TERMINOLOGY AND SYMBOLS FOR USE IN STUDIES OF ELECTROMAGNETIC INDUCTION IN THE EARTH

B. A. HOBBS

Chairman, Semantics Committee, IAGA WG I-2

(Received 17 September 1991)

Abstract. Induction studies currently suffer from a bewildering number of terms describing the same phenomenon, by definitions which are incompatible and by diverse and confusing presentation methods. IAGA Working Group I-2 (Electromagnetic Induction in the Earth) established an ad hoc Semantics Committee charged with proposing a set of standard terminologies and presentation methods for use in geomagnetic induction studies. The main text of this paper details the proposed standards following much involvement with the induction community. Background information detailing this involvement is given in a series of appendices.

1. Introduction

Increasing interest in induction studies, either alone or in multi-disciplinary settings, supports a large number of well-attended specialist meetings, a vigorous commercial sector and a proliferation of publications in a wide range of geophysical, geological, mathematical and exploration journals. With this expansion of the subject, a proliferation of terms has evolved that essentially describe the same quantity or technique and the graphical presentation of similar data assumes many bewildering forms. The communication of ideas and results from induction studies to other disciplines is severely hindered by such disparate descriptions and presentations. Indeed the understanding of communications between induction workers themselves is not always immediate. To alleviate this situation, IAGA Working Group I-2 (formerly I-3) established a Semantics Committee entrusted with the task of suggesting a set of standard terms and presentation methods for induction studies. To this end a letter, information sheet and questionnaire were distributed to 822 induction workers (using the WG's address list) in May 1990. These documents are reproduced in Appendices 1, 2 and 3 respectively. The information sheet, Appendix 2, describes various current terminologies and presentation methods and hopefully provides a useful background for reading and comparing papers prior to standardisation. In some cases this information sheet presents arguments in a particular direction. For the most part, the questionnaire, Appendix 3, simply requested a vote of preference.

Surveys in Geophysics **13**: 489–515, 1992.

2. Semantics Committee

The IAGA Working Group I-2 Semantics Committee, representing a spectrum of countries and both academic and commercial interests, consisted of Dr A. A. Adam (Hungary), Dr A. Duba (WG Co-Chairman, USA), Dr S. E. Hjelt (WG Chairman, Finland), Dr B. A. Hobbs (Chairman, UK), Dr M. R. Ingham (New Zealand), Dr A. G. Jones (Canada), Dr A. Schultz (USA), Dr G. Schwarz (Germany), Dr B. R. Spies (USA), and Professor L. L. Vanyan (USSR).

3. Questionnaire Returns

Replies were received from 84 induction workers from 22 countries and their distribution is given in Appendix 4. From the returns, charts were prepared showing the voting on each question with a selection of the comments received indicated alongside. These were displayed as a poster throughout the 10th Workshop on Electromagnetic Induction, Ensenada, Mexico, 22–29 August 1990 attended by 238 delegates from 30 countries. Opportunity was provided at the poster to make further written comments. During the Workshop an open discussion considered the results from each section and commented on the decisions likely to be made where voting produced an indecisive result. The induction community has therefore been involved as much as possible. IAGA Working Group I-2 believes that some standardisation should now be introduced to aid comprehension of induction studies and assimilation into multidisciplinary investigations.

The main text of this paper presents the suggested standards. For clarity all supporting documents are relegated to appendices. A table of voting returns is presented in Appendix 5.

4. Proposed Standard Terminology for Induction Studies

4.1. Magnetic and electric field notation

The following general notation and terminology is used in induction studies:

$\mathbf{H}$	magnetic field
$\mathbf{B}$	magnetic induction
$\mathbf{E}$	electric field
ω	angular frequency
f	frequency
μ	permeability
σ	conductivity
ρ	resistivity
t	time

(Note that despite recommendations, e.g., Quantities, Units and Symbols, The Royal Society, 1971, much literature refers to **B** as the magnetic field).

4.2. Harmonic time variations

For harmonic studies time variations of the form $exp(-i\omega t)$ should be used and stated. This adoption, with geomagnetic approximations, leads to **B** satisfying Helmholtz equation

$$\nabla^2\mathbf{B} + i\omega\mu\sigma\mathbf{B} = 0$$

4.3. Co-ordinate frame

For Cartesian work, the standard co-ordinate frame will be a right-handed Cartesian co-ordinate system in which the z-axis points vertically down and in which the x-axis points

north	– in one dimension
parallel to strike	– in two dimensions
along the longer horizontal axis	– in three dimensions

4.4. Physical properties of materials

A physical property sought in induction studies is *conductivity* or, equivalently, its reciprocal *resistivity*. Both terminologies may be used. For graphical representation of the relation between conductivity or resistivity and depth

(i) the abscissa shall be the logarithm (base ten) of resistivity increasing to the right

and

(ii) the ordinate shall be logarithm (base ten) of depth increasing downwards.

4.5. Terminology for field separation

The term *Primary field* represents an inducing field or a source field which is generated externally to the earth's surface. A time-varying primary field induces current flow within the earth and these currents have an associated induced or *Secondary field*. The *Normal field* consists of the primary field plus the secondary field induced in a one-dimensional or layered earth approximation. The *Anomalous field* is the total field minus the normal field.

4.6. Response functions

The various functions that interrelate quantities such as parts of magnetic fields internal and external to the earth's surface, or vertical and horizontal magnetic fields are collectively known as *Response functions*.

4.7. Impedance

Impedance, represented by the symbol Z, is the ratio of horizontal electric to horizontal magnetic fields,

$$Z = E/H\,(=\mu E/B) \quad \text{(scalar)};$$

$$\mathbf{E} = \mathbf{Z} \cdot \mathbf{H}\left(=\frac{1}{\mu}\mathbf{Z} \cdot \mathbf{B}\right) \quad \text{(tensor)}.$$

With E in V m^{-1}, H in A m^{-1} and B in Teslas, Z has the unit of Ohms.

The tensor impedance has elements Z_{xx}, Z_{xy}, Z_{yx} and Z_{yy} and these may be used to derive two impedance measures which are invariant to co-ordinate system rotation:

$$\text{Berdichevsky average impedance} = Z_{av} = 0.5(Z_{xy} - Z_{yx})$$

$$\text{Effective impedance} = Z_{\text{eff}} = \sqrt{(Z_{xx}Z_{yy} - Z_{xy}Z_{yx})}$$

The determinant given by

$$\text{Determinant} = \text{Det}\, Z = (Z_{xx}Z_{yy} - Z_{xy}Z_{yx}) = (Z_{\text{eff}})^2$$

is of course also invariant to co-ordinate system rotation but is not an impedance. (**Note:** If **B** is measured in Teslas, the *Telluric response function* **C** (upper case C) defined by

$$\mathbf{E} = \mathbf{C} \cdot \mathbf{B}$$

has the unit of velocity.)

4.8. c-response

The quantity $c = Z/(i\omega\mu)$ (lower case c) is the *c-response* or more explicitly *Schmucker's c-response*. (Workshop discussion suggested it was often helpful to associate a name with a quantity.)

4.9. Admittance

The reciprocal of impedance is *admittance*, with symbol Y (upper case).

4.10. Apparent resistivity and phase

4.10(a). *Definitions*

Magnetotelluric results may be presented in terms of *apparent resistivity* and *phase*. These derived quantities are defined as:

$$\text{apparent resistivity} = \rho_a = \frac{1}{\omega\mu}|E/H|^2 = \frac{\mu}{\omega}|E/B|^2 = \frac{1}{\omega\mu}|Z|^2$$

$$\text{phase} = \arg(E/H) = \arg Z$$

where Z is the impedance defined in 4.7.

(Note: Some useful alternative expressions for apparent resistivity are given by Spies & Eggers, *Geophysics* **51**, 1986. Apparent conductivity will no longer be used.)

4.10(b) *Presentation of Magnetotelluric Results*

The presentation of single station magnetotelluric results will be through *apparent resistivity and phase*. In order to make ready comparisons between results, graphical representations will be standardised as follows:-

(i) For both apparent resistivity and phase the abscissa shall be the logarithm (base ten) of period (seconds) increasing to the right
(ii) For apparent resistivity the ordinate shall be the logarithm (base ten) of apparent resistivity (Ωm) increasing upwards. The plot shall be square, with one decade in the ordinate being drawn the same length as one decade in period.
(iii) For phase the ordinate shall be linear increasing upwards.

4.11. Data transfer

The *impedance tensor* will be used for the transmission of data between researchers, with all eight quantities (real and imaginary parts of diagonal and off-diagonal elements) and their 1-standard deviations being provided at each frequency.

4.12. Modes of induction in two-dimensional problems

In a Cartesian co-ordinate system (x, y, z) an induction problem is two-dimensional if the conductivity is a function of two variables only, say $\sigma(y, z)$. In such cases Maxwell's equations separate into two distinct cases, one in which the electric field is directed along the x-axis and one in which the magnetic field is directed along the x-axis. These modes of induction are referred to as *E-polarisation* and *B-polarisation* respectively.

4.13. Geomagnetic deep sounding

Geomagnetic Deep Sounding (GDS) refers to studies relating vertical magnetic fields to horizontal magnetic fields using equations of the form

$$z(t) = a(t)x(t) + b(t)y(t) \quad \text{(time domain)}$$

and

$$Z(\omega) = A(\omega)X(\omega) + B(\omega)Y(\omega) \quad \text{(frequency domain)}$$

where x, y and z represent magnetic field variations in the north, east and downward directions respectively and X, Y and Z are their Fourier transforms. (Care should be taken to avoid the use of the symbol Z for a field component and for impedance in the same publication. Care should also be used in differentiating between $B(\omega)$ and the magnetic induction $\mathbf{B}$.)

The complex quantities $A = A_R + iA_I$ and $B = B_R + iB_I$ may be combined to form the two-dimensional vector (A, B), called the *magnetic response function*. The real parts of A and B and the imaginary parts of A and B may be combined to form $\pm(A_R, B_R)$ and (A_I, B_I). These may be drawn as lines on a geographic map which are termed *Induction arrows* but the sign adopted for the real parts must be explicitly stated. It is recommended to use the induction arrow $(-A_R, -B_R)$ (Parkinson convention) which tends to point towards areas of higher conductivity. The induction arrow (A_R, B_R) (Wiese convention) tends to point away from areas of higher conductivity.

4.14. Colour representations

Representation of conductivity or resistivity information (model values or derived apparent resistivities) by colours shall conform to the following relative scheme:

red: low resistivity/high conductivity
blue: high resistivity/low conductivity

5. Conclusions

A glance at Section 5.1, Appendix 2, where nine diverse terms are used to describe the same situation, or at Section 4, Appendix 2, where similar graphical information is presented in five different ways should be convincing evidence of the necessity of adopting some standardisation in induction studies. IAGA Working Group I-2, through whom this survey was conducted, hopes that this level of standardisation will be of significant help in the interaction between induction workers and those in other disciplines, and within the induction community itself.

Appendix 1: Letter to Induction Workers

4 May 1990

To all induction workers

Dear Colleague

Semantics in the induction community

Induction studies started long ago and in recent decades there has been a huge increase in interest resulting in a large number of well-attended specialist meetings, a vigorous commercial sector and a proliferation of publications in a wide range of geophysical, geological, mathematical and exploration journals. The increase in activity and communication of ideas is good for the science, especially within the induction community. However, multidisciplinary studies are now becoming standard and the communication of our results to workers in other disciplines needs more than ever to be readily comprehended and assimilated.

At present the description of electromagnetic induction techniques and the presentation of results mystifies an outsider because of the proliferation of terms for the *same* technique and because of the confusingly different ways of presenting the *same* graphical information. IAGA Working Group I-3 wishes to be able to suggest a set of standard terms and presentation methods for induction studies and is soliciting views from all induction workers so that the community is involved in the decision-making process. The semantics problem is illustrated in the attached document, together with arguments for and against some items. The document is in the form of a questionnaire and you may simply "vote" for your preference and may add further arguments and comments if desired. Please try to avoid voting for what *you* use at present simply because it will involve you in less change – please consider the merits or demerits of the arguments and remember what you are doing is for posterity!

We need a *large*, *world-wide response* to this questionnaire. Please return it by *8 JUNE 1990 if possible* to

B. A. Hobbs,
Department of Geology and Geophysics,
University of Edinburgh,
JCMB, King's Buildings,
Mayfield Road,
Edinburgh, EH9 3JZ,
U.K.

Appendix 2: Information Sheet

IAGA WORKING GROUP I-3

Semantics in the Induction Community

The following sections briefly present semantic problems with some introduction and comment. They are illustrated with references to the literature and in particular to the Special Issue on Electromagnetic Induction resulting from papers contributed to the Neuchatel Workshop in 1986, published in Physics of the Earth and Planetary Interiors, Vol. 53, Nos 3–4, March 1989 (hereinafter referred to as PEPSI). A great variety of nomenclature and presentation is contained in this one issue but other references will also be used. Some of these further sources are abbreviated as follows:

GEOMAG
Geomagnetism, Vol 3, J. A. Jacobs (ed), Academic Press (1989).
LB
Geophysics of the Solid Earth, the Moon and the Planets, Vol 2, Subvolume b, Landolt-Bornstein, Springer-Verlag (1985)
JGGSI
Journal of Geomagnetism and Geoelectricity, Vol 35, Nos 11, 12, (1983) (Special Issue of papers contributed to the 6th Workshop in Victoria)
SURVSI
Surveys in Geophysics, Vol 9, (1987), (Special Issue of Review Papers from the 8th Workshop in Neuchatel)
QUS
Quantities, Units and Symbols, The Royal Society, 1971.
ROKI
Geoelectromagnetic Investigation of the Earth's Crust and Mantle, Rokityanski, Springer-Verlag (1982)
MM
Magnetotelluric Methods (1986), SEG Geophysics reprint series, No 5, Vozoff (ed).

A reference will be quoted by referring to the journal only and not to the author's name, which is immaterial in this context. Of course the name could easily be determined. Apologies are extended to authors whose works are highlighted but to show fairness, the Chairman of this ad hoc committee will be unkindly quoted in Section 2.

Please consider each section and complete the relevant question on the enclosed question sheet.

(1) *Terminology for Field Separation*

A time-varying magnetic field H^e induces currents to flow in the conducting part of the earth and these currents give rise to an induced magnetic field H^i. The total magnetic field at the earth's surface is then

$$H = H^e + H^i$$

In a layered earth (with layer boundaries parallel to the earth's surface) the induced currents flow horizontally. Lateral changes in conductivity produce deviations from this horizontal current flow. The induced field H^i may be sub-divided into a part H_n^i representing the field of currents induced in a layered earth and a part H_a^i

representing deviations due to lateral inhomogeneity, so that

$$H^i = H_n^i + H_a^i$$

In the literature the word "normal" describes H_n^i as defined above (PEPSI page 279) but PEPSI page 360 defines "primary field" to be precisely H_n^i. GJI(1989), **98**, page 234 defines "primary field" to be H_n^i for a homogeneous earth and GEOMAG page 262 (same author as one of the above) defines "primary" to be H^e. In exploration geophysics, textbooks on EM methods refer to "primary" as the field of the transmitter (which corresponds to H^e) and "secondary" as the field of all induced currents.

Suggestion

Primary field = inducing field, source field
Normal field = field induced in a layered model by the primary field (layered model degenerating to a homogeneous model where appropriate)
(Note added July 1991: The normal field should have included the primary field)
Anomalous field = total field − normal field

Please answer Question 1

(2) *Conductivity or Resistivity?*
One aspect of geophysics is the determination of various physical properties of rocks. For example, seismologists try to determine the velocity of *P* and *S* waves. Seismologists also use slowness, the reciprocal of velocity, as a matter of elegance in some derivations and since in some regimes it may be linear and more easily integrable.

Induction studies seek conductivity or its reciprocal resistivity, mixing these terms arbitrarily (PEPSI page 290). Moreover, there seem no compelling arguments of elegance or of a fundamental nature that dictate the use of one or other in a given circumstance. Laboratory measurements on rocks are usually expressed in terms of conductivity, many theoretical papers work in conductivity, most field study reports present resistivity (though "conductivity anomalies" may appear in the title – PAGEOPH (1987), **125**). Apparent resistivity is a well-used term but apparent conductivity also appears (JGR, **92**, B10, page 10,645).

The following selection of titles illustrates the redundancy and the confusion presented to researchers in other disciplines:

'Electrical Conductivity, Temperatures and Fluids in the Lower Crust', *J. Geophys. Res.* **88**, 1983.
'Exploration of the High Resistivity Basement Using Electric and Magnetic Fields of Quasi-Static Point Sources', *Geophys. Prospect.* **31**, 1983.
'Geomagnetic Variations and Electrical Conductivity Structure in Southwestern Australia', *Phys. Earth Planet. Int.* **1**, 1967.
'Electrical Resistivity Structure Beneath the North-West Atlantic Ocean', *Geophys. J. R. astr. Soc.* **47**, 1976.

Seismologists usually present velocity structures within the earth and only seldom those of slowness. Perhaps we should present our results in terms of either conductivity or resistivity.

Please answer Question 2

3. *Response Functions/Transfer Functions*

There are a number of transfer functions in use with symbols including Q, W, V, Z, ρ_a, C and/or names such as impedance, apparent resistivity, inductive scale length, admittance. Some of these functions were proposed in specific pieces of work to reduce errors or to aid mathematical development and this should not be discouraged. However it may be considered desirable to standardise on a particular function for the presentation and discussion of results, particularly to workers in other fields. After a preliminary question (3.1) these functions are examined individually (3.2)–(3.8). Finally the choice of response/transfer function for data communication and presentation is considered (3.9).

3.1.

Is there any difference between response function and transfer function – if not, which description should we use?

Please answer Question 3.1

3.2.

There seems general agreement in the literature that Q = ratio of internal/external parts of a magnetic field. The reciprocal used to be used (called the amplitude ratio – *Phil. Trans. Roy. Soc. London*, *A*, **237**, 1937 page 524). Q and the amplitude ratio are complex quantities and either are presented in terms of amplitude and phase.

3.3.
An alternative to Q is the measure W (defined in *Geophys. J. R. astr. Soc.*, 1969, **17**, page 468). W is again complex and is given in terms of its amplitude and phase.

3.4.
V, the inverse of W, is defined in *Geophys. J. R. astr. Soc.* 1971, **22**, page 127 for reasons of algebraic advantage in the development of Fréchet kernels but no observational results appear in this form.

3.5. *Impedance*
In physics, impedance is a complex quantity whose real part is resistance and whose imaginary part is reactance. The units for impedance are thus Ohms. (QUS).

In induction studies impedance is ambiguously defined, sometimes as

$$Z = E/H \text{ (GEOMAG page 262, PEPSI page 246)}$$

and sometimes as

$$Z = E/B \text{ (LB page 114, PEPSI page 417, ROKI page 59).}$$

E is a horizontal component of the electric field at the earth's surface in V/km and H in Amperes/m (or B in Teslas) is the horizontal component of the magnetic field (or magnetic flux density or magnetic induction) orthogonal to E. E/H correctly has the unit of Ohms. E/B has the unit of velocity (and may be used as such, PEPSI page 429) but does not correspond to the physicists' meaning of impedance.

Please answer Question 3.5

3.6. "*C*"
This quantity is referred to variously as (i) inductive scale length (GEOMAG page 262), (ii) *C*-response (LB page 109), (iii) penetration depth and (iv) admittance (*JGR* **85**, page 4422). (However in physics admittance is the reciprocal of impedance so this latter usage seems incorrect – see Section 3.7).

Formulae for C differ because of the ambiguity in the definition of impedance (e.g. $C = Z/i\omega$ (LB page 115), $C = (i/\omega\mu)\, Z$ (SURVSI page 236)) and they also differ in sign as in these two examples, arising from the author's use of either $\exp(i\omega t)$ or $\exp(-i\omega t)$ to represent time variations – though these are seldom explicitly stated. The response C is a complex quantity and is presented in terms of its real and imaginary parts.

Please answer Question 3.6

3.7. *Admittance*

The reciprocal of impedance is admittance (QUS), with recommended symbol Y (as used in PEPSI page 203). The term admittance was used in *JGR* **85** page 4427 to define impedance but this usage seems incorrect and will not be considered further.

Please answer Question 3.7

3.8. *Apparent resistivity*

Apparent resistivity assumes many forms. It is sometimes defined as the real quantity

$$\rho_a = (1/\omega\mu)|E/H|^2$$

(GEOMAG page 270)

and it is sometimes written

$$\rho_a = 0.2(1/f)(E/H)^2$$

In this latter form it may be assumed real (PEPSI page 248); possibly real but compared with measured complex resistivities of soil samples (*JGGSI* pages 456/470); or may be defined as complex (*Geophys. J. R. astr. Soc.* **68** page 257). A series of further definitions appear in *Geophysics* **51**, 1986 page 1469. Ambiguous though it is, apparent resistivity has become so commonplace that it usually appears in the literature by name only, without reference to a defining formula.

When defined as a real number, depending on the squared modulus of impedance, apparent resistivity contains no phase information, yet "apparent resistivity and phase" is a commonplace expression and method of representation. What is meant by "phase" may be the phase of the impedance (*JGGSI* page 739), the phase of the complex resistivity (*Geophys. J. R. astr. Soc.* **68**, page 257) or $\pi/4$ − phase of impedance (*Geophys. J. R. astr. Soc.* **67**, page 259). The reciprocal, apparent conductivity, is also used (*JGR* **92**, B10 page 10,645).

A response or transfer function for the earth is necessarily a complex quantity containing both amplitude and phase information. For rock samples, complex resistivities are measured (*JGGSI* page 456) as are complex impedances (*JGGSI* page 767). It seems unnatural to describe a complex function using the amplitude of one quantity and the phase of another. Complex response or transfer functions are all related by simple equations such as

$$C = Z/i\omega \quad \text{(or its equivalent)}$$

and

$$\rho_a = i\omega\mu C^2.$$

Simple equations such as the latter are lost if ρ_a is defined as a real number and "phase" is that of impedance. When the measure is described only as "apparent resistivity and phase" researchers in other disciplines might naturally expect reference to the same complex quantity.

Please answer Question 3.8.

3.9. *Communication and Presentation*

For communicating *results* of an induction study to other researchers we will presumably use either model resistivities or conductivities depending on the answers to Question 2. What response/transfer function should we use to illustrate the *data* in a standard way – apparent resistivity/conductivity (however defined), impedance (however defined) or something else?

Please answer Question 3.9

(4) *Graphical Representations*

The literature contains a profusion of different ways of presenting graphically the variation of a response or transfer function with frequency or period. Taking apparent resistivity (real value or modulus of complex value) for illustration, the following examples show the diversification:

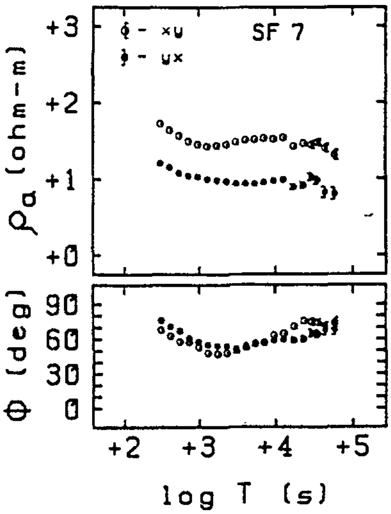

Diagram (i) (log T –>) Reproduced from Wannamaker et al.,Fig 8, page 14119.

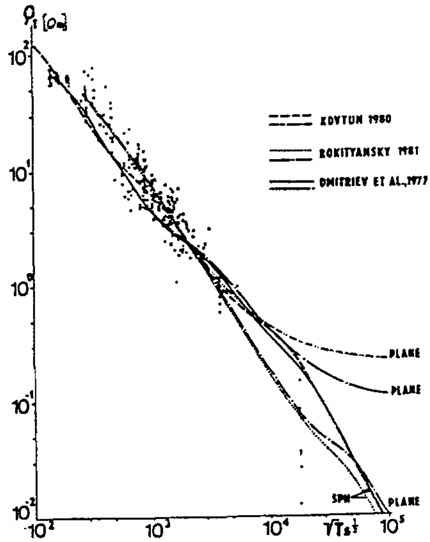

Diagram (ii) ($\sqrt{T}$ –>) Reproduced from Pecova et al.,Fig 5, page 307

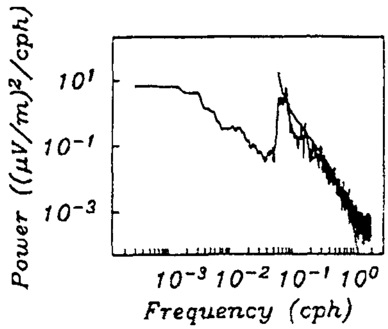

Diagram (iii) (log f –>) Reproduced from Chave at al., Fig 4, page 14158.

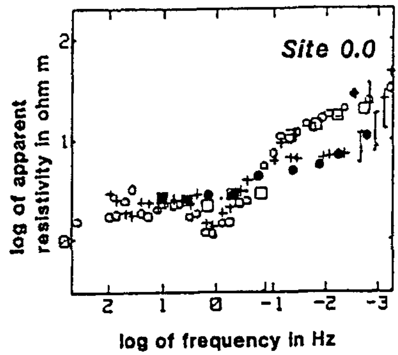

Diagram (iv) (log f <–) Reproduced from Young and Kitchen, 1989, Fig. 5, page 14188.

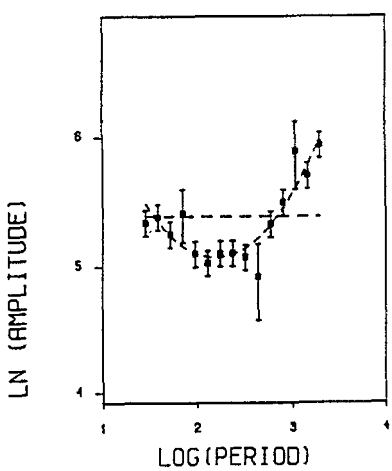

Diagram (v) (ln ρ v log T) Reproduced from Hobbs (1982), Fig. 6, page 263

Example (v) seems to have no advantages and will not be considered further. (i) and (iv) are basically the same, and even appear in the same paper – it seems a nonsense to have an axis labelled "frequency" which *decreases* to the right so (iv) will not be considered further. We are left to consider the merits of (i), (ii) and (iii). (i) and (iii) are the "opposite" ways of presenting data, and these can even appear in the same publication. (i) and (ii) although both in terms of increasing period, represent a division between east and west. Perhaps period increasing to the right is preferable as it then represents increasing depth penetration. The graph can be rotated clockwise through 90° to give an immediate indication of a resistivity profile in depth, with axis at the top giving resistivity (or conductivity) values.

We should adopt a single method of presentation, easily understandable by researchers in other disciplines.

Please answer Question 4.

(5) *Terminology for 2-D Induction Studies*

5.1. *Modes of Induction*

An induction problem is two-dimensional if the conductivity is a function of two variables e.g. $\sigma(x, z)$ where x is tangential to the earth's surface and z is vertically down. The strike of the lateral conductivity variation is then in the y-direction in cartesian coordinates (x, y, z). In this idealised case induction problems separate into two distinct modes – one in which the current flow and electric field have components only in the y-direction and one in which the magnetic field is only in the y-direction. The following terminology exists for these two cases:

(i)	E-polarisation	H-polarisation	(*GEOMAG* p. 286)
(ii)	E-polarisation	B-polarisation	(*PEPSI* p. 289)
(iii)	Transverse electric(TE)	Transverse magnetic(TM)	(*PEPSI* p. 365)
(iv)	Magnetic type	Electric type	(Stratton p. 30)
(v)	Poloidal magnetic(PM)	Toroidal magnetic(TM)	(*PEPSI* p. 351)
(vi)	$\rho^{\parallel}$	$\rho_{\perp}$	(*PEPSI* p. 198)
(vii)	ρ_{long}	ρ_{trans}	
(viii)	$E^{\parallel}$	$E^{\perp}$	(*PEPSI* p. 233)
(ix)	H-perp	E-perp	(*MM* p. 463)

Perusing this list we might reflect on how researchers in other disciplines must view our science! Note that (ii), (iii), (v), (vi) and (viii) all appeared in the *same* issue (PEPSI) and that in that issue, (iii) and (v) were used by the same author in different papers!

An electromagnetic field may be described by two partial fields in terms of

Hertz potentials (Stratton page 30), these potentials originating from a distribution of magnetic or electric dipoles. Accordingly these types of solutions are called "magnetic type" and "electric type". In "magnetic type" solutions the electric field is perpendicular to the dipole direction and in "electric type" solutions the magnetic field is perpendicular to the dipole direction. Schelkunoff introduced the terms "transverse electric" and "transverse magnetic" in 1937 to describe these partial fields. The term "transverse electric" meant the electric field had components only in the plane perpendicular to that describing the magnetic dipole. Induction workers have used a degenerate form in which the electric field is in only one direction in the transverse plane, that is the geological strike direction, calling this the TE mode. Since the electric field is now only in one direction it has been called E-polarisation. Since the electric currents flow only along the direction of strike it has been called $E^{\parallel}$, $\rho^{\parallel}$ and ρ_{long}. The unidirectional E-field has an associated poloidal magnetic field, hence the term PM instead of TE.

Similar arguments apply to "transverse magnetic" solutions except that TM now stands for either "transverse magnetic" or "toroidal magnetic" – the symmetric term PE for "poloidal electric" seems to have singularly escaped introduction! Also $E^{\perp}$, $\rho^{\perp}$ and ρ_{trans} no longer refer to a particular direction.

Chairman's view

2-D induction problems may be decomposed into two distinct cases where either the magnetic or the electric field is in one direction only, that of the geological strike. This seems to be a quite degenerate form of the transverse electric and transverse magnetic decompositions introduced by Schelkunoff. 2-D induction cases are most easily identifiable and comprehendable to other disciplines with the use of terms such as E-polarisation and B-polarisation. Neither this nor any other 2-D nomenclature may be of much use in describing 3-D problems.

Please answer Question 5.1

5.2. *Magnetic transfer/response function*

In the time domain, variations in $z(t)$ may be related to variations in $x(t)$ and $y(t)$ by the equation

$$z(t) = ax(t) + by(t) \tag{1}$$

where x, y and z represent magnetic field variations in the north, east and down directions respectively and a and b are real numbers. Near certain lateral conductivity changes these variations may lie on a preferred plane and the parameters of this plane may be represented on a geographical map by arrows or vectors. These time-domain functions a and b lead to:

(i) Parkinson vector/arrow.
The horizontal projection of the downward normal of the preferred plane.

$$\text{length} = \sqrt{a^2 + b^2}/\sqrt{1 + a^2 + b^2}$$

(ii) Wiese vector/arrow
The two-dimensional vector (a, b).

The Parkinson and Wiese arrows are of different lengths and in general the Parkinson arrow points towards a better conductor, the Wiese arrow points away from a better conductor.

It is more usual now to consider the transformation of Equation (1) to the frequency domain and to write

$$Z = AX + BY \tag{2}$$

where all quantities are functions of frequency. A and B may relate the anomalous Z field to the normal parts of X and Y or alternatively X, Y and Z may refer to total fields (*Rev. Geophys. Space Phys.* **19**, page 687).

Now that A and B are complex, with $A = A_R + iA_I$, $B = B_R + iB_I$, further definitions of arrows or vectors arise. Let i and j be unit vectors in the x and y directions respectively.

(iii) (A, B)

The two-dimensional vector (A, B) is called the "transfer function" (*PEPSI* **1**, page 25) or the "Tipper" (*MM* page 694, phase defined therein).

$$\text{Magnitude } T = \sqrt{A_R^2 + A_I^2 + B_R^2 + B_I^2}$$

(iv) In phase arrow $A_R i + B_R j$
Out-of-phase arrow $A_I i + B_I j$

These are sometimes referred to as Wiese vectors/arrows.

(v) In-phase arrow $-A_R i - B_R j$
Out-of-phase arrow $A_I i + B_I j$, (*Geophys. J. R. astr. Soc.* **39**, page 392)

The signs of A_R and B_R are reversed because then the in-phase arrow generally points towards the better conductor in keeping with (i). These are sometimes referred to as Parkinson vectors/arrows.

(vi) In phase arrow $-A_R i - B_R j$
Out-of-phase arrow $-A_I i - B_I j$ (PEPSI, page 427).

These are also referred to as Parkinson vectors/arrows.

In Section 5.1, different names or symbols were used to represent exactly the same situation. Here the opposite applies, there are a number of distinct representations but the names "Induction, Parkinson or Wiese" followed by "vector or arrow" may be used to represent several. The main usage seems to be the plotting of induction arrows/vectors in the frequency domain and these are further described as Parkinson or Wiese depending on the sign convention used. It may be that this situation is acceptable provided each author states the convention used clearly. See also *Rev. Geophys. and Space Phys.* **18**, pages 203–209 and **19**, pages 687–688 for further discussion.

There is an ambiguity in the description of components:

$$Z = AX + BY$$

X = north, Y = east, Z = vertically down (*JGG* page 638)

$$Z = AH + BD$$

H = north, D = east, Z = vertical (*PEPSI* page 279)

$$Z = AH + BD$$

H = north, D = declination (+ve west) Z = vertical (*JGG* page 593).

Studies involving the use of equations such as (1) or (2) are usually called "magnetovariational studies", (MV or MVS), "magnetic variation profiling" (MVP) or "geomagnetic deep sounding" (GDS). Note that the abbreviation MV is not symmetric with the abbreviation MT for magnetotellurics.

Please answer Question 5.2

6. *Colour Standard*

There is a colour scheme used in seismology to present velocity information – it is a built-in option in many standard, general purpose plotting routines although it is much varied by seismologists. In the Global Geoscience Transect Program, gravity and magnetics are adopting a common computer coding using the RGB or CMY colour codes.

The EM community ought also to have a standard colour scheme to represent apparent and model resistivity/conductivity. For EMSLAB, (*JGR* 1989 14277) blues represent high resistivity/low conductivity, reds represent low resistivity/high conductivity.

Note that in the seismic, gravity and magnetic scales, blue represents low values, red represents high values. The EMSLAB scale thus suggests we are representing conductivity. We could adopt an absolute scale (i.e. colours correspond to fixed bands of resistivity/conductivity) which has the advantage that a model or apparent resistivity is immediately identifiable. A disadvantage may be that small variations in some studies would not be representable.

Please answer Question 6

7. *Representation of Time Variations*

Time variations are sometimes assumed of the form $\exp(i\omega t)$ (*PEPSI* pages 188 and 331), sometimes as $\exp(-i\omega t)$ (*PEPSI* pages 337 and 433, and *GEOMAG*) and sometimes as both (*ROKI* page 31); equivalently forward Fourier transforms either have an exponent term or $i\omega t$ or $-i\omega t$. Frequently nothing is stated explicitly. Thus phase, leads and lags are ambiguous. We should adopt a single convention. $\mathrm{Exp}(-i\omega t)$ is suggested which, for example, leads to

$$\nabla^2 H + i\omega\mu\sigma H = 0$$

and has implications for the phase of various quantities such as impedance tensor terms.

Please answer Question 7

8. *Co-ordinate Frame*

To further ease immediate understanding of diagrams and notation, it is suggested that the standard frame should be a right-handed Cartesian co-ordinate system in which the x-axis points

north in 1-D
parallel to strike in 2-D
along the longer horizontal axis in 3-D,

the y-axis is 90° clockwise from the x-axis and the z-axis is positive vertically down.

Please answer Question 8

9. *E,B and H*

E usually stands for electric field or electric field strength, but what about B and H? H is called magnetic field (*PEPSI* page 222), magnetic field strength (*PEPSI* page 331), magnetic intensity or magnetising field and B is also called magnetic field (*PEPSI* page 337) or magnetic induction (*GEOMAG*) or magnetic flux density (*LB*).

Please answer Question 9

10. *Invariant Impedances*

There are two invariant impedances in use. One is

$$0.5^*(Z_{xy} - Z_{yx})$$

which may be called "average" (*GJ* **92**, page 165), "Berdichevsky average" or "mean" (*ROKI* page 192). The other is either

$$\sqrt{Z_{xx}Z_{yy} - Z_{xy}Z_{yx}}$$

or its square. It may be called "effective" (*ROKI* page 192) or "determinant" (*GJ* **92**, page 165) or its squared value may be called "determinant" (*JGR* **94**, page 14174). We should decide upon a particular terminology.

Please answer Question 10

References

Chave, A. D., Filloux, J. H., Luther, D. S., Law, L. A. and White, A.: 1989, 'Observations of Motional Electromagnetic Fields During EMSLAB', *J. Geophys. Res.* **94**, B10, 14153–14166.

Hobbs, B. A.: 1982, 'Automatic Model-finding for the One-dimensional Magnetotelluric Problem', *Geophys. J. R. astr. Soc.* **68**, 253–264.

Pecova, J., Martinec, Z. and Pec, K.: 1987, 'Appreciation of Spherically Symmetric Models of Electrical Conductivity', *PAGEOPH* **125**, 291–318.

Wannamaker, P. E., Booker, J. R., Filloux, J. H., Jones, A. G., Jiracek, G. J., Chave, A. D., Tarits, P., Waff, H. S., Egbert, G. D., Young, C. T., Stodt, J. A., Martinez, M., Law, L. A., Yukutake, T., Segawa, J. S., White, A. and Green Jr., A. W.: 1989, 'Magnetotelluric Observations Across the Juan de Fuca Subduction System in the EMSLAB Project', *J. Geophys. Res.* **94**, B10, 14111–14125.

Young, C. T. and Kitchen, M. R.: 1989, 'A Magnetotelluric Transect in the Oregon Coast Range, *J. Geophys. Res.* **94**, B10, 14185–14193.

Appendix 3: Questionnaire

IAGA WORKING GROUP I-3

Semantics in the Induction Community

Questionnaire

Please return by *8 June* if possible
(otherwise send it anyway!) to

Dr B. A. Hobbs
Department of Geology and Geophysics
University of Edinburgh
JCMB, King's Buildings
West Mains Road
Edinburgh EH9 3JZ
U.K.

Please indicate your answers with a tick against the appropriate statement and add any further comments if you wish.

Question 1
What does "primary field" stand for?

(a) External inducing field
(b) External inducing field plus field of currents induced in a layered earth
(c) Any other comments?

Question 2
What term shall we use to describe the physical property of the earth sought in induction studies and related laboratory measurements?

(a) Conductivity
(b) Resistivity
(c) Both
(d) Any other comments?

Question 3.1
Which term should we use to describe the response of the earth to magnetic field variations?

(a) Response function
(b) Transfer function
(c) Both
(d) Any other comments?

Question 3.5
Which definition should we use for impedance?

(a) $Z = E/H$
(b) $Z = E/B$
(c) Any other comments?

Question 3.6
What should we call "C"?

(a) Inductive scale length
(b) C-response
(c) Schmucker's C-response
(d) Penetration depth
(e) Admittance
(f) Any other comments?

Question 3.7
What should we call the response $Y = 1/Z$?

(a) Admittance
(b) Any other comments?

Question 3.8
If we use the term resistivity, how should we define apparent resistivity and phase?

(a) $\rho_a = (1/\omega\mu)|E/H|^2$ phase $= \arg(E/H)$
(b) $\rho_a = (1/\omega\mu)(E/H)^2$ phase $= \arg \rho_a$
(c) $\rho_a = (1/\omega\mu)|E/H|^2$ phase $= \pi/4 - \arg(E/H)$

If we use the term conductivity, how should we define apparent conductivity and phase?

(d) $\sigma_a = \omega\mu|H/E|^2$, phase $= \arg(E/H)$
(e) $\sigma_a = \omega\mu(H/E)^2$, using modulus and phase of σ_a
(f) Any other comments?

Note: the above may be defined in terms of B using $B = \mu H$.

Question 3.9
How should we communicate results to other researchers? Using:

(a) apparent resistivity/conductivity
(b) impedance
(c) Any other comments?

Question 4
In the graphical representation of apparent resistivity the ordinate of a plot should be the logarithm to base ten increasing upwards and the abscissa, increasing to the right, should be:

(a) log period (log T)
(b) log frequency (log f)
(c) log square root period (log $\sqrt{T}$)
(d) Any other comments?

Question 5.1
How shall we refer to 2-D modes of induction?

(a) E-polarisation	H-polarisation
(b) E-polarisation	B-polarisation
(c) Transverse electric(TE)	Transverse magnetic(TM)
(d) Magnetic type	Electric type

(e) Poloidal magnetic(PM)	Toroidal magnetic(TM)
(f) $\rho^{\parallel}$	$\rho^{\perp}$
(g) ρ_{long}	ρ_{trans}
(h) $E^{\parallel}$	$E_{\perp}$
(i) H-perp	E-perp
(j) Any other comments?	

Question 5.2

In the frequency domain representation

$$Z = AX + BY$$

or

$$Z = AH + BD$$

X and Y represent north and east components. What should the symbols H and D represent:

(a) H north component, D east component
(b) H north component, D declination (+ve west)
(c) H north component, D declination (+ve east) (see Section 8)
(d) Any other comments?

The complex functions A and B, with $A = A_R + iA_I$, $B = B_R + iB_I$ may be combined to form the two-dimensional vector (A, B). What should this be called:

(d) Transfer function
(e) Magnetic transfer function
(f) Tipper
(g) Any other comments?

The real and imaginary parts of A and B may be combined to form $(-A_R, -B_R)$, (A_I, B_I) and each may be represented by a line on a geographical map. What should these lines be called:

(h) Induction arrows
(i) Induction vectors
(j) Parkinson arrows
(k) Parkinson vectors
(l) Any other comments?

What should the lines representing (A_R, B_R), (A_I, B_I) be called:

(m) Induction arrows
(n) Induction vectors
(o) Wiese arrows

(p) Wiese vectors
(q) Any other comments?

What should studies of this nature be called:

(r) Magnetovariational studies (MV, MVS)
(s) Magnetic variation profiling (MVP)
(t) Geomagnetic deep sounding (GDS)
(u) Any other comments?

Question 6
Should the colour standard be:

(a) Relative

red: low resistivity/high conductivity
blue: high resistivity/low conductivity

(b) Relative

red: high resistivity/low conductivity
blue: low resistivity/high conductivity

(c) Absolute, e.g. in terms of resistivities:

>10,000 Ωm	Blacks
1,000 – 10,000 Ωm	Blues
100 – 1,000 Ωm	Greens
10 – 100 Ωm	Yellows
1 – 10 Ωm	Reds
<1 Ωm	Whites

(d) Absolute, using RGB or CMY colour codes
(e) Any other comments?

Question 7
What should we use for harmonic time variations and forward Fourier transforms?

(a) $\exp(-i\omega t)$
(b) $\exp(i\omega t)$
(c) Any other comments?

Question 8
Do you agree with the suggestion of a standard co-ordinate frame?

(a) Yes
(b) No

(c) Any other comments?

Question 9
Please write names for the following symbols:

(a) E
(b) B
(c) H
(d) Any other comments?

Question 10
What shall we call the invariant impedance $0.5^*(Z_{xy} - Z_{yx})$?

(a) Average
(b) Berdichevsky average
(c) Mean
(d) Any other comments?

What invariant imepdance should "determinant", Z_{det}, represent?

(e) $\sqrt{(Z_{xx}Z_{yy} - Z_{xy}Z_{yx})}$
(f) $(Z_{xx}Z_{yy} - Z_{xy}Z_{yx})$
(g) Any other comments?

What invariant impedance should "effective", Z_{eff}, represent?

(h) $\sqrt{(Z_{xx}Z_{yy} - Z_{xy}Z_{yx})}$
(i) $(Z_{xx}Z_{yy} - Z_{xy}Z_{yx})$
(j) Any other comments?

Appendix 4: Distribution of Questionnaire Replies

Australia	5
Brazil	2
Canada	12
China	2
Czechoslovakia	1
Ethiopia	1
Finland	3
France	2
Germany	7
Hungary	5
India	5
Ireland	1

Japan	1
Mexico	1
New Zealand	1
South Africa	2
Sweden	2
Switzerland	1
Turkey	1
USSR	9
UK	3
USA	17
Total	84

Appendix 5: Tabulation of % Votes Received for Each Question

Question	% Returns	% Votes				
1	95	(a) 87	(b) 8			
2	100	(a) 27	(b) 21	(c) 52		
3.1	93	(a) 43	(b) 30	(c) 20		
3.5	99	(a) 87	(b) 12			
3.6	81	(a) 23	(b) 33	(c) 13	(d) 11	(e) 1
3.7	99	(a) 99				
3.8.1	92	(a) 65	(b) 21	(c) 6		
3.8.2	67	(d) 46	(e) 20			
3.9	93	(a) 79	(b) 14			
4	98	(a) 63	(b) 12	(c) 23		
5.1	94	(a) 37	(b) 20	(c) 19	(d) 1	(e) 0
			(f) 6	(g) 1	(h) 10	(i) 1
5.2.1	74	(a) 61	(b) 3	(c) 10		
5.2.2	82	(d) 21	(e) 35	(f) 26		
5.2.3	83	(h) 30	(i) 22	(j) 12	(k) 19	
5.2.4	63	(m) 20	(n) 20	(o) 10	(p) 14	
5.2.5	82	(r) 36	(s) 8	(t) 38		
6	87	(a) 45	(b) 9	(c) 28	(d) 5	
7	79	(a) 55	(b) 23			
8	92	(a) 86	(b) 6			
9a	87	electric field(65); electric field strength(12); electric field intensity(5); horizontal electric field(4); electric intensity(1)				
9b	85	magnetic induction(54); magnetic flux density(17); magnetic field(11); horizontal magnetic induction(2); induced magnetic field(1)				

9c	86	magnetic field(49); magnetic field strength(11); magnetic field intensity(10); magnetic intensity(7); magnetising field(5); horizontal magnetic field(4); magnetising force(1)
10.1	77	(a) 31 (b) 30 (c) 16
10.2	82	(e) 35 (f) 48
10.3	65	(h) 57 (i) 8