Geode EM3D

p/n 68002-01 REV. D

Operation Manual

For

Geode EM3D running ***GeodEM*** *Ver. 3.0*

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Chapter 1: System Components

A. Introduction: basic theory of operation, networking, and data acquisition

The Geode EM3D is a distributed network of EM receivers. Each receiver has six channels which can be configured with up to three magnetic (H) channels and from three to six electric (E) channels, depending on the number of magnetic channels used. All receivers communicate to one another and to a PC Controller through a hard-wired Ethernet backbone. The fundamental theory of MT, AMT, and CSAMT can be found in a brief review in Appendix 1. Fig 1. shows a four-receiver network consisting of four receiver modules with twenty E-field channels and four H-field channels.

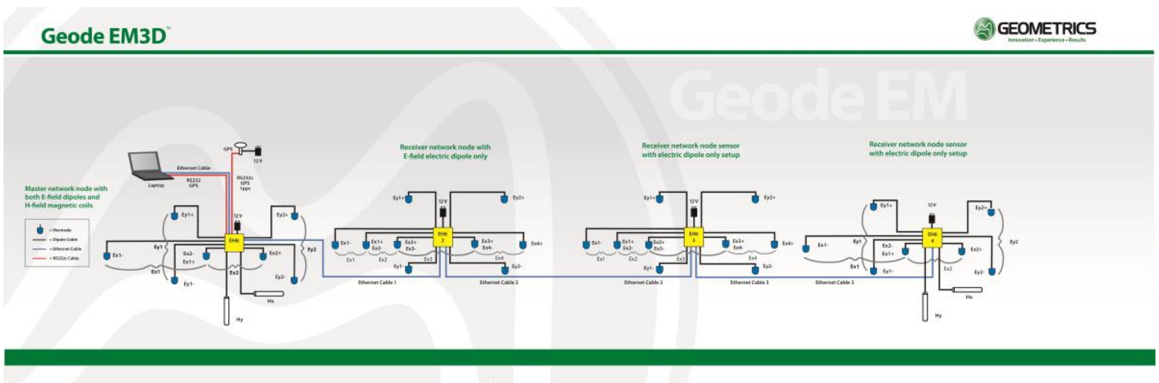


Fig. 1 Network sample setup

B. System components: A typical Geode EM3D will consist of the following components:

1. Laptop controller with the acquisition software and processing software

2. Network Interface Box (NIB)

Fig. 2 Network Interface box

The picture in Fig. 2 shows the NIB with two cables. The large yellow cable attaches to the Ethernet 10-pad connector on the NIB and the other end to the

10-pad connector on the receiver box. The black cable with the RJ45 connector connects to the RJ45 port on the PC Controller.

There are three positions to the NIM switch: “Battery Test”, “Enable Power Down”, and “Enable Power Up’”. Details of NIB operation is given in section *** below.

3. GEM3D Receiver: The six-channel GEM3D receiver is discussed in more detail in the receiver setup section below.

Fig. 3: GEM3D receiver box

4. Magnetic Induction Coil: The Geometrics G20K coils operate on a band width of 0.1 Hz to 20k Hz. The operation range of the Geode EM3D CSAMT system is 0.1 Hz to 10 kHz. Coils specifications are available at www.geometrics.com or by contacting sales@geometrics.com

Fig. 4: G20K magnetic coils.

5. Electrodes: Stainless steel stakes. Non-polarizing porous-pot electrodes have also been tested.   Both copper-copper sulfate and lead-lead chloride have been tested successfully. These can be supplied by the customer or at an additional cost by Geometrics.

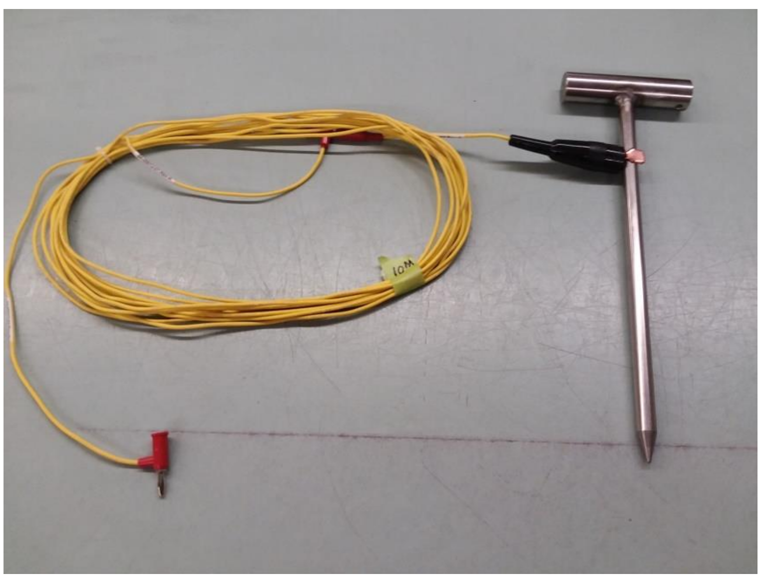


Fig. 5 Stainless steel electrode and cable

6. Ethernet Cables: The Geode EM3D uses a proprietary Ethernet cable that is specially ruggedized for field use. It also has an isolated “trigger” wire to synchronize all receiver channels on the network without concern for any delay

from the Ethernet communication protocol. The cable wiring and connectors are symmetrical so the connections are reversible.

Fig. 6: Ethernet cable with 10-pad connectors on each end.

7. GPS with cables: Synchronization between the CSAMT transmitter and the Geode EM3D receivers is through scheduler software using GPS time on the transmitter and PC Controller.   There is only one GPS unit to control all GEM3D receivers since the GPS connection is to the PC Controller which in turn triggers the acquisition through the dedicated trigger wire in the Ethernet cable described above.   The GPS used at the writing of this manual is the Global Sat BU-353S4 Receiver but nearly any good GPS will work.

Fig. 7 GPS receiver with USB cable and GPS antenna (black)

Chapter 2: Geode EM3D PC Controller setup

The GEM3D Controller is an MS Windows based, ruggedized PC controller designed for field acquisition work. The controller system consist of the ruggedized PC, an external GPS with antenna and USB cable and GPS driver software, a Network Interface Box (NIB), an Ethernet cable to the nearest GEM3D receiver, and the controller software.

a. Ruggedized PC: The Geode EM3D uses a commercial laptop computer specially adapted for field use operation.

b. GPS: The supplied GPS is used to synchronize the receiver acquisition to the controlled-source transmitter. It is used as a timing device to start all the receivers' acquisition at the same time. The antenna should be placed at a position that will allow optimal reception for the GPS satellites.   The USB cable functions both to send data from the GPS to the PC Controller and to provide power from the PC Controller to the GPS. The bottom left of the GeodEM2010 screen shows the number of satellites detected by the GPS receiver. In order to function properly you must lock on to at least three satellites.   The number of satellites detected may vary from GPS receiver to GPS receiver so consult your GPS operator's manual.

c. NIB (Network Interface Box): The NIB allows the Ethernet interface between the GEM3D receiver network and the Ethernet board on the PC Controller.   The toggle switch can be in any of three positions as follows:

    i. Enable Power UP: Pressing the switch to this position will automatically power up the GEM3D receiver. The startup signal is on a dedicated line in the Ethernet cable so it does not require a working Ethernet.
    ii. Enable Power Down: This will shut off the GEM3D receivers when the SAS software is closed.
    iii. Plug the Ethernet cable connector from the GEM3D into the Ethernet connector on the NIB as shown. Next plug the RJ45 connector from the NIB into the Ethernet port on the PC Controller.
    iv. The GEM3D connects to a PC via the Network Interface Box (NIB; see below). The NIB adapts the digital interface cable to a standard RJ45 connector, which plugs into the network port on your PC.

v.

Figure 8: Network Interface Boxes; single-line (left).

Figure9: Front panel of Network Interface Box.

In addition to being an adaptor, the NIB performs the function of powering the GEM3D receivers up and down. Refer to the above figure. Prior to starting SAS, switch to the **Enable Power Up** position. This will power up a portion of the acquisition board on the first GEM3D on each line, enabling them to respond to software commands. The first GEM3D receiver is the one closest to the acquisition computer in the array. Upon starting SAS, a start command will be sent to each of these GEM3D, which will in-turn power up the rest of the GEM3Ds. Once the software is up and running and all GEM3Ds are recognized, return the switch to the **Enable Power Down** position. This will cause all of the GEM3Ds to shut down when the software is closed.
Note: *If you forget to switch to the Enable Power Down position and the Geodes don't shut down when you close the software, you can restart the software, switch to Enable Power Down, and close the software again.*

Test Button

The **Test** button:

It powers up the GEM3D for testing purposes. This can be done while laying out the instrumentation – no connection to the controller PC or SAS is required. For instance, if you push the **Test** button on two adjacent GEM3Ds, a blinking link LED on each unit (see discussion of blink codes below) will indicate that each unit is receiving link pulses from the other.

d. Installation of required software onto Controller: All required software should have been pre-installed on the PC Controller from the Geometrics factory. The following information is only required if the software must be re-installed.
e. SAS (System Acquisition Software)
f. GPS software and drivers
g. GeodEM2010

Chapter 3: GEM3D receiver setup.

Connecting to the GEM3D receiver: The GEM3D receivers have panel connections for the power, Ethernet cables, ground, E-field dipoles, and magnetic sensors. We will look at each individually:

A. Panel-1 Electric field terminals

Fig 10: GEM3D receiver E-field (telluric) connectors

Perhaps the most difficult part of setting the connections to the GEM3D receiver is properly connecting the electric dipole cables to the terminals.   The red and black terminals of CH1 are + (red) and – (black) of E-field channel 1. .   The red and black terminals of CH2 are + (red) and – (black) of E-field channel 2. Channels 3, 4, 5, and 6 all have one or more common terminals as follows: CH3 red is + and yellow is -. CH4 yellow to right is channel 4 positive and yellow to left is channel 4 negative. CH5 yellow to right is channel 5 positive and yellow to left is channel 5 negative. CH6 yellow is positive and CH6 black is negative. All the yellow terminals share a common connection to the terminals to the right and/or left of them.

IMPORTANT NOTE: Because of the nature of shared electrodes all surveys should be laid out such that the first electrode in the line is the positive pole of Ex1. For example, if CH1 is Ey1 and CH2 is Ex1 the electrode connected to the red terminal of CH2 should be the first electrode in the profile line.

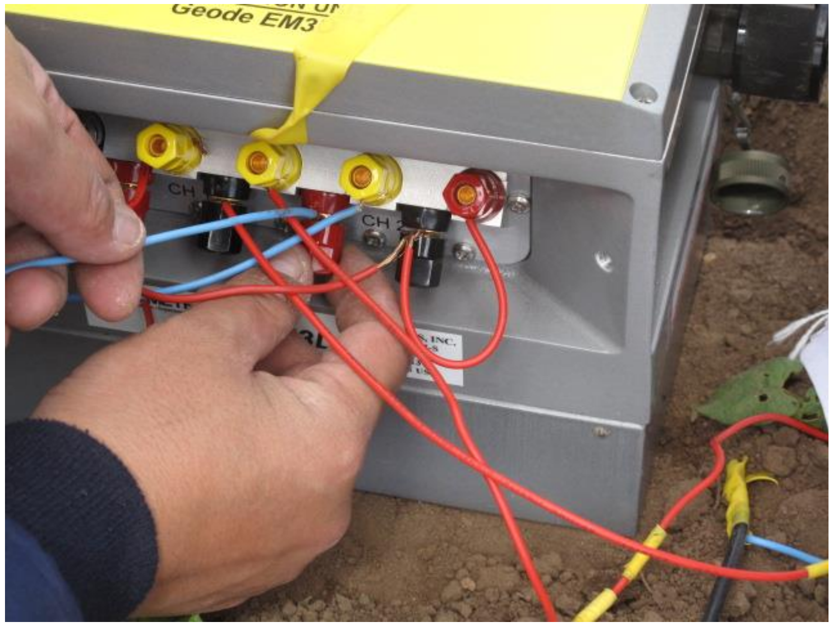


Fig. 11: connecting telluric lines (E field)

B. Panel-2 Magnetic field terminals

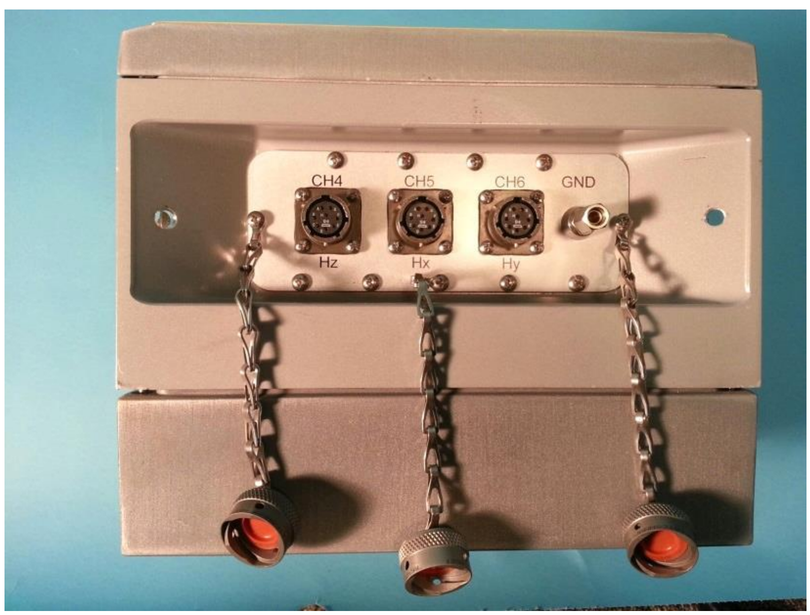


Fig. 12 Channel 4 = Hz, Channel 5 = Hx, Channel 6 = Hy

Fig. 13: Hy and Hx connected disabling E channels 6 and 5 respectively

There are three magnetic field channels on the GEM3D Receiver box. These are labeled from left to right as Hz/CH4, Hx/CH5, and Hy/CH6. If a coil is plugged into Hy the E-field channel CH6 is disabled and the H-field channel Hy/CH6 is enabled. If a coils is plugged into Hx the E-field channel CH5 is disabled, and if a coil is plugged into Hz the E-field channel E4 is disabled. For example, if coils are connected to Hx and Hy, the E channels 1, 2, 3, and 4 are available but channels 5 and 6 are not. This is done automatically when a coil is connected to one of the H channels.

C. Panel-3 Power + Ethernet

Fig.14: GEM3D side panel

There are two 12V power connectors. There is no internal battery so all power must be supplied by an external 12V battery. Having two power connectors allows the operator to swap batteries without turning off power to the receiver. The blue Ethernet LEDs flash at a rate of once per second when the Ethernet board is powered up (fast flash powered up mode). It changes to a rate of once every six seconds when the SAS acquisition software starts up and detects the Ethernet board in the GEM3D receiver (slow flash acquisition mode). The blue “12V DC” power LED flashes at the same rate as the Ethernet LED as an indicator the GEM3D receiver has adequate battery power.

i. Ethernet + Test Button

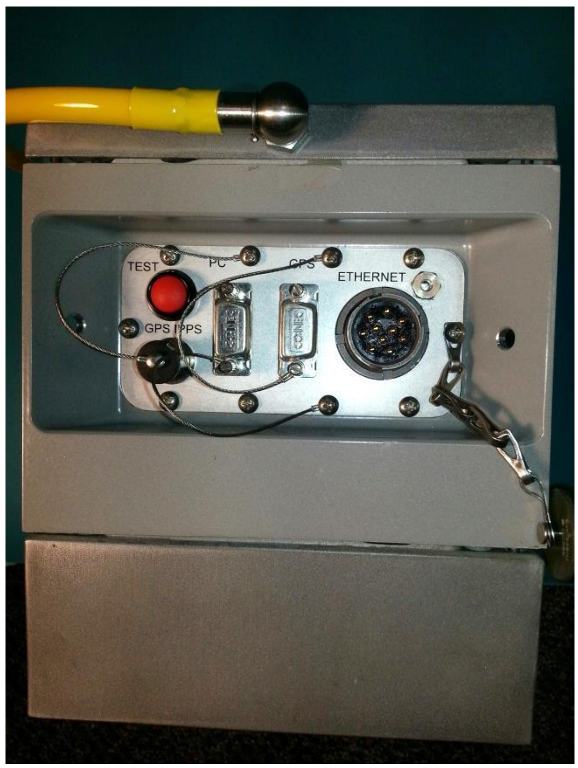


Fig. 15: GEM3D side panel

Fig. 16: Connecting Ethernet cable

There are two Ethernet connectors on the GEM3D receiver. One is on the same side as the power connectors and the other on the opposite side. The two connectors allows for network connections to two other adjacent receivers, or one receiver and the PC Controller. These connectors are reversible so it does not matter which side sends Ethernet to the PC Controller and which side connects to adjacent receivers. Pushing the red “Test” button will power up the GEM3D receiver if it has not already been power up with the NIB switch in “Enable Power Up” mode.

D. Electrodes and electrode cables:

Non-polarizing porous pot electrodes are recommended. The Geode EM3D does not use electrode buffers since calibration is done real-time in the field. There are nine electrode terminals as pictured in Fig. 10. The red terminals are considered to be positive by the software. Black terminals are negative, and yellow terminals are shared between two adjacent dipoles and can be either negative or positive, depend on which dipole. When a magnetic sensor is connected to Hy (channel 6) the E dipole on channel 6 is disabled. When Hx on channel 5 is connected the E-field connectors on channel 5 are disabled, and when mag Hz is connected to CH4 the E-field channel four is disabled. Make sure all E-field dipole cables are on the ground and not draped over plants, rocks, etc.. If the dipole cables are swaying or blowing in a wind or breeze it will generate low-frequency EM noise.

E. Magnetic coils and coil cables:

Magnetic coils should be buried to a depth of at least 30 cm to assure it is out of the range of seismic vibration, which can generate low-frequency EM noise. The coils need to be properly aligned and leveled. The Hy coil needs to be parallel to the Ey direction and the Hx coil needs to be parallel to the Ex direction. If using an Hz coil it must be buried vertically.

Fig. 17: Burying G20K magnetic coil

F. Ethernet cables:

The Ethernet cables connect one GEM3D receiver to up to two other GEM3D receivers or one other receiver and the PC controller. There are two Ethernet connectors on each GEM3D receiver box. Both connectors on an Ethernet cable are identical so either end of the Ethernet cable can be plugged into the connector. There is no fixed orientation for the direction of the Ethernet connections. That is, it does not matter if all the receiver boxes are facing the same way or not.

G. GPS:

The function of the GPS receiver is to synchronize the CSAMT transmitter with the GEM3D receiver acquisition. It is also used to set the PC Controller clock. The Geode EM3D scheduler software creates a file that sets all the transmission parameters including the start time of the transmission. The start time of the transmitter can be synchronized to the acquisition time of the receiver through a GPS on the transmitter and a GPS connected to the PC Controller. A GPS receiver is connected to the PC Controller through a USB port. When the scheduled transmission time is reached the PC Controller sends an acquisition trigger to all receivers via a hard-wired cable built into the Ethernet cable. The trigger is on its own dedicated wire inside the Ethernet cable.

H. Data acquisition: See section K.2. Software/GEM3D Controller Software.

I. Transmitter: See the manufacturer's manual or the make and model of the CSAMT transmitter you are using.

Chapter 4: Software

There are three software programs that must be installed for Geode EM3D acquisition operation. These are SAS (System Acquisition Software), GeoEM2010 which is the user interface software, and the GPS driver software. The current GPS is manufactured by GlobalSat, but this may change as GPS technology changes so contact Geometrics, Inc. for the latest information. Nearly any good GPS will work.

1. SAS backbone description: SAS (System Acquisition Software) is the underlying acquisition software which is a modified version of the acquisition components of the SAS seismic software (Seismic Acquisition Suite) for the Geometrics Geode DZ seismic system. It must be installed and operating on the Geode EM3D Controller before data acquisition can take place.
    a. The following files must be installed in order for acquisition to take place. The files "EMmain.exe", "EM.sas", and "EM.log" can be installed by running
        i. Geo2010.exe (location determined by user)
        ii. SAS.exe (c:\geometrics\Seismic Acquisition Suite\)
        iii. EMmain.exe (c:\geometrics\Seismic Acquisition Suite\Firmware)
        iv. EM.SAS (c:\GeometricsSurveyAndSettings\EM\Survey Parameters)
        v. EM.LOG (c:\GeometricsSurveyAndSettings\EM\Survey Parameters)
    b. Available SAS screens
        i. Noise monitor: Described below
        ii. System settings:
            1) Set Date/Time: This allows you to set the system time and date
            2) Test: Tests various performance parameters
            3) Sounds: Sets audio (sound) feedback.

NOTE: The power option for your acquisition computer should be set to never put the computer to sleep when it is on battery or plugged in. If the computer goes to sleep during acquisition it can shut down the system.

2. GEM3D Controller software, GeodEM2010: This is the software that the operator will use to start SAS, stop SAS, set up the transmitter and receiver scheduler, start acquisition, and all the other operational functions. Below is a brief summary of the functions available through the software.
    a. File
        i. Open SEG2 File: This option allows you to review raw SEG2 time series files before the SEG2 files are consolidated into a GTS file.

        ii. Open Setup File: Allows the operator to recall a previously configured patch setup for the current survey. This will allow the operator to use a previous setup as the starting template for the new survey.

iii. Open GTS file: The GeodEM2010 software creates a data file from a series of SEG2 files. The extension of the data file is .GTS . Opening a GTS file will display time series on the screen. Clicking "+" or "-" will allow the user to scroll through the time series displays for that acquisition sequence. Display control as follows:
   1. Use enter and backspace keys to scroll through the time series.
   2. Use "+" and "-" keys for zoom control.
   3. Use left and right arrow keys to show additional channel data if there are more channels than are displayed on the screen.

iv. Save Setup File: Saving a setup file will store all the setup parameters created for the survey. This can be recalled later as a template for a future survey using "Open Setup File".

v. Save GTS File: This allows you to save an edited GTS data file.

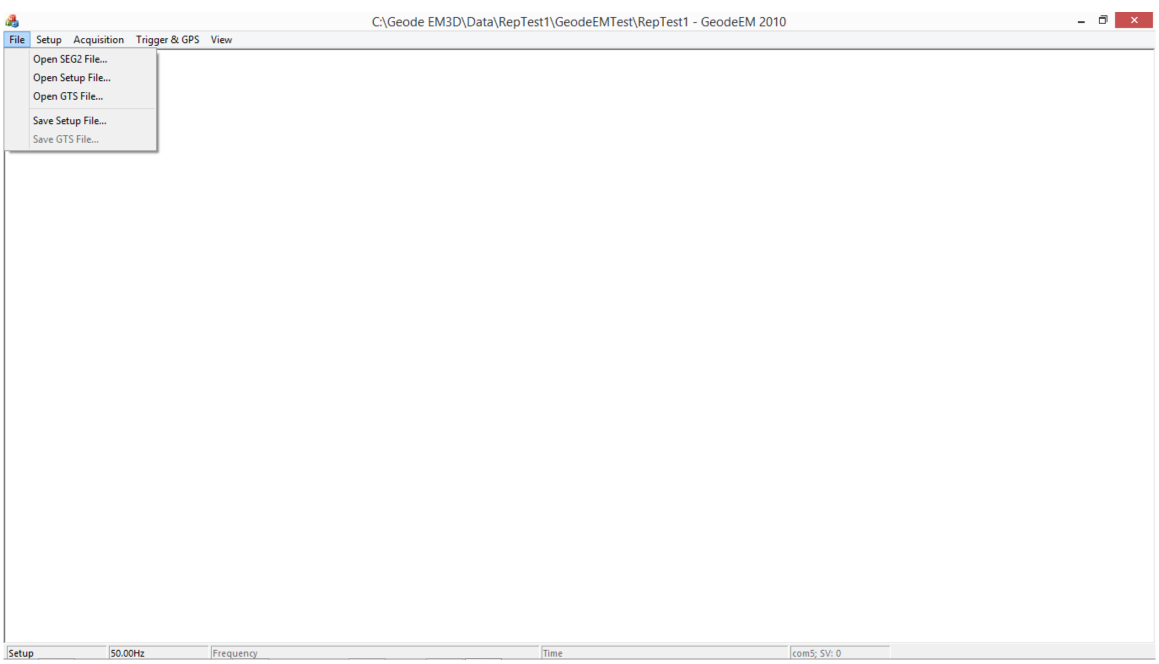


Fig. 18: GeoEM 2010 File menu

b. Setup

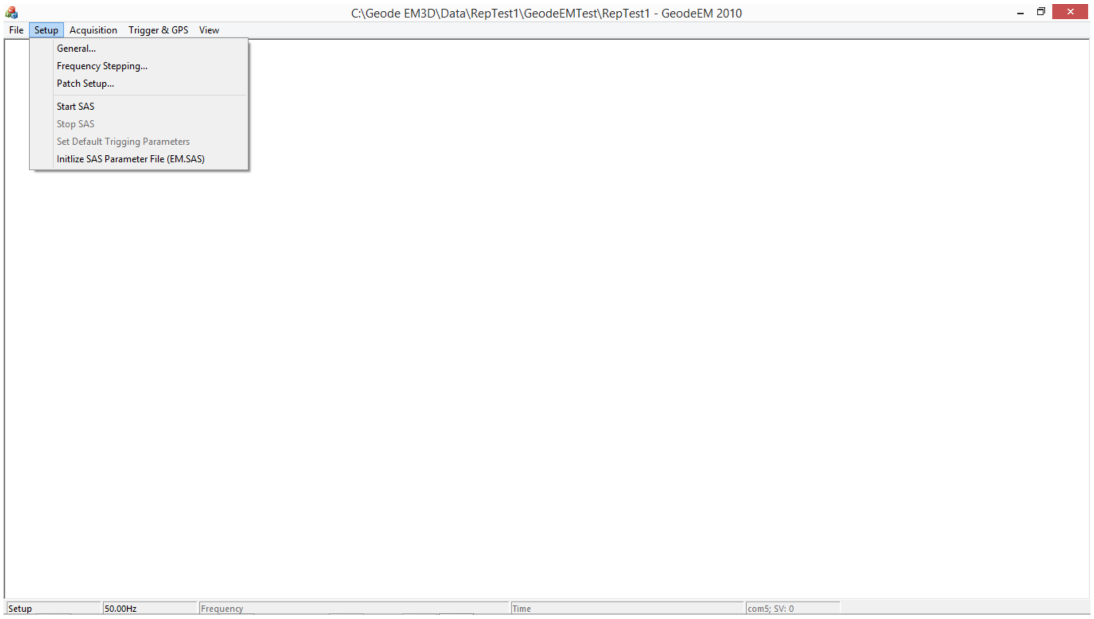


Fig. 19: GeoEM 2010 Setup menu

i. General
   1. Survey block: General information about the survey site.
   2. Coordinate System/Coordinate Parameters: General GPS coordinate information
   3. Line Frequency: Set powerline harmonic filter (50 or 60 Hz)
   4. Auto Line Freq Detection: Automatically sets powerline frequency filters.

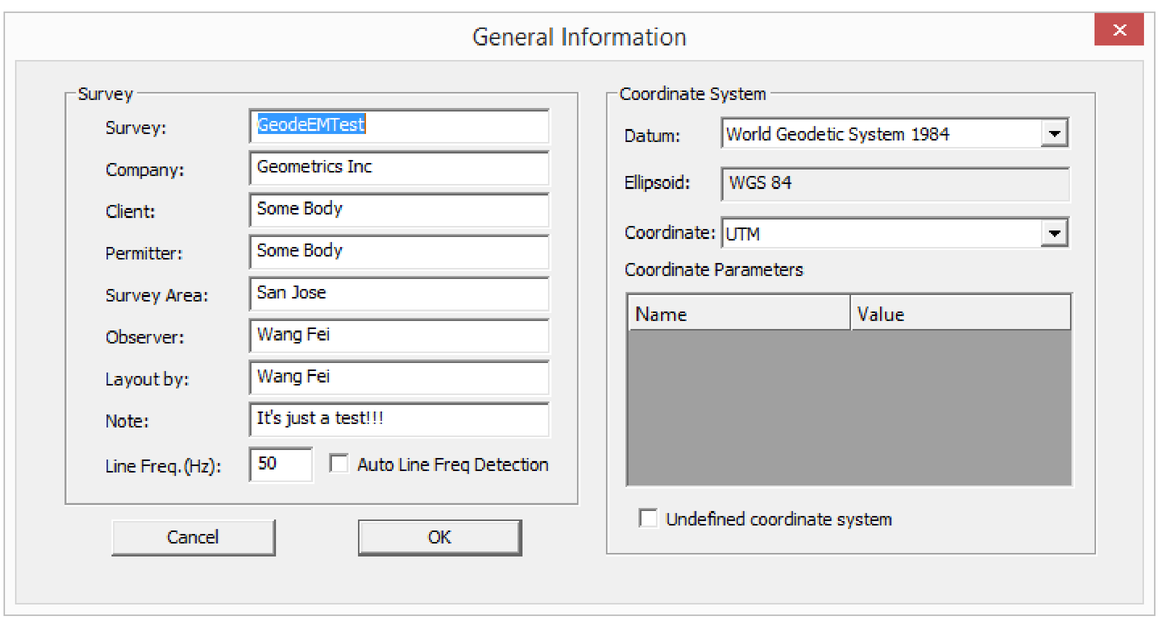


Fig. 20: Setup menu - General

ii. Frequency stepping: This screen allows the operator to set up a frequency schedule for both the CSAMT transmitter operation and the receivers' acquisition.

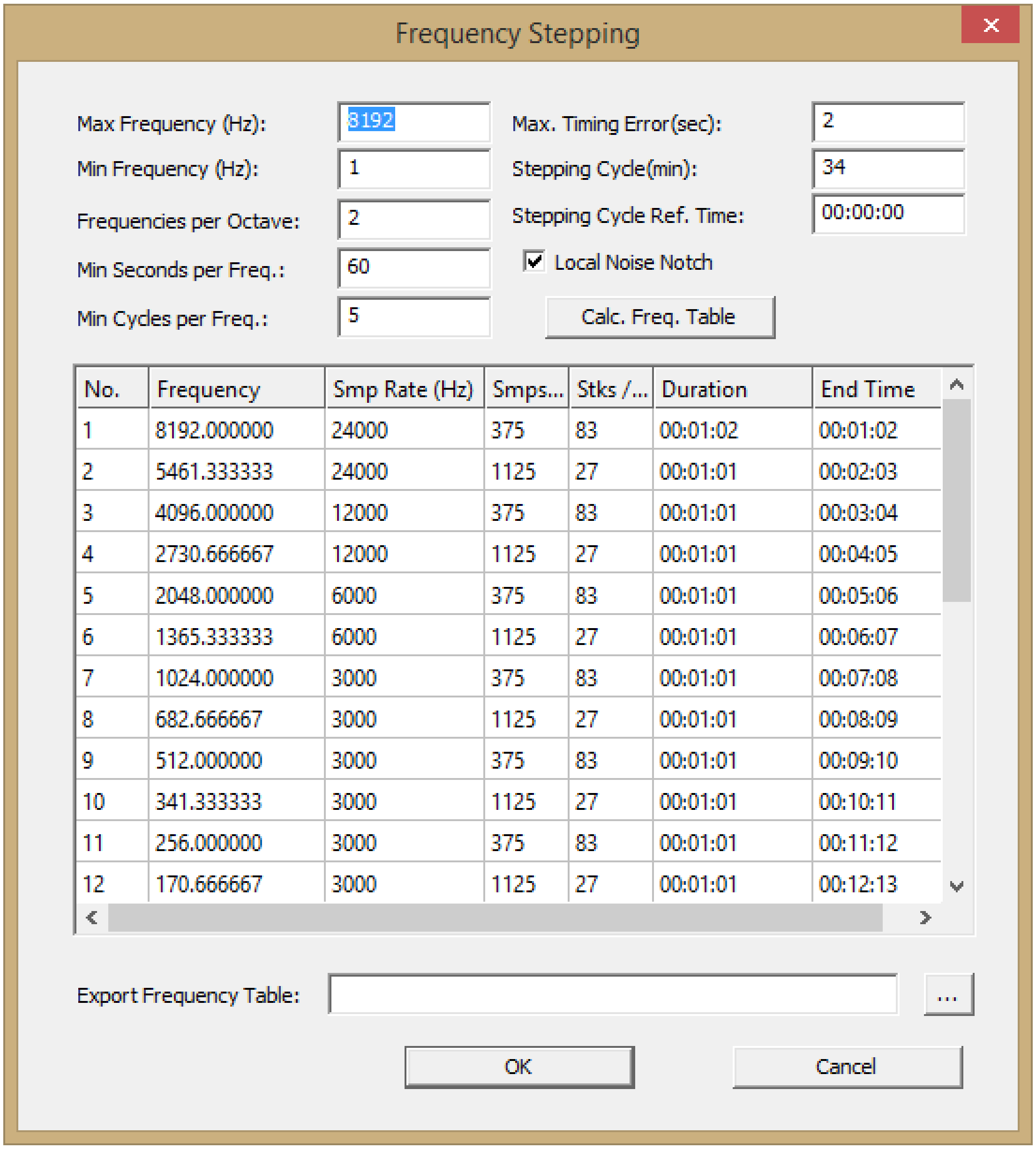


Fig. 21: Setup menu – Frequency stepping

1. Maximum frequency (Hz)
2. Minimum frequency (Hz)
3. Frequencies per octave
4. Minimum seconds per frequency
5. Minimum cycles per frequency
6. Maximum timing error

7. Stepping cycle: This is the amount of time to go through all the frequencies. It needs to be set to provide at least the minimum time to run through all the frequencies. If it is not set with enough time for all frequencies the lowest frequencies will be truncated or dropped. If it is more than the minimum, time will be added to the frequencies.
8. Stepping cycle reference time; Starting reference time
9. Local noise notch check box. When the box is checked it will look for high amplitude noise leaking into the CSAMT frequency acquisition band and filter out that noise. Note this only applies to CSAMT acquisition as it cannot be done in broad-band natural-field acquisition.

Setting the parameters in this window then clicking "Calc. Freq. Table" will generate the table of acquisition frequencies displayed in the window. Clicking "Export Frequency Table" will create the receiver and transmitter controller file. To export the frequency table click on the "…" box, give it a path to the file location, and click Save.

iii. Patch Setup:

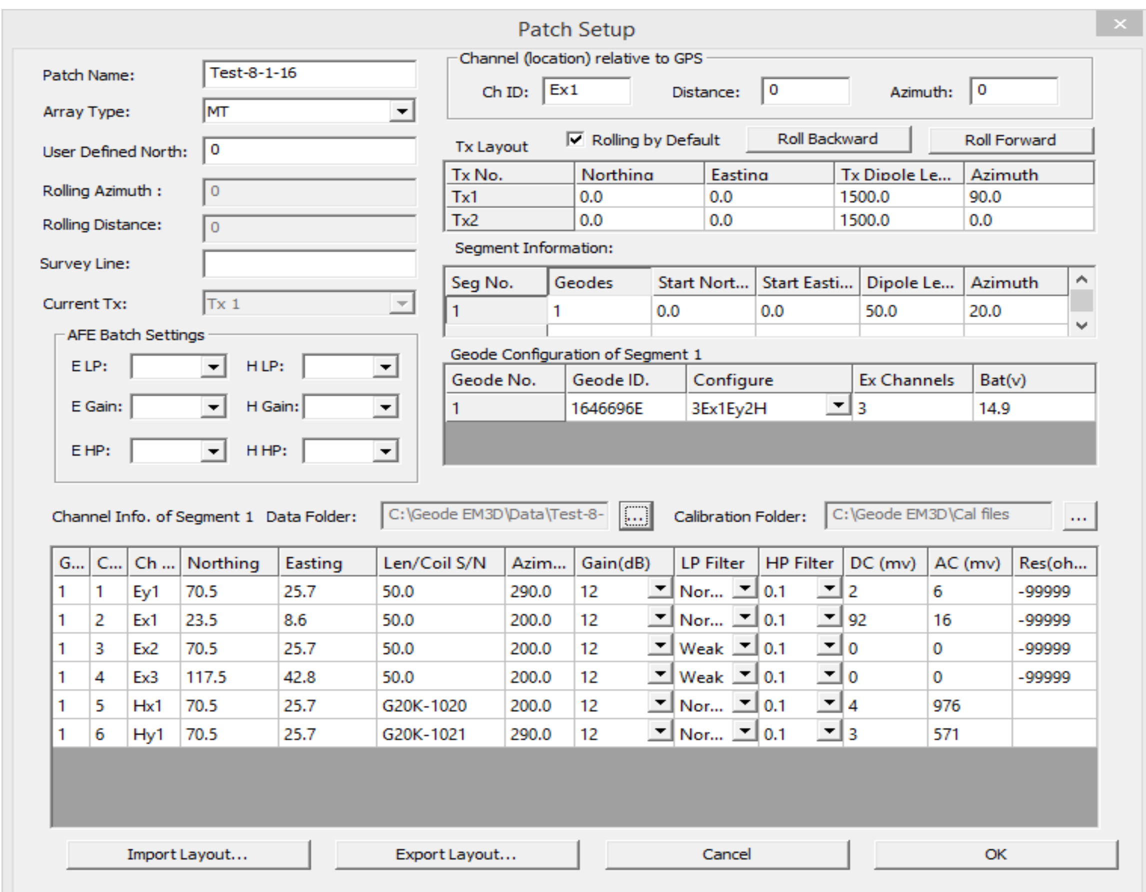


Fig. 22: Setup menu –Patch Setup

Patch Setup is to configure each channel on each GEM3D receiver in the active survey section

1. Patch Name: This is the name of the survey and is used to name the acquired data files**. NOTE: In order for the GeoCSAMT or MTPro processing software to create a continuous line when the stations are rolled to a new position the Patch Name must be change for the new location. If the Patch Name is the same, the processing software will average them together.**
2. User Defined North: The difference between true north and user defined north. Requires both Hx and Hy measurement.
3. Array type: Allows for the selection of the type of survey to be done. "Rotated Scalar CSAMT" allows the magnetic field to be rotated perpendicular to the Ex field.
4. Rolling Azimuth: For a line this is the line azimuth. "Roll Backward" and "Roll Forward" rolls the receiver array setup forward or backward along the profile line.
5. Transmitter Layout: Tx1 indicates one transmitter dipole is used (scalar). Tx2 indicates two transmitter dipoles are used (tensor).
   a. Tx1 easting, Tx1 northing, Tx1 elevation, Tx2 easting, Tx2 northing, Tx2 elevation: These fields are the user the defined orientation and elevation of the transmitter dipoles. Defined by the North reference. If "User Defined North" is set to "0" the azimuth is true compass azimuth.
   b. Tx1 dipole length, Tx2 dipole length: If two dipole are set up for a single transmitter or at two separate transmitters the dipole lengths may be different.
   c. Tx1 azimuth, Tx2 azimuth define compass bearing of two transmitter dipoles.
6. Segment information indicates the number of GEM3D receiver boxes in the line and the line information. The segment represents a single line of GEM3D receivers. The current version of the GeodeEM3D supports only one segment. For a 3-D survey set the single segment is laid out

in a serpentine shape to create multiple parallel lines. No LTU modules are used.

7. Geode Configuration of Segment 1: Allows the user to set or view the channel configuration for each GEM3D receiver in the segment (line). There is only one segment for the GEM3D setup.
8. AFE Batch Settings: Setup of gain and filter settings.
9. Channel Info of Segment 1: Allows for setting the grid coordinates, dipole length (or coil serial number), azimuth, filters and viewing the AC-DC noise and contact resistance for each channel.
10. Data Folder and Calibration Folder creates and points to the location of the data and calibration files respectively.
11. Import Layout and Export Layout reads or saves the patch setup as a template for future surveys.

iv. GPS:

This screen sets up parameters for GPS synchronization with the transmitter and provides information about the status of the GPS. The Com Port setting must match the Com Port assigned to the GPS. The available com ports are displayed in the "All Com Port(s)" field. If it is not clear which port is assigned to the GPS go to the Control Panel, select Device Manager then Ports and view the COM PORT assignment for the device.

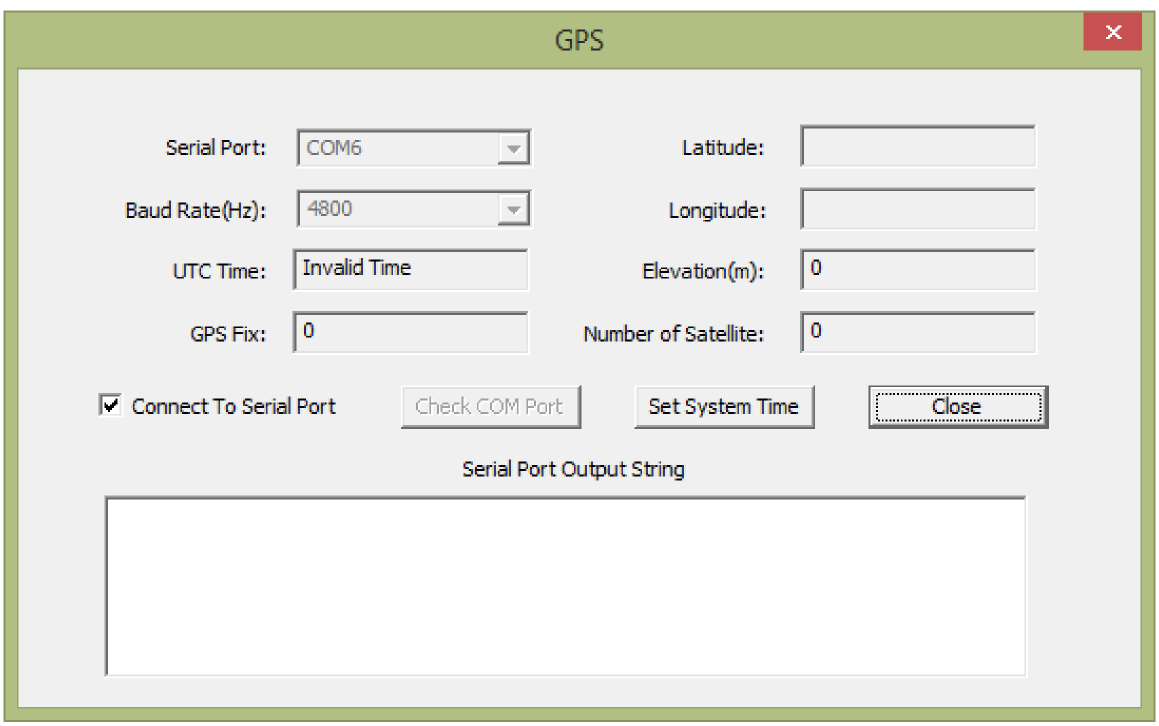


Fig: 30: GPS menu

The menu displays the supported GPS for synchronized triggering of acquisition to the CSAMT transmitter. In this example “UBlox GPS but other GPS receivers can be used.

v. Start SAS: Starts the background acquisition software: This will load the receiver acquisition software and display a noise monitor as pictured below:

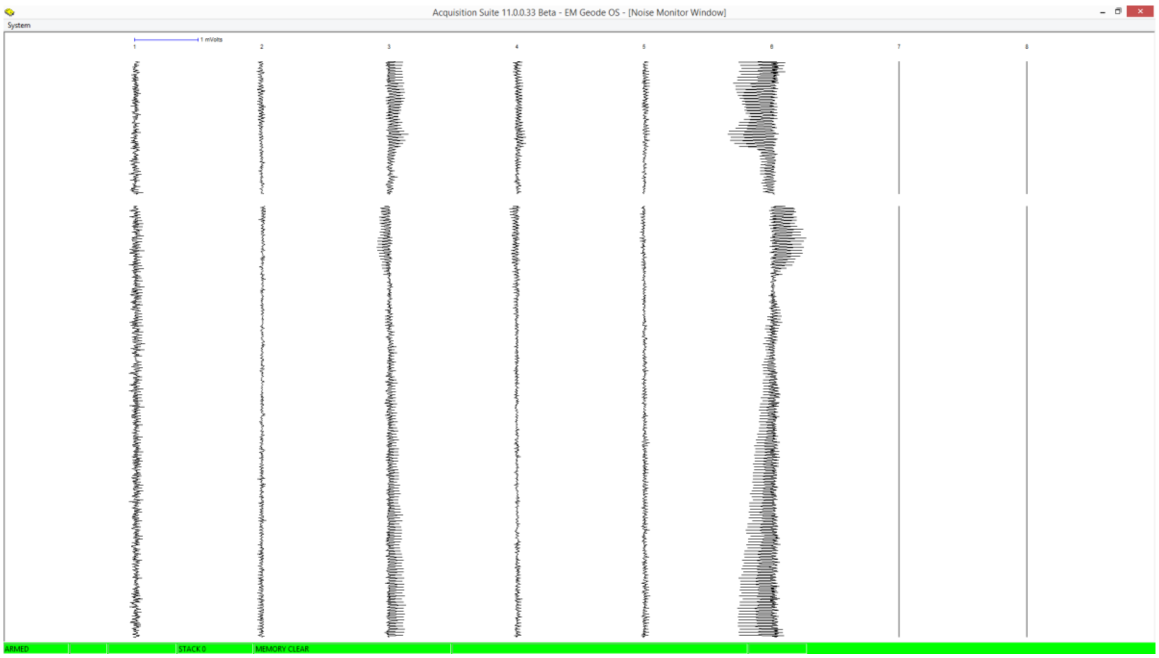


Fig 23: SAS Noise monitor menu

Note the word “System” at the upper left corner of the window. Clicking on the “System” will display the SAS software version number and allow the operator to change the system time and date, set receiver test parameters, and turn on or off various system sounds.

vi. Stop SAS: Closes the background acquisition software.

vii. Set Default Triggering Parameters: This sets a default trigger sensitivity at 50% and trigger hold off time at 0.2 seconds.

viii. Initialize SAS Parameter File (EM.SAS): This creates a new SAS parameter file located at: “C:\GeometricsSurveysandSetting\EM\Survey Parameters”

a. Acquisition: This menu is used to start measurement acquisition.

ix. MT Acq. and Processing

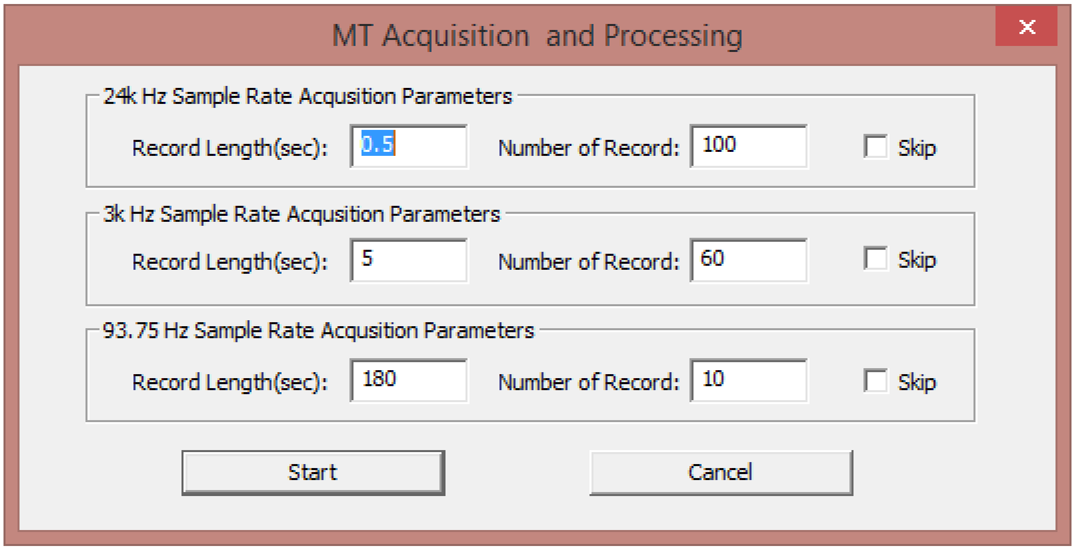


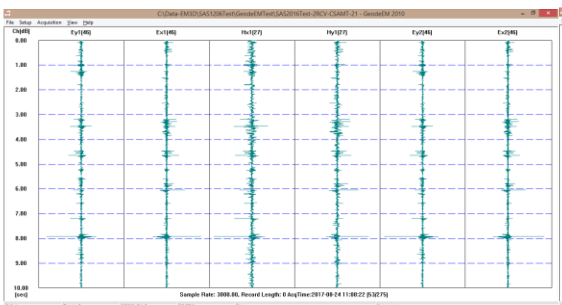
Fig. 25: Acquisition menu

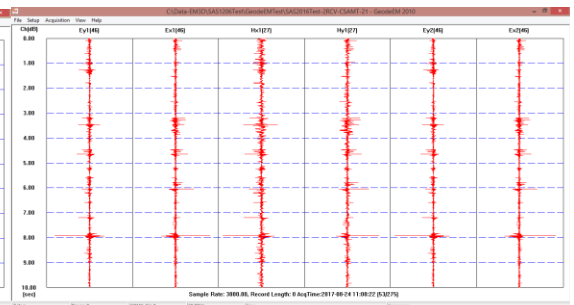
1. Sample rate of 24 kHz, 3 kHz, and 93.75 Hz defines the number of samples per second for the three acquisition frequency bands.
2. The "Record Length" specifies how long, in seconds, each time series will be at the specified sample rate.
3. The "Number of Records" specifies how many time series will be acquired at each sample rate.
4. Delay Between Bands (Sec) defines the delay time between each time series acquired. Each time series is acquired as a SEG2 file which is converted into a common GTS file for the survey.
5. Skip: Checking a skip box allows the operator to not acquire data in the designated frequency band.
6. Cycling Acquisition: The acquisition will automatically continue to cycle through the frequency bands until acquisition is manually stopped.
7. Note that you can change the time scale displayed on the screen by using the "-" and "+" keys to expand or contract the portion of the time series displayed.
8. Note that you can scroll through a sequence of time series by using the "enter" and "backspace" keys to go forward or backward in the sequence.

9. Use CTL-DEL to remove a time series.

How to review and edit time series after acquisition:

- To read in a previously recorded data set start *GeodeEM* and go to "File-Open GTS File".
- Navigate to the folder where the acquired data is stored and select the desired .GTS file. Click on "Open". The GTS file will be loaded into *GeodeEM.* The time series screen will be displayed.
- To move up to the next time series hit the "Enter" key. To move back to the previous time series hit the "Backspace" key.
- To mask the time series so it is not used in the data processing click "CTL-DEL". This will mask out all channels for that time series and the time series display will change from blue to red. See the images below as an example:
- Active time series De-activated time series





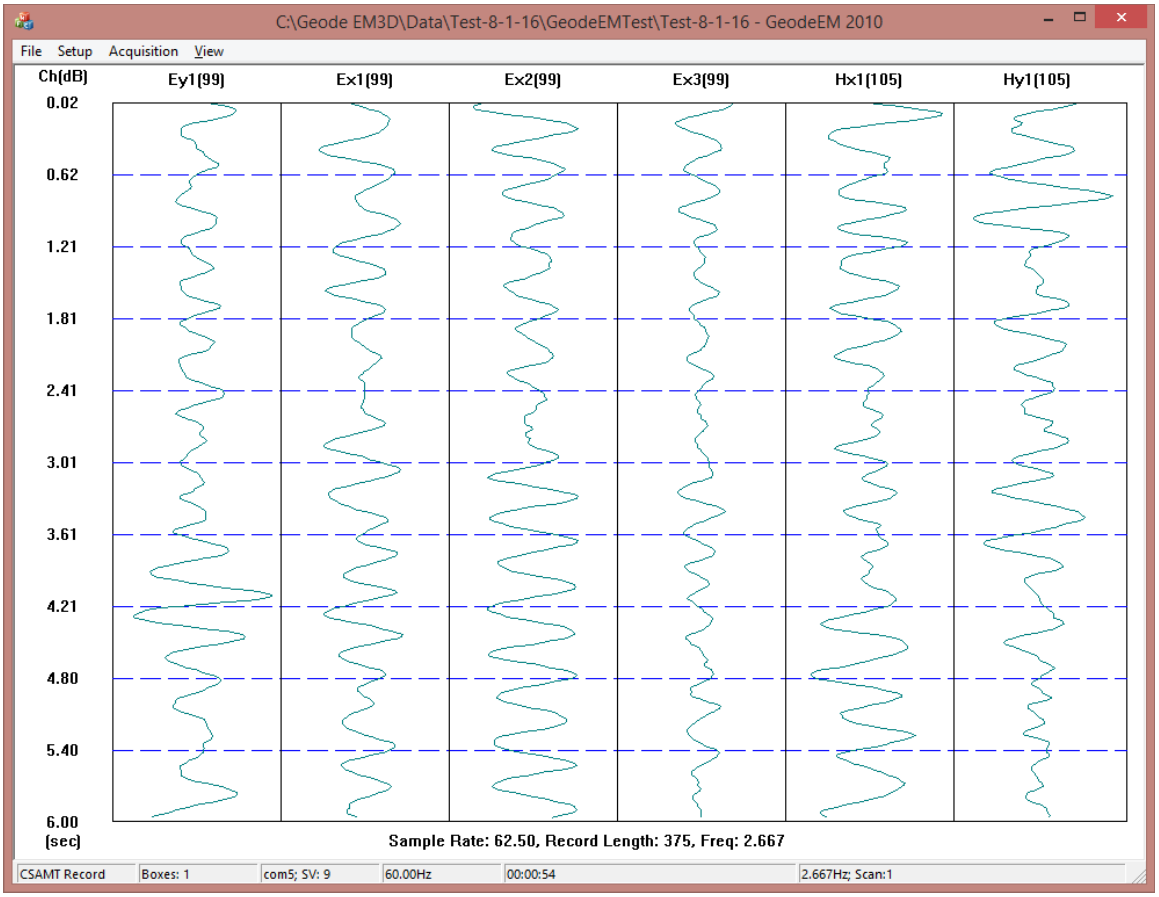
In the example above there is a 1 second delay between each record acquisition to allow for settling of the system between acquisitions, as defined in Delay Between Bands.

x. Stop Recording: Ends data acquisition sequence.

xi. Measure contact resistance: The contact resistance measurement determines the contract resistance on each E-field channels. The measurement is done simultaneous on channel 1 for all receivers, then channel 2, then channel 3, etc. When all E-field channels have been measured it displays the Patch Setup with contact resistance information for each active electric channel.

xii. Measure AC &DC Noise Level: The noise measurement determines the AC and DC noise level. The measurement is done simultaneous on channel 1 for all receivers, then channel 2, then channel 3, etc.. When all channels have been measured it displays the Patch Setup with AC and DC noise levels information for each active channel.

xiii. CSAMT Acquisition: This starts CSAMT acquisition based on the schedule set up in the "Setup/Frequency Stepping" menu. Once CSAMT acquisition is started the following screen is displayed.



The number of channels displayed was set up in the "View/Display Parameters" menu. If there are more channels acquired than displayed the left-right arrow keys will display additional channels. In the image above, the writing just below the traces shows the data was acquired at a sample rate of 62.50 Hz. The record length is 375 samples. The acquired frequency is 2.667 Hz.

The bottom field boxes show that CSAMT is being recorded, there is one receiver box; COM5 is used for the GPS with 9 satellites detected; a 60 Hz harmonics comb filter is active; the display is of an acquisition of 2.667 Hz; and it is the first time through the acquisition cycle.

Note that you can change the time scale displayed on the screen by using the "-" and "+" keys to expand or contract the portion of the time series displayed. Note that you can scroll through a sequence of time series by using the "enter" and "backspace" keys to go forward or backward in the sequence. You may need to read in the GTS file to scroll through the time series.

You can mask out a set of time series simply by pressing the DEL key. In older versions of the software it greyed out the time series traces. In newer versions the masked time series traces become red

xiv. View:

1. Display parameters

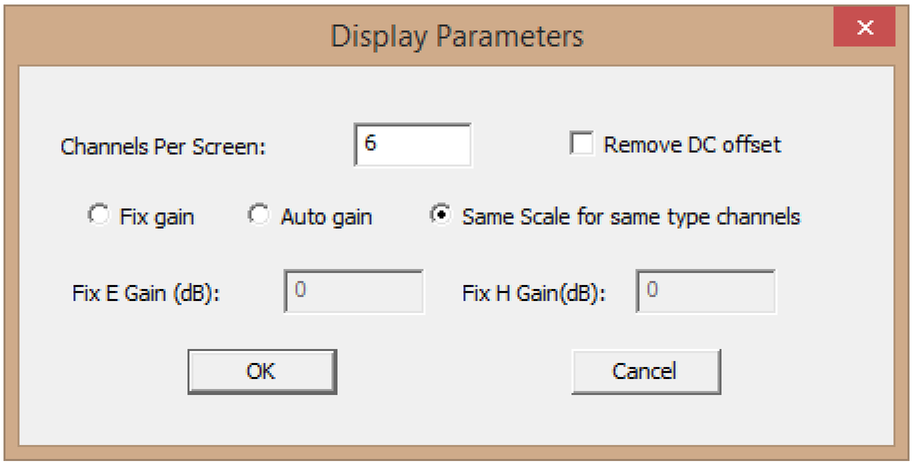


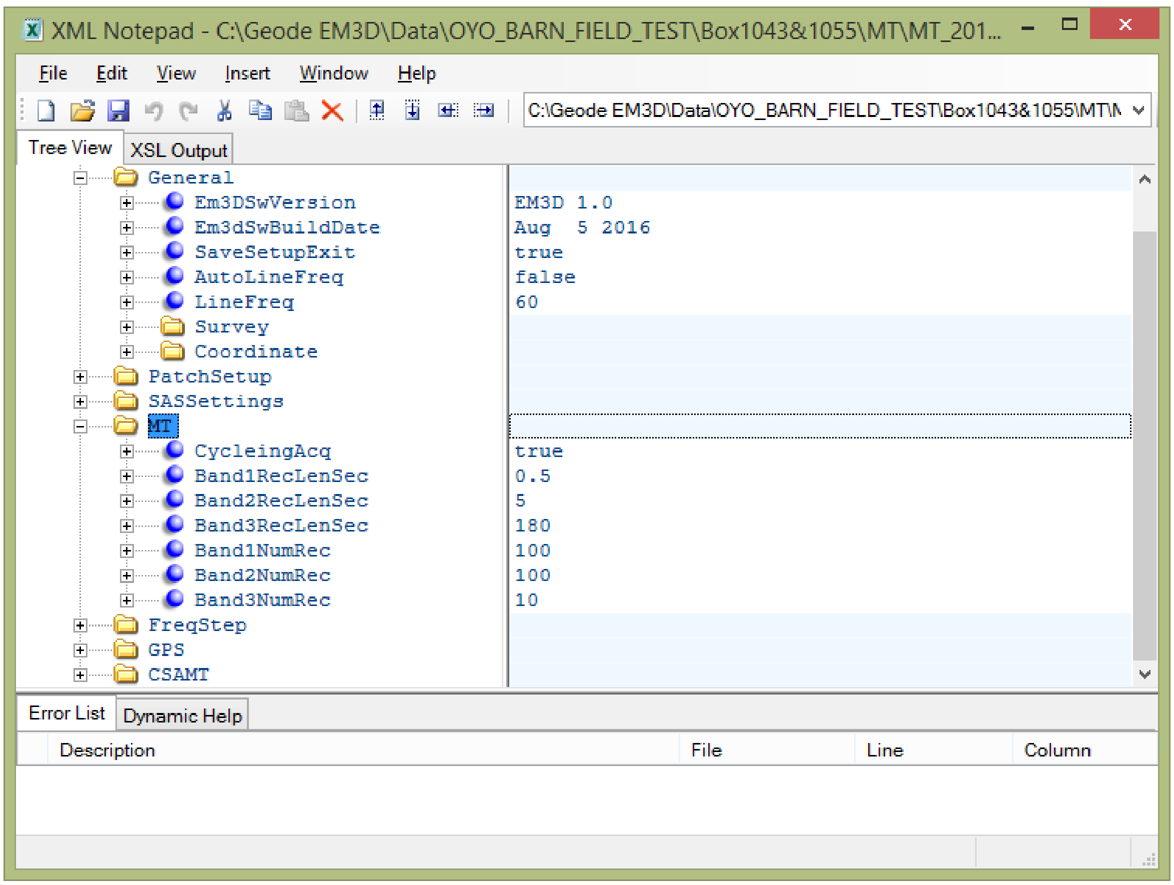
Fig. 31: Setting display parameters menu

2. "Channels Per Screen" sets the number of channels that are seen at the same time on the screen. The left-right keyboard arrows will allow you to scroll through the channels if there are more than the Channels Per Screen setting. For example if there are 36 channels (six receiver boxes) and the "Channels Per Screen" is set to "6" you can view each receiver box (six channels) individually by using the left-right arrow keys.
3. "Remove DC Offset" centers the time series display by removing any DC voltage offset.
4. Gain settings
    a. "Fixed gain" allows the operator to set a predetermined gain, in dB, for the E-field channels and independently for the H-field channels.
    b. "Auto gain" allows the system software to automatically set the gains for each channel depending on the amplitude of the measured signal.
    c. "Same scale for same type channels" tells the system software to automatically set the gains but

to set both E-field gains the same and both H-field gains the same.

ii. CSAMT Acquisition Simulation: This injects a predetermined test signal into each channel for acquisition simulation. Starting a true acquisition will stop simulated acquisition. This feature is disabled in the current software version.

Note: The Geo2010 software creates a setup file with all the system parameters recorded. This is an XML file which requires an XML reader such as XML Notepad. XML Notepad can be download for free from the Microsoft website. The XML setup file is located in the same older as the SEG2 (.dat) files for the survey. An example of a XML survey file is below.



Chapter 5: SAS (System Acquisition Software)

The SAS noise monitor allows you to view activity on the selected channels before, during, and after acquisition. Also refer to section "Chapter 4 Software, 2 GEM3D Controller setup, b Setup, IV Start SAS"

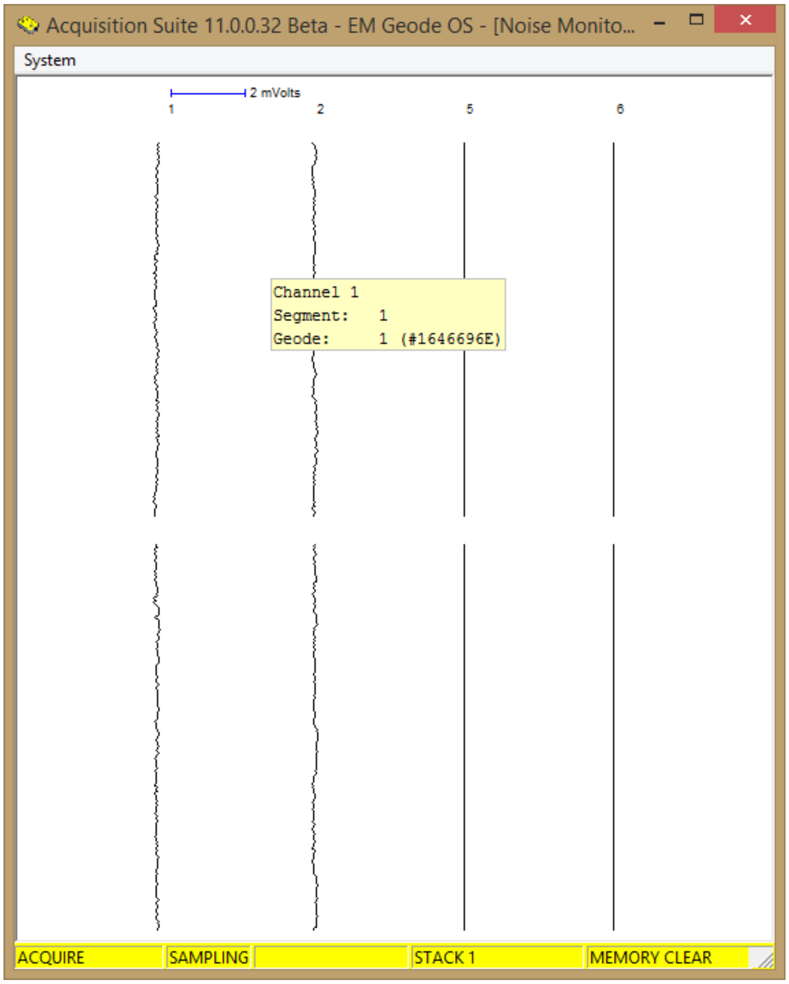


Fig 32: SAS noise monitor

Clicking on "System" will display the following:

Set Date/Time: This allows you to change the clock in the controller PC.

Test: The test mode.

Sounds: You can change the sounds.

Version Number: This shows the version number of the SAS software being used.

SAS commands available from SAS noise monitor window: There are a number of useful functions available through the System Operating Software (SAS) that can be accessed through the SAS Noise Monitor window. The SAS noise monitor is the only SAS window seen in the EM version of SAS. The noise monitor is pictured below.

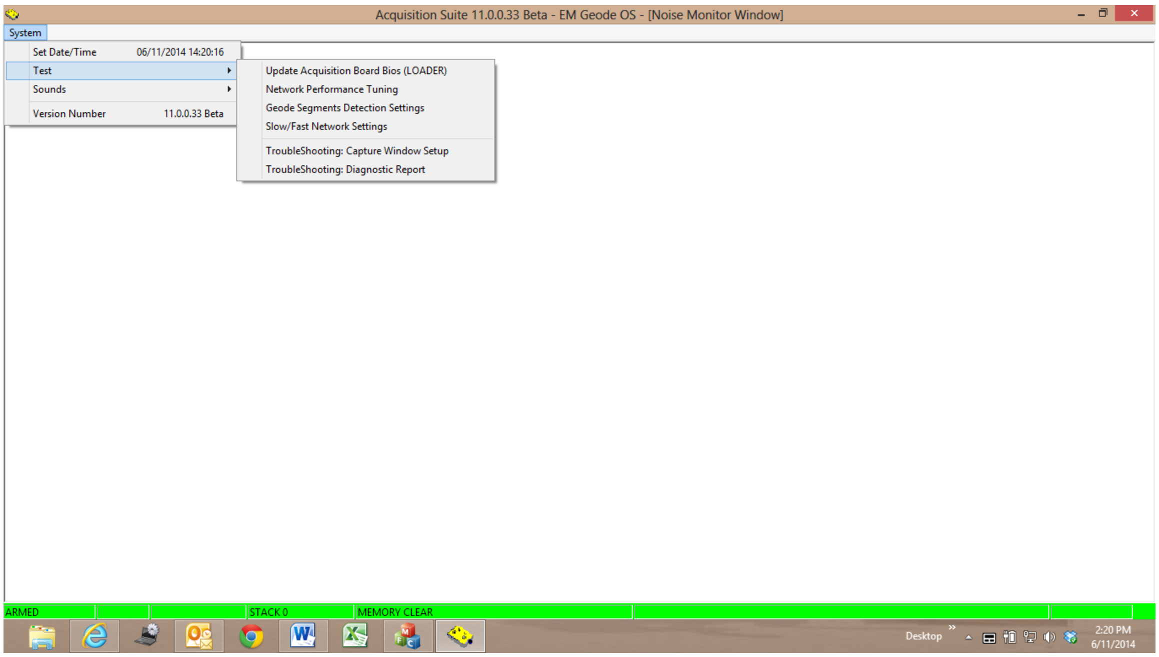


Fig. 33

When the PC controller is connected to one or more GEM3D receivers the Noise monitor will display a set of time series indicating background signal on each channel. Click on “System” to see the following:

5. “Set Date/Time” to set of system clock of the PC Controller,
“Test” described below
“Sounds” to set the beep indicators
“Version number” to view the version number of the SAS software being used.
6. Details of “SAS/System/Test” functions:
“Update acquisition board BIOS Loader”
“Network performance tuning”
“Geode segments detection setting”
“Slow/fast network settings”
“Troubleshooting capture window setup”
“Troubleshooting diagnostic report”

These settings are rarely if ever changed. Contact Geometric before changing these settings.

Chapter 6: Interface to a controlled-source transmitter

Interface to a controlled-source transmitter

a. Geode EM3D schedule software: The GEM3D Scheduler file is created under the "Setup/Frequency Stepping" menu in GeodEM 2010 software. The details of the frequency stepping menu is discussed in section "K-2-b-ii" of this manual. Once the schedule file is created it must be transferred to the transmitter controller. See you transmitter manual for transmitter operation details.

Chapter 7: CSAMT Processing with CSAMTPro

GeoCSAMT processing software is used to process the CSAMT raw acquisition data to impedance and phase.

Installing GeoCSAMT:

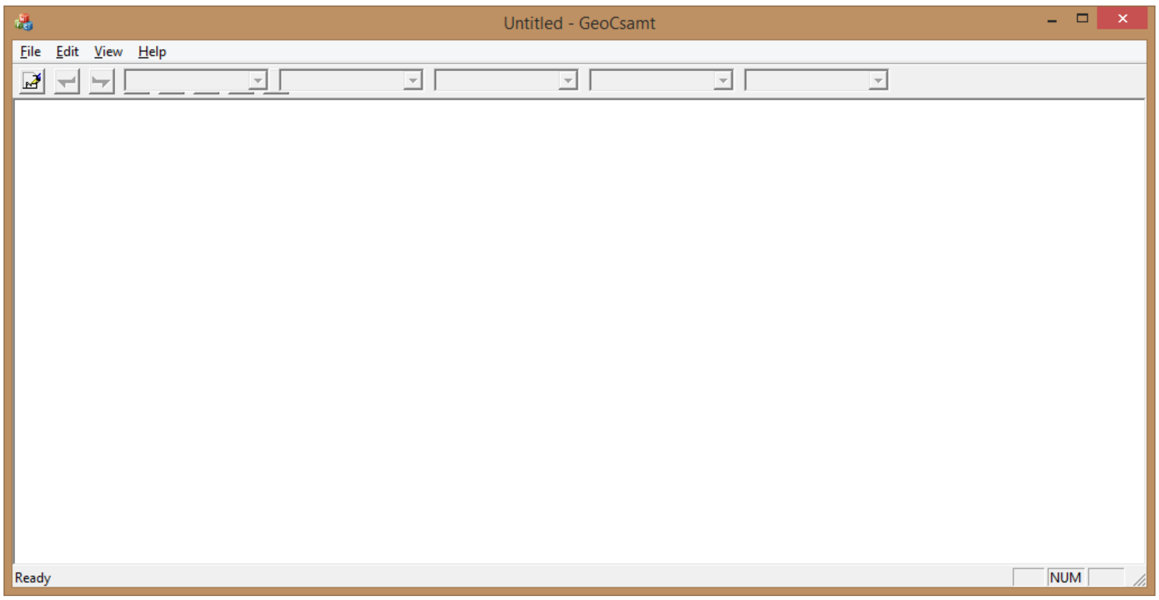
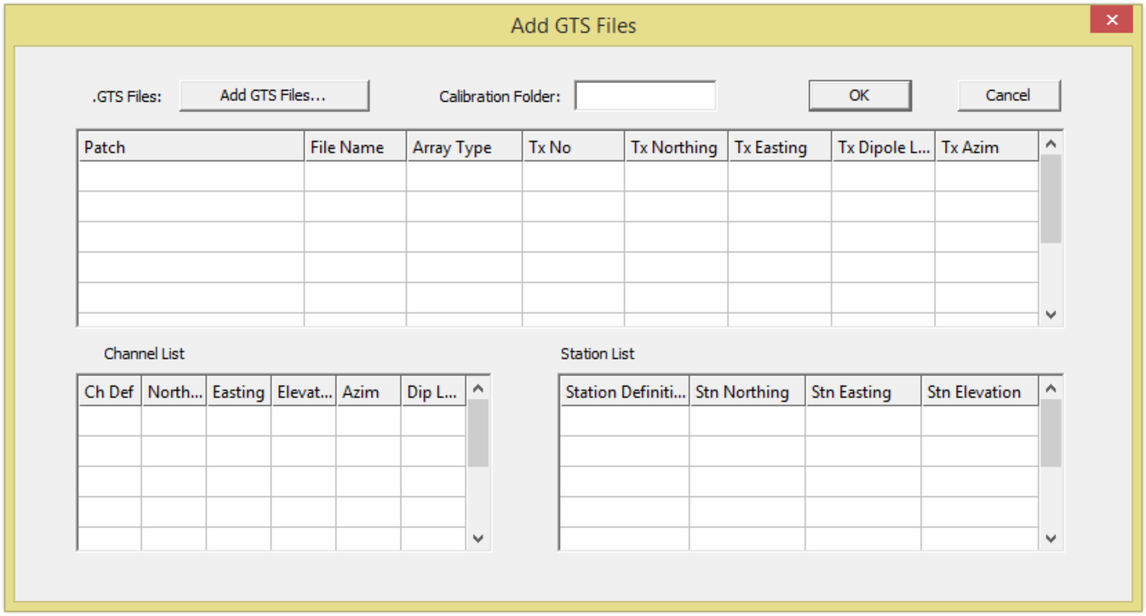


Fig.34: CSAMT processing software menu

Processing Steps:

After acquisition of either scalar or tensor CSAMT data the results can be processed to create impedance, phase, and other parameters. Do the following:

1. Open the program GeoCsamt
2. Click on “File” and select “Add *.GTS Files”
3. The window below will pop up. Click on “Add GTS Files”



4. Navigate to the data files previously set up in the Data Folder field in the Geode EM2010 program under Patch Setup.
5. Select anywhere from 1 to multiple CSAMT data files by doing a Ctrl-click on each one. Then click “Open”. The following window will be displayed.

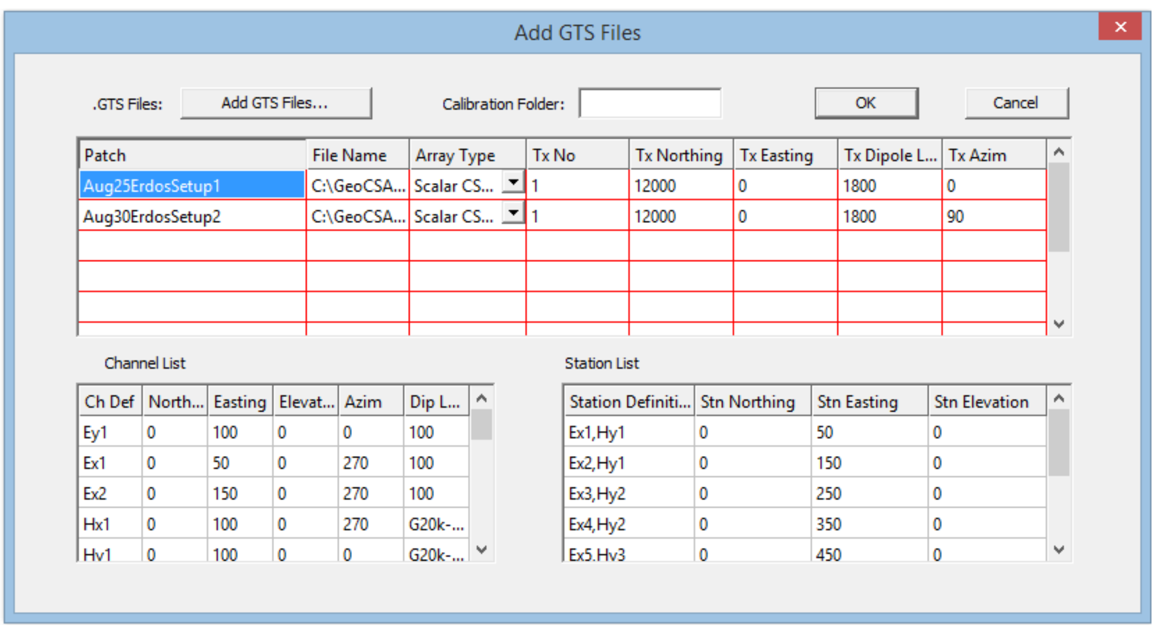


Fig35: Adding file for processing menu

NOTE: In order for the GeoCSAMT or MTPro processing software to create a continuous line when the stations are rolled to a new position the Patch Name must be different for each setup. If the Patch Name is the same, the processing software will average them together.

To do tensor processing the transmitter parameters must have been entered.

6. To change the array type click on “Array Type” to select any of Scalar, Tensor, Vector, or 2H Scalar array for processing.

7. Click “OK”.

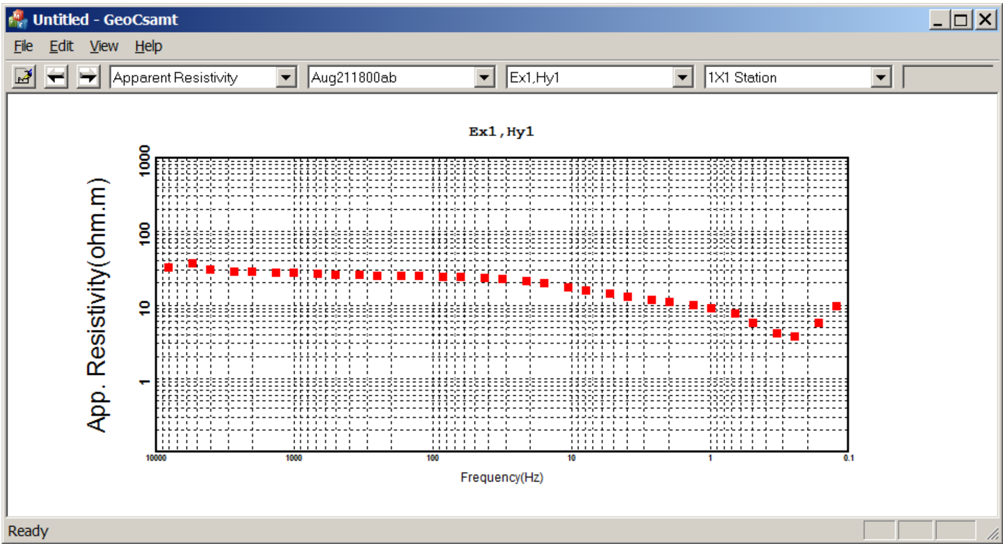


Fig.36: Sample CSAMT processed impedance curve

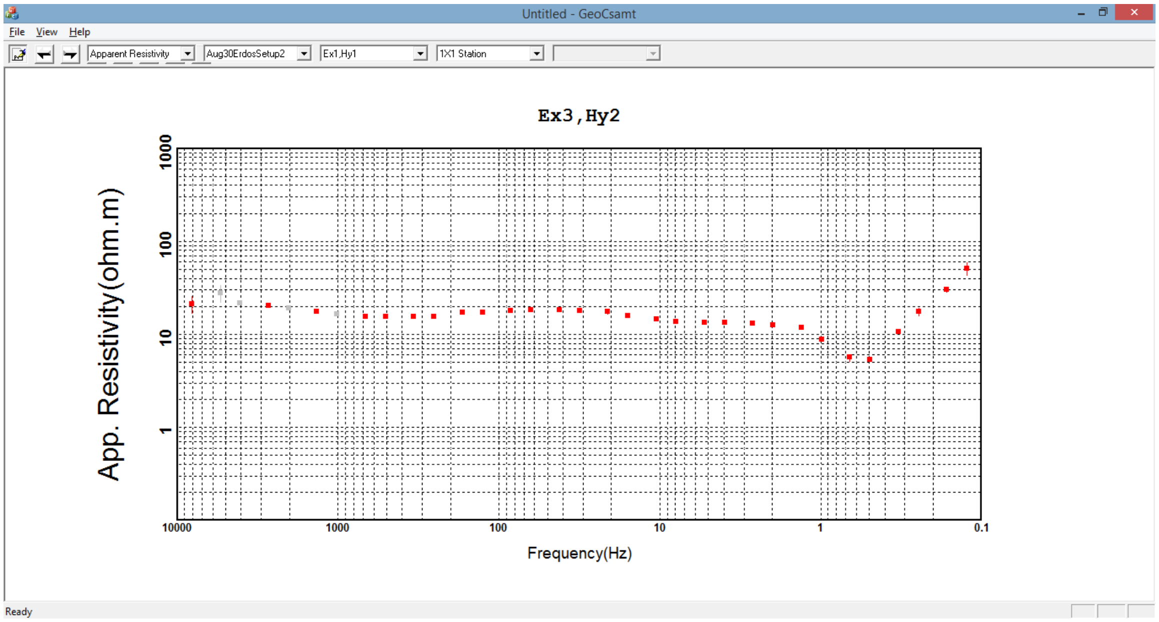
8. Apparent resistivity, impedance phase, and a number of other processed displays can be chosen by clicking on the “Plot Type” arrow.

9. Edit CSAMT data. To edit out specific frequencies:

a. Read in the GST file(s) to see the impedance curves.

b. Left click the edit icon at the far left of the top icon bar.

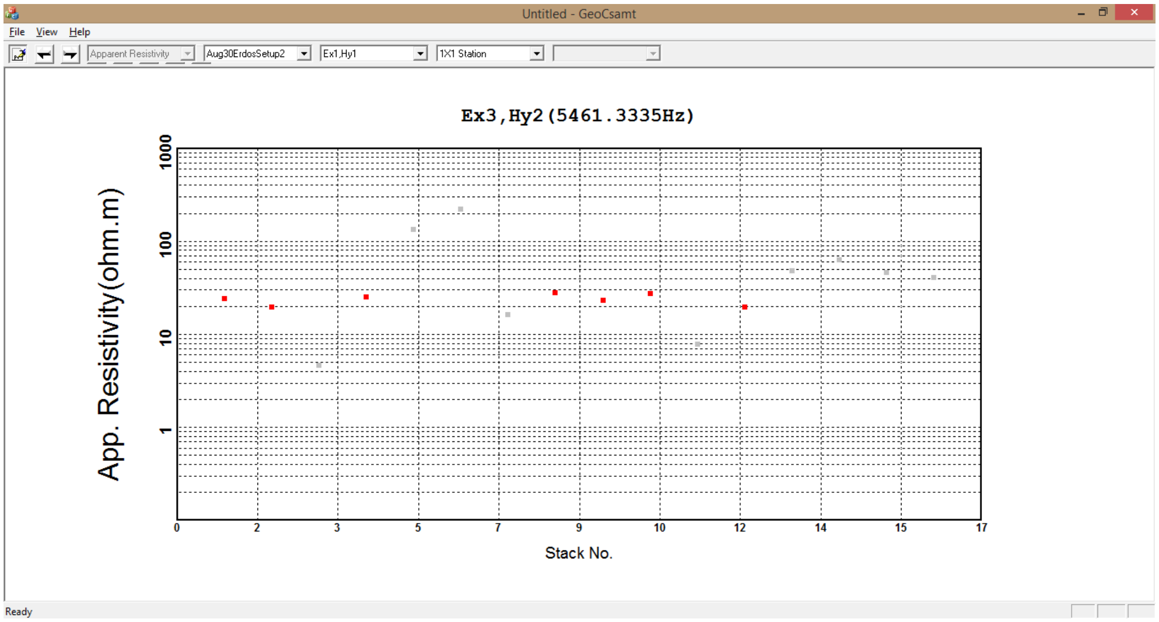
c. Left click on the data point you want to mask out of the exported data. The clicked point will be grayed out as shown below.



These edits only mask out the selected data points. They are not deleted. In order to save the edits the data must be exported by clicking on "File" and selected the desired export format, as explained below. You can also edit the individual stacks for each frequency. Right click on any frequency to see the individual stacks. Left click any data point for that frequency to mask out the point. Right click to return to the apparent resistivity curve.

To export the results of the CSAMT processing click on "File" then choose one of the export formats (USF, XYZ, Bostic, EDI, AVG). For example, to export the data file to be read by Zonge Engineering's "SCS2D" CSAMT inversion software you need to click "File" then select either the EDI or AVG format. If the EDI format has been chosen start the program "edi2avg.exe". Read the EDI file and convert it to the AVG format. The Zonge SCS2D program can read the AVG file and do a 1-D and 2-D inversion. No additional conversion is required for SCS2D to read the AVI file. Please see the operator's manual for SCS2D for more details.

d. You can also edit individual stacks at that frequency by putting the cursor over a data point and right clicking the point. The individual stacks will be displayed. Left click the stack points you want to mask out, then right click again to return to the impedance curve. An example of the edited stacks is shown below:



Exporting CSAMT data from CSAMTPro to third-party inversion program.:

After importing the GTS file(s) and seeing the impedance curve click on "File". You will see a list of possible file types for export. To export a GeoCSAMT data file to Zonge Geophysics' SCS2D inversion program for CSAMT data select "Export to Zonge ".AVG file". The export process will also create an MDE file and and STN file. These files are used by the SCS2D AMT-CSAMT inversion software. The files will have the same name but with an MDE and STN extension instead of an AVE extension.

1) CSAMT Pro can do CSAMT tensor processing. In order to do Tensor CSAMT, two perpendicular transmitter dipoles, which are called Tx1 and Tx2 respectively, are needed to set up in the field. Assume we first connect transmitter to Tx2, we need set "Array Type" as ***Tensor CSAMT*** and "Current Tx" as ***Tx2.***

Then start to make CSAMT measurements as normal scalar CSAMT measurement (Figure 1). After completing ***Tx2*** measurements, connect Tx1 dipole to transmitter and change "Current Tx" to ***Tx1*** in "Patch Setup" window and repeat the measurement as ***Tx2.***

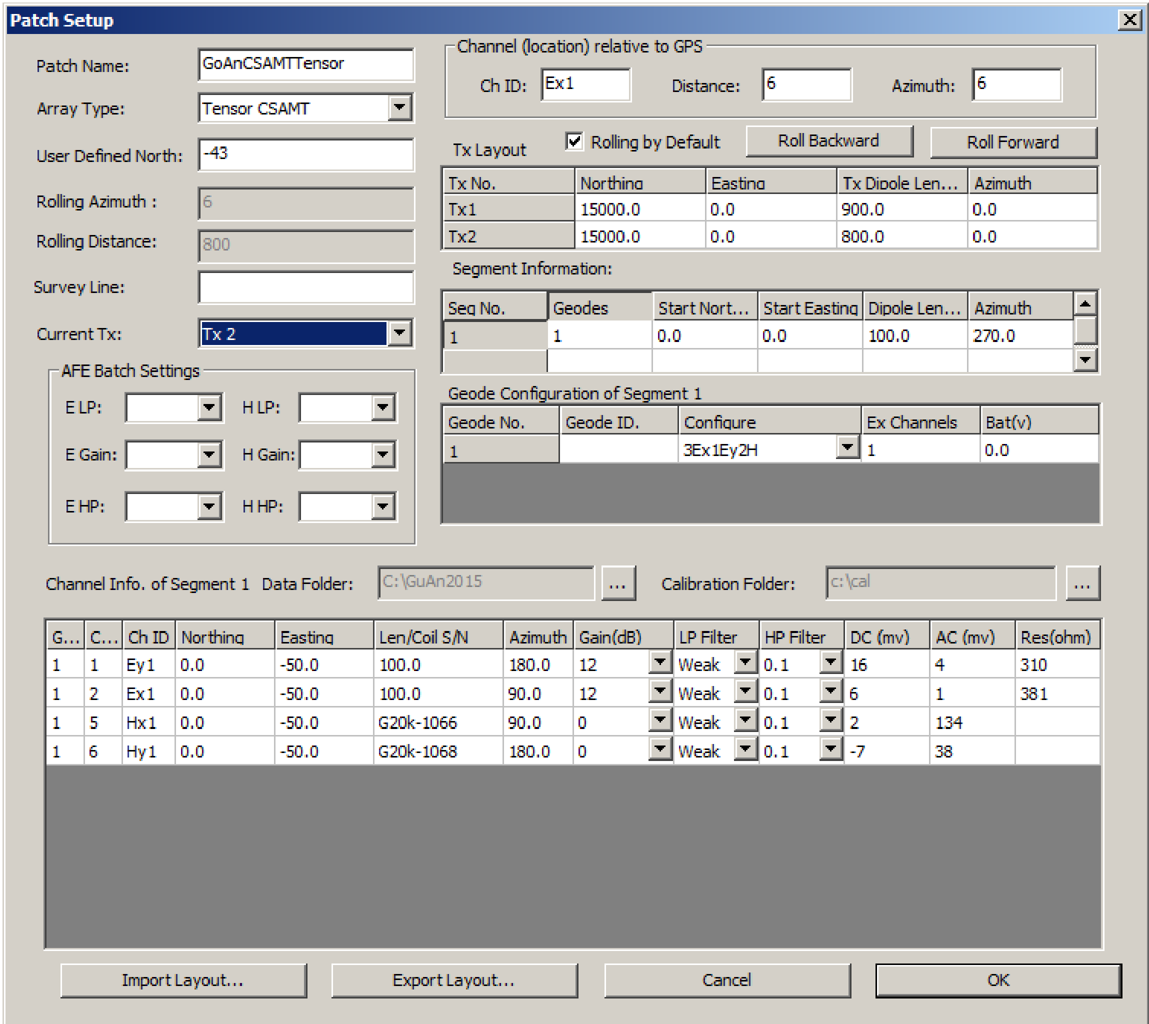


Figure 1

Assuming we got 2 GTS files (GuanCSAMTTensorTest.GTS and GuanCSAMTTensorTest(1)) . Run CSAMTPro program and select "Add GTS files..." menu (Fig2). Make sure the Patch Names are identical for same setup, array type is "CSAMT Tensor" and the Tx No. is correct for each GTS file. Click "OK" button and we will get CSAMT tensor data (Figure 3). As "MTPro" program, the red curve is Zxy and blue one is Zyx.

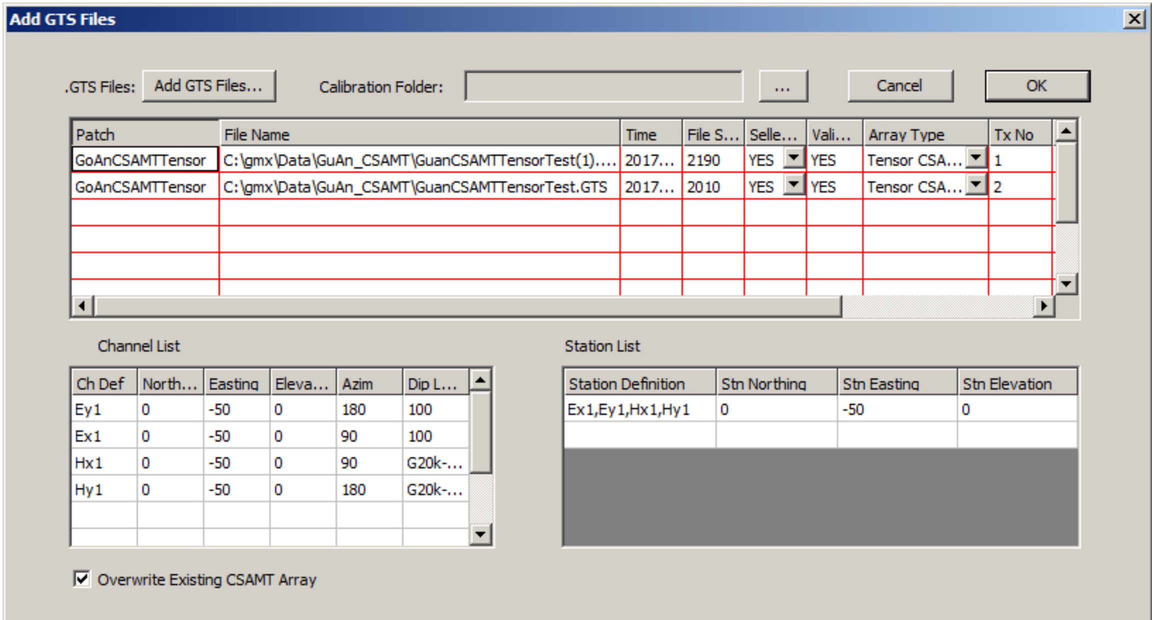


Figure 2

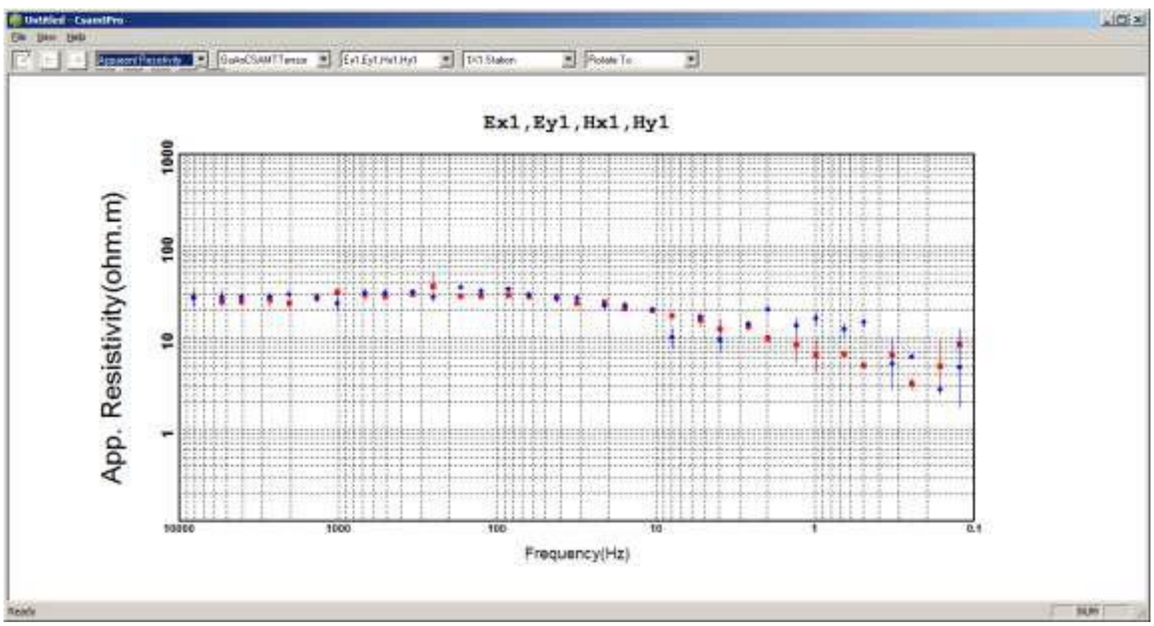
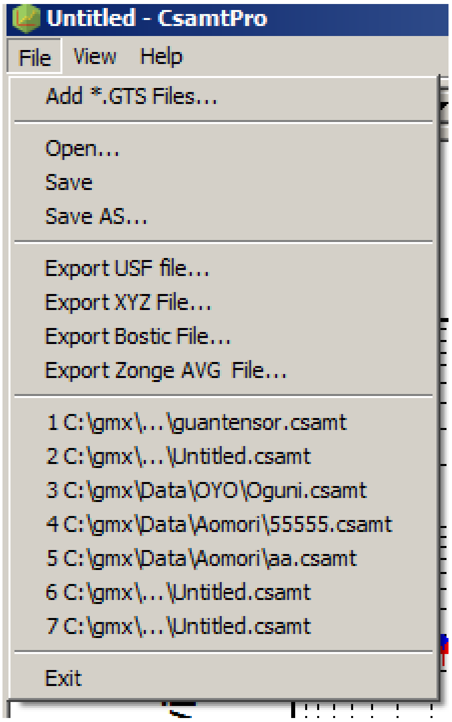


Figure 3: Note that Zxy impedance (X-direction) are the red squares and Zyx (Y-direction) are the blue diamonds. : Note that X-direction resistivites are the red squares and Y-direction resistivities are the blue diamonds.

Bostic transformation

The Bostic transformation of CSAMT data is a point-by-point conversion of apparent resistivity and depth to true resistivity and depth.

2) Similar to MTPro, database save and open features are added to CSAMT program



(Figure 4).

Chapter 8: AMT Processing with MTPro

MtPro processing software is used to process acquired MT time series to impedance and phase data.

A. *Installing and licensing of MTPro*:

Installation of MTPro is easy: Simply copy the executable file into a designated folder. This could be "C:\MTPro" for example. However , getting the license set up for your computer is a bit more complicated. MTPro can be used to process and view the data but without a license it cannot save or export the data for inversion or contouring.

To get the license do the following:

1. Click on HELP then ABOUT MTPRO. You will see a menu pop up with the fields "Computer ID" and "License key". There will be a code "Computer ID" field. Copy and Paste this code into an email message and send it to support@geometrics.com and/or wfei@geometrics.com .

2. You will be sent a License Key that you should copy into the "License Key" field. Close the window and the program then re-start MTPro. If you now go to "Help", "About MTPro" you will get the following screen with the words "This machine is licensed" in the License Key field. You will now be able to export data for using in other programs such as the Zonge SCS2D CSAMT-AMT inversion software.

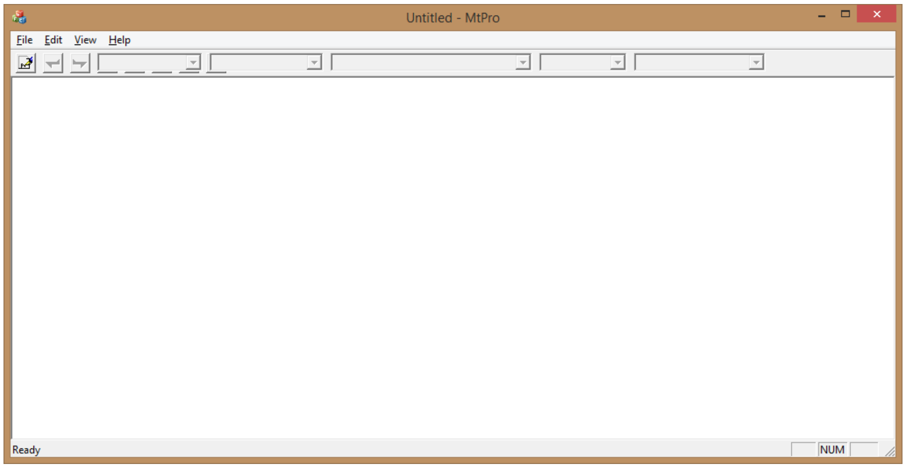
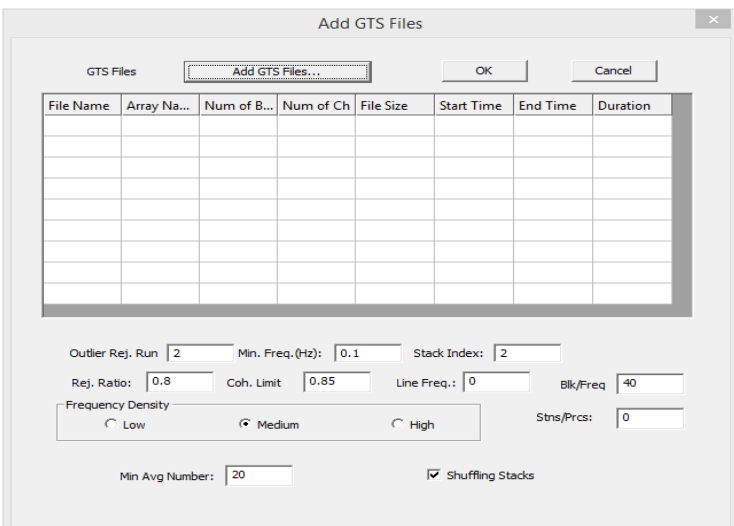


Fig. 37: AMT processing software menu

After acquisition of AMT data using GeoEM2010 the results can be processed to impedance, phase, and other parameters. Do the following:

1. Click on “File”, “Add GTS Files”.



2. A new window will pop up. Click on “Add GTS Files”
3. Navigate to the date files previous set up in the Data Folder field in the Geode EM2010 program under Patch Setup.
4. Select anywhere from 1 to multiple MT data files by doing a Ctrl-click on each one. Then click “Open”. The following window will be displayed.

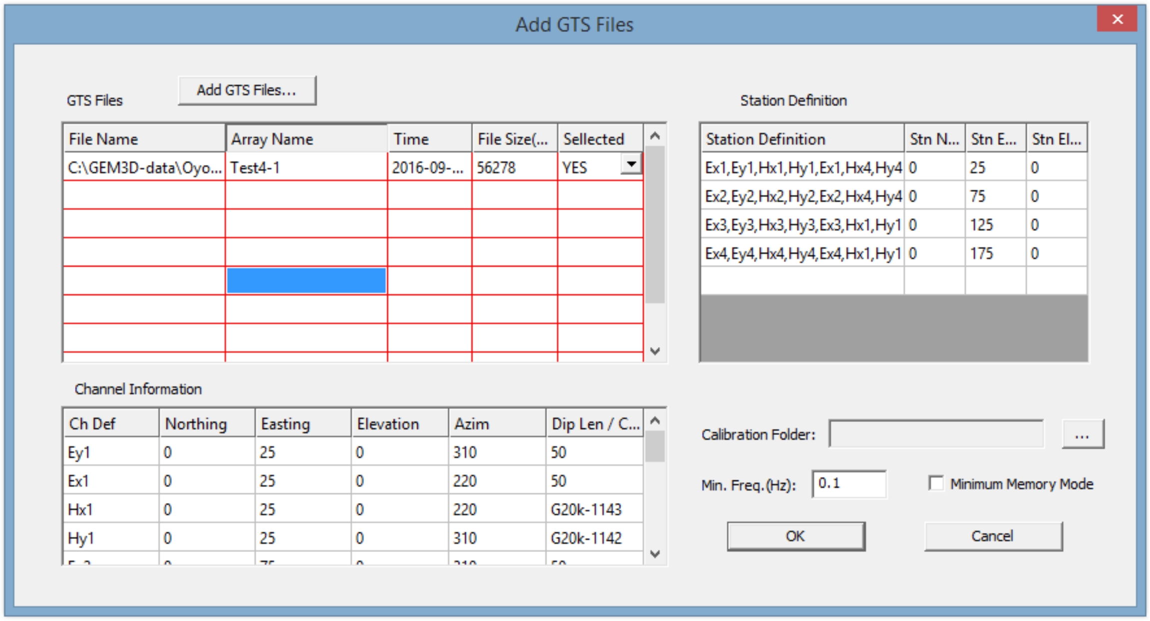


Fig. 38: Select files to be processed

NOTE: In order for the GeoCSAMT or MTPro processing software to create a continuous line when the stations are rolled to a new position the Patch Name must be different for each setup. If the Patch Name is the same, the processing software will average them together.

You will see a list of soundings based on the number of Ex stations in the file. Format is as follows for the selected sounding: Ex1,Ey1,Hx1,Hy1,Ex1,Hx4,Hy4 in this order.

Ex1= sounding station X dipole

Ey1 = sounding station y dipole

Hx1 = station Hx

Hy1 = station Hy

Ex1 = if this station used Hz it would be shown here. Since no Hz exists the position is filled with Ex1 and is not used.

Hx4 = local reference for in X direction

Hy4 = local reference for y direction

The reference sensors may be changed. For example, if the user prefers to use E-field measurements as the local reference the last two can be changed (in this example) from Hy4 and Hx4 to Ey4 and Ex4.

If the survey setup only has one receiver with no reference sensors the default will be Hx1 and Hy1 as references sensors. Since this is the same as the sounding magnetic field sensors this is the same as no local reference.

The station Easting, Northing, and Elevation are the center of the E-field dipoles and the position of the H-field sensors.

5. Click on OK. To see the following display.
6. Apparent resistivity, impedance phase, and a number of other processed displays can be chosen by clicking on the "Plot Type" arrow.

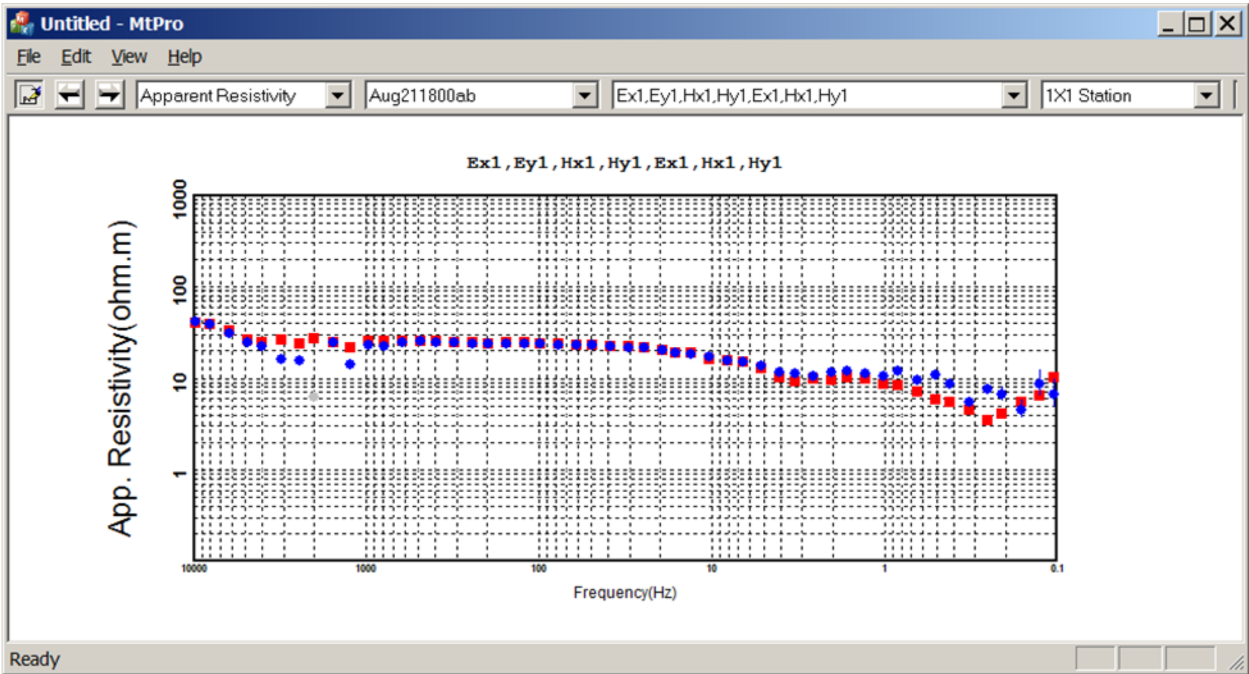


Fig. 39: AMT processed impedance files: Note that Zxy impedance (X-direction) are the red squares and Zyx (Y-direction) are the blue diamonds.

Clicking on the rotation button at the far right of the window allows you to rotate the station to any of the choices given on the rotation menu. Note that the default rotation is the angle of the measured station.

1. The plot layout button, second from the right, allows you to choose how many soundings are displayed.
2. The station arrow, third from the left, shows what channels are used in the sounding.
3. The patch arrow, second from the left, shows the data folder name.
4. The plot type display arrow at the left shows the various graphics that can be displayed as follows below.
    a. Apparent resistivity –calculated apparent resistivity for the selected station
    b. Impedance phase – calculated impedance phase for the selected station
    c. Impedance skew – calculated station skew
    d. Impedance strike – strike is either the default measurement strike of the station or the rotation selected in the rotation menu.
5. Clicking on the right-left arrows will select different stations for viewing.

7. The edit button to the far left of the screen  will allow editing of the displayed data. After selecting the edit button a right mouse click will swap the X-direction (Zxy) and Y-direction (Zyx) points. Clicking the left mouse button on a data point will mask out the that data point.

8. The FILE menu item at the upper left of the screen allows you to:

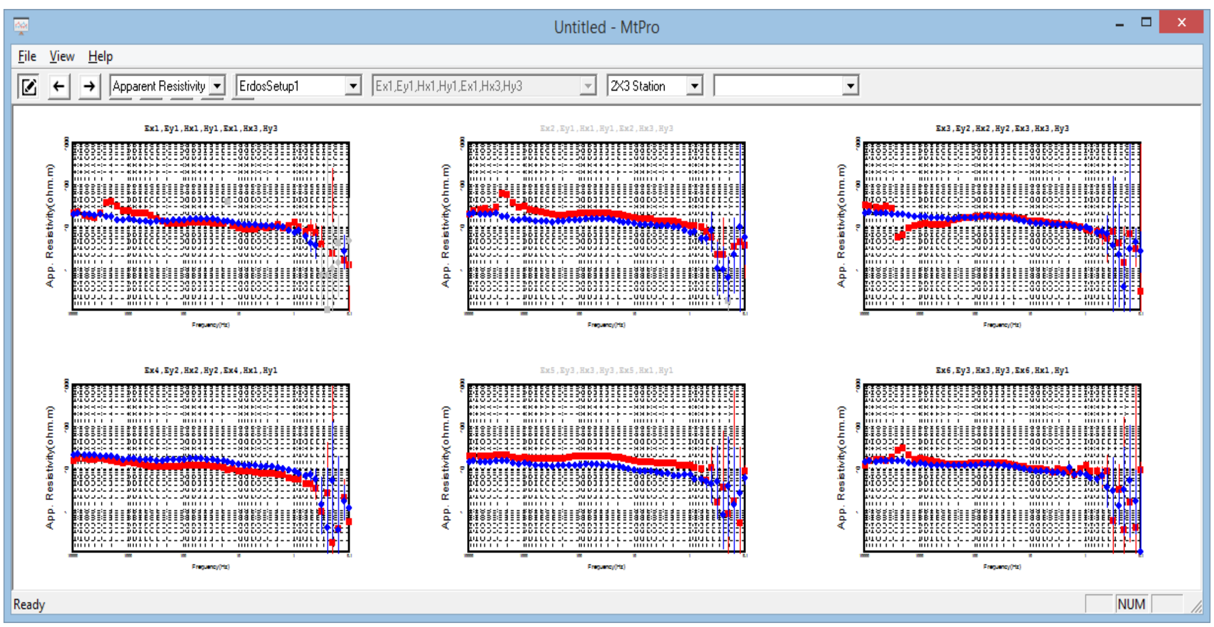
   a. Add a GTS data file for processing as described above.

   b. Open a previously processed MT file.

   c. Save or Save As the current GTS data as a processed MT file.

   d. Export the processed GTS or MT file as an ".AVG" file for inversion processing Zonge Geophysics SCS2D AMT-CSAMT inversion software.

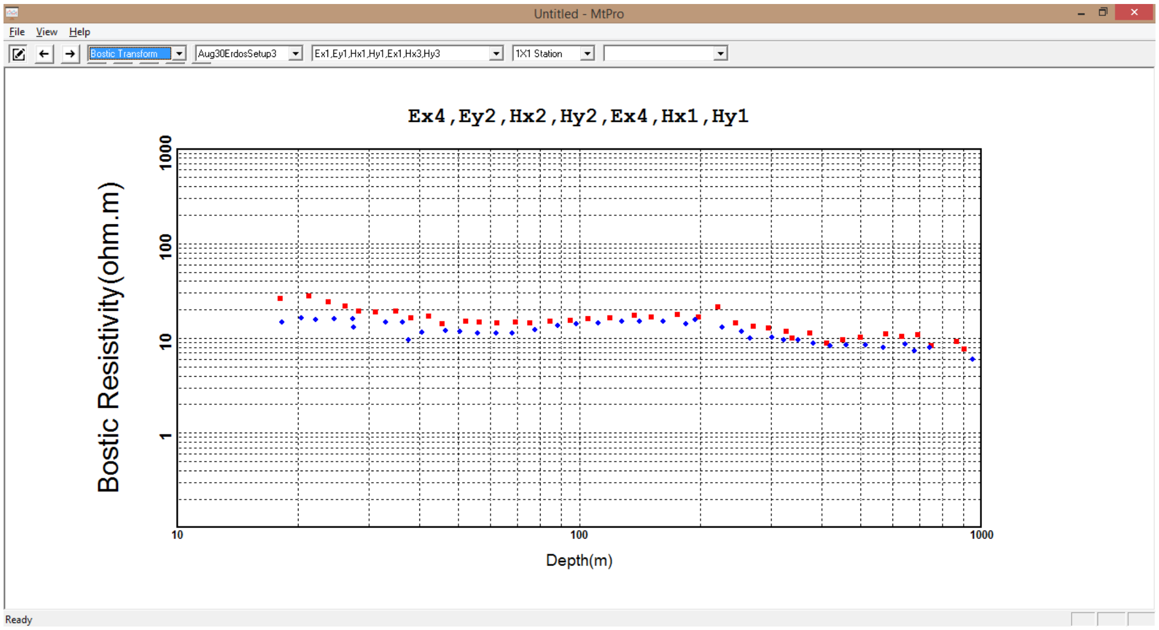
9. You can mask out the use of a sounding by doing a "Ctrl – right click" on the sounding you do not want to use or export. For example the image below shows the soundings for stations Ex2 and Ex5 have been disables. The sounding labels for Ex2 and Ex5 are greyed out to show they are masked.



Note that Zxy impedance (X-direction) are the red squares and Zyx (Y-direction) are the blue diamonds.

Bostic Transformation:

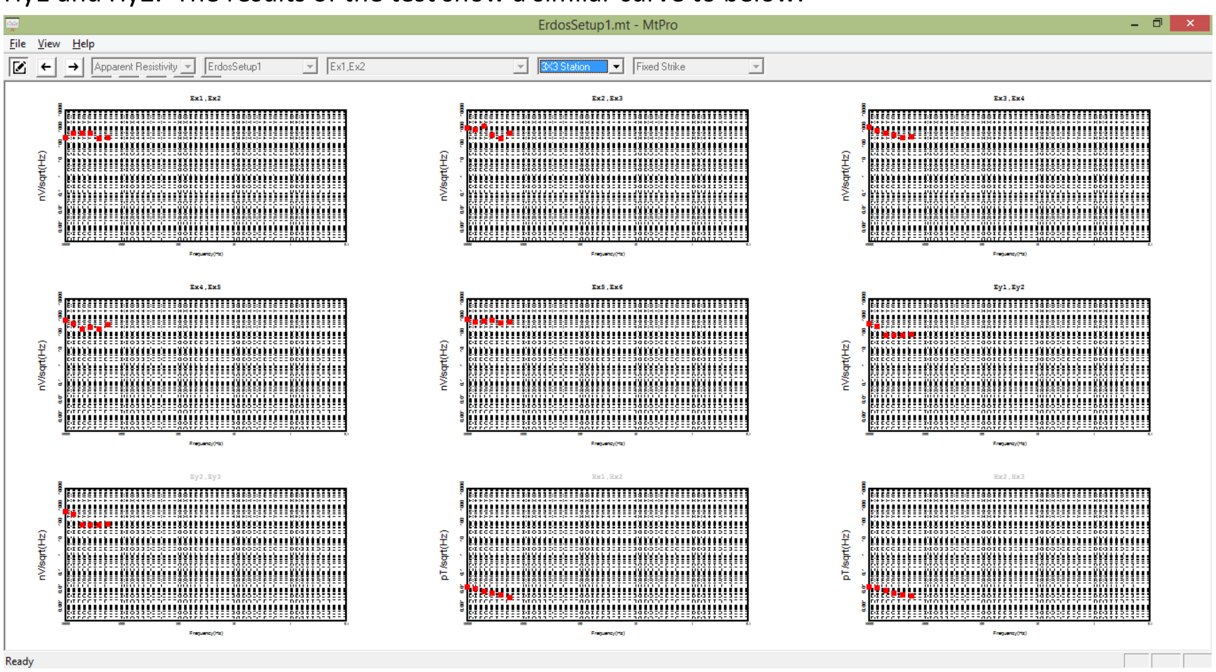
The Bostic Resistivity is a point-by-point transformation of apparent resistivity and frequency to true resistivity and depth. The display parameters are the similar to the impedance displays.



Bostick transform of AMT data to true resistivity and depth: Note that X-direction resistivites are the red squares and Y-direction resistivities are the blue diamonds.

Parallel Test Noise Calculation:

The parallel test noise calculation allows the user to do a basic field test of the noise level comparing any two pairs similar parallel sensors. For example Ex1 and Ex2 or Ey1 and Ey2 or Hy1 and Hy2. The results of the test show a similar curve to below:

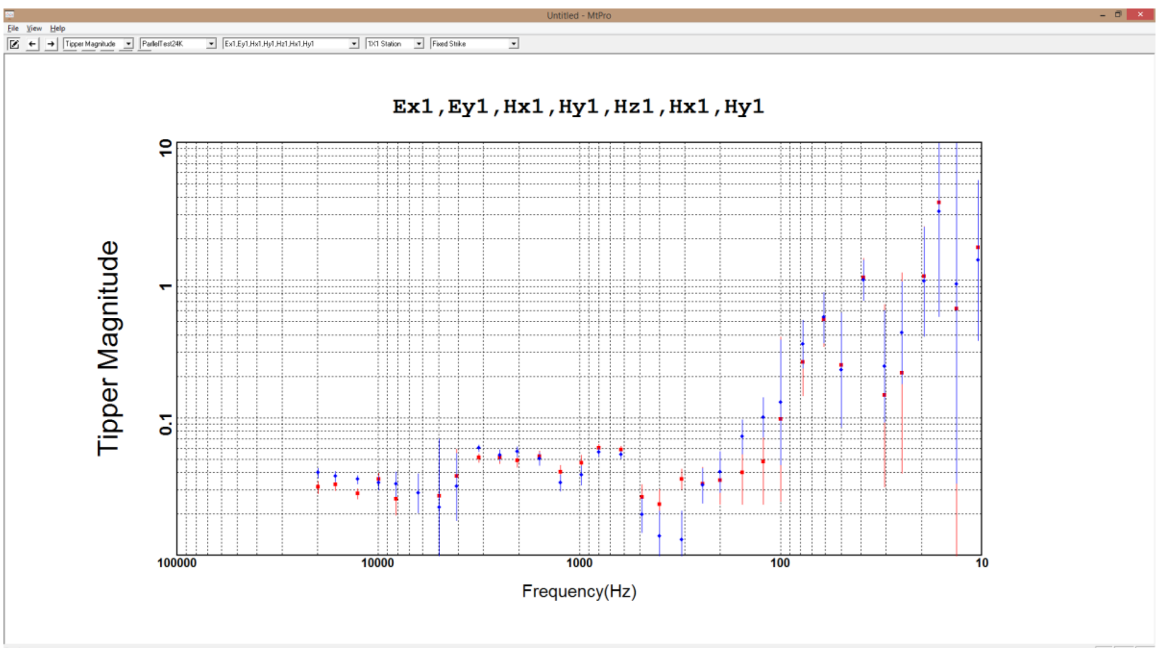


Tipper Data

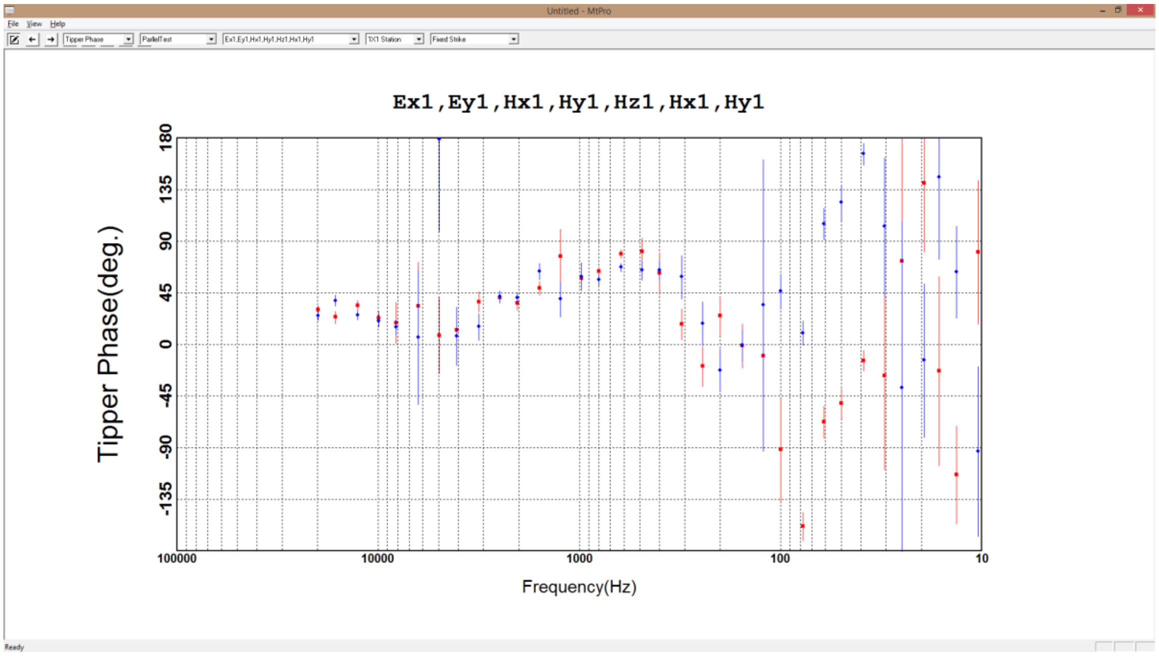
The magnetotelluric tipper is a complex number based on a ratio of the amplitudes of the horizontal magnetic fields (Hx and Hy) and the vertical magnetic field (Hz). The tipper values Tx and Ty are complex numbers. Various tipper parameters are offered by MtPro. These include the following selections: Tipper Magnitude, Tipper Phase, Tipper Strike, Tipper Coherence, Tipper Skew, and Tipper Beta.

It is beyond the scope of this manual to explain the geophysical uses of these functions. However, the most commonly viewed tipper functions are the magnitude and phase, as shown below.

For the Geode EM3D the vertical magnetic field, Hz, is generally measured by the G100K high-frequency coil. The lowest practical frequency of the G100K coils is 10 Hz. Therefore, the practical range of tipper values is between 10 to 20,000 Hz.



Tipper magnitude: : Note that Tx (X-direction) are the red squares and Ty (Y-direction) are the blue diamonds.

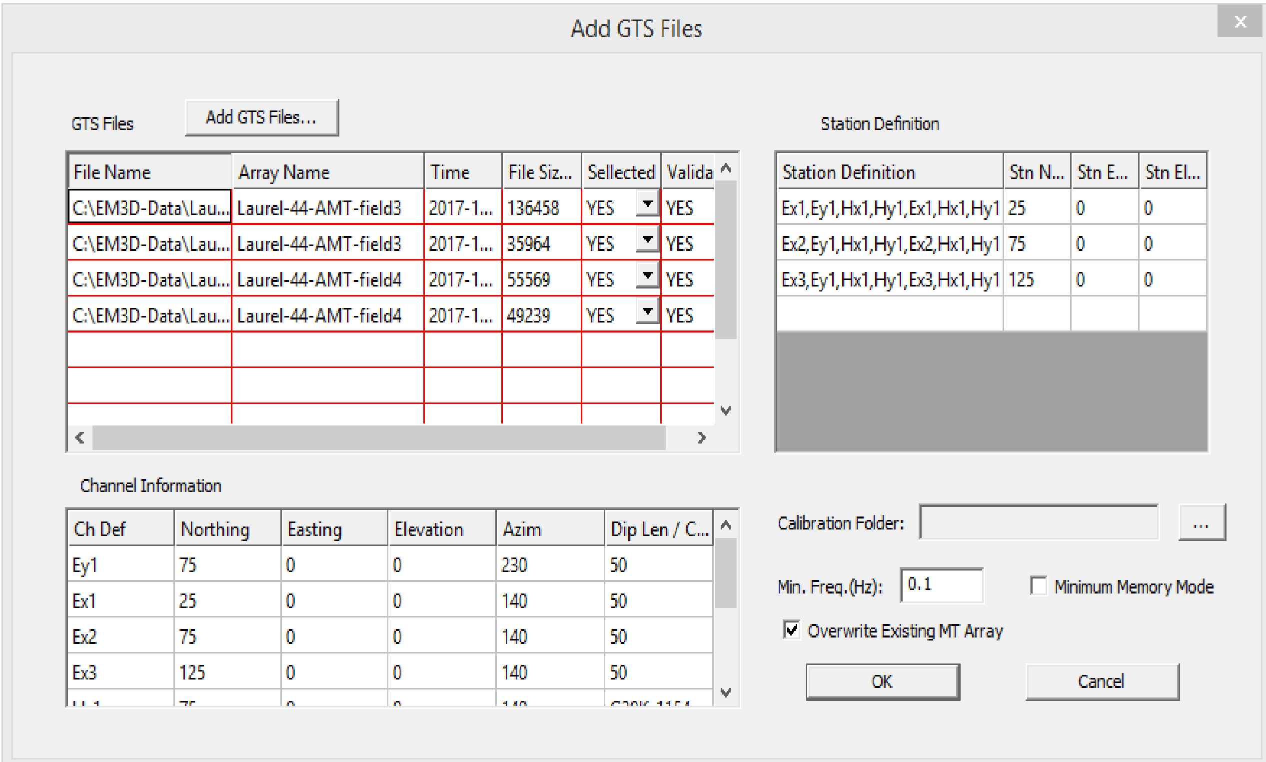


Tipper phase: Note that Tx (X-direction) are the red squares and Ty (Y-direction) are the blue diamonds.

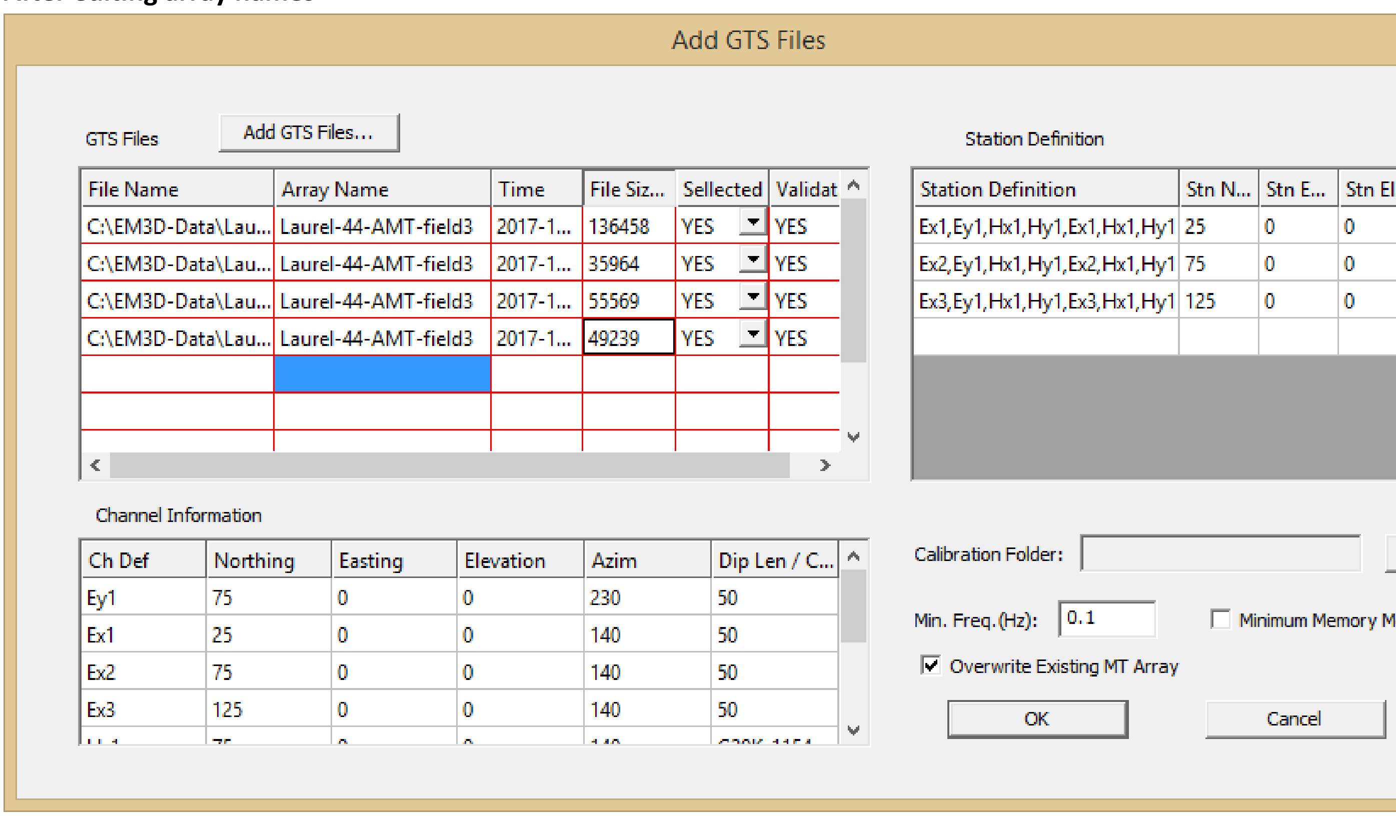
How to combine two files with different names to process them as a single file:

If you have two files with different patch names but you want to combine them as a single sounding you need to rename one of the files to they both match. For example in the image below there are two files with an array name of “Laurel-44-AMT-field3” and two files with the array name of “Laurel-44-AMT-field4”. If the names are not changed then “field4” soundings and “field3” soundings will be processed separately in MTPro. However if you change the names to match the two files will be processing as the same soundings. You must click on the array name of the file you want to change then edit then them. See the example below:

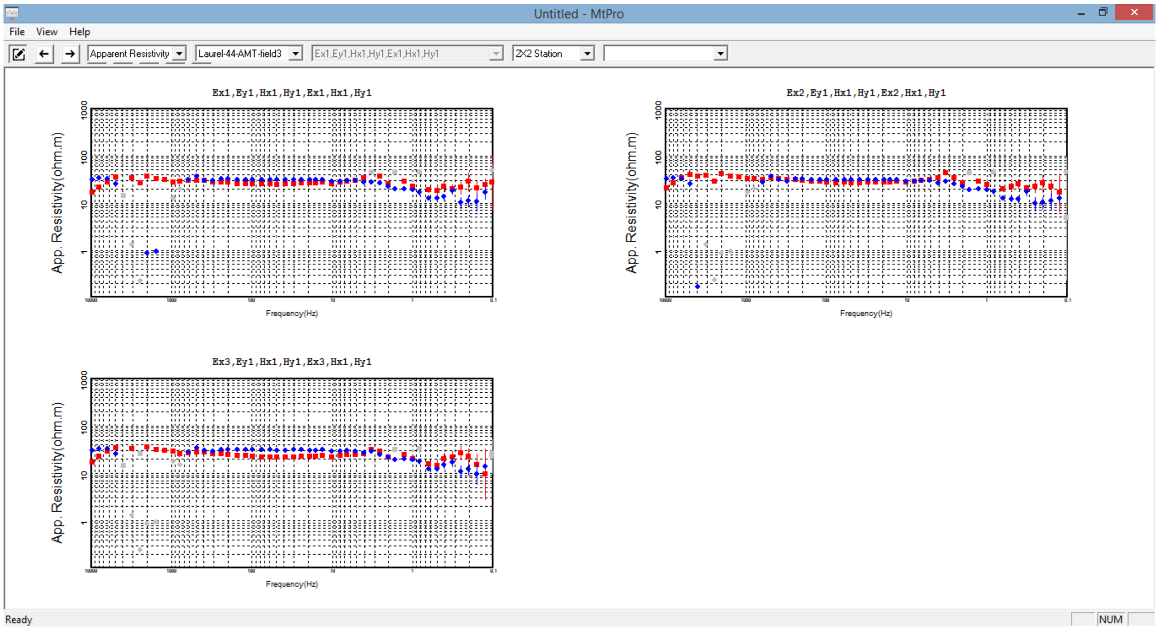
Selected files



After editing array names



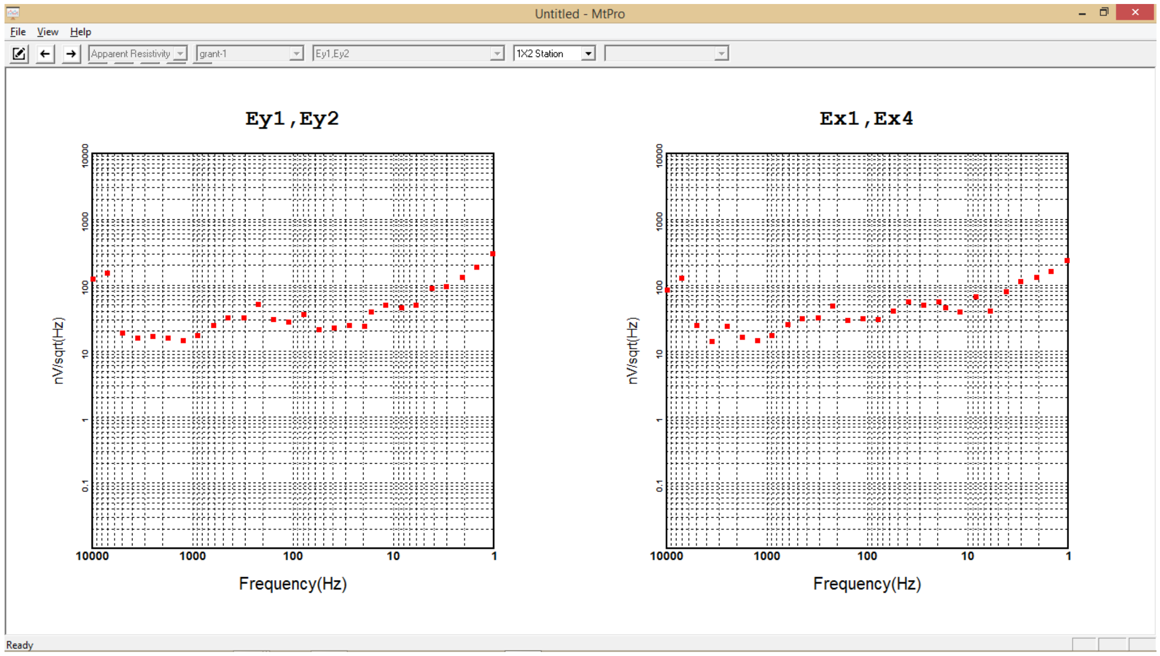
Result of both files processed together

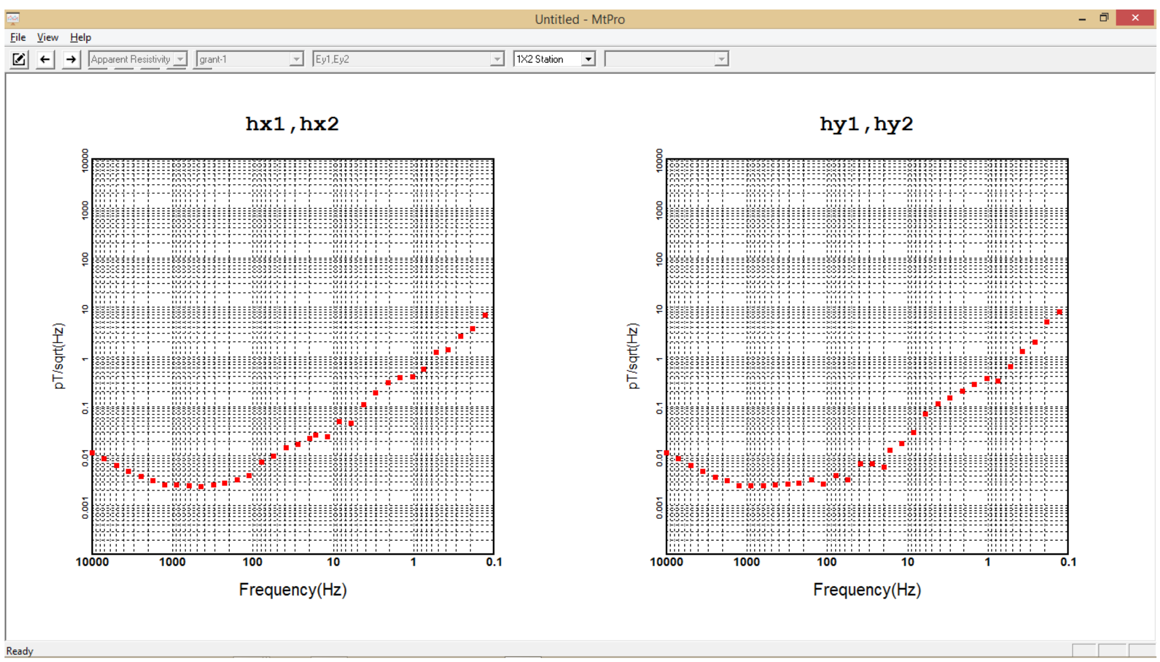


Sensor Noise Test:

In order to do a sensor noise test you must compare the sensors parallel to one another. For example if you have two receivers and Hy1 and Hy2 you can do a noise test for Hy1 and Hy2. It is the same for Hx1 and Hx2 or for Ex1 and Ex4 (if you have three Ex channels on each receiver). If you only have one receiver set the two coils parallel to one another and the electrodes parallel. Since E channels 3, 4, 5, and 6 have shared terminals to test all E channels and the H channels will require three acquisitions. As follows:

- Set channels 1, 2, 3, and 5 as E-dipoles parallel to one another. This will provide four E-field parallel measurements without any shared electrodes.
- Do an MT acquisition.
- Set channels 4 and 6 as parallel E-dipole channels.
- Do an MT acquisition
- Set Hx parallel to Hy.
- Do an acquisition.
- Start MTPro.
- Go to FILE\PARALLEL TEST NOISE CALCULATION.
- Add the GTS files from you parallel acquisitions
- Open and view the files as is done when viewing standard survey data.

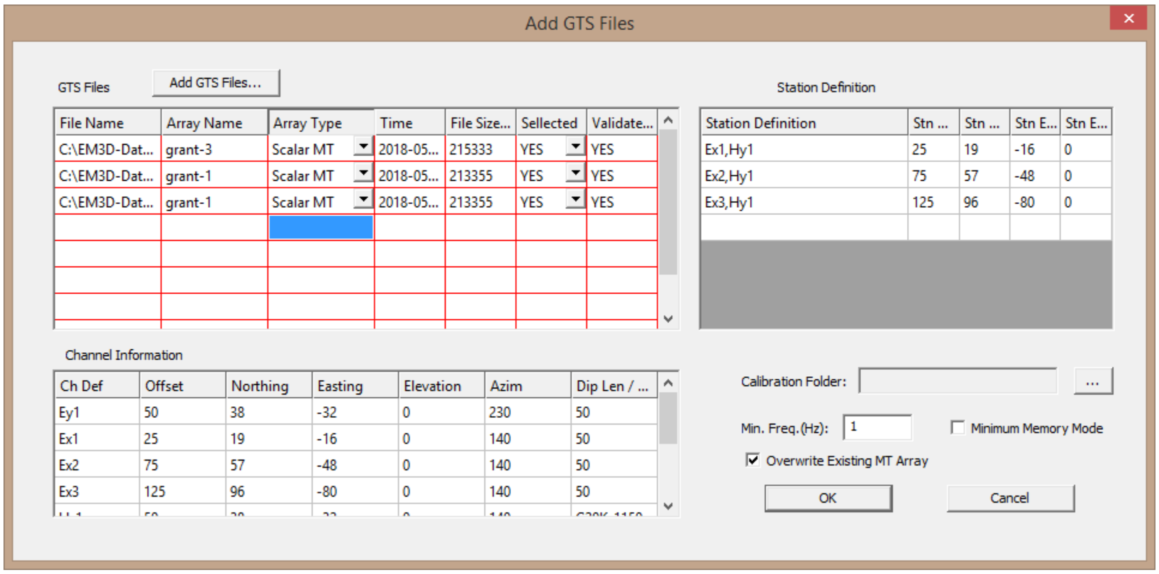


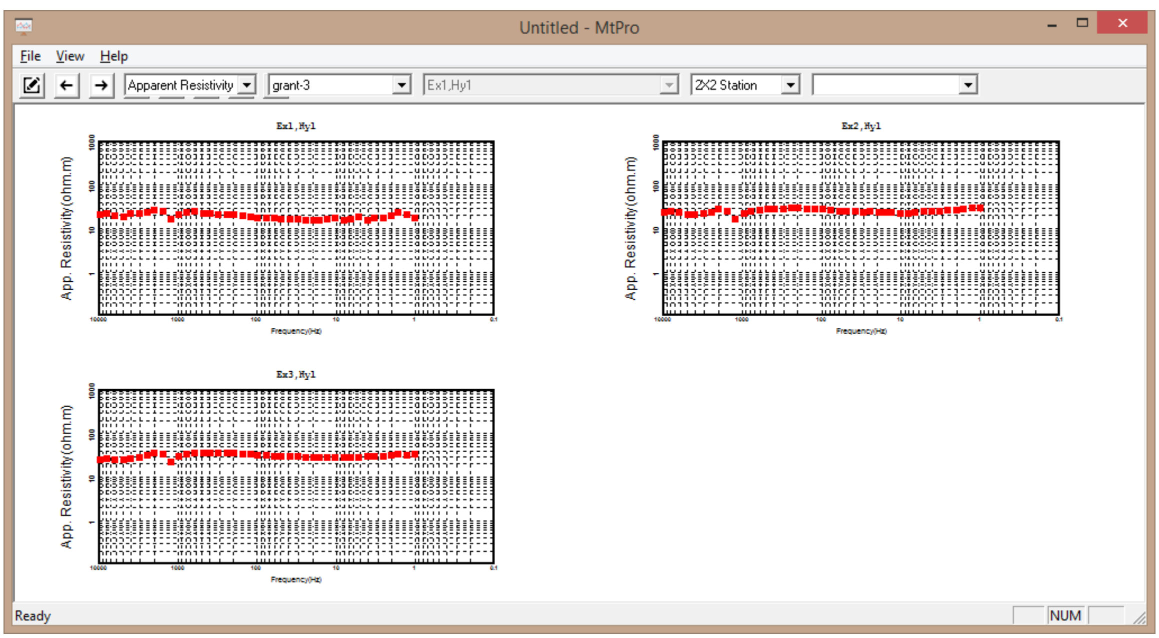


The relatively high low frequency noise in the graph above is the result of using metal stakes in the ground instead of porous-pot electrodes. At low frequencies below 1 Hz porous-pot electrodes are preferable for noise measurements.

Scalar Processing

To process the data as scalar data when adding GTS files change the click the “Array Type” menu arrow and select “Scalar MT”. This will allow MTPro to process the data as scalar only.





Example above of processed scalar data.

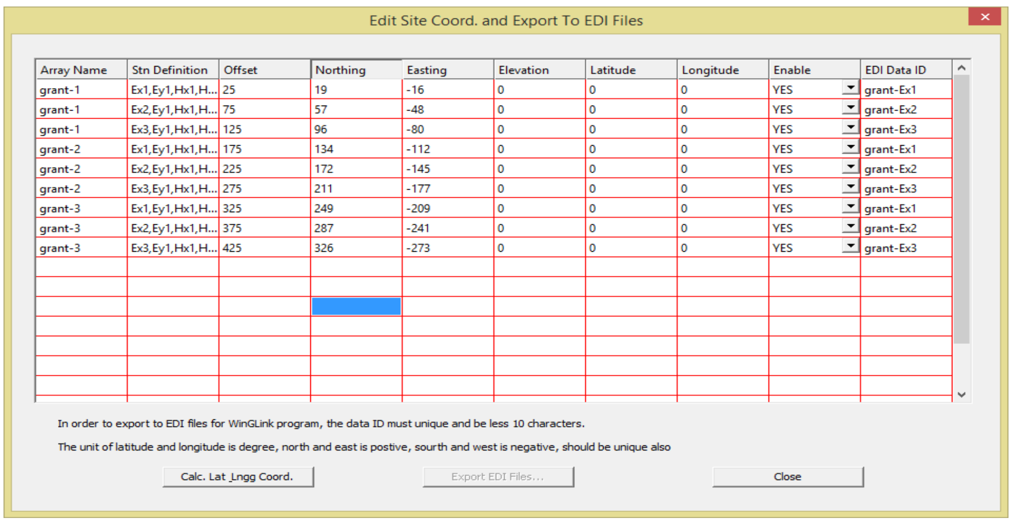
Exporting EDI files from MTPro

In order for MTPro to export Edi files it must be at least version 3.0 The GTS file must have been acquired in GeodeEM version 3.0 or greater. If the GTS file came from an older version it can be opened in version 3.0 or greater and edited to add the correct offset.

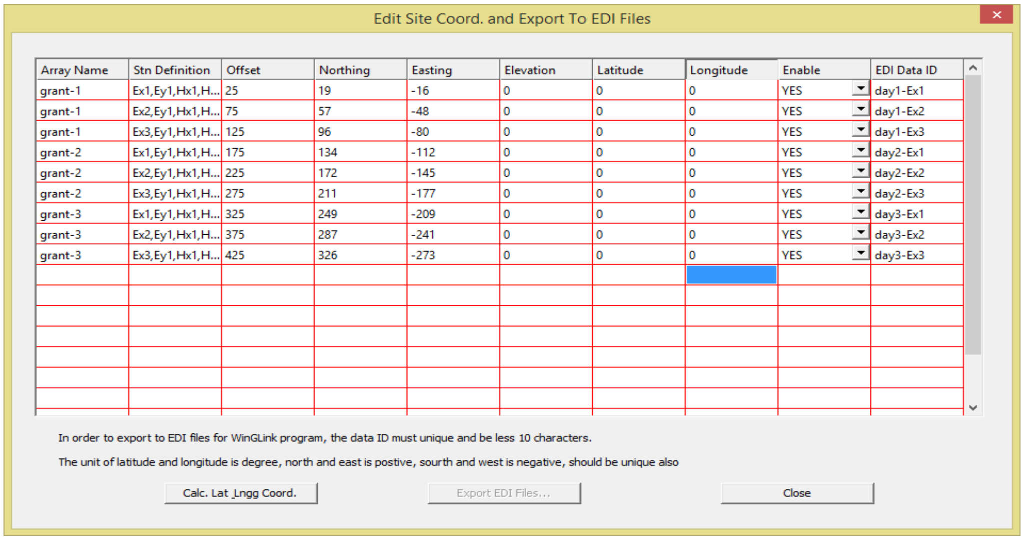
AA. How to export the EDI files:

The EDI files can be created in MTPro either from .GTS files or saved .MT files. The export of the EDI files is done as follows:

1) Read in the .GTS files or an .MT file into MTPro version 3.00 or greater. (Build date of May 11 or later)
2) Click “File”/”Export EDI file”. It will show you the EDI export menu as follows:

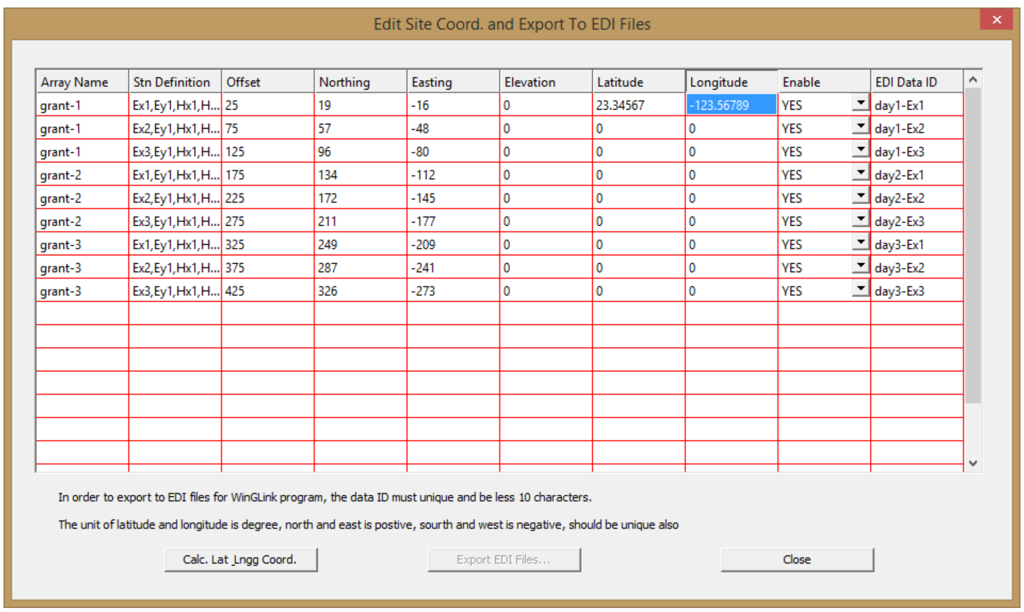


3) Make sure each EDI Data ID is unique for each station and the name length is 10 characters or less. In the example above the EDI Data ID’s are not uniquire. Therefore they need to be edited. The image below shows the edits to make each one unique for the sounding, and still be 10 characters or less.

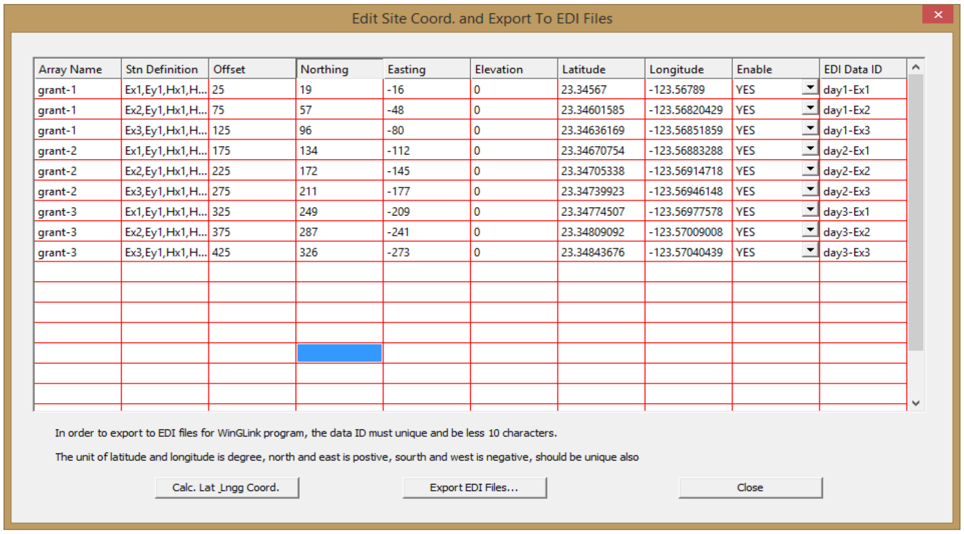


The 10 character limit is unique to WinGLing. Other programs reading EDI files may have be able to accept longer file names.

4) Enter a latitude and longitude reading for one of the stations. Use the negative singe (-) for latitudes in the southern hemisphere, and longitudes in the western hemisphere. For example:



5) Click on “Calc. Lat Lngg Coord” to have the program calculate all the Lat-Long positions for the other soundings. See below:



6) Click “Export EDI Files”

7) Navigate to the folder and location where you want the EDI files stored and click OK. The save file name will be the will be the EDI Data ID with a “.EDI” extension, for example “day1-Ex1.EDI”.

Note that the folder must have been created before this step is taken. The menu does not allow the creation of a new folder here.

BB. Additional notes:

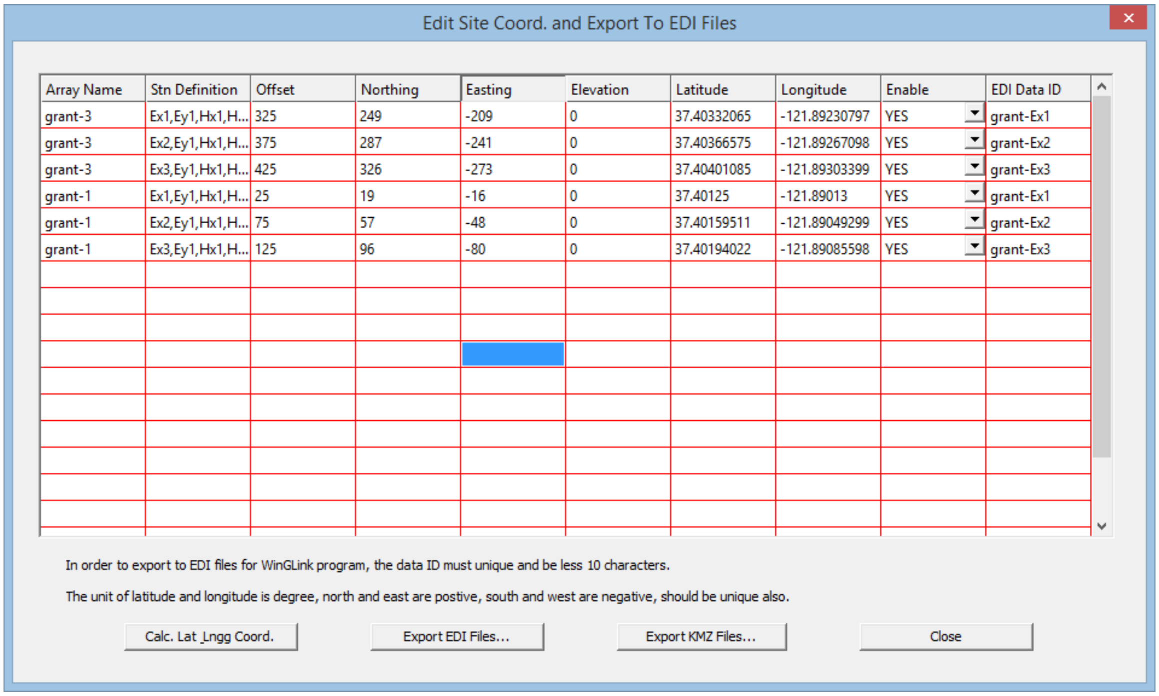
1) All fields can be edited in the table except for “Array Name” and the “Station Definition”. For example if one or more of the sounding stations (Ex) are off line then the GPS coordinates can be entered manually for those individual stations.

2) If incorrect GPS measurements were entered, you can re-enter the correct values in, then re-calculate all values by clicking on the “Cal. Lat Long Coord” while the changed value is still highlighted.

3) Any field sounding can be disabled by toggling the “Enable” field from “Yes” to “No”.

Export of Google Earth KMZ files for station locations

After the GPS locations have been calculated for each sounding those positions can be exported as KMZ files for plotting their positions in Google Earth. In the example below click on “Export KMZ File” to create Google Earth positions files for each sounding.


Edit Site Coord. and Export To EDI Files
Array Name | Stn Definition | Offset | Northing | Easting | Elevation | Latitude | Longitude | Enable | EDI Data ID
grant-3 | Ex1,Ey1,Hx1,H... | 325 | 249 | -209 | 0 | 37.40332065 | -121.89230797 | YES | grant-Ex1
grant-3 | Ex2,Ey1,Hx1,H... | 375 | 287 | -241 | 0 | 37.40366575 | -121.89267098 | YES | grant-Ex2
grant-3 | Ex3,Ey1,Hx1,H... | 425 | 326 | -273 | 0 | 37.40401085 | -121.89303399 | YES | grant-Ex3
grant-1 | Ex1,Ey1,Hx1,H... | 25 | 19 | -16 | 0 | 37.40125 | -121.89013 | YES | grant-Ex1
grant-1 | Ex2,Ey1,Hx1,H... | 75 | 57 | -48 | 0 | 37.40159511 | -121.89049299 | YES | grant-Ex2
grant-1 | Ex3,Ey1,Hx1,H... | 125 | 96 | -80 | 0 | 37.40194022 | -121.89085598 | YES | grant-Ex3
In order to export to EDI files for WinGLink program, the data ID must unique and be less 10 characters.
The unit of latitude and longitude is degree, north and east are postive, south and west are negative, should be unique also.
Calc. Lat_Lngg Coord.
Export EDI Files...
Export KMZ Files...
Close

Chapter 9: Factors determining good versus bad data for Controlled-Source Audio Magnetotellurics:

For CSAMT data acquisition all signal is provided by a controlled-source transmitter. All other electromagnetic sources can be considered to be noise. This includes obvious noise sources such as power line harmonics, industrial machinery, local power generators, and other environmental noise sources. Natural-field telluric currents can also be considered noise. The Geode EM3D CSAMT acquisition software uses a proprietary filtering technique to narrowly band limit the acquired frequencies to match the frequencies of the transmitter. Data quality determinates can be:

A. Transmitter synchronization: Geode EM3D schedulerfile must match the capabilities of the CS transmitter. The scheduler file is discussed in section "M" above.

B. Transmitter orientation: Maximum coupling between the CSAMT transmitter dipole and the receiver E-field dipole is when both are parallel. That is, if the receiver dipole is at a bearing of 200 degrees, for example, the transmitter dipole should also be at 200 degrees. . For tensor CSAMT one transmitter dipole should be parallel to Ex and the other parallel to Ey.

C. Transmitter signal amplitude: The GEM3D receiver has detected a 20 kW transmitter at a distance of 25 kilometers from the survey site. At that distance the transmitter signal amplitude is in the low microvolt range. As the distance increases and the ground resistivity between the transmitter dipole and receiver site changes there will be a point at which the transmitter signal amplitude will be too small to measure.

D. Environmental noise: The Geode EM transmitter synchronization filter does a very good job at filtering onto the exact transmitter frequency. However it is possible that local noise sources could bias the results. For example, the 41st harmonic of the 50 Hz power line current is 2050 Hz. Many transmitters will use binary frequencies, including 2048 Hz. With a very low transmitter signal and very high 50 Hz power line noise it is possible that the filter band width will allow some component of the 2050 Hz harmonic to leak through and bias the 2048 Hz data point.

E. Proper orientation, leveling and burying of the magnetic coils.

F. Proper preparation, orientation, and burial of the porous pot electrodes to maximize signal coupling and minimize contact resistance.

Chapter 10: General survey principles and typical survey operation:

A. There are three general areas of running a Geode EM3D survey. Planning, laying out the survey line(s), and data acquisition. It is important to note the following: On starting a survey line the first Ex electrode should be positive side of the dipole. For example if E-channel “1” is used for Ey1 and E-channel “2” is used for Ex1, the first electrode in the line should be connected to the red (positive) terminal of channel “2”.

B. Care and maintenance of the components
   a. Electrodes: Non-buffered porous-pot electrodes are recommended for the telluric (E-field) channels. Caution should be taken in the proper preparation and maintenance of the porous pots. For example, if copper-copper sulfate non-polarizing electrodes are used the solution must be kept saturated, meaning there should be undissolved CuSO4 crystals in the solution.
   b. Electrode dipole cables: If electrode cables are left out overnight they may be eaten by rodents causing shorting of the cables to ground.
   c. Coils: The coils do not need recalibration
   d. Coil cables: proper cable handling procedures are the responsibility of the field crew
   e. Ethernet cables: proper cable handling procedures are the responsibility of the field crew.
   f. GPS

C. Troubleshooting hints

D. Fundamental theory of CSAMT operation: Provide basic theory of CSAMT and list of available reference papers and books.

Chapter 11: Notes on AMT (natural field) versus CSAMT (controlled source)

The difference between CSAMT and AMT acquisition is that in MT (magnetotellurics) or AMT (audio magnetotellurics) only natural field signals are used. In CSAMT (controlled-source audio magnetotellurics) only the transmitter signals are used. Details of the mathematical basis of MT theory is given in Chapter 12 below. The question is when should AMT mode be used and when CSAMT mode be used. There are advantages and disadvantages of both.

MT and AMT advantages:

1. You do not need a transmitter source other than signals naturally generated in the atmosphere. These are mostly by distant lightning strikes, and by ionospheric currents in the MT band.

2. The processing of MT and AMT signals requires the signals to be both far-field (plane wave) and un-polarized (i.e. multiple polarizations). This is the nature of atmospheric signals. That means it does not require the processing software to included transmitter terms, i.e. any information about the transmitter can be ignored other than the assumption it is far field and un-polarized.

3. Because there are natural field signals from as low as 0.0001 Hz to over 50,000 Hz a great depth can be mapped using natural field MT and relatively shallow features detected in the AMT band.

MT and AMT disadvantages:

1. Natural field signals vary in strength with the time of day, time of year, location on the earth, and atmospheric conditions. The availability of good signal can be compromised during the survey resulting in poor quality data.

2. For MT measurements at frequencies below 0.1 Hz acquisition time can be anywhere from 6 to 12 hours for a single sounding making low-frequency MT expensive and time consuming. This is less of a problem with the higher-band AMT measurement.

3. Data quality is compromised from environmental noise can from power lines, cultural noise from factories, water pumps, power generators, electrified fences, etc.

CSAMT advantages:

1. The use of a controlled-source transmitter will provide signal without worrying about the time of day, weather conditions, etc.. It is always available and tends to be relatively strong compared to natural-field signals.

2. Because the receiver can be band limited to acquire only the exact frequency of the transmitter, you can work in more noisy environments than is possible with traditional MT and AMT.

3. Acquisition time can be reduced since the source is strong and always available.

CSAMT disadvantages:

1. CSAMT transmitters generally cost more than $80,000 USD.

2. The acquisition band of CS transmitters tends to be limited to a low end of 0.1 Hz in order to avoid near-field signal processing issues. This means very deep surveying (greater than 5 km) generally cannot be done using CSAMT.
3. A CSAMT transmitter generally can transmit up to 1,000 Volts at anywhere from 2 to 30 Amps into the ground. This requires health and safety precautions to be strictly observed.

4. Often when lower frequencies are acquired they enter into the near field. This is mostly seen in high resistivity sites when the transmitter is too close for far field measurements. If near-field measurements are made the results cannot be trusted without including the transmitter parameters into the processing.

In short MT and AMT work well in low-noise environments where good natural field signal is available. CSAMT is preferable in more noisy areas when the depth of investigation can be achieved with a band width of from 0.1 Hz to 10 kHz. In some areas signals approaching 0.01 Hz can be used if the ground is conductive (< 10 Ohm-m) and the transmitter is powerful enough to be placed at a great distance away (say 20 km).

Appendix 1: File and data structure

File Structure:

GTS file consists of file descriptor, file layout and data record blocks.

1) File Descriptor Block

GTS file starts with file descriptor block. So the byte number below is referenced from the beginning of the file.

Byte 0, 1(unsigned integer): It is 4645H. This integer identifies the file as GTS file format described in this document. The first byte is 45H and the second is 46H in a little endian machine. To make things simple, this document is based on little endian. If someone uses a big endian machine to read the file, the bit order needs to be reversed for multiple-bytes field.

Byte 2 ,3(unsigned integer) : Are the bytes of the file descriptor block without the free string part, it is 205 for version 1.

Byte 4(Unsigned Integer): Is the version number. It is 1 at time of documenting, May5, 2016;

Byte 5(Unsigned Integer): Number of Transmitter Dipole. The value is 2 for tensor measurement; otherwise it will be 1;
Byte 6(Unsigned Integer): Number of segment. The segment concept comes from 3D seismic layout. It is normally 1 and a maximum 2 without an LTU in Geode EM3D.

Byte 7(Unsigned Integer): Number of Boxes in the layout.
Byte 8(Unsigned Integer): Number of channels in the layout.
Byte 9(Unsigned Integer): Number of coils in the layout.
Byte 10(Unsigned Integer): line frequency, either 50 or 60 Hz;
Byte 11(Unsigned Integer): 0 if using GPS time, 1 if using PC time.
Byte 12(Unsigned Integer): 0 if using UTC time, 1 if local time;
Byte 13(Unsigned Integer): Type of configuration: 0-MT, 1-Scalar CSAMT(Ex & Hy),
2-2H Scalar CSAMT(Ex, Hx, Hy), 3-Vector CSAMT (Ex, Ey, Hx, Hy), 4- Tensor CSAMT;
Byte 14(Unsigned Integer): Current Tx in use for tensor CSAMT, either 1 or 2;
Byte 15(Unsigned Integer): Tx type, planning for future use, 0- dipole source, 1-horizontal loop ...
Byte 16(Unsigned Integer): Filter Mode. It is 1 if tracking local noise peak, 0 if not;

Byte 17,18,19,20(Unsigned Integer): The bytes of the file descriptor free string (explained later);
Byte 21,22,23,24(Unsigned Integer): Minutes of CSAMT frequency stepping cycle;
Byte 25,26,27,28(Unsigned Integer): Seconds of CSAMT frequency switching;
Byte 29,30,31,32(Unsigned Integer): Maximum seconds of a record transfer time (unused).

Byte 33,34,35,36(Unsigned Integer): Minimum seconds of per frequency;
Byte 37,38,39,40(Unsigned Integer): Minimum cycles of per frequency;
Byte 41,42,43,44(Unsigned Integer): Minimum records of per frequency;
Byte 45,46,47,48(Unsigned Integer): Requested Frequency stepping reference seconds from 00::00::00 of current date;
Byte 49,50,51,52(Unsigned Integer): Frequencies per octave(either 1 or 2)
Byte 53, 54, 55,56,57,58,59,60(Unsigned Integer): Actually reference time in seconds from 00::00::00 of 1/1/1970

Byte 61, 62,63,64,65,66,67,68 (8 bytes IEEE Float, sign bit, 11-bit exponent, 52-bit mantissa): Maximum frequency in Hz
Byte 69, 70,71,72,73,74,75,76 (8 bytes IEEE Float, sign bit, 11-bit exponent, 52-bit mantissa): Minimum frequency in Hz
Byte 77, 78,79,80,81,82,83,84 (8 bytes IEEE Float, sign bit, 11-bit exponent, 52-bit mantissa): Tx1 dipole azimuth in degree,
(The azimuth is defined as angle relative to user grid north. It is negative if on the west side, positive if on the east side. The definition is same for all "azimuth" mentioned in this memo.)

Byte 85, 86,87,88,89,90,91,92 (8 bytes IEEE Float, sign bit, 11-bit exponent, 52-bit mantissa): Tx1 dipole length in meters;
Byte 93, 94,95,96,97,98,99,100 (8 bytes IEEE Float, sign bit, 11-bit exponent, 52-bit mantissa): The easting coordinate of Tx1 dipole center.
Byte 101,102,103,104,105,106,107,108 (8 bytes IEEE Float, sign bit, 11-bit exponent, 52-bit mantissa): The elevation of Tx1 dipole center.

Byte 109,110,111,112,113,114,115,116 (8 bytes IEEE Float, sign bit, 11-bit exponent, 52-bit mantissa): The northing coordinate of Tx1 dipole center.

Byte 117,118,119,120,121,122,123,124 (8 bytes IEEE Float, sign bit, 11-bit exponent, 52-bit mantissa): Tx2 dipole azimuth in degree

Byte 125,126,127,128,129,130,131,132 (8 bytes IEEE Float, sign bit, 11-bit exponent, 52-bit mantissa): Tx2 dipole length in meters

Byte 133, 134, 135,136,137,138,139, 140 (8 bytes IEEE Float, sign bit, 11-bit exponent, 52-bit mantissa): The easting coordinate of Tx2

Byte 141, 142, 143,144,145,146,147,148 (8 bytes IEEE Float, sign bit, 11-bit exponent, 52-bit mantissa): The elevation of Tx2 dipole center.

Byte 149, 150, 151,152,153,154,155, 156 (8 bytes IEEE Float, sign bit, 11-bit exponent, 52-bit mantissa): The northing coordinate of Tx2 dipole center.

Byte 157, 158, 159,160,161,162,163,164,165, 166, 167,168,169,170,171,172 (ASCII character string):
The latitude string from GPS near controller in format "HDDMM.mmmmm", i.e. N40°56.93172'

Byte 173,174, 175,176,177,178,179,180,181, 182, 183,184,185,186,187,188 (ASCII character string):
It is the longitude string from GPS near controller in format "HDDDMM.mmmmm", i.e. W140°56.93172'.

Byte 189, 190, 191,192,193,194,195,196,197, 198, 199,200,201,202,203,204 (ASCII character string): The serial port name (i.e. COM1) GPS is connected.

To make the GTS format flexible to add new parameters during development, I use free format strings to store some parameters in a file descriptor. The string size in bytes is specified in *Byte 17,18,19,20* as mentioned above. Each item is a *keyword* and *value* string pair. There is no embedded white space in the keyword but values do have this restriction. A white space is used as a separator between the keyword and value strings. *Keyword* and *value* string pairs are separated by a NULL character.
Below are free string keywords at this moment (5/18/2016). But it could be modified in future if necessary.

SURVEY: Survey name of the field work
COMPANY: Company doing the survey
CLIENT: The client of the field work
PERMITTER: The people or organization approve the survey
OBSERVER: Operator
SURVEY_AREA:
LAYOUT_BY:
NOTE:
DATUM: Coordinate Datum
ELLIPSOID: Coordinate Ellipsoid
COORDINATE: Projection
UNDEFFINED_COORD_SYS: Y for user defined Coordinate system, N for standard Coordinate system
LINE_FREQ: 60 or 50 in Hz
AUTO_LINE_FREQ: Y to detect line frequency automatically, N to use line frequency in LINE_FREQ string.
POT_SHARE_MODE: Y to connect channel 2 negative and channel 3 positive terminals; N not shared.
DATA_FOLDER: Folder where data is stored.
CAL_FOLDER: Location where coil calibration is stored.

PATCH_NAME: Name of the setup;
SURVEY_LINE: Name of survey line;

Coil calibration response strings: The number of strings is determined by byte 9 (number of coil). For each coil calibration string, the keyword of the string pair is the coil calibration file, the value of the string pair is the frequency response in the pattern of "Freq1_RealRsp1_Imag_Rsp1_ Freq1_RealRsp1_Imag_Rsp1…. Freq2_RealRsp2_Imag_Rsp2"

Byte 6(Unsigned Integer): Number of segment. The segment concept comes from 3D seismic layout. It is normally 1 and maximum 2 without LTU in Geode EM3D.

Byte 7(Unsigned Integer): Number of Boxes in the layout.
Byte 8(Unsigned Integer): Number of channels in the layout.

2) Field Layout Block

The field Layout Block consists of segment, box and channels sub-blocks;

Segment sub-block:

Use the number of segments in byte 6 of file descriptor mentioned above to determine how many segment descriptor structures need to be read or written. The size of each segment description is 49 bytes. It contains following 6 fields;
Byte0-15: unused (it was assigned as the survey line the segment, but is disabled at this moment (May of 2016).
Byte 16 (unsigned integer): Number of receiver boxes in the segment.
Byte 17-24 (*8 bytes IEEE Float, sign bit, 11-bit exponent, 52-bit mantissa*): planned telluric dipole length in the segment. The actual E-channel dipole length can be changed in the program later. Program uses the length to automatically setup the array layout. But a user can change the dipole length of any channel if necessary.
Byte 25-32 (*8 bytes IEEE Float, sign bit, 11-bit exponent, 52-bit mantissa*):The azimuth of the segment.
Byte 33-40 (*8 bytes IEEE Float, sign bit, 11-bit exponent, 52-bit mantissa*): Starting easting coordinates of segment.
Byte 41-48 (*8 bytes IEEE Float, sign bit, 11-bit exponent, 52-bit mantissa*): Starting northing coordinates of segment.

Box definition sub-block:

Uses the number of boxes for each segment (byte 16) of segment sub-block mentioned above to determine how many box descriptors need to be read or written. The size of each box descriptor structure is 31 bytes. It contains the following 10 fields;

Byte 0 (unsigned integer): Number of channels used in the box.
Byte 1 (unsigned integer): Box configuration type: 0- unknown, 1-6Ex, 2-5Ex1H, 3-5Ex1Ey, 4-3Ex1Ey2H, 5-2Ex1Ey3H
Byte 2 (unsigned integer): Number of Ex channels used in the box.
Byte 3 (unsigned integer): Number of Ey channels used in the box.
Byte 4 (unsigned integer): Number of Hx channels used in the box.
Byte 5 (unsigned integer): Number of Hy channels used in the box.
Byte 6 (unsigned integer): Number of Hz channels used in the box.

Byte 7-14 (*8 bytes IEEE Float, sign bit, 11-bit exponent, 52-bit mantissa*): battery voltage in Volts (not used yet)
Byte 15-22 (*8 bytes IEEE Float, sign bit, 11-bit exponent, 52-bit mantissa*): The northing coordinates of box (not used yet)
Byte 23-30 (*8 bytes IEEE Float, sign bit, 11-bit exponent, 52-bit mantissa*): The easting coordinates of box (not used yet)

Channel description sub-block:

Uses the number of channels for each box (byte 0) of box sub-block mentioned above to determine how many channel descriptor structures need to be read or written. The size of each channel descriptor structure is 119 bytes. It contains the following 19 fields;
Byte 0 –Byte 15(*ASCII character string*): Channel definition;
Byte 16 –Byte 31(*ASCII character string*): Calibration file name for H channel;
Byte 32 (unsigned integer): Channel number in seg2 file created by SAS program;
Byte 33 (unsigned integer): Shared pots, 0- no shared pots, 1- share one pot, 2 –share two pots;
Byte 34 (unsigned integer): High pass filter settings, 0-DC coupling, 1-0.1 Hz cut-off frequency 2-0.01 Hz cut-off frequency

Byte 35 (unsigned integer):low pass setting, 0-weak LP, 1-normal LP, 2-strong LP
Byte 36 (unsigned integer): Gain setting, 0-x0.25, 1-x1, 2-x4, 3-x16
Byte 37 (unsigned integer): bootstrap feedback, 0-disable, 1-enable
Byte 38 (unsigned integer): unused

Byte 39-46 (8 bytes IEEE Float, sign bit, 11-bit exponent, 52-bit mantissa): Easting coordinate
Byte 47-54 (8 bytes IEEE Float, sign bit, 11-bit exponent, 52-bit mantissa): Northing coordinate
Byte 55-62 (8 bytes IEEE Float, sign bit, 11-bit exponent, 52-bit mantissa): Elevation
Byte 63-70 (8 bytes IEEE Float, sign bit, 11-bit exponent, 52-bit mantissa): Azimuth in degree
Byte 71-78 (8 bytes IEEE Float, sign bit, 11-bit exponent, 52-bit mantissa): dipole length (m)
Byte 79-86 (8 bytes IEEE Float, sign bit, 11-bit exponent, 52-bit mantissa): dummy
Byte 87-94 (8 bytes IEEE Float, sign bit, 11-bit exponent, 52-bit mantissa): AC noise level
Byte 95-102 (8 bytes IEEE Float, sign bit, 11-bit exponent, 52-bit mantissa): DC noise level

Byte 103-110 (8 bytes IEEE Float, sign bit, 11-bit exponent, 52-bit mantissa): contact resistance
Byte 111-118(Unsigned Integer): Contact resistance measurement time in seconds from 00::00::00 of 1/1/1970

3) Record Block

Record Tag sub-block

Byte 0-1(unsigned integer): Each record block starts with Record ID, 5354H, which identifiers the start of a record.
Byte 2-3(unsigned integer): record tag size in byte which is 45 at current time.
Byte 4-5(unsigned integer): transmitter No for the record.
Byte 6-7(unsigned integer): Number of channel in the record.

Byte 8(unsigned integer): Enable flag for the record. 0- disabled, 1-enabled;
Byte 9-12(unsigned integer): Bytes of free format string for the record.
Byte 13-20(Unsigned Integer): Record time in seconds from 00::00::00 of 1/1/1970
Byte 21-28 (8 bytes IEEE Float, sign bit, 11-bit exponent, 52-bit mantissa): Sample rate in Hz
Byte 29-32(unsigned integer): Samples per channel.
Byte 33-36 (4 bytes IEEE Float, sign bit, 8-bit exponent, 23-bit mantissa): Signal frequency in Hz
Byte 37-40(unsigned integer): Number of stacks in the record.
Byte 41-44(unsigned integer): Transmitter divisor based Tx clock frequency of 4,980,736 Hz;

To make file flexible to add new parameters during development, I use free format strings to store some parameters after each record tag. The string size in bytes is specified in *Byte 9-12* as mentioned above. Each item is *keyword* and *value* string pair. There is no embedded white space in the keyword but values do have this restriction. A white space is the separator between keyword and value string. *Keyword* and *value* string pairs are separated by a NULL character. Below are free string keywords at this moment (5/18/2016). But it could be modified in the future if necessary.
CHNO: Channel number sequence in seg2 file. The channel number is separated by "_", i.e. 1-2-5-6
CHDEF: Channel definition sequence. The channel number is separated by "_", i.e. Ey1-Ex1-Hx1-Hy1
SKEW: Channel skew sequence. The channel number is separated by "_", i.e. 0.0001-0.0004-0.4444 -0.22222
(4 bytes IEEE Float sign bit, 8-bit exponent, 23-bit mantissa

Record data sub-block

Record data is stored in 4 bytes IEEE floating point (sign bit, 8-bit exponent, and 23-bit mantissa). The record data is stored channel by channel. The bytes of each channel are 4 X number samples (bytes 29-32 in record tag).

Appendix 2: GPS Setup software

GPS Setup software: GPS timing is used to synchronize the GEM3D receiver and the transmitter in CSAMT mode. GPS synchronization is not required in the AMT mode since the transmitter is not used. In CSAMT acquisition the GPS is connected directly to the controller PC which in turn synchronizes the individual receiver boxes to a common time based on the scheduler program.

Appendix 3: Basic MT theory

Theory

Electromagnetic waves

The electromagnetic waves of interest to the MT practitioner are described by Maxwell's equations. In differential form they are

$$\nabla\times\mathbf{E} = -i\omega\mu\mathbf{H} \quad \text{(Faraday's Law)} \quad (1)$$

$$\nabla\times\mathbf{H} = (\sigma + i\omega\varepsilon)\mathbf{E} \quad \text{(Ampere's Law)} \quad (2)$$

$$\nabla\cdot\mathbf{H} = 0 \quad (3)$$

$$\nabla\cdot\mathbf{E} = \rho/\varepsilon \quad \text{(Coulomb's Law)} \quad (4)$$

where **E** is the electric field, **H** is the magnetic field, σ is conductivity, ε is permitivity, and ρ is free electric charge. Here the notation **E** and **H** indicates vector harmonic time dependency

$$e^{-i\omega t} = \cos(\omega t) - i\sin(\omega t)$$

so that the peak instantaneous vector value E of **E** is given by

$$\mathcal{E} = \mathrm{Re}(\mathbf{E}e^{i\omega t}).$$

where ω is angular frequency ($2\pi f$), $i=\sqrt{-1}$, t is time and Re indicates the real part. A differential equation for **E** is obtained by taking the curl of equation (1) and substituting equation (2) to get

$$\nabla\times\nabla\times\mathbf{E} = -i\omega\mu(\sigma + i\omega\varepsilon)\mathbf{E}.$$

It is customary to let $k^2 = -i\omega\mu\sigma + \omega^2\mu\varepsilon$ and apply the vector identity

$$\nabla\times\nabla\times\mathbf{A} = -\nabla^2\mathbf{A} + \nabla(\nabla\cdot\mathbf{A})$$

to obtain

$$\nabla^2 \mathbf{E} + k^2 \mathbf{E} = 0 , \qquad (5)$$

where we have also assumed that there is no free charge present (Ñ·**E** = 0). Equation (5) is the Helmholtz equation for E and *k* is the propagation constant. The source of MT signals is in the atmosphere where the conductivity is near 0, and here the propagation constant is

$$k = \omega \sqrt{\mu_0 \varepsilon_0} .$$

In the earth

$$k \approx \sqrt{-i\omega\mu\sigma}$$

because, for earth materials, $\sigma >> \omega\varepsilon$ at the frequencies we are interested in.

Propagation of electromagnetic waves

A fundamental assumption when interpreting MT measurements is that the source fields impinge on the earth as uniform plane waves: the **E** and **H** fields are constant in planes perpendicular to the direction of propagation. For a plane wave propagating into a uniform earth, where the z direction is positive downward, we need only consider the field components E_x and H_y and can set the other components of the **E** and **H** fields to zero. With

$$\nabla^2 \times \mathbf{E} = \nabla^2 E_x \hat{x} + \nabla^2 E_y \hat{y} + \nabla^2 E_z \hat{z}$$

equation (5) becomes

$$\frac{d^2 E_x}{dz^2} + k^2 E_x = 0 \qquad (6)$$

because the plane wave does not vary in the x and y directions. This differential equation has a general solution

$$E_x = E_0^+ e^{-ikz} + E_0^- e^{ikz}$$

where the coefficients E_0^+ and E_0^- are constants which can be found by applying boundary conditions. Because of the requirement that a wave not gain amplitude in the direction of propagation, the coefficients E_0^+ and E_0^- represent the amplitudes of the electric field waves traveling in the +z direction (downward) and -z direction (upward) respectively. For a plane wave propagating in a uniform earth, Ex is 0 at an infinite depth because we are infinitely far from the plane wave source. This implies that E_0^- represents the amplitude of a reflected wave, and in a uniform earth where there are no reflectors, its amplitude must also be zero. So

$$E_x = E_0^+ e^{-ikz} = E_0^+ e^{-iz\sqrt{-i\omega\mu\sigma}} = E_0^+ e^{-z(1+i)\sqrt{\omega\mu\sigma/2}}$$

or

$$E_x = E_0^+ e^{-z\sqrt{\omega\mu\sigma/2}} e^{-iz\sqrt{\omega\mu\sigma/2}}.$$

The term with the imaginary exponent represents the wave component of the electric field and the term with the real exponent defines the decay of the wave's amplitude with depth. It is convenient to specify distance in terms of the wavelength and, where EM waves penetrate conductors, it is customary to use one radian as the standard distance. This distance is called a skin depth. One wavelength is 2π radians so one skin depth is a bit less than one sixth of a wavelength. Wavelength is given by

$$\lambda = \frac{2\pi}{\kappa}$$

so one skin depth is given by

$$\delta = \frac{1}{\kappa}$$

where the wave number κ is

$$\kappa = \sqrt{\frac{\omega\mu\sigma}{2}}$$ so

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} = \sqrt{\frac{1}{4\pi^2 10^{-7}}}\sqrt{\frac{\rho}{f}} \approx 503\sqrt{\frac{\rho}{f}} \quad \text{(meters)}$$

At the earth's surface (z = 0) and from equation 6, Ex(0) = E_0^+. At the skin depth δ, the amplitude of the down-going wave has deceased to

$$E_x(\delta) = E_0^+ e^{-1}$$

which is 1/e or about 37 percent of its surface value. If a reflective layer existed at a depth δ, then the reflected, up-going wave would also be attenuated by 37 percent resulting in a total attenuation of about 86 percent relative to the surface value of the down going wave.

The presence of uniform plane-waves implies that the wave's source is distant: nearby sources are likely to generate waves with a spherical wave front that will not be uniform in the survey area. If sources are nearby, equations 1 and 2 are incomplete; they lack the appropriate source terms for a complete description of the fields and their interaction. Because it is difficult to specify sources that are beyond our control, it is best if they can be avoided. Both experimental results and numerical simulations indicate that at distances greater than 3 skin depths (1/2 wave length) from an electromagnetic transmitter, the uniform, and plane portion of the waves are dominant and at 6 or 7 skin depths (1 wave length) the waves are completely uniform and plane relative to the precision with which we can measure them.

Impedance

In the air, above a uniform earth, we expect to find an electromagnetic field composed of electromagnetic waves propagating downward and reflected waves propagating upward. This situation is described for an electric field component by

$$E_x^0 = E_0^+ e^{-ik_0 z} + E_0^- e^{-ik_0 z} \qquad (7)$$

The coefficient subscripts '0' indicate that this expression applies to layer 0, (the air) and the superscripts indicate the direction of travel (positive down). In a uniform earth (layer 1) there are no reflectors so:

$$E_x^1 = E_1^+ e^{-ik_1 z} \qquad (8)$$

The propagation constants in these expressions are:

$$k_0 = \omega\sqrt{\mu_0 \varepsilon_0}. \quad \text{and} \quad k_1 = e^{i\pi/4}\sqrt{\frac{\omega\mu}{\rho}}.$$

A solution for the unknown constants in equations 7 and 8 is obtained by enforcing the conditions that Ex and Hy must be continuous at the earth-air boundary. Applying Faraday's law to 7 and 8 gives the magnetic fields

$$H_y^0 = \frac{E_0^+}{\eta_0} e^{-ik_0 z} + \frac{E_0^-}{\eta_0} e^{-ik_0 z} \quad \text{and} \quad H_y^1 = \frac{E_1^+}{\eta_1} e^{-ik_1 z}$$

where η0 and η1 are the intrinsic impedance of the air and the earth given by

$$\eta_0 = \frac{i\omega\mu_0}{ik_0} = \sqrt{\frac{\mu_0}{\varepsilon_0}} \quad \text{and} \quad \eta_1 = \frac{i\omega\mu_0}{ik_1} = \sqrt{\omega\mu_0\rho}\,e^{i\pi/4}$$

Equating E and H fields at z = 0 yields

$$E_1^+ = E_0^+ + E_0^- \quad \text{and} \quad \frac{E_1^+}{\eta_1} = \frac{E_0^+}{\eta_0} - \frac{E_0^+}{\eta_0}.$$

The solution of these equations yields the amplitude of the transmitted wave and the reflected wave:

$$E_1^+ = \frac{2\eta_1}{\eta_0 + \eta_1} E_0^+ \quad \text{and} \quad E_0^- = \frac{\eta_1 - \eta_0}{\eta_0 + \eta_1} E_0^+.$$

These equations lead to expressions for the electric and magnetic field in the air in terms of impedance of the air and earth give by

$$E_x^0 = E_0^+ \left[e^{-ik_0 z} + \frac{\eta_1 - \eta_0}{\eta_1 + \eta_0} e^{-ik_0 z} \right] \quad \text{and} \quad H_y^0 = \frac{E_0^+}{\eta_0} \left[e^{-ik_0 z} - \frac{\eta_1 - \eta_0}{\eta_1 + \eta_0} e^{-ik_0 z} \right].$$

Similarly, in the earth we have

$$E_y^1 = E_0^+ \frac{2\eta_1}{\eta_1 + \eta_0} e^{-ik_1 z} \quad \text{and} \quad H_v^1 = E_0^+ \frac{2}{\eta_1 + \eta_0} e^{-ik_1 z}.$$

At the surface of the earth, these two sets of expressions are equal and the ratio of Ex/Hy is called the surface impedance Z. For the case of a homogeneous earth, Z = η. This is the basis for defining the apparent resistivity ρa: it is the resistivity of a homogeneous earth, which would yield the same surface impedance as measured over an inhomogeneous earth at a particular location and frequency. Because

$$\eta_1 = \frac{E_x}{H_v} = e^{i\pi/4} \sqrt{\omega \mu_0 \rho},$$

we can write

$$\rho_a = -\frac{i}{\omega \mu_0} \left(\frac{E_x}{H_y} \right)^2.$$

In general, apparent resistivity is complex (e.g. the IP phenomena), but we restrict our attention to the real component which is defined as

$$\rho_a = -\frac{i}{\omega \mu_0} \frac{|E_x|^2}{|H_y|^2}.$$

Impedance estimation

Modern magnetotelluric systems are designed to record variation of both the electric and magnetic fields in two orthogonal directions and use these records to calculate the surface impedance at a measurement site. The surface impedance **Z** is complex, frequency dependent, and, due to the presence of noise and earth structures, is also a tensor:

$$\overline{E}(\omega) = \overline{\overline{Z}}(\omega) \cdot \overline{H}(\omega) \quad \text{or} \quad \begin{aligned} E_x &= Z_{xx} H_x + Z_{xy} H_y \\ E_y &= Z_{yx} H_x + Z_{yy} H_y \end{aligned} .$$

It can be helpful to think of the surface impedance tensor as a two input, two output linear system where the inputs are the magnetic field components and the outputs are the electrical field components. This formulation of surface impedance is preferred over the scalar formulation because, when the source fields are nearly plane waves, the impedance elements Zij are time invariant. The scalar surface impedance

$$Z_{ij} = \frac{E_i}{H_j}$$

is easier to calculate but can vary as the direction of the source fields vary.

The tensor impedance can be calculated from a number of records (N) using the least-squares method where the difference between a measured electric field component is minimized relative to the predicted electric field component. For example just considering Ex, Hx and Hy

$$\psi = \sum_{i=1}^{N} (E_{xi} - Z_{xx} H_{xi} - Z_{xy} H_{yi})(E_{xi}^* - Z_{xi}^* H_{xi}^* - Z_{xy}^* H_{yi}^*)$$

and minimization with respect to Zxx and Zxy requires

$$\frac{\partial \psi}{\partial (reZ_{xx})} = \frac{\partial \psi}{\partial (imZ_{xx})} \quad \text{and} \quad \frac{\partial \psi}{\partial (reZ_{xy})} = \frac{\partial \psi}{\partial (imZ_{xy})}$$

which yields

$$\langle E_x H_x^* \rangle = \langle H_x H_x^* \rangle Z_{xx} + \langle H_y H_x^* \rangle Z_{xy} \quad \text{and} \quad \langle E_x H_y^* \rangle = \langle H_x H_y^* \rangle Z_{xx} + \langle H_y H_y^* \rangle Z_{xy} .$$

where, for example

$$\langle E_x H_x^* \rangle = \frac{1}{N} \sum_{i=1}^{N} E_{xi} H_{xi}^*$$

is an average cross power density spectrum and Ex is the discrete Fourier transform of the measured field Ex. The (*) symbol indicates complex conjugation. The two cross power expressions above combine to yield

$$Z_{xx} = \frac{\langle E_x H_y^* \rangle \langle H_y H_x^* \rangle - \langle E_x H_x^* \rangle \langle H_y H_y^* \rangle}{\langle H_x H_y^* \rangle \langle H_y H_x^* \rangle - \langle H_x X_x^* \rangle \langle H_y H_y^* \rangle} \quad \text{and} \quad Z_{xy} = \frac{\langle E_x H_y^* \rangle \langle H_x H_x^* \rangle - \langle E_x H_x^* \rangle \langle H_x H_y^* \rangle}{\langle H_y H_y^* \rangle \langle H_x H_x^* \rangle - \langle H_y X_x^* \rangle \langle H_x H_y^* \rangle}$$

and expressions for Zyx and Zyy are obtained in a similar way.

The surface impedance is usually expressed as apparent resistivity and impedance phase and they are calculated from the surface impedance components as

$$\rho_{ij} = \frac{1}{\omega \mu_0} |Z_{ij}|^2 = \frac{.2}{f} |Z_{ij}|^2 \quad \text{and} \quad \phi_{ij} = \tan^{-1}\left(\frac{\mathrm{Im}(Z_{ij})}{\mathrm{Re}(Z_{ij})} \right)$$

whether they are based on scalar or tensor calculations.