind compresses the Earth's magnetosphere (Yizengaw *et al.*, 2004) and the intense electric fields mapped along geomagnetic field lines to the high-latitude ionosphere occur. This happens if the polarity of the Sun's magnetic field embedded in the disturbed solar wind is southward when the shock wave hits the Earth's magnetic field such that the shock wave couples into Earth's magnetic field and cause large variations in the Earth's field. It is seen as an increase in the Ap and Kp indices. The intense electric fields drive and induce equatorward neutral winds through collisions by producing a rapid convection of ionospheric plasma at high latitudes (Blagoveshchensky *et al.*, 2003; Yizengaw *et al.*, 2005). These electric fields sometimes penetrate to low latitudes extending their effects there (Aarons and Rodger, 1991).

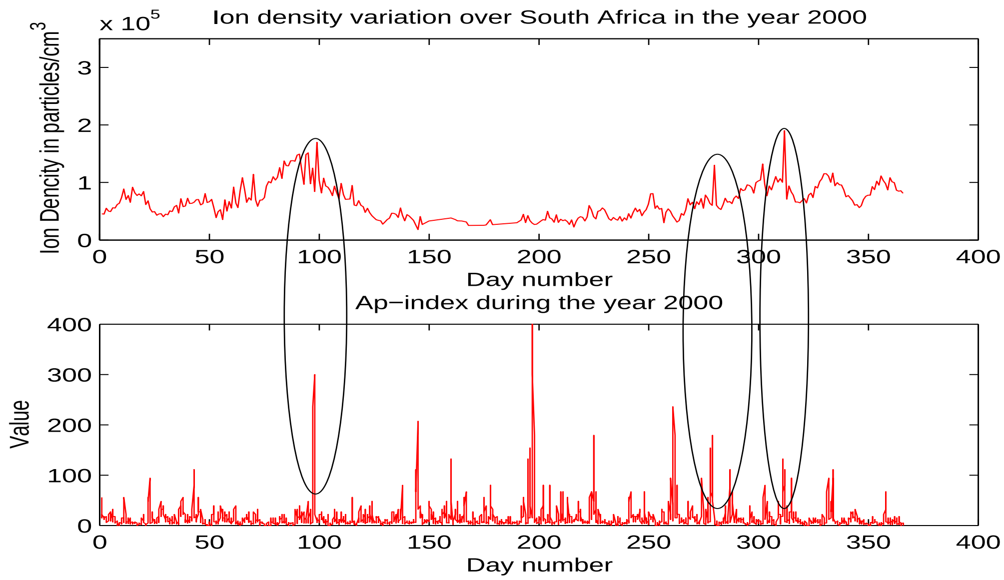


Figure 4.13: Top: DMSP F13 ion density over southern Africa during the year 2000 as a function of day number. bottom: Variation of the Ap-index during the year 2000

- The neutral winds are disturbed and produce polarisation electric fields by the dynamo effect as they collide with the plasma in the presence of the Earth's magnetic fields (Aarons and Rodger, 1991). The polarisation electric fields further affect the neutrals and the plasma.

- An increased cloud of charged energetic particles (protons and electrons) precipitate to the lower thermosphere expanding the Auroral zone and heat up the Earth's upper atmosphere increasing the ionospheric ionisation significantly at high latitudes (Yizengaw *et al.*, 2005). The atmospheric density at the orbit of satellites up to about altitudes of 1000 km could increase significantly.

- Intense particle precipitation of the South Altantic anomaly region could cover a wider geographical area. The geographical region affected by this particle precipitation could extend even to regions over South Africa and affect the dynamics of the ionosphere in this region.

Yizengaw *et al.* (2005) observed from both ground-based and satellite observations that during geomagnetic storm periods, the molecular concentration is increased and the atomic concentration reduced, leading to the reduction of the atom-to-molecule ratio by a considerable factor. Danilov and Lastovicka (2001) and Fuller-Rowell and Codrescu (1996) reported that such enriched air can be conveyed from high to middle and low latitudes by storm-induced equatorward winds. High solar wind disturbances can physically distort the Earth's magnetosphere, affecting the ionosphere by changing ionisation or de-ionisation rates or by thinning the F-Region (preventing refraction), and creating Aurora.

4.1.5 Correlation with solar activity

Solar matter containing high-energy charged particles is ejected from the Sun on a regular basis, and this comprises the solar wind. Averaged ion densities in the year 2000 are found to be generally higher than in the year 2004, according to Figure 4.14. The figure also indicates that the ionosphere was less disturbed in 2004 as compared than in 2000. This difference could be due to the fact that the year 2000 was near solar maximum while 2004 was near solar minimum. Solar minimum and solar maximum are two extremes of the Sun's 11-year activity cycle.

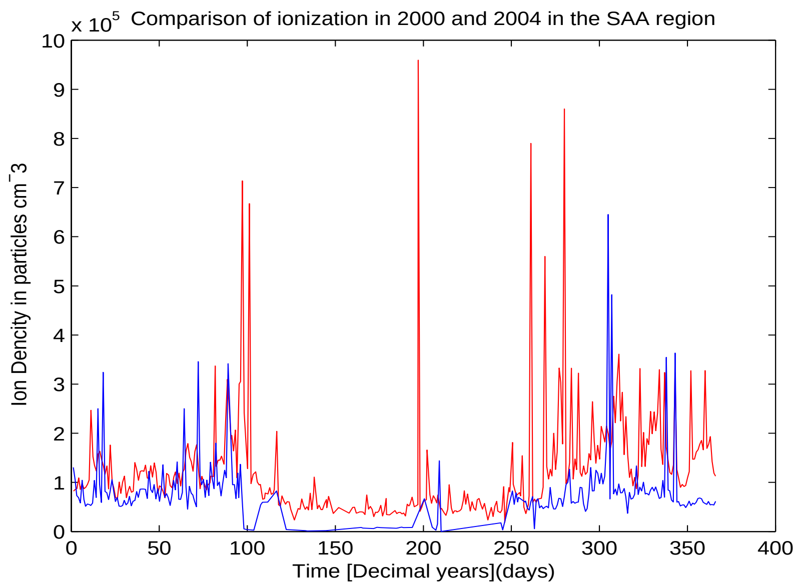


Figure 4.14: Comparison of the ionospheric ionisation in 2000 (red line) and in 2004 (blue line).

At solar maximum:

- The sunspot number is very high and solar flares erupt more frequently. Solar flares are explosions, usually near sunspots, which eject clouds of solar material composed of very energetic particles and electromagnetic energy (X-rays, Gamma-Rays and increased UV-radiation) towards Earth.

Sunspots are tied to ionisation of the F-region, and increase and decrease in an approximate 11-year cycle. At and near the maximum of a solar cycle the increased number of sunspots cause more ultraviolet radiation to impinge on the atmosphere. This results in significantly more F-region ionisation, allowing the ionosphere to refract higher frequencies. At and near the minimum between solar cycles the number of sunspots is low and higher frequencies go through the ionosphere into space.

4.2 The E-and F-layers over the South African region

4.2.1 E-region effects

Any form of particle precipitation will result in some changes in the dynamics and structure of the ionosphere. The effects may be global or may only affect certain regions depending on the magnitude of the event. Ionospheric measurements over South Africa using ionosondes are examined in efforts to track any irregularities which may be associated with particle precipitation observed over the SAA region and the polar region. Particles under investigation have energies in the range 30 eV-30 keV, which essentially deposit most of their energies in the F- and the E-regions, and therefore evidence of ionisation density irregularities in these regions of the ionosphere will indicate effects that could be attributed to particle precipitation. Variation of nighttime E-region ionisation is examined since daytime E-region has generally high electron density values such that any extra ionisation and irregularities that may be due to particle precipitation may not be well defined enough to be noticeable.

The required nighttime E-layer critical frequencies were not available in the ionosonde measurements at Grahamstown. Nighttime E-region is not measurable with an ionosonde due to the low electron densities and high ion-electron collision frequencies. The gaps in the plot of foE versus time on Figure 4.15 indicate times when data values were not available. Ionosonde measurements are the only available ground-based ionospheric measurements in South Africa in years before 2000, i.e. before GPS data became available. This makes it difficult to identify any irregularties that could be due to particle precipitation effects from ground based ionospheric measurements. It is therefore difficult to draw any concrete conclusions from the available data. However, a closer look at the time history of the daytime E-layer critical frequency on October 5 shown in Figure 4.16, reveals that the E-region

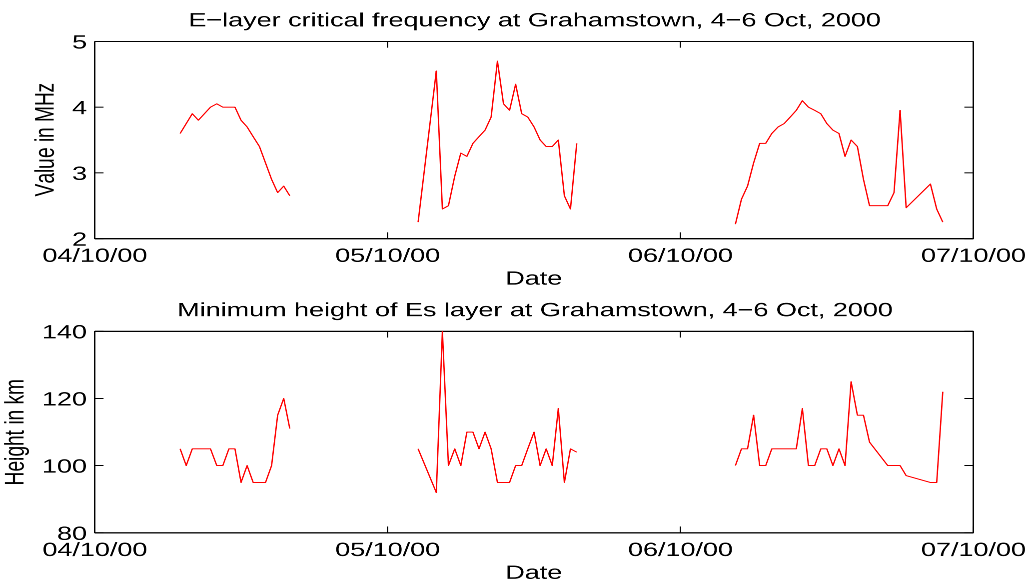


Figure 4.15: E-layer critical frequency at Grahamstown and the minimum height of Es layer from 4 to 6 Oct, 2000. Gaps in the plot indicate non-availability of data

ionosphere was generally perturbed between 03:00 and 14:00 UT. The observed E-region perturbations could be due to auroral precipitation effects. Most ionospheric disturbances associated with particle precipitation occur in the high latitude ionosphere where particle precipitation is observed in the cusp and the Aurora. The high latitude particle precipitation is a major source of

- energy input that results in frictional heating which can then alter the lower thermospheric composition and neutral winds (Yizengaw *et al.*, 2005). If the heating is impulsive, it can launch travelling atmospheric disturbances (TADs) which can propagate equatorward by lifting the constant pressure surfaces (Roble, 1992).

- ionisation, which is an important cause of enhanced conductivity. Due to the enhanced conductivity, currents can flow down to mid and low latitudes as the magnetospheric convection electric fields map down along magnetic field lines (Buonsanto, 1999).

Thus, disturbances created in the auroral regions could propagate to mid and low latitudes.

The ionograms shown in Figure 4.17(a) and 4.17(b) show patches of sporadic E-layers observed during the period when the ionosphere was perturbed. For comparisons, Figure 4.17(c) shows an ionogram which does not contain sporadic E. The

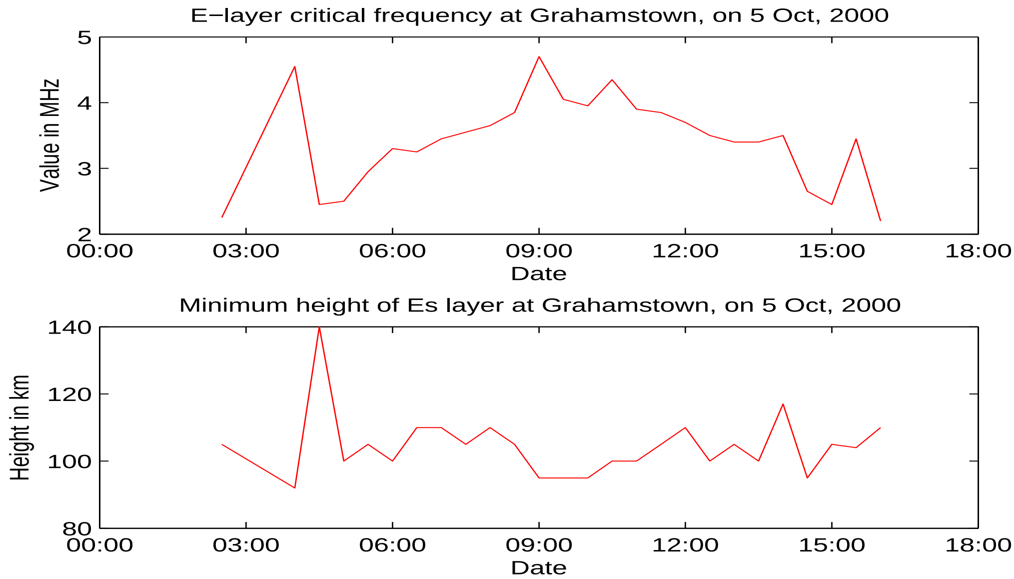


Figure 4.16: E-layer critical frequency on October 5, 2000 recorded at Grahamstown, showing disturbances in the E-region between 03:00 and 14:00 UT.

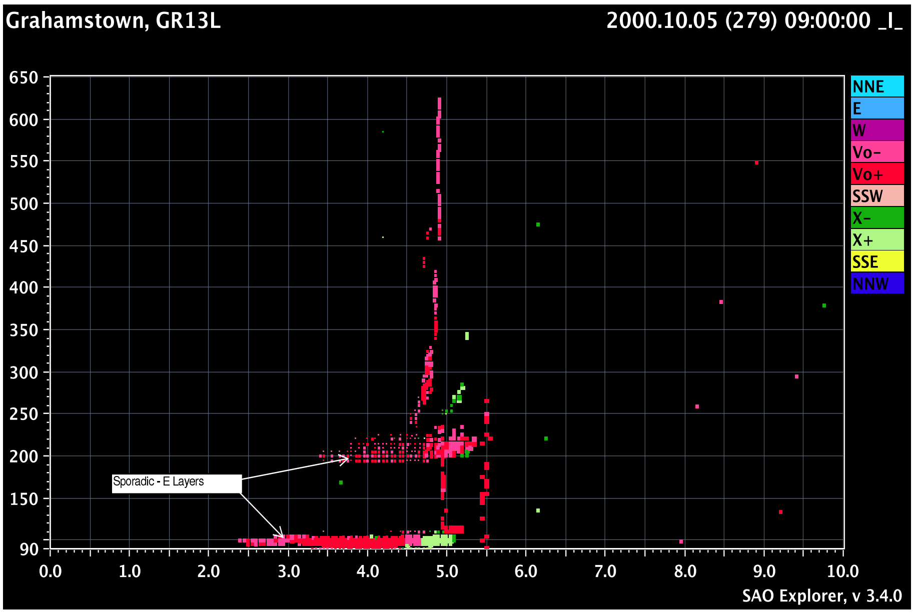
ionograms were generated using SAO-explorer program, a digisonde ionogram data visualisation and editing tool used for verification and editing of autoscaled digisonde ionograms, as well as a variety of derived ionospheric characteristics (Reinisch *et al.*, 2004).

4.2.2 F-region irregularities

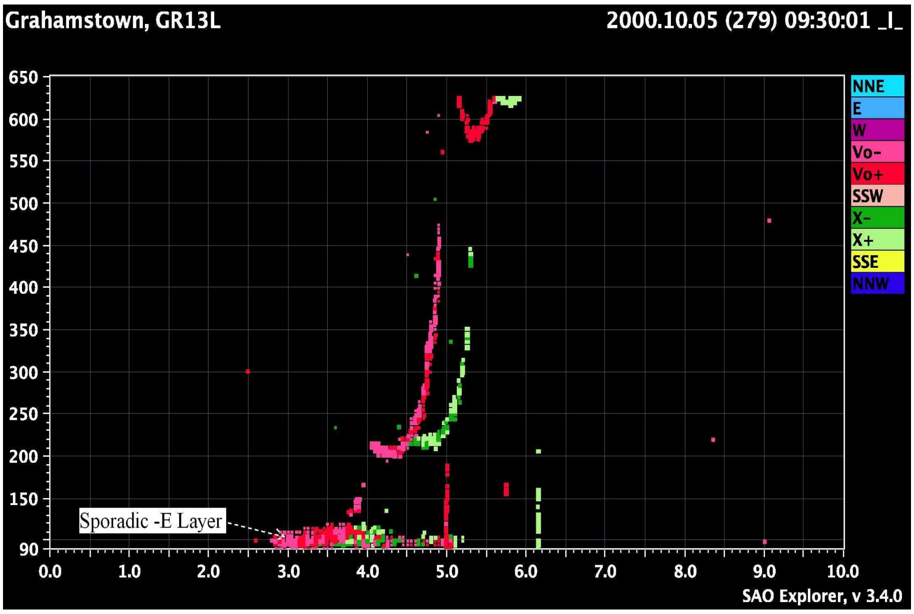
A visual inspection of the ionograms to look for the presence of spread-F in the ionosphere during the two events was done. However, no indication of spread-F was found in the data.

4.2.3 foF2 measurements using ionosonde

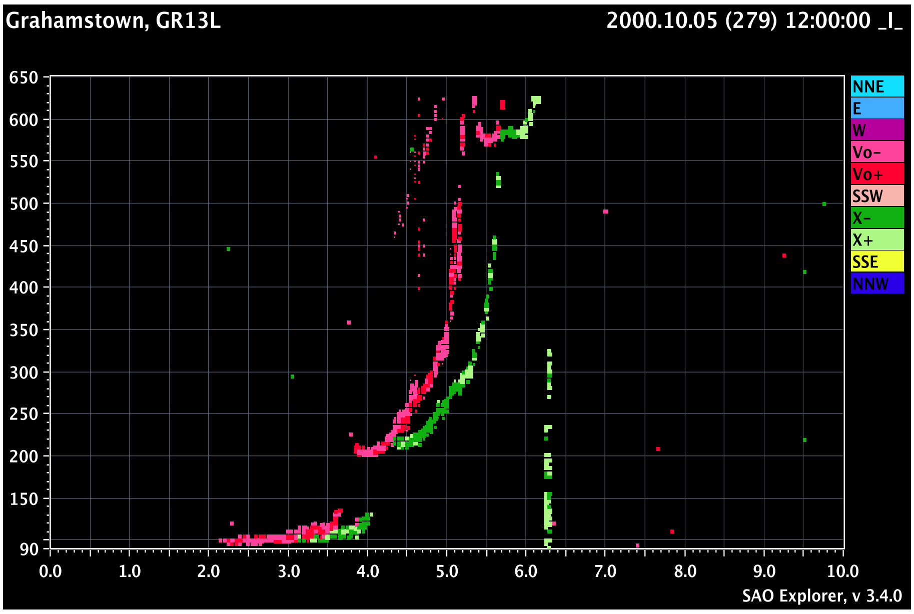
Figure 4.18 shows the foF2 time variation from 5-10 April 2000. A depletion of the foF2 is evident on 7 April over Grahamstown (33.3^o0S,26.5^o0E), a station that lies in the mid-latitude region. Figure 4.19 shows similar a observation of foF2 depletion during the October 5 event in the three South African digisonde stations, Grahamstown, Madimbo(22.4^oS,26.5^oE) and Louisvale (28.5^oS,21.2^oE), South Africa. The electron density values were lower in all three stations on October 5 than on the preceding and following days. This indicates a reduction in the level of ionisation at F-region heights during the events. Many authors have established that such



(a) Sporadic E at 09:00 UT



(b) Sporadic E at 09:30 UT



(c) Ionogram without sporadic E taken at 12:00 UT

Figure 4.17: Examples of ionograms with and without sporadic-E-layers observed at the Grahamstown ionosonde station on October 5, 2000.

variations of the foF2 are associated with magnetic disturbances (Buonsanto, 1999; Yizengaw *et al.*, 2005; Prölss, 1993). Ionospheric measurements using ionosondes are usually difficult to make during geomagnetically disturbed periods, and often the ionograms have to be rescaled manually to improve values of the foF2 and other ionospheric parameters.

The observed variation of the foF2 could be due to indirect effects of particle precipitation depositing a significant amount of energy into the auroral region and, to a lesser extent, in the SAA region. The depletion could be the result of rapid heating and expansion effects in the high latitude ionosphere. Electron precipitation and enhanced energy inputs due to the ionosphere-magnetosphere coupling by intense electric currents in the high latitude regions cause significant rapid heating of ionospheric constituents, which leads to uneven expansion of the thermosphere (Yizengaw *et al.*, 2005). When the thermosphere expands unevenly, pressure gradients which modify global thermospheric circulation are produced. This in turn drives strong and enhanced equatorward neutral winds by causing the air to move through constant pressure surfaces (Buonsanto, 1999). An increase in the cross-polar potential drop can also lead to an increased energy input at high latitudes and the expansion of the neutral atmosphere (Yizengaw *et al.*, 2004).

These thermospheric circulation disturbances change the composition of the neu-

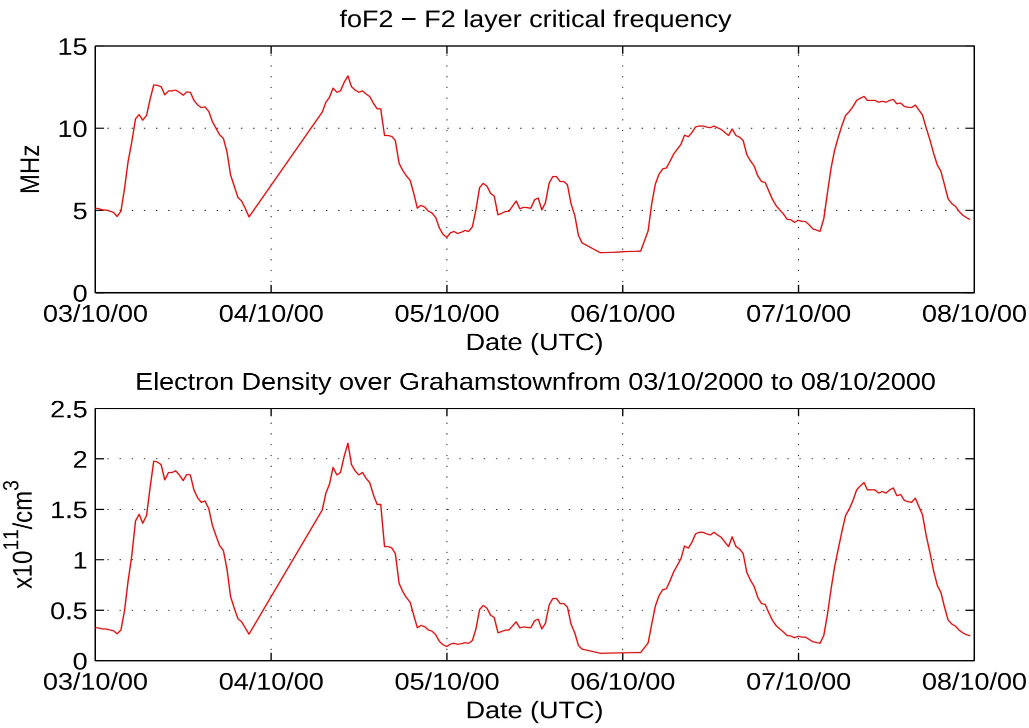


Figure 4.18: The foF2 time evolution from 5-10 April 2000, recorded at Grahamstown ionosonde station. There is a depletion on April 7, as the level of ionisation is much lower on this day compared to the preceding and following days.

tral atmosphere and moves the plasma up and down magnetic field lines, changing the rate of production and recombination of ionised species (Yizengaw *et al.*, 2005). This causes the depletion of the atom-to-molecule ratio as air of different composition is raised to higher altitudes. The change in chemical composition is responsible for the increase in recombination and the reduction in the ionisation concentration (Yizengaw *et al.*, 2005). The storm-induced nightside equatorward winds can transport the composition changes to middle and low-latitudes (Prölss, 1993) causing a reduction in the ionisation concentration of the F-region, even at low latitudes. Idenden (1998) also discussed this phenomenon and pointed out that mainly during polar cap expansion, the increase in recombination rate due to ion-neutral frictional heating could produce significant ionisation reduction in the F-region. Prölss (1993) observed that negative storm effects such as the depletion in the F-region ionisation occur in regions where the natural gas composition is changed such that the ratio of the molecular gas concentration to the atomic oxygen composition has increased. He also noted that these regions are produced by heating and upwelling of air by mag-

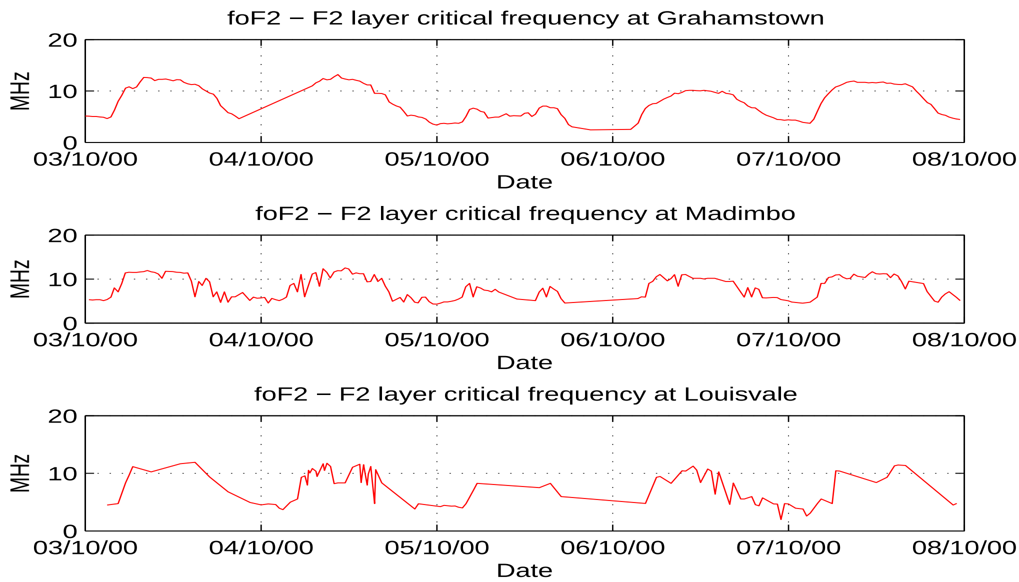


Figure 4.19: Variation of the foF2 between 3 and 7 October, 2000 in the three ionosonde stations of South Africa, Grahamstown, Madimbo and Louisvale, showing a depletion on October 5.

netospheric energy inputs at auroral latitudes. Fuller-Rowell *et al.* (1994) showed by computational simulations that the wind field of the storm circulation driven by the high latitude heat input can transport the region of composition change to low latitudes once it has been created.

The ionosphere at F-region heights during the April 7 event looked perturbed between 05:00 and 10:00 UT, as shown on Figure 4.19. The perturbation in the ionosphere could be as a result of particle precipitation in the SAA region, which the SSJ/4 particle detector on the DMSP F13 satellite monitored (Figure 4.4). Under conditions such as during magnetic storms, the SAA region covers a wider geographical area. Particle precipitation in the anomalous region could cause a complex response of the ionosphere even over South Africa and other regions within the vicinity of this region.

The perturbation could also be due to travelling ionospheric disturbances (TIDs) propagating from the Auroral region. Following large disturbances on the sun such as solar flares and coronal mass ejections, large TIDs with their energy travelling horizontally are generated in the auroral regions (McNamara, 1991). These TIDs can travel large distances and be observed many thousands of kilo metres from their source, as a consequence of the dispersive nature of wave propagating in the Earth's atmosphere which leads to different wave velocities for different wavelengths.

Particle precipitation could indirectly result in the increased prevalence of sporadic-E. Auroral type Sporadic-E has a direct relationship with geomagnetic disturbances, and often occurs in conjunction with auroral scatter. The birthplace of auroral type Sporadic-E is always within the auroral curtain (Hawk, 2001). This type of Sporadic-E can occur within the mid-latitudes such as in the South African region since the auroral curtain can extend well into the mid-latitudes during severe geomagnetic storms. Abdu *et al.* (2005) analysed the sporadic E-layer characteristics over Cachoeira Paulista ($22.6^o S, 315^o E$). They established that their occurrence and intensity exhibited significant enhancements during magnetically disturbed conditions, and attributed this to particle precipitation over the SAA region.

Chapter 5

Discussion and Conclusions

5.1 Discussion and recommendations for further research

An investigation into the effects of particle precipitation on the South African ionosphere has been done based on the variations of the ionospheric parameters, the foE, the electron density and the foF2 during two precipitation events, April 7, 2000 and October 5, 2000. This chapter presents a discussion on the observations and results that emerged from this investigation.

The DMSP SSJ/4 particle data provided evidence that no particle precipitation occurred over South Africa during these events and that it is unlikely to occur during other such events. The particle data show that the detectors on the F13 satellite did not detect any energetic particles over South Africa during the events looked at. Particle precipitation was encountered only at magnetic latitudes above $56^o S$. The DMSP satellite program investigate low energy electrons and protons (30 eV-30 keV) energy range.

This energy range does not take into account the heavy particle ions with higher energies of up to 100 keV, originating from the plasma sheet and are responsible for the production of neutral atom and ion proton aurora. Charge exchange between storm-time ring current ions and geo-coronal H and O atoms could lead to the precipitation of energetic neutral atoms (with energies in the order of tens of keV) important for the ionospheric effects in the equatorial and mid geomagnetic latitudes $(0 - 40^o)$ (Robinson *et al.*, 1985; Callis *et al.*, 1991b). The direct field aligned precipitation of energetic ions from the ring current is important at magnetic latitudes above 40^0 (Callis *et al.*, 1991b). Observations of the precipitation of such particles are also important in the study of the effects of particle precipitation in the mid and low latitude regions.

Future work should involve using data from the National Oceanic and Atmospheric Administration (NOAA) satellite program which monitor particles with higher energies, up to 2 MeV. This would widen the energy range of the particles observed and could help to draw better conclusions. The NOAA satellites are in polar orbits and monitor the dynamics of energetic particles from pole to pole.

Analysis of the DMSP SSIES ion density measurements showed that the level of ionisation, in the SAA region, at the altitudes where the satellite orbits, was higher during the precipitation events. Higher fluxes of energetic particles observed in this region during these events deposited significant amounts of energy into the region, which then triggered an increase in the ionisation rates. Enhanced ionisation observed in the SAA region was not present in the region over South Africa. As observed above, there were no energetic particle fluxes that were observed in this region that could cause ionisation enhancements. The surface magnetic field strength of the Earth is sufficient in this region to shield the Earth effectively from the fluxes of the direct solar wind and trapped energetic particles.

Another feature observed is the correlation between increased ionisation in the SAA region and geomagnetic activity, indicated by the Ap-index. The visual correlations are based on the variation of the magnetic activity and that of the average ionisation over a period of one year. As already noted, the observed enhanced ionisation observed in this region was due to the precipitation of the trapped proton and electron fluxes, which were monitored by the SSJ/4 detectors. Higher localised fluxes and higher average proton and electron energies were observed during geomagnetic storm periods. However, there were instances where the Ap-index indicated higher geomagnetic activity for which there was no corresponding increase in the level of ionisation. This could be related to the magnitudes of the storms, i.e. the less severe magnetic activities did not result in large enough energy inputs to cause significant ionisation effects. During geomagnetic storms, fluxes of energetic electrons in the outer regions of the radiation belts are enhanced and can diffuse to lower L-shells. These particles can then precipitate into the SAA and the polar ionospheres where the surface magnetic field strength is weaker. The result is a significant increase in ionospheric ionisation in these regions. Solar and geomagnetic activities are major drivers of energetic particle injections into the ionosphere.

Ionospheric measurements using the ionosonde at Grahamstown, (33.3^oS, 26.6^oE), revealed that the ionosphere in the F-region was generally perturbed during the studied events. In addition, there was a general reduction in the ionisation level of the F-region. Any form of particle precipitation should have an influence on the plasma parameters such as electron density, plasma turbulence and conductivities, which in turn produce effects that can correlate with the foF2 measurements. Yizengaw *et al.* (2005) showed that rapid heating and expansion of the atmosphere in the high latitude regions due to enhanced energy inputs by particle precipitation and enhanced electric fields could cause a reduction in the F-region ionisation. Rapid heating and expansion of the atmosphere results in the depletion of the atomic to molecular ratio and changes the chemical composition, important factors in the depletion of the foF2. This study confirms the occurrence of this phenomenon in the region over South Africa. Enhanced equatorward winds transport the composition changes that are generated in the high latitudes to mid and low-latitudes causing a reduction in the F-region ionisation level in these regions as well.

The E-region over Grahamstown was disturbed between 03:00 and 14:00 UT on October 5 as shown on Figure 4.16. This disturbance could be due to particle precipitation in the auroral region. Auroral precipitation could lead to enhanced conductivities which allow currents to flow down to middle and low latitudes as the magnetospheric convection electric fields map down along magnetic field lines. Again, auroral precipitation can launch travelling ionospheric disturbances (TIDs) which can propagate equatorward so that disturbances created in the auroral regions are transported to mid and low latitudes.

Analysis of ionograms recorded on the October 5 event revealed patches of sporadic E-layers during the period when the ionosphere was disturbed, as shown on Figure 4.17. Precipitating particles with energies between 2 keV and 40 keV can enhance E-region ionisation significantly and can lead to increased occurrence of sporadic E-layers. Sporadic E-layers have a screening effect, as they reflect signals which would normally penetrate the E-region and go up to the F-region. For the April 7 event, on the other hand, no sporadic E-layers were seen in the ionograms. The reason for this difference is not known to the author. Generally, the catalyst for sporadic-E is not known and the behaviour of mid-latitude sporadic-E is unpredictable (Hawk, 2001). The type of sporadic-E sometimes observed in the South African region is auroral which has a direct relation with geomagnetic disturbances, and often occurs in conjunction with auroral scatter. Foster *et al.* (1997) observed that during geomagnetic disturbances, particle populations that characterise the auroral region can expand equatorward extending their effects to the mid-latitudes. And Hawk (2001) observed that the auroral curtain which is the birthplace of auroral type Sporadic-E can extend well into the mid-latitudes during severe geomagnetic storms.

In addition, the occurrence of spread F was examined, but there were no spread F irregularities observed in the ionograms during the two events.

The irregularities observed in the ionospheric parameters using ionosondes attest that ionosondes have some capability to detect the presence of proton and electron precipitation, significant sources of energy inputs in the high latitude and the SAA regions, though they may not provide information on the type of particles.

The above analysis and observations suggest that energetic particles precipitating in the auroral region can significantly influence the dynamics of the low and mid-latitude ionospheres where particle precipitation does not necessarily occur. The influence can extend to low altitudes such as the F-and the E-regions.

The general observation of this study is that direct effects of particle precipitation on the South African ionosphere have been relatively hard to find. However, irregularities generated in the high latitude regions are found to be transported to mid and low latitudes by enhanced thermospheric winds, indirectly influencing the dynamics of the mid and low latitude ionospheres. This study has noted the influence of such disturbances in the South African region. One of the main problems encountered in this investigation is the non-availability of nighttime E-layer ionisation measurements for the South African region. The only ground based ionospheric measurements available for this region are those recorded by ionosondes. An ionosonde does not measure nighttime E-region because of the low electron densities and the high ion-electron collision frequencies. Nighttime E-region ionisation would have provided information on the extent of the particle precipitation in the E-region. It is generally approximated that precipitating particles with energies between 2 keV and 40 keV deposit their energy in the E-region (Gledhill, 1976), creating significant irregularities such as enhanced ionisation and sporadic E-layers in this region of the ionosphere. The daytime E-layer peak is normally relatively high compared to nighttime ionisation. Any irregularities that may be created by particle precipitation during daytime may not be distinct enough to be noticed. Thus, nighttime E-region ionisation is considered in investigating the effects of particle precipitation in the E-region. However these measurements are not available for the region over South Africa.

Hopefully nighttime E-region measurements may become possible in future when the Hermanus Magnetic Observatory acquires a low-latitude HF radar. These measurements should offer a unique opportunity to study the E-region over South Africa at night, which is not currently possible with the available ionosondes.

One step in furthering this study to determine the effects on the ionosphere due to the precipitation of energetic particles in greater detail, is to calculate the deposition of energy from particle penetration. The particle energy is absorbed by the atmosphere through collisions with, and scattering by, atmospheric constituents, which result in either dissociation or ionisation of the atmospheric constituents. Production of each electron pair within the atmosphere requires an energy deposition of approximately 35 eV. In addition to the energy imparted directly to the atmosphere during collisions, a certain amount of energy is converted to X-rays by the bremsstrahlung process. This is associated with the rapid deceleration of energetic electrons during their penetration into the atmosphere, providing additional ionisation down to altitudes of 20 km. This investigation would entail computing ionisation rate height profiles from a given energy spectrum. Lazarev (1965) derived an empirical function for the energy absorption of an electron beam in matter which could be used. The function is related to the energy distribution of an electron beam as it travels through air layers of different mass. Schiffler (1996) obtained a formula for computing the ionisation rate at various levels in the upper atmosphere during injection of electron beams of various energies. This method would require knowledge of energy and flux of the precipitating particles which can be obtained from the DMSP SSJ/4 data.

The correlations between particle precipitation and geomagnetic activity presented in this study are visual. Visualisation is a powerful method to study the space-time variability of energy deposition due to precipitating particles. To be more effective, future work should use statistical methods in determining the correlation. Statistical methods would reveal, in detail, the magnitude of geomagnetic activity required to produce significant increases in ionisation. It would entail the study of more precipitation events and would therefore require more volumes of data than used in the current study.

In this study, data from only one DMSP satellite was used although five satellites are in operation. Thus the South African region was monitored only twice per day. Future work should include data from the other satellites as well, which will increase the number of times per day a particular region under investigation is monitored. A clearer picture of the time evolution of particle precipitation through the day could be constructed. The use of data from more than one satellite would require detailed understanding of the orbital orientations of the satellites. It would also require access to more volumes of data and would require more time.

5.2 Conclusions

This study has presented an investigation into the effects of particle precipitation on the ionosphere in the region over South Africa. The main results emerging from this investigation are as follows:

1. DMSP observations of particle precipitation showed that there was no particle precipitation observed in the region over South Africa. The analysis was made for the periods when both the SAA and the auroral regions were populated with energetic electrons and protons on the events of October 5 and April 7, 2000. Energetic particle precipitation in the SAA region is a well established phenomenon and the aeronomic effects in terms of the enhanced ionisation that the precipitating particles cause are now well established based on the diverse results presented by Gledhill (1976); Abdu *et al.* (2005); Haggard (2004). During these events, high fluxes of electrons and protons in the SAA region deposited significant amounts of energy into the region triggering increases in ionisation. SSIES package ion density measurements revealed that higher average ionisation values were observed during the periods of particle precipitation in the two selected events. In region over South Africa, on the other hand, no density enhancements were observed.

2. There is a good "visual" correlation between geomagnetic activity and enhanced ionisation in the SAA region. Increased geomagnetic activities are associated with large energy inputs into the upper atmosphere in the form of energetic particle precipitation, enhanced electric fields and enhanced electric currents (Buonsanto, 1999). The increased energy inputs are responsible for the observed enhanced ionisation.

3. This study also confirms the previous results of Yizengaw *et al.* (2005) that precipitation of energetic electrons and protons in the auroral region could cause enhanced energy inputs into the upper atmosphere which could lead to considerable heating and expansion of the thermosphere resulting in the depletion of the foF2 value. The value of the foF2 is lower during the precipitation events than on the days before and after the events.

4. Other features observed are the disturbances in the F- and the E-regions during the precipitation events. Patches of sporadic E-layers were visible in the ionograms recorded during the October 5 event. Presence of sporadic E-layers in the ionosphere could prevent the high frequencies normally reflected in the F-layer from propagating to the F-region heights.

In conclusion, with the data used in this study, it was not possible to establish a direct connection between particle precipitation events and ionospheric disturbances over the South African region. However, with access to nighttime E-region ionisation data and a larger particle precipitation database, future work should reveal any correlations.

Appendix A

The DMSP SSJ/4 IDL program

A.1 Description

Interactive Data Language (IDL) software was used to analyse the particle data from the SSJ/4 instrument. IDL software is sufficient for data analysis and visualisation and has the capability to read unformatted binary data files.

The IDL program, energy.pro, reads the DMSP unformatted binary precipitating electron and ion data from the SSJ/4 instrument and plots the data interactively to the screen or to a postscript file.

The program has thirty five subroutines which perform different analysis procedures on the data. The details of each subroutine are explained in detail in the program prior to the subroutine.

A.2 User instructions

The program prompts the user to supply some input parameters on the location of the data to process and the outputs needed.

One set of data can be plotted per page, up to 30 minutes per plot. If the time span for the plot is 30 minutes or less, the maximum time span for each plot is set for that, and the minimum latitude is set for 0.0, the program will plot one data set per page.

The program can also produce a number of plots in a row (consecutive times). The user must set the start time for the first plot, set the end time for the end of the last plot, as well as the maximum amount of time per plot. The program will read in one set of data, plot it out, then read in another set and plot, e.t.c., until the last time is equal or greater than the end time. The minimum latitude should be set to 0.0. If the user specifies the minimum latitude, the program can plot a number of plots above the set minimum latitude. One or both hemispheres can be plotted.

The program allows users to enter lines and text on plots. The lines are from the bottom to the top of the energy flux plot, and are drawn at a specified time (hour, minute, second). The text is centered on a specified time and is 70% the size of the normal text.

The user is given options to either enter the input parameters from the keyboard or from a separate text file. A text file called jonly.txt containing the necessary input parameters is given and can be edited by the user. The user must specify the location of the file to enter the inputs from a file.

References

Aarons, J. and Rodger, A. S., “The effects of electric field and ring current energy increases on F-layer irregularities at auroral and subauroral latitudes,” *Radio Science.*, **26**: pp. 1115–1129, 1991.

Abdu, M. A., Ananthakrishnan, S., Coutinho, E. F., Krishnan, B. A. and Reis, E. M., “Azimuthal drift and precipitation of electrons into the South Atlantic geomagnetic anomaly during SC magnetic storm,” *Journal of Geophysical research*, **78**: pp. 5830–5838, 1973.

Abdu, M. A., Batista, I. S., Carrasco, A. J. and Brum, C. G. M., “South Atlantic anomaly ionisation: A review and a new focus on electrodynamic effects in the equatorial ionosphere,” *Journal of Atmospheric and Solar-Terrestrial Physics*, **67**: pp. 1643–1657, 2005.

Appleton, E. V., “Two Anomalies in the ionosphere,” *Nature*, **157**: p. 691, 1946.

Ashrafi, M., Kosch, M. J. and Honary, F., “Comparison of the characteristic energy of precipitating electrons derived from ground-based and DMSP satellite data,” *Annales Geophysicae*, **23**: pp. 135–145, 2005.

Baker, D. N., “Coupling between the solar wind, Magnetosphere, Ionosphere and Neutral Atmosphere,” University of Colorado, Boulder, CO 80309, 2004.

Balan, N. and Bailey, G. J., “Equatorial Plasma fountain and its effects: Possibility of an additional layer,” *Journal of Geophysical Research*, **100**(A11): pp. 21, 421, 1995.

Basua, S., Grovesa, K. M., Quinna, J. M., and Dohertyb, P., “A comparison of TEC fluctuations and scintillation at Ascension Island,” *Journal of Atmospheric and Solar Terrestrial Physics*, **61**: pp. 1219–1226, 1999.

Benbrook, J. R., Bering, E. A., Leverenz, H., Roeder, J. L. and Sheldon, W. R., "Quiet-time electron precipitation at L = 4 in the South Atlantic anomaly," *Journal of Geophysical Research*, **88**(17): pp. 189–199, 1983.

Bencze, P., Burešová, D., Laštovička, J. and Märcz, F., "Behaviour of the F1-region, and Es and spread-F phenomena at European middle latitudes, particularly under geomagnetic storm conditions," *Annals of Geophysics*, **47**(2/3): pp. 1131–1143, 2004.

Blagoveshchensky, D. V., Pirog, O. M., Polek, N. M. and Chistyakova, L. V., "Mid latitudes effects of the May 15, 19997 magnetic storm," *Journal of Atmospheric and Terrestrial Physics*, **65**: pp. 203–210, 2003.

Bob, A. and Thorne, R. M., "Modelling Energetic Electron Precipitation near the south African Anomaly," *Journal of Geophysical Research*, **104**(A4): pp. 7037–7044, 1999.

Boundouridis, A., Zesta, E., Lyons, L. R., Anderson, P. C. and Lumerzheim, D., "Enhanced solar wind geoeffectiveness after a sudden increase in dynamic pressure during southward IMF orientation," *Journal of Geophysical research*, **110**(A0514): pp. 1–15, 2005.

Bowman, G. G., "The nature of ionospheric spread-F irregularities in mid-latitude region," *Journal of Atmospheric and Terrestrial Physics*, **43**: pp. 65–79, 1981.

Buonsanto, M. J., "Ionospheric storms-a review," *Space Science Review*, **88**: pp. 563–601, 1999.

Callis, L. B., Boughner, R. E., Baker, D. N., Blake, J. B. and Lambeth, J. D., "Precipitation relativistic electrons - Their long-term effect on stratospheric odd nitrogen levels," *Journal of Geophysical Research*, **96**(15): pp. 2939–2976, 1991a.

Callis, P. N., Häggström, I., Kelly, K. and Rietveld, T., "EISCAT radar observations of enhanced incoherent scatter spectra; their relation to red aurora and field aligned currents," *Geophysical research letters*, **18**: pp. 1031–1034, 1991b.

Conkright, R. O., "SPIDR on the Web: Space Physics Interactive Data Resource on-line analysis tool," Proc. URSI XXVI GA, p. 491, Toronto, Canada, 1999.

Danilov, A. D. and Lastovicka, J., "Effects of geomagnetic storms on the ionosphere and atmosphere," *International Journal of Geomagnetic Aeronomy*, **2**: pp. 209–224, 2001.

DeMajistre, R., Brandt, P. C., Immel, T. J., Yee, J. H., Dalgarno, A., Paxton, L. J. and Kharchenko, V., "Storm-time enhancement of mid-latitude ultraviolet emissions due to energetic neutral atom precipitation," *GEOPHYSICAL RESEARCH LETTERS*, **32**(L15105), 2005.

Detrick, D. L. and Rosenberg, T. J., "A phased-array radiowave imager for studies of cosmic noise absorption," *Radio Science*, **25**: pp. 325–338, 1990.

Fanning, D. W., "Fanning Consulting - Day/Night terminator on Map," `http://www.dfanning.com/map_tips/terminator.html`, 2006.

Fejer, B. G. and Emmert, T. J., "Low latitude ionospheric disturbance electric field effects during the recovery phase of the October 19-21 1998 magnetic storm," *Journal of Geophysical research*, **108**(A2): p. 1454, 2003.

Foster, J. C., Cummer, S. and Inan, U. S., "Mid-Latitude Particle and Electric Field Effects at the Onset of the November 1993 Geomagnetic Storm," *Journal of Geophysical Research*, 1997.

Foster, J. C. and Rich, F. J., "Prompt mid-latitude electric field effects during severe geomagnetic storms," *Journal of Geophysical research*, **102**: pp. 1–5, 1997.

Fuller-Rowell, T. J. and Codrescu, M. V., "On the seasonal response of the thermosphere and ionosphere to geomagnetic storms," *Journal of Geophysical research*, **101**(A2): pp. 2343–2353, 1996.

Fuller-Rowell, T. J., Codrescu, M. V., Moffet, R. J. and Quegan, S., "Response of the thermosphere and ionosphere to geomagnetic storms," *Journal of Geophysical research*, **99**: pp. 3893–3914, 1994.

Fuselier, S. A., Gary, S. P., Thomsen, M. F., Claflin, E. S., Hubert, B., Sandel, B. R. and Immel, T., "Generation of Dayside sub-Auroral proton precipitation," *Journal of Geophysical Research*, **109**(A12227): pp. 1–11, 2004.

Galand, M., "Introduction to special section: Proton Precipitation in the Ionosphere." *Journal of Geophysical Research*, **106**(A1): pp. 1–6, 2001.

Galand, M., Baumgardner, J., Chakrabarti, S., Lovhaug, U. P., Isham, B., Jussila, J., Evans, D., Rich, F. and Lummerzheim, D., "Proton and Electron Aurora over EISCAT," in "Optical signature and associated Ionospheric Perturbations," Proc. of 30th annual European Meeting on Atmospheric Studies by Optical Methods, 2003.

Galand, M. and Evans, D., "Radiation Damage of the Proton MAPED Detector on POES(TIROS/NOAA) Satellites," Technical Report, NOAA Technical Report OAR, 2000.

Galand, M., Fuller-Rowell, T. J. and Codrescu, M. V., "Response of the upper atmosphere to auroral protons," *Journal of Geophysical Research*, **106**: pp. 127–139, 2001.

Galand, M., Lummerzheim, D., Stephan, A. W., Bush, B. C. and Chakrabart, S., "Electron and proton Aurora observed spectroscopically in the far ultraviolet," *Journal of Geophysical Research*, **107**(A7): pp. 1–14, 2002.

Galand, M. and Richmond, A. D., "Ionospheric Electrical Conductances Produced by Auroral Proton Precipitation," *Journal of Geophysical Research*, **106**(A1): pp. 117–125, 2001.

Gledhill, J. A., "Aeronomic Effects of the South Atlantic Anomaly," *Reviews of Geophysics and Space Physics*, **14**: pp. 173–187, 1976.

Haggard, R., The effects of particle precipitation on the ionosphere in the South Atlantic anomaly region, Ph.D. thesis, Rhodes University, 1994.

Haggard, R., "Particle precipitation effects in the day time E-region in the South Atlantic Anomaly region," *South African Journal of science*, **100**: pp. 527–530, 2004.

Hardy, D. A., Gussenhoven, M. S. and Brautigam, D., "A statistical model of auroral ion precipitation," *Journal of Geophysical Research*, **94**: pp. 370–392, 1989.

Hardy, D. A., Gussenhoven, M. S. and Holeman, E., "A statistical model of auroral electron precipitation," *Journal of Geophysical Research*, **90**: pp. 4229–4248, 1985.

Hardy, D. A., Smith, L. K., Gussenhoven, M. S., Marshall, F. J., Yeh, H. C., Shumaker, T. L., Hube, A. and Pantazis, J., "Precipitating electron and ion detectors (SSJ/4) for the block 5D/rights 6-10 DMSP satellites Calibration and data presentation," Technical Report, Hanscom Air Force Base Mass., Rep. AFGL-TR-84-0317 Air Force Geophys. Lab., 1984.

Hawk, M., "Mid-Latitude Sporadic-E - A review," 2001.

Heelis, R. A., Bailey, G. J. and Hanson, W. B., "Ion Temperature troughs and interhemispheric transport observed in the equatorial ionosphere," *Journal of Geophysical Research*, **83**: p. 3683, 1978.

Holmes-Siedle, A. and Adams, L., "Trapped Radiation and the South Atlantic Anomaly," in "Handbook of Radiation Effects," p. 642, Oxford University Press, Ithaca, New York, 2002.

Horne, R. B. and Thorne, R. M., "Relativistic electron acceleration and precipitation during resonant interactions with whistler-mode chorus," *Geophysical Research letters*, **30**(10): pp. 34–1–34–4, 2003.

Hunsucker, R. D., "Radio techniques for probing the terrestrial ionosphere," Technical Report, Springer-Verlag:Berlin, 1991.

Idenden, D., "The thermospheric effects of a rapid polar cap expansion," *Annales Geophysicae*, **16**: pp. 1380–1391, 1998.

Ishimoto, M. and Torr, M. R., "Energetic He(+) precipitation in a mid-latitude aurora," *Journal of Geophysical research*, **92**: pp. 3284–3292, 1987.

Kelly, M. C., The Earth's ionosphere. Plasma physics and electrodynamics, Academic Press. Inc., London, 1989.

Lang, K. R., Planet Earth. Ch. 2 in Astrophysical Data: Planets and Stars, New York Springer-Verlag, 1992.

Lazarev, V. I., "Absorption of the energy of an electron beam in the upper atmosphere," *Geomagnetism and Aeronomy*, **7**: pp. 219–223, 1965.

Li, X., Baker, D. N., Elkington, S., Temerin, M., Reeves, G. D., Belian, R. D., Blake, J. B., Singer, H. J., Peria, W. and Parks, G., "Energetic Particle Injections in the Inner Magnetosphere as a Response to an Inter planetary Shock," *Journal of Atmospheric and Solar Terrestrial Physics*, **65**: pp. 233–244, 2003.

Lilensten, J. and Galand, M., "Proton/electron precipitation effects on the electron production and density above EISCAT and ESR," *Annales Geophysicae*, **16**: pp. 1299–1307, 1998.

Liu, J., Chen, Y., Jhuang, H. and Lin, Y., "Ionospheric foF2 and TEC Anomalous Days Associated with $M > 5.0$ Earthquakes in Taiwan during 1997-1999," *TAO*, **15**(3): pp. 371–383, 2004.

Mangalev, V. S., Krisvilev, V. N. and Mingaleva, G. I., "Precipitating soft corpuscle influence on the parameters of the ionosphere E and F regions an the cusp region," *Geomagnetism and Aeronomy*, **34**: pp. 200–204, 1994.

Matthews, J. D., "Sporadic E: current views and recent progress," *Journal of Atmospheric and Solar-Terrestrial Physics*, **60**: pp. 413–435, 1998.

McNamara, L. F., The ionosphere: Communications, surveillance and direction finding, Kriegner publishing company, Malabar, Florida, 1991.

Nashimo, M., Nozawa, S. and Holtet, J. A., "Daytime Ionospheric Absorption Features in the Polar Cap Associated with Poleward Drifting F-region Plasma Patches," *Earth Planets Space*, **50**: pp. 107–117, 1998.

Nishino, M., Makita, K., Yumoto, K., Rodrigues, F. S., Schuch, N. J. and Abdu, M. A., "Usual ionospheric absorption characterising energetic electron precipitation into the South Atlatic magnetic anomaly," *Earth Planets and Space*, **54**: pp. 907–916, 2002.

Østgaard, N., Stadsnes, J., Bjordal, J., Thorsen, E., Vondrak, R. R., Cummer, S. A., Chenette, D. L., Parks, G. K., Brittnacher, M. J. and McKenzie, D. L., "Global Scale Electron Precipitation During Substorm Expansions," *Journal of Geophysical Research*, **104**(10): pp. 191–204, 1999.

Prölss, G. W., "On explaining the local time variation of ionospheric storm effects," *Annales Geophysicae*, **11**: p. 1, 1993.

Rassoul, H. K., Rohrbaugh, R. P. and Tinsley, B. A., "Low-Latitude Particle Precipitation and Associated Local Magnetic Disturbances," *Journal of Geophysical research*, **97**(A4): p. 40414052, 1992.

Rassoul, H. K., Rohrbaugh, R. P., Tinsley, B. A. and Slater, D. W., "Spectrometric and photometric observations of low latitude auroras," *Journal of Geophysical research*, **98**: pp. 7695–7701, 1993.

Rassoul, K. and Hamid-Reza, Characteristics of Optical Emissions and Particle Precipitation in Mid/low Latitude Aurorae, Ph.D. thesis, THE UNIVERSITY OF TEXAS AT DALLAS, 1987.

Reinisch, B., Galkin, I. A., Khmyrov, G., Kozlov, A. and Kitrosser, D. F., "Automated collection and dissemination of ionospheric data from the digisonde network," *Advances in Radio Science*, **2**: pp. 241–247, 2004.

Rich, F. and Foster, J., "Dmsp data request; accessed in February 2006," `http://leadbelly.lanl.gov/GEM_Storms/storms/data/DMSP/DMSP.html`, 1998.

Ridley, A., IDL program to read binary DMSP SSJ/4 data and output plots and ASCII data, `ftp://dropbox.plh.af.mil/pub/dmsp/idl/`, 1994.

Robinson, R. M., Mende, S. B., Vondrak, R. R., Kozyra, J. U. and Nagy, A. F., "Radar and photometric measurements of an intense type A red aurora," *Journal of Geophysical research*, **90**: pp. 457–466, 1985.

Roble, R. G., "The Polar Lower Thermosphere," *Planet Space Science*, **40**: pp. 271–297, 1992.

Schiffler, A., SuperDARN measurements of double-peaked velocity spectra, Master's thesis, Institute of Space and Atmospheric Studies (ISAS), 1996.

Senior, C., "Solar and particle contributions to auroral height-integrated conductivities from EISCAT data: A statistical study," *Annales Geophysicae*, **9**: pp. 449–460, 1991.

Sherrill, T. J., "Orbital Science's 'Bermuda Triangle'," *Sky and Telescope*, pp. 134–139, 1991.

Søraas, F., Lindalen, R. H., Mâseide, K., Engeland, A., Sten, T. A. and Evance, D. S., "Proton precipitation and the H_β emission in a postbreakup auroral glow," *Journal of Geophysical research*, **79**: pp. 1851–1859, 1974.

Stern, D. and Peredo, M., "The exploration of the magnetosphere," 1995, `http://www-spof.gsfc.nasa.gov/Education/wradbelt.html`.

Thorne, R. M. and Kennel, C. F., "Relativistic electron precipitation during magnetic storm main phase," *Journal of Geophysical research*, **76**(A7): p. 4446, 1971.

Townsend, R. E., Source Book of the Solar-Geophysical Environment, AFGWC/WSE, Offutt AFB, Neb., 1982.

Vampola, A. L. and Gorney, D. J., "Electron energy deposition in the middle atmosphere," *Journal of Geophysical Research*, **88**(17): pp. 6267–6274, 1983.

Venkatraman, S. and Heelis, R., "Longitudinal and seasonal variations in night time plasma temperatures in the equatorial topside ionosphere during solar maximum," *Journal of Geophysical Research*, **104**(A2): pp. 2603–2612, 1999.

Wang, Z., Rosenberg, T. J., Stauning, P., Basu, S. and Crowley, G., "Calculation of Riometer Absorption Associated with F-region Plasma Structures based on Sondre Stromfjord Incoherent Scatter Radar Observation," *Radio Science*, **29**: pp. 209–215, 1994.

Whitehead, J. D., "The formation of the sporadic E-layer in the temperate zones," *Journal of Atmospheric and Terrestrial Physics*, **20**: pp. 49–58, 1961.

Yahnin, A. G., Yahnina, T. A. and Demekhov, A. G., "The VLF and ULF related Particle Precipitations and Cold Plasma Structures in the Equatorial Magnetosphere," in "Physics of Auroral phenomena 2003," Proc. XXVI Annual Seminar,Apatity, pp. 131–134, Kola Science center, Russian Academy of Science, 2003.

Yizengaw, E., Dyson, P. L., Essex, E. A. and Moldwin, M. B., "Ionosphere dynamics over the Southern Hemisphere during the 31 March, 2001 severe magnetic storm using multi-instrument measurement data," *Annales Geophysicae*, **23**: pp. 707–721, 2005.

Yizengaw, E., Essex, E. A. and Birsa, R., "The Southern Hemisphere and Equatorial region ionisation response for September 22, 1999 severe magnetic storm," *Annales Geophysicae*, **22**: pp. 2765–2773, 2004.