GEOPHYSICS, VOL. 55, NO. 9 (SEPTEMBER 1990); P. 1242–1250, 11 FIGS.

Transient electromagnetic inversion: A remedy for magnetotelluric static shifts

Louise Pellerin* and Gerald W. Hohmann*

ABSTRACT

Surficial bodies can severely distort magnetotelluric (MT) apparent resistivity data to arbitrarily low frequencies. This distortion, known as the MT static shift, is due to an electric field generated from boundary charges on surficial inhomogeneities, and persists throughout the entire MT recording range. Static shifts are manifested in the data as vertical, parallel shifts of log-log apparent resistivity sounding curves, the impedance phase being unaffected. Using a three-dimensional (3-D) numerical modeling algorithm, simulated MT data with finite length electrode arrays are generated. Significant static shifts are produced in this simulation; however, for some geometries they are impossible to identify.

Techniques such as spatial averaging and electromagnetic array profiling (EMAP) are effective in removing static shifts, but they are expensive, especially for correcting a previously collected MT data set. Parametric representation and use of a single invariant quantity, such as the impedance tensor determinant, are only useful in limited circumstances and can lead the MT interpreter astray. Transient electromagnetic (TEM) sounding data are relatively inexpensive to collect, do not involve electric field measurements, and are only affected at very early times by surficial bodies. Hence, using TEM data acquired at the same location provides a natural remedy for the MT static shift.

We describe a correction scheme to shift distorted MT curves to their correct values based on 1-D inversion of a TEM sounding taken at the same location as the MT site. From this estimated 1-D resistivity structure an MT sounding is computed at frequencies on the order of 1 Hz and higher. The observed MT curves are then shifted to the position of the computed curve, thus eliminating static shifts. This scheme is accurate when the overlap region between the MT and TEM sounding is 1-D, but helpful information can be gleaned even in multidimensional environments. Other advantages of this scheme are that it is straightforward to ascertain if the correction scheme is being accurately applied and it is easy to implement on a personal computer.

INTRODUCTION

The magnetotelluric (MT) method is an important exploration technique for investigations of deep resistivity structures within the earth (Swift, 1967; Vozoff, 1972; Berdichevsky et al., 1980; Wannamaker, 1983). However, to obtain an accurate interpretation of MT data, care must be taken to account for effects of boundary charges—galvanic effects—on two- and three- dimensional (2-D and 3-D) bodies (Park et al., 1983; Wannamaker et al., 1984b; Park, 1985). The effect of boundary charges persists to arbitrarily low frequencies, causing distortion of the MT apparent resistivity sounding curve over a wide range of frequencies.

Inhomogeneities large enough to produce a frequency-dependent response within the MT recording range can be recognized by the anisotropy of the polarization modes in both apparent resistivity and phase sounding data. Such bodies are often the target of an MT survey and should be modeled as part of the interpretation. A small, shallow body, however, may have a galvanic response that is essentially independent of frequency within the range of an MT sounding (Berdichevsky and Dmitriev, 1976). This galvanic response of a small body, called the MT static shift, is manifested in the data as a vertical, parallel shift of the log-log apparent resistivity sounding curves, the impedance phase being unaffected.

For a layered earth the XY (electric field parallel to the x-axis) and YX (electric field parallel to the y-axis) polarization modes

Manuscript received by the Editor March 21, 1989; revised manuscript received March 26, 1990.
*Department of Geology and Geophysics, University of Utah, Salt Lake City, UT 84112-1183.
©1990 Society of Exploration Geophysicists. All rights reserved.

are identical, because the only conductivity boundaries are in the vertical direction. Thus if two measured apparent resistivity sounding curves have the same shape but exhibit a vertical, parallel displacement, they are probably affected by a surficial body. A static shift in data taken over a 3-D structure at depth is not as easy to identify; the apparent resistivity sounding curves for the two polarization modes are parallel not to each other but to the unshifted curves associated with a 3-D earth not containing a small-scale, surficial body.

This common distortion (Berdichevsky and Dmitriev, 1976; Sternberg et al., 1988) can be severe although quite difficult to recognize in data, and hence can lead to erroneous interpretations. Layered-earth inversion of an apparent resistivity sounding curve depressed by the galvanic response of a surficial body will indicate layers that are too shallow and too conductive. Conversely, 1-D inversion of a curve elevated by the galvanic response of a surficial body will indicate layers erroneously deep and resistive. Hence static shifts must be removed before accurate interpretations of deep structures can be made.

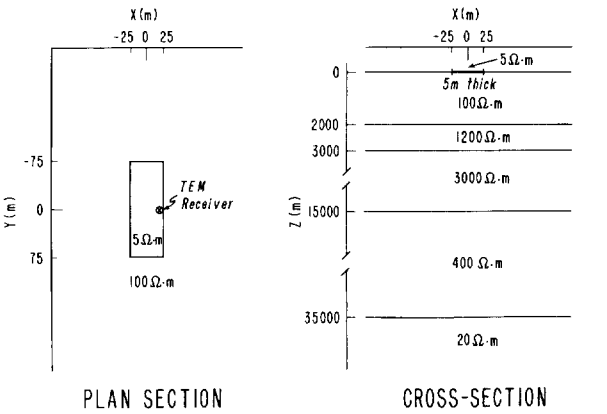


FIG. 1. Geometry of model 1. A small (50 m × 150 m × 5 m), conductive, surficial inhomogeneity in a layered earth. The plan view shows the central-loop TEM receiver position used in the study. Note the thickness of the surficial body relative to the layered earth in the cross-section.

We propose an effective scheme for shifting a distorted MT curve to the correct curve, which is given by computing the MT response of a shallow, 1-D model based upon inversion of a central-loop transient electromagnetic (TEM) sounding. This study complements the work of Sternberg et al. (1988): an empirically based study that directly compares MT and TEM sounding data or employs a 1-D MT-TEM joint inversion. In our scheme TEM sounding data are transformed into MT sounding data, thus eliminating direct comparison of data from two different EM techniques. To examine our correction method, a 3-D model study is presented along with a field example.

THE MAGNETOTELLURIC STATIC SHIFT

We computed the MT responses of 3-D bodies in a layered earth using the integral-equation algorithm of Wannamaker et al. (1984a), which is an extension of the work by Ting and Hohmann (1981). Problems, such as numerical inaccuracies, can be encountered when this algorithm is used for outcropping bodies. Judicious model design is necessary to avoid these problems. Criteria relating to smoothness, symmetry, and agreement with 2-D results were applied to apparent resistivity profiles to determine the body discretization and receiver positioning that give the most accurate results. We determined that discretization of the surficial 3-D body of model 1 (Figure 1) into cubic cells, 5 m on a side with receivers located only on interior cell corners, best satisfied the criteria.

Models presented were designed with two important points in mind. First, integral equation solutions to 3-D EM problems are computationally demanding. Therefore, to use available computer time most efficiently, models were designed to exploit symmetry. Second, simple models, designed to isolate particular effects, such as the static shift, increase physical and interpretational intuition. Complicated models make it difficult to separate various causes and effects. The models in this study were designed explicitly to illustrate the effects of near-surface inhomogeneities. It is also important to address scaling when applying this study to specific data sets. A body of a certain size at a particular depth may cause a static shift distortion in one survey, while being a target in another survey. Therefore, a model and frequency range were chosen to illustrate relevant points, not to cover all possible cases. It is up to the MT interpreter to extend this study to his or her specific survey requirements.

The first model presented is that of a surficial, conductive patch in a 1-D earth (Figure 1). The cross-section illustrates how thin the surficial body is relative to the layered-earth structure. The 1-D earth was taken to represent layering in the northern Basin and Range province of the western United States (Wannamaker, 1983). The conductive patch, which could represent a zone of alluvium, has a moderate resistivity contrast of 1:20 with the host layer and exhibits a frequency-independent response over the entire MT frequency range.

Point receivers do not accurately simulate the electric field components measured in an MT survey. In practice electric field values are obtained by measuring the voltage between two electrodes and dividing by the separation distance — typically 100 m or more. The magnetic field is essentially measured at a point. For accurate simulation of electric field quantities, we use electric field values that are the average of evenly spaced (10 m spacing) point receivers along the dipole length. Points averaged along the x-directed dipole are used to compute MT results for the XY polarization mode and along the y-directed line for the YX mode. Accordingly, the impedance tensor is computed with averaged electric field values and point magnetic field values. Impedance rotation is not considered because the dipoles are already parallel and perpendicular to boundaries of the 3-D structure.

The relationship between dipole length and the depth and size of resistivity structures is a key concept in electromagnetic array profiling (EMAP) (Torres-Verdin and Bostick, 1990), where spatial filtering is a function of dipole length. In a conventional MT survey, electrode separations are fixed and there is no spatial filter, but it is illustrative to study the effect of dipole length on the response of a surficial body.

Figure 2 shows apparent resistivity sounding curves for the XY mode computed near the end of the body (y = 70 m) with electrode separations varying from less than one-half to four times the width of the body. Dipole lengths and electrode locations are depicted in Figure 2. Soundings (not shown) were also computed across the middle of the body (y = 0 m) and outside the body (y = 80 m) with essentially the same results. For dipoles completely within the body, significant static shifts are produced.

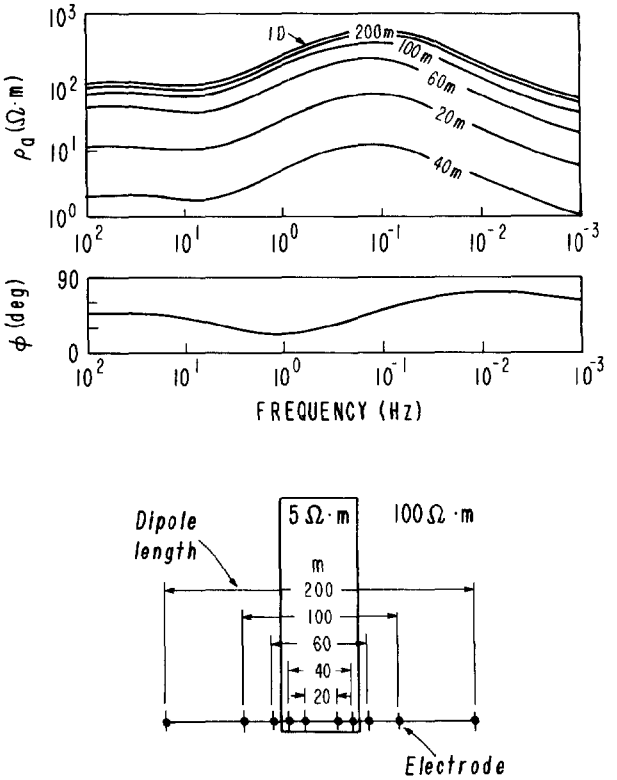


FIG. 2. The effect of dipole length on static shifts as illustrated by a suite of apparent resistivity sounding curves. The soundings for five dipoles, with lengths varying from 20 m (less than half the width of the body) to 200 m (four times the width of the body), are computed near the edge (y = 70 m) of the surficial body of model 1. The phase sounding curves for each dipole length are also shown.

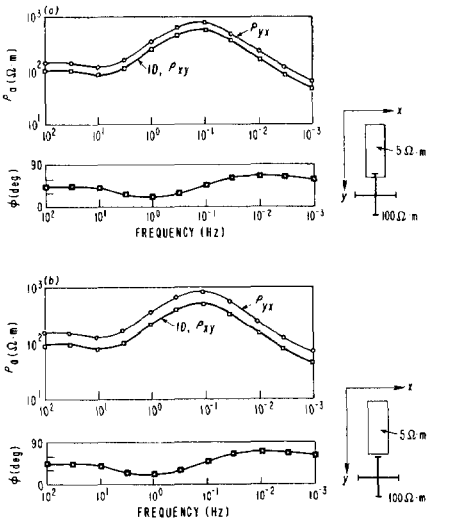


FIG. 3. MT sounding curves for model 1 for two different electrode array locations. (a) One electrode inside the surficial body and a static shift of one-eighth the decade is produced. (b) One electrode near, but outside, the body produces an equivalent shift.

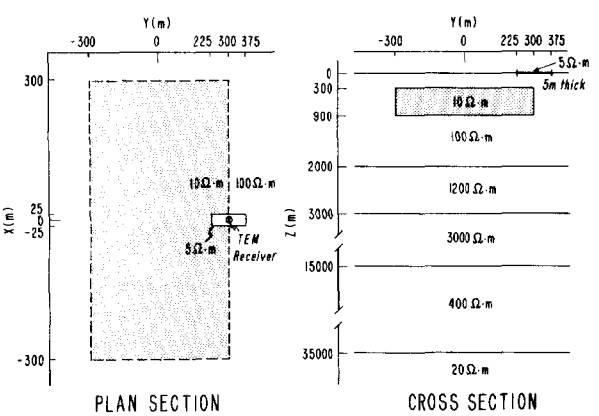


FIG. 4. Geometry for model 2. A conductive, surficial inhomogeneity and a large, buried 3-D body in a layered earth. The layered earth and surficial body are as in model 1 (Figure 1). The stippled area represents a 10 Ω•m body embedded in the top 100 Ω•m layer. The central-loop TEM receiver location is centered on the surficial body.

Once the dipole length is greater than the body width, the shift is roughly halved as the dipole length is doubled. The static shift is slight (less than one-tenth of a decade) once the dipole length is four times the width of the body. Even though a dipole array will not be centered on a surficial body, but will cross it arbitrarily, this exercise gives insight into the sensitivity of MT to a surficial inhomogeneity.

Various dipole array configurations and locations were computed for model 1. Soundings computed for 100 m X electrode configurations at two locations are presented; the array location is depicted on each figure. An X array is laid out with five electrodes: $+x$, $-x$, $+y$, $-y$, and a common ground. Figure 3a shows a static shift is produced when just one electrode is inside a surficial body. Figure 3b demonstrates that just one electrode near a boundary, but not inside the inhomogeneity, can result in a static shift. These shifts are slight and may not seriously distort an interpretation, but the resistivity contrasts in this study are moderate and in a survey much higher contrasts can be encountered, resulting in misinterpretation.

Our second model is the same as the first except that a large 10 Ω•m body is embedded in the top 100 Ω•m layer, as shown in both plan view and cross-section in Figure 4. Figures 5a and 5b illustrate the deceptive nature of the static shift distortion. The MT interpreter could be deceived easily by the sounding curves of Figure 5a. The YX and XY apparent resistivity sounding curves (denoted by circles and squares, respectively) are not parallel and the phase data are not identical from 100 to 1 Hz, indicating an inductive response from a deeper 2-D or 3-D structure (Wannamaker et al., 1984b). From the apparent resistivity sounding curves it would appear that the curves for the two polarization modes converge at frequencies above the recording range. Therefore, the interpreter might assume that no shifts are present. Comparison of the distorted and undistorted responses, however, shows that a static shift of one-quarter decade in the XY mode and one-eighth decade in the YX mode are present. In contrast, Figure 5b clearly shows a divergence of the two curves at high frequencies. In this case static shifts of one-quarter decade or more would be present even if the curves were brought into agreement at high frequency.

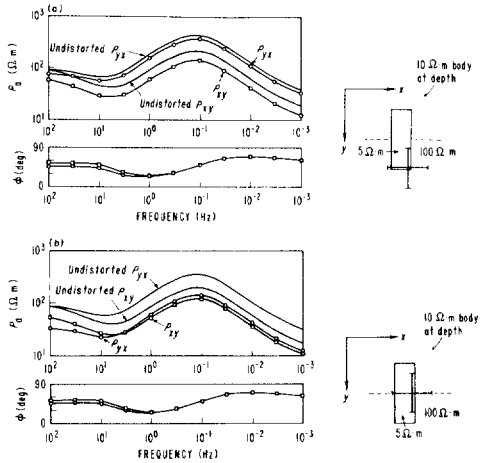


FIG. 5. MT sounding curves for model 2 (Figure 4) using a 100 m X array as shown. The distorted YX and XY polarization modes of the apparent resistivity and phase data are denoted by circles and squares, respectively. Curves labeled undistorted XY and undistorted YX represent the unshifted response for the two polarization modes. (a) The curves seem to be converging at high frequencies, masking a static shift. (b) The curves are diverging at high frequencies, indicating a possible shift.

REMEDIES FOR THE MT STATIC SHIFT

Review of techniques for correcting static shifts

Static shifts must be removed or taken into account during interpretation. Detailed modeling of near-surface inhomogeneities is not practical, because 3-D computations rapidly become prohibitive in memory and cost, and not enough data are available. Even for 2-D structures, where more efficient modeling algorithms can be applied, the interpreter does not know whether or how the curves are distorted by static shifts.

Spatial averaging of MT soundings has been used (Berdichevsky et al., 1980; Sternberg et al., 1988) with some success to correct static shifts, but high station densities necessary for such filtering make this costly. Another filtering scheme, EMAP (Torres-Verdin and Bostick, 1990), is a low-pass, spatial-filtering technique that uses continuous electric-field measurements along a profile perpendicular to geoelectric strike; the filter length is on the order of a skin depth for each frequency. EMAP, which has successfully eliminated 3-D static effects due to surficial inhomogeneities, is similar to MT in that both employ the same natural source and operate in the same frequency range. However, the differences in field operation and data processing are significant enough for the two methods to be considered distinct. EMAP, a relatively expensive technique, is presently used for detailed surveys and would not be employed merely to correct previously collected MT data.

Static-shift correction methods that do not require collecting additional data are appealing because they are less expensive and can be employed for conventional MT data. For an MT profile with a characteristic layer at depth, parametric representation (Jones, 1987) can be applied. Unfortunately, not all survey areas contain such a layer and the resistivity of the layer may vary laterally so that this technique is applicable only in a limited number of cases.

Use of a single, invariant quantity, such as the impedance tensor determinant, is gaining popularity as a means of correcting for galvanic effects, but this technique can easily lead to inaccurate interpretations (Park and Livelybrooks, 1989). The aim of a static-shift correction is to remove the effects of surficial bodies, whereas use of single, invariant quantities is a way of attaining a curve for 1-D interpretation in the face of 2-D or 3-D effects. Invariant quantities only remove static shifts in very specific situations, e.g., outside a body where one mode is depressed and the other is equally elevated, but the dipole array location relative to a near-surface heterogeneity is usually not known.

Electric field measurements are responsible for the static shift, so it is natural to consider geophysical techniques that only measure the magnetic field as a means to correct MT data. Case histories (Andrieux and Wightman, 1984; Sternberg et al., 1988) have shown TEM soundings to be quite effective in this respect. We believe the central-loop TEM sounding technique is best suited to correct MT static shifts, because it is less sensitive to lateral resistivity variations than are other TEM configurations (Spies, 1980).

Central-loop TEM inversion correction technique

Sternberg et al. (1988) compare central-loop TEM sounding data to MT sounding curves after multiplying the reciprocal of time in milliseconds by a conversion factor of 200 to obtain an equivalent frequency. This is a fast and easy field technique, but problems can be encountered when directly comparing apparent resistivity quantities (Spies and Eggers, 1986). Also proposed in their study is use of a joint 1-D inversion of the TEM and E-polarization MT sounding curves, in which a shift factor adjusts for the MT static shift distortion.

The correction scheme proposed here transforms TEM sounding data into 1-D MT sounding data for responses due to shallow structures. It is an efficient, straightforward means of correcting MT static shifts based on 1-D inversion of central-loop TEM soundings. The estimated geoelectric structure resulting from the TEM inversion is used to compute a 1-D MT response at high frequencies. This computed MT response is then a reference to which the distorted MT apparent resistivity sounding curves can be shifted. This scheme differs from that of Sternberg et al. (1988) in two important ways: (1) there is no direct comparison of two different data sets, which are difficult to match if the curves are steep; and (2) it is not a prerequisite to pick the appropriate polarization mode from the two MT curves for joint 1-D inversion.

We computed TEM responses for MT models 1 and 2 using the 3-D integral equation algorithm of Newman et al. (1986), which is based upon the work of Wannamaker et al. (1984a) and Ting and Hohmann (1981). With this algorithm, field values are computed in the frequency domain and then transformed to the time domain. To ensure accuracy of the time-domain transformation, we used 36 frequencies ranging from 100 000 to 0.01 Hz. Model 2, with 194 cells comprising the two bodies, took approximately 9 minutes per frequency to compute on a Cray X-MP 48 supercomputer with one processor and used about three megawords of memory (all that was available at the time).

Transient EM, vertical magnetic field sounding data were inverted using an approximate technique developed by Eaton and Hohmann (1989) and based on a scheme proposed by MacNae

and Lamontagne (1987). This technique is based on tracking a descending image of the transmitting loop; the resulting estimated resistivity structure is a continuous function of depth. Although any TEM inversion routine can be used for this correction scheme, we chose the image solution because it is computationally rapid, is not influenced by a starting model, provides meaningful interpretations even when the data are contaminated by noise, and is less biased by 3-D effects than conventional layered-earth model fitting routines using constrained nonlinear optimization (Eaton and Hohmann, 1989).

Raiche (1983) and Spies and Eggers (1986) show that apparent resistivities defined from measurements of the time derivative of the vertical magnetic field (i.e., voltage) can be nonexistent or multivalued, whereas the relationship between the vertical magnetic field and apparent resistivity is one-to-one. Hence, apparent resistivities are computed using an iterative solution to the nonlinear equation for a vertical magnetic field at the center of a horizontal loop over a half-space derived in Ward and Hohmann (1988).

No interpretation schemes can be applied blindly. For this correction scheme to be accurate, the following criteria must be met. (1) The MT sounding data (both collected and computed from the TEM inversion) should display a 1-D response, i.e., the apparent resistivity curves should be parallel and the phase values at each frequency should be the same, at appropriately high frequencies. (2) This high-frequency band, determined by the minimum depth of penetration of the MT sounding and the maximum penetration depth of the TEM sounding, must be wide enough to estimate the shallow structure adequately. If these criteria are not met, however, helpful information can still be obtained by implementing this correction scheme.

Application in a 1-D earth.—Figure 6a shows the central loop TEM apparent resistivity sounding curve computed for model 1 (Figure 1). For purposes of illustration the theoretical TEM time range is extended to include the response of the surficial body. From 10^{-6} to 10^{-5} s the apparent resistivity curve of Figure 6a indicates a response from a conductive structure. Clearly, there is a time-dependent vertical magnetic field response of a surficial body.

The smooth curve in Figure 6b, which is the estimated resistivity based on the TEM inversion, determines the geoelectric structure from which the correct MT curve at high frequencies is computed. The resistivity for the true structure is plotted as a stepwise curve for comparison. The continuous 1-D curve was discretized into six layers, as noted by the dashed lines, to compute the corresponding MT response.

Figure 7 shows the computed MT curve (dotted) along with the undistorted (1-D) response (solid) and the distorted curves for both polarization modes (*XY* mode denoted by squares and the *YX* mode by circles) computed for the *X* electrode array located as shown. If the two distorted curves are shifted to match the computed one, the data are ready for distortion-free interpretation.

Model 1 is a best-case example for the correction scheme. The high-frequency ends of the MT sounding curves (Figure 7) are flat, a situation where the correction scheme works best, because the shallow resistivity structure can be accurately estimated with most inversion routines. Inspection of the MT sounding curves reveals that the apparent resistivity curves are exactly parallel and the two phase curves are identical, indicating a 1-D earth with a shallow inhomogeneity. Further evidence of the accuracy of the correction scheme is given in the close fit, with respect to shape, of the computed MT curve and the distorted curves for both modes. The fact that the three curves are parallel indicates that the computed curve from the TEM model is responding to the same 1-D earth as are the distorted MT curves.

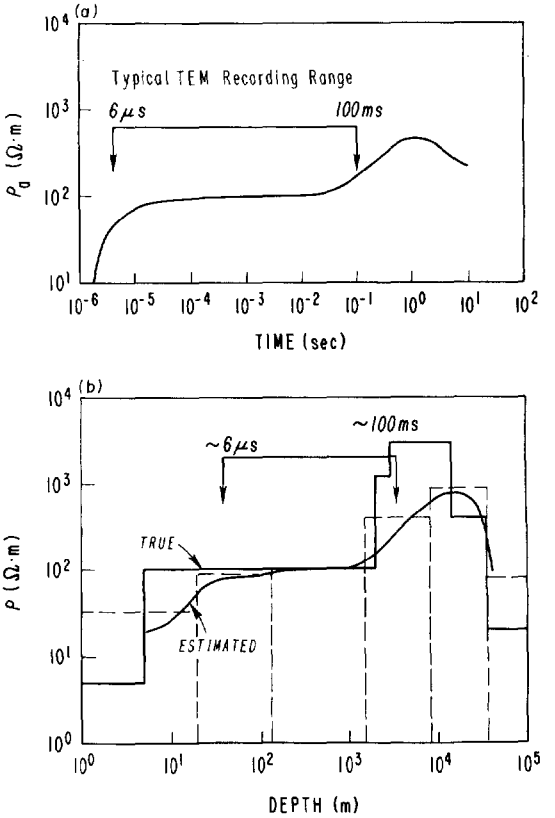


FIG. 6. Central-loop TEM apparent resistivity and image inversion for model 1. (a) The receiver is located on the surficial body as in Figure 1. The square transmitting loop is 250 m on a side. Arrows show typical recording range. (b) The estimated resistivity structure is depicted by the smooth, continuous curve labeled "estimated." The resistivity of the actual geoelectric structure is labeled "true." The discretization used to compute the 1-D MT response is denoted by dashed lines. The depth of investigation for a typical recording range is also noted.

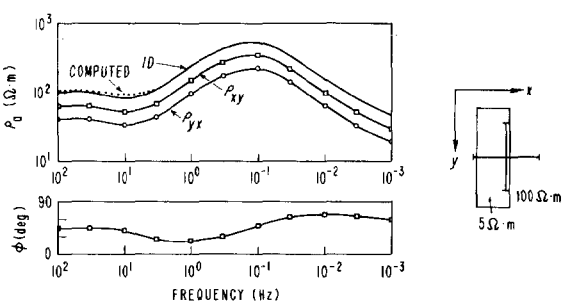


FIG. 7. MT apparent resistivity and phase sounding curves for model 1 (Figure 1), using an *X* electrode array located as shown. The figure includes the undistorted, 1-D response (solid line) curves for the *XY* and *YX* polarization modes for the distorted case denoted by squares and circles, respectively, and the computed correction curve (dotted line) to which the distorted ones are shifted.

For the 1-D inversion to be accurate, the distorted and computed MT curves should be parallel over an appropriate frequency range. This range is determined by the overlap between the minimum depth of investigation of the MT sounding and the maximum depth of penetration of the TEM sounding. Spies (1989) gives a detailed explanation of the depth of investigation for EM systems. Specifically pertinent to this study, he analyzes the investigation zones of MT and central-loop TEM soundings. MT depth of investigation is proportional to the square root of resistivity while that for TEM varies depending on whether magnetic fields or voltages are being measured and whether or not measurements are taken in the near zone (induction number greater than unity) or far zone (induction number less than 0.1).

Sternberg et al. (1988) provide a rule of thumb, based upon depth of investigation considerations, for determining MT and TEM recording equivalences, i.e., equating frequency with the reciprocal of time:

$$f\,(\mathrm{Hz}) \approx \frac{194}{t\,(\mathrm{ms})}\ .$$

Thus a TEM sounding recorded to a latest time window of 100 ms overlaps the MT sounding for frequencies above 2 Hz. Below 2 Hz the computed curve becomes the response of the basal half-space of the estimated TEM structure.

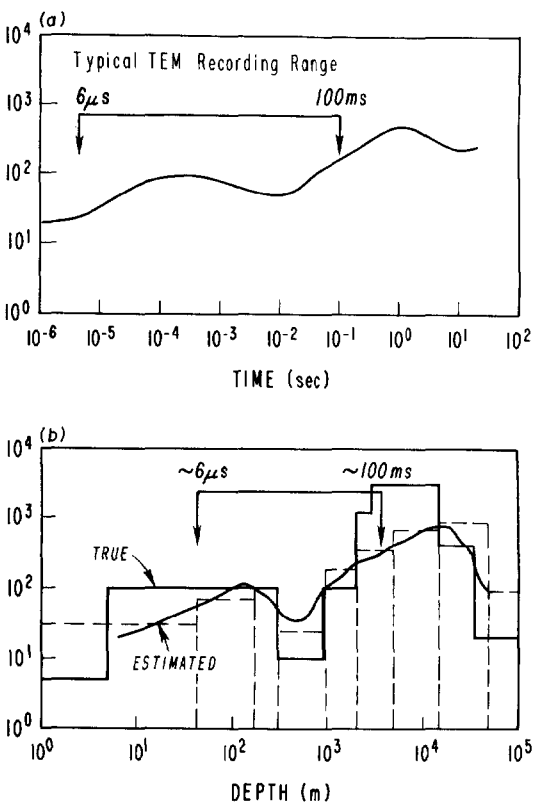


FIG. 8, Central-loop TEM apparent resistivity sounding curve and image inversion of model 2. (a) The receiver is centered on the surficial body as in Figure 4. The square transmitting loop is 250 m on a side. Arrows show typical TEM recording range of 6 μs to 100 ms. (b) The estimated resistivity structure is depicted by the smooth, continuous curve labeled "estimated." The resistivity of the actual geoelectric structure is labeled "true." The dashed lines denote the discretization used to compute the 1-D MT response. The depth of investigation for a typical recording range is also noted.

Application in a 3-D earth.—Figure 8a shows the TEM apparent resistivity sounding curve for model 2. The square transmitting loop is 250 m on a side with the receiver centered on the surficial body as shown in Figure 4. A recording range to 100 ms includes the response of the conductive body at depth. Figure 8b shows the corresponding image inversion. The actual resistivity structure is labeled true while the estimated curve is the result of the image inversion. The dashed lines show the discretization used to obtain the MT layered-earth response.

Figure 9, which illustrates the use of the correction scheme in a 3-D environment, contains five MT sounding curves as follows: the curve computed from the shallow, TEM-estimated, geoelectric structure (dotted line); the undistorted 3-D response of the model for both polarization modes (solid lines); and the XY and YX curves (solid lines with squares and circles, respectively) distorted by a conductive, surficial patch. Concentrating on the undistorted curves first, we see that the apparent resistivity curves are not parallel and the phase curves are not identical for the first one and one-half decades, indicating a 2-D or 3-D response within the MT recording range that should be modeled in the interpretation. Note that the distorted YX apparent resistivity curve is parallel to the undistorted YX apparent resistivity curve and similarly for the XY mode, i.e., a static shift is present. Shifting the distorted curves to the position of the undistorted curves removes the static shift, but not the 3-D response. The 3-D body is the target of the interpretation, and we do not want

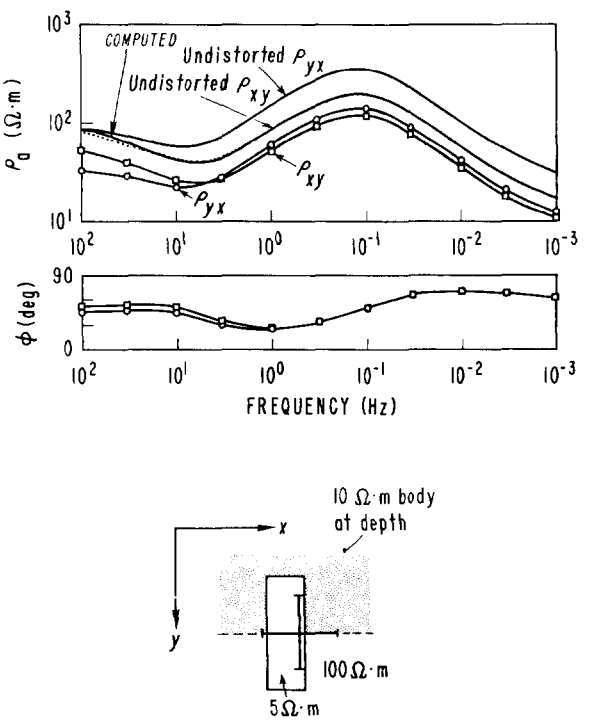


FIG. 9. MT apparent resistivity and phase sounding curves for model 2 (Figure 4), using an X electrode array located as shown. The figure includes the undistorted responses for two polarization modes (solid lines labeled undistorted XY and undistorted YX), curves for the XY and YX polarization modes for the distorted case denoted by squares and circles, respectively, and the computed correction curve (dotted line labeled computed) to which the distorted ones are shifted.

to remove or distort its response. The divergence of the distorted apparent resistivity curves at high frequencies alerts the MT interpreter that a static shift could be present and should be removed before interpretation commences.

The good fit of the distorted XY polarization curve with the computed curve (Figure 9) makes it so easy to see where to shift this mode. The question is what to do with the other mode. In this case, shifting the YX mode to attain convergence at 100 Hz would be the correct solution, but this would not necessarily be so. The correction scheme is not reliable here, because within the MT-TEM overlap the curves of interest are not parallel. Therefore, the MT-TEM overlap region cannot be considered 1-D as required by the correction scheme. However, the computed curve based on the TEM model follows the true apparent resistivity curve for the XY mode very closely. This is because for a receiver station centered along an elongated body (strike in the x direction), the XY mode is an approximation of the 2-D transverse electric (TE) polarization mode. If the survey area were not approximately 2-D, all three curves would have different shapes. The TE mode is often used for 1-D interpretation, because it is not affected by boundary charges. In general the earth is a 3-D environment and both modes are affected by boundary charges, but the TEM data can help determine if a 2-D approximation is valid and which curve approximates the TE mode.

If the highest recorded frequency were 3 Hz, a static shift might be considered negligible or, given a reasonable amount of data scatter, nonexistent. The problem of applying the correction scheme here is that there is not enough overlap between the MT and TEM sounding ranges to determine accurately if the criteria for the correction scheme are being met. Even with such limited information, however, the computed MT curve reveals a static shift that might otherwise have gone unnoticed.

Effect of transmitting-loop size.—Figure 10a shows a suite of simulated TEM central-loop soundings using square transmitting loops, 50 m, 125 m, 250 m, and 500 m on a side, and centered on the surficial body of model 2. Loop size has an effect because at early times the system responds to a relatively small volume of ground, mostly within the transmitting loop, and hence is sensitive to shallow features. Figure 10b shows the estimated geoelectric structure for these four loop sizes along with the true resistivity structure. The presence of the small surficial body did not significantly bias the inversion results for depths greater than 100 m, even for a small transmitting loop. Therefore, small TEM transmitting loops can be used to correct MT static shifts if adequate depth of investigation is attained.

As pointed out by Spies (1989), TEM depth of investigation is a function of transmitter geometry for magnetic field measurements and of transmitter geometry and conductivity for voltage measurements. Thus loop size needs to be taken into account if the TEM survey is being designed specifically to correct an MT survey. Sternberg et al. (1988) empirically determined that a transmitting-loop size of 250 m was appropriate for correcting regional MT surveys in terrain as varied as the Basin and Range, High Lava Plains and the Cascade Mountain Range, but Spies shows that much smaller loops can be used in conductive areas.

Where static shifts are introduced by topography, the TEM remedy should work as long as variations in transmitting- and receiving-loop sizes are taken into account.

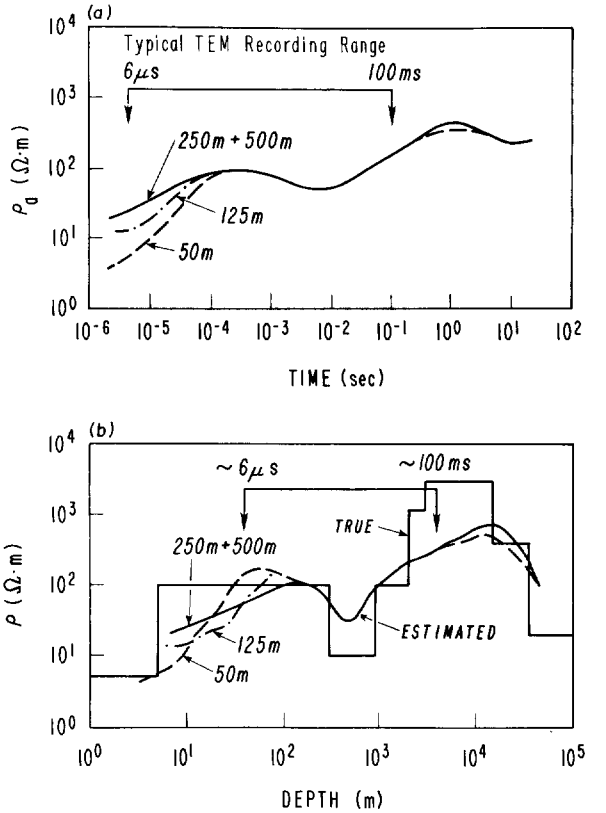


FIG. 10. Central-loop TEM apparent resistivity sounding curves and image inversion for model 2 using four transmitting-loop sizes: 50 m, 125 m, 250 m, and 500 m on a side. (a) Receiver is centered on the surficial body as in Figure 4. The 50 m loop sounding is depicted by a dashed line and the 125 m loop sounding by a dot-dashed line. The 250 m and 500 m loop soundings, being indistinguishable, are denoted by a solid line. The 6 μs to 100 ms TEM recording range is marked on the figure. (b) The actual resistivity structure is labeled true. The estimated geoelectric structures denoted by the smooth dashed, dot-dashed, and solid curves are for the 50 m, 125 m, and 250 m, and 500 m loop soundings, respectively. Note that within the depth of investigation, estimated from the recording range, the inversion is unaffected by the transmitting-loop size.

Field example.—We have used a model study to examine the validity of the correction scheme, but correction of field data is the ultimate application of any method. Figure 11 shows MT sounding data collected in Long Valley, California, with a remote-reference MT system. The apparent resistivity values, denoted by circles for the YX polarization mode and squares for the XY mode, display approximately one-half decade of a vertical, parallel, frequency-independent separation. At each frequency the value of the phase data for the two polarization modes is the same, within the data scatter. Thus this sounding is an excellent candidate for the correction scheme. Geonics EM37, central-loop TEM sounding data collected by The Earth Technology Corp. in the vicinity of the MT array were made available by Unocal Corp. to test the correction scheme.

As with the synthetic data, we computed TEM inversion results with the image technique, and then discretized the continuous resistivity estimate to compute an MT layered-earth

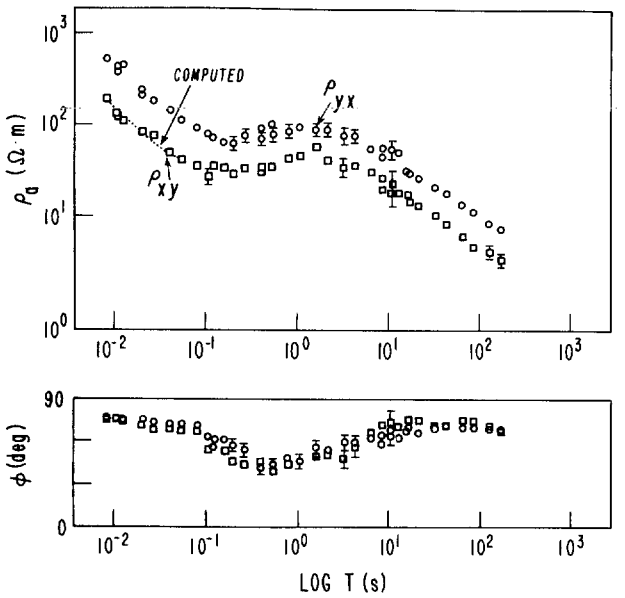


FIG. 11. MT field example of distorted apparent resistivity sounding curve with the computed apparent resistivity curve (dotted line) for shifting the distorted data to the correct value. Impedance phase is also shown. The *XY* and *YX* polarization modes are denoted by squares and circles, respectively. Data were collected in Long Valley, California, with the University of Utah remote reference MT system. The computed curve is based upon the 1-D image inversion of central-loop EM37 data.

response. We also used a TEM layered-earth inversion computed previously. Due to a structure that varied rapidly (steep apparent resistivity curve) at high frequencies and a model with two few layers, the computed MT sounding curve resulting from this layered earth inversion did not fit the MT field data. Inversion with the image technique more accurately estimated the structure, as is apparent in the good fit of the MT data and computed curve (dotted). Figure 11 shows that the computed curve provides adequate overlap—approximately one decade—with the distorted curves. In the overlap frequency range all three curves have the same shape and are parallel; therefore, the corrected curves should be accurate. Furthermore, other MT soundings without static shifts as well as other TEM inversions in the same area show apparent resistivities similar to the computed curve.

CONCLUSIONS

Surficial inhomogeneities cause static shifts of MT apparent resistivity sounding curves. Such shifts are ubiquitous but can be difficult to identify in the data. Realistic modeling of shifted responses using electrode arrays of finite length illustrates that severe static shifts can occur with finite-length dipoles. Interpreting data that have not been corrected for static shifts can lead to erroneous results; therefore, some correction scheme must be applied. An effective correction scheme employs an additional data set that does not use electric field measurements, specifically TEM central-loop soundings as in our study.

The scheme proposed—of inverting TEM soundings and then computing the MT response of the estimated, shallow, geoelectric structure to attain a reference curve at high frequencies to which the distorted MT sounding can be shifted—has advantages over other correction methods reviewed. TEM data are relatively easy and inexpensive to collect and can be collected before, during, or after an MT survey. The TEM data are transformed into MT data instead of directly comparing the two distinct data sets. Also the computer programs for 1-D TEM inversion and 1-D forward MT computation can be implemented on a personal computer, so that the data can be corrected in the field.

The reliability of the scheme for a particular case is easily determined by the fit of the computed MT curve with the shifted data. For the 1-D case, all three curves will be parallel and the scheme will accurately correct the data. If the curves are not parallel within the specified frequency range, 2-D or 3-D effects are present. Unfortunately, the tools available for 3-D interpretation are extremely limited and 1-D techniques are not sufficient for an accurate 3-D interpretation. Implementation of this correction scheme, however, can increase the interpreter's insight by ascertaining if a static shift is present and if the survey area is approximately 2-D. For a 2-D environment the TEM data can identify which mode should be used for a first-pass 1-D interpretation on which a 2-D interpretation can be built.

ACKNOWLEDGMENTS

We are grateful for the valuable suggestions of our colleagues Jeffery M. Johnston, John A. Stodt, Philip E. Wannamaker, and Stanley H. Ward and reviewers Steve K. Park and Brian R. Spies. Constructive criticism and financial support were provided by the University of Utah EM Modeling Consortium, which includes Amoco Production Co., ARCO Oil and Gas Co., BHP/Utah International, Chevron Resources Co., CRA Exploration Pty. Ltd., and Unocal Corp. In particular, we would like to thank Unocal Corp. for supplying data to test the correction scheme. Bob Wheeler of the Howard Hughes Medical Institute developed the graphics software used to present these results. Time on the San Diego Supercomputer Center Cray X-MP/48 supercomputer was funded by the National Science Foundation.

REFERENCES

Andrieux, P., and Wightman, W. E., 1984, The so-called static correction in magnetotelluric measurements: Presented at the 54th Ann. Mtg. and Expos., Soc. Explor. Geophys.

Berdichevsky, M. N., and Dmitriev, V. I., 1976, Distortion of magnetic and electric fields by near-surface lateral inhomogeneities: Acta Grodaet. Geophys. et Mantanist. Acad. Sci. Hung., **11**, 447–221.

Berdichevsky, M. N., Vanyan, L. L., Kuznetsov, V. A., Levadny, V. T., Mandelbaum, M. M., Nechaeva, G. P., Okulessky, B. A., Shilosky, P. P., and Shpak, I. P., 1980, Geoelectrical model of the Baikal region: Phys. Earth Plan. Int., **22**, 1–11.

Eaton, P. A., and Hohmann, G. W., 1989, Approximate inversion for transient electromagnetic soundings: Phys. Earth Plan. Int., **53**, 384–404.

Jones, A. G., 1987, Static-shift of magnetotelluric data and its removal in a sedimentary basin environment: Geophysics, **53**, 967–978.

MacNae, J., and Lamontagne, Y., 1987, Imaging quasi-layered conductive structures by simple processing of transient electromagnetic data: Geophysics, **52**, 545–554.

Newman, G. A., Hohmann, G. W., and Anderson, W. L., 1986, Transient electromagnetic response of a three-dimensional body in layered earths: Geophysics, **51**, 1608–1627.

Park, S. K., 1985, Distortion of magnetotelluric sounding curves by three-dimensional structures: Geophysics, **50**, 786–797.

Park, S. K., and Livelybrooks, D., 1989, Quantitative interpretation of rotationally invariant parameters in magnetotellurics: Geophysics, **54**, 1483–1490.

Park, S. K., Orange, A. S., and Madden, T. R., 1983, Effects of three-dimensional structure on magnetotelluric sounding curves: Geophysics, **48**, 1402–1405.

Raiche, A. P., 1983, Comparison of apparent resistivity functions for transient electromagnetic methods: Geophysics, **50**, 1618–1627.

Spies, B. R., 1980, Interpretation and design of time domain EM surveys

in areas of conductive overburden: Bull. Austral. Soc. Expl. Geophys., **11,** 272–281.
—— 1989, Depth of investigation of electromagnetic sounding methods: Geophysics, **54,** 872–888.
Spies, B. R., and Eggers, D. E., 1986, The use and misuse of apparent resistivity in electromagnetic methods: Geophysics, **51,** 1462–1471.
Sternberg, B. K., Washburne, J. C., and Pellerin, L., 1988, Correction for the static shift in magnetotellurics using transient electromagnetic soundings: Geophysics, **53,** 1459–1468.
Swift, C. M., 1967, A magnetotelluric investigation of an electrical conductivity anomaly in the southwestern United States: Ph.D. thesis, Massachusetts Institute of Technology.
Ting, S. C., and Hohmann, G. W., 1981, Integral equation modeling of three-dimensional magnetotelluric response: Geophysics, **46,** 182–197.
Torres-Verdin, C., and Bostick, F. X., 1990, Principles of spatial surface electric field filtering in magnetotellurics: The EMAP technique: Geophysics, submitted.
Vozoff, K., 1972, The magnetotelluric method in the exploration of sedimentary basins: Geophysics, **37,** 98–141.
Wannamaker, P. E., 1983, Resistivity structure of the northern Basin and Range, *in* Eaton, G. P., Ed., The role of heat in development of energy and mineral resources in the northern Basin and Range Province: Geoth. Res. Counc., Spec. Rep., **13,** 345–362.
Wannamaker, P. E., Hohmann, G. W., and San Filipo, W. A., 1984a, Electromagnetic modeling of the three-dimensional bodies in layered earths using integral equations: Geophysics, **49,** 60–74.
Wannamaker, P. E., Hohmann, G. W., and Ward, S. H., 1984b, Magnetotelluric responses of three-dimensional bodies in layered earths: Geophysics, **49,** 1517–1533.
Ward, S. H., and Hohmann, G. W., 1988, Electromagnetic methods in applied geophysics, *in* Nabighian, M., Ed., Investigations in geophysics, **1,** Theory: Soc. Expl. Geophys., 131–312.