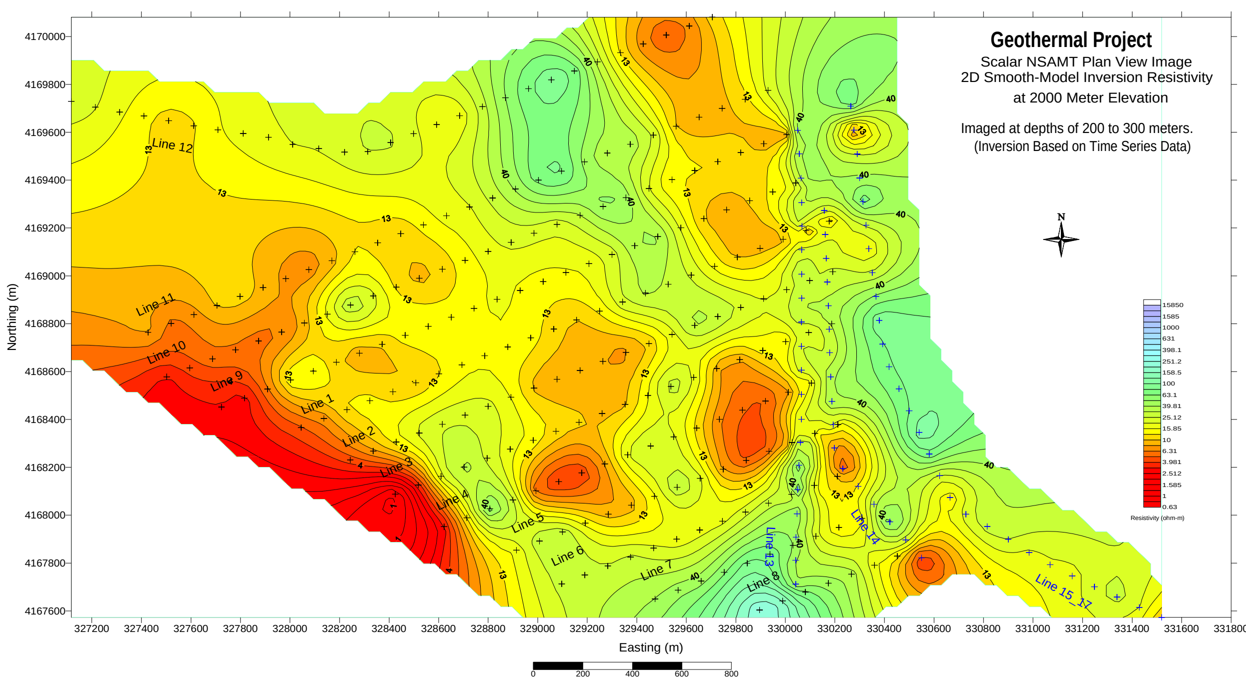
NSAMT

Natural Source Audio-frequency Magnetotelluric Imaging



This constant elevation NSAMT Plan-View of 2-D inversion results is from data collected with the Zonge AMT System. Useful modeled depths exceeded 600 meters on this project. Acquired on this project were 28 line kilometers of scalar NSAMT in an area crossed by a high-voltage power line, above-ground water utility pipeline and two highways. Conductive (red) and resistive (blue-green) trends identified on this inversion model relate to geology, not culture.

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Introducing the Zonge International AMT/MT System

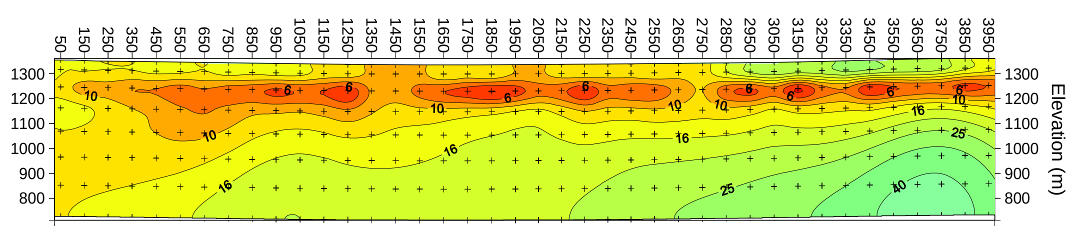
Zonge Natural Source AMT/MT Imaging starts with the GDP-32[II] geophysical digital processor, a highly successful geophysical receiver used for electric and electromagnetic surveys. The GDP-32[II] based AMT system used for natural source resistivity imaging can be configured to collect either SCALAR or TENSOR natural source magnetotelluric (MT) data in the audio-frequency range as well as the standard MT range. Audio range MT is commonly referred to as AMT. Zonge field crews have performed AMT surveys in mining exploration, ground water basin studies and geothermal programs. MT is used to identify frequencies below the AMT band.

Imaging Natural Source AMT/MT data is a multistage process. Cagniard Resistivity and Impedance Phase data are calculated from these electric E-field and magnetic H-field data. Cagniard Resistivity (RhoC) is a frequency dependent apparent resistivity calculation based on values of electric E-field and magnetic H-field data. The difference between the E and H components of the electromagnetic field is defined as Impedance Phase ($\Delta\varnothing$). Both RhoC and $\Delta\varnothing$ are used in Zonge 1-D and 2-D inversion models to image actual Resistivity changes associated with geology.

The two-dimensional (2-D) plan-view Resistivity image shown on the first page is an inversion model of natural source AMT data recently collected on a geothermal program. The plan view image is constructed from a series of vertical depth images, such as Basin Profile 1 collected as part of a hydrological study. Scalar AMT data were collected on both projects.

This is a 2-D natural source AMT inversion model of resistivity verses depth image:

Basin Profile 1



Example A, Scalar AMT with a = 100 m

This AMT line is 4 kilometers long and was completed in less than two days, sounding to a basal frequency of 3 Hz. Values plotted are resistivities in ohmmeters. While the water table clearly shows as a conductive horizon, the deep, more important reservoir is interpreted in this image as the thicker conductive section to the left. A dry river channel about 500 meters wide is centered near station 1750.

More about Natural Source AMT, commonly called NSAMT

AMT designates MT data collected in the audio-frequency range, typically from 8192 to 3 Hz. For high-resolution NSAMT coverage, CSAMT-style scalar coverage is recommended to optimize field production. High-resolution AMT coverage provides data densities suitable for the two-dimensional (2-D) inversion of AMT without the restrictions sometimes found in data collected with CSAMT*, Controlled Source AMT. CSAMT is dependent upon a remote signal source transmitting up to 30 KW of high-voltage power that limits portability. While 300 Hz is considered by many to be the MT high-frequency limit, AMT data are usually collected to 3 Hz using the Zonge system. There is overlap in frequencies commonly used by AMT and MT.

Two-dimensional inversion models of NSAMT Cagniard Resistivity and Impedance Phase data provide detailed images of the geology at depth while avoiding possible interference of transmitter "overprint" or "near-field" distortions. SCS2D is the Zonge 2-D inversion software used to image AMT data shown in this review. Topographic profiles can be included in the SCS2D inversion to correct Cagniard Resistivities for changes in surface elevation.

Topography is important when imaging AMT and MT data crossing ridges and valleys. 2-D imaged profiles clearly show geologic contacts between resistive and conductive rock units without complications introduced by topography. NSAMT is useful for imaging both deep geologic structure and near-surface geology, and can provide significant detail.

Using the latest magnetic field sensor technology (for example the high-frequency Zonge ANT/6 coil) and "time-series" post-processing techniques, AMT can provide reliable results with data collected in the "attenuation band" at 2000 Hz or in areas with cultural noise. The natural source AMT technique is passive, requiring no high-voltage electrodes, and logistics are relatively easy to support in the field.

** Note: CSAMT, short for Controlled Source AMT, uses a remote high-power transmitter. CSAMT has been used in geophysical exploration since the early 1970's. Over the years, more than a few researchers have contributed to the development and understanding of the CSAMT technique, including Dr Myron Goldstein and Professor Keeva Vozoff.*

Zonge International first built digital CSAMT equipment in 1976. Since that time Zonge has improved equipment, developed processing tools and resistivity imaging techniques suitable for CSAMT. Today, CSAMT is an industry standard.

<u>Natural Source Magnetotellurics Explained</u>

Electric currents within the earth produce magnetotelluric signals that are measured by the Zonge AMT/MT System, but mostly these signals are controlled by natural electromagnetic activity above the earth's surface. The name "natural source" is used to differentiate from "controlled source" signals produced by remote transmitters; hence the term NSAMT used by Zonge to describe the natural source AMT process.

Atmospheric conditions create seasonal worldwide electromagnetic signals, the one most obvious and most important high frequency source being lightning. Also important are electromagnetic signals associated with the interaction between the earth's magnetosphere and the solar wind, a tenuous plasma gas ejected from the sun. The resultant electromagnetic energy is channeled by the earth's atmosphere, which acts as a "wave guide". By measuring the electric and magnetic fields, it is possible to determine in-phase and out-of-phase ground resistivity values, which are defined by Cagniard Resistivity (RhoC) and the Impedance Phase ($\Delta\varnothing$) values.

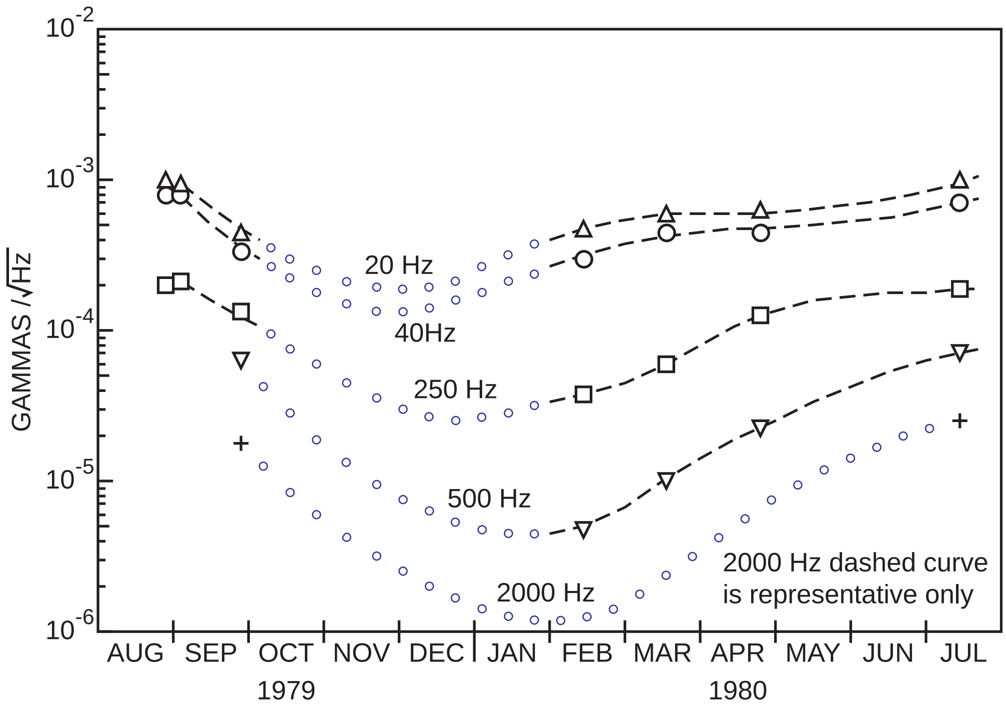
NSAMT data are generally collected by Zonge using the frequency band from 3.0 Hz to 8192 Hz for mining applications. Resistivities are calculated as ohmmeters. Seasonal variations in the magnetic field spectral density can be expected to be high, as shown in the graph below. Signal amplitudes also depend on the latitude. While situations may differ, generally background signal levels observed at most locations are satisfactory for AMT and MT surveys.

While 300 Hz is normally considered the top of MT frequency range, the Zonge AMT/MT system can easily collect these mid-range frequencies with either AMT or MT surveys. This ability is linked to the frequency bands used by the GDP-32^{II} AMT/MT System, which closely match the typical frequency range used by CSAMT, and the magnetic field sensors used by Zonge (see page 9). Because of the extended time required to collect data below 3.0 Hz, survey strategies more suitable for conventional MT-like surveys are generally used for collecting data in the low frequency band. One way to maintain production rates for low frequency MT surveys is to collect TENSOR data over fewer, more widely separated, stations. If the survey objective is to look deep, effective survey resolution is not sacrificed by increasing (within reason) the distance between stations.

One potential problem in collecting NSAMT data is the signal level in the "attenuation band" centered at 2000 Hz. In this band natural source signals are generally absent. While commonly called the "attenuation band", the actual problem is that the atmospheric "wave guide" channeling natural source electromagnetic signals is transparent to these frequencies. Natural electromagnetic (EM) energy is dissipated! Often, cultural electromagnetic noise fills the gap.

A graph of the twelve-month variation in the natural source power spectra is shown below. While a gap appears in this graph from October to January, predictable trends are shown in blue.

The 2000 Hz response is extrapolated from results observed at 20, 40, 250 and 500 Hz. Experience indicates that the natural source signal level at 2000 Hz can be expected to approach 10^{-6} *γ/√Hz* on this graph. This is the threshold signal level of the Zonge ANT/6 magnetic field sensor used for NSAMT.



The ○ ○ ○ ○ dashed segments, added to the original Plate, show how natural source AMT signals decrease in the Attenuation Band centered at 2000 Hz.

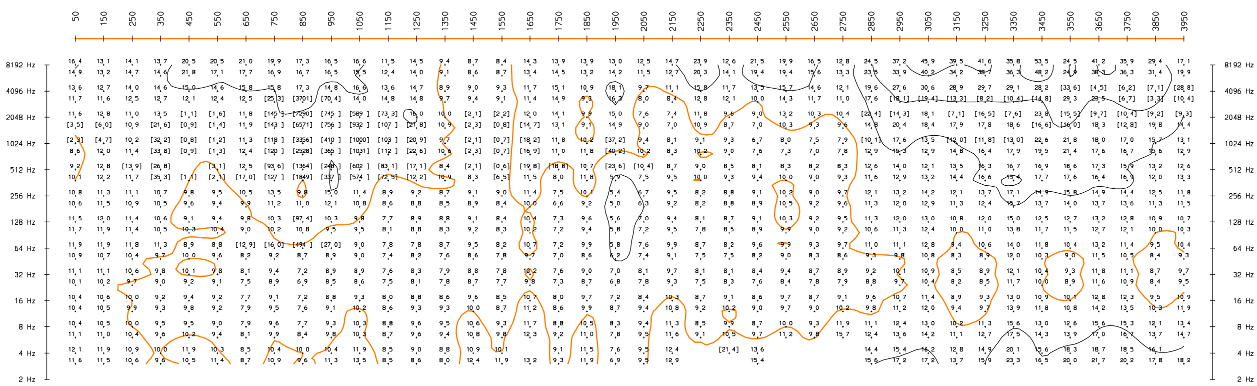
Twelve month Variations in Magnetic Field Spectral Density
(Based on Labson et al Geophysics, Vol. 50 No. 4 (April 1985) pages 656-664)

NSAMT Field Data

Field data are generally presented as Cagniard Resistivity and Impedance Phase values. Data are generally shown as black-and-white contoured plots referred to as pseudosections, with values vertically listed by frequency under each station. Decreasing frequencies relate to increased depth and form the vertical axis. NSAMT stations form the horizontal axis. Results are contoured. Because the relationship between frequency and depth is complicated, these plots do not represent actual cross sections.

Scalar values on the apparent resistivity pseudosection shown below are obtained from post-processed "time-series" NSAMT data. The brackets [ ] indicate measurements with unacceptable coherency between the electric field (Ex) and magnetic field (Hy). Some low frequency data is missing because data is simply lacking. While a few bracketed resistivities are located in the "attenuation band" centered between 256 Hz and 4096 Hz, this represents a small percentage of the total NSAMT data collected on this line.

Apparent Resistivity, Basin Profile 1



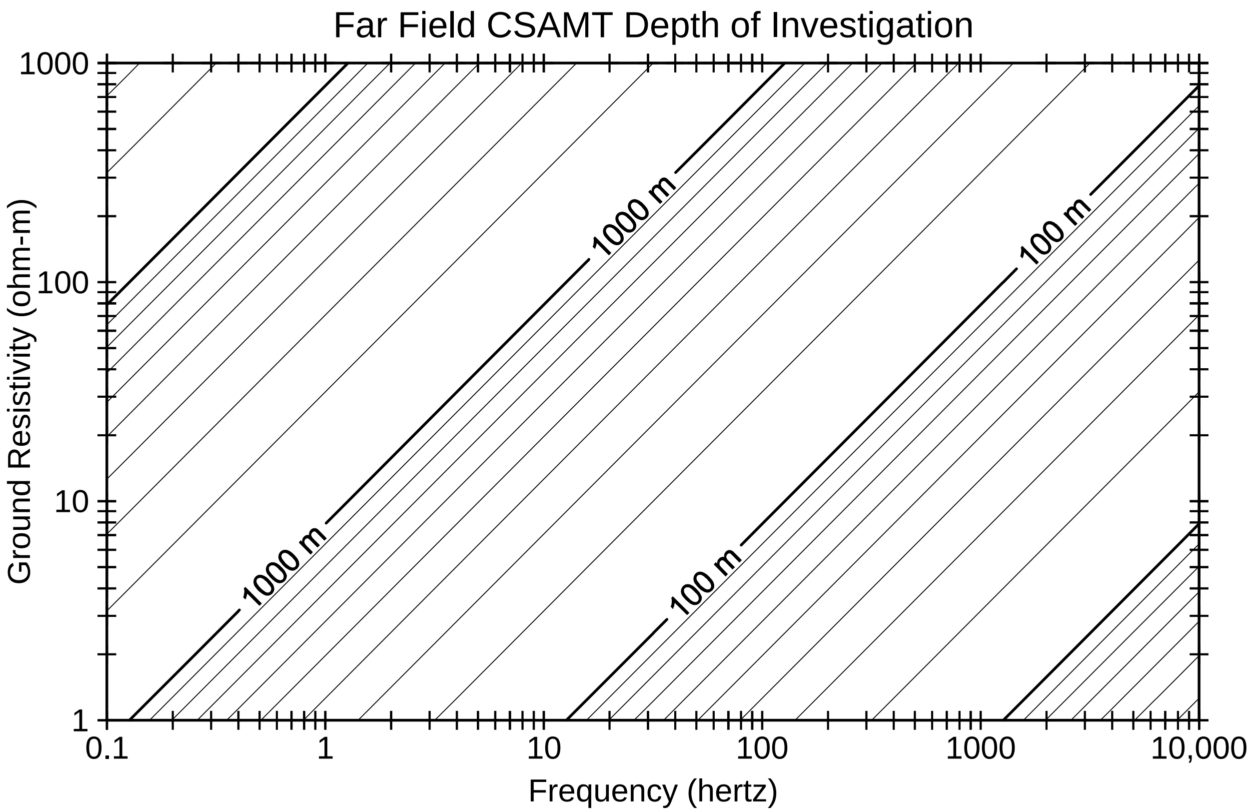
Pseudosection: scalar NSAMT Cagniard Resistivity

$$\text{Scalar RhoC}_{xy} = \frac{1}{5f}\left|\frac{E_X}{H_Y}\right|^2 \quad \text{(ohm-meters)}$$

Apparent depth as a function of a single resistivity characterizing the geology (Rho) is given by the following formula. This estimate of the low frequency limit needed to reach target depths is useful in planning AMT/ MT surveys.

$$\text{Depth Estimate} = 356 \times \sqrt{\frac{\text{Rho}}{f}} \quad \text{(meters)}$$

For example, based on a background resistivity of 10 ohmmeters and a frequency (f) of 3 Hz, a maximum depth of investigation of about 600 meters is indicated (refer to the 2-D inversion for Basin Profile 1).

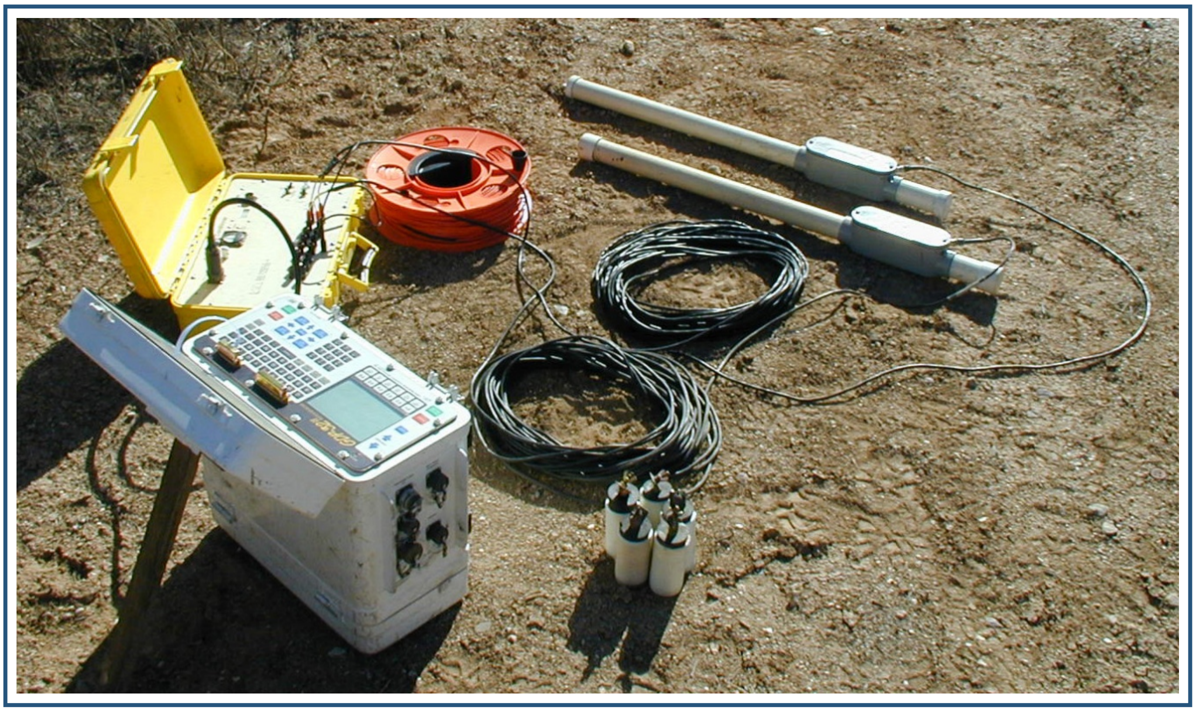


NSAMT uses "Far-Field" electromagnetic signals, where calculated resistivities depend on geology beneath the receiver, not the distance to any source. "Far-Field" assumes that signal sources are remote and that AMT is measuring a plane-wave electromagnetic field. The position of nearby electromagnetic sources (such as 50 or 60 Hz power lines) can corrupt Cagniard Resistivity and Impedance Phase data.

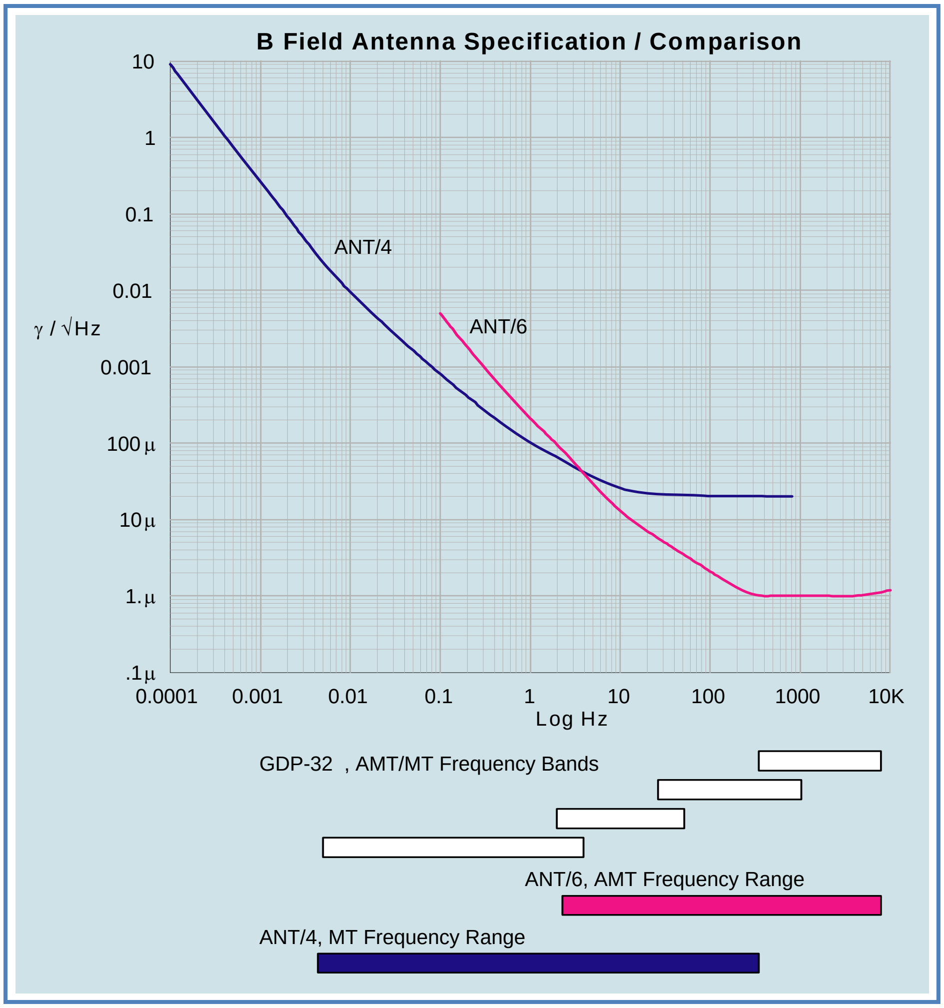
Useful electric E-field and magnetic H-field magnitudes are measurements of the background AMT power spectra, a product of many distant electromagnetic sources. For AMT or low frequency MT, the ability to obtain coherent data in the earth's natural frequency absorption bands is important. E and H fields are used to calculate Cagniard Resistivity (RhoC), and Impedance Phase ($\Delta\varnothing$). These "Far-Field" data are important in the 2-D inversion models. Where data is not measurable, information useful for the 2-D inversion is lost.

Zonge Equipment Used in Natural Source AMT and MT Surveys

This is a picture of the Zonge natural source AMT system. Shown is the 16 analog channel GDP-32^{II} geophysical data processor (the receiver). In clockwise order are shown the 8 channel SC-8 Signal Conditioner, two ANT/6 Magnetic Field Sensors, electric field array cabling and five porous porcelain copper sulfate electrodes typically used for measuring ground potentials. The GDP-32^{II} AMT system is easily transported. Multiple AMT systems can be synchronized for remote reference processing of time-series data.



The backpack-portable GDP-32^{II} receiver is a 16-bit microprocessor-controlled receiver capable of gathering data on as many as sixteen analog channels simultaneously. For AMT and MT surveys the GDP-32^{II} can operate in the scalar or tensor NSAMT mode, menu selectable by the operator. The Zonge ANT/6 magnetic field sensor, recommended for AMT data collection, has a noise threshold level below typical AMT and MT range natural source signal levels. With this setup it is possible to collect useful most AMT data in the "attenuation band" under most conditions. A second ANT/6 magnetic field sensor can be used for "Reference" data collection. Low power electronic noise observed in one coil can be isolated and rejected by matching output signals from two sensors. This noise rejection improves the low signal magnetic field measurements whether using the ANT/6 or ANT/4 magnetic field sensor.



When collecting MT data at frequencies below 3.0 Hz, the Zonge ANT/4 magnetic field sensor provides significantly better results than the ANT/6 (compare the B-field gains below 3 Hz). For tensor MT coverage, two ANT/4 sensors are needed to measure Hx and Hy. Reference MT would require operation with four ANT/4 sensors. At some point, simply doubling the magnetic field sensors to minimize magnetic field sensor noise may conflict with limitations imposed by field logistics. Intelligent survey planning will ensure the best use of available equipment.

If using dual magnetic field sensors is critical in measuring low amplitude magnetic field signals, then using two GDP-32^{II} receivers is one option. Collecting TENSOR data, with two or more "time-schedule matched" GDP-32^{II} receivers, increases daily NSAMT production and allows the "Remote Reference" option to be used for robust processing of the NSAMT data using MT-Tools©. (It is possible to collect multiple Time-Series data files with two or more synchronized Zonge AMT systems.)

Natural Source AMT/MT signals appear to geophysical instrumentation as wide-band electromagnetic signals with a long-term time average value of "zero". Source locations and signal levels change with time. To bring some organization to this, the NSAMT data acquisition program for the GDP-32^{II} separates information collection into four distinct bands as listed below. The choice is operator controlled.

Band	Frequencies (Hz)	Sample Rate (Hz)
Very High Band, AMT	384-8192	32768
High, AMT	48-1024	8192
Medium, AMT or MT	3-64	256
Low, MT	0.0007-4	16

Incoming electric field intensities are generally at the microvolt level, with magnetic field intensities in microgammas. Radio-frequency noise (RF) from AM/FM radio transmitters and television can sometimes produce millivolts of signals. Operators have to contend with low frequency SP drift that produce ground reference problems. Both RF noise and SP can cause problems with signal saturation at various stages in instrument electronics.

To deal with these problems it is highly desirable to include the Zonge SC-8 Signal Conditioner as part of the Zonge AMT/MT system. The SC-8 operates at 24 volts providing superior protection against high-frequency RF electromagnetic pickup, special high and low pass signal filtering options, and additional gain stages for preconditioning incoming electric and magnetic signals. The SC-8 uses a single multi-conductor communications cable to link to the GDP-32^{II}. Cabling from magnetic field sensors and electric field dipoles plug into the SC-8 instrument. Two SC-8's are easily attached to the 16 channel GDP-32^{II} receiver.

While the GDP-32^{II} includes a 16 bit A/D, the over-sampling design of the GDP-32^{II} provides 18 bits of effective resolution at AMT frequencies.

AMT and MT Data Processing

Because of the random variations characterizing the earth's magnetotelluric field, natural source AMT data cannot be stacked as synchronous data. AMT/MT results are collected as a continuous time series set of data. The Cascade Decimation Method (Wight and Bostick, 1980) is a computationally efficient method for transforming time series data from the time to "frequency" domain. This process is used to analyze all AMT/MT results, regardless of the level of application.

l) NSAMT Cagniard Resistivity and Impedance Phase are summarized concisely by the GDP-32^{II} in the block-averaged natural source .RAW field files. These data are post-processed by Zonge using NSAVG©. Many of the unusable .RAW data can be replaced with post-processed Time-Series data.

2) As an operator option, Time-Series records may be stored for all AMT/MT data collected as a series of files on a hard disk internal to the GDP-32^{II}. These data are available for separate analysis using robust AMT/MT processing in the MT-Tools© program. The value of post-processing is in the enhancement of AMT/MT signal to noise ratios.

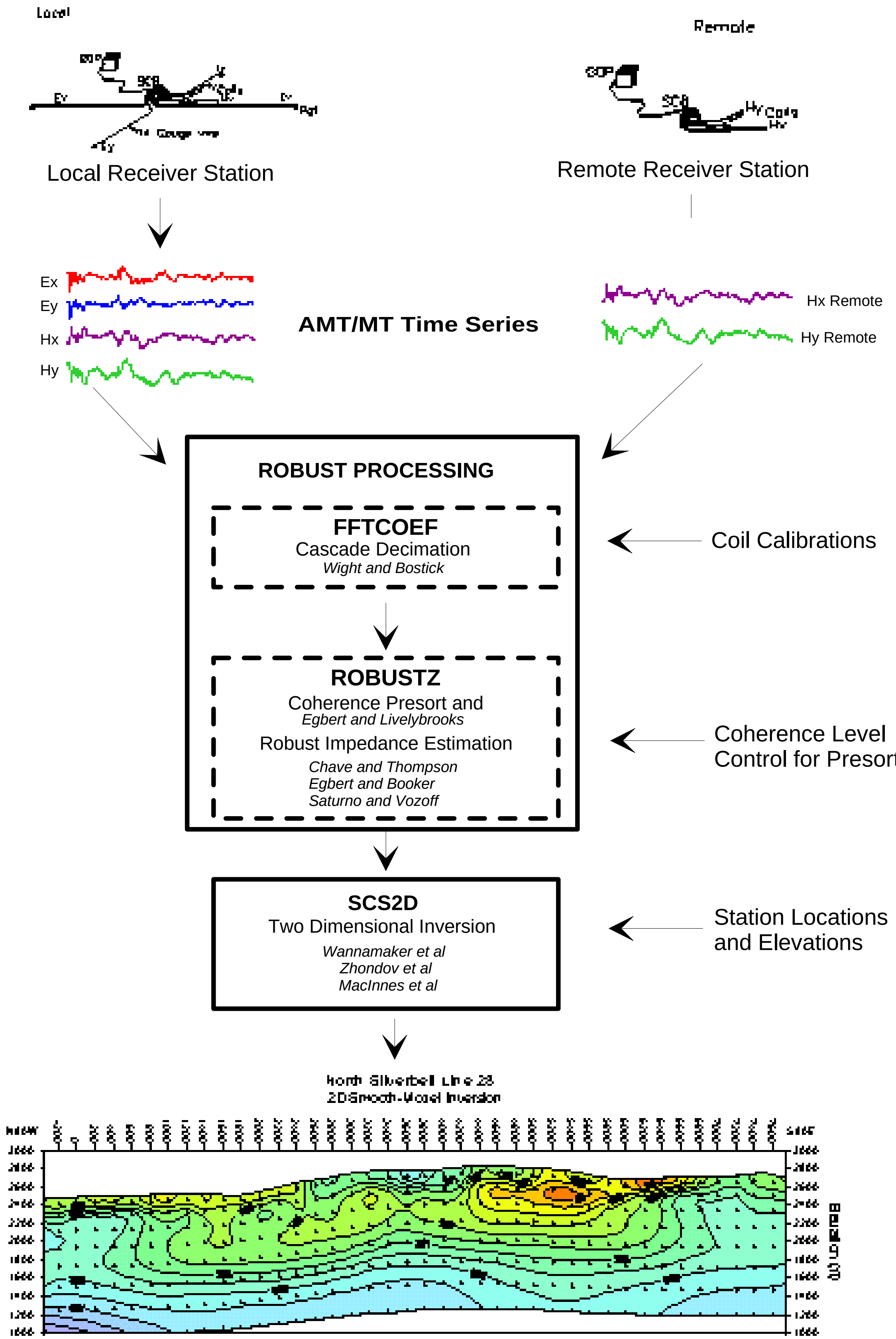
Coherency coefficients relate to the causal relationship between the electric E-field and the magnetic H-field. Separate coherency coefficient limits can be applied to AMT/MT post-processing provided by the Zonge NSAMT averaging routine. NSAVG removes portions of the data with low coherence values between the electric and magnetic field data.

In practice this tends to remove periods of low signal strength and portions of the data contaminated by major local noise sources. At this stage of the processing the impedance phase of each portion of the data set is checked to ensure that it is in the proper quadrant. This coherency check has proven to be often effective in removing the effects of large coherent noise sources that are effectively acting as near-field transmitters. The resulting NSAVG averaged Resistivity and Impedance Phase values are suitable for AMT/MT pseudosections**.**

Robust Processing is a more sophisticated procedure, an iterative process based on Robust Processing (Chave and Thompson, 1989). The Time-Series file is divided into smaller, more statistically meaningful time segments of data required for Robust Processing.

The first stage of Robust Processing makes a "least squares" estimate of the impedance values. For "least-squares" methods to successfully estimate the impedance, the inherent errors must have a Gaussian distribution, an assumption that is often not met by natural source MT-type data. The Robust Processing method forces a Gaussian distribution by down-weighting Outlier points and then calculates a new least squares estimate. This process continues until a stable solution is obtained. This process effectively eliminates the influence of a small number of high power anomalous readings. Calculated values failing to meet Coherency Coefficient criteria are shown in the pseudosection as bracketed [ ] Max/Min values, or are left blank.

Processing Flow for Remote Reference AMT/MT Data



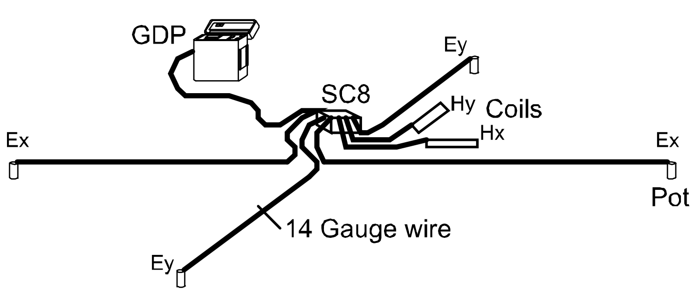
Scalar and Tensor Arrays used in AMT/MT

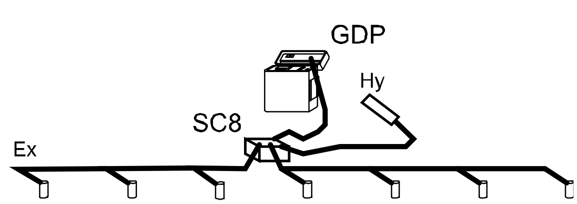
While electric field and magnetic field tensor measurements provide more comprehensive detail at each station, production rates using the scalar AMT array helps maximize production coverage (distances of one or more line-kilometers per day). With an eight channel GDP-32^{II} and one external eight channel SC-8 Signal Conditioner, up to eight analog signals can be acquired. A typical AMT scalar setup might employ up to seven 100-meter electric field dipoles (each measuring Ex, for a total setup length of 700 meters) and a single magnetic field sensor (Hy). Past geothermal and water basin studies have used six 100-meter electric field dipoles. On certain high-resolution mining related program, seven 25-meter electric field dipoles have been used with the ANT/6 magnetic field sensor for a total coverage of 175 meters for each setup.

Up to 16 analog channels are available using the GDP-32^{II}. There are practical logistical constraints to measuring over eight electric and magnetic signals from a single location. This is especially true operating in rough terrain with poor access along survey lines. A much better solution is to use multiple GDP-32^{II}'s in this situation. Multiple GDP-32^{II}'s can be synchronized together. This allows the "Remote Reference" Robust Processing option to be used with multiple Time-Series files collected with uniform clock-time.

Natural Source AMT/MT Arrays

Tensor MT Setup

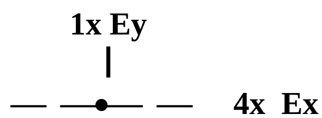




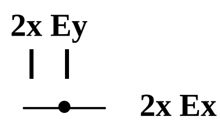
Scalar MT Setup

These are examples of two array types used by Zonge crews in the field. In practice tensor data are often collected using several array configurations rather than the typical single-station "**X**" style MT tensor array shown above. In the specialized quasi-tensor arrays shown below, magnetic field sensors located near the GDP-32^{II} are used with multiple electric field dipoles. In this schematic, multiple electric field dipoles "—" are linked to a centrally connected receiver "• ", like this "—•—**".**

A schematic of the crossed "**T**" electric field tensor array looks like this:



A schematic of the double "**LL**" electric field tensor array looks like this:



Use of the "**T**" and "**LL**" arrays are appropriate for projects where continuous tensor coverage is desired. While neither of these specialized arrays provide symmetry for electric and magnetic field measurements, tensor-like production in the traverse direction (along Ex) is increased. Never the less, the best linear production rates are obtained with the scalar AMT array already pictured. This array provides NSAMT inversion models that are comparable to controlled source CSAMT, an accepted industry standard.

The electric-field signal is sensed as a voltage by non-polarizable porous electrodes located at the ends of each dipole shown in the arrays. This voltage is then transmitted to the receiver with 14-gauge insulated wire and is recorded as a potential difference.

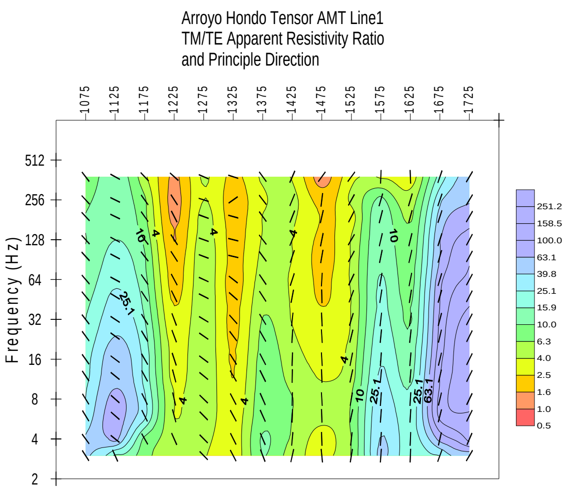
While scalar arrays are easily modified to accommodate needs in the field, tensor coverage tends to be more structured. If time is important, there are fewer choices for optimizing data quality and daily AMT production when using the tensor array. In general, the scalar option provides faster production than is possible with the tensor array.

The Importance of TM and TE Modes

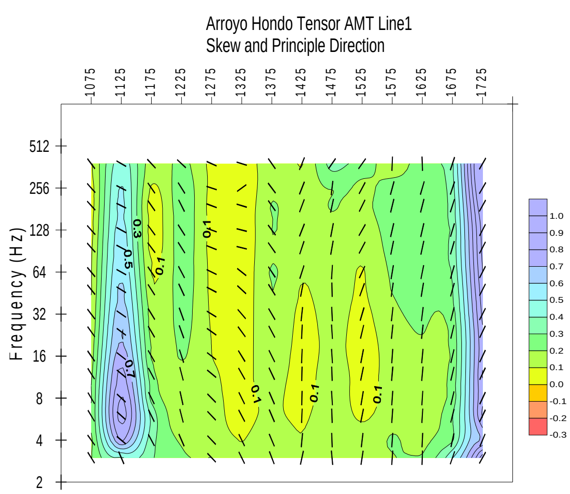
TM and TE are actually defined by geologic strike and the position of the AMT array, and only have real meaning in 2-D or 3-D situations. Strike and direction are not part of the 1-D layered "universe".

AMT data collected with the electric field perpendicular to geologic strike is defined as the Transverse Magnetic (TM) Mode direction. Data collected with the electric field parallel to strike are defined as Transverse Electric (TE) Mode. TM and TE modes are affected differently by the position of any multi-dimensional structure. Scalar results are generally inverted in the TM mode. This may cause distortions if geologic contacts are strongly three-dimensional, or if contacts are parallel or sharply oblique to the survey line. Tensor results are inverted when combining the TM and TE modes. This helps to image multi-dimensional changes.

The apparent resistivity ratio TM/TE is used in tensor MT analysis. The "Principle Direction" represents the electrical orientation with respect to the survey line. While both factors are useful in displaying tensor results, the importance of TM and TE for Zonge has more to do with imaging geology with the SCS2D 2-D inversion.



In the real world of tensor AMT, the TM/TE ratio may change from frequency-to-frequency. A plot combining the TM/TE ratio with "Principle Direction" is shown here. (These plots should be compared with the 2-D resistivity image from the Arroyo Hondo tensor AMT survey seen on page 18.) These TM/TE ratios relate to multi-dimensional resistivity changes. The orientation of the "Principle Direction" does not represent a solution defining geologic strike. It simply shows the alignment of the TM response with respect to the survey line.



The Skew plot is based on off-diagonal values that are part of the AMT tensor matrix. Similar to the TM/TE resistivity ratio, skew is a measure of non-symmetric geologic contacts crossing the survey line. Both the TM/TE ratio and Skew images suggest resistive features beneath stations 1075 and 1725. A high-angle resistive contact may extend below station 1375.

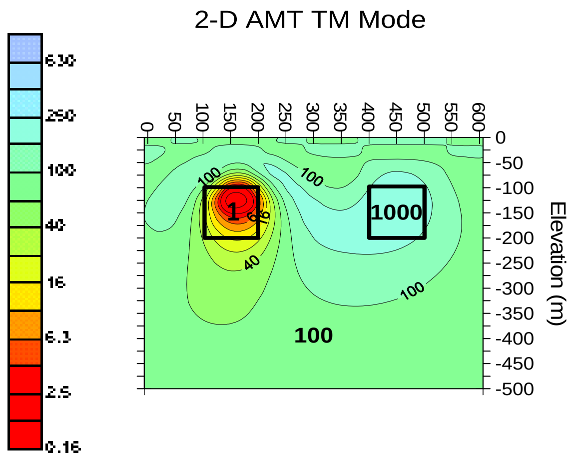
2-D Inversion Models Imaged with SCS2D

To obtain the best use of these far-field NSAMT data, the Zonge two-dimensional earth inversion (SCS2D) is applied to image resistivities. Ex and Ey refer to the directions of the array used to measure the electric field. Typically Ex are scalar data collected in the traverse direction, similar to the standard convention used in most CSAMT surveys. 2-D inversions of scalar data are generally based on the scalar values of Ex and the matching orthogonal Hy value. Tensor NSAMT data measure additional components which provide information about directionality.

For the 2-D inversion models, the AMT array orientation is important. In many situations strike and grid directions do not always coincide. TM and TE mode data are defined by geologic strike. Survey line orientation needs to be considered if scalar 1-D and 2-D inversion modeling are required. Where possible, it is best to align scalar NSAMT traverse lines perpendicular to geologic strike. TM modeling will correctly image conductive and resistive features crossed by such lines.

While oblique contacts and multi-dimensional geologic features may strongly influence scalar results, in general scalar data effectively images most geologic contacts when data is collected roughly perpendicular to geologic strike. The $RhoC_{xy}$ resistivity, calculated from Ex and Hy, will represent the TM response. The result is that the 2-D inversion models based on scalar data reasonably image geology beneath the transect. Scalar NSAMT logistics provide great flexibility where survey line orientations can be changed to match geologic targets.

2-D inversion models have several advantages over 1-D models in that the 2-D inversion shows two-dimensional shaped structures (for example, edges associated with contacts at depth). Through use of the 2-D inversion, topographic effects are removed from modeled resistivities and correct depths are calculated accordingly. Small, shallow conductivity anomalies responsible for static-shift are recognizable. The 2-D inversion removes the need to perform static-shift corrections normally required for the 1-D inversions. The 2-D inversion is able to successfully model either the TM or TE dipole orientation, but assumes the survey line crosses geologic strike on the perpendicular. The 2-D assumption assumes that the calculated conductivity extends infinitely perpendicular to the section (in and out of this page). The plane of this page represents the AMT modeled depth section in the traverse direction.



The forward 2-D Model used for this Synthetic AMT Inversion is shown in BOLD lines with resistivities in ohm-m

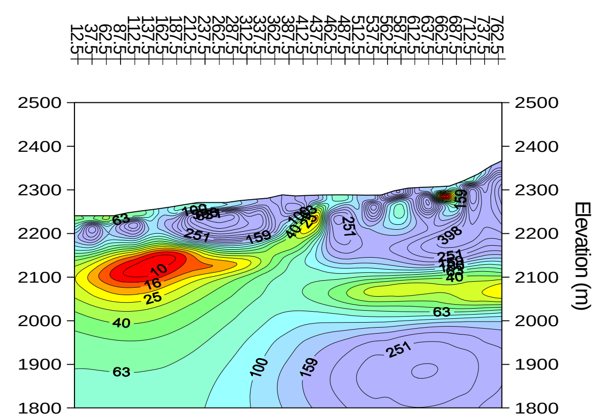
This 2-D inversion of TM mode data illustrates imaging of conductive and resistive bodies. In this modeling exercise, synthetic AMT data were generated for a conductive and a resistive prism embedded in a uniform 100 ohm-m background. Both prisms were 100 m below the surface, 100 m wide, 100 m deep, and with infinite strike length. The modeled results in this case accurately image both the conductive and resistive prisms, and provide good estimates for the depth and width of each.

The 2-D inversion of the TE view is not shown. While the TE mode effectively images the conductive prism, resistive features are only seen with difficulty...if at all.

Results for all 2-D inversion models are shown as color shaded cross sections, with stations listed across the top and increasing depth down the side. In these plots, low resistivities are shown with "warm" colors (orange, red) and high resistivities are shown in "cool" colors (blue, green). It is important to note that the smooth-model inversion program shows gradational changes in resistivity, rather than abrupt, blocky changes, regardless of the true geological structure.

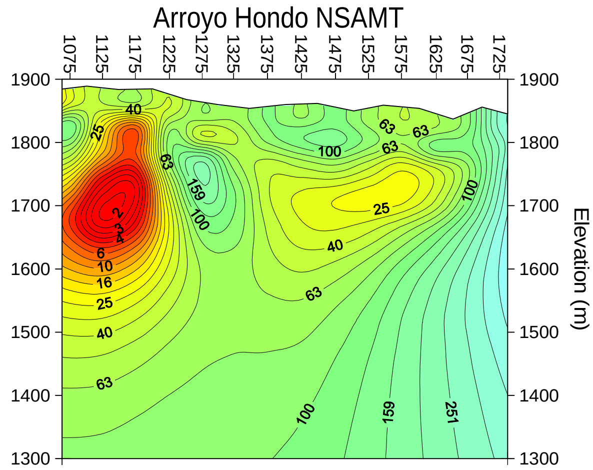
Two 2-D inversion models are provided as examples. Inversion calculations are controlled by limits set to control the sensitivity and smoothness of the modeled results. These control parameters can be important where localized changes in data quality are observed. Controls can also define geologic contacts. Boundary conditions can be set to create a neutral solution response. The 2-D inversion models shown here are based on SCS2D default inversion parameters.

This is an example of a 2-D image produced from scalar NSAMT resistivity data ($RhoC_{xy}$). This images geology in the vicinity of underground mine workings with ore-grade deposits controlled by geologic contacts beneath station 475. The high-angle contact separates resistive intrusive rock from a more conductive shale-limestone complex.



Scalar NSAMT Survey
2-D Smooth-Model Inversion of
Scalar NSAMT Impedance Data
Based on NSAMT Raw Data
a = 25 meters

**Data provided by Minas Comermin, S.A. de C.V.
San Martin Mine, Queretaro, Mexico**



2D Smooth-Model Inversion
Tensor AMT Data

Length =50 m

Data provided by La Cuesta International
Arroyo Hondo Prospect, Durango, Mexico

This is an example of a 2-D image produced from tensor NSAMT resistivities. A plot of the corresponding apparent resistivity TM/TE ratios and "Principle Direction" vectors is shown on page 15. While dipole-dipole resistivity data identify a thin horizon of conductive shale at an elevation of 1700 meters (confirmed by drilling), the tensor NSAMT images suggest this conductive horizon may be cut by high-angle resistive structure. The combined TM/TE ratio and "apparent strike vector" image confirm this observation. The effective depth of this tensor NSAMT survey is thought to be 400 to 500 meters.

2-D inversions have been shown from groundwater basin studies, geothermal investigations and mine exploration work. These 2-D inversion models show reasonable detail to depths of 500 meters (about 1600 feet). It is possible for AMT/MT results to image geology below 500 meters in more resistive ground by decreasing the floor frequency. However there are practical limitations in resolving features below certain sizes at depth. This limitation relates to target size and conductivity contrasts. Because of these limitations, interpretations based on either 1-D or 2-D data at depths significantly below 500 meters should be viewed critically in terms of target expectations.

Only features the size of 15% of the burial depth, or more, will be reliably imaged at depth. This is one reason that survey strategies used in natural source AMT and MT surveys may radically differ. Not only are production rates significantly different because of the extending stacking and averaging time required for MT surveys, but also target sizes required seeing at depth with the deeper MT soundings are much larger in comparison to near-surface features easily identified by NSAMT.

NSAMT, an Environmentally Friendly Approach to Electromagnetic Geophysics

NSAMT is a passive electromagnetic imaging technique using the earth's magnetotelluric field to map geologic contacts and structure typically to depths of 500 meters or more. With the lower MT frequencies, imaging can be extended deeper. The ability of identify geologic features varies with depth and depends upon target size, resistivity contrasts and contact geometry.

The Zonge AMT system can be configured to investigate a number of different targets by selecting an appropriate array configuration and frequency bandwidth. Besides selecting suitable dipoles for measuring the electric field, the AMT array is easily configured to collect CSAMT-type scalar, vector or tensor field data. All of these data are easily processed with Zonge DATPRO© software with results imaged by SCS2D inversion software. In this paper, examples of 2-D imaged scalar and tensor NSAMT data demonstrate different applications.

These 2-D images clearly identify key geologic features whether the target is groundwater, geothermal or mine related. NSAMT data collection, with the Zonge GDP-32^{II}, is a practical geophysical tool for imaging resistive and conductive geology at depth. In addition, the passive NSAMT technique is inherently safe for use in areas with people and livestock. A major survey was recently completed is a popular recreational area without incident. No explosives or high-voltage electric power sources are required to produce remote signal sources for the NSAMT survey. The field system is highly portable and the hardware easily fits into several medium sized shipping cases.

Whether the task is engineering oriented or involves exploration services, natural source AMT could be the answer for your program. In the last two years, Zonge NSAMT has been used in mining, water resource management and geothermal programs. Historically, MT has been an accepted geophysical tool used in natural gas and petroleum exploration programs. The Zonge AMT System is designed to collect MT data as well.

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