ELECTROMAGNETIC METHODS IN APPLIED GEOPHYSICS

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Abstract. Applied electromagnetic research in recent years has been influenced by the growing importance of geothermal energy, coal, and permafrost, in addition to the traditional area of minerals. The interest in near-insulators such as coal and ice encouraged development of radars and other VHF-UHF techniques. Interpreting such measurements required reliable physical properties data for those materials over a frequency range of 6–10 decades. The utility of the high frequency field data has been improved through the use of transient techniques for data acquisition, and data processing schemes similar to those used in reflection seismology. The major developments in the more usual frequency range of applied geophysics (30 Hz–3 kHz) have also dealt with transients. In certain circumstances they appear to have a fundamental sensitivity not readily obtained by discrete frequency methods.

Computer modelling of 3-D problems is progressing slowly. Improved 2-D inversion programs are in use, but their capabilities are very limited.

Superconductivity plays a role in several new instrument developments. SQUIDs, and SQUID gradiometers have improved considerably since the last Workshop. Robust SQUID magnetometers having noise levels of $10^{-5}-10^{-6}$ nT/$\sqrt{\text{Hz}}$ can now be obtained commercially. Gradiometer sensitivities have improved accordingly. A superconducting loop 3 metres in diameter, to be test flown early in 1979, is the prototype of a new low frequency system to map conductivity from a helicopter. It is expected to have greater depth penetration in conductive terranes than the best existing systems, because of the low frequency and anticipated low system noise.

A new magnetotelluric procedure, using a remote field reference, reduced the scatter in apparent resistivities and other response functions to a few percent. Further improvements must now be made in modelling and interpreting MT results if we are to benefit from this development.

1. Introduction

It is well known that there are as many definitions of the term 'applied geophysics' as there are geophysicists. Therefore the choice of topics in a review of this nature must be somewhat arbitrary.

At any time, research in applied geophysics tends to concentrate on a few particular problems having special economic or engineering significance. My impression is that the areas of concentration in the past few years were geothermal exploration, together with a set of problems in which the zones of interest are highly resistive. The latter include coal seams, permafrost, the lunar surface, and ice sheets.

The geothermal work encouraged the further development of existing EM methods, including transient decay methods. It was responsible for new and improved instruments and for much more powerful interpretive tools. These tools gave us a better understanding of the behavior of electromagnetic fields in our real earth. The other problem areas required the development and application of techniques which were not traditionally geophysical. Instead, the high resistivity values suggested the use of high frequencies,

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including conventional radar technology. Since little was known about the physical properties of earth materials at these high frequencies, it was also necessary to establish improved laboratories and techniques, and to measure the complex electrical properties of many samples. In many cases this was done over a frequency range of more than ten decades.

Mineral exploration technology benefitted in a number of ways from these developments, and mining geophysical research also contributed, particularly on instrument development.

In what follows, I would like to describe particular research developments from these several sources that appear to me to be of special importance.

2. Electrical Properties of Earth Materials

Prompted largely by studies of the Moon, a quantum step improvement occurred in facilities for measuring the electromagnetic properties of rocks and soils. From this emerged a much more complete and reliable *description* of these properties over a wide range of temperatures, chemical environments, pressures, and a truly enormous range of frequencies (Katsube and Collett, 1976; Olhoeft, 1976; Davis and Annan, 1977, Pelton *et al.*, 1978). Unfortunately it seems that we still cannot *explain* even the d.c. resistivity of a water-saturated rock near the earth's surface (Madden, 1976). However the *descriptions* are necessary if we are to study the distribution of these materials by geophysical means. For example, the success of high frequency EM and radar work, mentioned later, demands that we know how dielectric constant varies with frequency.

Thus the properties of large suites of magnetic rocks, of frozen and unfrozen soil samples (for permafrost studies), of samples containing metallic minerals (for mineral exploration purposes), of lunar samples, and of highly resistive rocks (coal, salt, granite, etc.) were measured in a few laboratories.

Eventually it was necessary to agree on a terminology for the (complex) impedances which are observed. A detailed proposal was prepared (Olhoeft *et al.*, 1978) and recommended for adoption by the Society of Exploration Geophysicists.

The results of the measurements are not easily summarized. One result commonly shown is Figure 1 from Davis and Annan (1977). Here K' is the real dielectric constant and K'' is the dielectric loss. Complex dielectric constant is

$$K^* = K' - i(K'' + \sigma_{\text{d.c.}}/\omega\epsilon_0),$$

$$K^* = \epsilon/\epsilon_0.$$

This illustrates both the large variation in K^* and the wide frequency range of interest.

Pelton and others (1977, 1978) measured complex $\rho(\omega)$, or its phase, in a large suite of rocks, containing metallic mineralization. Over the frequency range $10^{-2}-10^{-4}$ or 10^{-5} Hz they confirmed Madden and Cantwell's (1967) result that the (often large) variation

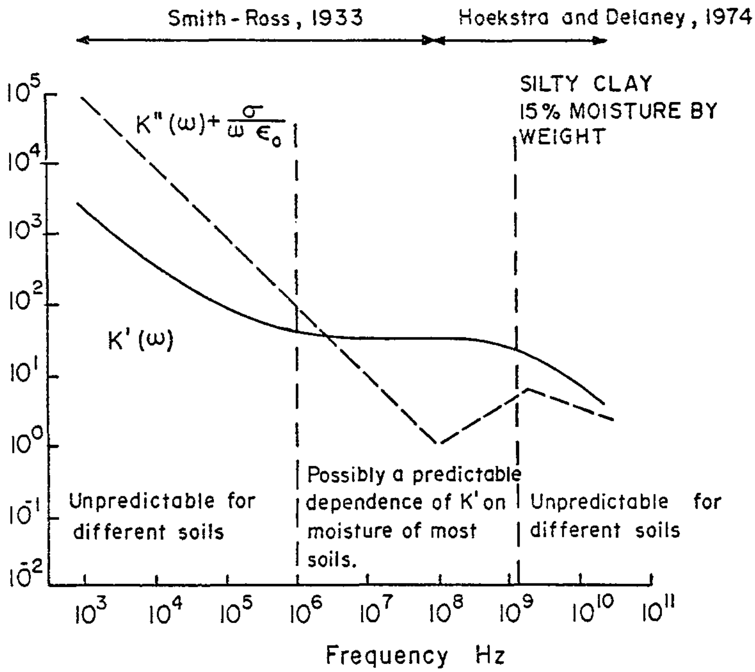

Fig. 1. Frequency spectrum of the complex dielectric constant over eight decades for one wet clay sample (from Davis and Annan, 1977).

can be described by a Cole–Cole model representing a spectrum of relaxation time constants. Thus instead of a simple $\exp(-t/\tau)$, the voltage decay when a d.c. current is shut off is of the form

$$\sum_n \frac{(t/\tau)^{an}}{\Gamma(an+1)}$$

Here the τ are time constants, Γ is the gamma function, and $a < 1$. Figure 2 shows the frequency response of one such example. Pelton *et al.* also demonstrated a marked dependence of response on grain size distribution of the metallic minerals.

Measurements of real resistivity and loss tangent in frozen permafrost clay gave resistivity values $>10^5$ ohm-m at $-10°$C and $>10^6$ ohm-m at $-27°$C, near 1 Hz. By 10^6 Hz this had decreased to 100 ohm-m (Olhoeft, 1977). Nevertheless, when a sample is frozen, both (d.c.) resistivity and (1 GHz) dielectric constant change more or less abruptly. On freezing, the dielectric constant K' decreases and the resistivity increases, often by an order of magnitude. Measurements by the same author (Olhoeft, 1978) on natural sedimentary salt showed a drop in real resistivity with frequency, from $\sim 10^8$ ohm-m at d.c., to 10^6 at 10 Hz and 10^3 at 1 MHz. These are 10^5 lower than values for pure salt crystals, a fact attributed to impurity content.

One of the earlier measurements, whose significance to applied geophysics may be

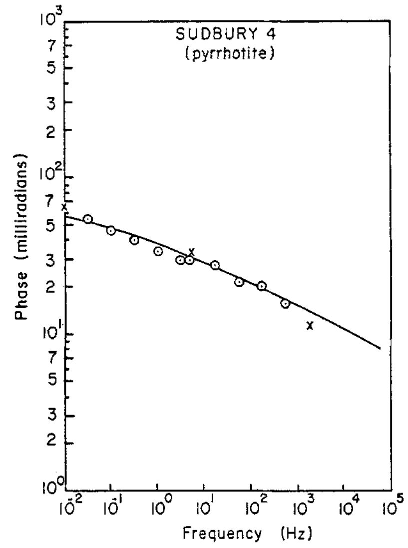

Fig. 2. Resistivity phase spectrum of a nickelferous pyrrhotite (from Pelton *et al.*, 1977).

greater than has been realized, is that of magnetic relaxation (Olhoeft and Strangway, 1974). This appears as a complex frequency dependence of B/H, persisting to low frequencies, and unrelated to conductivity. Because *it is linear* at low field strengths and occurs even at frequencies below 100 Hz, it offers the opportunity for a new geophysical measurement, at the surface, in a borehole, or even from the air (Becker *et al.*, 1978).

Applications of Short EM Waves

The frequencies used for EM exploration gradually decreased over the past 30 years as geophysicists became uncomfortably aware that common earth materials can be very conductive. We slowly recognized the real limitations on exploration depth imposed by skin effects, and tried to overcome these by reducing typical frequencies over the years, from tens of kHz to 100 Hz or less. Thus the interest in methods operating in the MHz–GHz range, even for special applications, is a radically new trend.

When one considers the propagation constant

$$k^2 = i\mu\omega\sigma + \omega^2\mu\epsilon$$

it is clear that a 'reflection' will occur in a propagating field whenever there is a change in either σ or ϵ, or even in μ. This reflection can be observed at a receiver only at distances r so small that it has not been lost through ($\omega\mu\sigma$) absorption or through geometric attenuation. Thus in these special applications both σ and r tend to be small. The materials penetrated include salt, coal, permafrost, glacier and sea ice, granite and schist, lunar materials, and even normal soils. In one example, reflections from short bursts (1–1½ cycles) of 30 MHz were measured at the face of coal seams in mines, to test for disruptions in the seams. These disruptions affect automatic mining operations, and can cost several million dollars a year in one large mine. Reflections from distances of 20–30 m have been observed (Cook, 1977), but this should be doubled for greatest effectiveness.

In this range of parameters one is often dealing with waves, although they are dispersed and absorbed. Thus one can indentify reflections, refractions, diffractions, wavelengths and velocities, and most other wave phenomena. Therefore it is natural to apply the concepts used so succesfully for processing seismic data to improve the EM data. Moffatt and Puskar (1976) use the seismic Normal Move Out (NMO) procedure to estimate velocity in the propagating medium, as a means of identifying the medium geologically. In this procedure the reflection time is measured at two or more Source-Receiver separations (Figure 3). These are sufficient to solve for the two unknowns, V_1 and d.

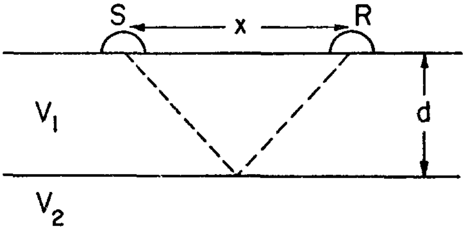

Fig. 3. Geometry for velocity and depth to overburden determination by seismic or radar reflection methods.

Olhoeft *et al.* (1978) use conventional seismic reflection plotting to present their EM reflection results (Figure 4). This is closely related to the transient EM pseudosection used in mineral exploration, which is used by Coggon (1978).

A major improvement in *seismic* data quality has come about through the use of the Common Depth Point (CDP) or Common Reflection Point (CRP) scheme. In this method, sources and receivers are moved in such a way as to obtain reflections at many angles of incidence from selected subsurface points. Those reflections are then added together so as to enhance the desired signals and to suppress the nonsystematic geologic noise. This geological noise, or 'clutter', is extremely large in earth radar measurements because of roughness on the surface where the antennas are placed, and inhomogeneity within the rocks. It often completely obscures the desired radar reflections, so that several groups (e.g. Fowler and Still, 1977) are using CDP procedures to overcome this and to enhance the reflections. The visual appearance of these records is further improved by whitening the spectrum, using deconvolution schemes developed for processing seismic data (Moffatt and Puskar, 1976). These convert broad wave trains to single narrow impulses at the arrival times of the events.

Radar techniques have been used for geophysical purposes for a number of years, to measure thickness of glacier and sea ice, and for lunar surface probing. It is their recent vigorous development for geological engineering and mining applications of HF, VHF, and UHF EM techniques which makes the topic so interesting at this present time. The

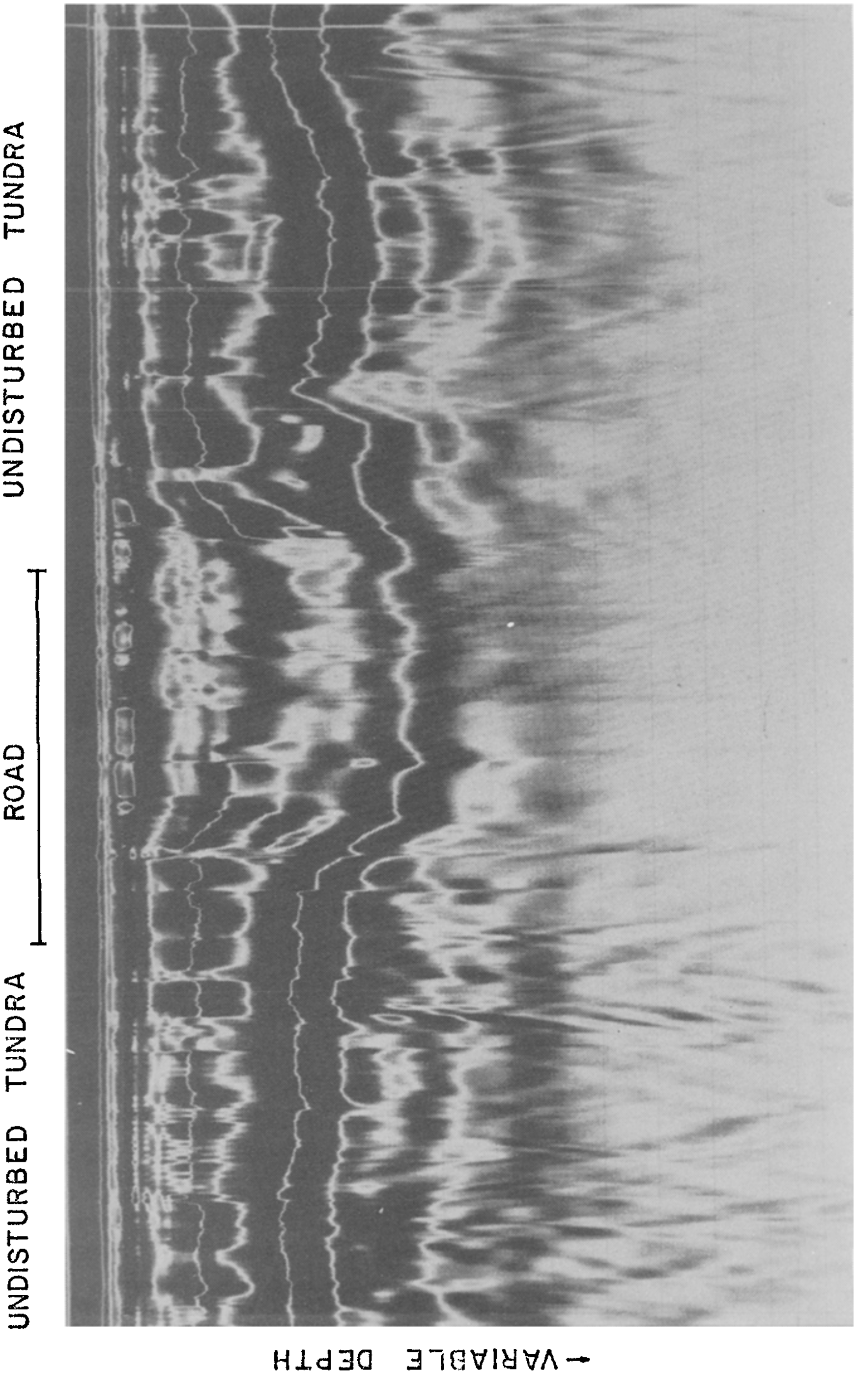

Fig. 4. Radar time section across a road in permafrost (from Olhoeft *et al.*, 1977). Distances are about 5 m full scale vertically and 25 m across horizontally. Data are unprocessed. A clear depression of the permafrost level is visible under the road.

severe limits on their range must not be forgotten. Aside from the geometric factors associated with small ($\sim$1 m) antennas, losses in most rocks exceed one order of magnitude in 20 m (1 db/m) at 100 MHz (Cook, 1975). Theoretical maximum ranges for existing Earth probing radar equipment were calculated and tabulated by Annan and Davis (1977).

The transient wave approach has also been applied to much larger scale problems by Clay, as mentioned elsewhere in this paper.

SLOWER TRANSIENTS

Major changes in EM exploration equipment are rare occurrences. For years, exploration geophysicists measured the coupling between a transmitting loop and a receiving loop at a few selected frequencies. The frequencies decreased as more surveys were carried out in highly conductive arid regions. Frequencies also became more numerous as improvements in electronics permitted, the waveforms improved, and phase information was added by providing a reference signal at the receiver. However the changes were evolutionary, not revolutionary.

One large step was the installation of EM equipment into aircraft, around 1950. Although the configurations were the same as used on the surface, great effort was required to achieve the necessary increased sensitivity and low noise.

Another major change occurred about 1960. More or less simultaneously at least three groups turned their attention to measuring the decay transients arising when an applied field is interrupted (Enenstein *et al.*, 1959; Dolan *et al.*, 1966; Barringer, 1963). (These followed by some years the thorough theoretical and field research of Yost (1952), Yost *et al.*, (1952), and Orsinger and Van Nostrand (1954), but a full quantitative theoretical interpretation of their results is only now becoming possible.) In theory, this transient response is equivalent to the Laplace transform of the quadrature response, as is well known, but in practice the transient decay measurement proves to have many advantages. Consequently, its use appears to be rapidly growing at the expense of the continuous wave techniques. Among the advantages are the ease and speed with which a broad spectrum is sampled, the fact that transmitter current need not be so carefully regulated, and the insensitivity to precise transmitter position since only the secondary field is observed. To help interpret the measurements, several careful analytical, numerical, and physical modeling studies were carried out or are in progress (Clay, 1977; Lee, 1975; also see papers by Clay, Nabighian, Spies, and West, in Braham *et al.*, 1978), and some of the extensive Soviet literature is being translated (Kaufman, 1973, 1977, 1978a, 1978b, 1979). These verify another advantage, pointed out by Wait many years ago, that decay transients show a kind of superposition which considerably simplifies interpretation. That is, at late times the responses due to overburden, isolated conductors, and host medium are simply additive, to a first approximation (Figure 5). The reason is that mutual inductive interactions between regions decay more quickly than their self-induction. Kaufman (1978b) also demonstrated that, for a conductor buried in a more resistive host, transient response is more easily observed than CW response if transmitter and receiver are relatively close together.

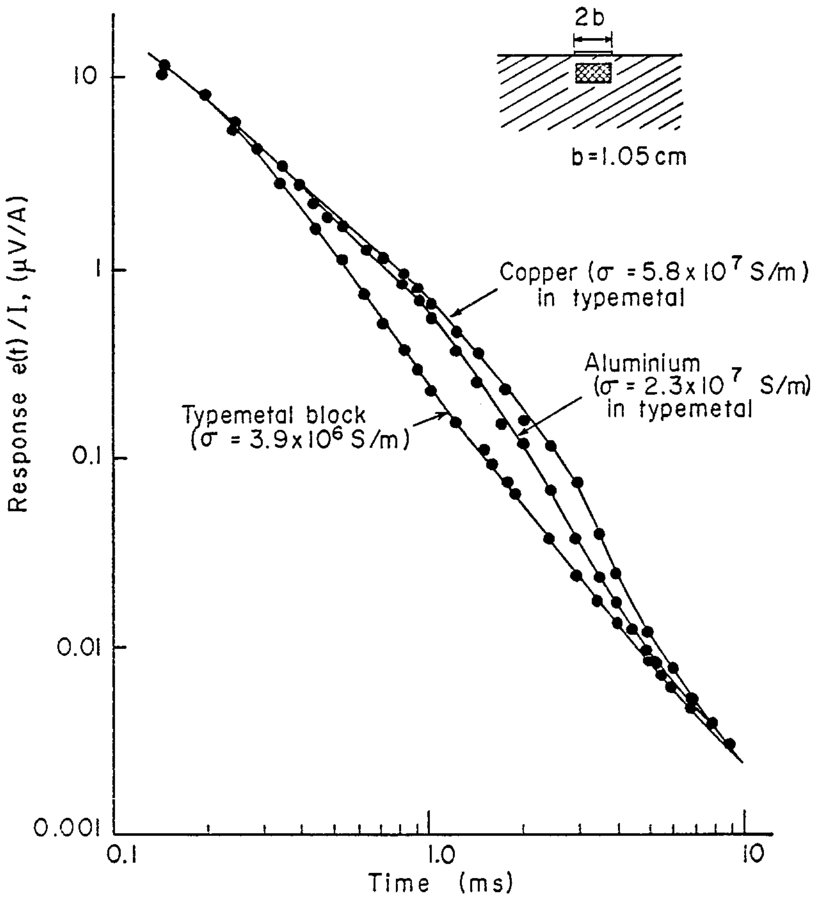

Fig. 5. TEM (single loop) decay curves of a typemetal 'half-space' alone, and with two different 'orebodies'. I is the loop current; $e(t)$ is decay voltage in loop.

The transient approach has been implemented through several kinds of equipment, whose relative advantages are now being investigated. One version uses a pair of loops to send and receive. In another the field is set up by applying a current through a long wire connected at both ends to earth. Both of these systems directly correspond to configurations which use sinusoidal current. A third type of equipment, using only one loop, so far is practicable only in the transient domain. In this system a direct current is applied for a time at $t < 0$. At $t = 0$ the current is interrupted and the loop is electronically connected to a voltmeter, which measures the decay. Since its initial commercial version (MFPO-1) developed in the U.S.S.R. this instrument has undergone a number of significant instrumental improvements. A version recently developed in Australia (SIROTEM) is based on a microprocessor which automatically controls timing, switching, and data acquisition and processing.

Interpretation for a single loop system is inherently simpler than for systems having separate transmitter and receiver, since there is one less variable, but ambiguity may be more severe. Interpretation of transient results is assisted by an important theoretical result which has been verified in scale models. That is, the functional form of decay depends on the dimensionality of the target. Over spheres and cylinders the decay voltage from a current step in the loop is the sum of one or more exponentials. It is asymptotic to an exponential at late times. Over a uniform or a stratified half-sprace the decay at late times is as $t^{-\alpha}$. Thus at early times the decay is dominated by effects of nearby isolated conductive bodies: at late times that 'host' medium decay is dominant (Kaufman, 1978a).

The theoretical results of Velikin and Bulgakov (1967), Kaufman (1977), Lee (1975) and others were confirmed in a very convenient scale model system of Spies (1978 a, b). Low melting point alloys (Woods metal, type metal, etc.) are ideal materials to represent the 'half-space' in reduced size. Carefully-machined blocks of copper, graphite, etc. can be placed in the liquid metal as it cools, to simulate 'orebodies' having conductivity contrasts as low as 3:1. As is well known, two of the greatest problems encountered in EM scale modeling tanks are finding materials which have a small contrast with salt water, and making the model container large enough that the bottom and sides do not affect the results. Spies' solution overcomes both of these difficulties.

Using the same time range as the full scale equipment (~0.3–30 ms), his models are typically 0.2 X 0.2 X 0.1 m in size. Spies also demonstrated that the response of the one-loop system on a half-space is the same as that of a two-loop system in the limit as the spacing between the loops approaches zero.

Can propagating wavelet concepts also be applied to transients in structures on a size scale of kilometers? Clay and others (1974, 1977, 1978) and Kan (1975) extended the research of Yost and his associates, to show that the transient response of a layered medium is closely approximated as a half-space (surface wave) response plus reflections from each interface. The reflections are small. Their waveforms depend on transmitter-receiver distance, and on layer conductivities and thicknesses because of dispersion and attenuation. Multiple reflections can essentially be ignored. In a practical example, measurements were taken at several distances to 40 km in a precambrian shield area believed to become conductive at some depth in the crust. Matched filters were calculated for trial interface depths, for each receiver position, and for the precise transmitter waveform and receiver response. The half-space response was then subtracted from the received signals and the remaining signals were correlated with the various matched filters. The correlations were summed over receiver position. The depth for which these summed correlations was greatest was taken to be approximately correct. The signal, the various filters, and their outputs for a theoretical model are shown in Figure 6.

There is obviously much more to be done with this approach. Clay shows how the reflections can be evaluated if the interfaces are not horizontal. More recently West (1978) and Mathon and Johnston (1977) showed that the interfaces do not even have to be planar for some approximate methods to be used to model their 'reflections'.

The problem treated by Clay was of course solved in the frequency domain many years ago by Foster and by Wait. Clay's contribution shows us another way to understand the physics of the process. It also opens the door to new approaches to modeling that may

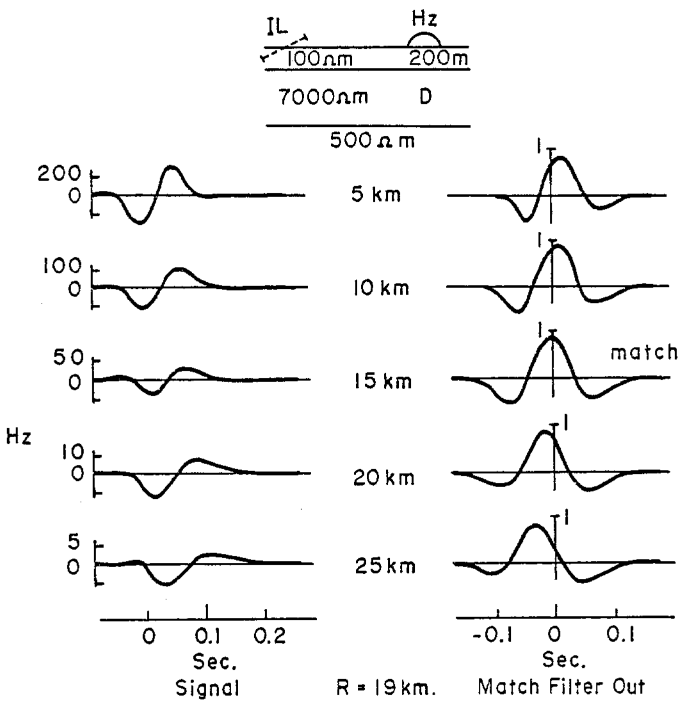

Fig. 6. On the left side are signals (H_Z) for different depths D at a sender-receiver separation R of 19 km. On the right side are shown the outputs when these signals are matched-filtered with a filter computed for a separation of 19 km and a D of 15 km. (From Clay, 1977).

prove to be superior to those now used.

Similar comment can be made about Nabighian's recent (1978) physical interpretation of the transient fields beneath a horizontal loop. He showed numerically that, in a uniform conductive half-space, the E and H fields can be represented as due to a system of horizontal loop currents increasing in size and propagating downward with a linearly decreasing velocity. Thus the E fields resemble smoke rings, 'blown' from the loop into the Earth. When such a ring encounters a region having a different conductivity, its velocity changes accordingly. The representation shows many of the features which are observed in practice (Figure 7).

3. Superconducting Instruments

There were a number of developments involving superconduction that will influence applied geophysics for many years. SQUID magnetometers were mentioned at the previous Workshop. They are now widely used for practical Magnetotelluric work, and to a

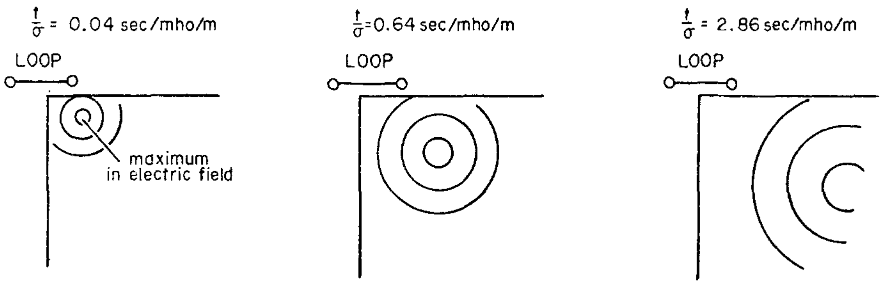

Fig. 7. 'Smoke rings' of magnetic field as it diffuses away from beneath the loop over a half space with increasing time (Nabighian, 1978). t is time from current.

lesser extent for other EM surveys. Continuing research led to several improvements which are of interest to us. Noise levels were further reduced so that equivalent noise fields of 10^{-5}–10^{-6} nT/$\sqrt{\text{Hz}}$ are now possible, for frequencies above 0.02 Hz (Clarke, 1977). At lower frequencies, noise varies as (frequency)$^{-1}$. The physical processes are not fully understood, but they are common to both r.f. and d.c. SQUIDS. Since the spectrum of natural magnetic fields increases more rapidly than noise at long periods, this presents no problem in most geophysical applications.

Frequency response at high frequencies is limited, not by the SQUID, but rather by the associated electronic circuits. The limiting factor is the maximum slewing rate which can be obtained from the output circuits. This has been steadily improved so that 20 kHz signals can be measured, although some reduction in sensitivity is required to achieve this.

SQUID magnetometers are extremely linear within a limited range. However, when the flux change through the device exceeds some multiple of the flux quantum, a step change occurs in this magnetometer output. In practice, such changes most commonly result from nearby lightning discharges. Common practice has been to provide a metallic shield surrounding the device, which effectively attenuates these transients. Shields behave like low-pass single-stage passive filters, and are designed to provide a selected corner frequency. By using tuned flux transformers it is also possible to achieve a narrow bandwidth at selected frequencies.

Several types of SQUID magnetic gradiometers were constructed (Ketchen *et al.*, 1978). In size they are comparable with the SQUIDS themselves – 10^{-1} to 10^{-2} m in their largest dimensions. Sensitivities of 10^{-5} nT/m$\sqrt{\text{Hz}}$ are possible with first derivative devices. In addition, configurations were built which respond to second spatial derivatives. Some interesting geophysical applications of these gradiometers have been proposed (Morrison, 1978; Quon *et al.*, 1978), and others will no doubt emerge. A feature of particular importance is that these devices respond directly to field gradients. That is, they do not rely upon electronic differencing. Therefore they are able to function in the presence of a much larger uniform field. EM measurements can be made in industrial areas for example, where large 50 or 60 Hz fields make other measurements impossible.

As noted above, SQUID magnetometers are widely used in North America for MT

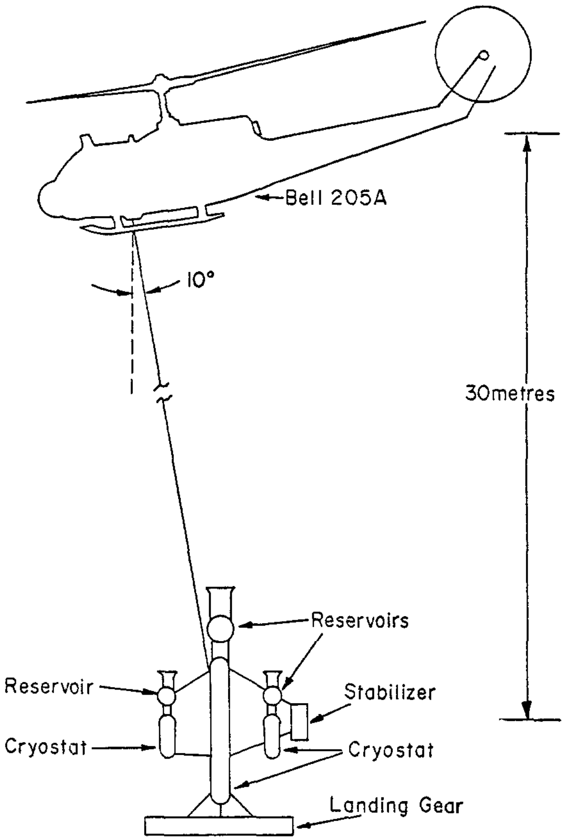

Fig. 8. Sketch of the Unicoil system (from Morrison *et al.*, 1976).

surveys (e.g., Stanley *et al.*, 1977). In other EM applications Keller (1978) used them for EM surveys at distances of several kilometers from a high-current grounded wire source. Morrison *et al.* (1978) built, and are now testing, a field system with a loop source and a three component SQUID receiver. Source waveforms, data acquisition, and data processing are all under microprocessor control. This is designed to operate at frequencies from 0.002 to 10^{+3} Hz, with transmitter-receiver separations to several km. Spies recently demonstrated that a vertical component SQUID can be operated at the center of a 100 m loop driven by a square wave of current. To do this while accurately observing the resulting transient, he found it necessary to cancel the primary field at the SQUID by means of a small auxilliary loop carrying a portion of the applied current. Developments of this kind can improve the quality of both deep crustal sounding data and exploration data.

Another development I would like to describe is that of a new airborne EM exploration system. Airborne EM systems have flown millions of line miles of traverse, and have found thousands of mineral deposits. However, in a careful compilation of the results, Paterson showed that very few of the *economic* deposits found were at depths greater than 15–20 m. There are several reasons for this, two of which are system noises and undesirably high operating frequencies. The first is partly electronic, partly due to motions of the receiver loop relative to the sending loop and to the earth's field. An increase in operating frequency permits the use of smaller loops and lower transmitter currents. However, increasing the frequency also limits the depth of penetration in areas where the near-surface is conductive, and causes many more responses from small zones of relatively low conductivity. Hence every airborne system design incorporates some compromise, and only one or two operate at frequencies below 400 Hz. It is now fairly well established that enormous areas having good exploration potential are covered by 100 m or more of 1–10 S/m material (Nickel, 1978). At 400 Hz, the skin depth at 10 S/m is only 80 m, so existing systems must expect to have great difficulty.

The superconducting Unicoil system (Figures 8, 9) presently being developed by Morrison *et al.* (1976) has two advantages in this situation. It operates at lower frequency, around 30 Hz, and it has only one coil, so that noise due to motion between coils vanishes. This system consists of a single, large (3 m) vertical, superconducting loop. Impedance of this loop, measured at the operating frequency, is affected by the conductivity of the Earth. Since the *resistive* impedance of an isolated superconducting loop is intrinsically low it is possible to measure the small changes due to the Earth. For this large loop the resistance of the entire circuit is about 1 ohm, while the resistance changes predicted for various half-space and sphere models are in the range 10^{-4}–10^{-6} ohms. As the noise level is about 3×10^{-6} ohms, it appears that the system will be a significant improvement over existing equipment. The prototype is expected to be flown in early 1979. Although it will

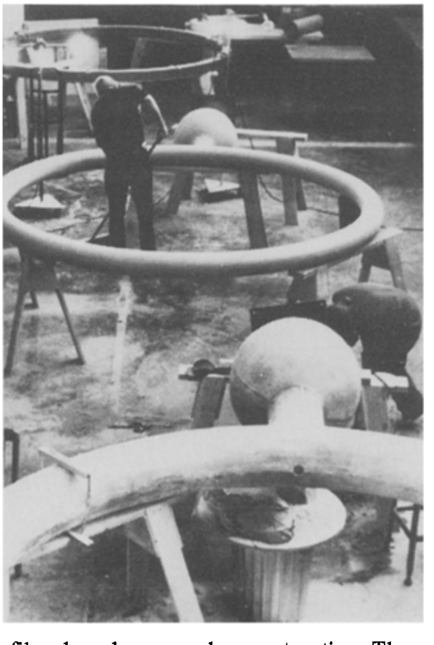

Fig. 9. Photograph of 3 m fiberglass dewars under construction. The conductive loop is contained within the ring, which is filled with liquid helium. The bulbs are the reservoirs (see Figure 8).

be large and heavy, it is merely a prototype, so that lighter systems can be expected in the future.

Morrison also designed a small, powerful, low frequency EM transmitter for use on the surface. This uses a superconducting loop having a 1 m diameter, a moment $IA = 10^6 - 10^7$ amp-m^{-2}, and a mass of about 250 kg, rotated about a vertical axis at frequencies from 0–10Hz. It should prove particularly useful in applications where there is insufficient space for a large transmitting loop. Examples are built-up areas around producing oil wells and mines, and underground workings.

Despite all the advantages of superconducting devices, it should be borne in mind that liquid helium is not easily obtained in many parts of the world. It is costly and difficult to store and, even more so to transport. Many airlines will not accept liquid helium shipments. These factors should be carefully weighed against the advantages of the instruments. One development which will be helpful is that of portable, nonmagnetic helium refrigerators. These will require the added complication of gas recovery plumbing, but should nearly eliminate the need for frequent expensive transport and large storage dewars (Zimmerman *et al.*, 1977; Zimmerman *et al.*, 1978).

4. Modeling and MT

Geothermal exploration also helped to support a great deal of computer modeling research, and was largely responsible for the unprecedented growth in the use of MT in Western countries. (The rapid increase in the cost of processing seismic reflection data has further encouraged this growth.) Some of the developments in EM modeling and MT deserve mention.

Progress in 3D forward modeling was reviewed at two recent Workshops (Braham *et al.*, 1978; Goldstein, 1978). Briefly, it has been steady, but slow, since the last Workshop in Sopron. I am aware of several computer programs in which the source, the conductivity distribution, or both, are 3D. In each case they are expensive, and not entirely reliable for use over a wide frequency range (Hohmann, 1978; Dey, 1978; West, 1978a; Pridmore, 1978). At the present time, it is very desirable that results be cross-checked by two or more computation methods. There is considerable interest in establishing a suite of standard models, to be used for evaluating both numerical and physical scale model results (Braham *et al.*, 1978, Session 25).

Ranganayaki and Madden show how to reduce the number of dimensions by one in the special case in which all lateral conductivity changes occur in a depth range which is thin compared to the skin depth (Ranganayaki, 1978). In this case the 'two-dimensional' model is accurately represented by a one-dimensional computation, and the 'three-dimensional' problem becomes two-dimensional. They also show that long period ($T > 10^3$) MT apparent resistivities must be interpreted carefully, because the combination of a very conductive upper crust and a very resistive lower crust causes lateral effects to persist for distances of hundreds of kilometers for the transverse magnetic mode.

The two-dimensional MT inversion program written by David Jupp has been used on data from surveys in sedimentary basins, cratons, and geothermal areas. Input consists of combinations of apparent resistivity and/or phase from either or both polarizations, at a number of frequencies, from a number of sites along a traverse. In addition, a starting model consisting of no more than 29 independent resistivity regions must be provided. The inversion adjusts the resitivity values within the original regions but does not alter the regions. It also provides resolution estimates for the final conductivity values for a given data variance (also input). The method is easy to use provided that the data are relatively two-dimensional and polarization is unambiguous. Then the greatest errors arise in regions of complex lateral conductivity change, where more 'regions' are needed than are available (Jupp and Vozoff, 1977a). One of the results of MT surveys and 2D modeling is a Tipper, or directed ratio of vertical to horizontal magnetic field for the TE polarization. This ratio is closely related to the Parkinson and Weise induction vectors. It is almost the only information collected in most GDS surveys. We have not used it as an explicit input to our 2D inverse program, although it is used implicitly in the selection of a starting model. Following a suggestion by Edwards, we will examine the possibility of modifying the program to use the Tipper explicitly, both alone and in conjunction with the present inputs.

The joint inversion concept was applied to MT and Schlumberger measurements over a horizontally layered, anisotropic medium, following up a suggestion by G.V. Keller. Both the horizontal and the vertical conductivity elements are found this way (Jupp and Vozoff, 1977b).

The partial derivatives of apparent resistivity (and phase) with respect to the parameters of models indicate how 'visible' those parameters are in a particular set of measurements. More specifically, in the Jacobian matrix, if the eigenvalue that corresponds to a particular parameter is large, then the parameter in the particular model must be well resolved. This property can be used to evaluate the likely effectiveness of a geophysical survey in detecting a particular target, and to study the effects of altering survey parameters such as type of measurement, site location, measurement precision, frequency range, etc. It applies to any geophysical measurement in which the Jacobian can be calculated, including EM and d.c. resistivity. The concept was used to evaluate techniques for detecting possible conductivity changes within the resistive deep crust and upper mantle. It was found that, in an exposed shield area, MT measurements alone can detect a change, but the resolution was improved by adding a few large-spacing d.c. measurements as well. However, in the presence of a modest cover of conductive sediments, the d.c. data were incapable of adding information (Vozoff and Jupp, 1977). The methods should enhance the economic effectiveness of geophysics in the future, especially in large surveys. A major complication is the fact that the problem is non-linear. A change in any one parameter, especially one which is well-resolved, changes the resolution estimates of all. Therefore, it is important that the model is reasonably correct.

Finally, I would like to mention a new development which has succeeded in reducing drastically the scatter in MT apparent resistivities, phases, etc. Anav *et al.* (1976) proposed and built a system to improve the sensitivity of satellite magnetometers by arraying them in pairs, oriented in parallel directions. The power of those components in a frequency band of interest was calculated by multiplying the two signals, and then integrating the product. Thus the outputs of two parallel magnetometers after amplification and filtering are $v_1(t)$ and $v_2(t)$. Each contains a common signal $s(t)$ and noises $n_1(t)$ and $n_2(t)$. If the two noises are uncorreletaed, then the integrated product

$$w(t) = \frac{1}{\Delta T} \int_0^{\Delta T} v_1(t) v_2(t) \mathrm{d}t$$

will be independent of the noises provided ΔT is long enough. This gives a means of obtaining a power spectrum of the uncontaminated signal with magnetometers having relatively low sensitivity. In effect, the process is equivalent to synchronous detection, with each magnetometer providing the reference signal to the other.

Quite independently, Gamble *et al.* (1978 a, b) introduced this procedure to improve their magnetotelluric data for geothermal exploration, and provided a very thorough error analysis for the functions (ρ_a, etc.) derived from these data. Calling the usual impedance estimate Z^H and that using the remote reference Z^R,

$$Z^H = [EH]\,[HH]^{-1}$$

and

$$Z^R = [ER]\,[HR]^{-1}$$

where, for example, $[EH]$ is the determinant

$$\begin{vmatrix} E_x H_x^* & E_x H_y^* \\ E_y H_x^* & E_y H_y^* \end{vmatrix}$$

Twenty-eight hours of data were recorded at a pair of sites 4.8 km apart, in frequency bands extending from 0.01–50 Hz. Table I and Figure 10 show a comparison of the two processing techniques. The superiority of the new method is evident in all of the response functions.

TABLE I

Percent disagreement in apparent resistivities between bands.

Bands	Remote reference	Standard	No. of values compared
1,2	1.8	5.9	12
2,3	4.5	41.5	4
3,4	6.3	11.5	8

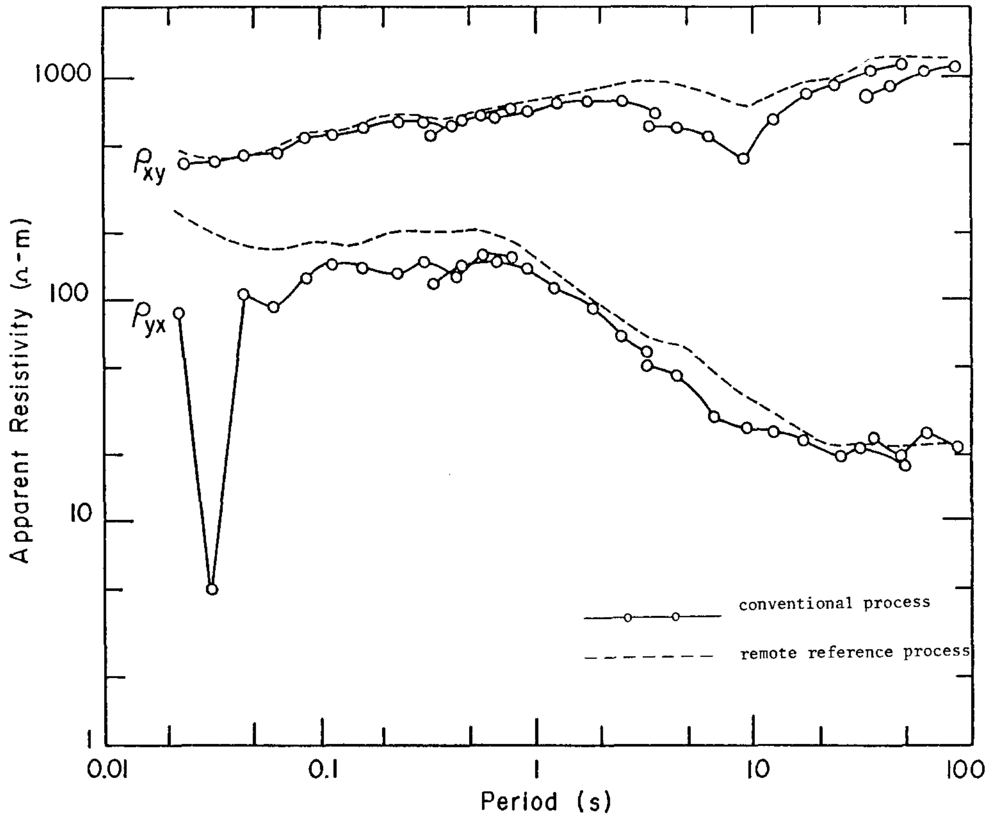

Fig. 10. Apparent resistivities, Upper La Gloria, with conventional processing (solid line) and remote reference processing (dashed line). (Gamble *et al.*, 1978).

Another useful byproduct of the remote reference method is an unbiased estimate of the noise in each channel. The scatter in conventionally-processed MT data is not well explained. It is often much larger than expected considering signal levels and equipment noises. Conventional processing gave a predicted E^P

$$E^P = Z^H H$$

but Z^H is biased downward by noise in either magnetic channel so the E^P are systematically low. Using Z^R instead,

$$E^P = Z^R H$$

and very nearly unbiased power spectral estimates of signals and noise can be calculated. These include the crosspowers between noises in the four data channels, which would indicate sources of noise. Figure 11 shows a pair of E signal and noise spectra.

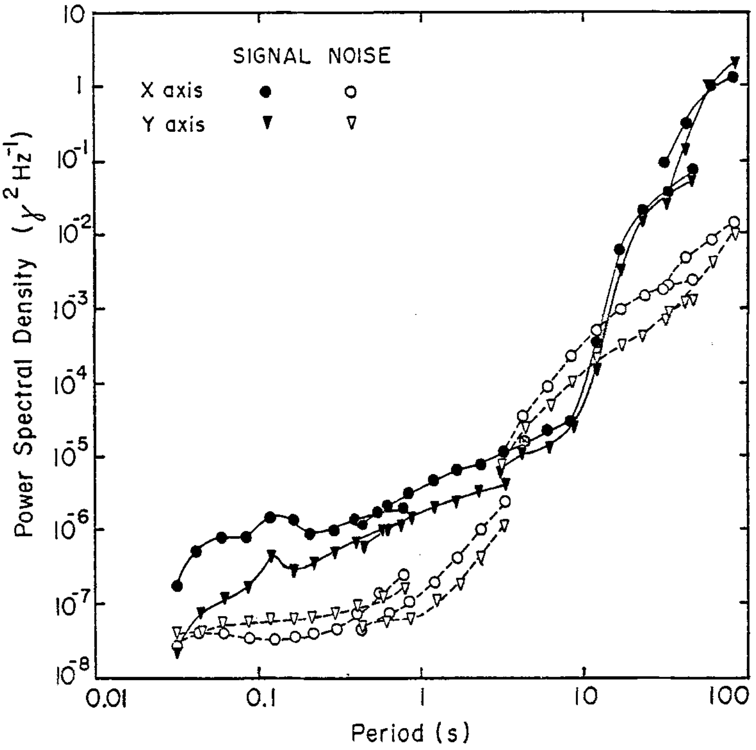

Fig. 11. Magnetic field signal and noise power density spectra for the remote reference signals used (Gamble *et al.*, 1978b). Note that apparent resistivities (Figure 10) are irregular at frequencies where noise exceeds signal, but the remote reference process is less affected than the conventional process.

The advantages to be had using a remote reference seem to be numerous in MT and other studies where random signals are contaminated by random noises. In MT surveys, the added cost of operating two sets of equipment is partly offset by using both for surveying. A common time base is provided, sometimes by radio telemetry and at other times by synchronous crystal clocks. It has not yet been determined how widely separated the two sites can be, although one experimental study is now in progress. Earlier studies of the spatial correlation of micropulsations are directly relevant. They suggest that for long periods, sites can be separated by hundreds of kilometers. The question is particularly important to AMT, in which field strength is often less than magnetometer noise in the 0.5–5 kHz band. Obviously, with data like this we will have to sharpen our interpretive skills.

5. Conclusions

In summary then, the development of EM methods in applied geophysics has been both active and diverse. In the traditional, low frequency, CW technology this has consisted of slow, steady progress in modeling numerically, and a potentially major development in cryogenic coil systems. In the newer area of transient applications, the most impressive results are coming from the use of seismic processing with earth-penetrating radar, and a rapid development of transient EM equipment, theory, and experience. The basic question, as to whether time or frequency is generally superior, may have no simple answer.

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