Electrical Resistivity Imaging of Groundwater Systems using Natural and Controlled Source Magnetotellurics

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1. Introduction

Electrical resistivity varies from 0.1 to 10^6 Ohm-meters in natural materials that comprise groundwater systems and their surroundings. It is a function of groundwater quality, host materials, and hydrogeologic structure amongst other factors. For these reasons, it is an attractive measurement parameter for characterization of groundwater systems. Advances in instrumentation, computation, digital signal processing and data modeling which have occurred within the last decade make electrical resistivity imaging a reliable, cost effective and practical tool for noninvasive investigation of groundwater and environmental contamination problems. This is especially true because of the miniaturization and lower power requirements of equipment used in the field that have resulted from advances in microelectronics. This document is written for non-specialists in hydrology, environmental science, hydrogeology geophysics, and related fields. Its primary purpose is to provide a simple basis for understanding the most highly developed and arguably most efficient techniques, based on the magnetotelluric method, for field subsurface resistivity imaging. As with all geophysical imaging techniques, successful application of electromagnetic methods, such as those based on magnetotellurics, requires knowledge of both the their capabilities and limitations. This involves both inherent facets of the techniques in an idealized sense, and practical considerations in site-specific deployments such as structural complexity, rock and sediment types, styles of permeability, and local levels of electromagnetic noise. These considerations are covered as much as possible in a non-theoretical treatment of the subject. Readers should have sufficient background to understand most articles in Scientific American.

Successful interpretation of electrical resistivity images of the subsurface is as important as data acquisition and modeling. This involves a number of important considerations and knowledge of the ranges electrical resistivities of earth materials in situ in local hydrogeologic environments including possible resistivity anisotropy, which can accompany permeability anisotropy. The most important considerations and relevant data are discussed and/or referenced in the literature for further study. Some *comparisons of resistivity imaging with other geophysical techniques are made where appropriate.*

Overview of the Basics: Magnetotellurics

2a. What are Electrical Conductivity and Resistivity?

Electrical conductivity, σ, *itself is a measure of how well any particular material will conduct electricity in the presence of an electric force field. The higher the conductivity, the greater the electrical current that will flow when an electric field is present. The values of this parameter are stated in a variety of units (i.e. Siemens/meter, reciprocal ohm-meters, mhos/meter, millisemens/meter). An alternate parameter in common usage is the* ***electrical resistivity****, ρ, which is the reciprocal of the electrical conductivity,* $\rho = 1/\sigma$. *Units of ρ are typically ohm-meters or ohm-centimeters.*

2b. How Electrical Resistivity is measured in the Subsurface - The Simple Physics Behind Magnetotellurics

This is all about electric fields, magnetic fields, electromagnetic waves, electrical currents, and how they all work together and are related to each other. First, a field is any quantity that has a definite value at all points in space and in time. Common examples are temperature, atmospheric pressure, water speed and velocity in a stream, and wind velocity.

We typically are interested in fields in a restricted environment and over a limited range of time. An example is temperature variation within a room throughout the month. The temperature field is the temperature at every point within the room over the duration of one month. This is what is called a ***scalar field,*** *which has magnitude but not direction. The speed of a vehicle over a given period of time is an example of another simple scalar field. If, on the other hand, if we talk about the velocity of a vehicle over time, we must consider both the magnitude (its speed) and the direction in which it is traveling through time. This is known as a* ***vector field,*** *which has both magnitude and direction. An especially important vector field is a force field. Intuitively force is a push or pull. In more precise terms,* ***force*** *is any action capable of accelerating an object. A* ***force field*** *is the magnitude and direction of a particular kind of force will exert on a body (i.e. Gravity, magnetic, electric) throughout some region of interest through a given time period.*

Electric and magnetic fields are especially important to us in resistivity imaging. We are accustomed to the Earth's "static" magnetic field by compass usage. However, it is not the static field but the time varying fields, both electric and magnetic, that are used in resistivity depth profiling using magnetotellurics. Maxwell demonstrated that a time-varying electric field generated a time-varying magnetic field and vice versa. The result is production of ***electromagnetic (EM) waves*** *that travel out from the source at the velocity of light in air and space but much slower in typical Earth materials. Common experience is with radio and TV waves. EM waves traveling into the Earth cause currents* *to flow in materials that can conduct electricity, as is practically the case for most Earth materials. A remarkable feature of these waves is that as they pass into the earth their electric fields cause electric current to flow in rocks and sediments, which are, to varying degrees, conducting. We also know from Maxwell and Ampere that any time an electric current is flowing that it generates its own magnetic field. Earth currents, known as telluric currents do this. These currents vary in time (they are alternating current), so their associated magnetic fields also vary in time, producing what we call secondary magnetic fields and therefore electromagnetic waves that travel outwards from the conductors in all directions in space. When these waves, generated by inducted telluric currents, arrive at the Earth's outer surface, their electric and magnetic fields sum with those of the primary fields of the original EM wave that entered the Earth and set up the current flow in the first place. How does this allow us to determine subsurface conductivity? First of all, we know precisely how the electric and magnetic field of an incoming electromagnetic wave from space are related to each other if there are no secondary fields present from induced currents. We can, therefore subtract out the primary EM wave and look only at the wave produced by induced currents flowing in conductors located below the Earth's surface. It turns out that the size of the secondary fields produced by induced current flow in earth materials and the ratios of components of these fields are directly related to the conductivity or resistivity of the interior materials. The higher the material resistivity, the larger the ratio of the electric to magnetic field strengths (in perpendicular directions) must be. Modern magnetometers and electric field measuring devices allow us to precisely measure the electric and magnetic field variations at the surface, subtract out the field components due to the primary field, and determine the conductivity of the subsurface that is consistent with those fields. This is basically the heart of* ***magnetotellurics (MT)****. Magneto refers to electromagnetically induced currents. Tellurics refers to currents flowing in the Earth. Here MT is used to cover all types of electromagnetic sounding techniques that are based on the assumptions and theoretical basis of magnetotellurics. These include both natural source and controlled source methods. A number of acronyms are in current usage for these methods, but all are basically MT-based techniques. MT has enjoyed the greatest development of modeling codes of all the methods used in subsurface electrical conductivity/resistivity determinations. The acronym* ***MT*** *has traditionally been associated with so called "wide band", natural source field magnetotellurics in the low frequency range from* 10^{-4} *up to about 50 Hertz.* ***AMT*** *is identical except that it is specifically in the audio frequency range of 10 to perhaps 10,000 Hertz.* ***CSAMT****, Controlled-Source Audio Magnetotellurics refers to an audio frequency MT system utilizing a man-made source field.* ***ASMT*** *refers to Active Source Magnetotellurics, and is basically the same as CSAMT. The sources of the primary inducing EM waves are discussed in the next section.*

A consequence of flowing current in the Earth, as a result of passing EM waves, is that part of the energy contained in the waves is lost to frictional heating within the conductors in which current is flowing. As a result, the strength or amplitude of the waves will be attenuated with distance of travel as the wave energy is lost to frictional heating. This is in addition to loss of energy because of geometrical spreading of the waves into ever increasing volume with time. In material with constant conductivity, the *electric and magnetic field components of the waves are exponentially damped with increasing depth of travel into a conductor according to*

$$E = E_0 \sin(\omega t)\exp(-kz) \quad \textit{and} \quad H = H_0 \sin(\omega t)\exp(-kz)\,, \qquad (1)$$

where E and H are the electric and magnetic field strengths, respectively, at time t, angular frequency ω and depth z, and k is the damping coefficient. It is somewhat important to note that the fields described by these equations are plane waves, which is to say that the strength of the fields is the same in a plane perpendicular to the direction of propagation, z. The entire theory of MT breaks down if the incoming waves inducing currents into structures within the interior are anything other than plane waves. When the source is located far from the region of study, as is the case with natural source fields, this condition is satisfied. This is discussed further in a later section, as it can be an important factor in designing CSAMT surveys. The damping coefficient and thus the amount of attenuation of the wave in passage through a distance z in the conductor is a function of the frequency, f, *of the wave. The depth δ, at which the strength or amplitude of the wave has dropped to 1/e of its value on entry into the conductor is called the* ***penetration depth*** *and is given by*

$$\delta = 503\sqrt{\frac{\rho_a}{f}} \ \textit{(in meters)}, \qquad (2)$$

where ρ_a is the apparent resistivity of the conducting body, and f *is the wave frequency. The* ***apparent resistivity*** *at a particular frequency, f, is determined from perpendicular values of the electric and magnetic fields measured at the surface*

$$\rho_a = \frac{1}{5f}\left|E_x(f)/H_y(f)\right|^2 \qquad (3)$$

Here x *and* y *subscripts indicate electric and magnetic fields measured in two perpendicular directions at frequency f. Caniard (1953) found that if the Earth could be represented as a conducting half-space with constant resistivity everywhere, then the apparent resistivity is equal to the real resistivity. In the real Earth, however, resistivity or conductivity generally varies with depth and often with horizontal coordinates, so apparent resistivity isn't necessarily real. Nonetheless, it is a useful concept, and is useful in initial field interpretation and assessment of data quality. Apparent resistivities can be calculated in two perpendicular directions yielding information about the dimensionality of subsurface structure in the vicinity of the sounding site, as well as the electrical strike direction of buried conductors.*

The beauty of all this is that one may interrogate the electrical structure of the subsurface at different depths simply by using a variety of different frequencies, each of which samples resistivity or conductivity at different depths. In general, wave energy is too small at a given frequency to induce currents into conductors whose secondary electric and magnetic fields can be successfully measured at the surface. Thus, the penetration *depth at the lowest frequency determines a practical upper limit for the depth of investigation for a region with effective resistivity ρ_a. In reality, the useful maximum interrogation depth is somewhat less than the penetration depth.*

An important aspect of plane EM waves is that they are polarized. Light waves are very high frequency polarized waves. This means that the electric or magnetic fields associated with the wave will occur in one direction in the plane that is perpendicular to the direction of propagation. MT theory assumes that waves are arriving with random polarizations. Having waves arrive with polarizations that are perpendicular to each other allows us to interrogate the subsurface resistivity in two perpendicular directions in MT. From this we can determine electrical strike directions of any structures that have contrasting conductivity. For example, it is generally possible to determine the strike direction of a buried fault beneath a line of occupied sites using MT. In addition, if a narrow conducting body extends beneath the line, the strike direction of the body can often be determined. Because of this, electric and magnetic field variations are usually measured in two perpendicular directions simultaneously in MT surveys. In this case, apparent resistivities, ρ_x and ρ_y are determined in two perpendicular directions, typically in the north-south direction and in the east-west direction. In data processing, these data are rotated to find apparent resistivities parallel and perpendicular to the electrical strike directions.

Once apparent resistivities are obtained over a wide range of frequencies at a number of sites on a line or grid, the entire data set can be modeled to yield real resistivities versus depth in two or possibly three dimensions, as discussed in Section 5. Typical surveys are run along linear transects on the surface with corrections for surface topography. An advantage of MT methods over other EM sounding methods is that it provides accurate information about the departure of subsurface structure from 2-D through a parameter called skewness. Investigators are thus aware of the possibility of 3-D effects in a data set.

Energy Sources

3.a Natural Sources *Nature provides a rich, broad spectrum of incoming electromagnetic waves that are essentially plane waves on their arrival at the Earth's surface. The natural source field is due primarily to two mechanisms. One is lightning that provide useful electromagnetic wave energy in the frequency range from about 1 Hz to 2,000 Hz. A major source of this energy is generated in the thousands of lightning storms occurring daily in the tropics. The wave energy is efficiently transmitted to the latitudes of North America via a waveguide effect between the Earth's surface and layers of the ionosphere. These waves are rather weak above 300 Hz, and using them in culturally impacted regions is not always successful in MT. Especially favorable wave sources at frequencies above 1 Hz are relatively local electrical storms, perhaps up to 200 km distance but not so close as to saturate MT field instruments. These storms can provide much greater signal strengths and high signal-to-noise ratios in measured MT parameters.*

Lower frequency energy is generated largely by ionized particles from the solar wind, which become trapped by the Earth's magnetic field lines considerably above the atmosphere. These charged particles travel along the field lines from pole to pole in a helical fashion, producing magnetic fields. Since the solar wind is not constant in intensity with time, changes occur in the currents following the magnetic field lines in time. Thus, the resulting magnetic fields vary in time and, therefore produce electric fields and are a source of traveling electromagnetic waves. These waves occur mostly within the frequency range of 10^{-4} to 1 Hz and generally increase in intensity with lower frequency. The lowest frequency waves indicated penetrate through the crust and into the mantle. The energy arriving from both sources is useful over the frequency range of 10^{-1} to 300 Hz is useful in groundwater and environmental studies within the top few kilometers of the Earth.

The chief advantage of using natural source fields is that no transmitter is required and logistics are relatively simple. In addition, source fields at frequencies below about 10^{-1} Hz are far stronger than realistic man-made sources. The disadvantages of natural source fields are: (1) that they not always stationary and can produce bias in the data, (2) the typical absence of utilizable energy levels in parts of the high frequency spectrum needed for shallow characterization, and (3) the erratic signal strength of the natural source fields. When signal strength is low in a particular part of the spectrum, it may be difficult and time consuming to collect data over a meaningful frequency range. In worst cases, data collection may be impossible within critical parts of the frequency range. The situation is further aggravated, in regions such as cities that are heavily impacted by culturally produced noise. Low signal strength is most typical in the range of 10^{-1} to 1.0 Hz, affectionately called the dead band. In some hydrogeologic settings, especially in moist sedimentary environments, where deep aquifers need characterization (i.e., depths greater than a kilometer), this can a critical part of the sounding frequency range needed in MT methods.

Natural energy sources, plane electromagnetic waves, arrive at a point on the earth's surface from all directions in space. However, on entry into the electrically conducting earth, they loose energy along their travel path by inducing electric currents to flow, which produces frictional heat energy as they are attenuated with increasing depth. This results in what is called wave propagation in an energy dispersive medium. A major consequence for the MT technique is that this dispersion results in a very great reduction in wave velocity in the conducting earth as opposed to the velocity of light at which these waves propagate in space. Refraction or bending of the waves occurs at the air-earth interface. It is described by Snell's Law, and results in the waves traveling essentially vertically into the earth as shown in Figure (1).

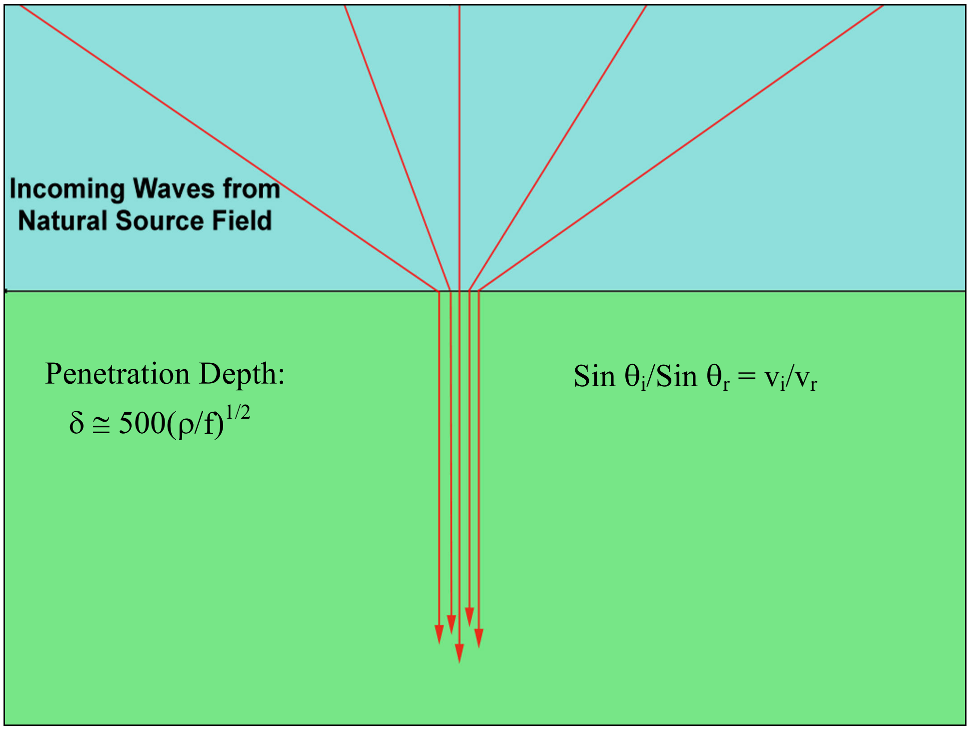

Figure (1)

***3.b Controlled Sources** have been used to successfully overcome the disadvantages of natural source fields in the higher frequency part of the EM spectrum, which is typically most essential in hydrogeologic studies. These sources involve use of (1) a transmitter which can produce large output power over the range of frequencies needed in MT for a particular application, and (2) an antenna capable of radiating EM waves efficiently at the frequencies of interest.. Typically the transmitter produces sine wave output at each of many frequencies across the spectrum. Two types of antennas are used for MT applications. One is one or two perpendicular **grounded dipoles**. Two long wire cables, of sufficient size to carry 5 to 25 amperes of current, connect the transmitter with two ground connections, one at each end of the antenna, which are as much as 1 to 2 kilometers apart. The ground connections must be very good to allow this level of current to flow into the earth. In arid environments, it is often necessary to bury and connect large quantities of thick aluminum foil or ground stakes to the cable end, or make some other equivalent system with large surface contact area, to achieve sufficiently low contact resistance with the ground. Water or salt water is used on the metal to enhance connectivity with the ground. In regions with more conducting soils, it is often sufficient to drive a number of metal stakes a few feet into the ground and connect them to together in parallel for each electrode. Once the antenna is constructed and connected to the transmitter, the system is able to deliver stable, high intensity EM waves over distances of several kilometers throughout the frequency range of about 10^{-1} Hz to 10 Kilohertz. The highest frequency that can be transmitted with a grounded bipole antenna is limited by the reactive component of inductance of the antenna, which increases with increasing frequency. The power output of the transmitter must often be decreased significantly when transmitting above 2 kHz to prevent destruction of the output devices in the transmitter. This type of antenna is therefore limited in its upper* *frequency capability. MT studies in hydrogeological environments where shallow aquifers are present require higher frequencies, up to 100 kHz, for which the grounded bipole antenna system is unsuitable by itself as an energy source. Resolving capability in the shallow environment is especially limited in resistive localities such as arid and semi-arid deserts. However, when the frequency range of a grounded bipole type of controlled source is correct for target depths and local ground resistivities (low values), it can produce higher signal to noise ratios than any other type of system, even in the presence of substantial cultural noise.*

A second type of controlled source uses a pair of vertically oriented magnetic loops or half loops placed on the ground surface. The magnetic loop or ***magnetic dipole source*** *is generally used only for the frequencies above 500 Hz, but can, when used with appropriate transmitters, produce useable output waves to frequencies in access of 100 kHz. This type of source is appropriate for high resolution, shallow (i.e. less than 100 meters depth, and in some cases considerably less depth) MT studies only. However, it can be battery operated and is backpack able, and can, therefore, be easily deployed in practically any location. Generally this type of source is located a few hundred meters from the survey location, and is easily moved as if the survey progresses over several hundred meters. By itself, the vertical magnetic loop source is fairly limited in hydrogeologic investigations.*

An interesting approach has been taken by EMI/Geometrics in their Stratagem MT system, used in this survey. This system uses a hybrid source, which uses paired vertical magnetic dipoles from 500 or 1000 Hz to about 92 kHz, and natural source fields from 500 to 10 or 10^{-1} Hz, depending on the type of transmitter and magnetic sensors used. This system extends the frequency range upward sufficiently to deliver high resolution of conductivity structure, typically within the outer few tens of meters. At the same time, it extends the lower frequencies downward enough to cover depths of several hundred meters to perhaps three kilometers, depending on the local subsurface resistivity and system options. With lower frequency sensors, this system is capable of soundings to several kilometers depth in many environments.

A major requirement for using a controlled source transmitter for MT soundings that are to be modeled using conventional MT theory, is elimination of the ground path signals. EM waves emanate from the transmitter in all directions, including into the ground. It is essential that only the air path signals arrive at the subsurface structure under interrogation when the MT method is used. This is generally accomplished by locating the transmitter far enough away so that signals transmitted directly through the ground are attenuated to insignificance by the time they reach the MT survey sites. Strangway has shown that this requires separation distances of 3 to 5 penetration depths. It is the author's experience that the larger of these distances is often required to provide good results. Even more separation distance is needed if a highly resistive layer, lying beneath conducting overburden, is to be interrogated. Butterworth (1988) has examined this problem in detail. The tradeoff is one of obtaining sufficient separation distance to eliminate ground path signals while, at the same time, providing sufficient transmitter power to yield high signal-to-noise ratios (See Figure (2)).

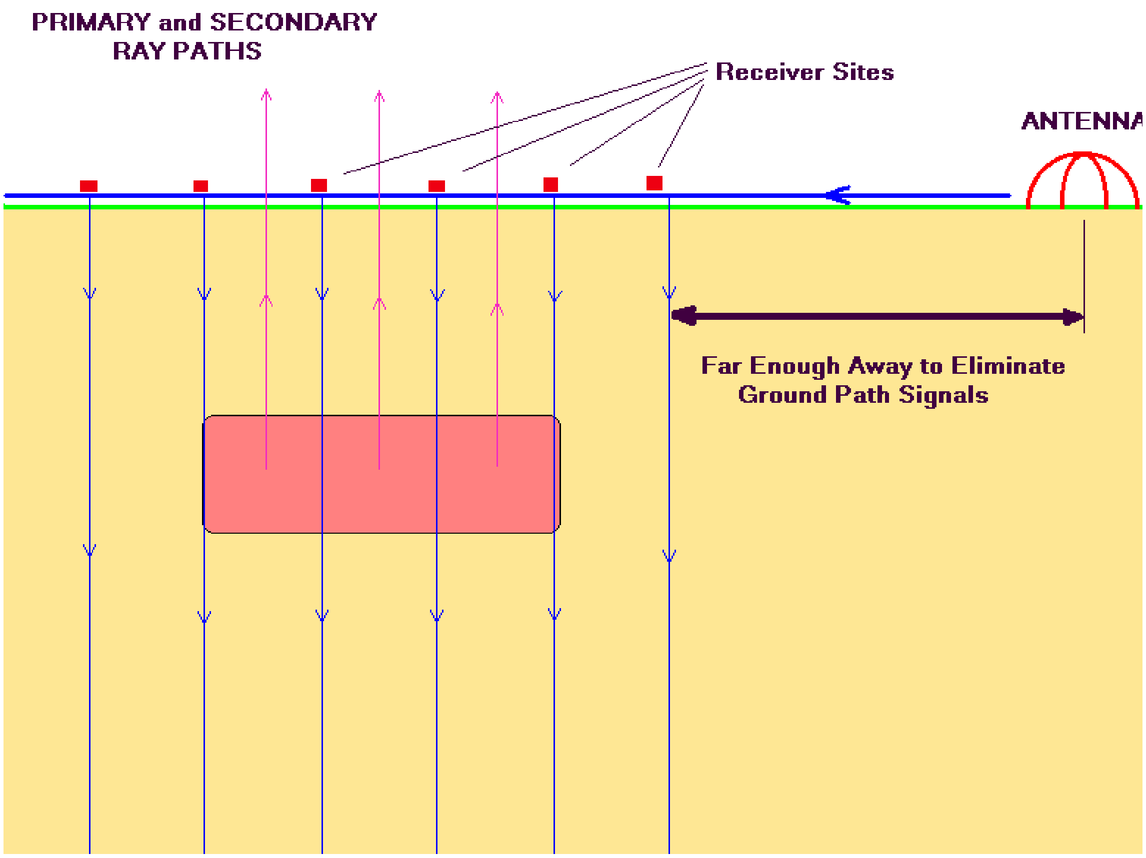

Figure (2). Signal strength falls off as reciprocal separation distance cubed. Even with this difficulty, it is generally possible to produce controlled source signal strengths far in excess of natural source field strengths, a major advantage in heavily noise-impacted areas. Modeling codes, discussed below, are available for modeling data acquired with a controlled source in both the near and far fields in a 1D layered situation.

Survey Design and Execution Considerations

4.a Magnetotellurics Receivers

MT receivers basically consist of magnetic and electric field sensors and a high dynamic range geophysical data logger and data processor. The latter is used to record the amplitudes and phases of the data and display various types of output graphically which are useful for in-field assessment of data quality, adjustment of survey parameters, determination of needed site occupation times and display of preliminary estimates of resistivity or conductivity depth profiles. Contemporary MT receivers are typically miniaturized versions of their predecessors that are battery powered and back-packable.

4.b Magnetic Field Variation Sensors

The best magnetic field variation sensors available today are SQUIDs (Super-Conducting Quantum Interference Devices), but because of their needs for cryogenic *fluid (liquid helium), and their bulk, they have enjoyed limited field use in recent years. Further developments and miniaturization may bring them to the forefront in the future, but for now coil sensors dominate MT instrumentation. Copper-wound coils on extremely low-loss μ-metal or other low-loss core materials achieve sufficiently good noise figures to be practical MT sensors, and are used in most systems, regardless of the frequency band coverage. Coil sensors used at the high frequencies needed in groundwater investigations are small and lightweight as are the receivers, making their use unrestricted to road access in the field.*

Magnetic field sensors measure tiny field strength variations in a given direction. If the sensors, themselves, tilt or rotate even slightly when data are being acquired over time, they produce noise signals, since they are moving in the Earth's main magnetic field which is perhaps 10^7 or 10^8 times larger than the field variations which are need to be measured in MT. This means that the tiniest motion of the sensors can produce induced voltages in the output, which corrupt the actual telluric signals which we must measure. Such sensor motion can result from the miniscule tilting and rotation of the ground that results from vegetation and trees swaying in the wind and actual wind noise coupling directly to the ground, or for that matter the magnetometer itself if it is above ground. One can actually observe in the magnetic field output of a swaying tree at precisely its sway frequency in the 0.1 to 1.0 Hz band. This type of noise is generally only a problem at frequencies less than 1.0 Hz. Wind noise can occur over a higher frequency range, extending into the audio frequency range. Burying the magnetic sensors attenuates wind noise significantly, and it is prudent practice to do so in windy conditions, if not at all times. Thus a shovel becomes part of the MT equipment arsenal. The axes of the sensors must be oriented both horizontally and vertically within a couple of degrees or so using a level and compass. In addition, the magnetic sensors are generally placed on the ground a meter or two away from the preamplifier box if there is any likelihood whatsoever of magnetic materials inside. The same goes for site marker stakes if they are if they contain iron. Preferably, nonmagnetic stakes should be used in the first place. During data acquisition, don't walk in the vicinity of the sensors, as this will be picked up as additional noise. It takes two forms. The first is acoustic noise. The second is electrostatic noise that can be a problem in arid conditions. Obviously field vehicles should be parked far away from measurement sites and care taken not to acquire data if vehicles are passing closely on nearby roads.

4.c Electric Field Variation Sensors

Electric Fields are recorded in units of volts/meter. The sensors consist of a pair of electrodes consisting of metal stakes driven into the ground at a predetermined separation distance. Then the small voltage variations between the two electrodes is returned to a central, ultra-low-noise, thermally stable preamplifier which amplifies the signal before it is passed along to the MT receiver for digitizing and recording for a pre-determined set of time intervals, as discussed above. Simple metal stakes work well for frequencies above about 1 Hz. Below that frequency special non-polarizing electrodes such as copper/copper-sulfate types are used. In order to get high signal-to-noise ratios, *the contact of the electrodes with the ground must be good. Ground resistance across measuring electrodes in access of 10,000 to 50,000, depending on the system electronics and frequency, do not generally produce satisfactory results. Improvement in ground contact in highly resistive surface materials is obtained by saturating the ground around the electrodes with water. In extreme cases, either salt or copper-sulfate, as appropriate, can be added to the water to enhance electrode-ground contact. Ground contact resistance between electrodes is easily measured with an analog ohm meter. If this measurement is omitted, high ground contact resistance will manifest itself as noisy electric field data.*

The separation distance between electrodes determines the minimum lateral resolving capability of the survey. The shorter the distance, the higher the structural resolution at relatively shallow depths. The minimum useable separation distance is dictated by signal-to-noise ratio, and is probably 3 to 5 meters for most systems. Shorter separations simply do not produce enough signal voltage to overcome the inherent noise of the preamplifiers. On the other extreme, maximum electrode spacings are dictated mostly by the length of connecting wires that can be laid on the ground surface, considering property divisions, topography and the existence of human structures. The connecting wires should be laid on the ground if possible since if suspended they can oscillate in wind and produce spurious electrical fields at the oscillation frequency.

4.d Practical Considerations in Field Deployment of MT Systems

4.d.1 Natural Source Field MT *MT deployment is performed as either a combination of single sites or as a line or series of lines of sites as in E-mapping. If some knowledge of the local geologic structure is known ahead of time, lines are generally laid out perpendicular to strike directions of structural features. Two horizontal magnetic field sensors are deployed near the center of the site in two perpendicular directions, generally along and perpendicular the survey line direction. Two electric dipole sensors are deployed in the same two directions about the center of the site with lengths of the electrodes determined by the considerations indicated in Section 4.c. When a line of sites is planned, it is always useful to carefully deploy site marker flags in advance. The electrode spacings are usually chosen to be the same at each site, but it is possible to vary this without compromising the survey provided that the lengths of the lines and site locations are recorded on the MT receiver. This is sometimes necessary because of structures or topography that precludes a uniform spatial deployment.*

4.d.2 Controlled Source Audio Magnetotellurics *CSAMT surveys are performed with a EM wave source, such as that described in Section 3.b. Waves propagate out from the source in all directions, both within the Earth and in the atmosphere above the Earth. They arrive at the MT receiver site by two paths. One is the ground path in which they travel through the solid earth to the vicinity of the sounding site. The other is the air path in which they travel in the air along the surface of the ground. Some of the energy contained in the air path waves traveling along the surface is refracted into the Earth at all points along the surface. Because the subsurface is highly electrically conducting* *compared with air, which is essentially an insulator, the refracted waves loose energy fairly rapidly as they travel into the earth. In wave theory this is called a highly dispersive medium. The main point is that in such media, the velocity of the EM waves is much smaller than it is for these waves traveling in air. The net result is that the refracted waves travel into the ground at nearly vertical angles. In addition, they are plane waves, which means that they can be used to perform magnetotellurics soundings. Importantly, the arriving plane waves taking the air path do not interact with the conducting subsurface until they are refracted into the ground, so they are path-independent. This is not true for the ground path waves. Since they interact with earth conductors all along the path from the transmitter to the receiver, they are influenced by the Earth conductivity structure all along the path, not just in the vicinity of the receiver site. This results in an inherent modeling ambiguity, since the path conductivity is typically unknown. Modeling can be done for both ground path and air path waves, but assumptions have to be made about the conductivity structure beneath the transmitter site and along the ground path (see Butterworth, 1998). It is desirable to eliminate the ground path signals entirely and necessary if purely magnetotellurics modeling theory is to be used. This can be accomplished if the transmitter is located far enough away from the receiver sites so that the ground path waves have been highly attenuated by conversion of their energy to heat via induced currents, as described in Section 2.b. The ground path waves are sufficiently attenuated, compared with the air path waves, when the transmitter is located several penetration depths away from the nearest receiver site. Typically the transmitter-receiver separation is* 3δ *to* 5δ *away according to Formula (2). The value of the ground resistivity used in this formula is estimated by 1-D soundings. If the estimate is incorrect, the bias produced in the data is clearly identifiable in the apparent resistivities determined at the receiver sites in the field. When this much separation exists between the transmitter and receiver site locations, it is called the* ***far-field*** *or* ***plane wave zone****. This is where controlled source systems operate as MT systems. A typical field deployment of a CSAMT system is shown in Figure (3). Note that the electric (E) and magnetic (H) field sensors are oriented parallel and perpendicular to the survey line. In some systems a vertical magnetic field sensor is also used. This provides some additional constraints on two and three-dimensional geoelectric structure.*

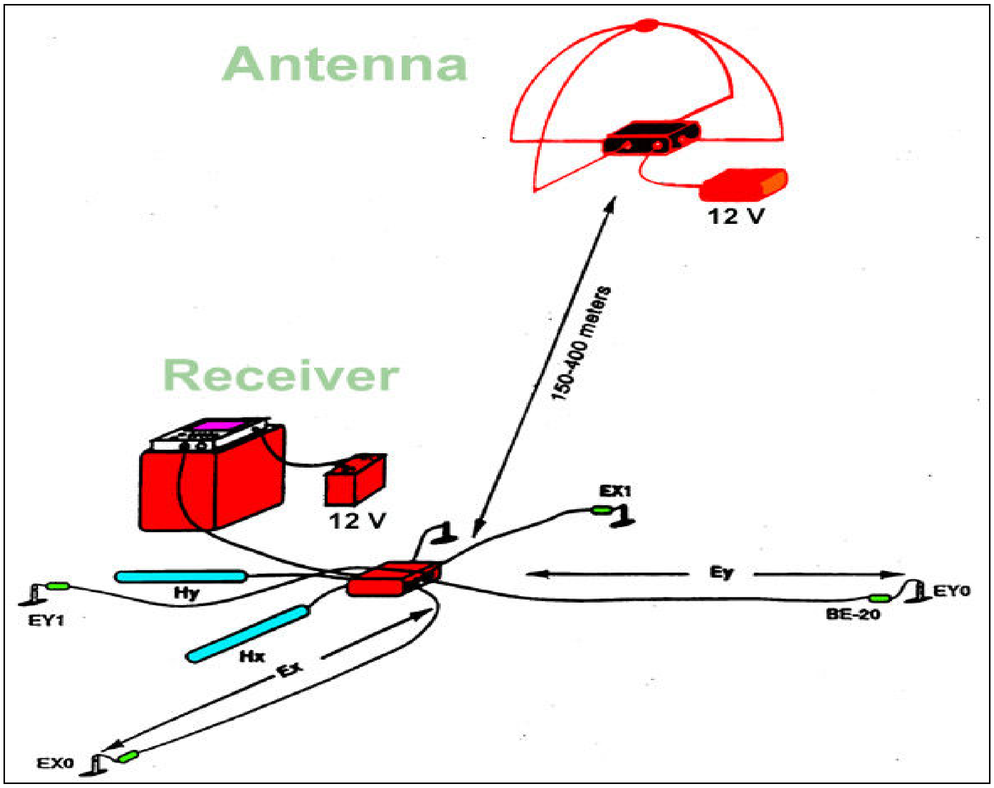

Figure (3)

4.d.3 Electromagnetic Noise Considerations *A major consideration in MT surveys is electromagnetic noise. Culturally produced noise can compromise the quality and validity of some or all aspects of an MT survey, and should be considered ahead of time in survey feasibility studies. Knowledge of the types of noise produced by various sources, their frequencies or frequency ranges, distances from the sites in a desired survey location, and potential noise intensities and durations are important and usually come only with experience.*

Passing railroad or subway trains can be serious, especially if they run on dc electrical current that is varied and switched on and off, which produces amazing amounts of electromagnetic noise. Some electromagnetic surveys have had to be aborted completely because of these difficulties. In environments impacted by this kind of noise, only MT-based systems with the most sophisticated digital signal processing and electronics can operate successfully.

Electrical storms can produce excellent source fields, if several are in progress simultaneously. However, if one storm approaches the survey area too closely, the electrical discharges will produce saturations in the MT receiver. If the data series are edited for saturations, it is still possible to obtain data in situation unless lightening strokes occur frequently. Where noise is concerned, an important characteristic of receivers is ***dynamic range****. This is effectively the range from the noise floor of the instrument to the maximum level of input signal, which can be amplified, digitized and recorded faithfully without driving it into saturation. When systems saturate, they do not* *faithfully record signals and a finite recovery time is needed to get out of saturation. Thus records can be invalidated by saturations. Modern receivers have either 16 or 18 or even 24 bit analog-to-digital converters. The higher the value, the better the system is at avoiding saturations.*

Another major source of noise is power lines. AC power lines produce large emitted radiation (1) at 60 Hz and its odd harmonics, 180, 300, etc., and (2) across broad frequency bands. Unless these lines are in the far field (located far enough from the receiver that radiation at the latter is of the plane wave type, they produce bias in electric and magnetic fields, which invalidate MT data taken at these frequencies unless a powerful controlled source is used as part of the system. The main culprits are the high voltage lines that are major distribution lines and smaller local lines carrying high currents. Occasionally, if operating too close to such a line, the noise fields are so great that MT instruments, even of the controlled source variety, cannot operate satisfactorily. Again, high instrument dynamic range is a considerable help in these marginal situations. With such instruments, data can often be taken satisfactorily over substantial parts of the frequency spectrum, even though data will be corrupted at or near 60 Hz and its odd harmonics. In the close vicinity of 3-phase power lines, the even harmonic at 120 Hz is also a problem. A spectrum analyzer in the field is very useful in diagnosing noise on site. Some MT-based commercial systems have this capability built in and routinely use it during depth soundings. Even if saturations do not occur, the power line radiation can produce bias in the resulting apparent resistivities and calculated resistivities versus depth that contain bias errors. If this occurs, it is usually apparent at the power line frequency and its harmonics and affected data can be removed satisfactorily from the data sets without harming results. However, broad-band radiation, which can be produced by high current switching on power lines by electric motors and devices used in farming and water well pumping is more insidious because it cannot be easily recognized at specific frequencies, as can radiation at power line harmonic frequencies. Data with very high electric-to-magnetic field coherence is produced by this kind of noise, not discriminated against in MT receivers. This type of noise can bias recorded data significantly, and is the main reason natural source field systems have been used mostly only at considerable distance from power lines in the past. The use of a controlled source transmitter that produces considerably larger signals at various frequencies than present in the natural source field is often effective at eliminating the effects of this kind of noise.

Nearby radio stations can sometimes induce radio frequency interference into MT equipment, causing poor performance. Fortunately, this is less common than power line noise contamination. It should be noted that even with the noise present in and near many culturally inhabited areas, it is usually possible to obtain useful data with the best systems available today, especially where a controlled source in utilized.

5. How Field Data are Processed

In a typical MT receiver, data is taken from four or five electric and magnetic field sensors digitized and recorded as a function of time over predetermined sampling *intervals. The data are then corrected for sensor response characteristics, which are never perfect. At this point, the data are re-recorded digitally and now represent time series of the electric and magnetic field strengths in two perpendicular horizontal directions plus often the vertical magnetic field strength. These are field strength variations versus time. Natural source fields contain a wide variety of signals simultaneously with a broad spectrum of frequencies, much as does sound detected by human ears. What is needed to determine resistivities are the various field strengths at specific frequencies spread approximately evenly throughout the range of interest. This is so because electric and magnetic field strengths at each frequency must be known to determine apparent resistivities according to formula (3) and ultimately true resistivities versus depth in data modeling. To convert the field strength data versus time to field strength versus frequency, Fast Fourier Transforms (**FFT's**) are used. After this operation, the horizontal components of perpendicular electric and magnetic fields at each frequency are used according to formula (2) to determine apparent resistivities versus frequency.*

*These data are typically displayed, along with statistical error bars immediately in the field for resistivity in the north-south and east-west directions or along and perpendicular to electrical strike directions. The data quality can then be assessed as it is being accumulated in the field, and a rough idea obtained about the characteristics of electrical structure in the vicinity of each site. Data obtained from Individual time series of the field strengths are stacked with each other providing an increase in the signal to noise ratio that goes as the square root of the number of stacks. The number of stacks is generally increased until a satisfactory signal to noise ratio is obtained at each frequency. Sometimes this is not possible at all frequencies, and most modern signal processing software will reject poor data automatically. If incoming signals are true plane waves without noise, the electric and perpendicular magnetic fields will be perfectly correlated with each other. That rarely happens. A good quantitative measure of this correlation is a factor called **coherency**, which can be determined at each frequency. Coherency has a value of one for true plane waves, and zero for totally uncorrelated electric and perpendicular magnetic fields at a given frequency. Acceptable data quality is generally when the coherency is 0.8 or above.*

*A major problem historically with magnetotelluric surveys has been bias in data taken at specific sites due to **static shift** in the electric fields. These shifts are caused by shallow conductivity variations, which sometimes occur on the scale of the electrode spacing of the electric field sensors. Static shifts bias the apparent and real resistivities at affected sites throughout the entire frequency range of the sounding. Unless these shifts are removed from the data, artificial structure appears in both apparent and real resistivities. Figure (4) shows apparent resistivities perpendicular and parallel to strike as a function of frequency obtained at a site that was affected by static shift. If sites on a deployment line are spatially separated from each other more than the electrode spacing, static shifts can be removed in a very approximate way by shifting the apparent resistivity curves up or down so that they coincide at the high frequency end of the curve. The shift is made so that the apparent resistivities join smoothly with those obtained at neighboring sites. This type of correction is superior to no correction at all, but can* *result in obliteration of real electrical structure in the shallowest part of the subsurface. A sophisticated solution to this problem was developed by Bostick (1986) and Torres-Verdin and Bostick (1992) using a technique called* ***spatial wavelength filtering****. In this context the term wavelength refers to the extent of in space of a subsurface body that has a contrast in electrical properties relative to its surroundings. For example, its horizontal extent beneath a survey line would be characterized as its spatial wavelength. This type of filtering also considers the depth of burial of anomalously conducting or resistive bodies. Deep bodies of small spatial extent will have no appreciable effect on surface measurements, whereas the same bodies at shallow depths will have significant effects on the data. The rate at which changes occur in measured fields and subsequently apparent resistivities with distance along a line relate to the maximum depth of burial of the anomalous bodies in the same way they do in other geophysical techniques such as gravity or static-field magnetics. In MT the spatial wavelength filtering technique requires that field data be acquired with sites spaced apart from each other by exactly the length of the electrode spacing used for an individual site, as shown in Figure (5). In this type of line deployment, the electrode at one end of the E field sensor for one site becomes the new electrode for one end of the E field sensor for the next site, and so on down the line. In this way, the electric field is determined continuously down the line. The technique works as follows. For high frequencies, which interrogate only the shallowest part of the subsurface, electric fields are determined by the electric field determined across the electrodes at the local site only. Thus, near surface resistivity variations associated with resistivity variations on the scale of the individual site electrode spacing are detected. At lower frequencies, which interrogate progressively deeper electrical structure, the electric field along the line direction uses progressively wider effective electrode spacings by choosing non-local electrodes that are successively further down the line from the local site. The idea here is that the longer the electrode separation, the more the effect of very shallow resistivity variations will be averaged out. This effectively eliminates the artificial effect of the shallow resistivity variations on resistivities of the structures that lie at greater depth and are interrogated at lower frequencies. The effective length of the electrode spacing is progressively increased as progressively lower frequency data are processed, effectively eliminating static shifts, which would otherwise be present due to shallower resistivity variations. Bostick (1986), and Torres-Verdin and Bostick (1992) have termed this method* ***E-mapping****. It is one of the most significant advances in MT data modeling, and is well suited to hydrogeologic studies since the depths of investigation are generally shallow enough to allow continuous profiling of the electric field strength. It is an automatic computational feature of some commercial systems designed for relatively shallow investigations such as environmental assessment and hydrogeologic studies. In larger scale studies such as that of the deeper crust or upper mantle, it is impractical to deploy electrode lines across many kilometers of the surface as would be required for E-mapping. It should be a routine procedure in studies limited to depths within the upper one or two kilometers.*

6. Modeling of Field Data

Field MT data in the form of apparent resistivities versus frequency can often be qualitatively analyzed successfully for many of the general features of the subsurface beneath the survey sites. This generally involves knowledge of "type curves" for apparent resistivities, theoretically generated for various types of electrical structures commonly encountered in natural geological settings. Of course, this requires an experience in MT data modeling. Quantitative modeling is considerably more satisfactory, and is accomplished using one of two methods that are based on theory: forward and inverse methods. Forward models, used extensively until the 90's, begin with an assumed subsurface conductivity structure, and yield the apparent resistivities that would result at the surface from such structure. The output resistivities of forward modeling are calculated for each frequency of interest that would be used in acquisition of field data. This output is generated for each surface location at which a site has been occupied. Next the actual field data is compared with the model-determined values. Where departures in the two exist, the modeler changes one or more parameters in the model, such as the depth to and lateral extent of the assumed conducting structures, and the values of conductivity or resistivity assigned to each. If intuition is correct, the model is recalculated and the results for the new conductivity structure fit the field data more closely. The idea is to repeat this process until a conductivity structure is obtained which produces reasonably good agreement with field acquired data at all sites within the survey. This is a time-consuming process, and for that reason it does not lend itself easily to finding optimized solutions of the conductivity structure. Testing model space to determine what the data can resolve and what it can't is extremely tedious with forward modeling.

Two dimensional inverse MT modeling is highly developed at this time (Smith & Booker, Macke, Vozoff). Morrison & … make a convincing case that approximate 2-D modeling, based on simple 1-D Bostick inversions combined with E-mapping, produce faithful renderings of subsurface structure at the typically shallow environments of hydrologic systems. This approximate modeling is very useful for determining approximate conductivity structure beneath a line of sites rapidly, even in the field. It is debatable whether or not further full inverse modeling contributes significant improvement in many such settings.

3-D forward modeling programs are available at this time. Several determinations of surface apparent resistivities and phases produced by discrete three dimensional conducting anomalies exist in the literature. These are pedagogically useful as guides to the nature of distortions that 3-D structures produce in two-dimensional modeling. Fully three-dimensional inverse modeling is beyond the computational scope of commercial and academic geophysics groups today but the rapid advances in computer hardware and software will likely change this picture in the near future. The lack of full 3-D modeling capability is not so severe a problem as one might expect. This is because many of the 3-D structures encountered in geological structure appear to be nearly 2-D when crossed at an edge. The actual data analysis used in many MT systems *yields skewness for magnetotelluric data acquired at each sounding frequency. As discussed above, skewness is a measure of departure from 1-D and 2-D structure, so it can be used as an indicator of the appropriateness of 2-D modeling.*

Routh and Oldenburg(1999) have developed a 1D inversion model and code for controlled source audio-frequency magnetotellurics data, which can be used in both near and far field applications.

8..References

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