Review of recent research in geomagnetism and aeronomy in South Africa: 2003-2006

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This paper gives a brief review of research results of South African institutes with activities relating to the International Association of Geomagnetism and Aeronomy (IAGA) during the quadrennium 2003-2006. The report forms part of the South African National Report to the International Union of Geodesy and Geophysics (IUGG) for presentation at the IUGG General Assembly to be held in Perugia, Italy, during July 2007. South African institutions actively involved in IAGA-related activities during the last four years included: School of Physics, University of KwaZulu-Natal, Durban; Hermanus Magnetic Observatory (HMO), NRF, Hermanus; Department of Physics and Electronics, Rhodes University, Grahamstown; Unit for Space Physics, Department of Physics, North-West University, Potchefstroom. The report will be organized according to core activities of IAGA as pursued at the various research organizations in South Africa.

Geomagnetism

Geomagnetic observatories, field surveys and modelling

Continuous recording of geomagnetic field variations are conducted at Hermanus (34º 25.5’ S, 19º 13.5’ E), Hartebeesthoek (25º 52.9’ S, 27º 42.4’ E) and Tsumeb (19º 12’ S, 17º 35’ E). All these observatories comply with INTERMAGNET standards. The primary instrument for recording of magnetic field variations is the FGE fluxgate magnetometer, manufactured by the Danish Meteorological Institute in Copenhagen, Denmark. This instrument is based on three-axis linear-core fluxgate technology, optimised for long-term stability and records the components H, D and Z. An Overhauser-type magnetometer further provides absolute total field information, while baselines for the other components are obtained using a DI Flux theodolite.

For field survey purposes, field stations are marked by concrete beacons, ensuring that all observation points are exactly reoccupied during surveys. Most measurements are taken on a standard 1.2m pillar, while in a few cases observers had to use a tripod mounted above a clearly marked shorter beacon.

The international and local geophysics communities have expressed significant interest in the rapid decrease of the geomagnetic main field in the southern African region [Kotzé, 2003a], which suggests that a reverse dynamo may be developing below South Africa

[Hulot *et al*, 2002]. The HMO and the GeoForschungsZentrum (GFZ), Potsdam, Germany, have commenced with a collaborative effort to study this phenomenon using ground based and satellite data. This cooperative project between Germany and South Africa, called *Inkaba ye Africa*, the COMPASS (COmprehensive Magnetic Processes under the African Southern Sub-continent) program aims to study the geomagnetic field and in particular its evolutionary behaviour. In addition to a rapid decrease of the geomagnetic field in this region as evidenced by the 20% decrease observed at Hermanus, the orientation of the geomagnetic field in southern Africa is also changing rapidly [Kotzé, 2003b]. In the north-western part of southern Africa the declination of the magnetic field is propagating eastward (Tsumeb) and in the south-eastern part westward (Hermanus and Hartebeesthoek). This results in the spatial gradient over the subcontinent to increase with time. During 2005 and 2006 joint field survey campaigns were conducted by the Hermanus Magnetic Observatory (HMO) and the GeoForschungsZentrum (GFZ) in southern Africa, including countries like South Africa, Namibia and Botswana in order to characterize the time variation of various components of the geomagnetic field. The field surveys of 2005/2006 were separated into three different sectors. At first a survey was done by only HMO field surveyors, shown by the blue markers in figure 1. Then 2 independent teams, each consisting of a staff member from HMO and GFZ, conducted a simultaneous field survey in southern Africa, shown by the green and yellow markers respectively in figure 1. Those positions with red circles were found not suitable for field survey measurements. Mostly it was a case that the region was no more magnetically quiet, or that the observation pillar was destroyed due to urban expansion projects. A DI fluxgate magnetometer was used as primary instrument during field surveys to obtain values of D and I, while an Overhauser magnetometer delivered values of total field intensity (F). Corrections for diurnal variation and other disturbing effects were made by comparing field station observations with magnetic data recorded on site with a LEMI suspended tri-axis fluxgate instrument [Korte *et al*, 2006]. This proved to be a vast improvement by using magnetic observatories, sometimes a distance of more than 300 km away. Results obtained from this field survey, together with information obtained from the previous field survey during 2004 at 8 field stations as well as the data from the 3 continuous recording magnetic observatories in southern Africa at Hermanus, Hartebeesthoek and Tsumeb, have been used to model the geomagnetic field time variation for 2004-2005, employing a polynomial approach [Kotzé *et al,* 2006].

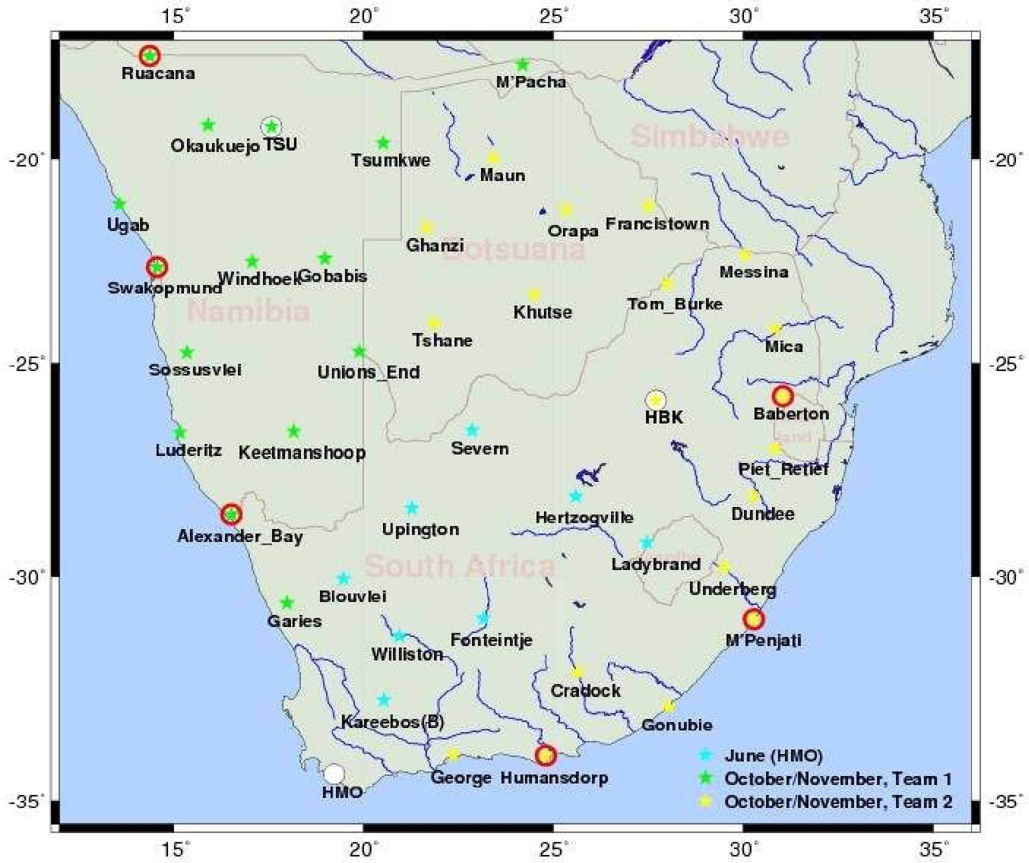

Figure 1: Repeat stations visited during 2005 field survey

As part of the collaboration between GFZ and HMO, instruments for a new magnetic observatory at Keetmanshoop in Namibia, were installed at the local airport during 2005 [Linthe *et al,* 2006]. This location was specifically chosen about halfway between Hermanus in the South and Tsumeb in the North in order to correct for disturbance effects from external sources and to refer the repeat station data to a common epoch during field surveys. This newly-established INTERMAGNET-grade observatory will play a key role in the region, as:

1. a reference magnetic observatory for field stations within a radius of 600 km located in the large area between the Northern Cape and southern Namibia, a region which has not been adequately covered in the past.

2. an accurate monitor of spatial changes in secular variation across southern Africa. At present the declination secular variations at the south-eastern and north-western borders of southern Africa are currently 11 arc min/yr westward and 6 arc min/yr eastward, respectively (see bellow). Keetmanshoop observatory, located between HER and TSU in a North-South direction, as well as in an East-West direction on approximately the same magnetic latitude of Hartebeesthoek, will help to accurately monitor the spatial change of secular variation across southern Africa.

This was done with excellent logistical support from the Geological Survey of Namibia as well as the Namibia Airports Company. The recording instruments, a 3-axis FGE fluxgate magnetometer, an Overhauser absolute magnetometer, as well as a DI Flux theodolite for doing absolute measurements, were provided by GFZ, while HMO provided the glass-fibre box for housing the instruments. The design of this magnetic observatory is quite unique, as it deviates substantially from the traditional setup we have become used to. The whole observatory is buried underground in the glass fibre container, and then filled with water bottles for temperature stabilization. The data recording computer with its cell phone technology for data transmission were installed early in 2006. At present data are transmitted to Hermanus on a daily basis, while base-lines are determined at regular intervals by personnel of the Keetmanshoop Airport in Namibia.

ULF geomagnetic pulsation data

The HMO continued to record ultra low frequency geomagnetic pulsation data at Hermanus, and also at Sutherland [32^o 24' S, 20^o 40' E].
The data were obtained by measuring the voltages induced in two horizontally mounted induction sensors, one oriented approximately in the magnetic meridian (H-component) and the other perpendicular to this direction (D-component). The data are logged digitally on a PC with sampling at 1 sec intervals and accurate timing provided by a GPS receiver. The appearance of Pi2 pulsations in the data are regularly utilised by researchers world-wide to determine the occurrence and timing of substorm onsets and enhancements.

Aeronomic phenomena

Total Electron Content (TEC) Mapping

The Grahamstown, South Africa (33.3°S, 26.5°E) ionospheric field station operates a UMass Lowell digital pulse ionospheric sounder (Digisonde) and an Ashtech geodetic grade dual frequency GPS receiver. The GPS receiver is owned by Chief Directorate Surveys and Mapping (CDSM) in Cape Town, forms part of the national TrigNet network and was installed in February 2005. The sampling rates of the GPS receiver and Digisonde were set to 1 second and 15 minutes respectively. Data from four continuous months, March to June 2005 inclusive, were considered in this initial investigation. Data available from the Grahamstown GPS receiver was limited, and, therefore, only these 4 months have been considered. Total Electron Content (TEC) values were determined from GPS measurements obtained from satellites passing near vertical (within an 80° elevation) to the station. TEC values were obtained from ionograms recorded at times within 5 minutes of the near vertical GPS measurement [Cilliers *et al*, 2004]. The GPS derived TEC values are referred to as GTEC and the ionogram derived TEC values as ITEC. Comparisons of GTEC and ITEC values were obtained. The differential clock biases of the GPS satellites and receivers are taken into account. The plasmaspheric contribution to the TEC could be inferred from the results, and confirmed findings obtained by other groups.

South Africa has three operational ionosondes, including the Grahamstown one, whose data has been utilised in developing a national model. The South African network of GPS receivers, as shown in Figure 2, is expanding and it is the long term plan to utilise the data from these receivers to derive ionospheric information over the areas that are not covered by the current ionosondes. This will allow using an existing network to supplement the ionospheric network, thereby providing a more comprehensive map of ionospheric behaviour over South Africa.

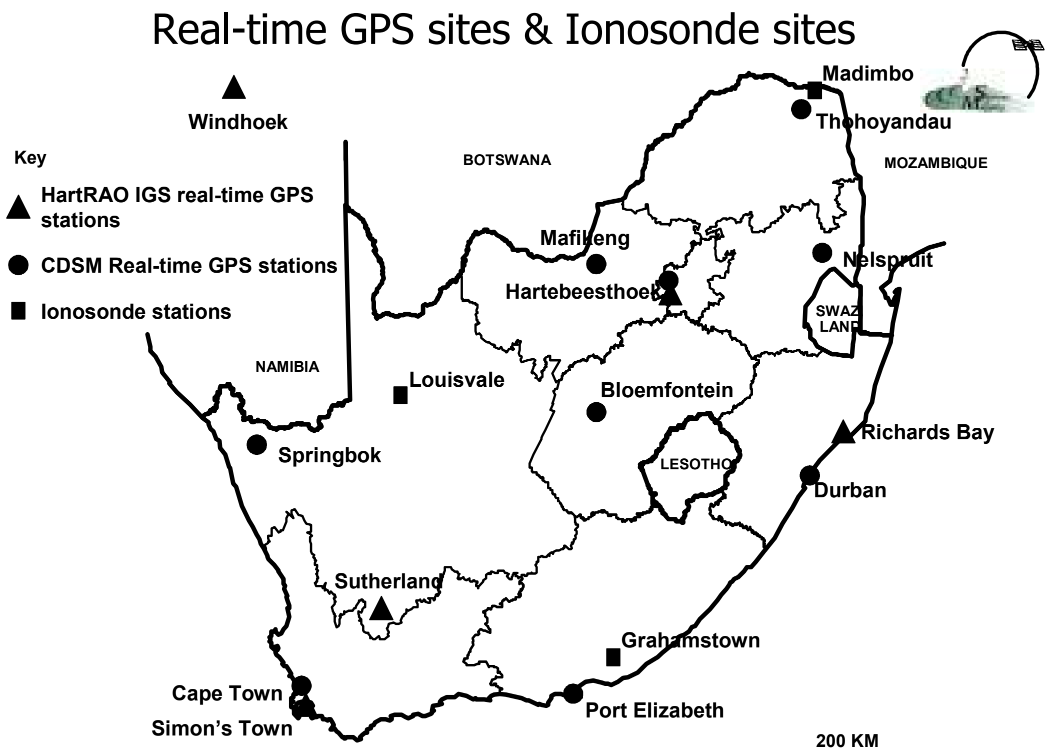

Figure 2: A map of South Africa depicting the real time GPS and ionosonde sites.

Neural Network Modelling of Ionospheric Parameters

Neural networks (NNs) are proving to be ideal tools for modeling the behaviour of the ionosphere. The NNs are trained using a database of archived data describing the relationship between the output parameter and an input space. The input space is designed from knowledge of those variables that affect the behaviour of the output parameter. For ionospheric parameters this input space would always include a solar variable due to the strong influence that the sun has on ionospheric behaviour.

An investigation was done, using the critical frequency of the F2 layer, foF2, which provides an indication of the ionospheric maximum electron density, to demonstrate how NNs can be used to determine the optimum solar input variable for use in predicting foF2 [Oyeyemi, *et al,* 2004]. Amongst the solar inputs used are the daily sunspot number, the F10.7cm solar radio flux, and the solar irradiance. Varying time lengths of these parameters are also investigated. The criteria used in determining the optimum input is the root mean square (rms) error between the measured and predicted output parameters.

The technique of neural networks has provided a highly successful new method for developing models to predict and forecast the highly non linear ionospheric behaviour [Oyeyemi *et al,* 2005a]. In addition, it was illustrated that NNs can provide another means for determining the optimum input parameters required for the prediction of ionospheric parameters. NNs can also provide evidence of the existence of new relationships between unknown geophysical parameters and the ionospheric output and the extent of that relationship.
NNs can also be seen as a powerful modeling technique that combines existing archived databases providing the history of ionospheric behaviour, the experience and expertise gained from years of analytical analysis and measurements, and the advanced computing power, skills and technologies of today, to give a all in one solution to a non-linear problem.

The use of neural networks (NNs) has been employed in another investigation to develop a global model of the ionospheric F2 region critical frequency, foF2 [Oyeyemi *et al,* 2005b]. The main principle behind this particular approach has been to utilize parameters other than simple geographic coordinates, on which foF2 is known to depend, and to exploit the ability of NNs to establish and model this nonlinear relationship for predictive purposes. The foF2 data used in the training of the NNs were obtained from 59 ionospheric stations across the globe at various times from 1964 to 1986, on the basis of availability. To test the success of this approach, one NN (NN1) was trained without data from 13 stations, selected for their geographic remoteness, which could then be used to validate the predictions of the NN for those remote coordinates. These stations were subsequently included in the final NN (NN2). The input parameters consisted of day number (day of the year), universal time, solar activity, magnetic activity, geographic latitude, angle of meridian relative to subsolar point, magnetic dip angle, magnetic declination, and solar zenith angle. Comparisons between foF2 values determined using NNs and the International Reference Ionosphere (IRI) model (from Union Radio Scientifique Internationale (URSI) and International Radio Consultative Committee (CCIR) coefficients) with observed values are given with their root-mean-square (RMS) error differences for test stations. The results from NN2 are used to produce the global behavior of hourly values of foF2 and are compared with the IRI model using URSI and CCIR coefficients. The results obtained (i.e., RMS error differences), which compare favorably with the IRI models, justify this technique for global foF2 modeling.

The use of the neural network (NN) technique for the development of a near-real time global foF2 (NRTNN) empirical model was undertaken by Rhodes University [Oyeyemi *et al*, 2006a]. The data used are hourly daily values of foF2 from 26 worldwide ionospheric stations (based on availability) during the period 1976–1986 for training the NN and between 1977 and 1989 for verifying the prediction accuracy. The training data set includes all periods of quiet and disturbed geomagnetic conditions. Two categories of input parameters were used as inputs to the NN. The first category consists of geophysical parameters that are temporally or spatially related to the training stations. The second category, which is related to the foF2 itself, consists of three recent past observations of foF2 (i.e. real-time foF2 (F0), 2 h (F_2) and 1 h (F_1) prior to F0) from four control stations (i.e. Boulder (40.01N, 254.71E), Grahamstown (33.31S, 26.51E), Dourbes (50.11N, 4.61E) and Port Stanley (51.71S, 302.21E). The performance of the NRTNN was verified under both geomagnetically quiet and disturbed conditions with observed data from a few veri.cation stations. A comparison of the root mean square error (RMSE) differences between measured values and the NRTNN predictions with our earlier standard foF2 NN empirical model is also illustrated. The results reveal that NRTNN will predict foF2 in near-real time with about 1MHz RMSE difference anywhere on the globe, provided real time data is available at the four control stations. From the results it is also evident that in addition to the geophysical information from any geographical location, recent past observations of foF2 from these control stations could be used as inputs to a NN for near-real time foF2 predictions. Results also reveal that there is a temporal correlation between measured foF2 values at different locations.

The application of NNs was further extended to develop a global model of the ionospheric propagation factor M(3000)F2 [Oyeyemi *et al,* 2006b]. NNs were trained with daily hourly values of M(3000)F2 from various ionospheric stations spanning the period 1964 to 1986 with the following temporal and spatial input parameters: Universal Time, geographic latitude, magnetic inclination, magnetic declination, solar zenith angle, day of the year, A16 index (a 2-day running mean of the 3-hour planetary magnetic a_p index), R2 index (a 2-month running mean of sunspot number), and the angle of meridian relative to the subsolar point. The performance of the NNs was verified by comparing the predicted values of M(3000)F2 with observed values from a few selected ionospheric stations and the IRI (International Reference Ionosphere) model (CCIR M(3000)F2 model) predicted values. The results obtained compared favourably with the IRI model. Based on the error differences, the result obtained justifies the potential of the NN technique for the predictions of M(3000)F2 values on a global scale.

Furthermore, a new neural network (NN) based global empirical model for the F2 peak electron density (NmF2) has been developed by Oyeyami and McKinnell from Rhodes University, using extended temporal and spatial geophysical relevant inputs. Measured ground based ionosonde data, from 80 global stations, spanning the period 1995 to 2005 and, for a few stations from 1976 to 1986, and from various resources of the World Data Centre (WDC) archives (Space Physics Interactive Data Resource SPIDR, the Digital Ionogram Database, DIDBase, and IPS Radio and Space Services) have been used for training a NN. The training data set includes all periods of quiet and disturbed magnetic activity. A comprehensive comparison for all conditions (e.g. magnetic storms, levels of solar activity, season and different regions of latitudes etc) between foF2 value predictions using the NN based model and International Reference Ionosphere (IRI) model (including both the International Union of Radio Science (URSI) and International

Radio Consultative Committee (CCIR) coefficients) with observed values was investigated. The root-mean-square (RMS) error differences for a few selected stations showed a substantial improvement.

The results of the foF2 NN model presented in this work, which compare favourably with the IRI model, and in some cases with improvement, successfully demonstrate that this new model can be used as a replacement option for the URSI and CCIR maps within the IRI model for the purpose of F2 peak electron density predictions.

Recently neural networks have been applied to model the ionospheric electron density profiles over both South Africa (LAM model) and high latitudes. The NN based model IMAZ (Ionospheric Model for the Auroral Zone) was developed in a joint South African-Austrian effort [McKinnell et al., 2006] to provide a reliable prediction tool for the electron density profile at the altitudes below 150 km and at high latitudes. A combination of data obtained from the European Incoherent Scatter Radar (EISCAT) and measurements from rocketborne wave propagation experiments provided enough high latitude data to cover one solar cycle. The inputs to this model are local magnetic time, total absorption, local magnetic activity, solar zenith angle, and the F10.7 cm solar flux value. The pressure surface, which combines the effects of the seasonal variation (day number) and the altitude, is also included as an input parameter. The output is the electron density at the given input pressure (i.e. altitude).

Both models provide realistic electron density profiles within the boundaries laid down by the data with which the NNs were trained and the purposes for which the models were developed. Predicted profiles from each model are compared with other similar existing models, indicating that the technique of NNs provides a more successful approach to electron density profiling than analytical techniques.

Stratospheric studies

During January, 2005, there were several large X-class solar flares and associated solar energetic particle (SEP) events. Coincidentally, the MINIS balloon campaign had multiple payloads aloft in the stratosphere above Antarctica measuring dc electric fields, conductivity and x-ray flux. One-to-one increases in the electrical conductivity and decreases to near zero of both the vertical and horizontal electric field components were observed by a team of researchers from University of KwaZulu-Natal and other institutions, in conjunction with an increase in particle flux at SEP onset [Kokorowski *et al,* 2006]. Combined with an atmospheric electric field mapping model, these data are consistent with a shorting out of the global electric circuit and point toward substantial ionospheric convection modifications. Additionally, two subsequent, rapid changes were detected in the vertical electric field component several hours after SEP onset. These changes result in similar fluctuations in the calculated vertical current density. The rigidity cut-off dynamics were found to be crucial in understanding these sudden jumps in the vertical electric field.

From the MINIS observations, it is evident that the 20 January, 2005 SEP event had a significant impact on atmospheric electrodynamics. Although the MINIS observations are consistent with previous measurements, deviations from previous observations are also observed. Previous in-situ measurements described a sudden vertical electric field magnitude decrease and conductivity enhancement coinciding with the onset of an SEP event. The MINIS data are consistent with this basic observation. What sets the MINIS data apart are the two subsequent, rapid jumps in the dc vertical field several hours afterwards and the observations of the total (not just vertical) electric field disappearing suddenly at SEP onset. These two unique features of the MINIS data set cannot be explained by simply enhancing the atmospheric conductivity. Rather, it is likely that the rapid vertical fluctuations are related to rigidity cutoff motion while the vanishing of the horizontal field may be connected to more interesting magnetosphere dynamics.

Magnetospheric Phenomena

Cosmic radio noise absorption and auroral luminosity studies

Cosmic radio waves of 5-10 meter wavelengths recorded by the riometers at the Antarctic base at Vesleskarvet have been used to investigate structures of ionization in the ionosphere. In correlated studies, the structures in riometer absorption were compared with digitized all-sky images of auroral optical emissions recorded by a low light-level TV system. Stoker *et al.* (2005) digitized all-sky images of auroral optical emissions, recorded by the low light level TV system at Sanae (70.3° S, 2.4° W, L = 4.0), and then mapped them onto the angular sensitivity functions of both a broad, single-beam riometer and narrow beams of an imaging riometer.
Observations during a substorm expansive phase at the SouthAfrican Antarctic base at SANAE IV (L = 4.1) showed that the 630.0-nm auroral spectral line closely followed the variations in the auroral white light (mainly green and blue spectral lines), and preceded the white light variations from about 0 to 5 s during the time of observation of the pre-midnight substorm on 19 July 2003. Absorptions in cosmic radio noise appeared to vary in a way both related and unrelated to optical emissions. Associated variations were delayed relative to optical variations from 2 to 12 s. These temporal differences in variations support the idea of a local dispersionless acceleration region associated with the expansion phase of the substorm. The temporal differences suggest an increasing electric field as an acceleration mechanism. The unrelated absorptions in cosmic radio noise had then to originate from a different acceleration region.

Studies of Pi2 pulsations

It is well known that Pi2 pulsations, which are impulsive, strongly damped, ultra low frequency oscillations of the geomagnetic field, occur at the time of magnetospheric substorm onsets and intensifications. In particular, Pi2 pulsations recorded at low latitudes, where amplitudes typically lie in the range 0.25-2.5 nT, are one of the clearest indicators of substorm onsets. The Hermanus Magnetic Observatory (HMO) has played an important role in a number of studies carried out at local and overseas institutions to gain a better understanding of the dynamics of the earth's plasma sheet. The HMO's contribution has been to provide and analyse low-latitude, ground-based ULF pulsation data, primarily Pi2 pulsations.

Nosé et al (2003) investigated a Pi2 pulsation that occurred at 0538 UT on 20 September 1995, using data from ground stations and the ETS-VI and EXOS-D satellites. Since ground stations at L = 1.45 _ 12.6 and the two satellites were located at 7–10 hours of magnetic local time (MLT), we could investigate characteristics of the morning side Pi2 pulsation in detail. We also examined geomagnetic field data from equatorial and low-latitude (L _ 1.5) stations at 0200 MLT and 1500 MLT. Our findings include the following: (1) Pi2 pulsations on the morning side were observed over a wide range of L (L < 6.1) with almost identical period (T _ 70 s) and waveforms; (2) the ETS-VI satellite located above the geomagnetic equator at L = 6.3 observed a Pi2 pulsation that had nearly the same period and waveforms as the ground Pi2 pulsation; (3) the Pi2 pulsation observed by ETS-VI appeared in the compressional and radial components; (4) phase lag between the compressional and radial components was _180_ (5) the ground-to-satellite phase lag was _180_ (_0_) for the X component and the compressional (radial) component; (6) the EXOS-D observation placed the plasmapause location at L = 6.8, across which ground Pi2 pulsations changed their characteristics; and (7) no phase delay was found between low-latitude Pi2 pulsations observed around 0700 MLT, 0200 MLT, and 1500 MLT. From these results they concluded that the morning side Pi2 pulsation was caused by the plasmaspheric cavity mode resonance and that its longitudinal structure was rather uniform.

Further studies by Nosé et al (2006) on the longitudinal characteristics of Pi2 pulsations as observed at Kakioka and Hermanus revealed the longitudinal structure of the plasmaspheric cavity mode. They used the geomagnetic field data from two ground stations, Kakioka (27.2° geomagnetic latitude, 208.5° geomagnetic longitude) and Hermanus (_33.9° geomagnetic latitude, 82.2° geomagnetic longitude), and auroral image data acquired by the ultraviolet imager onboard the Polar satellite for the period of December 4, 1996 to March 3, 1997. Our findings include the following: (1) Pi2 amplitude is the largest around the magnetic local time of the auroral breakup site and decreases away from it; (2) when a nightside Pi2 pulsation has large amplitude, a dayside Pi2 pulsation can be observed with a similar waveform; (3) Pi2 pulsations generally have no clear phase differences (mean phase difference of 3.3°) between Kakioka and Hermanus, except for some events; and (4) the phase difference is independent on ΔMLT (difference of magnetic local time between a station and the auroral breakup). These observations suggest that the plasmaspheric cavity mode can be excited globally with a very small value of the azimuthal wave number (*m*_0).

K.-H. Kim et al (2005) on the other hand identified Pi2 pulsations associated with the poleward boundary intensifications during the absence of substorms. Pi2 pulsations during the intervals of extremely quiet geomagnetic conditions (Kp = 0) have been reported by Sutcliffe and Lyons [2002]. These authors observed that several Pi2 bursts occurred simultaneously at high (magnetic latitude = 71°) and low (42°) latitudes during the absence of magnetospheric substorms and found that the bursts are strongly correlated with poleward boundary intensifications (PBIs). The authors discussed the correlation between the PBI-associated Pi2 (PBI-Pi2) bursts and enhancements of energetic particle fluxes in the plasma sheet, but they did not focus on the wave properties of the PBI-Pi2 pulsations. In this study we examine whether the PBI-Pi2 pulsations at middle/low latitudes exhibit spatial variations similar to substorm-associated Pi2 pulsations. Using ground-based data from latitudinally and longitudinally extended magnetometer network and spacecraft data in the duskside, these authors investigate the spatial variation of the frequency, amplitude, phase, and interstation coherence of the PBI-Pi2 events. They show that the PBI-Pi2 pulsations in this study have different features at different local times and suggest that their period and duration are determined at a source region, where fast earthward flows brake.

It has for the first time been possible to extract and clearly resolve Pi2 pulsations from low Earth orbit satellite data due to the unprecedented accuracy and resolution of the CHAMP magnetic field measurements. Sutcliffe et al (2003, 2004) presented initial results of a comparative study of Pi2 pulsations observed by the CHAMP satellite and at the Sutherland ground station [32^{o} 24’ S, 20^{o} 40’ E]. Times when a Pi2 pulsation was observed on the ground (predominantly during night-time) and when CHAMP was located within 30° of longitude of Sutherland and at latitudes less than 50° N and S were selected for study. Following pre-processing and inspection to exclude unsuitable events, the satellite vector magnetic field data were rotated into a field aligned coordinate system and band-pass filtered in the Pi2 frequency band (typically .005 - .05 Hz).

Initial findings to date are the following:

- The correlation between satellite and ground Pi2s is improved by subtraction of a lithospheric magnetic field anomaly model from the satellite data.
- The H-component signal on the ground is well correlated with the compressional (Bcom) and poloidal (Bpol) components above the ionosphere.
- Typical H-component amplitudes on the ground are 0.5 to 2 nT, while at CHAMP the Bcom and Bpol amplitudes are roughly 0.7 and 1.4 times this respectively.
- In the southern hemisphere Bcom and Bpol oscillate in phase with H; however, in the northern hemisphere Bpol appears to oscillate in anti-phase with Bcom and H.

A. Collier et al (2006a) further presented evidence of standing waves during Pi2 events as observed on the CLUSTER satellite mission. Observations of Pi2 pulsations at middle and low latitudes have been explained in terms of cavity mode resonances, whereas transients associated with field-aligned currents appear to be responsible for the high latitude Pi2 signature. Data from Cluster are used to study a Pi2 event observed at 18:09 UTC on 21 January 2003, when three of the satellites were within the plasmasphere (L=4.7, 4.5 and 4.6) while the fourth was on the plasmapause or in the plasmatrough (L=6.6). Simultaneous pulsations at ground observatories and the injection of particles at geosynchronous orbit corroborate the occurrence of a substorm. Evidence of a cavity mode resonance is established by considering the phase relationship between the orthogonal electric and magnetic field components associated with radial and field-aligned standing waves. The relative phase between satellites located on either side of the geomagnetic equator indicates that the field-aligned oscillation is an odd harmonic. Finite azimuthal Poynting flux suggests that the cavity is effectively open-ended and the azimuthal wave number is estimated as m~13.5.

Studies of Pc5 pulsations

The magnetospheric response at times when sudden increases in the solar wind dynamic pressure cause terrestrial magnetic storms has been studied with data from the pulsation magnetometer at the South African Antarctic research base, SANAE-IV [Sundberg et al, 2005]. For solar wind events that lead to a sudden increase in the terrestrial magnetic field at Hermanus and Kakioka, related pulsations are found in the SANAE-IV data. Seven solar wind events of special interest were studied in the time period 19 February 2003 to 18 February 2004. The events can be divided into two main pulsation groups: one group which has a well defined frequency and a duration of about 15 minutes while the other has a less well defined frequency content, longer duration and exhibits large amplitude fluctuations. The analysis confirms the conclusion that the measured response time of the magnetosphere to disturbances in the solar wind is broadly consistent with the propagation speed of magneto-hydrodynamic waves driven by solar wind dynamic pressure.

Using the solar wind and Dst correlation method described above, twelve events of special interest were found during the period studied. All of the events show a fairly sudden increase in the absolute magnetic field value at Kakioka (140.18 E, 36.23 N, L=1.34)[18] and Hermanus (19.22 E, 34.40 S, L=1.84).[18] The time-delays observed between solar wind events and geomagnetic reactions correspond well with simple solar wind speed estimates in comparison to calculations made using only the downstream ACE solar wind velocity which tend to yield time estimates that are far later than the observed impact times.

A very clear example of the cause and effect relationship between a solar wind pressure increase and magnetic field pulsations is the event found in the ACE data on 8 April 2003 at 00:15 UT. The Earthward shock propagation speed is estimated to be approximately 420 kms^{-1}. ACE was located at a distance of 1.43 million km from Earth, which gives the expected impact time at 01:12 UT. This time estimate corresponds well to the initial reaction in the magnetic field at Hermanus. Using the estimated impact time, the impulse in the SANAE-IV data starting at 01:11 UT is located and attributed to a geomagnetic reaction to the magnetospheric compression. Of the twelve events selected, three were not considered further as the SANAE-IV magnetometer was already saturated at the time of the expected event. Two other samples were noisy but not saturated. For these, a slight increase of the pulsation amplitude could be observed at a time close to that expected, but not clear enough for any conclusions to be drawn regarding their origin.

The remaining seven pulsation events are of two main types. One type consists of pulsations of a rather well defined frequency (though with an event to event variation) and an amplitude that decreases with time. This kind of response is referred to as *transient*. Three events of this type were found and their average duration was approximately 15 minutes. All three events showed clear polarised signals, though the type and direction of the polarisation varies. The event of 8 April is mainly linearly polarised in a north-west to south-east direction.

The other type of response consists of a much larger range of frequencies, and is labelled *quasi-stationary*. All of these examples saturate the magnetometer. The duration of this type of event is longer than the transient event, with durations ranging from half an hour up to several hours. A clear example of a pulsation of this type occurred at 22 January 2004, 01:35 UT. No clear polarisation can be observed for any of these events, the two components seem to fluctuate independently.
The abrupt increases in the solar wind dynamic pressure causing sudden impulses are sometimes related to geomagnetic pulsations in the Pc5 range. Of these, two different categories have been found: one transient response type and one quasi-stationary. The transient impulses show a distinct main pulsation frequency, and have a lifetime of 15 minutes or less. The quasi-stationary pulsations have a duration of half an hour or more, as well as a much wider frequency band. However, none of the undefinable events could be ruled out as being related to the observed solar wind impulses.

Studies of lightning-induced whistlers

Whistlers are dispersed Very Low Frequency (VLF) electromagnetic signatures of lightning discharges, received after propagating through the magnetosphere in field-aligned ducts of enhanced plasma density. They usually originate from discharges in the conjugate hemisphere. This is particularly true at low latitudes; at higher latitudes the signal may echo back and forth between hemispheres. Lightning Imaging Sensor (LIS) data have been analysed by Collier et al (2006b) from the University of KwaZulu-Natal to ascertain the statistical pattern of lightning occurrence over southern Africa. The diurnal and seasonal variations are mapped in detail. The highest flash rates (107.2 km-2y-1) occur close to the equator but maxima are also found over Madagascar (32.1 km-2y-1) and South Africa (26.4 km-2y-1). A feature of the statistics is a relatively steady contribution from over the ocean off the east coast of South Africa that appears to be associated with the Agulhas current. Lightning statistics are of intrinsic meteorological interest but they also relate to the occurrence of whistlers in the conjugate region. Whistler observations are made at Tihany, Hungary. Statistics reveal that the period of most frequent whistler occurrence does not correspond to the maximum in lightning activity in the conjugate region but is strongly in-fluenced by ionospheric illumination and other factors. The whistler/flash ratio, R, shows remarkable variations during the year and has a peak that is narrowly confined to February and March.
Within South Africa peak activity is found in the Drakensberg mountains and Lesotho, with only slightly less activity in the highveld. A notable exception to this is a region off the east coast where activity maximises in the autumn and is lowest during spring. Tihany’s conjugate point lies within this offshore region. The diurnal variation in lightning activity has a pronounced peak in excess of 5200 flashes/h between 14:00 and 20:00 SAST in summer. This declines to less that 1200 flashes/h in winter. A considerable level of persistent lightning incidence was observed off the east coast of South Africa and is thought to be caused by the warm waters of the Agulhas current. A similar effect is apparent over the Gulf Stream. Whistler occurrence in Tihany peaks in February, the month in which lightning activity is a maximum in the source region. However the whistler pattern is not directly related to lightning activity as the diurnal

peak in whistler incidence occurs between 20:00 and 03:00 SAST, whereas the peak in conjugate lightning activity occurs between 14:00 and 20:00 SAST. It was noted before that whistlers were most frequently observed during the night, suggesting that their passage through the ionosphere was attenuated during daylight by absorption in the D region. The diurnal variation in whistler activity reported here is similar to that recorded at higher latitude stations where the greatest activity occurs during the night, with a maximum before dawn.

Acknowledgements

This report was compiled by quoting extensively from the research papers reviewed. I thank the researchers involved for providing reprints and preprints of their work.

References

Cilliers P.J., B.Opperman**,** C.N. Mitchell, Electron density profiles determined from tomographic reconstruction of total electron content obtained from GPS dual frequency data: First results from the South African network of dual frequency GPS receiver stations*, Adv. Space Res.*, **34**, 2049-2055, 2004.

Collier, A. B., A. R.W. Hughes, L. G. Blomberg, and P. R. Sutcliffe, Evidence of standing waves during a Pi2 pulsation event observed on Cluster, *Ann. Geophys.*, **24**, 2719–2733, 2006a.

Collier, A.B., A. R. W. Hughes, J. Lichtenberger and P. Steinbach, Seasonal and Diurnal Variation of Lightning Activity over Southern Africa and Correlation with European Whistler Observations, *Ann. Geophys*, **24**, 1-14, 2006b.

Kim, K.-H., K. Takahashi, D.-H. Lee, P. R. Sutcliffe, and K. Yumoto , Pi2 pulsations associated with poleward boundary intensifications during the absence of substorms, *J. Geophys. Res.*, **110**, A01217, doi:10.1029/2004JA010780, 2005.

M.Kokorowski, J. G Sample, R. H. Holzworth, A. Bering, S. D. Bale, J. B. Blake, A. B**.** Collier, A. R. W. Hughes**,** E. Lay, R. P. Lin, M. P. McCarthy, R. M. Millan, H. Moraal, T. P. O'Brien, G. K. Parks, M. Pulupa, B. D. Reddell, D. M. Smith, P. H. Stoker and L. Woodger, Rapid fluctions in stratospheric electric field following a solar energetic particle event, *Geophys. Res. Lett.* **33**, L20105, doi:10.1029/2006GL027718, 2006

Korte, M., P. Kotze, M. Mandea, M. Fredow, E. Nahayo, B Pretorius, Towards better observation of the geomagnetic field in repeat station networks, *XII IAGA Workshop on Geomagnetic Observatory Instruments, Data Acquisition and Processing,* Belsk, Poland Abstr. Vol., p78, 2006

Kotzé, P.B., Southern Africa's geomagnetic secular variation, *S. Afr. J. Science,* **99**, 584-587, 2003a

Kotzé, P.B., The time-varying geomagnetic field of Southern Africa, *Earth Planets Space,* **55**, 111-116, 2003b

Kotzé, P.B., M. Mandea, M. Korte, E. Nahayo, B. Pretorius, Modelling of southern African secular variation observations, *XII IAGA Workshop on Geomagnetic Observatory Instruments, Data Acquisition and Processing,* Belsk, Poland, Abstr. Vol., p77, 2006

Linthe, H.-J., P. Kotzé, M. Mandea, H. Theron, Keetmanshoop – A new observatory in Namibia, *XII IAGA Workshop on Geomagnetic Observatory Instruments, Data Acquisition and Processing,* Belsk, Poland, Abstr. Vol., p38, 2006

McKinnell, L.A., and M. Friedrich, IMAZ for IRI: An assessment of the lower ionosphere options in IRI, *Paper presented at International Reference Ionosphere (IRI) Workshop 2006*, oral presentation, Buenos Aires, Argentina, 16 - 21 October 2006

Nose, M., K. Takahashi, T. Uozumi, K. Yumoto, Y. Miyoshi, A. Morioka, D. K. Milling, P. R. Sutcliffe, H. Matsumoto, T. Goka, and H. Nakata, Multipoint observations of a Pi2 pulsation on morning side: The 20 September 1995 event, *J. Geophys. Res.*, **108**(A5), 1219, doi:10.1029/2002JA009747, 2003.

Nosé, M., K. Liou, and P. R. Sutcliffe, Longitudinal dependence of characteristics of low-latitude Pi2 pulsations observed at Kakioka and Hermanus, *Earth Planets Space*, 58, 775–783, 2006.

Oyeyemi, E.O., Poole, A.W.V., Towards the development of a new global foF2 empirical model using neural networks, *Adv. Space Res*., 34, 1966-1972, 2004.

Oyeyemi, E.O., Poole A.W.V., McKinnell, L.A., On the global model for foF2 using neural networks, *Radio Science.,* **40**, RS6011, doi: 1029/2004RS003223, 2005a.

Oyeyemi, E.O., Poole A.W.V., McKinnell, L.A., On the global short-term forecasting of the ionospheric critical frequency foF2 up to five hours in advance using neural networks, *Radio Science,* **40**, RS6012, 2005b

Oyeyemi, E.O., L.A. McKinnell, A.W.V. Poole, Near-real time foF2 predictions using neural networks, *J. Atm. Terr. Phys.,* **68**, 1807-1818, 2006a

Oyeyemi E.O., McKinnell L.A. and Poole A.W.V., Neural network based prediction techniques for global modeling of M(3000)F2 ionospheric parameter, *Advances in Space Research*, in press, 2006b.

Stoker, P.H., and B. Bijker, Auroral optical emissions related to imaging riometer observations, *S. Afr. J. Sci,* **101**, 2005

Sundberg, T., A. R. W. Hughes, A. B. Collier, P. T. I. Eriksson and L. G. Blomberg, Magnetic field oscillations at SANAE IV related to sudden increases in solar wind dynamic pressure, *S. Afr. J. Sci*, **101**, 539-543, 2005

Sutcliffe, P. R. and H. Lühr, A comparison of Pi2 pulsations observed by CHAMP in low Earth orbit and on the ground at low latitudes, *Geophys. Res. Lett.*, 30(21), 2105, doi:10.1029/2003GL018270, 2003.

Sutcliffe, P. R. and H. Lühr, A comparative study of geomagnetic Pi2 pulsations observed by CHAMP and on the ground, *Earth Observation with CHAMP: Results from Three Years in Orbit*, pp 389-394, Springer, Potsdam, Germany, August 2004.