THE ROLE OF THE HERMANUS MAGNETIC OBSERVATORY IN GEOMAGNETIC FIELD RESEARCH

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Abstract. Geomagnetic field research carried out at the Hermanus Magnetic Observatory over the past decade is reviewed. An important aspect of this research has been the study of geomagnetic field variations, with particular emphasis on ULF geomagnetic pulsations. Features of geomagnetic pulsations which are unique to low latitude locations have been investigated, such as the cavity mode nature of low latitude Pi 2 pulsations and the role played by ionospheric O^+ ions in the field line resonances responsible for Pc 3 pulsations. A theoretical model has been developed which is able to account for the observed relationships between geomagnetic pulsations and oscillations in the frequency of HF radio waves traversing ionospheric paths. Other facets of the research have been geomagnetic field modelling, aimed at improving the accuracy and resolution of regional geomagnetic field models, and the development of improved geomagnetic activity indices.

Key words: Geophysics, geomagnetic field.

1 Introduction

The Hermanus Magnetic Observatory (HMO) had its origin during the Second Polar Year 1932–1933, an international cooperative project conceived to gain a better understanding of the Earth and its environment. Thus the HMO began its existence due to man's quest for scientific knowledge and understanding. Over the years, however, the prime objectives and culture of the HMO have changed. Particularly significant changes occurred after 1986 when the CSIR, of which the HMO forms part, was reformed to become a more market oriented organisation with the prime objective that research results should be implemented for the benefit of South African industry and society.

Over most of the past decade the HMO has functioned primarily as a service providing and technology development body. The service provision aspect entails the provision of information and data on the geomagnetic field to clients mainly for use in the fields of navigation and geophysical exploration. Notwithstanding these changes, the HMO still finds it essential to carry out fundamental and applied research, albeit at a reduced level compared to earlier years.

In this paper research carried out at the HMO since 1986 is reviewed. The work falls into three main categories, namely, the study of geomagnetic variations of various types, geomagnetic field modelling, and geomagnetic activity indices.

2 Geomagnetic Field Variations

A variety of temporal variations, spanning periodicities from fractions of a second up to millions of years, take place in the Earth's magnetic field. Studies at the

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HMO have primarily been concerned with geomagnetic pulsations, which are small ultra low frequency (ULF) oscillations of the Earth's magnetic field. However, other types of variations have and are also being studied. For example, cooperative research has been carried out with other groups in South Africa to study dynamical aspects of magnetospheric substorms (Gledhill *et al.*, 1987) and the aurora (Mravlag *et al.*, 1991). The geomagnetic solar quiet day (Sq) variation is presently being studied and quantified with the objective of generating an Sq model for the Southern African region. Indications are that such a model might be utilised to facilitate the removal of the Sq variation when processing satellite magnetometer data over Southern Africa and be usefully incorporated into a navigation system based on magnetometer technology.

2.1 GEOMAGNETIC Pi 2 PULSATIONS

Pi 2 geomagnetic pulsations are impulsive, damped oscillations of the geomagnetic field in the frequency range 5–30 mHz observed in association with magnetospheric substorm onsets and intensifications. They are observed at all latitudes from the auroral oval to the equator and are generally regarded to be nighttime phenomena. At high latitudes ($L > 4$) the observation of ground based Pi 2 pulsations is closely associated with the instantaneous location of the auroral electrojet (Olson and Rostoker, 1975). Singer *et al.* (1983) reported that the spatial extent of Pi 2 pulsation fields is longitudinally localized to within 30° of the 23 LT meridian of geosynchronous orbit. At mid latitude ($2 < L < 4$) Pi 2s on the ground are clearly observed with similar signatures over at least 60° in longitude (Singer *et al.*, 1983). In contrast, however, a number of researchers (e.g. Sastry *et al.*, 1983) found that daytime Pi 2 pulsations with an enhancement in amplitude, occur near to the dip equator in association with many nighttime Pi 2s. A knowledge of the spatial extent and structure of Pi 2 pulsation fields is of cardinal importance for the understanding of generation and propagation mechanisms. However, until recently, there was still uncertainty about the manner in which these pulsations propagate to low latitudes (Yumoto, 1986). In a study of low latitude Pi 2 pulsations, Sutcliffe and Yumoto (1989, 1991) provided new observational evidence to shed light on the source mechanism of low-latitude Pi 2 pulsations.

To this end Sutcliffe and Yumoto (1989, 1991) investigated the occurrence of daytime Pi 2 pulsations in the latitude region between the equator, where they were known definitely to occur, and mid to high latitudes, where they appear not to occur. They used data from two low latitude stations Hermanus (HER), in South Africa, and Onagawa (ONW), in Japan, which are well separated in longitude (~ 122°); consequently, for many events, when one station was located in the nightside hemisphere, the other was located in the dayside hemisphere. The objective of the study was to use the nightside hemisphere data to identify Pi 2 pulsations and then determine whether they occur simultaneously in the dayside hemisphere. Three representative examples are shown in Figure 1; in each, the upper trace is the HER H component, the centre trace the low pass filtered HER

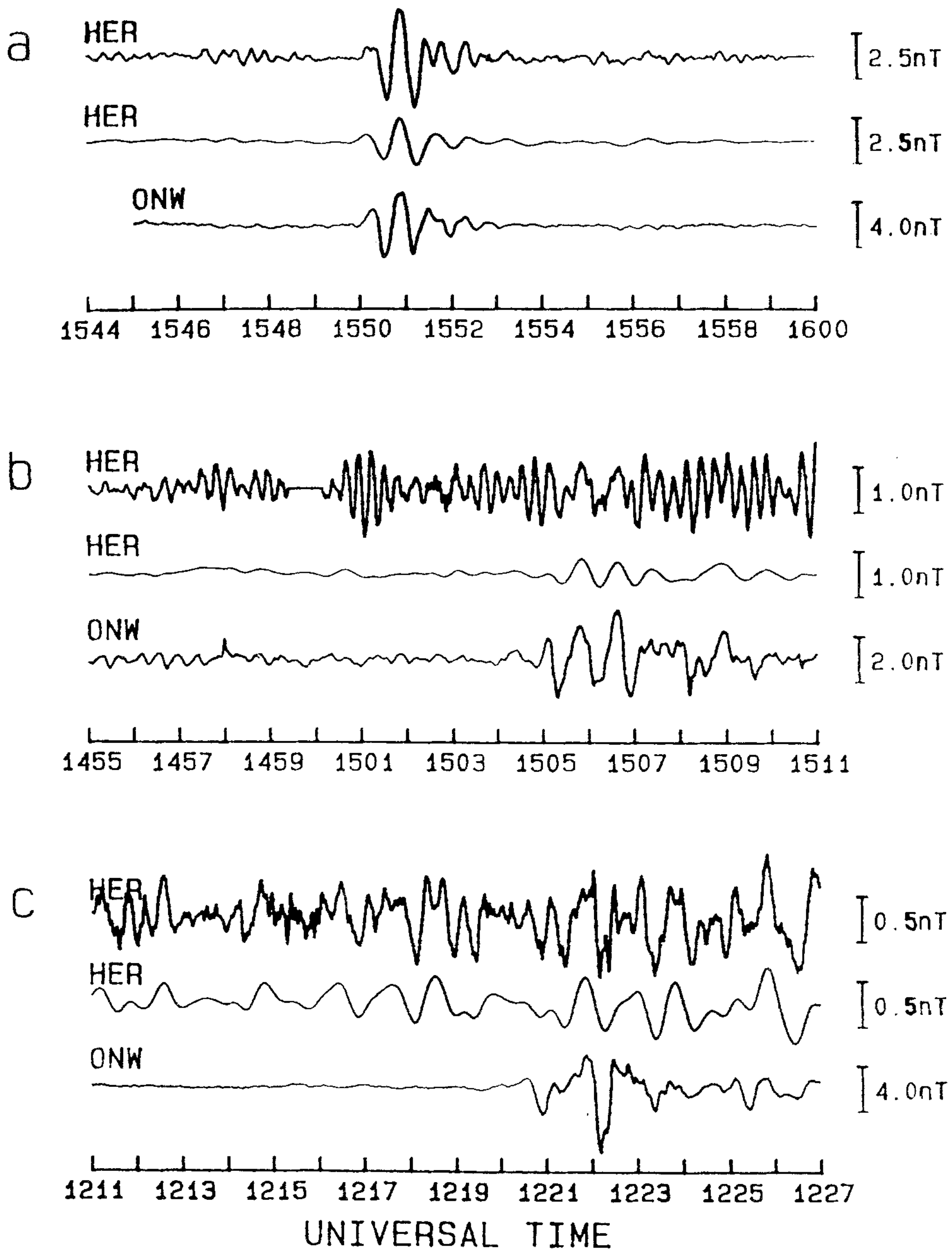

Fig. 1. Induction magnetometer H component data from HER and ONW for the 16-min intervals commencing at (a) 1544 UT on day 242, (b) 1455 UT on day 240, and (c) 1211 UT on day 221 of 1986. (Taken from Sutcliffe and Yumoto, 1991.)

H component, and the lower trace the ONW H component. The example in Figure 1(a) is one where very little pulsation activity was present at HER prior to Pi 2 onset at ONW. In all examples of this type a simultaneous daytime Pi 2 was visually identifiable at HER, as illustrated. Figure 1(b) shows an example where prior pulsation activity at HER made identification of a Pi 2 difficult. Here low-pass filtering to some extent clarifies the presence of a Pi 2 at HER. In Figure 1(c), the positive identification of a Pi 2 remains uncertain following low-pass filtering.

In order to overcome the problem of establishing whether or not a daytime Pi 2 has occurred when other distracting pulsations are present, Sutcliffe and Yumoto (1989) made use of a data adaptive filtering technique known as Correlated Adaptive Noise Cancelling or CANC (Hattingh, 1988). In their application of CANC, Sutcliffe and Yumoto (1989) considered the HER data as the primary signal containing the desired signal (possible daytime Pi 2) plus noise (daytime Pc 3 or other pulsation activity). The ONW data were considered as the reference input containing a signal (nighttime Pi 2) similar to that which was to be extracted from the HER data. The output from CANC indicates whether or not the Pi 2 at HER is present. If a daytime Pi 2 is present, as in Figure 2(a), the output of CANC will be a near replica of the reference Pi 2, but scaled to the amplitude of the daytime Pi 2. If no Pi 2 is present at HER, a near zero output signal is obtained. This latter situation is illustrated in Figure 2(b) which was obtained by applying CANC using the same ONW reference signal, but to an adjacent segment of the HER data. Note that the data used in Figure 2 are those previously illustrated in Figure 1(c), from which it is clear that the corresponding adjacent data segment at ONW contained no Pi 2 pulsation. The results of Sutcliffe and Yumoto (1989) provided compelling new evidence revealing that at low latitudes Pi 2 pulsations are a common dayside phenomenon.

Sutcliffe and Yumoto (1991) extended the work of Sutcliffe and Yumoto (1989). The technique of data adaptive filtering was used to provide further evidence to confirm that the pulsations occur almost simultaneously in both the nightside and dayside hemispheres at low latitudes. They demonstrated that the spectra of the dayside and nightside pulsations are similar. The spectra of Pi 2 pulsations were furthermore compared with those of Pc 3 pulsations and shown to be different in a number of respects. They interpreted these various observed characteristics as a consequence of the cavity mode nature of low-latitude Pi 2 pulsations.

Sutcliffe and Nielsen (1990) for the first time used STARE (Scandinavian Twin Auroral Radar Experiment) observations to isolate and show the configuration of the ionospheric electric field associated with a classical Pi 2 pulsation. The data used in their study consisted of ionospheric electron drift velocities measured by STARE over Northern Scandinavia (Nielsen, 1982). These were supplemented by induction magnetometer data from the low latitude Hermanus Magnetic Observatory and fluxgate magnetometer data from the EISCAT Magnetometer Cross (Lühr *et al.*, 1984) which is located below the STARE field of view. A major problem in using STARE data to study Pi 2 pulsations is the limited temporal

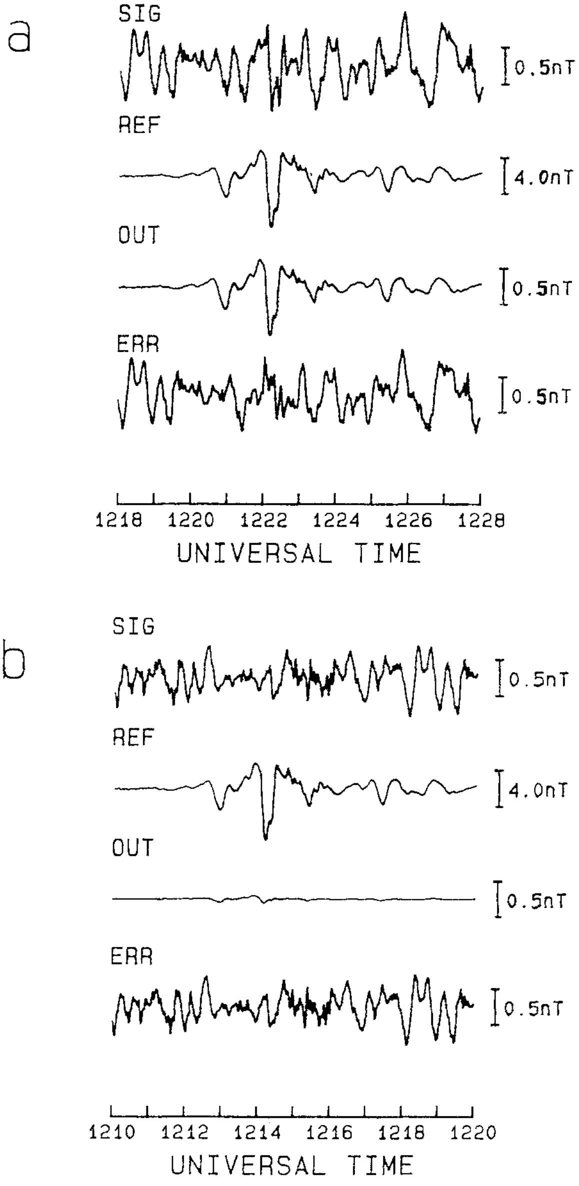

Fig. 2. Results of CANC analysis applied to the signals in Figure 1c. (a) An example where a Pi 2 is positively identified in the output (OUT). The HER signal (SIG) and ONW reference (REF) both commenced at 1218 UT. (b) An example where there is no Pi 2 in the output (OUT). In this case the same ONW reference signal was used, but the HER signal (selected for an interval with no Pi 2 at ONW) commenced at 1210 UT. (Taken from Sutcliffe and Yumoto, 1991.)

resolution of STARE, normally 20 s, compared to the Pi 2 pulsation period, which can be as short as 30 s. This is aggravated by the fact that the Pi 2 occurs during the most dynamic part of the substorm process, thus further complicating the data and making them more difficult to analyse and interpret. The process of isolation was achieved by effectively high pass filtering the data for each spatial grid point in the STARE field of view, after having applied some spatial averaging. A good correlation of the magnetic field computed from the electric field observations using the Biot-Savart law was obtained with the observed magnetic field variations. This demonstrated that the technique which was used for isolating the oscillations worked reasonably well and furthermore confirmed that the oscillating field was indeed that associated with the Pi 2.

Sutcliffe and Nielsen (1992) extended the work to isolate classical Pi 2 pulsations in STARE data. A number of additional events were identified in which pulsation electric fields up to 50 mV/m were observed. The ionospheric signature of a Pi 2 was found to be located slightly poleward of the core of the auroral breakup region where the southward, westward, and northward directed background electric fields converge; the strongest pulsation fields occurred in the region of equatorward directed electric fields. The ionospheric electric field patterns of the Pi 2 pulsations determined from the STARE data correlated well with those modelled for a transverse Alfvén wave incident on an east-west aligned high-conductivity strip in the ionosphere.

2.2 GEOMAGNETIC Pc 3 PULSATIONS

The ULF geomagnetic pulsations most commonly observed at low latitudes ($L < 2$) during daytime are Pc 3 pulsations. The frequency of oscillation is generally in the range 25–100 mHz and amplitudes typically range from 0.1–1.0 nT. The characteristics of these pulsations are consistent with those expected of transverse standing Alfvén waves along geomagnetic field lines. In an attempt to determine the longitudinal wave numbers and phase velocities of these pulsations, Sutcliffe *et al.* (1987) studied Pc 3 pulsations recorded at three stations along the $L \cong 1.78$ shell and spanning 35° in longitude during July 1983. However, this investigation was thwarted when they discovered that the pulsations recorded at Gough Island ($10°W$) had higher frequencies than those recorded at two stations in South Africa ($20°E$ and $25°E$). Local time effects or small differences in the magnetic field configuration did not account for the differences in resonant frequency. They concluded that the higher pulsation frequency at Gough Island was due to a lower plasma mass density on that field line relative to the others and that oxygen ions play a significant role. Factors which may have contributed to the lower plasma mass density are the lower rate of production of O^+ by solar ultraviolet radiation, F region heating by energetic particle precipitation, and the greater loss of O^+ caused by meridional winds.

The concept of a vibrating field line has been used by various workers to predict Pc 3 pulsation eigenperiods. An approach often adopted has been to assume a dipole field model and attempt to solve the wave equation describing low-frequency propagation of Alfvén waves in a cold, collisionless, magnetized plasma. A simple plasma model consisting only of H^+, the concentration of which is assumed to vary along a field line according to the inverse power of the radial distance, has most commonly been used. Singer *et al.* (1981) improved on these simple models by considering the effect of a more realistic magnetic field model. Poulter *et al.* (1984) on the other hand used a more realistic plasma model for calculating pulsation eigenperiods. They found that the inclusion of O^+ in their plasma model had little effect on eigenperiods at mid-latitudes. Hattingh and Sutcliffe (1987) discussed the determination of pulsation eigenperiods at low latitudes. Their work differed from previous work in a number of respects; they used both realistic magnetic field and plasma models and their results pertained to low latitudes ($L < 2$) which had not previously been considered. They determined and compared eigenperiods for two magnetic field models, namely, a dipole field and the International Geomagnetic Reference Field (IGRF). They also investigated the effect of a physically realistic plasma distribution which included the oxygen ion. The calculated eigenperiods obtained using the dipole field model and the IGRF model were found to be similar. However, the inclusion of the F region O^+ in the plasma distribution noticeably affected the calculated eigenperiods at low latitudes. This effect decreased with increasing L value. Pulsation periods obtained from recordings made at four stations lying along a geomagnetic meridian are shown as a function of L-value in Figure 3. The eigenperiods calculated with and without O^+, also shown in Figure 3, demonstrated the importance of including O^+ in the plasma model if realistic periods are to be determined at low latitudes.

2.3 IONOSPHERIC SIGNATURES OF GEOMAGNETIC PULSATIONS

Over the past 3 decades observations of a relationship between rapid geomagnetic pulsations and oscillations in the frequency of radio waves traversing ionospheric paths have been reported in the literature. These ionospheric signatures of pulsations (ISPs) have manifested themselves as Doppler frequency (or Doppler velocity) oscillations of ionospherically reflected radio waves (see Watermann, 1987, for references), as oscillations in the carrier frequency along radio ray paths between geostationary satellites and the ground (see Poole and Sutcliffe, 1987, for references), and in the backscattered signals received by HF over-the-horizon radars (Bourdillon *et al.*, 1989). In a recent detailed study, Watermann (1987) concluded that the existing theoretical models were not adequately supported by the observations and consequently required major revisions.

An active research area at the HMO has been the development and improvement of a theoretical model to account for the observed features of ISPs. Part of this research has been carried out in collaboration with the Department of Physics at Rhodes University. This cooperative project had its origin in 1983 when ionospheric Doppler velocity oscillations were observed by a digital chirp ionosonde

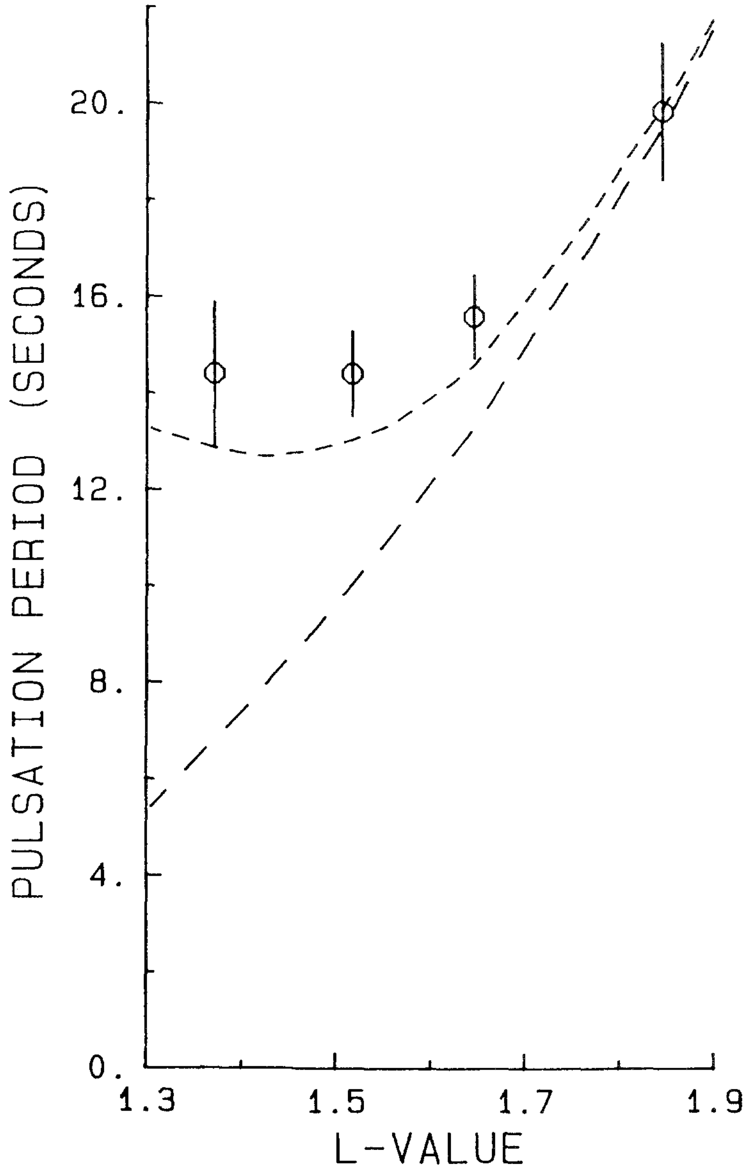

Fig. 3. The means and standard deviations of the dominant periods of the H component Pc 3 pulsations observed at four stations with different L-values are indicated by the circles and error bars respectively. The short dashed line shows the periods computed using a plasma model containing both O^+ and H^+ as a function of L value. The long dashed line shows the periods computed with the same H^+ distribution, but with O^+ excluded. (Taken from Hattingh and Sutcliffe, 1987.)

at Grahamstown in association with Pc 3 pulsations recorded at ground level as shown in Figure 4 (Sutcliffe and Poole, 1984).

Poole *et al.* (1988) investigated the mechanisms which relate the ground based magnetometer pulsations and simultaneous oscillations of Doppler frequency shifts in ionospherically reflected radio frequency echoes for the vertical incidence case at low to mid latitudes. They considered the effects of oscillating electric and magnetic fields at ionospheric heights on the phase path of the reflected radio wave which gives rise to the Doppler shifts. They identified three main mechanisms at work in the ionosphere, which are applicable at all latitudes. By quantifying the electric and magnetic pulsation fields for a partially reflected downcoming Alfvén wave, they derived a quantitative phase and amplitude relationship between the rate of change of phase path on Doppler velocity and the pulsation magnetic field measured on the ground. A surprising result was that the dominant mechanism was not necessarily the vertical component of bulk plasma movement, as had been previously suggested. In many cases, the dominant mechanism was compression and rarefaction of plasma frozen onto the field lines as they oscillated under the action of the field-aligned component of the pulsation magnetic field.

Sutcliffe and Poole (1989) made some refinements to this ISP model. They showed that a generally held belief that field-aligned electron velocities associated with the corresponding currents could be ignored, was unfounded in the case of magnetic pulsations. These field-aligned velocities contribute significantly to two of the three mechanisms identified in the earlier work. The following briefly summarises the derivation of the model presented by Sutcliffe and Poole (1989).

For a radio wave vertically incident upon the ionosphere the phase height is given by:

$$h^* = \int_o^{z_R} \mu dz \tag{1}$$

where integration with respect to z is in the vertical direction, μ is the real part of the refractive index given by the Appleton-Hartree formula, and z_R is the height of reflection. The Doppler velocity V^*, defined as the time rate of change of the phase height for the reflected radio wave, is given by:

$$V^* = \frac{dh^*}{dt} = \frac{d}{dt}\int_o^{z_R} \mu dz. \tag{2}$$

In the derivation of an expression for the Doppler velocity V^*, they assumed that the refractive index varies with oscillations in both the electron concentration N and the geomagnetic induction $\mathbf{B} = \mathbf{B}_o + \mathbf{b}e^{-i\omega t}$ where $\mathbf{B}_o$ is the background field and $\mathbf{b}$ and ω are the pulsation field amplitude and angular frequency, respectively. Explicitly expressing this functional dependence, the Doppler velocity in Eq. (2) can be written:

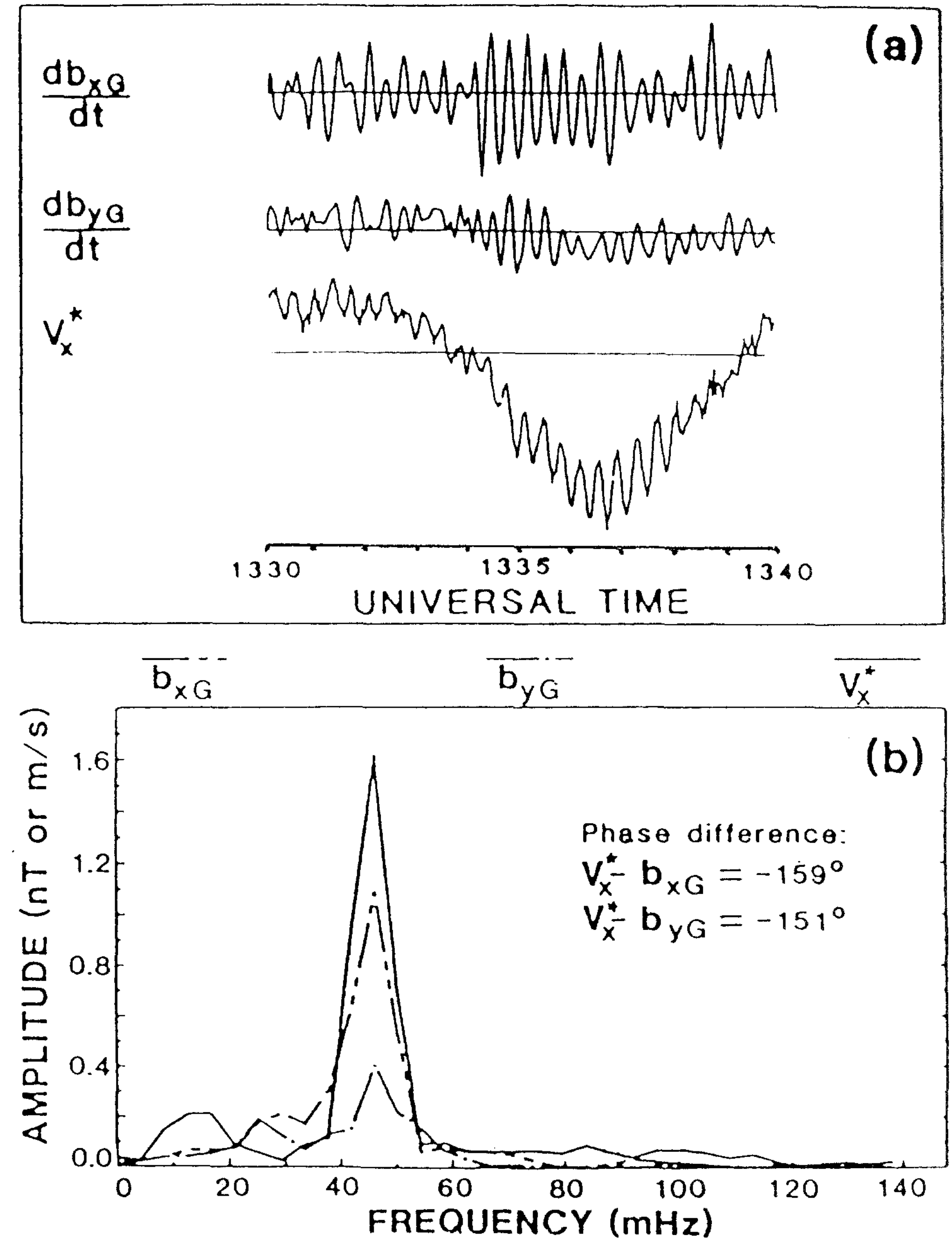

Fig. 4. (a) Example of Pc 3 pulsations (db_x/dt and db_y/dt) and Doppler velocity (V_x^*) oscillations recorded at GRM on 30 November 1983. (b) Spectra for the 4 minute segments of pulsations commencing at 1334 UT. (Taken from Sutcliffe and Poole, 1984.)

$$V^* = \int_0^{z_R} \mu[B_L(z,t), B_T(z,t), N(z,t)]dz \tag{3}$$

where B_L and B_T are the components of the Earth's magnetic induction parallel (longitudinal) and transverse to the radio wave direction respectively. Carrying out the time differentiation yields:

$$V^* = \int_0^{z_R} \left[\frac{\partial\mu}{\partial B_L}\frac{\partial B_L}{\partial t} + \frac{\partial\mu}{\partial B_T}\frac{\partial B_T}{\partial t} + \frac{\partial\mu}{\partial N}\frac{\partial N}{\partial t}\right] dz. \tag{4}$$

They next made use of the continuity equation for electrons in the ionosphere in which it was assumed that production and loss terms could be neglected, thus:

$$\frac{\partial N}{\partial t} = -\nabla N \cdot \mathbf{v} - N(\nabla \cdot \mathbf{v}) \tag{5}$$

where $\mathbf{v}$ is the electron drift velocity. Combining Eqs. (4) and (5) V^* was expressed in terms of three separate mechanisms, that is:

$$V^* = V_1 + V_2 + V_3 \tag{6}$$

where

$$V_1 \approx -i\omega \int_0^{z_R} \left[\frac{\partial\mu}{\partial B_L}b_z + \frac{\partial\mu}{\partial B_T}b_x\right] dz, \tag{7}$$

$$V_2 = -\int_0^{z_R} \left[\frac{\partial\mu}{\partial N}\frac{\partial N}{\partial z}v_z\right] dz \tag{8}$$

and

$$V_3 = -\int_0^{z_R} \left[\frac{\partial\mu}{\partial N}(\nabla \cdot \mathbf{v})\right] dz. \tag{9}$$

The 'magnetic' mechanism 1, i.e. V_1, arises from changes in the refractive index through its dependence on the magnetic field intensity. The 'advection' mechanism 2, i.e. V_2, arises from changes in the ionospheric refractive index due to the vertical component of the bulk motion of electrons in the ionosphere. The 'compression' mechanism 3, i.e. V_3, arises from changes in the refractive index due to the divergence of electron velocity along the ray path. Note that if production and loss terms, which were assumed to be zero in Eq. (5), are not negligible, then a fourth mechanism will arise. The latter would likely be the situation if the model were to be applied to observations at auroral latitudes.

Sutcliffe and Poole (1990) used the above model to predict the Doppler velocities expected for a normalised ground level geomagnetic pulsation and specified geophysical conditions. Parameters which were varied in their study included radio sounding frequency, electron concentration profile, magnetoionic mode, geomagnetic inclination, and pulsation frequency and wave number. In order to assess V^* for a particular set of geophysical parameters, it is convenient to plot height profiles in which each value of V^*, calculated as a function of radio sounding frequency, is plotted at the real height at which reflection of that frequency would take place. Examples of such profiles for V^* and its component parts V_1, V_2, and V_3 are shown in Figure 5 for the O-mode, calculated for a typical set of geophysical parameters. The electron concentration profile used was taken from the International Reference Ionosphere (IRI 90), and is typical for a mid-latitude station (Hermanus 34.4°S, 19.2°E) for ionospheric conditions during summer and sunspot maximum at local midday. The results were normalized to give b_x (NS pulsation field) at ground level an amplitude of 1 nT and phase of 0^o. A detailed discussion of the effects which the various geophysical parameters have on the Doppler velocity predictions was given by Sutcliffe and Poole (1990).

An evaluation of the model predictions was made by Sutcliffe (1994). This was done by considering how the predicted amplitudes and phases of the Doppler velocity for various changes in geophysical parameters compared with observations as published in the literature. The predicted amplitudes are in good agreement with observations and particularly with the results of a detailed statistical study of observations of SIs and Pi 2s presented by Watermann (1987). Furthermore, the Doppler velocity depends on electron concentration and is typically more than an order of magnitude greater during the night than during the day, greater in the F-region than in the E-region, and greatest close to the ionospheric cusps. These various predictions are in reasonable general agreement with observations. However, a comparison of observations with model predictions where all parameters are chosen to be as close as practicable to the observed set has not yet been made. Such a comparison would indicate in which respects the model might be improved.

Sutcliffe and Poole (1993) discussed how the Doppler velocities expected in ionospherically reflected radio signals and computed using their model may be utilized for practical applications. If the model were to be extended for oblique incidence, then the phase shifts expected in radio signals transmitted from satellites or in over-the-horizon (OTH) radars during times of geomagnetic pulsations should be predictable. Assuming that such an extension of the model is successful, an example of the type of application envisaged is in the processing of OTH radar data. The phase shifts caused by geomagnetic pulsations on the Doppler shift of HF waves which have propagated through the ionosphere appear as an important source of contamination in sea state remote sensing experiments. The ability to model the contaminating ionospheric phase shifts may enable more efficient and accurate corrections to be made to the radar signals than is currently possible.

The model, as originally developed by Poole *et al.* (1988) and Sutcliffe and Poole (1989), appeared to be successful in accounting for the observations of ISP signatures associated with longer period ULF pulsations. However it was not able to account for certain ionospheric signatures, such as amplitude modulation, recent-

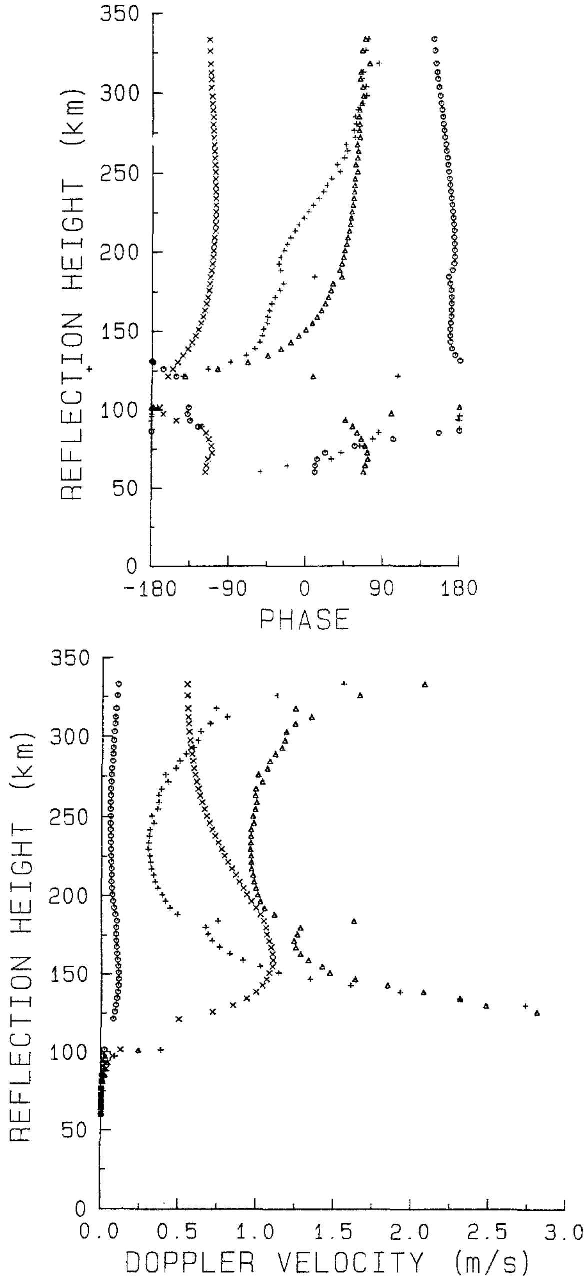

Fig. 5. V^* profiles for the parameters, $I = -60°, B_o = 30000nT, T = 2/\omega = 20s, L_x = 500km, L_y = 6000km$ for the O-mode for the IRI 90 ionosphere corresponding to summer, sunspot maximum and midday at Hermanus. Symbols: $(O) = V_1; (x) = V_2; (\Delta) = V_3; (+) = V^*$. (Taken from Sutcliffe, 1994.)

ly reported to be associated with Pc 1 pulsations. Consequently, Sutcliffe (1992) introduced a complex ionospheric phase refractive index into the model and utilized this improvement to investigate the degree to which radio wave absorption is modulated at the ULF pulsation frequency. It was found that the degree of modulation: (i) varies significantly with radio sounding frequency; (ii) increases with decreasing ULF pulsation period; and (iii) increases with decreasing pulsation field scale length. Considering these points it was concluded that it is quite feasible that modulation of radio wave absorption can account for the large oscillations in echo amplitude observed by British Antarctica Survey scientists in Pc 1 pulsation events. Furthermore, due to the greater scale length and period of Pc 3 pulsations, it is likely that such modulation in the case of Pc 3 pulsations will be too low to observe.

3 Geomagnetic Field Modelling

A reasonable approximation to the magnetic field close to the Earth's surface is given by the field of a magnetic dipole positioned at the Earth's centre and inclined by about 11° to the axis of rotation. However, this field is distorted from above by the solar wind and at latitudes greater than 60° or distances beyond 4 Earth radii the dipolar structure becomes highly deformed. From below, this field is distorted by upper mantle and crustal anomalies. Consequently, more accurate global and regional magnetic field models are required for many purposes. Models are used in fundamental research, for example in determining charged particle motions and mapping plasma distributions, and in practical applications, for example in navigation and mineral exploration. Most models are phenomenological but are expressed in mathematical form since they are based on physical equations but require observational data for the determination of their coefficients.

3.1 GLOBAL FIELD MODELLING

The International Geomagnetic Reference Field (IGRF) is a global spherical harmonic analysis model obtained as a solution of Laplace's equation expressed in spherical polar coordinates. By international agreement, the IGRF coefficients are updated every 5 years using magnetic observatory data, magnetic field survey data, and satellite magnetometer data.

Kotzé (1992) made an evaluation of candidate models, submitted to IAGA Working Group V-8, for the 1985 and 1990 IGRFs (DGRF85 and IGRF90 respectively) against results of magnetic surveys conducted by the Hermanus Magnetic Observatory over the Southern African sub-continent (Namibia, Botswana, Zimbabwe and the RSA). The main field candidate models were of degree 10, whereas the predictive secular variation models for the interval 1990–1995 were of degree 8. The evaluation of the various IGRF candidate models revealed that they were of a high standard, giving similar results. For epoch 1985 there were no statistically significant differences between the various models. A comparison of 1990 candidate main field models revealed that the USGS model was to be preferred for D and H, whereas the UK/US model provided the best results for F and Z. Mean model differences were also greater at 1990 than at 1985. This could be ascribed to the fact that all 1990 models made use of data projected in time. The method of using project MAGNET data in deriving secular variation models was obvious in the case of the USGS secular variation model for 1990–1995, rendering this model more accurate than others.

3.2 REGIONAL FIELD MODELLING

The purpose of regional geomagnetic field modelling is to express mathematically the geomagnetic field over a portion of the Earth's surface, given data over that area. The data may consist of either scalar or vector observations and may include ground observations, aeromagnetic measurements, and satellite data such as that from the POGS and MAGSAT missions. Regional field models are based on denser data than global models and should therefore be more accurate over their areas. Furthermore, they are able to represent wavelengths shorter than those of global models, and therefore represent not only sources in the core and mantle but also crustal anomalies.

The Polar Orbiting Geomagnetic Survey (POGS) satellite represents the US Navy's continuing effort, as part of Project MAGNET, to secure the necessary data to maintain accurate magnetic field models in support of their requirements. The HMO was granted access to POGS data via Internet and has been able to obtain the data on a regular basis. The POGS data have been utilised in a cooperative project with British Geological Survey (BGS) to derive magnetic field models over Southern Africa (Kotzé and Barraclough, 1995). POGS total intensity data were analysed over the Southern African region covering the area between $10°S$ and $45°S$ in latitude and between $10°E$ and $45°E$ in longitude. Data were selected corresponding to magnetically quiet conditions during local night times between 9 pm and 3 am. A total of 152 POGS passes, corresponding to a total of 7142 measurements in F, could be selected in this way, covering the period January 1991 till June 1993. In order to carry out an analysis of external fields, winter and summer data were subdivided into Dst bins 5 nT wide, centered at 5 nT intervals between 10 and -50 nT. Spherical Cap Harmonic Analysis was then applied to each of these Dst data bins to obtain external field coefficients corresponding to k=1. Regression analysis revealed a linear relationship between the q_o^o coefficient and Dst for both winter and summer periods. After applying these external field corrections, the POGS data were downward continued and modelled by Spherical Cap Harmonic Analysis to reveal component data at ground level.

4 Geomagnetic Activity Indices

Inspection of a continuous recording of any one of the vector components of the geomagnetic field typically reveals two types of variations. First, recordings will almost always exhibit a smooth regular variation which closely repeats itself each day and is known as the solar quiet day or Sq variation. Secondly, recordings sometimes exhibit rapid irregular fluctuations of varying degrees of magnitude. These irregular fluctuations are referred to as magnetic disturbances or, in the case when their magnitude is relatively large, as magnetic storms. Information on the degree of disturbance of the geomagnetic field is either essential or, at least, extremely desirable for a variety of purposes in both fundamental space physics research and in practical technological applications. A number of geomagnetic activity indices have been devised and are generated on a regular basis to provide information on the state of the geomagnetic field.

The most commonly used and useful indices are the K index and its global average K_p. The objective of the K index, originally introduced by Bartels in 1937, was to differentiate between the regular quiet day variation and irregular variations caused mainly by solar particle radiation. K indices have traditionally been hand-scaled from analogue records. Hattingh *et al.* (1989) described a new method that can be used to estimate K-indices automatically, using either pre-recorded or real-time digital data, by computer. They discussed the underlying philosophy of the method and gave a short description of the mathematics involved. They showed how existing ideas in the relatively new field of data-adaptive filtering could be modified and extended to develop a powerful Linear-phase Robust Nonlinear Smoothing method (LRNS method). The properties of this method are ideally suited for the computer K-index estimation problem. The method was applied to Hermanus digital geomagnetic data which extend to nearly one decade. Even with this large amount of data a 99 per cent agreement with handscaled values was obtained when differences of 1 in the K-values were neglected. A 70–80 per cent total agreement was determined with the majority of the differences occurring during quiet days. This is the result of the very small dynamic range of small K-indices (0 and 1) at Hermanus due to the handscaler frequently giving a value of 0 where the computer can detect a small variation and gives a value of 1. What is more important, is that the performance of the method stays virtually the same irrespective of the day or month of the year, or the year or years used in the comparisons. This proves the method's adaptiveness to any changes in the quiet day pattern irrespective of day-to-day, seasonal or solar activity variations. The method has also been shown to adapt to data from different geographical locations thus providing a global method. The LRNS method has been internationally approved by the International Association of Geomagnetism and Aeronomy.

A magnetospheric substorm is a transient process initiated on the nightside of the Earth in which a significant amount of energy derived from the solar wind-magnetosphere interaction is deposited in the auroral ionosphere and in the magnetosphere (Rostoker *et al.*, 1980). It is well-known that at low latitudes Pi 2 pulsations occur in one-to-one correspondence with substorms and that they are particularly clearly observed over a very wide region of the nightside hemisphere (Saito *et al.*, 1976). Furthermore, extremely small substorms, hardly detectable with the AE index, are easily detected by low-latitude Pi 2 pulsations. At low latitudes Pi 2 pulsations are also simultaneously detectable in the dayside hemisphere (Sutcliffe and Yumoto, 1989; 1991). As a consequence of these facts, various researchers have in the past expressed the desirability of continuously monitoring Pi 2 pulsations from three low latitude ground stations spaced evenly in longitude in order to indicate the occurrence of substorms in real time. In recent work, Sutcliffe (1995) demonstrated the development of a Pi 2 based substorm index. The techniques of data adaptive filtering and maximum entropy spectrum analysis were used and results using synthetic and real data considered. The possibility of utilising artificial neural networks is currently being investigated.

5 Conclusion

Research carried out at the HMO since 1986 and reviewed in this paper has been primarily concentrated in three fields. The first has been the study of geomagnetic field variations of various types, primarily geomagnetic pulsations. This work serves to develop a general knowledge of magnetospheric dynamics and an understanding of geomagnetic field variations. Magnetic field modelling, the second research field, contributes directly to the provision of more accurate and higher resolution magnetic field models and enables the provision of models extending beyond the country's borders. Finally, work aimed at improving geomagnetic activity indices assists in the provision of geomagnetic disturbance alerts to local clients and contributes to the HMO's functioning as part of the international network of geomagnetic observatories.

The HMO, like a number of other similar institutions around the world, has been obliged to become market oriented during the past decade in order to survive. However, a certain level of fundamental and applied research is equally important to ensure longterm survival. The work reviewed here testifies to a good balance having been attained at the HMO.

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