AGSO

Transient and Induced Variations in Aeromagnetics

(Report of Meeting on 18th September 1996)

compiled by

Peter R. Milligan
Charles E. Barton

AGSO Record 1997/27

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AUSTRALIAN
GEOLOGICAL SURVEY
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DEPARTMENT OF PRIMARY INDUSTRIES AND ENERGY

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PREFACE

This publication is an outcome of a meeting entitled "Transient and Induced Variations in Aeromagnetics" that was held in Canberra on 18 September 1996 to discuss the effects of rapid fluctuations of the geomagnetic field on high-resolution aeromagnetic surveys and airborne detection systems. The meeting brought together people from the exploration and mining industry, Defence, Government Science, and Universities with common interests in the nature and applications of external magnetic fields and of the electromagnetic properties of the Earth's crust and oceans. Inevitably, much of the focus was on the use of base stations and tie lines for correcting for the influence of geomagnetic fluctuations in survey data. However, the discussion ranged widely from magnetospheric physics to the magnetic effects of ocean swells at aeromagnetic elevations.

The first contribution in the volume (Barton) gives an introduction to the problems caused by transient geomagnetic fluctuations and associated crustal induction effects in modern high-resolution aeromagnetic surveys. This is followed by a transcript of the report of the proceedings of the September meeting that was circulated to participants. This report contains pertinent comments by several participants who do not have formal contributions elsewhere in this volume, and includes recommendations about future directions. The next twelve papers cover presentations that were given at the meeting; Graham Heinson's paper was displayed as a poster as he was unable to attend. The final two contributions were not presented by speakers, but are included here because of their relevance to the theme of the meeting: the abstract of Jonathon Whellam's Ph.D. thesis, and a paper by Richard Marshall about a Pc3 index that was presented at the STP Workshop, Japan in January 1996.

Participants at the September meeting were enthusiastic about maintaining and expanding cooperation and collaborative efforts in the future.

CEB, PRM

AGSO, 27 May 1997

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Transient and Induced Variations in Aeromagnetics: an Introduction.

C.E. Barton

Australian Geological Survey Organisation
GPO Box 378
Canberra ACT 2601

A discussion meeting entitled *"Transient and Induced Variations in Aeromagnetics"* was held at the Australian Geological Survey Organisation (AGSO) in Canberra on 18 September 1996. The meeting arose from a growing interest in the effects of rapid natural variations of the geomagnetic field on high resolution aeromagnetic surveys and naval detection systems (Figure 1). The meeting was a lively affair, attended by representatives from exploration and mining companies, several universities with research interests in external and internal geomagnetic fields, the Defence Science and Technology Organisation (DSTO), the Ionospheric Prediction Service, Radio and Space Services (IPS), and the Australian Geological Survey Organisation (AGSO).

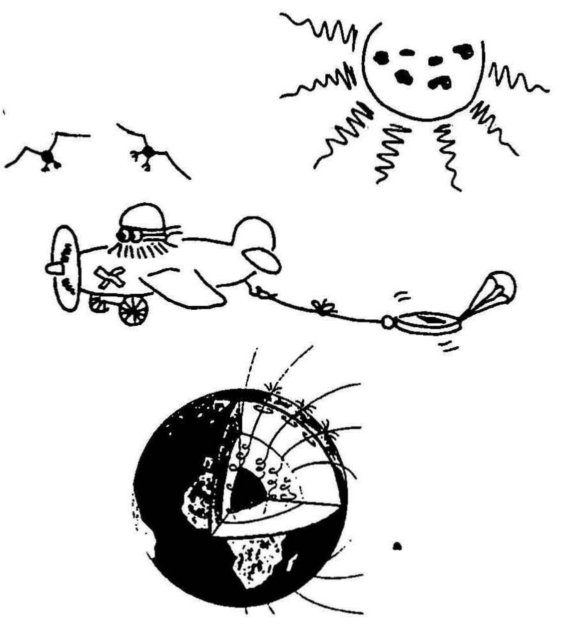

Figure 1. Transient and induced effects in aeromagnetics

Micropulsations and other rapid fluctuations of the field have generally been ignored in traditional aeromagnetic survey work as being below the detection thresholds and sampling rates of magnetometers. The advent of high-resolution survey capability (sub-nanotesla sensitivity and sub-second sampling rates) has changed this situation, and rapid time-variations of the field can now be an important noise source that may necessitate considerable investment in tie-line flying.

The overlap between the range of parameters used in modern high-resolution surveys and the spectrum of short-period geomagnetic variations can be gauged from Figure 2 and Table 1. The table gives the classification nomenclature for micropulsations and shows the distances that a survey aircraft flying at a typical speed of 65 ms^{-1} will cover during one micropulsation period. These distances are comparable to the scale of magnetic anomalies of interest.

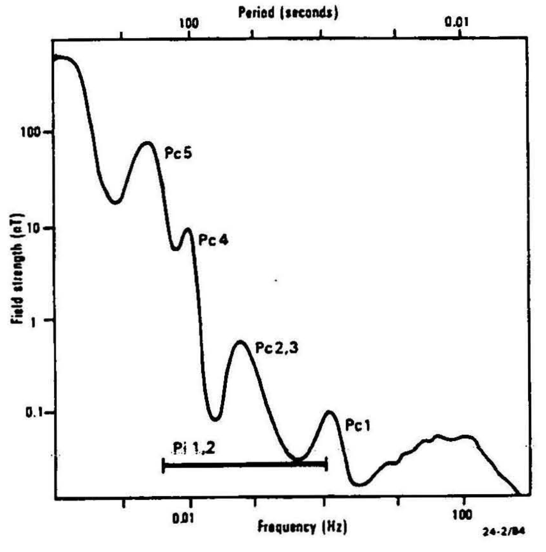

Figure 2. The spectrum of short-period geomagnetic variations.

Table 1. The IAGA classification of pulsations* and corresponding flight line wavelengths.

	Period range (s)	Wavelength when flying at 65 ms^{-1} (m)
Continuous		
Pc1	0.2 – 5.0	13 – 325
Pc2	5.0 – 10	325 – 650
Pc3	10 – 45	650 – 29250
Pc4	45 – 150	2925 – 9750
Impulsive		
Pi1	1 – 40	65 – 2600
Pi2	40 – 150	2600 – 9750

*Continuous pulsations are designated Pc; impulsive pulsations, which look like damped oscillations, are designated Pi.

Aeromagnetic surveys are now targeting nanotesla-level anomalies, such as those associated with hydrocarbon accumulations in sedimentary basins. The use of single base-stations to remove transient effects[1] from such survey data is of questionable value when the spatial homogeneity of the base-station signal is unknown. External current systems

[1] meaning the effects of short-period variations of the geomagnetic field, including contributions from associated currents induced in the Earth's crust.

responsible for rapid fluctuations of the field exhibit spatial heterogeneity that is related to their proximity to the Earth's surface—ionospheric sources being near-surface and magnetospheric ones being remote. Additional complexity arises from the variability of crustal induction effects associated with short period signals. (Long-period variations sample crustal conductivity to greater depths, several km or more, so are less sensitive to local anomalies.)

The scale of localized crustal structures that may carry induced currents that would contribute to transient effects can be gauged from the electromagnetic skin depth of the source signal,

$$\partial = \sqrt{T / \pi \mu \sigma}$$

where T = period, $\mu = 4\pi 10^{-7}(1+\chi)$, χ = volume susceptibility, and σ = electrical conductivity, all in S.I. units. Values of ∂ are illustrated in Table 2 for selected crustal materials. At short periods, surficial features such as ground water bodies and salinity will influence the crustal induction component of base-station signals on a localized scale.

The scientific challenges we face are:
(i) to understand the nature and temporal distribution of transient effects (e.g., daily, annual, and solar-cycle variabilities);
(ii) to determine the distribution of transient effects over the Australian continent and its offshore margins, including altitude effects, with particular regard to the the influence of local variability in crustal induction responses;
(iii) to develop scenarios for a cost-effective balance between the use of tie-lines and base-stations, and to identify conditions under which surveys should not be flown; and
(iv) to evaluate the performance of base-stations for monitoring geomagnetic variations offshore under varying geomagnetic and ocean conditions.

The purpose of the meeting was to provide a scientific focus for such work, to create an educational forum, to identify the key questions and the types of investigations needed to address them, and to establish a basis for future cooperation. A strong consensus at the meeting favoured continuation of these activities, with some recognised though informal framework. The name TRIVIA has been adopted for this framework (use the full name if you prefer); it refers not to any particular project, but rather to an area in which we share interdisciplinary and multi-application interests. There is a parallel in the name SEDI, which has provided a successful focus for Studies of the Earth's Deep Interior.

Table 2. Skin depths for crustal materials

	Conductivity (Sm^{-1})	Susceptibility (10^{-6} SI units)	Skin depth @ 0.1 s (km)	Skin depth @ 1 s (km)	Skin depth @ 10 s (km)
Brine	4	.14	.08	.25	.8
Clays	.1	300	.5	1.6	5
Weathered hard rocks	.01	10000	1.6	5	16
Dry sediments	.001	100	5.0	16	50

Transient and Induced Variations in Aeromagnetics: Discussion Meeting Report

C.E. Barton and W. Welsh

Australian Geological Survey Organisation
GPO Box 378
Canberra ACT 2601

The problem of reducing the effects of rapid fluctuations of the geomagnetic field on aeromagnetic survey data has come to prominence since the introduction of high-resolution surveys. The problem is also of interest to Defence in the context of magnetic detection offshore and detonation of magnetic mines. A meeting was held at the Australian Geological Survey Organisation (AGSO) in Canberra, 18th September 1996 to discuss this and related problems. The aims of the meeting were to:

- focus scientific attention on the problem;
- summarise progress already made in areas related to the central problem;
- identify the principal questions that aeromagnetic exploration companies and Defence wish to see addressed;
- develop strategies for future work and cooperation.

This report summarises the proceedings of the meeting.

MEETING PARTICIPANTS

Companies

Sam Bullock (Kevron)
Euan Clarke (Austirex-WGC)
Steve T. Mudge (RGC Exploration)
Jonathon Whellams (Pitt Research)

Government

Charles Barton (AGSO)
David Cole, Director (IPS)
David Denham (AGSO)
Peter Gunn (AGSO)
Peter Hopgood (AGSO)
Richard Marshall (IPS)
Phil McFadden (AGSO)
Peter Milligan (AGSO)
David Robson (NSW Geological Survey)
Jim Smelt (DSTO)
Alan Theobald (DSTO)
Julian Vrbancich (DSTO)
Wendy Welsh (AGSO)
Phil Wilkinson (IPS)

Universities

François H. Chamalaun (Flinders University of S.A.)
Brian J. Fraser (University of Newcastle)
Adrian Hitchman (Australian National University)
Ted Lilley (Australian National University)
Robert L. McPherron (University of California, Los Angeles)
Liejun Wang (Australian National University)
John T. Weaver (University of Victoria, Canada)

INTRODUCTION

To introduce the meeting, Charlie Barton (AGSO) welcomed the visitors, especially those from overseas. He outlined the purpose of the meeting, as stated above, and emphasised that this was not a meeting for academics, but was setup to address the needs of exploration companies and Defence. The present initiative has grown largely out of the AWAGS (Australia-Wide Array of Geomagnetic Stations) experiment that monitored magnetic variations over the whole continent for 9 months at 1-minute/1 nT resolution. Array experiments can address the question of the effect on base stations of spatial inhomogeneity in the natural fluctuations of the geomagnetic field and their associated inductive response from the crust. Widespread use of high-resolution survey methods (sub-second sampling, sub-nanotesla resolution) has shifted interest towards the interfering effects of micropulsations and other rapid geomagnetic fluctuations.

Peter Gunn (AGSO) described the parameters of modern aeromagnetic surveys and pointed out that geomagnetic fluctuations now comprise the biggest noise contribution in high-resolution surveys. Tie lines are used to reduce the effects, but add 10% or more to the cost of a survey and flying must still be stopped during magnetic storms. More use of high-resolution base stations may be helpful, but they are costly and there is not enough field evidence to determine when and where more base stations might be cost-effective. Geomagnetic fluctuations at the frequency of the tie lines are particularly bothersome; these fall into the micropulsation range. Gunn stressed that the meeting should focus on the needs of the aeromagnetic exploration community resulting from the increasing use of high-resolution aeromagnetic surveys.

Clarke reinforced the concerns contractors have about high-frequency noise. He noted that at 1 km tie-line spacing, crossovers occur about every 15 s along track, which is in the Pc3 range. WGC uses up to 3 base stations to cover surveys of 1000 km in extent.

Mudge mentioned that 1-second sampling (typically a ground interval of 60 to 80 m), is too slow for small targets such as mineral sand deposits. At higher frequencies, along-line interference from transient effects may be a serious problem and is difficult to avoid through the use of tie lines when searching for small targets.

WHAT THE INVESTIGATORS SAID

Peter Milligan (AGSO) said that it is usually assumed that micropulsations and longer-period variations are removed by using base stations and tie lines, but this is probably not so. AGSO uses a single base station for surveys. Milligan described results from two high-frequency magnetometer array studies conducted in conjunction with AGSO aeromagnetic surveys. Helium total-field instruments and several Flinders 3-axis fluxgate magnetometers with a ring-core modification to permit 0.1 nT/5 s sampling were used. Across a 40 km-wide area of low-magnetic-relief near Ballarat, micropulsations were found to be spatially uniform. Across a larger, 150 x 100 km area near Bendigo, Pc3 (~20 s) micropulsations were found to vary significantly in amplitude but not in phase. Inhomogeneities in longer period variations (60–600 s) were significant for both amplitude and phase, and indicated a N–S conductivity anomaly. Milligan mentioned that it is often difficult to see evidence of micropulsations in total field measurements—a view reiterated by McPherron.

For future work, Milligan suggested investigation of the coast effect and the effects of shallow good conductors, e.g., saline deposits. He also added that 0.5 s sampling at a base station would be adequate if perfect data could be acquired; in practice, more rapid sampling is useful so that digital filtering can be applied to remove interference.

François Chamalaun (Flinders University) outlined the magnetometer array studies carried out by Flinders University to determine the spatial inhomogeneities of geomagnetic field fluctuations at scales ranging from continental (AWAGS) to aeromagnetic-survey size. Inhomogeneities are such that surveys employing single base stations do contain errors. Results from the Canning Basin, where a large conductivity anomaly has been identified, highlight the problem and show that, even under magnetically quiet conditions, spatial inhomogeneities exist that cannot be removed by the use of a single base station. Chamalaun concluded that it is unwise to rely on tie lines or single base stations, and presented a histogram from Whellams' thesis that shows the distributions of tie line cross over errors for the SAMAS survey processed with (i) no base station corrections, (ii) a single base station signal removed, and (iii) signals from multiple base stations removed. A big reduction in cross-over errors occurs from step (i) to step (ii), but a much smaller gain from step (ii) to step (iii). The Flinders group has experience of working with contractors on magnetometer array studies linked to aeromagnetic surveys, and wishes to extend this relationship.

Chamalaun pointed out the relatively low cost of the fluxgate magnetometers developed at Flinders University (<$10 000 per instrument) and their ease of deployment (stand-alone units that can be hand-buried).

Jonathon Whellams (Pitt) alluded briefly to the extensive work covered in his recent Ph.D. thesis "Spatial inhomogeneity of geomagnetic fluctuation fields and their influence on high resolution aeromagnetic surveys". The thesis work analyses inhomogeneity effects in aeromagnetic surveys arising from crustal and coastal induction effects using three array studies: AWAGS, the Canning Basin study, and the SAMAS Synchronous Aeromagnetic-Magnetometer Array Study in SE South Australia. Horizontal variation gradients can be as large as several tens of nT/100 km under disturbed conditions in the vicinity of conductivity anomalies. Even under quiet conditions the gradients may be significant—typically 1-2 nT/100 km for the AWAGS data and up to 10 nT/100 km in the Canning Basin.

Whellams showed some impressive computer-animations of fluctuating field patterns over Australia on different time scales, highlighting their spatial variability and demonstrating the power of animation as an investigative as well as a display technique.

Lilley pointed out that the coast effect at the long periods of the daily variation is more complex than at shorter periods. The reason is that a regional (primary) component in the vertical field is present at daily-variation periods, which adds vectorially (it generally has a different phase) to the vertical component induced in the usual "coast-effect" manner. At shorter periods, the vertical regional component is usually negligible.

Graham Heinson (Flinders University) was unable to attend the meeting, but provided poster material to illustrate:

(i) the theoretical frequency/depth-dependence of attenuation by seawater of geomagnetic fluctuations, and

(ii) signals observed experimentally using a line of seabed vector magnetometers running offshore, along, and just beyond the continental shelf, and also across the Reykjanes Ridge in the North Atlantic.

Ted Lilley (ANU) gave an historical introduction to aeromagnetic exploration in Australia, started by BMR in the 1950s using fluxgate magnetometers. Use of a proton-precession sensor in the aircraft (after 1962) made practical the method of diurnal removal by subtraction of a base-station record, and so brought into focus the question of the spatial uniformity of the "diurnal" fluctuating magnetic fields. At the same time, W.D. Parkinson of BMR was working on understanding the physical basis of such non-uniformity, as exemplified in the geomagnetic "coast effect".

Lilley then outlined some of the work carried out by himself and colleagues at the Australian National University, using magnetometer arrays to map magnetic fluctuations in parts of the Australian continent. He traced a series of published papers that linked the patterns of magnetic fluctuation to their effects on airborne magnetometer data, and which explained the importance of crustal induction effects as a noise factor in aeromagnetic survey data.

Lilley described some new equipment for recording magnetic signals in the marine environment. Three-component fluxgate magnetometers were deployed earlier this year on the floor of the Southern Ocean near the spreading ridge between Australia and Antarctica, and under the Antarctic Circumpolar Ocean Current (a joint project with Flinders University). A total field instrument is under development to record magnetic fluctuations when floating on the sea surface or when profiling down through the deep-ocean column.

Lilley drew attention to the practice of using 3-component rather than total-field base-station data for locating conductivity anomalies, but pointed out that total-field base-station data can give useful reconnaissance information on conductivity anomalies if combined with horizontal-field data from a reference observatory, even though the reference observatory may be hundreds of kilometres away. He pointed out that (following Parkinson) natural induction effects are seen predominantly as a vertical response to a horizontal inducing field; hence there is a strong latitude dependence of how local induction effects map into total-field measurements.

McPherron also alluded to the advantages of combining vector and total field instruments, citing an example from seismo-magnetic studies on the San Andreas Fault.

Liejun Wang (ANU) described a thin sheet electrical conductivity model of Australia that is consistent with the known crustal conductivity anomalies (i.e., induction vector data) and simulates very well coastal induction effects as they propagate inland. Wang alluded to the predictive capabilities of such a conductivity model for identifying where induction phenomena will most influence aeromagnetic surveys. The conductivity model is available in digital form on request.

Adrian Hitchman (ANU) reviewed a study by Le Borgne and Le Mouël (1975) that used aeromagnetic tie-line misfits to identify an electrical conductivity anomaly beneath the Mediterranean Sea. Hitchman is embarking on a similar study in Australia as part of his Ph.D. work.

John Weaver (Victoria University, B.C.) summarised his now-classical analysis of the magnetic signal produced by electromagnetic induction in ocean swells. Theory shows that the magnitude of the effect increases linearly with amplitude of the swell and depends strongly on the frequency of the waves. For normal swell conditions (amplitudes up to a few metres and periods of 10-60 s), the induced signal at typical aeromagnetic survey elevations ranges from 0.1 to several nT, hence is readily recorded in aeromagnetic survey data. The geometry of the swells and flight lines needs to be taken into account.

Bullock noted that the magnetic signal varies little with elevation for long-period swells (beyond about 30 s), but attenuates rapidly for periods below about 10 s.

Clarke said he has encountered strong signals in marine aeromagnetic surveys produced by ocean swells that are often of the same order as the geological signal and are not always easy to remove. The effects are more difficult to deal with near the edge of the continental shelf where the wavelength and amplitude characteristics of swells change.

Robert McPherron (UCLA) gave a lucid description of the magnetic environment outside the Earth. He proceeded to explain the multiple effects of external stimulation by the solar wind and the field line and cavity resonances this produces. He explained the solar wind conditions that lead to magnetic storms and magnetospheric substorms, and how measurement of solar wind conditions in space can be used for prediction. McPherron concluded that the relationship of micropulsations to the solar wind and to the activity that causes them is less well understood than for storms and substorms. He urged users to make greater use of prediction services and to articulate their needs.

Clarke welcomed disturbance predictions, but said that in practice contractors usually keep flying and subsequently throw out bad lines. They stop flying only on really bad days—perhaps two per year, depending on latitude and the phase of the solar cycle.

Bullock pointed out that sitting-out a magnetic storm really saves only fuel costs, most other costs being fixed.

Brian Fraser (Newcastle University) elaborated on the theme of the origin and nature of micropulsations and noted that micropulsations are a day-time phenomenon, more common during the morning than during the afternoon. Fraser described N-S and E-W linear arrays of induction instruments used by the University of Newcastle to determine the spatial and temporal properties of micropulsations over Australia. Amplitudes of the Pc3 to Pc5 categories are typically 1-5 nT, and phases are reasonably constant (within 50°) over the continent. Pc5s come in wave packets that are readily traceable between stations—best seen in the X-component and less apparent in Y.

Lilley pointed out that lack of spatial coherence of micropulsations may be caused by crustal conductivity structures.

Phil Wilkinson (IPS) summarised the activities, prediction methods, and data services provided by IPS Radio and Space Services. IPS focuses on solar-terrestrial environments, taking a top-down view of phenomena observed at ground level. IPS operates recording instruments at locations across the country, and collaborates with AGSO's magnetic observatory program, the University of Newcastle, and with the STEL project. IPS welcomes opportunities to apply their expertise and expand their services to the exploration community.

Editor's note: STEL is run by Prof. K. Yumoto, Solar-Terrestrial Environment Laboratory, Nagoya University, Japan. High-resolution variometers (1 s, 0.1 nT) are operated along a N-S band centred about the 210° magnetic meridian. Stations in the Australian region are located at Mount Stromlo near Canberra, Dalby near Brisbane, Katanning near Perth, Learmonth, Adelaide, Birdsville, and Weipa. Information about STEL and availability of 210 MM data can be found at http://stelab2.stelab.nagoya-u.ac.jp/omosaic/goin95/geomag.html.

Richard Marshall (IPS) described the space weather information that IPS provides to customers and his recent work on developing indices for micropulsations. Marshall anticipates that IPS reports will be extended to include real-time and forecast maps of geomagnetic pulsation activity levels based on a Pc3 pulsation index, Kc3. He said some Pc3 pulsations are coherent over no more than 80 km in the north-south direction.

Fraser noted that Pc5s are notably more coherent in the E-W direction than in the N-S direction. Bob McPherron mentioned that it is not easy to predict micropulsations because we don't understand the relevant solar-terrestrial source mechanisms well-enough.

Charlie Barton (AGSO) pointed to AGSO's range of roles and interests in the present context: conducting aeromagnetic surveys and processing data, running the national network of magnetic observatories, providing disturbance indices and support for IPS, and conducting magnetometer array experiments. Eight observatories are operated, six on the mainland and two in Antarctica; all but Learmonth are now able to record 1-second data at a resolution of 0.1 nT and timing to an accuracy of between 0.1 and 0.5 s, depending on the observatory. Accurate GPS timing is gradually being installed at the observatories.

Barton showed an "Aeromagnetic Risk Map" of Australia, based on the scatter of induction vectors, that gives a relative measure of base station errors in different parts of Australia. This map is being updated as more array data become available, and will be extended from the present period range of 40-60 minutes to shorter periods.

He also showed a video animation of the AWAGS data, developed with Herb McQueen (ANU), that illustrates how different animation techniques can be used as a tool for investigating spatial inhomogeneities of magnetic field fluctuations.

WHAT THE USERS SAID

Euan Clarke (WGC-Austirex) outlined the extent of WGC activities and their emphasis on overseas operations (10–20 aircraft operating world-wide; 1–2 in Australia). Noise at periods of tens of seconds is a problem, both from geomagnetic (micropulsation) sources and from ocean swells, so good base stations with accurate (GPS) timing are important. Better, high-resolution base station data are needed so that fewer data have to be thrown out. However, base stations are costly, e.g., $50 000 for a Caesium system with GPS timing. The additional high cost of deployment, both in time and money, and the difficulty of finding suitable sites (accessible, clean power, security, low environmental noise) are additional disincentives to the use of multiple base stations. WGC uses up to three base stations to cover survey distances of 1000 km.

Clarke emphasised the value of high-quality base station data from permanent stations, such as the AGSO observatories and variometer stations installed by IPS and STELab. Such data provide a check on the performance of field base stations, can be used directly, and permit reprocessing of old data. Absolute data are not of particular value and most clients are content if data are recorded to within 100 nT of absolute values. Research activity should be concentrated in areas where exploration licences are held—particularly petroleum areas where more sensitive data are required. Information for overseas regions, e.g., the islands north of Australia, would be useful.

Clarke (and Mudge) suspect that ground temperature might affect the magnetisation of certain rocks sufficiently to be seen in aeromagnetic data. Nobody had a clear answer, though Chamalaun ventured that a very large volume of very magnetic rock would be needed. McPherron warned that coil instruments such as fluxgates are very temperature sensitive (typically >1 nT/°C), and precautions should be taken at base stations to reduce exposure to temperature fluctuations.

Barton asked if a location-dependent aeromagnetic "risk" indicator (i.e., some measure of the spatial inhomogeneity of crustal induction properties) would be of value. Clarke replied not really; information about ocean swell and micropulsation noise would be useful, and also long-range forecasts of large disturbances. He said the latter are not very accurate at present on a timescale that would influence the planning of aeromagnetic surveys; if they were, then aircraft servicing could be scheduled accordingly.

Sam Bullock (Kevron) started off by saying that removal of fluctuations of the Earth's magnetic field is the limiting factor for modern surveys, which seek to contour anomalies to better than 0.1 nT (for both oil and mineral exploration).

Bullock criticised the subjectivity of existing processing methods (diurnal subtraction, tie-line levelling, then microlevelling), and advocated a more scientific basis with less art-work. He suggested that a student (say) should use the many existing datasets to test different processing algorithms and develop more rigorous processing methods. He expressed willingness to provide test data for this purpose.

In common with earlier views, Bullock advocated a balloon or airship experiment to compare base station signals with aircraft signal as a function of elevation. Clarke said this should be done over the sea as well as land.

Bullock thought that survey tender specifications, particularly diurnal tolerances, are too arbitrary, and should be made more realistic with a scientific basis. He saw the advantages of having a common template for typical aeromagnetic survey specifications, which might be developed by AGSO. The aim should be not to get rid of tie lines by using more base stations (Bullock expects more and more tie lines to be used), but to achieve a rational match between survey techniques and survey specifications so that flying can continue under all conditions.

Alan Theobald (DSTO) described the sources of magnetic signals from submarines and surface vessels that are of interest to Defence (notably the Navy). Defence are often looking for small targets and need to track their movements. Theobald pointed out that the range of magnetic signals of concern to Defence for magnetic detection (or avoidance thereof) and for magnetic detonation of mines are similar to those of aeromagnetic interest. Defence wants to know more about the effectiveness of coastal base stations for monitoring natural geomagnetic noise offshore (above and below surface). The emphasis is largely on shallow-water shelf environments and choke points where vessels are obliged to pass. Detailed magnetic anomaly maps of shelf areas around Australia and a knowledge of geomagnetic noise characteristics offshore are important in this regard. Defence uses arrays of three axis magnetometers that operate at 10 Hz at depths down to about 30 m for measuring the magnetic signatures of vessels. Theobald was not sure what magnetic disturbance prediction requirements Defence might have.

Lilley mentioned that Wang's work on crustal conductivity modelling could be extended offshore. Theobald noted that AGSO's gravity map of Australia extends offshore, but there is a lack of corresponding magnetic coverage. Where overlap occurs, he has noted a degree of correspondence between the two maps.

David Robson (NSW Dept. Minerals & Energy) explained why NSW is the best place to do aeromagnetic surveys. He described the extensive program undertaken by NSW, particularly during the past 18 months, and highlighted the interest in subtle magnetic anomalies that can now be detected. Just under half their surveys are for petroleum exploration. For high-resolution survey, a N-S striping can occur at the tie-line spacing of 2 km. In common with other users, he has found that rapid fluctuations of the geomagnetic field are a serious noise consideration at high resolution.

Robson shared Bullock's view that there is a gap between commonly-used tender specifications and what is realistic. He stated that two separate base stations might be specified (e.g., one at an airport and one within 100 km of the flying site) but data from only one station gets used for processing by the contractor, the other being discarded. Bullock agreed and said there is no software for processing with dual base stations—that's what we're here to address. Clarke concurred.

Robson advocated increased efforts by AGSO to provide high-resolution base station data from observatories, and, possibly, additional stations. He would like IPS to be more proactive and attend ASEG meetings.

Steve Mudge (RGC) described his experiences surveying a mineral sand deposits. One in Australia is about 100 m wide with a magnetic signature of 2–25 nT. Helicopter measurements were made at 20–30 m elevation with 0.2-0.3 nT resolution. The deposit in Florida gave 0.5 nT anomalies that were difficult to reproduce on sequential days—the deposit is underlain by a water-logged swamp. In both cases, noise from rapid fluctuations of the geomagnetic field posed serious problems that warranted the use of a base station, rather than tie-lines, to remove low amplitude temporal variations of the field.

FUTURE ACTIVITIES

The final stage of the meeting was a discussion about what work needs to be done, who might do it, and where support might come from. Some priority areas were identified [possible activists in square brackets] as follows.

Field experiments

• Field experiments in many different locations to test the effectiveness of multiple base stations vs tie lines for reducing the noise in surveys. [It was felt that government and universities should take a leading role in this research, and come up with solutions, including data processing methods and software, that could be used by industry.]

• Experimental determination of the difference between ground-based measurements and those at survey elevations, e.g., by using a high-resolution magnetometer in a balloon varying up to, say, 100 m above ground level. This would need to be done in different environments and under different conditions of magnetic disturbance. [Bullock is particularly keen on this, and felt AGSO should take a lead role.]

• Determination of the ground temperature-dependence of crustal magnetic properties as a possible source of contamination in aeromagnetic survey data.

Reference data

• Base station data collected during aeromagnetic surveys should be available to the whole exploration community. [Companies, AGSO coordination.]

• One-second data should be collected routinely by observatories and archived—it may be useful in future years for reprocessing old data [AGSO].

• Should AGSO maintain high-resolution variometers (base stations) in addition to the existing observatory network? Variometer stations are easy to operate compared to magnetic observatories because there is no need for accurate absolute control. What sensitivity and sampling rate, and where should they be placed? [The Tennyson-Woods observatory vault at Flinders University is a candidate.]

Prediction and external sources

• Prediction of quiet days as well as disturbed days. [IPS might provide this as a new service.]

• Clarification of the spatial and temporal distribution of micropulsations and other rapid variations over Australia.

Instrument development

• Development of a low-cost high resolution base station with accurate timing—possibly a higher-resolution version of the Flinders magnetometer with a GPS clock. [Flinders, AGSO,...?.]

Tender specifications

• Create a template to be used for writing more realistic tender specifications [AGSO?].

The most demanding, and the most important undertaking in the above list is probably the development and systematic evaluation of multiple-base station methods. One snag is the lack of available high-resolution base station instruments with accurate timing. Commercial instruments are costly (e.g., $50 000 for a system).

Financial support: the companies represented pointed out that they are poorly positioned to provide financial support, but are willing to cooperate in the provision of data for research and in field experiments.

CONCLUSION

Participants felt that the interdisciplinary focus of the meeting on a common problem was highly informative and rewarding. We agreed to continue to cooperate, pool results, and hold future meetings under some umbrella framework—e.g., something akin to that operated successful by the multidisciplinary group SEDI (Studies of the Earth's Deep Interior), and that AGSO is well-placed to play a coordinating role. Wider participation, especially by companies, was welcomed.

Meetings: support was shown for a follow up meeting, at which the issues raised at the present meeting could be addressed to a wider audience. The next ASEG meeting (late February 1997, or the following one in Hobart in late 1998) was suggested as a possible occasion, although it is too late to get anything included formally in the program.

POSTSCRIPT CONCERNING ACRONYMS

A ballot was held after the meeting to decide on an acronym for the group. The acronyms proposed show considerable ingenuity and are listed below.

ACTIVE	Aeromagnetic Corrections Through Inhomogeneous Variational Earth-currents
AMPERE	Aero-Magnetic Profile Errors Resulting from Earth-currents
AMOUR	Aeromagnetic Misalignments Owing to Underground Resistivity
CICADA	Clarifying Ionospheric/Induction Contributions to Aeromagnetic Data in Australia
DRIFT	Diurnally and Regionally-Induced Field Transients
EVA	Electromagnetic Variations in Aeromagnetics
SIGFASE	Studying Implications of Geomagnetic Fluctuations on Aeromagnetic Survey Errors
SPADE	Short-Period Aeromagnetic Diurnal Effects
TIHRADE	Transient and Induced High-Resolution Aeromagnetic Diurnal Effects.
TRIAD	TRansients In Aeromagnetic Diurnals
TRIVIA	TRansient and Induced Variations In Aeromagnetics.

TRIVIA was the most popular choice and has been adopted; CICADA came a close second. The latter acronym, which was proposed by Ted Lilley, is being used for the activities of his group at the Australian National University.

Micropulsations from an airborne magnetic survey perspective

Peter R. Milligan

Australian Geological Survey Organisation
GPO Box 378
Canberra ACT 2601

THE PROBLEM

Micropulsations are (arguably) now considered to be the major source of noise in airborne magnetic surveys from non-ground sources. They often occur during daylight hours, have a spectrum of periods from a few seconds to many minutes, and a range of amplitudes from fractions of a nT to several nT. As this spectrum overlaps that of near-surface ground magnetic sources, their detection and removal is highly desirable to avoid false interpretations of the data.

Modern alkali-vapour total-field magnetometers, such as used by most airborne survey operators, have a resolution of better than 0.01 nT, a noise envelope of better than 0.1 nT on a sample to sample basis, and record at 10 samples per second. The other major external short-period noise source is from aircraft manoeuvres; with modern compensation systems this noise can be reduced to the sub-nT level. Thus micropulsations are a more significant source of noise than either of these two sources.

Electrical interference, particularly from power lines, can introduce irregular noise into the data, but this is usually very localised and the source is obvious. For surveys conducted over the oceans, ocean swell noise can often be observed as regular oscillations of the magnetic field. In such circumstances, this will become the dominant noise source.

PRESENT SOLUTIONS

There are several ways in which an attempt can be made to remove noise from airborne magnetic data, depending upon its source. For longer-period natural external variations of the geomagnetic field, tie-line levelling usually removes most of their effects. This does not, however, remove micropulsation signals as their periods are too short, and it would be too expensive to fly sufficient ties lines for their adequate removal.

Most airborne surveys deploy a single base-station total-field magnetometer. Some sample the geomagnetic field at the same rate as the survey aircraft, such as for AGSO's surveys, but a slower rate is often used. The assumption is made that subtraction of this base data from the aircraft data removes the unwanted natural high-frequency variations. This, of course, assumes that the micropulsations amplitude and frequency are exactly the same at the base as they are at the aircraft recording instrument, i.e., that pulsations are uniform in both time and space across a typical survey area of 150 km by 100 km.

Ocean wave noise can have a frequency content that is distinct from that produced by ground sources and may, therefore, be successfully filtered from the aircraft data (as was the case for the AGSO Bass Strait survey). However, this may not always be the case, and removal then would be much more difficult.

SOME OBSERVATIONS OF MICROPULSATIONS

- Micropulsations occur very often, particularly in the morning sector as "pearls" of oscillations. This is illustrated in Figures 1 and 2, which show micropulsations recorded at the Canberra Magnetic Observatory (CMO) while a new Caesium base station magnetometer was being compared with the observatory Narod instrument. Figure 1 also provides a comparison of pulsations recorded at CMO with those recorded at Goulburn by a Helium magnetometer, 65 km to the north-east of CMO, during an AGSO airborne survey.

- Micropulsations are very difficult to observe directly in airborne data records, although they must add to the noise content. This means that their effects are virtually indistinguishable from those produced by ground sources.

- There is probably no point in worrying about them except for areas where the crustal magnetic field varies smoothly, such as over sedimentary basins. In other areas, where the magnetic basement is near to surface, the amplitude and frequency of crustal features will completely swamp subtle external variations.

- Micropulsations will be of greater importance in coastal / offshore surveys, where the spatial non-uniformity is likely to be much greater due to the "coast-effect".

PREVIOUS STUDIES BY AGSO

Two small array experiments were undertaken by the author as pilot studies to help determine the temporal / spatial variability of micropulsations recorded in conjunction with AGSO airborne surveys.

Pulsations recorded during the AGSO survey of Ballarat showed only minor variations in amplitude and phase over a small area of 40 sq. km. (Milligan *et al.*, 1993).

During the AGSO Bendigo survey, micropulsations were recorded at three sites spanning the whole 1:250 000 map sheet area, with the survey alkali-vapour base-station in the south-west at Bendigo Airport, and two three-component fluxgate magnetometers situated in the north-west and the north-east corners of the sheet, respectively (Milligan, 1995). Micropulsations were found to be uniform in phase but variable in amplitude. Longer-period variations were much more variable in both amplitude and phase. A single base-station in this case is inadequate for the total removal of micropulsations from the survey data.

The likely variability of geomagnetic variations across a survey area depends on the uniformity of the source-field and also the variability of the geology as it affects the subsurface electrical conductivity. Hence, while one particular area may well show spatial uniformity in pulsations across hundreds of kilometers, another area may show great variability.

FUTURE EXPERIMENTS

Three studies are planned for the near future.

The "coast-effect" at high-frequencies

The aim of this experiment is to study the effect of the sea / land interface on the variability of pulsations. The coast-effect is well-known at longer periods, with an enhancement of the vertical component towards the coast due to induced currents flowing parallel to the coastline, but has not been studied in detail for short-period variations.

This work will extend the previous measurements made by Ted Lilley of the Australian National University (ANU) (Lilley *et al.*, 1989) on a profile perpendicular to the east coast of Australia, and is planned to commence in September 1997. High-resolution 3-component ring-core fluxgate magnetometers and an alkali-vapour total-field instrument will be used in this collaborative project between AGSO and ANU.

The influence of near-surface good conductors, such as salt-prone areas, on micropulsations

Near-surface areas of high conductivity could be expected to influence the amplitude and phase of micropulsations, which have a much smaller skin-depth of penetration than longer-period geomagnetic variations. It is planned to test for this with an array of high-resolution instruments in a suitable small area of saline land-degradation. This will not only provide information for airborne magnetic surveys, but will also test whether such small arrays of high-resolution instruments may be capable of helping to determine the possible extent of such saline degradation, particularly in places where degradation may not yet have become obvious from surface inspection.

The effect of altitude on micropulsations

Aircraft typically fly at 60 m to 150 m above ground level during airborne magnetic surveys. How representative are ground-based observations at these altitudes? This question arises often during discussion meetings, so it is proposed to resolve the issue by experimentation.

With light-weight low-power portable alkali-vapour magnetometers now available, simultaneous measurements can be made by two instruments, one recording at altitude suspended by hot-air (or helium) balloon, and the other on the ground directly underneath.

CONCLUDING REMARKS

The experiments outlined above should determine whether micropulsations can be successfully removed from airborne magnetic data. In some cases, it may be quite adequate to continue as is presently done, and assume they are spatially uniform and can be subtracted out using one base instrument. In other cases, the non-uniformity could be measured by an instrument array and, by interpolation in space and time, the variations subtracted out.

It may be possible to record with a small array of instruments for a short while, say one week, use the results to model the spatial field variations, then use a single base-station for the remainder of the survey. This would require 3-component instruments for the array.

Perhaps the only realistic solution may be to note micropulsation occurrences, and treat the data with caution.

If micropulsations and longer-period variations of the geomagnetic field can be adequately removed by a small array of magnetometers deployed with each survey, then perhaps there would be no need to fly such closely spaced tie-lines as is done at present. This could result in a considerable cost-saving, despite the extra instrument purchase, deployment and data processing costs.

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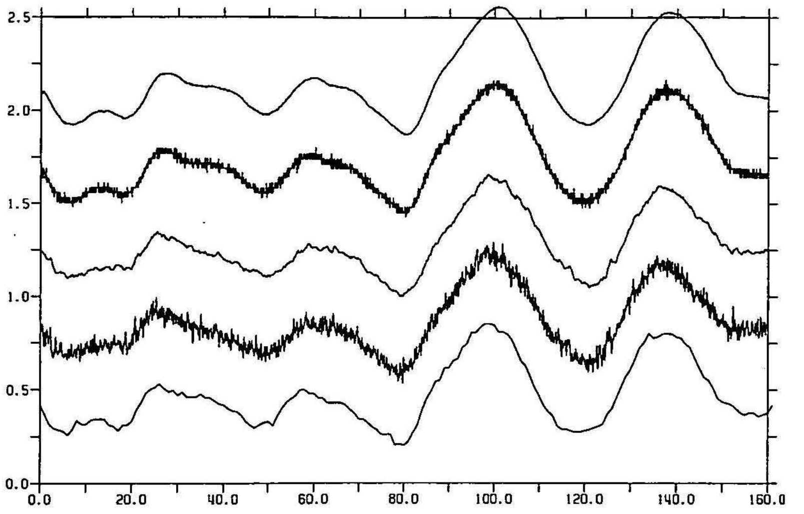

Figure 1. A comparison of total-field records of Narod and Caesium magnetometers located at the Canberra Magnetic Observatory, and a Helium magnetometer located at Goulburn, 65 km to the north-east. The bottom trace is 1 s Narod data, the two traces above are Helium data, and the top two traces are Caesium data. The Helium and Caesium instruments sample at 0.1 s (bottom of each pair), and have been average filtered to remove the noise (top of each pair). The x-axis scale is in seconds, the y-axis scale in nT.

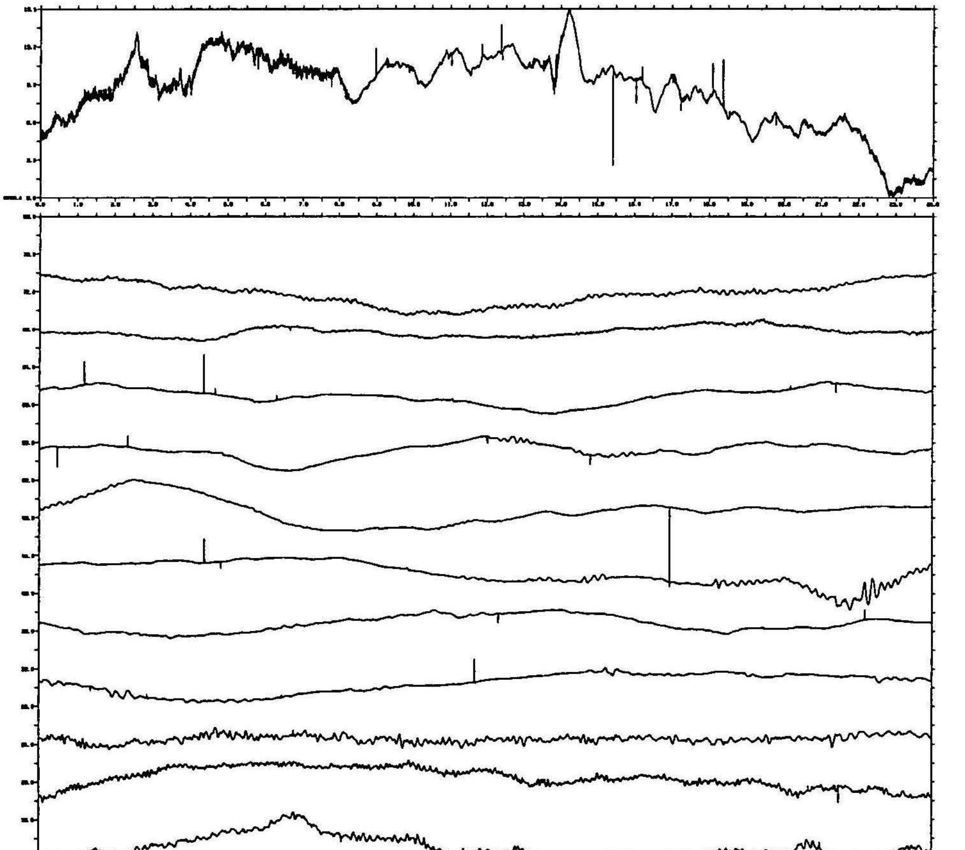

Figure 2. Total-field record derived from the Narod magnetometer located at the Canberra Magnetic Observatory. The bottom section has a chart width of two hours, and represents time from 0 UT (1000 EST) from bottom trace to top trace. The top section has a chart width of 24 hours. Vertical scale for the bottom section is 4 nT per numbered division, and the top section is autoscaled to 16.5 nT. Micropulsations are clearly visible from 1000 to 1800 EST, and most have sub-nT amplitudes.

Spatial inhomogeneities of the geomagnetic fluctuation field and aeromagnetic surveys

F.H. Chamalaun [1] & J. M. Whellams [2]

[1] The Flinders University of South Australia
GPO Box 2100
Adelaide SA 5001

[2] Pitt Research Pty Ltd
45 Hackney Road
Hackney SA 5069

In aeromagnetic surveys, the magnetic record obtained along the flight path needs to be separated into a temporal and spatial component. The spatial variation is the information sought and is related to the contrast in magnetic properties of the subsurface. The temporal variations are due to the fluctuations in the Earth's magnetic field and represent a source of noise or errors in magnetic surveys. In modern quality-controlled aeromagnetic surveys, the errors arising from navigation or the instrumentation are very small and the next major source of error arises from imperfect separation of the temporal variations from the spatial ones. At the same time, modern interpretation methods are increasingly concerned with subtle variations in the spatial variations that may indicate significant deep seated or small magnetic contrasts. The usual approach to removing the temporal variations is to record the temporal variation at a base station and to subtract such a record from the flight record, and/or to fly tie lines and to adjust the data so as to minimise the tie-line misfits over a survey area. A further protection against severe errors arising from the temporal fluctuations is not to fly when the base station suggests that the geomagnetic field is severely disturbed.

Our research (Whellams, 1996) has been concerned with the spatial inhomogeneities of the temporal fluctuations to which there are two main contributions. The first one is simply that the fluctuations in the Earth's magnetic field are themselves not spatially homogeneous. Using the AWAGS (Chamalaun and Barton, 1990; 1993) data set, maps have been constructed of the total field variations across Australia for a range of periods ranging from a few minutes to several hours (such as the daily variation). Because the external field arises from complex phenomena in the ionosphere and plasma sphere, the maps reveal complex patterns (Figure 1) that vary with period and are difficult to summarise in simple rules. However, gradients of several nT per 100 km are common over most of the continent, especially in coastal regions.

The second contribution arises from electrical conductivity contrasts at depth. The external field fluctuations induce electrical currents in the Earth, whose associated magnetic fields are added to the external field at the surface. An electrical conductor produces a spatial variation of the fluctuating fields, which will depend on the time of flight. Strong conductors can produce apparent aeromagnetic anomalies of tenth's of nT even on magnetically quiet days (Chamalaun and Cunneen, 1990). They cannot be simply corrected for with a single base station or tie lines (Figure 2).

To investigate the effects on an actual survey, an array of 36 roughly equally spaced magnetometers was deployed over an aeromagnetic survey area in the South-east of South Australia and the fluctuations in the geomagnetic field recorded at the same time as the aeromagnetic survey was flown. The array data were used to compute the temporal field for any time of the survey and for any position of the aircraft. A comparison between tie-line misfits using the single-station corrected data and array-corrected data showed a distinct improvement (Figure 3), even though, in this survey, errors from other sources were quite significant.

The results encourage us to believe that magnetometer arrays should be an effective way to correct for the temporal variations. The cost of deploying an array is compensated for by reducing the need for a dense tie-line grid and the ability to fly even on geomagnetically disturbed days.

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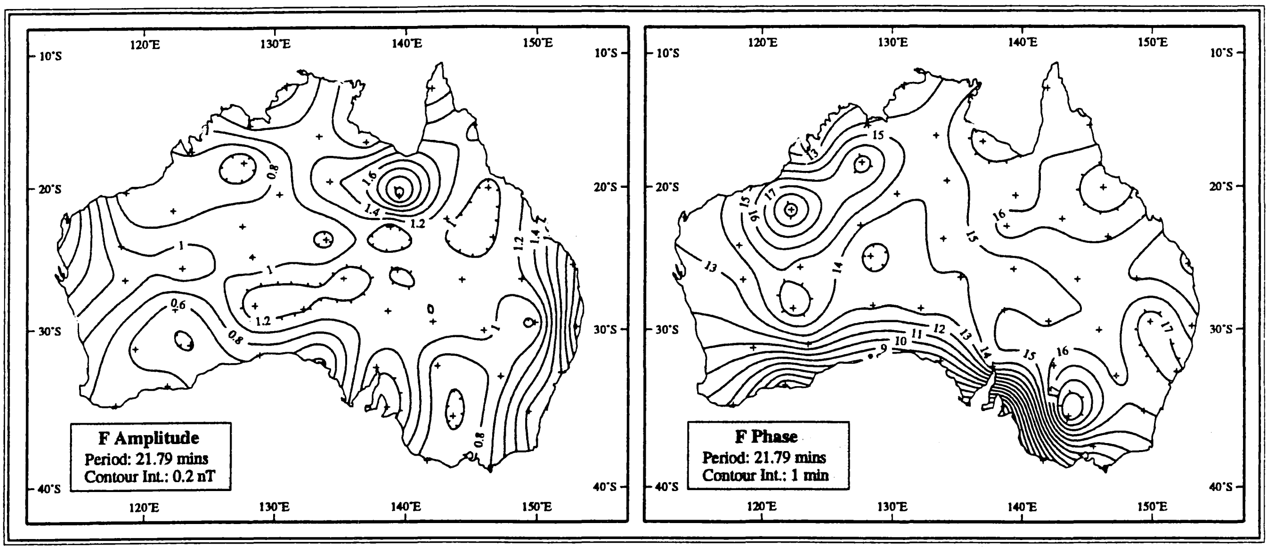

Figure 1 Fourier coefficient amplitude and phase lag maps at period 21.79 minutes based upon a two hour stretch of geomagnetically disturbed data from December 1, 1989 as recorded by the AWAGS array.

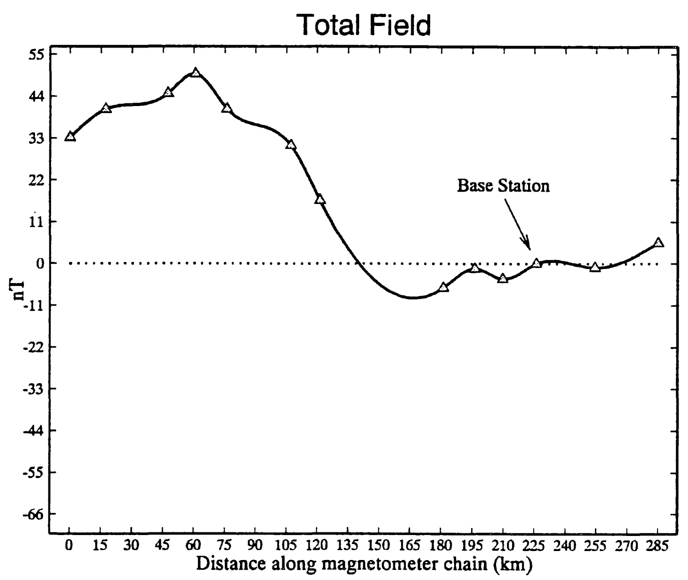

Figure 2. Inhomogeneity of total magnetic intensity fluctuations observed along a 285 km transect across the Canning Basin, Western Australia. Values plotted at each magnetometer site (marked by a filled triangle) correspond to offsets relative to the total field intensity observed several hours earlier after normalisation using the base station magnetometer indicated. The fact that the observed plot is by no means uniform about zero indicates that the geomagnetic field exhibits significant spatial inhomogeneity in this region of Australia.

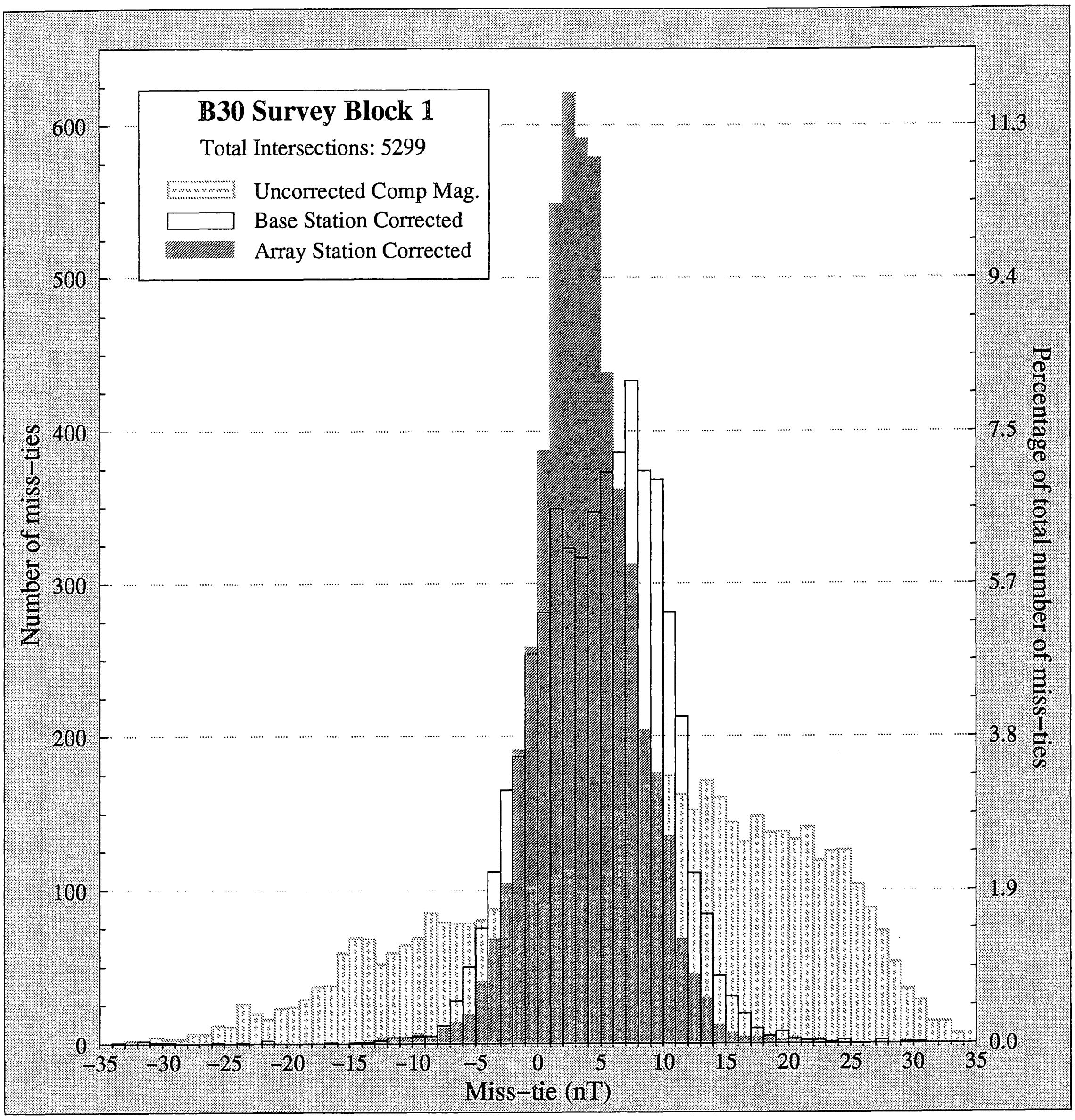

Figure 3. Histogram presentation of miss-tie values from SAEI aeromagnetic survey B30 displaying the merits of applying base station corrections and the improvements that can be obtained by employing an array of base stations.

A critical review of a case history from the literature on aeromagnetic tie-line misfits showing a conductivity anomaly

Adrian P. Hitchman

Research School of Earth Sciences
Australian National University
Canberra ACT 0200

Le Borgne and Le Mouël (1975) discuss an aeromagnetic survey conducted over the Alboran Sea in the western Mediterranean during 1973. Misfits in the total field recorded at crossover points were analysed and used to delineate a conductivity anomaly in the area. (A total field magnetometer operated as a base station during the survey and the base station record was subtracted from the aircraft record, "point by point", before tie-line crossover misfits were calculated.)

If a crossover point is represented by the letter P and a base station by the letter S, then the misfit measured at a crossover, ΔF(P), can be represented by

$$\Delta F(P) = \partial PS(t_L) - \partial PS(t_T) \;, \qquad (1)$$

where $\partial PS(t_L)$ represents the difference between the transient fields at the crossover point and the base station while flying the LINE over the point P, and $\partial PS(t_T)$ represents a similar difference while flying the TIE over P.

Since the time taken to fly a tie line (about 1 hour) is short relative to the period of the Sq magnetic variations, the term $\partial PS(t_T)$ is approximately constant for all crossover points on a particular tie line. This constant (C) is determined for each tie line by averaging all of the misfits on the tie and noting that the contribution of the lines to the misfit is approximately zero, on average, due to the practice of flying lines about a local maximum in the quiet magnetic field.

Equation (1) then becomes

$$\Delta F(P) = \partial PS(t_L) - C \;, \qquad (2)$$

which can be rearranged to allow the difference between the transient fields at P and S, while flying the LINE over P, to be determined:

$$\partial PS(t_L) \approx \Delta F(P) + C \;. \qquad (3)$$

This quantity can be calculated for each crossover point in the surveyed area. Along each LINE it approximately represents the anomalous total field that would have been measured at the median time of flying the line. By plotting the anomaly along lines flown continuously on a particular day, a systematic evolution of the anomaly during the day is evident in some parts of the surveyed area, reflecting the passage of the Sq vortex over a conductor.

By modelling the anomalous field along such lines using a simple 2D technique, compelling evidence for a conductivity anomaly emerges. The suggested body is approximated as conducting a horizontal line current at a maximum depth of 60 km below a section of the Alboran Sea.

In review, the possibility is assessed that the anomaly detected may reflect the coast effect in the region, as the shape of the conductor roughly parallels the coastlines to the immediate north and south. The conductor is terminated to the west just where deep water ends, and to the east just as the northern coastline makes a sharp northward turn.

An alternative possibility emerged with the recent publication of a paper by Seber *et al.* (1996). In it, Bouguer gravity anomaly and seismological data are presented, which suggest that a portion of downward-bulging lithoshpere below the Alboran Sea has detached and begun to sink into the asthenosphere. This has allowed hot, more electrically conducting asthenosphere to move up below the crust.

Whether the earlier paper detected the coast effect or, in fact, observed early evidence of lithospheric delamination in the region, it strongly suggests that misfits at crossover points in aeromagnetic surveys can provide useful information about conductivity anomalies in the surveyed area. An important implication for aeromagnetic surveying is that if such anomalies can be clearly delineated using similar techniques, then it will be possible to remove their effects from the data and significantly enhance the quality of the survey.

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Generation of magnetic signals by waves and swells

J.T.Weaver[1]

Research School of Earth Sciences
The Australian National University
Canberra ACT 0200

It has long been realised that the time-varying magnetic field associated with the electric currents induced in seawater by its motion across the Earth's main magnetic field when ocean waves and swells are present can be of sufficient magnitude (up to a few nT) to be easily detectable with modern magnetometers. In an earlier paper (Weaver, 1965), a simple theory was developed for the magnetic field generated by surface gravity waves in an ocean of infinite depth. The simple theory has since been generalized to include the effects of a conducting seafloor, internal waves, etc. (Beal and Weaver, 1970; Podney, 1975). Various field measurements, e.g., by Maclure *et al.* (1964) and Ochadlick (1989), have substantially confirmed the validity of the theory.

Although the primary application considered in the early paper cited above was the measurement of magnetic fields at sea by a buoy-suspended magnetometer, it is clear that such signals will also be picked up by low-flying aircraft conducting aeromagnetic surveys. It is, therefore, of interest to determine the likely significance of this wave induced "noise" and to estimate, if possible, the minimum altitude at which aircraft should fly in order to minimize its contamination of the geological signal. The simple theory developed previously still applies except that for application in the southern hemisphere the Earth's main magnetic field is directed out of the Earth rather than into it, and attention here is focused on the signal generated in the air above the sea surface rather than within the ocean itself.

Consider a simple harmonic surface gravity wave, of amplitude a and period $T \equiv 2\pi/\omega$, propagating in the x-direction of a right-handed coordinate system defined by unit vectors $\hat{\mathbf{x}}$, $\hat{\mathbf{y}}$ and $\hat{\mathbf{z}}$ where the z-axis is directed vertically downwards into the sea. It is well known that, for the incompressible and irrotational flow in such a wave, the velocity of the seawater is given by $\mathbf{V} = \operatorname{grad}\phi$ where, with $m = 2\pi/\lambda = \omega^2/g$ (g denoting the acceleration due to gravity), the velocity potential ϕ is

$$\phi = (ag/\omega)\exp(i\omega t - imx - mz).$$

It follows that

$$\mathbf{V} = \mathbf{v}(z)\exp(i\omega t - imx) \qquad (1)$$

with $\mathbf{v}(z) = -a\omega(i\hat{\mathbf{x}} + \hat{\mathbf{z}})\exp(-mz)$. Note that in the notation introduced above, ω, m, and λ are, respectively, the angular frequency, wave number, and wavelength of the ocean wave. The phase velocity of the wave is g/ω.

Let the angle θ measured from the positive x-axis define the direction of geomagnetic north and let the Earth's main field $\mathbf{F}$ be directed *out of* (southern hemisphere) the Earth's surface at an inclination I with the horizontal plane. Then, expressed in component form, we have

$$\mathbf{F} = F(\hat{\mathbf{x}}\cos I\cos\theta - \hat{\mathbf{y}}\cos I\sin\theta - \hat{\mathbf{z}}\sin I).$$

The electric $\mathbf{E}$ and magnetic $\mathbf{B}$ fields associated with the electric currents induced in the seawater satisfy the pre-Maxwell or induction equations (displacement currents are negligible)

$$\operatorname{curl}\mathbf{E} = -\partial\mathbf{B}/\partial t, \qquad \operatorname{curl}\mathbf{B} = \mu_0\mathbf{J}, \qquad (2)$$

where $\mathbf{J}$ is the electric current density and μ_0 is the permeability of free space which is assumed to hold approximately throughout the region. Because the seawater is in motion, the *total* electric field within it is

$$\mathbf{E} + \mathbf{V}\times(\mathbf{B}+\mathbf{F}) \approx \mathbf{E} + \mathbf{V}\times\mathbf{F}$$

since $|\mathbf{B}| << |\mathbf{F}|$ (the magnetic signals of interest are of the order of a nT whereas the Earth's main field is approximately 5×10^4 nT). Denoting the conductivity of seawater by σ, we may, therefore, express the second inducation equation (2) in the form

$$\operatorname{curl}\mathbf{B} = \mu_0\sigma(\mathbf{E} + \mathbf{V}\times\mathbf{F}). \qquad (3)$$

Given the harmonic form (1) of the ocean wave, it is helpful to write

$$\mathbf{E} = \mathbf{e}(z)\exp(i\omega t - imx), \quad \mathbf{B} = \mathbf{b}(z)\exp(i\omega t - imx)$$

before taking the curl of (3) and eliminating $\mathbf{E}$ with the aid of the first of equations (2). The resulting equation is

$$\mathbf{b}''(z) = \gamma_m^2\mathbf{b}(z) + im\mu_0\sigma FC\mathbf{v}(z), \qquad (4)$$

where we have defined

$$\gamma_m = \sqrt{m^2 + i\omega\mu_0\sigma}, \qquad C = \cos I\cos\theta + i\sin I.$$

In $z < 0$, the non-conducting air above the ocean where $\sigma = 0$, this reduces to $\mathbf{b}''(z) = m^2\mathbf{b}(z)$ with the solution that satisfies $\operatorname{div}\mathbf{B} = 0$ and the condition $|\mathbf{b}| \to 0$ as $z \to -\infty$ taking the obvious form

[1] On leave from the Department of Physics & Astronomy, University of Victoria, Victoria, BC, Canada, V8W 3P6.

$$\mathbf{b}(z) = b_0(\hat{\mathbf{x}} + i\hat{\mathbf{z}})\exp(mz), \tag{5}$$

where $b_0 = b_x(0)$. The solution of (4) in the region $z > 0$ beneath the ocean surface, and which vanishes as $z \to \infty$, is slightly more complicated but with the aid of (1) is readily verified to be

$$\begin{aligned}\mathbf{b}(z) &= amFC(i\hat{\mathbf{x}} + \hat{\mathbf{z}})\exp(-mz) \\ &-(ib_0 + amFC)[i\hat{\mathbf{x}} + (m/\gamma_m)\hat{\mathbf{z}}]\exp(-\gamma_m z).\end{aligned} \tag{6}$$

The value of b_0 is determined by matching the vertical magnetic component $b_z(0)$, as given by (5) and (6), across the surface $z = 0$. Substituting this value into (5) and rewriting $m = \omega^2/g = 4\pi^2/gT^2$, we then recover the final solution for the field above the ocean in the form

$$\mathbf{b}(z) = \frac{Tag\mu_0\sigma FC}{2\pi(1+\sqrt{1+i\beta})^2}(\hat{\mathbf{x}} + i\hat{\mathbf{z}})\exp(-4\pi^2|z|/gT^2), \tag{7}$$

where $\beta = \mu_0\sigma g^2/\omega^3$. For typical periods encountered with ocean waves and swells, we may generally assert that $\beta \ll 1$. For example, even a wave with the fairly long period of 10 s gives $\beta \approx 0.002$. Making this approximation in (7) and obtaining the component $b_F = b_x\cos\theta\cos I - b_z\sin I$ along the main field (the signal measured by total field magnetometers), we deduce that

$$b_F = \frac{Tag\mu_0\sigma F}{8\pi}(\cos^2\theta\cos^2 I + \sin^2 I)\exp(-4\pi^2|z|/gT^2), \tag{8}$$

which is purely real. The important point to note in this equation is that the magnitude of the observed magnetic signal is not only proportional to the amplitude a of the wave but also to its period T. Thus a long period swell of only a few centimetres amplitude can generate a more significant signal than a short period, wind-generated wave of much larger amplitude.

The nature of solution (8) suggests plotting $\log_{10}(b_F/a)$ against altitude $|z|$ for various periods. In the accompanying diagram this has been done for the special case of a wave progressing northwards ($\theta = 0$) and the assigned values $g = 10\ \mathrm{ms}^{-2}$, $\mu_0 = 4\pi\times10^{-7}\ \mathrm{Hm}^{-1}$, $\sigma = 4\ \mathrm{Sm}^{-1}$, and $F = 5\times10^4$ nT. Note that, for this particular direction of propagation, the dependence on the dip angle I in (8) vanishes. Substituting these values in (8) and taking logarithms, we obtain the following linear equation relating the magnetic signal in nT per unit amplitude of the wave in m, to the altitude $|z|$ in m:

$$\log_{10}(b_F/a) = -1.175\times(|z|/T^2) - 1 + \log_{10}T.$$

Graphs of this equation have been plotted in the figure for periods ranging from 5 s up to 60 s, at which point the approximation $\beta \ll 1$ is starting to fail so that one must revert to the more accurate formula (7).

When ocean signals are detected by aircraft-based magnetometers, it is necessary, of course, to transform the actual frequency of the ocean waves into the observed apparent frequency accounting for the speed and relative direction of the aircraft. This is a straightforward exercise which we omit in this short note.

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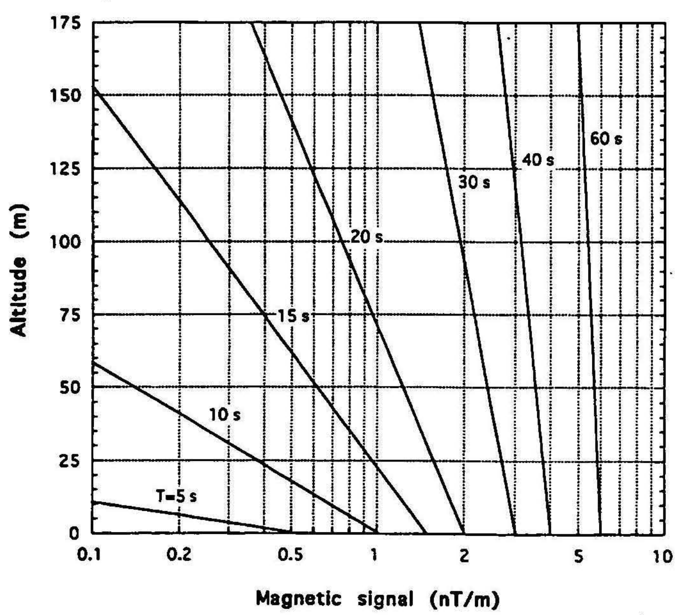

Origin of micropulsations and their relation to magnetic activity

Robert L. McPherron[1]

Visiting Professor, Department of Physics
University of Newcastle
Newcastle NSW 2308

INTRODUCTION

ULF waves or micropulsations are small perturbations in the Earth's magnetic field produced by a variety of processes in the ionosphere and magnetosphere. These waves are a form of geomagnetic activity which also includes substorms and storms. ULF waves are natural electromagnetic waves with periods from 1 to 1000 s. Their amplitudes generally decrease with frequency inversely as the second or third power of frequency. However, on any given day their amplitude may change by one to two orders of magnitude. Typical values are from fractions of a nanotesla (nT) to 100 nT. There are very strong latitude and local time effects on amplitude as well. ULF waves are used in exploration to probe the conductivity structure of the Earth's outer layer. They are also thought to be a problem in high resolution aeromagnetic surveys where they may be one of the many sources of noise that are not currently removed from the survey data.

The ionosphere is the upper portion of the Earth's atmosphere where some or all atoms and molecules have been stripped of at least one electron. The magnetosphere is defined as the region of space threaded by the Earth's magnetic field lines and bounded by a sheet of electrical current. An approximate scale drawing of the magnetosphere is shown in Figure 1. The outer boundary, called the magnetopause, consists of a sheet of current produced by solar wind particles as they turn in the Earth's magnetic field. Inside the magnetosphere are several cavities produced by internal boundaries. They include the outer magnetosphere (outside the plasmapause), the plasmasphere, the tail lobes (field above and below the plasma sheet), and the plasma sheet. The boundaries of these inner cavities are produced by different processes involving the interaction of the Earth's field with the solar wind magnetic field and particles. The cavities are threaded by magnetic field lines that emerge from the Earth and either return to the Earth or are connected to the magnetic field of the solar wind.

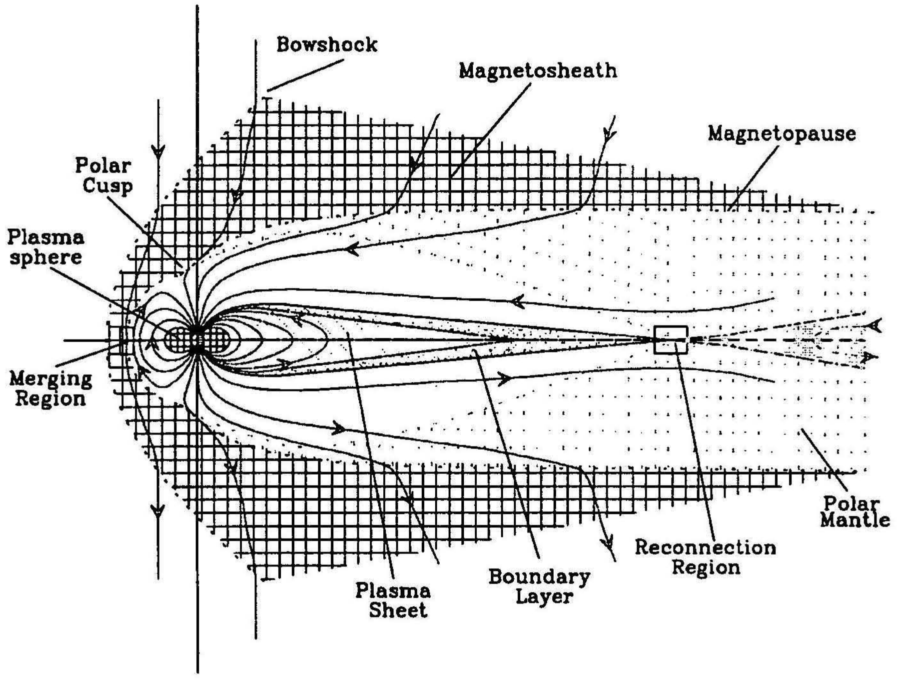

Figure 1: An approximate scale drawing of the Earth's magnetosphere showing the various boundaries and regions of which it is constructed.

[1] Permanent Address, University of California, Los Angeles, CA 90095-1567; email: rmcpherron@igpp.ucla.edu

MAGNETIC ACTIVITY

The process by which the Earth's field lines connect to the solar wind is called *magnetic reconnection.* This process is responsible for most magnetic activity including *magnetic storms* and *magnetospheric substorms.* Magnetic reconnection opens the magnetic field of the Earth to the solar wind at the subsolar point so that the motional electric field of the solar wind is imposed on the polar caps. This electric field drives ionospheric currents and bulk motion of the ionospheric ions. This motion is anti-Sunward over the polar caps and Sunward in the dawn and dusk auroral ovals. Electric currents associated with this two-celled convection pattern are called the *auroral electrojets.* The electrojets create magnetic perturbations on the ground known as *magnetic bays.*

Magnetic field lines opened on the dayside are transported over the polar caps and pressed into the tail lobes. They compress the plasma sheet as it is simultaneously pulled forward by the convection pattern. Eventually, the open field lines must reconnect on the night side becoming closed field lines that are returned to the dayside by convection. This reconnection usually does not begin at the distant x-line (60-150 Re) (labeled *reconnection region* in Figure 1) but instead begins at a near-Earth (15-30 Re) x-line inside the plasma sheet. The near-Earth x-line jets plasma and magnetic field earthward where it piles up beyond synchronous orbit near midnight. Plasma then either precipitates into the midnight auroral oval causing the aurora, or it is injected into the radiation belts where its constituent particles then drift around the Earth. Positive particles drift westward (towards dusk) and electrons drift eastward. Together these drifts create a westward ring of current called the *ring current.* The magnetic effect of this ring current on the ground is a southward magnetic perturbation. If there are many particles injected, the current created by the radiation belts is intense and a *magnetic storm* is said to be in progress.

MICROPULSATION ENERGY SOURCES

ULF waves are produced by two types of processes, external stimulation by the solar wind and internal plasma instabilities. Sources of external stimulation include pressures pulses and steps imbedded in the solar wind; interplanetary Alfven waves; waves created by particles reflected by the bow shock; turbulence in the bow shock; and surface waves on the magnetopause. Waves created by these processes penetrate the magnetopause and stimulate resonances within the magnetospheric cavities as discussed below. Sources of internal instability are diverse. Any process that creates a gradient in the distribution of particles in space, or of their distributions in velocity can, create waves. The waves are initiated by noise and then grow in amplitude off the energy provided by the steep gradients. Their growth destroys the gradient unless it is continually maintained by some other process.

EXTERNALLY DRIVEN RESONANCES

There are two types of externally driven resonances. The first is *field line resonance.* Every magnetic field line in the magnetosphere is loaded with particles (mass) and has a restoring force (tension) provided by the magnetic field. Because of the high conductivity of the magnetospheric plasma, magnetic field lines and particles are frozen together. Any force that displaces the particles also deflects the field. However, tension in the field tries to restore the field line to its equilibrium position. The particles provide inertia and the field line oscillates about its equilibrium position like a guitar string. This process is called *field line resonance.* Every field line in the magnetosphere has its natural resonant frequency. Both inside and outside the plasmapause, this frequency decreases with distance from the Earth. However, at the plasmapause a large increase in particle density (moving earthward) causes a sudden decrease in resonant frequency.

When internal magnetic field lines are excited by a monochromatic wave penetrating from outside, every field line will be affected to some extent. Those with identical resonant frequencies oscillate with large amplitude. If the frequency is too high, the response is weaker and lags the driving frequency. If it is too low, the response is again weak but leads the driver. Similar resonant frequencies tend to occur on shells around the Earth so that a monochromatic wave excites a wave that has peak amplitude at a particular latitude. Its phase changes rapidly with latitude, changing by π radians across the resonance. Field line resonances are associated with waves that carry field-aligned electric current. This current must close through the ionosphere. If the conductivity is high, as it is on the day side of the Earth, there will be little dissipation and the waves can grow to high amplitude. On the night side, the waves are rapidly damped and this type of micropulsation is rarely observed there.

Generally, waves incident on the magnetosphere have a broad spectrum of frequencies. In this situation, every field line will oscillate with all frequencies, but the largest amplitude oscillation is at its resonant frequency. In such cases, the ground signal is dominated by the frequency of field lines with feet at the observation point, but also contains frequencies from field lines both poleward and equatorward of the point. Changes in the input spectrum can cause significant jumps in the amplitude and phase of the ground signal.

The second type of externally driven ULF wave is *cavity resonance.* Each of the cavities mentioned above has characteristic frequencies established by the dimensions of the cavity and by its imbedded magnetic field and plasma. In contrast to the field line resonances, cavity resonances have constant frequency throughout the cavity. For radial modes, this translates to constant phase as a function of latitudes with jumps of π radians at nodes of the standing waves. At certain locations within the cavities, the cavity resonance frequency may match the field line resonant frequency. On these shells, energy from the cavity resonance can couple to the field line resonance, which then transfers energy to the ionosphere via field-aligned current. This coupling damps the cavity resonance. Cavity resonances can also tunnel through the plasmapause exciting the inner cavity responsible for pulsations at lower latitudes. Both field line and cavity resonances can be excited at multiple harmonics of their fundamental frequencies. Very complex interaction are possible as different harmonics of the two types couple in different combinations.

INTERNAL INSTABILITIES

Geomagnetic activity in the form of substorms and storms create circumstances that produce ULF waves by internal *instabilities.* For example, the convection system driven by the solar wind moves particles earthward in the tail. The particles are generally injected into the radiation belts mirroring close to the equator as they bounce back and forth along the field. This limited bounce motion represents a gradient in particle velocity distribution that is unstable to the *cyclotron instability*. Particles gyrating around a magnetic field line create a current that radiates a wave with frequency comparable to the gyro frequency. The wave grows, extracting energy from the particles and moving their mirror points away from the equator. Protons in the ring current at synchronous orbit will generate waves of about 10 s period. Higher frequencies are generated closer to the Earth.

Some instabilities are driven by resonance between waves bouncing along field lines and particles moving along the same field line (*bounce resonance*). Other instabilities are driven by particles drifting around the Earth with azimuthal velocities comparable to the velocity of waves propagating azimuthally (*drift resonance*). Sharp radial gradients in particle density may be unstable to the *interchange instability* (overturn of water on top of oil). Steep gradients in the bulk velocity of plasma may be unstable to the *Kelvin-Helmholz instability* (wind over water).

MAGNETOSPHERIC SUBSTORMS

Magnetospheric substorms are the cause of both the aurora and the auroral electrojets. At high magnetic latitudes, the effects of substorms are enormous compared to ULF waves, typically being of order 1000 nT and sometimes as large as 2000 nT. Substorms create the gradients that cause internal instabilities. They also modulate the ionospheric conductivity as auroral particles bombard the ionosphere. DC electrical currents flowing through the ionosphere as part of the substorm vary as a consequence of the changes in conductivity and radiate ULF waves. Plasma instabilities caused by velocity shears and particle beams also generate ULF waves. These waves are superimposed on the magnetic fields produced by the ionospheric and field-aligned currents.

A major part of every substorm is a field-aligned current system called the *substorm current wedge*. This is a current of order one million Amps that is diverted from the inner edge of the tail current through the midnight ionosphere. Its ionospheric closure is westward across the midnight region of bright aurora. This current is superimposed on the auroral electrojets driven by convection, and is the cause of sudden changes in the surface magnetic field. At midlatitudes the substorm current wedge causes magnetic perturbations known as midlatitude positive and negative bays. Typical disturbance amplitudes at these latitudes are 10-100 nT over 30-60 m, again much larger than typical ULF pulsations at these latitudes.

Magnetospheric substorms are an internal instability of the convection system driven by the solar wind. This system in driven by a southward turning of the interplanetary magnetic field, which initiates magnetic reconnection at the subsolar point (labeled *merging region* in Figure 1). The gross characteristics of substorms, as measured by the auroral electrojet indices, are highly predictable provided the upstream properties of the solar wind are known. However, the internal instabilities that generate ULF waves are dependent on the detailed development of a particular substorm and the past history of magnetic activity. They are, thus, less predictable than substorms.

MAGNETIC STORMS

Magnetic storms are also caused by a southward interplanetary magnetic field. Storms result when the solar wind blows at high speed with a strong southward magnetic field. These conditions guarantee that a large amount of magnetic flux will be forced against the dayside magnetopause and reconnect. Reconnection then drives a very strong internal convection system that injects many energetic particles into the radiation belts. The resulting distribution of particles is very unstable to the generation of ULF waves. These waves help move the particles in space and velocity contributing to the decay of the ring current by charge exchange with atmospheric neutral particles. The gross behavior of the ring current is even more predictable than it is for substorms, again provided one has knowledge of the upstream solar wind. The associated instabilities again depend more on details so that internal monitors of the magnetosphere would be required to predict the occurrence of ULF waves.

PREDICTION OF STORMS, SUBSTORMS AND MICROPULSATIONS

Geomagnetic activity, and the ULF waves that result from some plasma instabilities are ultimately caused by a southward interplanetary magnetic field. Structures in the solar wind that have a southward field have been identified and their causes are partially understood. These structures include high speed streams from coronal holes and coronal mass ejections from active regions on the photosphere of the Sun. The cause of these structures is poorly understood and not yet predictable using remote observations from the Earth. However, spacecraft between the Earth and Sun can detect these structures as they pass by and can transmit information about them to the Earth. This information typically arrives at the Earth one hour before the solar wind and gives a small amount of advance warning of impending activity. Some structures, such as coronal mass ejections (magnetic bubbles or flux ropes), have highly organised structures and once detected provide information about conditions for some hours ahead. The only convenient location for a solar wind monitor is at the first Lagrange point (250 Re upstream on the Earth-Sun line). Here the gravity of the Earth and Sun balance and a spacecraft can orbit the Sun with the same period as the Earth despite the fact that it is closer to the Sun. The relation of ULF waves to the solar wind is indirect for the instabilities and not nearly as predictable as substorms and storms. For field line and cavity resonances, the relation to the solar wind is better understood. However, these relations depend on details of the solar wind structure as it interacts with the Earth's magnetic field and there is usually not a satellite in the proper location to provide the input necessary for accurate prediction.

CONCLUSIONS

Magnetic activity in the form of magnetic storms, magnetospheric substorms, and ULF waves is a problem in any aeromagnetic survey since fields of external origin must be removed from the survey data to reveal subsurface anomalies of economic interest. The amplitude and frequency of magnetic variations are strong functions of magnetic latitude, local time, and conditions in the solar wind. Disturbances range from 1000's of nT in the auroral zone to fractions of a nT at midlatitudes. It is generally the case that fields of external origin are spatially homogenous on scales of at least 100 km (the minimum distance to ionospheric currents). However, the magnetic field induced in the Earth by these external fields depends on the local magnetic susceptibility and conductivity, and can change on scales of interest in surveys. The normal technique of subtracting the total field measured at a base station from remote observations succeeds in eliminating only the spatially homogenous external and induced parts of the field. It is a necessary first order correction, but there are residuals remaining for a variety of reasons.

ULF waves are a possible source of contamination of the total field measurements made in an aeromagnetic survey, but they are small in amplitude compared to effects of storms and substorms. The primary question is what is the amplitude of the disturbances that occur at frequencies comparable to the sampling frequency used in aeromagnetic surveys? Large amplitude fluctuations of substorms and storms have longer periods, but their spectrum may contain as much or more energy than do ULF waves at the same frequency. Other sources of noise in aeromagnetic surveys include topographic variations, altitude fluctuations of the aircraft, electronic noise, and human artefacts on the ground. It seems quite likely that all of these may be as important, or more important, than ULF waves.

Since ULF wave occurrence is difficult to predict, and since they have complex spatial distributions of amplitude and phase, they will be difficult to monitor and remove from aeromagnetic data. It would be wise to carry out extensive studies to demonstrate that they are truly the cause of noise in aeromagnetic data. If they are not, other phenomena may be more easily predicted and removed.

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Geomagnetic pulsations in the Australian region: typical signatures

B.J. Fraser

Department of Physics
University of Newcastle
Newcastle NSW 2308

INTRODUCTION

The Earth's near-space environment on the dayside is dominated by a complex dynamic interaction between the solar wind, the interplanetary field, and the geomagnetic field. The interaction region, the high latitude magnetosphere and ionosphere, is the site of substantial energy transfer (5×10^5 MW) from the solar wind through to the atmosphere and biosphere on field lines which map to the dayside high latitude ionospheric regions. The resultant plasma instabilities give rise to a broad spectrum of ultra-low frequency (ULF) waves including ion cyclotron waves, hydromagnetic waves, and other waves. Effects of this energy input are seen at middle and low latitudes through ionospheric current systems and magnetohydromagnetic (MHD) wave propagation and resonance. On the nightside, energy is explosively transmitted into magnetosphere by magnetospheric substorms.

The signatures of MHD waves from the magnetosphere are seen as geomagnetic pulsations, small variations in the Earth's magnetic field in the frequency range 1 mHz - 5 Hz (T = 0.2-1000 s). Amplitudes at the lowest frequencies can exceed 5 nT in the Australian region and up to many tens of nanotesla in the auroral zones. Of greatest importance to the external contamination of aeromagnetic survey data at low and middle latitudes are the longer period pulsations in the Pc3-5 1.7-1000 mHz frequency band (T = 1-600 s). The higher-frequency pulsations, Pc1-2, in the frequency band 0.2-5 Hz (T = 0.2-5 s) occur mostly at night time and during the few days following moderate to severe magnetic storms (Fraser, 1968). They occur in wave trains with durations of about 10 m to a few hours and amplitudes are very low, typically 10-100 pT. Consequently, they will not normally be a significant source of contamination in aeromagnetic data at middle and low latitudes.

This paper reviews and documents the characteristics of Pc3-5 pulsations observed on the ground at middle and low latitudes in the Australian region. Emphasis is on daytime activity and the aim is to provide aeromagnetic surveyors with a basic understanding of the influence they may expect to see in their data from geomagnetic pulsation signatures and suggestions on how these effects may be identified.

PULSATION SOURCES

The source of the stimulation of Pc3-5 pulsations is external to the Earth's magnetosphere and is controlled by the upstream solar wind and the interplanetary magnetic field (IMF). The occurrence of geomagnetic pulsations is, therefore, dependent on upstream interplanetary conditions such as properties of the solar wind plasma i.e., energy density, pressure, density, and the magnitude and orientation of the IMF. For example, emperical relationships have been statistically determined for Pc3-4 waves seen in the magnetosphere, which show pulsations frequencies are given by $f\,(\mathrm{mHz}) = 6B_{IMF}\,(\mathrm{nT})$ (Troitskaya *et al.*, 1971). Other external sources related to the solar wind include pressure pulses, bow shock turbulence, and boundary waves.

The external sources may transmit energy into the magnetosphere in a number of different ways. These include impulsive movement of the magnetopause on the dayside near the subsolar region, direct entry of waves into the high latitude cusp regions, and the generation of waves through viscous interaction between the streaming solar wind and the flanks of the magnetopause by the Kelvin-Helmholtz instability (analogous to waves produced by wind over water). Many of these mechanisms can carry wave energy from the outer magnetosphere, through the plasmapause deep into the higher density plasmasphere, where they may be detected on the ground at low latitudes. A schematic showing these wave sources and entry processes is seen in Figure 1 (after Allan and Poulter, 1992).

Wave energy entering the magnetosphere may either propagate within the cavity or may stimulate standing wave resonances. At Pc3-5 frequencies, the wavelengths of the waves are of the same order as the size of the magnetospheric cavity and, therefore, resonances involving standing waves are more likely to be seen. In contrast, the properties of the higher frequency shorter wavelength Pc1-2 pulsations are easily explained by consideration of propagating wave packets.

RESONANCES

There are two types of resonances within the magnetospheric cavity that may be stimulated by external sources: field line resonances, and cavity or waveguide mode resonances. MHD wave propagation in the magnetosphere is described by a closed set of three equations originally derived by Dungey in 1954 (see, for example, Hughes, 1994). From this theory, it can be shown that two wave modes result, the so-called toroidal and poloidal oscillations. In toroidal mode oscillations, the magnetic and velocity perturbations are azimuthal (Y or D component), and propagation is along the geomagnetic field direction at the Alfven velocity $V = B/(\mu_0\rho)^{1/2}$, where ρ is the plasma density. This creates a standing wave pattern along field lines between hemispheres and provides a field line resonance similar to a resonance on a violin string. The wave cannot propagate normal to the field and complete magnetospheric L-shells (analogous to onion skins) decouple and perform torsional oscillations with a latitude-dependent frequency. Higher frequencies (Pc3) are seen on the shorter field lines at lower latitudes while the lower frequencies (Pc5) are characteristic of the higher auroral latitudes.

The poloidal mode is a compressional (fast mode) wave, the electric field is azimuthally directed, and the magnetic and velocity perturbations are radial. Propagation is isotropic for this mode and the waves are not guided. Thus, the whole cavity between the magnetopause and the ionosphere may resonate with the same frequency and there will be no latitude-dependent frequency. They are commonly referred to as compressional cavity mode waves (CCM) or just cavity mode waves. If they have an azimuthal velocity component, they will propagate azimuthally and are denoted waveguide modes. Field line resonances (FLR) and cavity mode resonances (CCM) are indicated in Figure 1. It is these waves that propagate through the ionosphere to the ground and provide the Pc3-5 pulsation signatures. There are other waves present in the magnetosphere that are less common but these will not be considered here. They include bounce and drift resonances involving interactions with hot plasma in the Van Allan radiation belts, and, possibly, plasmapause surface waves. Much of the experimental research undertaken has concentrated on identifying the characteristics of FLR and CCM MHD waves in ground-based observations of geomagnetic signatures. Currently, FLR are well understood, but the identification of CCM is more difficult. FLR are observed at high, middle, and low latitudes with increasing amplitude and decreasing frequency with increasing latitude. On the other hand, CCM, because of their resonance characteristics, are more likely to be seen at very low and equatorial latitudes (see Figure 1). The remaining sections of this paper will describe the characteristics of FLR with respect to the Australian region.

TEMPORAL VARIATIONS

On the dayside of the Earth's magnetosphere, it is possible to excite FLR by providing an impulsive stimulus at the magnetopause or direct wave entry at the subsolar region (nose) of the magnetosphere or the high latitude cusp regions (Figure 1). These waves will penetrate into the magnetosphere and couple to the latitude-dependent FLR where their frequencies match. With an impulsive source and a broad spectrum of wave frequency input, a number of regions of resonant coupling may result. The resulting pulsations seen on the ground in the Australian region are local FLRs, typically in the Pc3-4 band (10–100 mHz) with maximum amplitudes of about 1 nT (Ziesolleck *et al.*, 1993) and peaking around local noon. They commence at dawn when the ionospheric conductivity increases, cease at dusk, and are seen on most days with a reasonably constant frequency which is characteristic of the latitude of observation (see Figure 2). These pulsations are most sinusoidal or narrow band in the morning and early afternoon. In general, the late-afternoon pulsations are sporadic with short wavetrains of a few cycles. Seasonally, Pc3 wave activity is more likely to occur with greatest amplitude around the equinoxes.

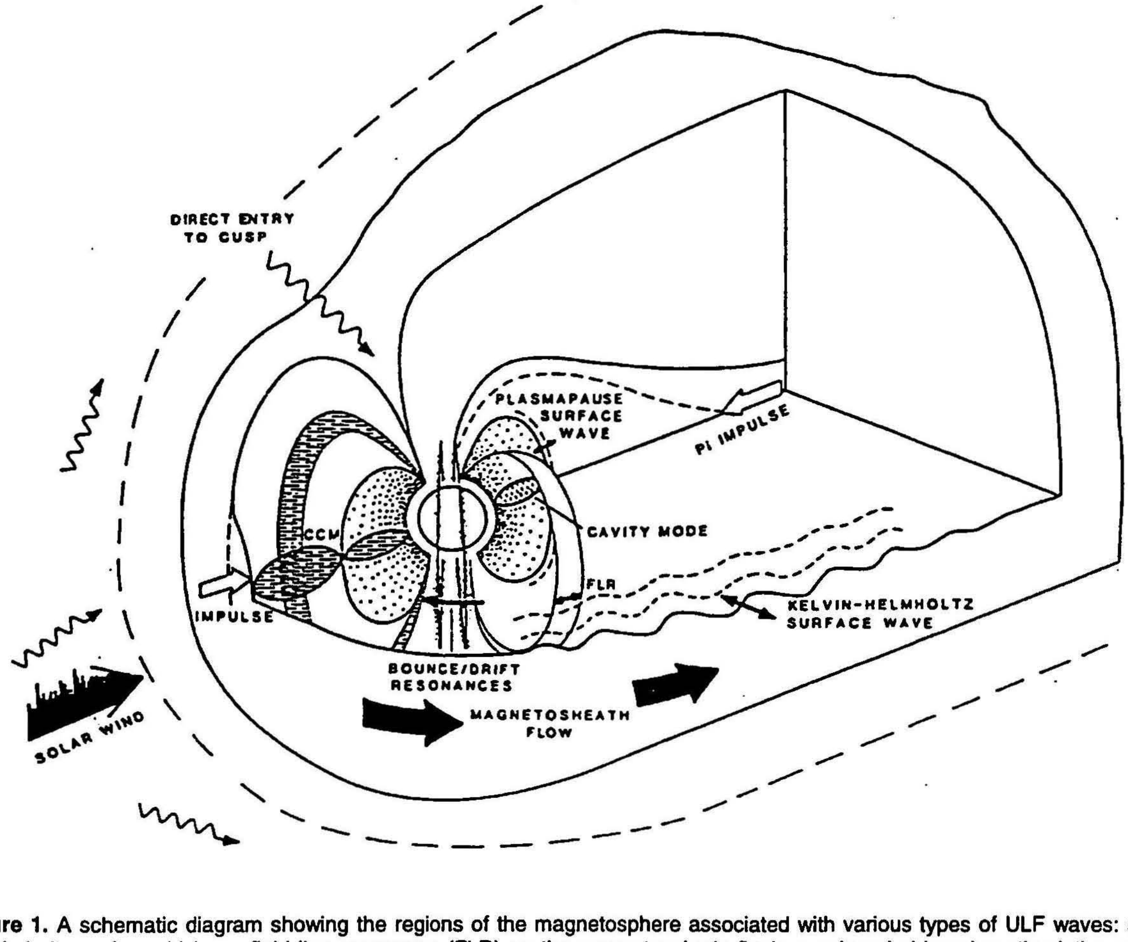

Figure 1. A schematic diagram showing the regions of the magnetosphere associated with various types of ULF waves: a Kelvin-Helmholtz surface driving a field line resonance (FLR) on the magnetospheric flank; a solar wind impulse stimulating a coupled cavity mode (CCM) in the dayside magnetosphere, including the associated FLR effects; a Pi2 impulse from the tail plasmasheet generating a plasmapause surface wave and a plasmasphere cavity mode; direct entry of hydromagnetic wave energy at the cusps. Bounce and drift resonances are also shown (after Allan and Poulter, 1992).

There is also a contribution to the pulsation spectrum seen in the Australian region from the higher latitude lower frequency FLR waves from the outer magnetosphere. These are at Pc5 frequencies (1-10 mHz) and "leak" to the lower latitudes where they exhibit amplitudes of up to 10 nT (Ziesolleck and Chamalaun, 1993). Amplitudes peak in the mid-morning and mid-afternoon with a minimum around local noon. This suggests a source of these high latitude pulsations that may be related to the Kelvin-Helmholtz instability established towards the flanks of the magnetopause where solar and velocities are high (see Figure 1).

In the equatorial region where geomagnetic field line lengths are minimal, most of the field line may be located in the ionosphere and field line resonances cannot be sustained due to wave damping and other reasons. Here, regular and continuous pulsations due to CCM waves are most likely to be observed and their spectral characteristics may show frequencies 10-30 mHz, which are apparently unrelated to the low and middle latitude Pc3 pulsations associated with FLR waves. This is currently an unexplored area of research.

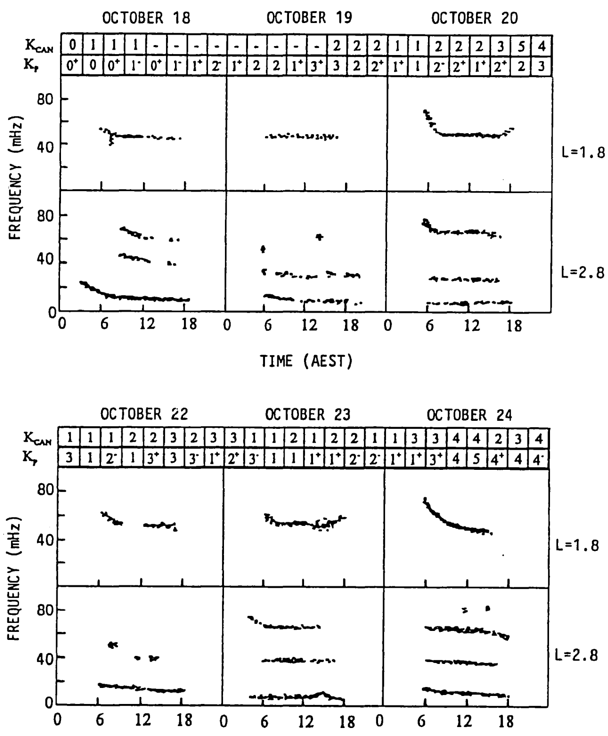

Figure 2. Dynamic cross-phase spectra plotted over three consecutive days, showing the evolution of the daytime local Pc3-4 field line resonance frequencies and harmonics at Newcastle (L = 1.8) and Launceston (L = 2.8). These resonances have been seen on all but three days over a two month recording interval (after Waters *et al.*, 1994).

SPATIAL VARIATIONS

Since both Pc3-4 and Pc5 pulsations are seen over the middle-to-low latitude Australian region and they have different frequencies and possibly sources, the spatial characteristics of both classes must be considered. Of particular importance are the latitudinal and longitudinal variations, over some 15° of geographic latitude and 40° of geographic longitude, in parameters that include pulsation amplitude, wave frequency and spectral content, and phase. The wave polarization in the horizontal plane of the Earth also provides important information on phase stability at a given location and across a network. It is these parameters that provide the information necessary to enable naturally occurring pulsation effects to be removed from aeromagnetic data.

The pulsation amplitude and frequency, available from the signal time series, are the most commonly measured parameters. However, amplitude measurements are prone to noise contamination and are not often reliable and the frequency of a signal may not be monochromatic. Experience has shown that the inclusion of signal phase information generally allows a more complete description of the signal, while the signal spectrum will provide full information on frequency content, including harmonics if present (Fraser, 1993).

In order to appreciate the issues noted above, three relevant studies of ground based spaced station observations of Pc3-4 and Pc pulsations are described.

A study of the spatial characteristics of Pc5 pulsations in the 1-8 mHz band was reported by Ziesolleck and Chamalaun (1993) using data from the Australia Wide Array of Geomagnetic Stations (AWAGS). This is a network of 57 three-component digital fluxgate magnetometers. A line of nine stations located longitudinally from the west coast to the east coast at 30° S geographic latitude and a north-south line of seven stations on the 142° E meridian from Cape York to the Victorian coast formed a cross, ideally suited for spatial studies. In order to remove noise from the coherent pulsation signals, pure state analysis methods were employed (Samson and Olson, 1981). With amplitudes up to 8 nT and wave periods in the range 100-1000 s, these pulsations are those most likely to be seen in aeromagnetic data.

Ziesolleck and Chamalaun (1993) found that Pc5 frequencies were independent of latitude and longitude, while X and Y (D and H) component amplitudes were constant with longitude, but decreased with decreasing latitude. The vertical component was generally small except at coastal locations due to the coastal induction effect. Wave polarisation in the horizontal (X, Y) plane showed the usual left-hand rotation (when viewed in the direction of the ambient field) in the morning with a switch around noon to right-hand in the afternoon. The spatial variation in polarisation, and also signal phase across the array, is generally small. Signal phase on average is constant with latitude to within 20° , but deviations of up to about ±30° are seen. Longitudinally, the phase data indicates progressive variations across the continent totalling 40° with deviations of ± 40° , with a gradient of about 1° of phase per degree of longitude, and a positive slope before noon and negative slope afternoon. This is consistent with westward (eastward) signal propagation in the morning (afternoon). A convenient measure of longitudinal phase characteristics is the angular wave number. This wave number, or m value as it is often called, is defined as the phase difference (in degrees) between two stations divided by the longitudinal station spacing in degrees, and is the number of wavelengths encircling the circumference of the Earth. Here, wave numbers were in the range $1 < |m| < 3$, indicating extremely long azimuthal wavelengths.

At Pc3-4 frequencies (10-100 mHz), Ansari and Fraser (1986) have studied variations over 15° of longitude between Woomera, Broken Hill, and Newcastle (at a latitude of about 32° geographic), while Ziesolleck *et al.* (1993) studied the latitudinal variation on the 150° E meridian using seven stations between Gladstone (Qld) and Launceston (Tas).

From the analysis of six months of pulsation data, Ansari and Fraser described longitudinal characteristics of Pc3-4 waves which were later replicated in the lower frequency Pc5 observations of Ziesolleck and Chamalaun (1993). The study showed that waves in the prenoon daytime sector propagated westward with left-hand polarisation, and in the afternoon propagated eastward with right-hand polarisation. Most signals were observed in the 20-80 mHz band and amplitudes were typically 1 nT. In the meridional study of Pc3-4 pulsation characteristics, Ziesolleck *et al.* did not find the constant phase over the chain from north to south that was seen in the earlier described Pc5 data. The field line resonances at Pc5 frequencies (1-10 mHz) occur at high latitudes on field lines well poleward of Australia and no significant phase change is expected distant in latitude from the source. However, the field lines that support resonance at Pc3-4 frequencies (10-100 mHz) may be located at low latitudes within the meridional chain. Consequently, as shown by Ziesolleck *et al.* (1993), the phase variation with latitude follows the classical resonance phase response with a minimum at the resonance location (Fraser, 1993). Phase changes over the chain north or south of the resonance location may be up to ~150°. Frequencies that will typically show local resonances over Australian latitudes are in the range 20-80 mHz, with the higher frequencies occurring in the north. Frequencies below about 15 mHz relate to resonances occurring over Tasmania or locations further south. The pulsation frequency is reasonably constant with latitude while the amplitude shows a peak (1-2 nT) at resonance, and the expected wave polarisation reversal is also seen. These results support the idea that only a single or local field line resonance is seen. The conclusion here is that local field line resonance may be excited deep within the plasmasphere (inner magnetosphere) at low latitudes.

IONOSPHERIC EFFECTS

The pulsation signals observed on the ground as ULF electromagnetic waves originate as MHD waves in the magnetosphere and must be transmitted through the ionosphere. The ionosphere attenuates the signal, and if uniform, it also rotates the polarisation ellipse of an Alfven or slow mode wave by $\pi/2$ (Hughes and Southwood, 1976). The rotation occurs because the field-aligned current of the Alfven wave cannot continue to the ground through the insulating atmosphere. Horizontal conductivity gradients or discontinuities in the ionosphere can give rotations different from $\pi/2$. In contrast, the fast wave mode does not exhibit a polarisation rotation. Since the Alfven wave electric field cannot be zero in the ionosphere, ionospheric Joule heating will also occur.

A limited or short wavelength spatial extent of the wave structure above the ionosphere can also lead to amplitude attenuation between the ionosphere and the ground, smearing of structure, shifting of the FLR polarisation reversal, and increased apparent damping (Hughes and Southwood, 1976). Theoretically, these may not be too much of a problem at middle and low latitudes where low azimuthal wave numbers are observed corresponding to long wavelengths and large spatial structures, but experimentally they can cause difficulties in data interpretation.

DISCUSSION AND CONCLUSIONS

The observational evidence presented in this paper highlights the extent of Pc3-4 and Pc5 ULF wave propagation across the Australian continent and emphasises the properties of importance for aeromagnetic surveys. It has been shown that Pc3-4 waves are present almost every day and commence at local dawn and cease at dusk. They occur in the 10-100 mHz (T=10-100 s) band and their amplitude, typically 1 nT but often 2-3 nT during storms, decreases with decreasing latitude and is reasonably constant with longitude. Pc5 waves (1-10 mHz; T = 100-1000 s) have amplitudes of up to 10 nT, but exhibit the same properties as Pc3-4 pulsations noted above. Both the Pc3-4 and Pc5 waves show decreasing phase with longitude away from noon with westward propagation in the morning and eastward in the evening. Pc5 waves, with their FLR sources well south of Australia, show constant phase with latitude, while Pc3-4 waves may show significant phase variations associated with local FLRs. The ionosphere will rotate the polarisation pattern in the plane of the Earth by $\pi/2$ such that the azimuthal Y(D) component in the magnetosphere will be seen as the north-south X(H) component on the ground.

While it has not been proven that some of the variations seen in the total field magnetometer aeromagnetic records and attributed to ULF wave sources are pulsation signatures of magnetosphere or ionospheric origin, there are a number of recommendations that can be made. These include:

(i) Undertake surveys in the post midnight to dawn interval (01-06 hr LT) to completely remove the effects of daytime Pc3-5 pulsations. However, this may not be practical.
(ii) Utilise stable calibrated triaxial fluxgate magnetometers as base stations providing ground truth. These provide component information and will show the presence of pulsations more easily since signals will often predominate on one of the horizontal components, most typically the X component. Because of the long azimuthal wavelengths of Pc5 pulsations and the stability of phase both latitudinally and longitudinally, only a few magnetometers would be needed to ground monitor the survey block.
(iii) Improved and more sophisticated data processing techniques could be employed in the analysis of data. For example, state vector multichannel time series analysis techniques incorporating polarisation filtering to remove noise may be useful in locating consistent conductivity anomalies.
(iv) It may be worthwhile to distribute a set of aeromagnetic survey data, covering known anomalies, to interested signal processing laboratories to see how their techniques may identify the anomalies. If pulsations are present the removal of these could also be tested.

In conclusion, geomagnetic pulsations may contribute to contamination in aeromagnetic data but there are probably other sources such as aircraft induced motion and terrain contour effects that play a role. It is probably worthwhile pursuing these issues further through collaborative studies.

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Geomagnetic Pulsations Service

Richard Marshall

IPS Radio and Space Services
PO Box 5606
West Chatswood NSW 2057

Geomagnetic pulsations represent a definite noise source to geomagnetic surveys, in particular aeromagnetic surveys. Three types of information maybe useful when contending with these short term variations of the Earth's magnetic field:

(1) Real-Time Data.
(2) Forecast Information.
(3) Post Acquisition Data Processing.

It is the intention of IPS Radio and Space Services, in conjunction with other organisations such as AGSO, to provide real-time and forecast information to geophysics customers. The information would be provided in the form of regional contour maps generated from pulsation indices (Figure 1). These maps, used in conjunction with conductivity maps (ANU) or "risk maps" (AGSO) should provide a reasonable estimate of geomagnetic pulsation activity levels.

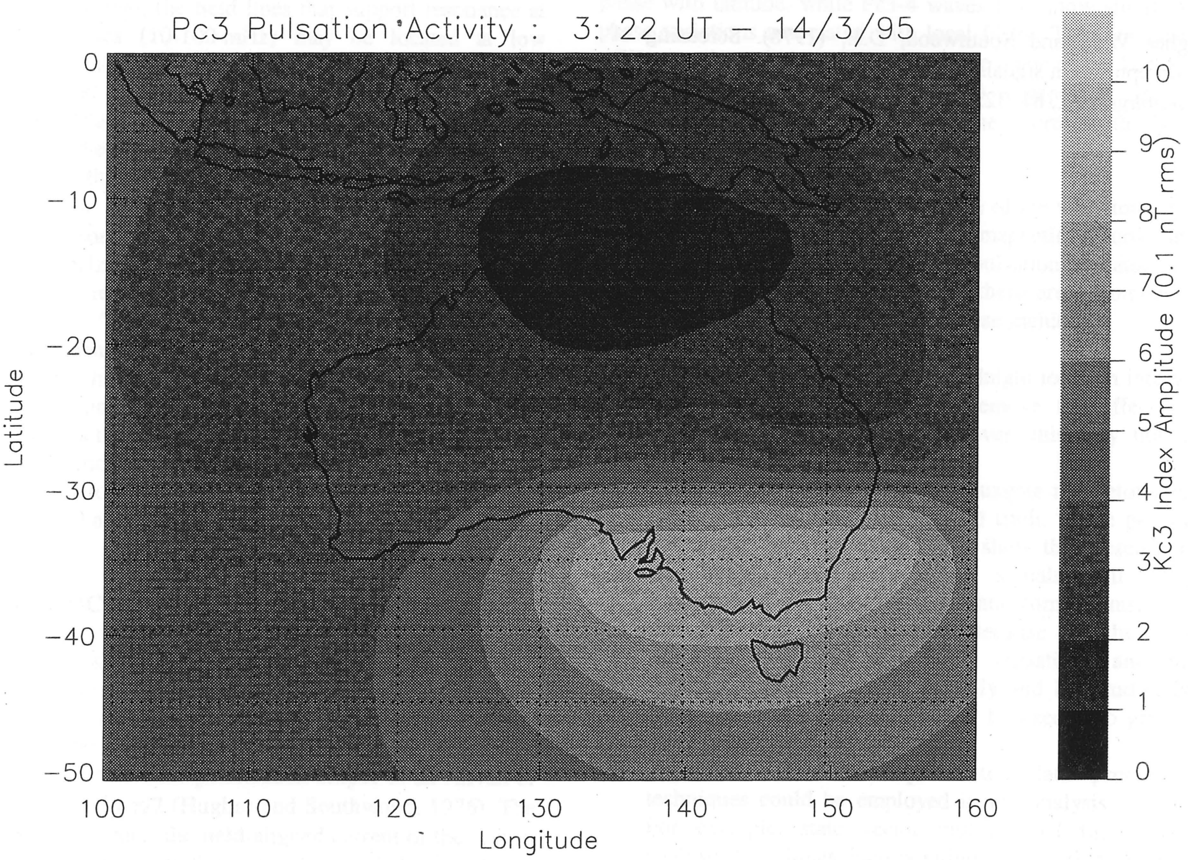

Figure 1. An example regional contour map of Pc3 pulsation indices generated from data recorded at seven stations. Such maps may be used in conjunction with conductivity maps (ANU) or "risk maps" (AGSO) to provide a reasonable representation of Pc3 pulsation activity levels.

Real-time maps would represent current activity levels of pulsation source fields and would require a real-time network of variometers. IPS's real-time Ionosonde network may provide a suitable infrastructure, however, collaboration would be necessary to provide the appropriate network.

The provision of forecast maps of pulsation activity is currently being investigated. A linear relationship has been observed between a daily pulsation index generated from Learmonth (WA) data and the Ap index. The existence of such relationships at other field stations would provide a series of calibration curves from which a forecast map may be generated.

A technique which adequately removes pulsations, and their induced effects, from magnetic survey data is highly desirable, however, is not currently under investigation at IPS.

An "Aeromagnetic Risk Map" of Australia

C.E. Barton

Australian Geological Survey Organisation
GPO Box 378
Canberra ACT 2601

ABSTRACT

A prototype "Aeromagnetic Risk Map" of Australia has been produced that provides a relative measure of base-station reliability on the Australian mainland, i.e., how well a base-station at any location tracks temporal fluctuations of the geomagnetic field at a remote survey point. The map depicts an "aeromagnetic risk factor" that is calculated at any point from the dispersion in magnitude and direction of neighbouring Parkinson induction vectors. The data set used was a set of the induction vectors in the period range 42 to 80 min obtained from the Australia-wide Array of Geomagnetic Stations (AWAGS) and from earlier regional array studies. The aeromagnetic risk factor is frequency dependent, so further risk maps can be developed for shorter periods, that will be indicative of the inductive influence of shallower conductivity structures.

INTRODUCTION

Aeromagnetic surveyors must contend not only with the temporal (diurnal) variations of the geomagnetic field caused by external currents, but also with the complications arising from the heterogeneous nature of crustal induction effects that distort the diurnal variation on a local as well as a regional scale. A knowledge of the induction properties of the crust can be used to identify regions subject to large (or small) spatial variability in the diurnal field variation. Hence it is possible to construct maps depicting the errors inherent in using a base-station for making corrections to aeromagnetic survey data. This leads us to the concept of an "aeromagnetic risk map" of Australia.

INDUCTION DATA

Induction properties of the crust can be represented conveniently by Parkinson induction vectors that are computed for a particular periodicity of field fluctuations (Parkinson, 1959). In broad terms, the Parkinson vectors should point towards an electrical conductor. The vectors are small either directly over the conductor or far away from the conductor. The lengths of the vectors reflect the strength of the induction effects, which relate to both the scale and electrical conductivity of the conducting region. For example, in coastal regions the inductions arrows usually point towards the conducting ocean – the well-known "coast-effect" (Parkinson, 1959; Parkinson and Jones, 1975). The coast-effect is generally detectable up to several hundred kilometres inland from the edge of the continental shelf.

Figure 1 shows the real parts of the set of the induction vectors in the period range 42 to 80 min that were used for the present analysis. These were compiled from results from the Australia-wide Array of Geomagnetic Stations (AWAGS) (Chamalaun and Barton, 1993a; 1993b) and from selected stations from earlier regional array studies (Chamalaun, 1985; Chamalaun, 1986; Chamalaun and Cunneen, 1990; Everett and Hyndman, 1967; Gough *et al.*, 1972, 1974; Lilley, 1976; Lilley and Bennett, 1972; Milligan *et al.*, 1989; Parkinson *et al.*, 1988; White and Milligan, 1984; Woods and Lilley, 1979; Woods and Lilley, 1980).

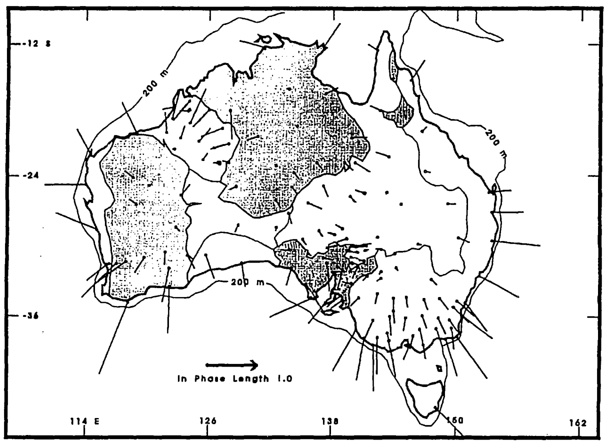

Figure 1. Magnetic induction vectors (real parts) for periods from 42 to 80 min used in the present analysis.

BASE-STATION RELIABILITY

It is clear from Figure 1 that there are few areas in Australia free from crustal or oceanic induction effects. The implication is that there are few areas where the assumption of spatial homogeneity of the time-varying field, extensively used in aeromagnetic data reduction, holds over large distances. It is, therefore, important when deploying base-stations for aeromagnetic or marine survey work to have prior knowledge of the spatial scale over which time-variations of the field may be considered to be uniform (within the tolerances acceptable for the survey). This amounts to having a measure of the expected differences between the diurnal signal at a base-station and the corresponding signal at a survey point at some given distance.

The induction arrows shown in Figure 1 are not directly related to base-station errors, but nevertheless do provide a crude aeromagnetic risk map of the country. The figure clearly delineates areas where large base-station errors can be expected (high dispersion of large induction vectors), and areas where they are going to be small (short or parallel patterns of arrows). The factor that determines the size of the base-station error is a combination of the size of the induction vectors and the directional scatter. Thus short vectors with large angular dispersion, or large vectors with low angular dispersion each present a low risk. A very large, yet uniform coastal induction effect will only present a low aeromagnetic risk. To produce a large base-station error requires both large and scattered vectors.

AEROMAGNETIC RISK FACTOR

An "aeromagnetic risk factor" (ARF) has been designed to reflect the spatial inhomogeneity of the disturbance field according to the above considerations. ARF is defined at any location in terms of the dispersion of the real part of the Parkinson induction vectors for neighbouring stations. ARF will, therefore, be a function of the period for which the Parkinson vectors are computed. First, all the induction vectors at a particular period (or band of periods within which there will not be any significant variation) are compiled. A minimum threshold number of induction vectors (e.g., four) and a minimum spherical cap cell radius (e.g., 1°) are chosen. If the cell centred about the location in question contains fewer than the threshold number of vectors, then the cell is incremented in radius at pre-set steps (usually 0.2°) until it contains the required number of vectors, or more. The vector average for the cell is then computed and the magnitude of the vector difference between each vector and the vector average is found. ARF is the average of these scalar magnitudes multiplied by 100.

If there are N vectors ($\boldsymbol{r}_i$, i =1, N) in a spherical cap-shaped cell, the average vector is

$$\boldsymbol{R} = 1/N \sum_i \boldsymbol{r}_i \qquad \text{for } i = 1, N,$$

and the i^{th} vector difference is

$$\boldsymbol{d}_i = \boldsymbol{r}_i - \boldsymbol{R}$$

Hence

$$ARF = 100/N \sum_i |\boldsymbol{d}i|$$

This procedure has the advantage of providing a uniformly gridded map of the country, but it suffers from the problem that each grid points represents a spherical cap-shaped region of variable size, the size depending on the local density of available induction vectors.

Figure 2 shows ARF values over Australia at 1° grid points, using a minimum of 3 vectors per cell, and an initial cell size of 1° incremented at 0.2° steps. The initial set of induction vectors (real part) used to produce Figure 2 is that shown in Figure 1, periods being in the range 42 to 80 minutes, but padded with zero values at 2° grid points in the oceans (151 vectors and 151 pads for the region bounded by latitude -10° to -40°N, longitude 110° to 156°E). It is necessary to interpret Figure 2 in the light of the variable data coverage.

DISCUSSION AND CONCLUSION

The general character of the risk map conforms to that expected from Figure 1. There are high risk values resulting from the coast effect, and high values in the known conductivity anomalies (Canning Basin, Eyre Peninsula, Flinders Ranges, etc.). Low values are centred about the Pre-cambrian cratonic blocks. The most anomalous region is around Albany, which has an extraordinarily large induction vector.

Four obvious refinements are needed. Firstly, the data set of induction vectors can be expanded (Liejun Wang at ANU has a better set that he has been using for thin sheet electrical conductivity modelling of the Australian crust). Secondly, the analysis needs to be repeated for different periodicity ranges in order to give a better picture of the risks at higher frequencies. Thirdly, the effect of crustal induction on the scalar field (i.e., the usual case in aeromagnetics) will depend on the angle between the total field vector and the Parkinson vector; this should be allowed for in calculation of the aeromagnetic risk factor (as pointed out by Ted Lilley). Fourthly, the present risk factor provides only a relative measure of risk and needs to be calibrated such that base-station errors can be predicted as a function of distance to the remote station.

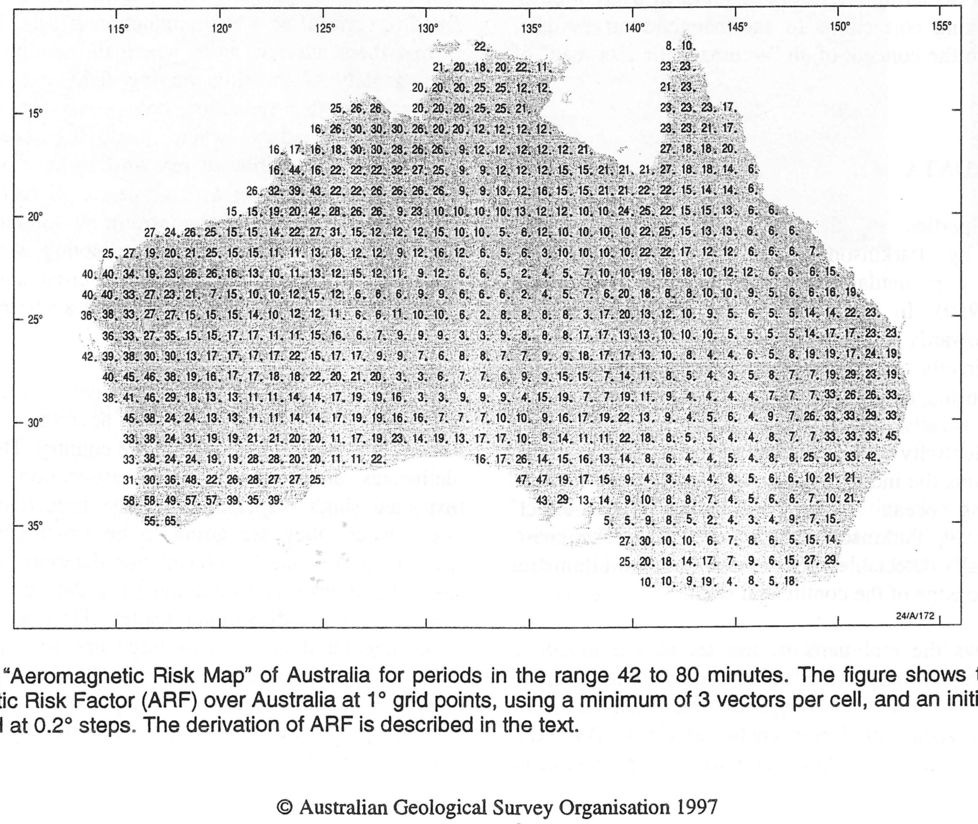

Figure 2. The "Aeromagnetic Risk Map" of Australia for periods in the range 42 to 80 minutes. The figure shows the base-station Aeromagnetic Risk Factor (ARF) over Australia at 1° grid points, using a minimum of 3 vectors per cell, and an initial cell size of 1° incremented at 0.2° steps. The derivation of ARF is described in the text.

Nevertheless, the risk map can be used in its present form to give a first indication of base-station reliability in different parts of the mainland for low frequencies. Regions that give anomalous conductivity results at low frequency are also likely to be anomalous down to periods of minutes. Hardly any induction data are yet available at micropulsation frequencies.

ACKNOWLEDGEMENT

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World Geoscience Corp. interests in TRIVIA

Euan Clarke

Austirex International (part of WGC)
27 Merriwa St
Gordon NSW 2072

World Geoscience Corp. is the world's largest airborne geophysical contractor and, as such, is interested in all factors affecting the quality of its magnetic and electromagnetic survey data, and in all factors that may aid the interpretation of these datasets. Euan Clarke is a geoscientist employed by WGC in data processing, aircraft system calibration, quality control, and in development of new processing and acquisition procedures.

Euan has been involved in several airborne surveys employing one-second-or-less Cesium vapor magnetometer diurnal base stations. Critical to the usefulness of such data is an accurate recording of time. GPS time was used as the basis of time for these diurnal base stations. Work is needed to determine the change in diurnal signature with altitude and, hence, the relevance of a ground-based diurnal station to an airborne survey. Of interest also are the factors controlling the change in amplitude and phase of short-period magnetic disturbances with distance, both on and offshore.

Magnetic effects induced by ocean swells are well documented. Euan has been involved in studies aimed at removing the effects from airborne data sets. In at least one instance, magnetic effects have been seen in offshore airborne surveys that can not be attributed to ocean swells.

Selection of the best site to locate a high sensitivity magnetic diurnal monitor is a very difficult task. Often the site is governed by proximity to power, easy access, and minimal disturbance from vehicle traffic. As the sensitivity increases, so do the number of factors that can introduce magnetic artifacts. Some of these factors are: power surges in town power grids, heavy haulage trucks have been sensed up to 250 metres away, near-coast swell or current induced magnetic effects, possible changes in the magnetic properties of soil and rock due to temperature change during the day, and electrified railway lines. It would be useful to have a method of rapidly and cheaply evaluating a proposed site.

Interpretation of airborne magnetic data collected for the petroleum industry, both on and off shore, has shown that some fault planes have a magnetic signature that can not be easily explained. The magnetic effect may be due to fault plane mineralization, movement of conductive fluids, or current channeling. Drill-hole core has been logged for magnetic properties and can not explain these anomalies.

A resume on Defence's interest in magnetics

Alan G. Theobald

Maritime Operations Division
Defence Science and Technology Organisation, Materials Research Laboratories
PO Box 44 Pyrmont NSW 2009

Defence's interest in magnetics arises from the magnetic signatures of various military platforms, predominantly naval vessels, which can be used to identify the presence of the platform as a potential target and to explicitly target that platform once identified. Defence, therefore, is concerned with magnetic signature minimisation and signature processing and synthesis.

The magnetic signature arises from a number of sources and exists across a range of frequencies. At DC, or more precisely quasi-static, the signature arises from a combination of the ferromagnetic source (most vessels are made of steel) and the magnetic field arising from the corrosion current cell which exists between the hull and the propeller (this latter is often referred to as the Underwater Electric Potential, UEP). In most instances, the former source dominates, but in the far-field, or if the ferromagnetic source is especially low, then the UEP source will dominate. At AC, and we are concerned in this application with frequencies up to about 1 Khz, there are a number of independent sources. For Mine Countermeasures Vessels (MCMVs) especially, which are specifically made of minimal magnetic materials, magnetic fields occur at frequencies equal to the roll and pitch rate and are produced by eddy currents created in metal sheets or cables as they move in the Earth's field. In addition, there are fields produced by items of equipment onboard (generators for example) - these are referred to as stray fields. These vessels have very stringent magnetic signature requirements as befits their role. In recent years, we have also identified magnetic fields arising from a modulation of the corrosion current cell by the rotation of the propeller shaft which thus produces magnetic (and electric) fields at the shaft rate (typically 1 Hz to 5 Hz depending on the vessel and speed) and multiple harmonics thereof which are readily detectable. Finally, we also observe magnetic (and electric) fields at 60 Hz, and harmonics thereof, which arise from the onboard electrical system.

The areas in which these fields are used are essentially 3-fold.

(1) The longest established role is in mine warfare, where many, if not most, sea mines use the magnetic signature as the final target classifier that will initiate the detonation sequence. It is notable that this signature is also used in some land mines, targeting armoured vehicles, and that some missile proximity fuses have a magnetic sensor. These sensors are generally fluxgate vector magnetometers (often single axis).

(2) The second area, which came into its own during the Cold War as a result of the submarine threat, is in Anti Submarine Warfare (ASW). The magnetic signature of a submerged submarine is used as the final target localiser prior to the weapon release by rotary and fixed wing ASW aircraft. These sensors are invariably total field precession magnetometers and the whole system comes complete with an extensive aircraft noise compensation system and target identification aids.

(3) The final area, and this is an area which is not used in Australia at present, is in the surveillance of choke points, such as harbours and shipping channels. Here, the magnetic signature is used, in conjunction with other sensors, to alert observers to the presence of a vessel.

The RAN identifies magnetic signature management as a high priority issue since it relates to ship self-protection. The latter is achieved by a combination of deperming and degaussing, the extent depending on the vessel class. In addition, mine countermeasures in general, have been identified as a key component of RAN capability and in this regard the ability to sweep mines plays a significant role. In order to sweep mines, an artificial source is used – in the RAN's case, the sweep comprises a number of towed buoyant magnets which replicate the signature of the ship in question.

DSTO's role is to provide the scientific and technical advice for current capabilities and to perform research into future capability requirements which covers both the mine and the countermeasure aspects.

Clearly an understanding of geomagnetic noise spatial and temporal characteristics is an important aspect of the current and future capability. Specifically, DSTO's aim is to identify a method of determining geomagnetic noise offshore, both on the continental shelf and in coastal waters (representing the ASW and mining threat), so that this information can be provided to the local commander to be used for tactical development.

Specifically, for a submarine commander, a knowledge of local geomagnetic characteristics, especially on the continental shelf, might allow for, in the first instance, a determination of the vessel's current vulnerability to detection and, secondly, the option to relocate to an area of lower vulnerability if tactically possible. Conversely, such knowledge by the operators on a Maritime Patrol Aircraft would assist in determining the tactics to be adopted in attempting to locate a submerged submarine. Similar arguments relate to the mining threat and vulnerability of MCMVs. Clearly, mapping the continental shelf for geomagnetic noise characteristics is a mammoth task and, indeed, is not feasible for forward operating areas. DSTO's interest, then, in this geomagnetic noise forum is ultimately to be able to demonstrate a means of obtaining such noise information and to provide this to the appropriate commander on a real-time basis.

Within DSTO we have an extensive array of (vector) magnetometer data acquisition systems which can be used offshore in waters up to 50 m deep (depending on the system) and covering all frequencies up to 600 Hz. In addition, we may have access to information provided for the Jindalee Over-the Horizon radar system and to total field magnetometer data from Maritime Patrol Aircraft (P3-Cs and possibly SeaHawks), depending on tasking by the RAAF and RAN respectively.

Some problems with magnetic micro-pulsations and geophysical surveys for heavy mineral sand deposits

Stephen Mudge

RGC Exploration Pty Ltd
P.O Box 322
Victoria Park WA 6100

Magnetic surveys are often effective in detecting and mapping magnetic heavy mineral sand deposits. Ilmenite, a titanium bearing heavy mineral containing iron, often has a magnetic susceptibility high enough that near-surface accumulations of the mineral produce measurable magnetic anomalies.

Economic deposits of ilmenite (magnetic) and other heavy minerals such as zircon, monazite and rutile (all non-magnetic) are generally buried no deeper than about 50 m. The width of the economic placers varies from about 100 m up to 300 to 400 m. The width of the thicker and, therefore, more magnetic part can be less than this. Their thickness can be up to about 20 m.

The very weak magnetic susceptibility of ilmentite, and the highly variable thickness of the placers, means that the anomalies observed with ground magnetic surveys vary considerably from less than 0.1 nT to as high as about 20 nT (rare). Anomalies of less than 5 nT are typical (see Mudge, 1994, for a case history from Eneabba WA). Ground magnetic surveys require strict controls on magnetic contamination from the operator, cultural effects (fences, etc.) and surface maghemite occurrences - all of which obliterate the weak target responses. Also, noise in the base-station record will contaminate the survey results, either obliterating the target responses or producing false anomalies.

Airborne surveys are used extensively for detecting ilmenite-rich placers. However, at the elevation of airborne surveys (10 m using helicopters) the target anomalies are strongly attenuated. It is imperative that survey data are free of noise in order to resolve the target anomalies.

Airborne surveys are conducted at about 40 ms^{-1} (144 kmh^{-1}) and magnetometer readings are made every 0.1 s, about every 4 m along line. It takes the survey aircraft about 3 to 6 s to pass over the thicker and most magnetic parts of the placer deposit. Any measurable variation in the Earth's magnetic field, having an amplitude less than about 5 nT, (larger amplitude responses tend to be downgraded as cultural anomalies) and a period of up to, say, 10 s (equivalent to an along-line width of up to 400 m) can be erroneously identified as target anomalies.

Accurate monitoring of time variations of the Earth's magnetic field is crucial for the success of a magnetic survey to detect the weak target anomalies of heavy mineral sand deposits. The ability to identify and separate micro-pulsations from target anomalies would be useful.

Also, the location of the base-station magnetometer is crucial. Ideally, this should be within the survey area. However, heavy mineral sand deposits are very large in strike length, 5 to 10 km (they have to be, to be economic, as they are relatively thin and narrow - essentially 2D in geometry). Consequently, survey areas extend over large distances, sometimes up to 100 km from the survey base where the base-station magnetometer is located. The spatial/time based errors in applying drift corrections to the survey data can degrade the survey data to obliterate weak target responses or to induce false anomalies into the processed data.

Gradiometer measurements of the field, in order to obtain drift-free measurements, have proved unsatisfactory in resolving the weak target gradient responses as gradiometer orientation errors induce noise which generally exceeds the predicted target responses.

At Eneabba, WA, and Green Cove Springs, Florida, the sand deposits are located below the water table. I have observed weak ground magnetic responses that vary with time (over a few hours, and from day to day) of up to about 5 nT that I can only attribute to telluric currents induced in the conductive ground water. These responses produce false target responses in survey data and are generally not accurately removed with local base-station data, despite the fact that similar responses are observed in the base-station record.

The use of multiple base-stations deployed around the survey area seems like a solution to monitoring and correcting the spatial/time variations in the magnetic field. But I don't know how to combine the records of a group of widely distributed base-stations or how to use them effectively in accurately correcting survey data.

The use of high-resolution magnetics for detecting the weak magnetic responses of heavy mineral sand deposits is an interesting and an important application of magnetics.

In 1996/97 RGC Exploration acquired approximately 220 000 line km of airborne magnetic data for mineral sand exploration. We plan to acquire at least a further 42 000 line km in 1997/98.

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Flinders University Seafloor EM Instrumentation

Graham Heinson

The Flinders University of South Australia
GPO Box 2100
Adelaide SA 5001

INSTRUMENTS

Currently, the Flinders seafloor EM instruments measure the three-component magnetic field and two-component electric field at a sample rate of 5–60 s and with a magnetic resolution of 0.1 nT and electric field resolution of 0.05 μVm^{-1}. They will record for 75 days at a sample rate of 5 s on EPROMS, and require about 75 Ah in battery power. We currently use alkaline batteries. The instruments are self contained and are dropped to the seafloor. Recovery is aided by an acoustic transponder system. Orientation of the magnetometer can be obtained by rotating the horizontal fields into geomagnetic north and east orientations. A two-axis clinometer allows the magnetometer to he levelled to better than a tenth of a degree. A tilt measurement is made every 78 readings and recorded along with temperature and battery voltage.

FIGURES

The following figures cover some experimental basics and show examples of data from two experiments.

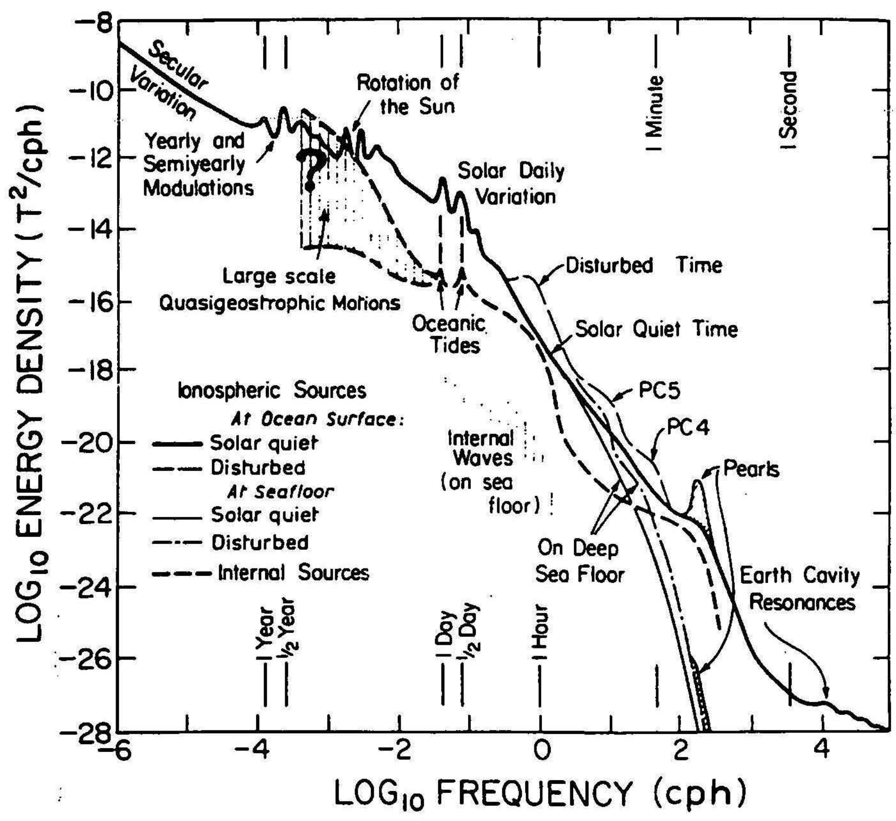


Figure 3. Spectra of natural magnetic variations in the open ocean. Because of a significant latitudinal variability the spectral levels represented are for mid-latitudes. The oceanic depth is assumed to be average, around 5 km. For frequencies below 2 cph, ionospheric EM variations are negligibly attenuated at the sea floor. At frequencies higher than 5 cph, sea-floor magnetic variations undergo considerable attenuation. The most important spectral features of interest are indicated, both for external (ionospheric) sources and internal (motional) sources.

Figure 1. A classic figure of the magnetic spectra from Filloux's (1987) review in *Geomagnetism*. The drop in the magnetic field at periods below 1000 s is shown relative to the ambient field.

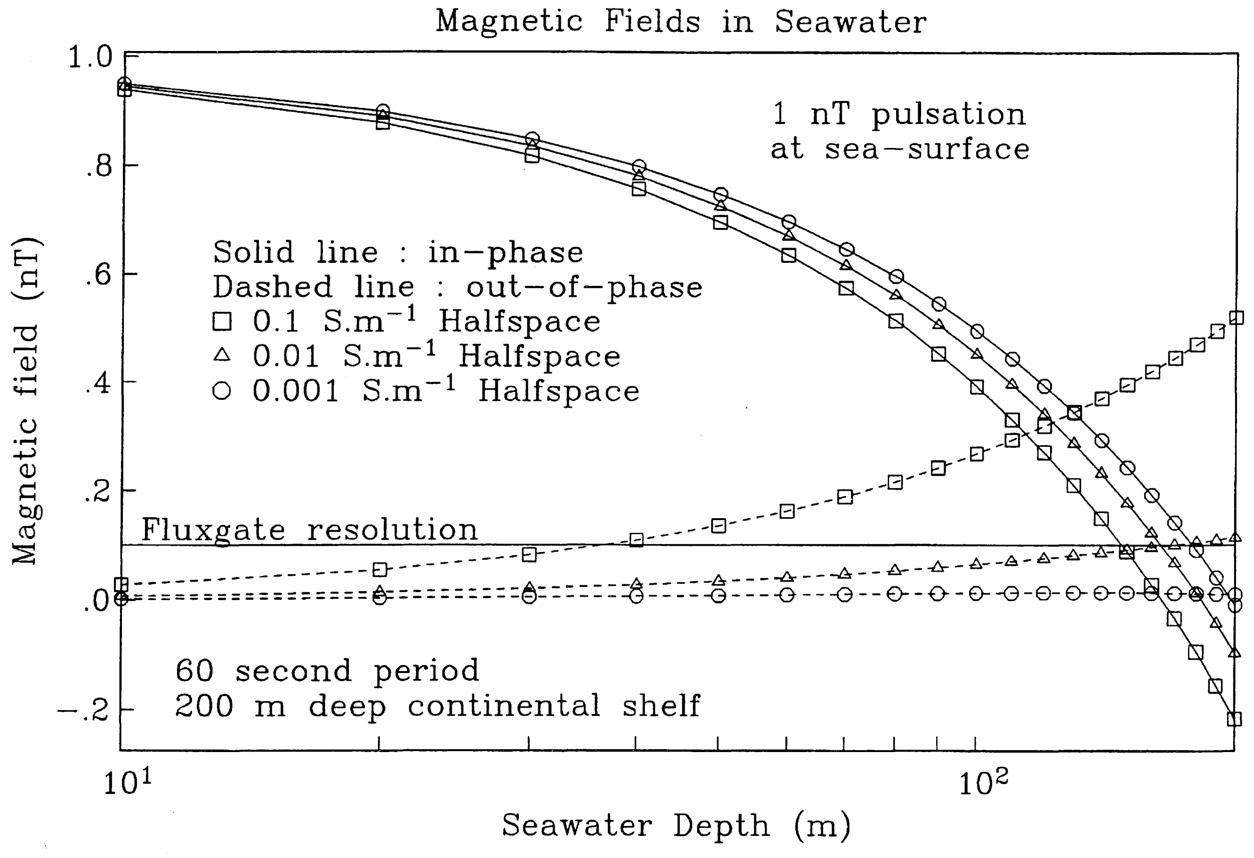


Figure 2. Magnetic field strengths as a function of depth through a seawater layer. The seawater layer is 200 m deep, underlain by a half-space of various conductivities. A 1 nT pulsation of period 60 s occurs at the surface. The magnetic fields are shown as in-phase (solid line) and out-of-phase (dashed line) components. At a depth of a little over 100 m, the fields are below 0.1 nT, which is the current least count of the magnetometers.

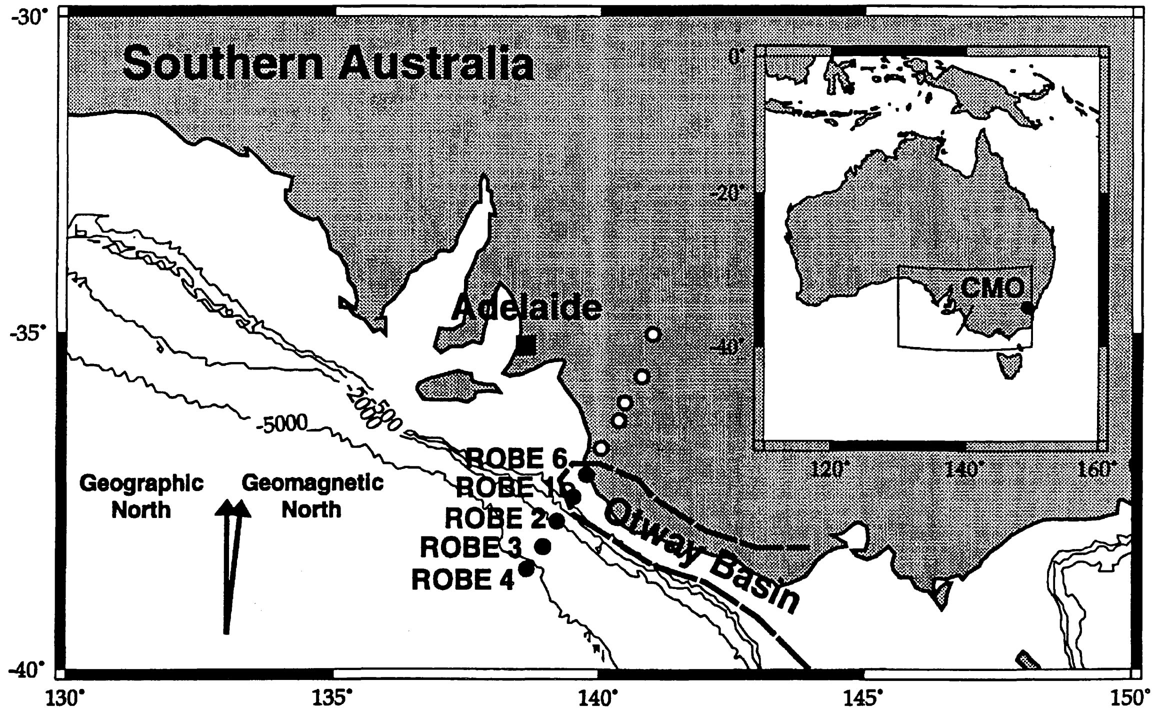


Figure 3. A map of the magnetometer sites offshore from Robe. The shallowest site was Robe 1 at 142 m, the deepest was Robe 4, at 5000 m. The magnetometer at Robe 3 was not recovered. The magnetometers sampled at 60 s with a resolution of 1 nT.

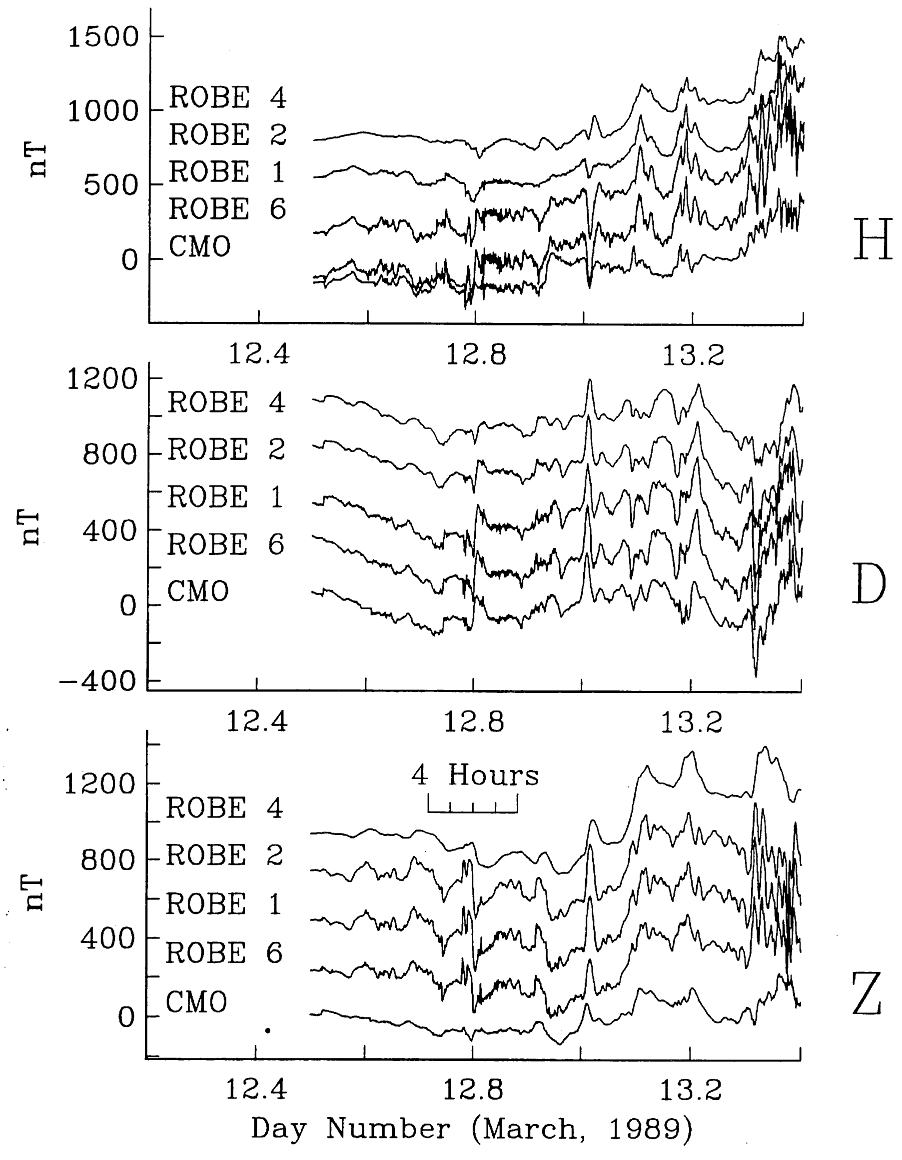


Figure 4. Three-component data from the experiment during one of the largest ever recorded magnetic storms on 13th March, 1989. Note (a) increasing attenuation with depth in H and D, (b) there are some phase shifts.

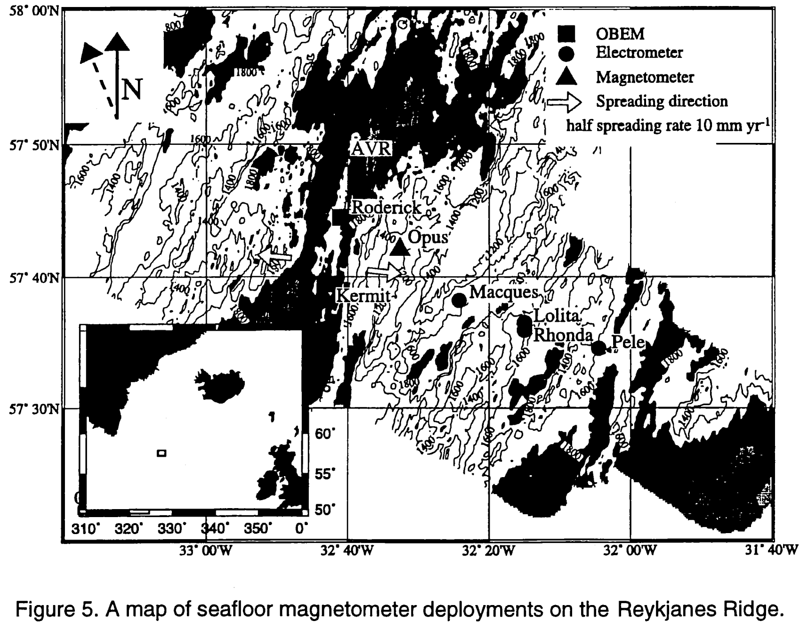
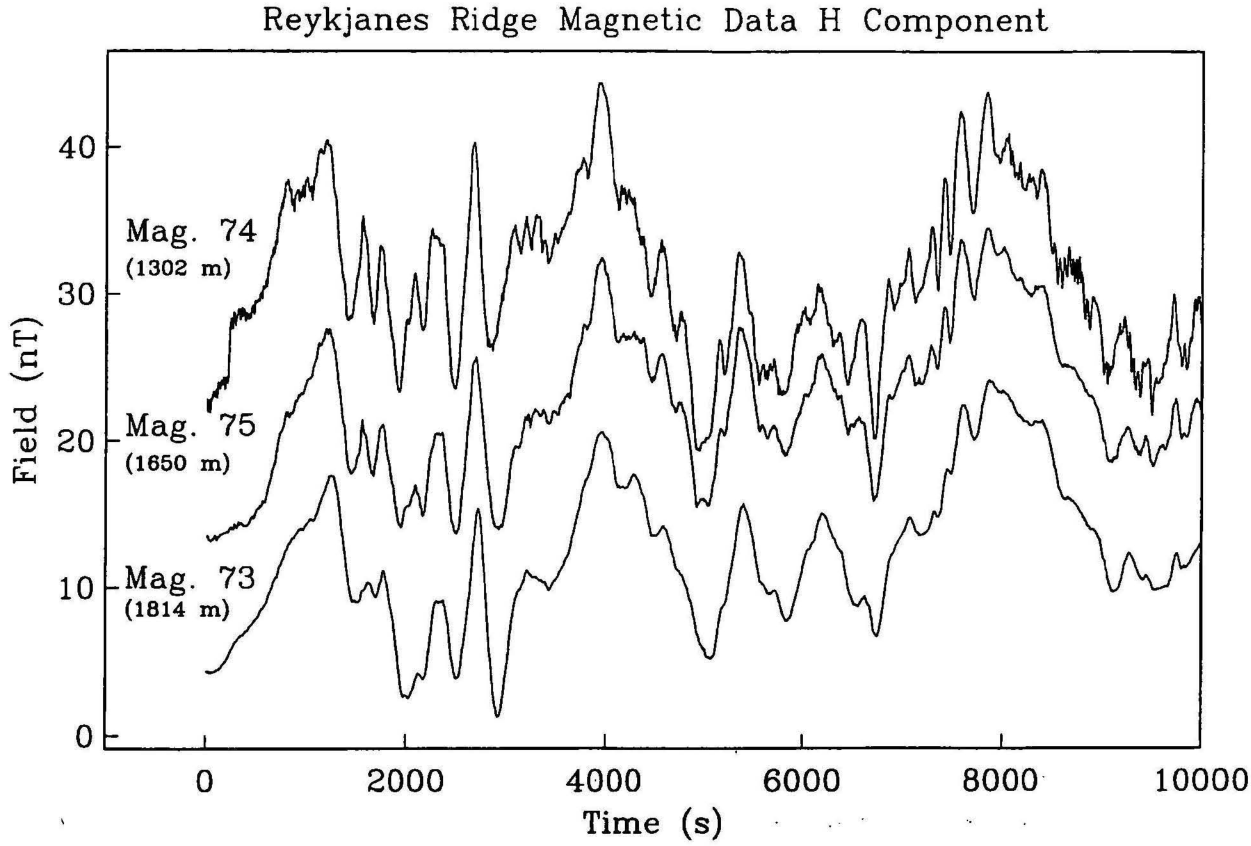
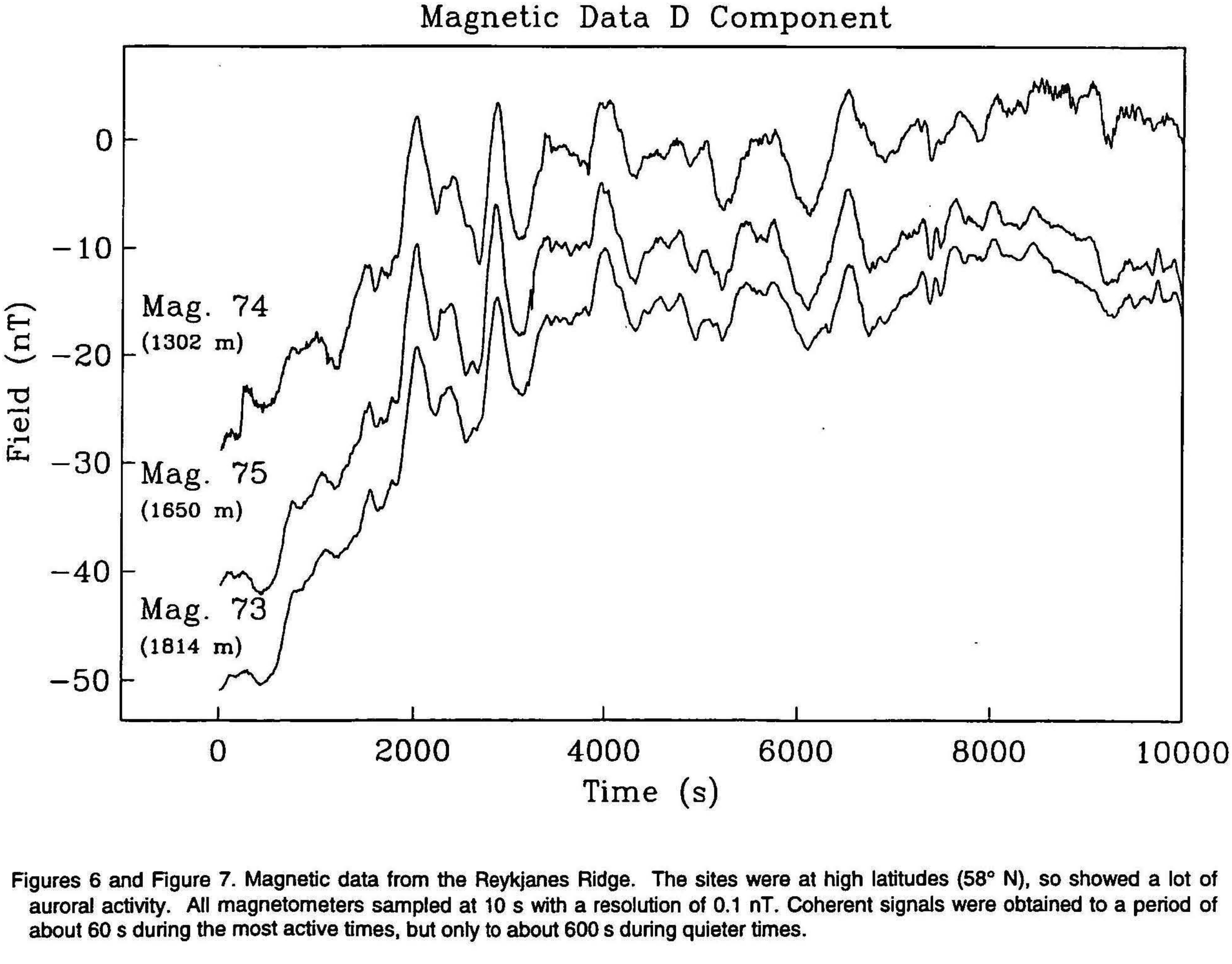


Figure 5. A map of seafloor magnetometer deployments on the Reykjanes Ridge.





Figures 6 and Figure 7. Magnetic data from the Reykjanes Ridge. The sites were at high latitudes (58° N), so showed a lot of auroral activity. All magnetometers sampled at 10 s with a resolution of 0.1 nT. Coherent signals were obtained to a period of about 60 s during the most active times, but only to about 600 s during quieter times.

Spatial inhomogeneity of geomagnetic fluctuation fields and their influence on high resolution aeromagnetic surveys (Abstract of Ph.D. thesis from The Flinders University of South Australia)

Jonathon M. Whellams

Pitt Research Pty Ltd.
45 Hackney Road
Hackney South Australia 5069

It is standard procedure in aeromagnetic data processing to remove the influence of geomagnetic field fluctuations by subtraction of a basestation magnetometer record. Provided the fluctuations observed at the stationary base station are always indicative of those experienced at the aircraft position, this method works well. Though it has long been recognised that geomagnetic fluctuations are not necessarily spatially homogeneous, related errors have been considered a minor contribution to the total error budget of an aeromagnetic survey. However over the past decade technological advances, particularly in the field of positioning systems, has enabled extremely precise data acquisition. Moreover digital image processing techniques now allow processors to resolve anomalies of sub-nanoTesla amplitude. Consequently the spatial inhomogeneity of geomagnetic fluctuations is now the principal factor limiting the integrity of high resolution aeromagnetic data.

Over recent years there has been prolific large scale, high resolution aeromagnetic survey activity in Australia. Thus it is timely to explore the spatial characteristics of geomagnetic fluctuations in the Australian region to assess the likely influence upon aeromagnetic data acquired therein. Three separate magnetometer array data sets are drawn upon in this investigation. Firstly an Australia wide array of 57 magnetometers constitutes a regional study. Analysis of diurnal variations, geomagnetic storms and pulsations illuminate numerous characteristics of these fluctuations. Animation proves to be a convenient format for revealing spatial properties of transient events and consequently such presentations are used extensively. This regional analysis suggests that in general spatial inhomogeneity stems principally from the induced internal component. Consequently fluctuation field inhomogeneity is enhanced about Australia's coastal margins and also in the vicinity of known inland conductivity anomalies.

Amongst the numerous mainland induction anomalies disclosed within Australia perhaps the most prominent is that found in the Canning Basin of Western Australia. In 1988 a chain of magnetometers was deployed across the basin orthogonal to the surmised axis of the induction anomaly. Aeromagnetic survey activities were conducted in coincidence with the magnetometer recording period and special flights were arranged to over fly the magnetometer chain. This synchronous multi base station and aeromagnetic data constitutes the second data set to be considered. Analysis of the magnetometer records themselves reveals a significant degree of geomagnetic field inhomogeneity within the basin especially in the vicinity of the induction anomaly. As the inhomogeneity arises from induction effects it is most pronounced during geomagnetic disturbances. However even during quiescent geomagnetic conditions differences of up to 30 nT can be observed between stations separated by less than 100 km. The acquired aeromagnetic data is shown to suffer from such influences. By opting to correct the aeromagnetic data with records from the magnetometer chain rather than the actual base station used, tie line errors can be reduced several fold. The cumulative influence of incurred errors is portrayed through the results of aeromagnetic survey simulations. Such simulations combined with data from actual aeromagnetic flights, indicate that an inherent spatially inhomogeneous fluctuation field in the Canning Basin can seriously affect the integrity of aeromagnetic data acquired therein. Use of a single base station to monitor field fluctuation in such an environment is clearly inadequate.

An investigation of the influence of fluctuation field inhomogeneity upon a typical modern aeromagnetic survey conducted over an area with no known resident conductivity anomalies was facilitated by the Synchronous Aeromagnetic--Magnetometer Array Study (SAMAS) undertaken in the south-east of South Australia in 1995. The SAMAS data set comprises over 39,000 line kilometres of detailed aeromagnetic data combined with the coincident records from a 25 station magnetometer array spanning the entire survey area. Analysis of this data confirms that even under favourable conditions aeromagnetic data still suffers from spatial inhomogeneity of the fluctuation field. Even for airborne data recorded within 50 km of the base station, appreciable errors of 5 nT were observed. Utilising the base station array in aeromagnetic data reduction led to a significant decrease in miss-tie values thus indicating the benefit of multiple base station deployment. With such considerations in mind, current methods to account for geomagnetic fluctuations within aeromagnetic survey data are discussed and their limitations outlined. While gradiometry techniques prove to be a viable alternative the nature of the acquired data is not suitable for all aeromagnetic data applications while inherent technical difficulties plague the method. Thus conventional total field surveys are expected to continue in Australia. However if such surveys are to deliver data with a precision comparable to that promised by modern acquisition systems then more spatially thorough monitoring of fluctuation fields is deemed necessary.

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APPLICATIONS FOR A PC3 PULSATIONS INDEX

Richard Marshall
IPS Radio and Space Services, PO Box 5606
West Chatswood NSW 2057, Australia

ABSTRACT

Over the years, the Kp, Ap and Dst indices have become useful for providing a global picture of geomagnetic activity levels. However, these indices discriminate towards slowly changing major departures of the Earth's main field. Geomagnetic pulsations require an index more tailored to higher frequency, lower amplitude field variations. This paper presents applications for a Pc3 pulsations index. One such application is the production of contour maps of Pc3 pulsation activity, useful when interpreting magnetic survey data. These maps are anticipated to be provided near real-time by IPS Radio and Space Services, in conjunction with the Australian Geological Survey Organisation. An application for forecasting Pc3 pulsation activity is also presented. Recurrence charts, based on a daily pulsations index, are presented for several months of data.

1. PULSATION INDEX

Temporal variations of the Earths magnetic field, such as magnetic storms, diurnal variations and geomagnetic pulsations, all present problems when interpreting magnetic survey data. Petroleum exploration surveys often have stringent requirements that the ground magnetic trace deviation does not exceed 2 nT in 2 minutes. Further, recent developments in instrumentation have made possible the definition of small, high frequency magnetic responses that may be related to very small changes (as low as 0.1 nT) in the magnetic character of near-surface sediments. In these situations, geomagnetic pulsations constitute a definite source of noise. It is the intention of IPS Radio and Space Services, in conjunction with the Australian Geological Survey Organisation (AGSO), to provide a service which extends the current solar and geophysical reports to include geomagnetic pulsation information based on a pulsation index.

Saito (1964) defined a new index for Pc3 geomagnetic pulsations, the "Kc3" index, for relating Pc3 pulsation activity to Solar M-regions. Here an rms index is defined by:

$$Kc\alpha_{ms} = \sqrt{\frac{\sum_{i=1}^{n} (X_i - \overline{X})^2}{n}} \quad (1)$$

where the X_i's are the filtered field amplitude values, n is the number of points in the interval, and α is the appropriate passband, where α=3 indicates the Pc3 frequency range, α=4 indicates the Pc4 frequency range, and so on.

Indices are calculated using both the X and Y components, and are given by the square root of the sum of the squares, i.e.,

$$Kc\alpha = \sqrt{Kc\alpha(X)^2 + Kc\alpha(Y)^2} \quad (2)$$

Comparison between Kc3 indices calculated for approximate 20 minute intervals over several days in 1995, with Kp values for the same days, revealed considerable differences which reinforce the need for an index other than Kp to represent geomagnetic pulsation activity. Comparison between Kc3 and Kc4 indices reveals a much larger variation between Kc3 indices generated from different stations than for corresponding Kc4 indices. Therefore, Kc3 index information is considered more valuable to large scale magnetic surveys than Kc4.

2. PC3 PULSATION ACTIVITY MAPS

Airborne magnetic surveys cover large areas, in the order of hundreds to thousands of square kilometres. The proposed service therefore needs to provide information for large areas. One index for the whole of the Australian region would provide insufficient spatial detail. The proposed service therefore relies on data from several stations and incorporates some estimation and interpolation procedures.

Waters (1992) presented correlation values as a function of distance between stations for daytime Pc3 pulsations. The correlation values decrease rapidly above about 100 km for observatories separated in the north-south direction. However, correlation values remain high for separations in the east-west direction of up to approximately 500 km. These east-west scale lengths, L_0, may be incorporated into expressions used to estimate Kc3 values from indices generated directly from field station data.

If x_0 denotes the station longitude corresponding to the Kc3 value for that station, then the Kc3 values can be estimated to extend eastward to longitude x^+ and westward to longitude x^-, i.e,

$$Kc3(x^+) = Kc3(x_o) = Kc3(x^-) \tag{3}$$

As the scale size values, L_0, are for daytime Pc3 pulsations, the longitudes x^+ and x^- should be a function of the solar zenith angle, ψ. These longitudes are determined using the expressions

$$x^+ = x_o + L_o\sqrt{\cos(\psi(t))} \tag{4}$$

and

$$x^- = x_o - L_o\sqrt{\cos(\psi(t+\Delta t))} \tag{5}$$

where t is the local time at longitude x_0 and Δt is set at the local time difference between longitude x_0 and the location 500 km west. These expressions incorporate the dependence of Pc3 pulsation activity on E-region conductivity. The corresponding latitudes, y^+ and y^- are given by

$$y^+ = y_o = y^- \tag{6}$$

where y_0 is the latitude associated with longitude x_0. Hence, given station latitude, longitude and Kc3 value (x_0,y_0,Kc3), estimates of Kc3 values at (x^+,y^+) and (x^-,y^-) can be determined.

The contour map of Figure 1 was produced using Kc3 indices generated for the 20 minute period centred on 3:22 UT, from data from seven Australian stations: Learmonth, Weipa, Dalby, Canberra, Adelaide (data courtesy Yumoto et al., 1992), Alice Springs and Kakadu (data courtesy AGSO). Kc3 indices were also estimated for each of the seven stations using Eqs. 3 - 6. The Kc3 indices were then incorporated into a Kriging algorithm which uses an exponential covariance function, C(d), for the semivariogram i.e.,

$$C(d) = C_1 e^{-3d/R} \qquad if\ d \neq 0 \tag{7}$$

$$C(d) = C_1 + C_0 \qquad d = 0 \tag{8}$$

where d = distance between points, C_0 = 0.0 is the "nugget" value used, C_1 = variance of sample points and R = 30.0 is the range value for the semivariogram. The grid values were then contoured using a contour following algorithm.

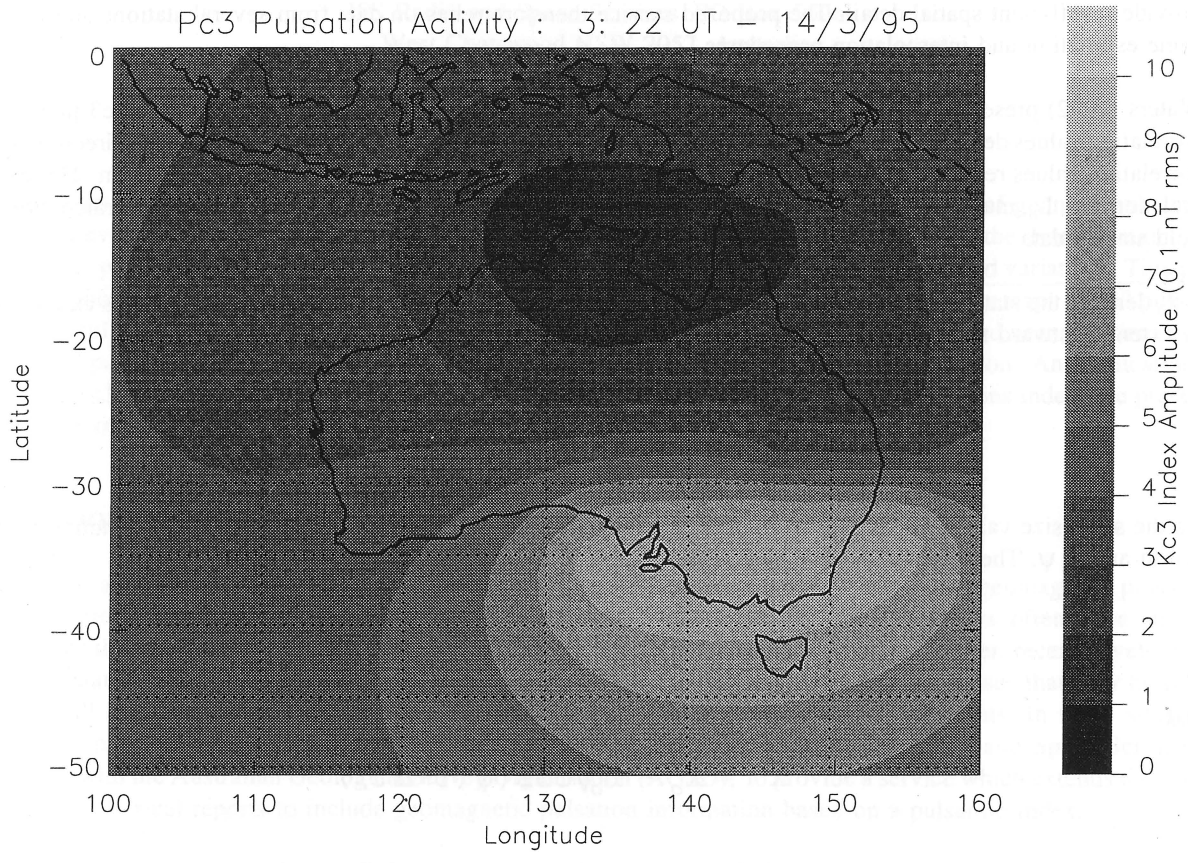

Figure 1. Contour plot of Pc3 pulsation activity over the Australian region, determined using data from seven field stations and estimations based on daytime Pc3 pulsation scale sizes.

Inspection of this map shows increasing activity with latitude, in agreement with the findings of Menk et al. (1994). Provision of such maps on a near real-time basis is envisaged to provide confirmation of Pc3 pulsations activity during high resolution aeromagnetic surveys and subsequent data processing. Further studies are being conducted into the integration of these maps into the processing algorithms, in an effort to reduce interference from geomagnetic pulsations.

3. PC3 PULSATION ACTIVITY FORECASTING

Lam (1989) proposed using an index related to the activity levels of Pc5 pulsations, referred to as the DRX index, to forecast appropriate periods for conducting geomagnetic surveys. A similar application for the Kc3 index is used here to forecast periods of Pc3 pulsation activity. Presently, one magnetic activity forecasting tool used by IPS is the recurrence chart based on Kp values, which shows magnetic activity levels stacked each successive 27 day solar rotation period. Figure 2 shows a recurrence chart based on a daily Kc3 index for 4 months of data. Daily Kc3 indices are generated using Kc3 indices evaluated every 20 minute period, which are summed over the hours 0400 to 1900 LT for values greater than 1. These daily Kc3 indices, or ΣKc3, are then used to indicate the Pc3 pulsation activity level in the recurrence chart, from which future ΣKc3 values levels may be extrapolated.

4. SUMMARY

This paper presented applications of a pulsation index defined as the rms value of Pc3 band filtered magnetic field data over an approximate 20 minute period, and denoted Kc3. These indices were used to produce contour maps of Pc3 pulsation activity, which may be useful when interpreting high resolution aeromagnetic surveys. Kc3 indices may also be used to produce daily indices which form the basis of recurrence charts used for forecasting Pc3 pulsation activity.

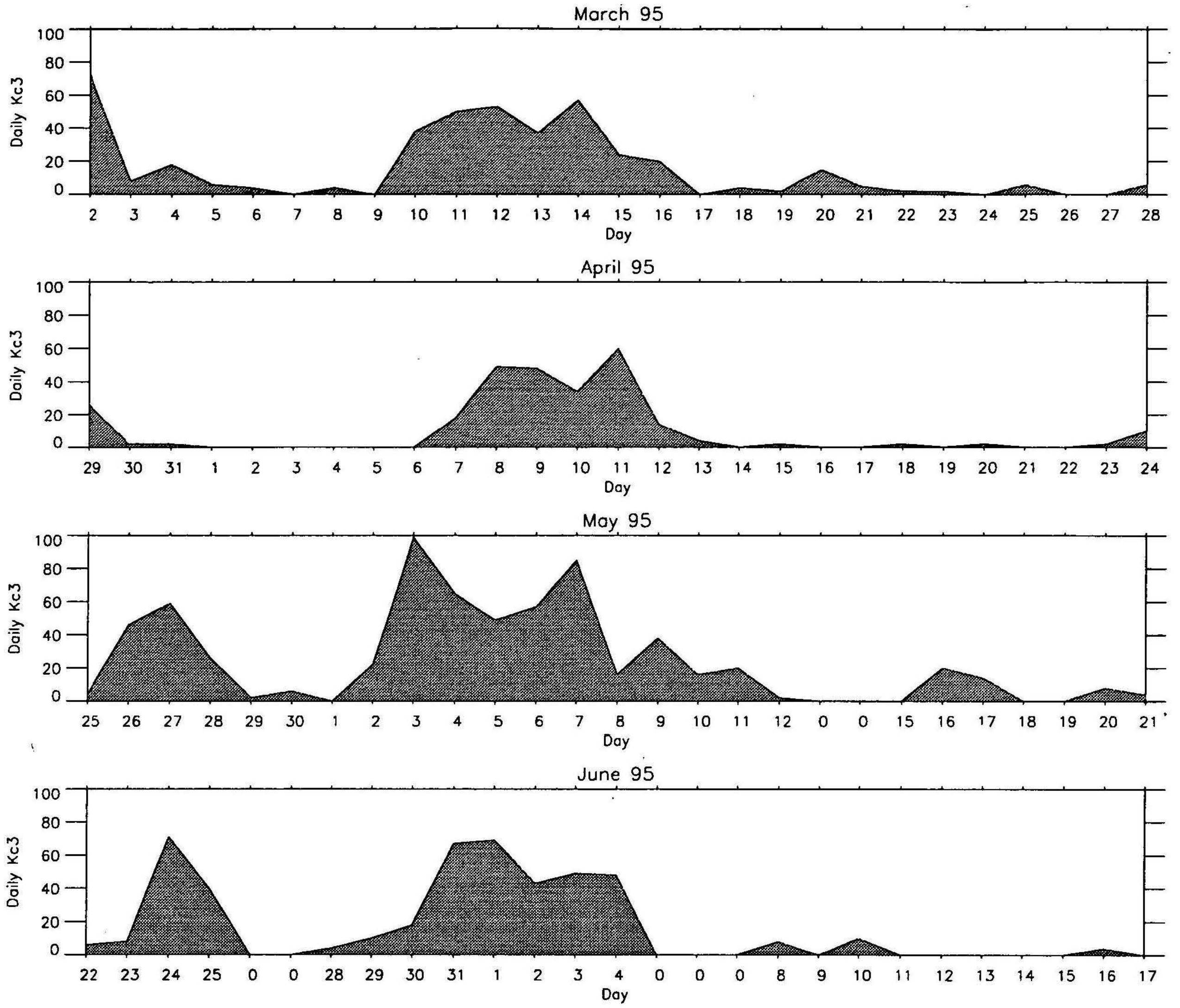

Figure 2. Recurrence chart produced from daily Kc3 indices generated from approximately 4 months of Learmonth magnetometer data. Days for which data were unavailable are indicated as 0.

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APPENDIX — Address List

(Rev. 5th February 1997)

This appendix lists the names and addresses of people interested in transient and induced variations in aeromagnetics, and forms the AGSO mailing list for future information. If you are interested in having your name included on the list, please contact either Charles Barton (cbarton@agso.gov.au) or Peter Milligan (pmilliga@agso.gov.au).

COMPANIES

Sam Bullock tel: 09-325 2877
Kevron Pty Ltd fax: 09-481 0323
PO Box 6325
Hay Street
EAST PERTH WA 6892

Steve T. Mudge, Chief Geophysicist tel: 09-442 8100
RGC Exploration Pty Ltd fax: 09-442 8181
PO Box 322
VICTORIA PARK WA 6100

Dr Jonathon Whellams tel: 08-8362 9966
Pitt Research Inc. fax: 08-8362 9977
PO Box 110 jmw@pitt.com.au
KENT TOWN SA 5071

Euan Clarke tel: 02-9498 2299
Austirex International fax: 02-9418 1292
27 Merriwa St
GORDON NSW 2072

Dr Don Pridmore tel: 09-273 6400
Aerodata Division fax: 09-273 6466
World Geoscience Coprporation
Cnr Brockway & McGillivary Rd
FLOREAT WA 6014

Nick Sheard tel: 07-3214 9164
MIM Exploration Pty Ltd tel: 07-3214 9164
GPO Box 1042 fax: 07-3214 9111
Brisbane QLD 4001

Noel G Mattocks, Mng Director tel: 09-364 8444
Rod Pullin
Tesla-10 fax: 09-364 6575
41 Kishorn Road
APPLECROSS WA 6153

Brett Merritt tel: 043-400 122
Tesla-10 fax: 043-400 155
3 Fox Close tesla10@ozemail.com.au
KARIONG NSW 2250

Dr Ted Tyne tel: 02-9957 4117
Encom Technology Pty Ltd fax: 02-9922 6141
PO Box 422 (Level2, 118 Alfred Street) ted@encom.com.au
Milsons Point NSW 2601 http://www.encom.com.au

Peter Wolfgram tel: 02-9418 8077
Geoterrex Pty. Ltd. fax: 02-9418 8581
PO Box 386 (7-9 George Place)
peter.wolfgram@geoterrex.com.au
ARTARMON NSW 2064

Richard Smith tel: +1-613-731 9571
Geoterrex Pty. Ltd. fax: +1-613-731 0453
2060 Walkley Rd smith@geoterrex.ca
OTTAWA K1G 3P5 CANADA

Joe Cuccuza tel: 03-9679 9955
Australian Mineral Ind. Res. Ass. fax: 03-9654 8661
113 Grand Boulevard
MONTMORENCY VIC 3094

Dr B. David Johnson tel: 06-251 3511
EarthWare Systems mob: 0419 614 705
PO Box 704 fax: 06-251 3581
Jamison Centre djohnson@spirit.com.au
MACQUARIE ACT 2614
http://spirit.com.au/earthware/

Dr Shanti Rajagopalan tel: 03-9230 1240
CRA Exploration Pty Ltd fax: 03-9230 1199
Exploration Tech & Info. Group
Private Bag 3 shanti.rajagopalan@expl.riotinto.com.au
BUNDOORA VIC 3083

Robert J. Smith tel: 03-9230 1260
Chief Geophysicist fax: 03-9230 1199
Exploration Tech & Info. Group mob: 0411 149 639
CRA Exploration Pty Ltd
Private Bag 3 robert.smith@craeeti.cra.com.au
BUNDOORA VIC 3083

Doug Price tel: 07-3834 7665
BHP Minerals fax: 07-3839 1235
PO Box 425 price@bhpmbne.com.au
SPRING HILL QLD 4004

Peter Williams, Chief Geophysicist — tel: 09-479 8400
Western Mining Corp. — fax: 09-479 8449
191 Great Eastern Highway
BELMONT WA 6104

Graham Boyd — tel: 08-8464 2200
Normandy Poseidon Ltd — fax: 08-8278 6251
16 Centre Way
BELAIR SA 5052

Dr James Mcnae — tel: 02-9906 6221
4A Whiting Street — fax: 02-9906 1778
La Montagne Geophysics Ltd.
ARTARMON NSW 2064

David Wilson — tel: 09-270 7070
Newcrest Mining Ltd. — fax: 09-221 7339
Hyatt Centre
Level 2, 30 Terrace Road
EAST PERTH WA 6004

UNIVERSITIES

Dr François H. Chamalaun — tel: 08-8201 2319
School of Earth Sciences — fax: 08-8201 2676
Flinders University of S.A. — mgfhc@es.flinders.ed.au
BEDFORD PARK SA 5042

Dr Antony White — tel: 08-8201 2359
School of Earth Sciences — fax: 08-8201 2676
Flinders University of S.A. — mgaw@flinders.edu.au
BEDFORD PARK SA 5042

Dr Graham Heinson — tel: 08-8201 2978
School of Earth Sciences — fax: 08-8201 2676
Flinders University of S.A. — mggsh@flinders.edu.au
BEDFORD PARK SA 5042

Prof. Brian J. Fraser — tel: 049-21 5445
Physics Department — fax: 049-21 6907
University of Newcastle — PHBJF@cc.newcastle.edu.au
Rankin Drive
NEWCASTLE NSW 2308

Dr Fred Menk — tel: 049-21 5424
Physics Department — fax: 049-21 6907
University of Newcastle — physpuls3@cc.newcastle.edu.au
Rankin Drive
NEWCASTLE NSW 2308

Dr Ted Lilley — tel: 06-249 4174
Research School of Earth Sciences — fax: 06-249 0738
Australian National University — ted.lilley@anu.edu.au
CANBERRA ACT 0200

Liejun Wang — tel: 06-249 3424
Research School of Earth Sciences — fax: 06-249 0738
Australian National University — liejun.wang@anu.edu.au
CANBERRA ACT 0200

Adrian Hitchman — tel: 06-249 3424
Research School of Earth Sciences — fax: 06-249 0738
Australian National University — adrian.hitchman@anu.edu.au
CANBERRA ACT 0200

Prof. Robert L. McPherron — tel: +1-213-825 1882
Inst. Geophysics & Planetary Phys — fax: +1-310-206 3051
University of California — rmcpherron@igpp.ucla.edu
405 Hilgard Avenue
Los Angeles CA 90024-1567 USA

Dr John M. Stanley — tel: 067-73 2617
Geophysical Research Institute — fax: 067-71 1661
University of New England — johns@gri.une.edu.au
ARMIDALE NSW 2351

Prof. John T. Weaver — tel: +1-604-721 7768
Dept. Physics & Astronomy — fax: +1-604-721 7715
University of Victoria — weaver@uvphys.phys.uvic.ca
PO Box 3055
Victoria BC
CANADA V8W 3P6

GOVERNMENT

David Robson — tel: 02-9498 2299
Geological Survey — fax: 02-9233 7017
NSW Department of Mineral Resources
Minerals & Energy House
PO Box 536
ST LEONARDS NSW 2065

Gary Reed — tel: 08-8274 7619
Geological Survey — mob: 0419 037 958
Department of Mines & Energy — fax: 08-8373 3269
PO Box 151 — reed@ostrich.mesa.sa.gov.au
EASTWOOD SA 5063

Dr Bob Richardson — tel: 03-6233 8324
Manager, GIS & Geophysics — fax: 03-6233 8388
Tasmanian Dept. Development Res — rrichard@mrt.tas.gov.au
P.O. Box 56
ROSNY PARK TAS 7018

Alan Willocks, Manager — tel: 03-9412 7862
Geophysics — fax: 03-9412 7803
Geological Survey of Victoria
PO Box 3145 MDC
FITZROY VIC 3065

Richie Huber tel: 07-3237 1499
Geological Survey of Queensland fax: 07-3235 4074
Department of Mines & Energy
GPO Box 194
BRISBANE QLD 4001

Dr Phillip W. Schmidt tel: 02-9887 8873
CSIRO Div. Exploration & Mining fax: 02-9887 8921/8874
PO Box 136 phil.schmidt@dem.csiro.au
NORTH RYDE NSW 2113

David Clark tel: 02-9887 8872
CSIRO Div. Exploration & Mining fax: 02-9887 8921/8874
PO Box 136 d.clark@dem.csiro.au
NORTH RYDE NSW 2113

Dr Alan Theobald tel: 02-9692 1487
Maritime Operations Division fax: 02-9692 1560
DSTO Materials Research Labs
PO Box 44 theobald@dsto.defence.gov.au
PYRMONT NSW 2009

Dr Julian Vrbanich tel: 02-9692 1486
Maritime Operations Division fax: 02-9692 1560
DSTO Materials Research Labs
PO Box 44 vrbancich@dsto.defence.gov.au
PYRMONT NSW 2009

Dr Jim Smelt tel: 02-9692 1488
Maritime Operations Division fax: 02-9692 1560
DSTO Materials Research Labs smelt@dsto.defence.gov.au
PO Box 44
PYRMONT NSW 2009

Dr David Cole, Director tel: 02-9414 8335
IPS Radio and Space Services fax: 02-9414 8340/8331
PO Box 5606 david@ips.gov.au
WEST CHATSWOOD NSW 2057 http://www.ips.gov.au

Dr Phil Wilkinson tel: 02-9414 8339
IPS Radio and Space Services fax: 02-9414 8340/8331
P.O. Box 5606 phil@ips.gov.au
WEST CHATSWOOD NSW 2057 http://www.ips.gov.au

Dr Richard Marshall tel: 02-9414 8327
IPS Radio and Space Services fax: 02-9414 8340/8331
P.O. Box 5606 ram@ips.gov.au
WEST CHATSWOOD NSW 2057 http://www.ips.gov.au

Dr Charles Barton tel: 06-249 9611
Australian Geological Survey Org. fax: 06-249 9986
GPO Box 378 cbarton@agso.gov.au
CANBERRA ACT 2601 http://www.agso.gov.au

Dr David Denham tel: 06-249 9327
Australian Geological Survey Org. fax: 06-249 9983
GPO Box 378 ddenham@agso.gov.au
CANBERRA ACT 2601 http://www.agso.gov.au

Dr Peter Gunn tel: 06-249 9226
Australian Geological Survey Org. fax: 06-249 9986
GPO Box 378 pgunn@agso.gov.au
CANBERRA ACT 2601 http://www.agso.gov.au

Dr Phil McFadden tel: 06-249 9612
Australian Geological Survey Org. fax: 06-249 9986
GPO Box 378 pmcfadde@agso.gov.au
CANBERRA ACT 2601 http://www.agso.gov.au

Dr Peter Milligan tel: 06-249 9224
Australian Geological Survey Org. fax: 06-249 9986
GPO Box 378 pmilliga@agso.gov.au
CANBERRA ACT 2601 http://www.agso.gov.au

Ms Wendy Welsh tel: 06-249 9320
Australian Geological Survey Org. fax: 06-249 9986
GPO Box 378 wwelsh@agso.gov.au
CANBERRA ACT 2601 http://www.agso.gov.au

