STUDIES ON SIMULATING HIGHLY CONDUCTIVE MODELS IN EMIGMA FREQUENCY RESPONSES AND TIME DOMAIN RESPONSES

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<u>The question “How high a conductivity that can be modeled in EMIGMA” is an ill-posed question.</u>

For many years, geophysical researchers developing simulation algorithms for EM have often stated such things as the limits of contrast between anomaly and background or conducting limitations in regard to their algorithms. But, these statements have often not been correct as researchers have not always considered the full range of issues effecting the accuracy of EM simulations.

For this question to be more answerable “How high a conductivity can be simulated in EMIGMA” must be accompanied by additional information to make the question well posed. Such issues as those listed below must be considered.

a) Aspect ratios of the model
b) Background electrical properties
c) Spectrum of interest
d) Source characteristics
e) Characteristics of source field (e.g. electric, magnetic, high or low gradients)
f) Electrical properties of the model – (conductivity, magnetic susceptibility, electrical polarization)
g) Location and type of receivers

There are, of course, many scattering processes at work in EM as this is why there are several algorithms in EMIGMA to try to reproduce these scattering processes. Each algorithm has its benefits and drawbacks and each has its limitations depending upon the issues listed above:

Algorithms for use with EM Simulations:

- LN (NonLinear Scattering Operators) – electric and magnetic secondary fields due to primary and secondary electric source fields
- FSPlate – magnetic secondary fields due to magnetic source fields
- VHPlate – electric and magnetic secondary fields due to electric and magnetic source fields
- Sphere – electric and magnetic secondary fields due to electric and magnetic source fields

There are 2 other algorithms MLN and LNFD which will not be discussed here

This study is exclusive to relatively small moving inductive sources and the measurement of magnetic fields. This study includes the use of only 3 algorithms, Freespace Plate (FSPlate), VHPlate and LNPrism shortened to FSP,VHP and LNP. While the Sphere algorithm could be useful to such studies, its present limitation to only a magnetic dipole source makes the use of this algorithm for study of such sources awkward. Using this algorithm for such a loop system is not difficult but at present requires a little bookkeeping and post processing. We are presently working to add the direct use of an inductive loop.

Algorithms in this study: We assume for this study that the target is conductive and not magnetic and non- polarizable with the permittivity of free space. We assume the host medium is moderately to highly resistive and also non-magnetic, non-polarizable and with the permittivity of a vacuum. While all algorithms are coded for use with frequencies up to low MHz, this study is limited to 200KHz.

- LN – to study the effects of induced currents in the media as well as electric field pickup by the target. There is no practical limitation to conductivities utilized for anomalies but current saturation of a conductor limits will cause the response to asymptote to a limit at high conductivities. The formulation does not rule out the effects of magnetic induction but much like the standard difference and finite element codes, the simulated response is dominated by the galvanic potential due to its dominance in any electric field formulation to solve EM scattering. In practice, therefore, the inductive response is not represented accurately even for weak conductors. But, nevertheless must be considered for higher frequencies.

- VHPlate – While limited to a thin-sheet, this algorithm includes the effects of magnetic induction by the source field as well as incident electric fields either due to electric fields induced in the host or electric fields transmitted by the loop wires. It also computes the interaction between the induced currents in the plate due to induction and incident currents from the host. The algorithm has several limitations which are generally related to a limitation on the complexity of the secondary currents produced inside the plate. The algorithm was calibrated to thin aluminum oxide plates but the experimental results of the aluminum oxide plates were limited due to the experimental setup and the background resistivity encountered by the experimental system due primarily to steel supports in the floors and walls. The algorithm was compared to other similar algorithms with results generally superior. The algorithm uses a series of polynomial functions to represent the anomalous current produced within the plate.

- FSPlate – magnetic secondary fields due to magnetic source fields. Only induction is estimated with no effects from electric fields either from the source or induced in the host rock. This algorithm is a re-formulation of a technique utilizing a serious of eigenpotentials (eigencurrents) to represent the anomalous current produced within the plate. The algorithm has been compared against VHPlate and two other similar but simpler programs which allow only a simple representation of the currents. In comparison to other similar algorithms, this algorithm is better able to reproduce solutions when the gradients of the source field impressed upon the plate are more complex.

Neither VHPlate nor FSPLate are recommended for receivers extremely close or on the models. This is not the case for the LN algorithm which is stable both near and inside the anomaly. In the case of VHPlate and FSPlate, these algorithms are not coded for interactions between anomalies. The LN is coded for several different types of anomaly interactions.

The database provided contains a series of simulation studies which can be used for the basis of further study. The studies utilize

- A moving system with an inductive source: one loop of area 266 m^2 and another of 900 m^2
- 2 dipolar magnetic receivers: Bz (vertical component) , Bx (horizontal component in the direction of the movement)
- Responses include spectral responses from 1Hz to 200KHz covering the typical range of geophysical instruments
- Time domain responses both during ON and OFF times for a typical airborne TEM waveform with base frequencies of 30&8 Hz
- All spectral responses can easily be transformed to the time domain if required
- Total, Background, Freespace, Scattered (secondary), Total-Freespace
- The simulated responses are computed on a single profile (survey line) but these can be extended easily to multiple survey lines

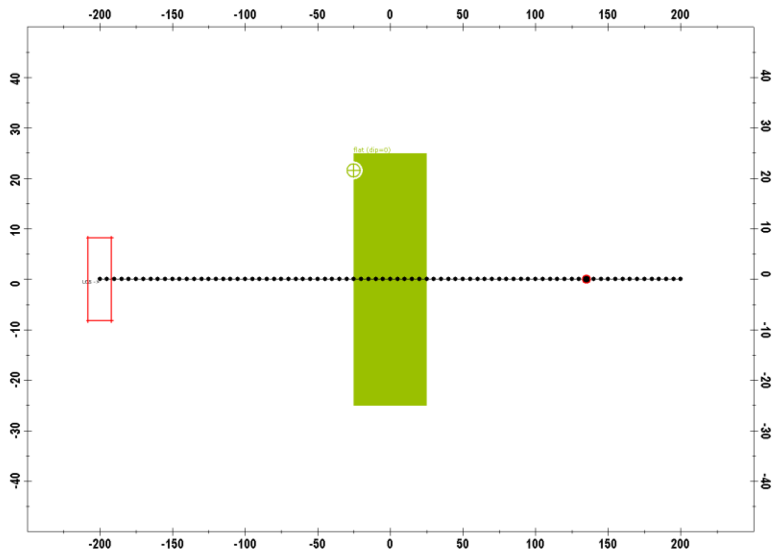
A summary of the models is listed below:

- Thin-sheet and thin prism models are utilized either strictly flat (normal vertical) or vertical (normal horizontal)
- Models are generally centered on the
- For many models, VHPlate, and FSPlate are utilized to compute the response for comparison. LNPrism is also run to show increasing effect of the electric fields as the frequency increases. The prism is thin with an equivalent conductance.
- FSPlate was generally computed using 7 eigenfunctions, the differences with different eigenfunctions are also explored
- The conductance of the models range from 5Siemans up to 8000Siemans with matching conductivities for the prism models
- In general, the background resistivity is set at 5000 Ωm which well above what is experienced in practice. A more representative background derived from a recent study in northern Canada is also used for comparison. In a few cases, the resistivity of the background is increased substantially.

- The flat model is a 50m x 50m plate buried at 5m. The system is 1m above the ground in order to have the a source field incident on the plate with relatively high gradients but not extremely high gradients
- The vertical plate is 200m in length x 50m in depth with its top buried to 10m below ground. The EM system is 30m above the ground to represent a typical helicopter towed airborne system

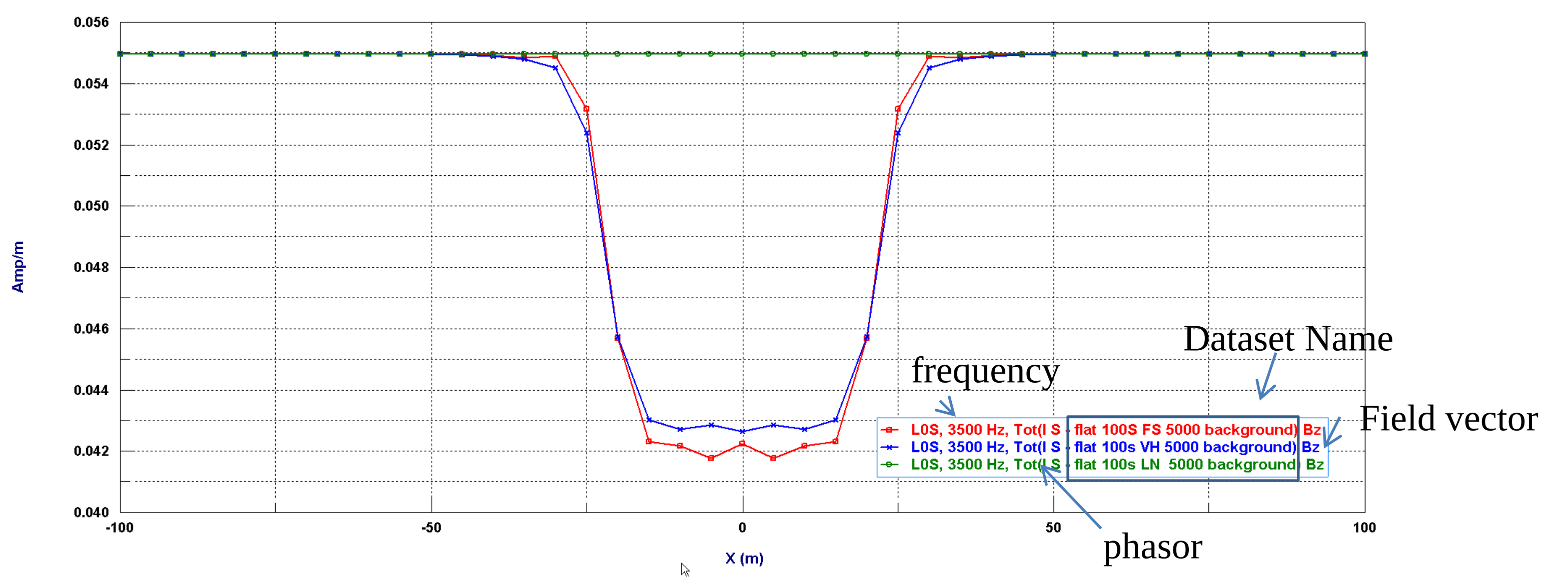
PROJECT 1: Moving Loop Flat Conductor: Two survey subsets, one primarily spectral response of flat conductor varying from 5-12,000S with 5000Ωm host and the second primarily time domain. Also, studies of background electric fields.
PROJECT 2: Moving Loop with Vertical Conductor: Sprectral and TEM responses , 5-8000S, with 5000Ωm or 20,000 Ωm host
PROJECT 3: Moving Loop Flat Conductor with lower resistivity background: flat conductor, 100-5000S with 3 layer background
PROJECT 4: Moving grounded current source for more completeness

EXAMPLE 1: Project ID 1: Survey ID 1



Example 1:
Instrument: 1m above ground, 266m^2, in loop Rx
Plate: 50m x 50m, oriented NS-EW, no dip
Depth to Top: 5m
Conductance: 100Siemens
Background: 5000 Ohm-m
Algorithms: FSP (7), VHP, LNP
Components: Hz, Hx (Units Amps/m)

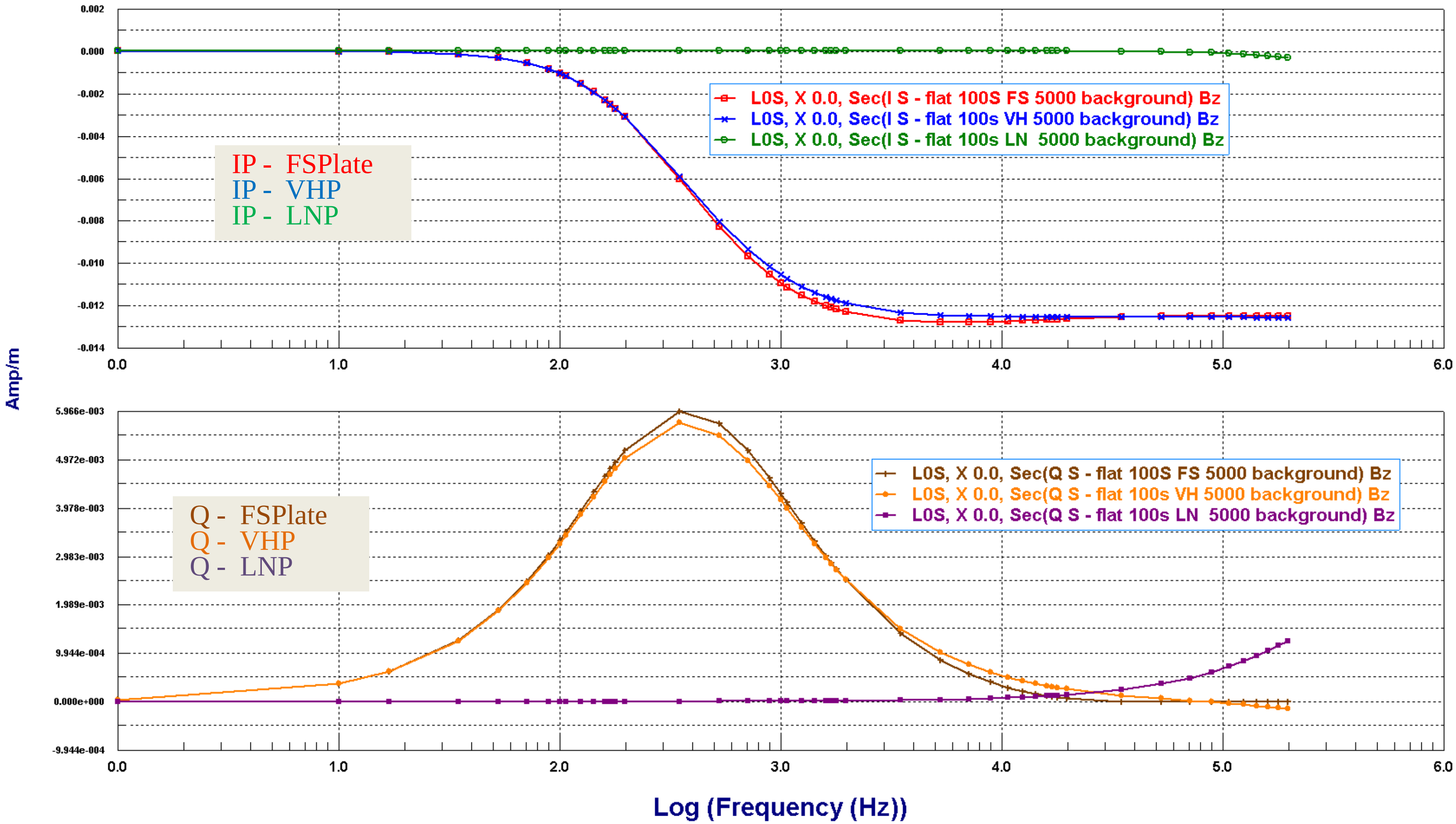
Plot Legend: Line, Phasor, Frequency/Time, db Model Name, Fields



CASE 1: Project 1:
Survey ID:1

Example 1: HZ , X=0
Plate: 50m x 50m, oriented NS-EW, no dip
Depth to Top: 5m
Conductance: 100Siemans
Background: 5000 Ohm-m
Algorithms: FSP, VHP, LNP
Components: Hz (Units Amps/m)

Sprectral Response at x=0, Hz
Secondary/Scattered Field ONLY

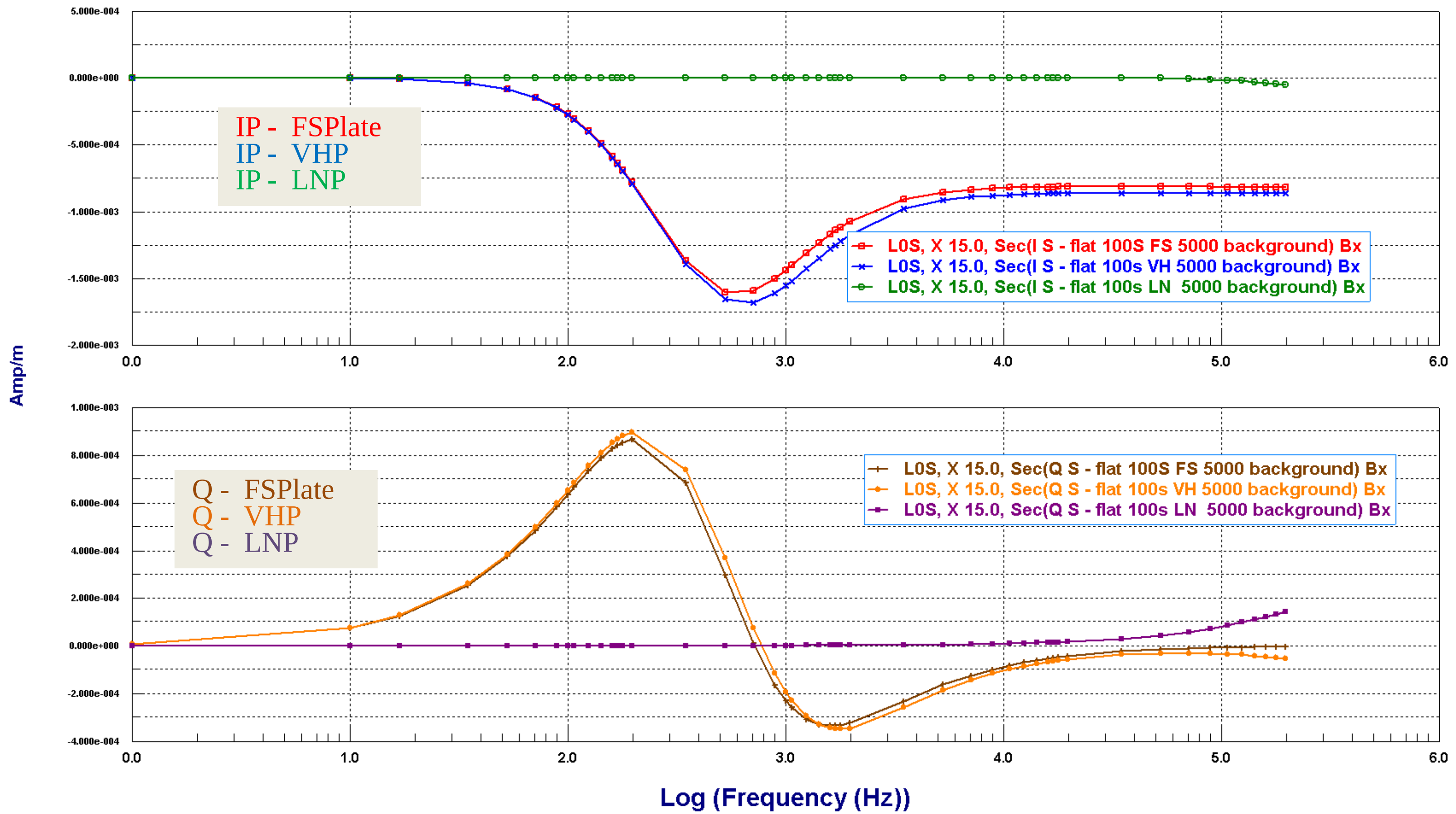


CASE 1: Project 1: Survey ID:1

Sprectral Response at x =15, HX, Secondary (Scattered) Field ONLY

Example 2: HX , x=15m
Plate: 50m x 50m, oriented NS-EW, no dip
Depth to Top: 5m
Conductance: 100Siemans
Background: 5000 Ohm-m
Algorithms: FSP, VHP, LNP
Components: Hx (Units Amps/m)

Notes: Pgs 6-7. 1) The model responses for FSP and VHP generally are very similar from low frequency up beyond 10KHz. There likely is no method presently available to determine which is more accurate. However, the algorithms use entirely different approaches and generally agree to the extent in these models. 2) VHP and FSP start to disagree in the quadrature starting around 20Khz. The LNP response begins to rise at this frequency. These two issues are both due to the effect of the electric fields which will be a combination of the effects of induced currents in the background and E-field pickup by the conductors from the primary electric fields emitted from the source. (*see the following page*)

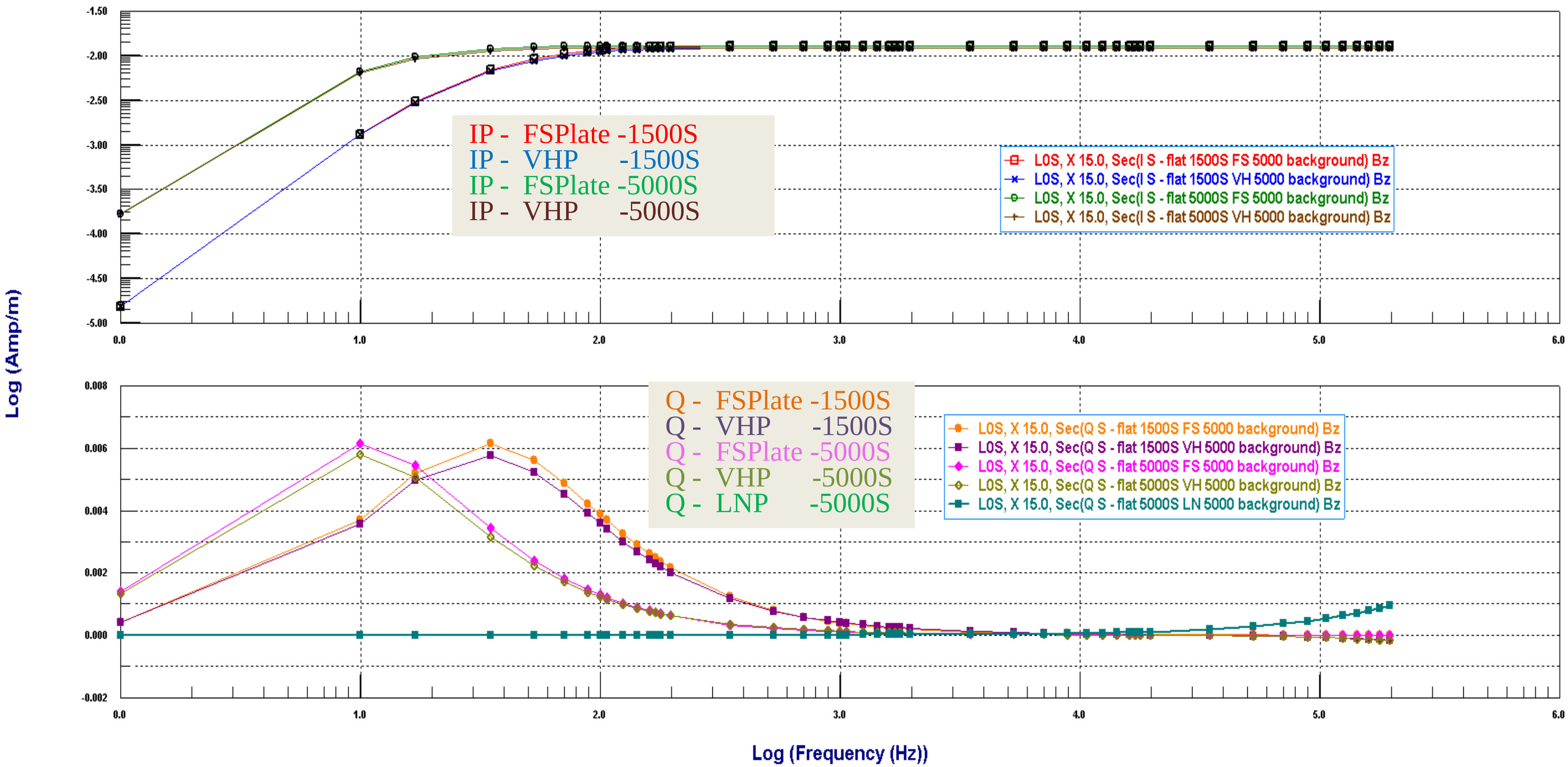


CASE 1: Project 1: Survey ID:1

Sprectral Response at x =15, HZ, Secondary (Scattered) Field ONLY

Example 3: HZ 15m offset
Plate: 50m x 50m, oriented NS-EW, no dip
Depth to Top: 5m
Conductance: 1500 and 5000 Siemens
Background: 5000 Ohm-m
Algorithms: FSP, VHP, LNP
Components: Hz (Units Amps/m)

Below a comparison of 2 plates at 1500S and 5000S computed with the 2 plate algorithms, VHP and FSP. In the IN Phase (IP), the response reaches an asymptote just after 100Hz. This is one reason for many TDEM exploration instruments having a significant part of their bandwidth less than 1,000Hz. In the quadrature, the main difference in the responses is that the 5000S plate peaks around 10Hz while the 1500S plate peaks around 35Hz. The VHP and FSP differ at the very high frequency where VHP includes a current channeling response due to electric field effects. The LNP includes the antennae pickup effect of the electric fields in a vacuum as well as current channeling.

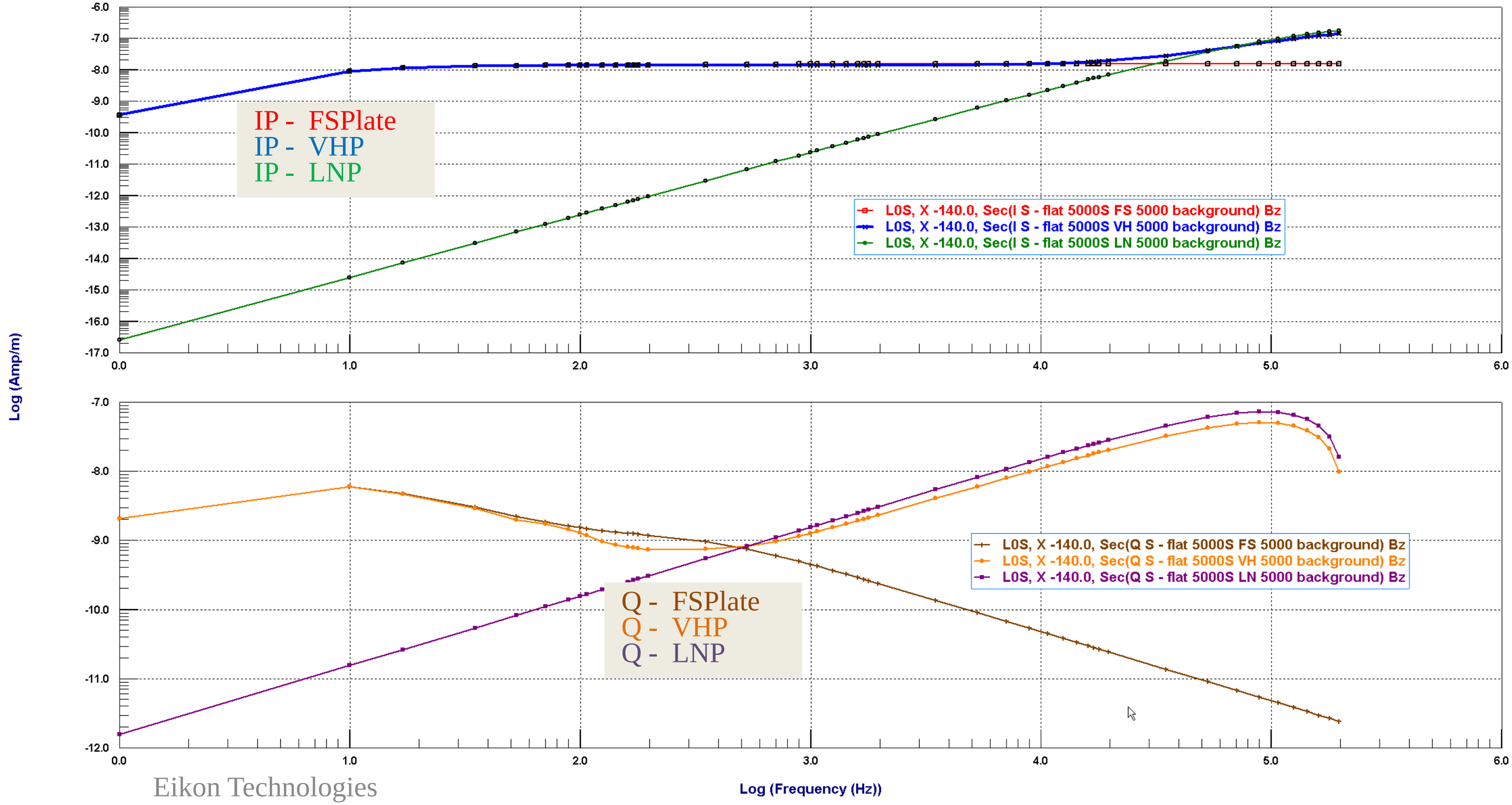


CASE 1: Project 1: Survey ID:1

Sprectral Response at x = -140, HZ, Secondary (Scattered) Field ONLY

Example 4: HZ Distant 140 Offset
Plate: 50m x 50m, oriented NS-EW, no dip
Depth to Top: 5m
Conductance: 1500 and 5000 Siemens
Background: 5000 Ohm-m
Algorithms: FSP, VHP, LNP
Components: Hz (Units Amps/m)

A common misunderstanding in geophysics that as conductivity and frequency increase, the magnetic field asymptotes to a constant IN phase value and a null quadrature value often incorrectly termed the inductive limit. In addition to the magnetic field emitted from the Tx, there are two electric fields present in space. The direct magnetic field produced in a vacuum must be accompanied by an electric field as the magnetic field is the electric field retarded in time as explained by special relativity. We term these fields, for convenience, the freespace magnetic and electric fields. The second electric field is that produced via induction in the host. Here we use a very high background resistivity generally not encountered in the natural world. In this case, removed from the tx, the total inphase response deviates from the purely inductive response beginning at approximately 20Khz. In quadrature, the response begins to deviate from the inductive response at a much lower frequency and by 20Khz is a strong as the inphase response.



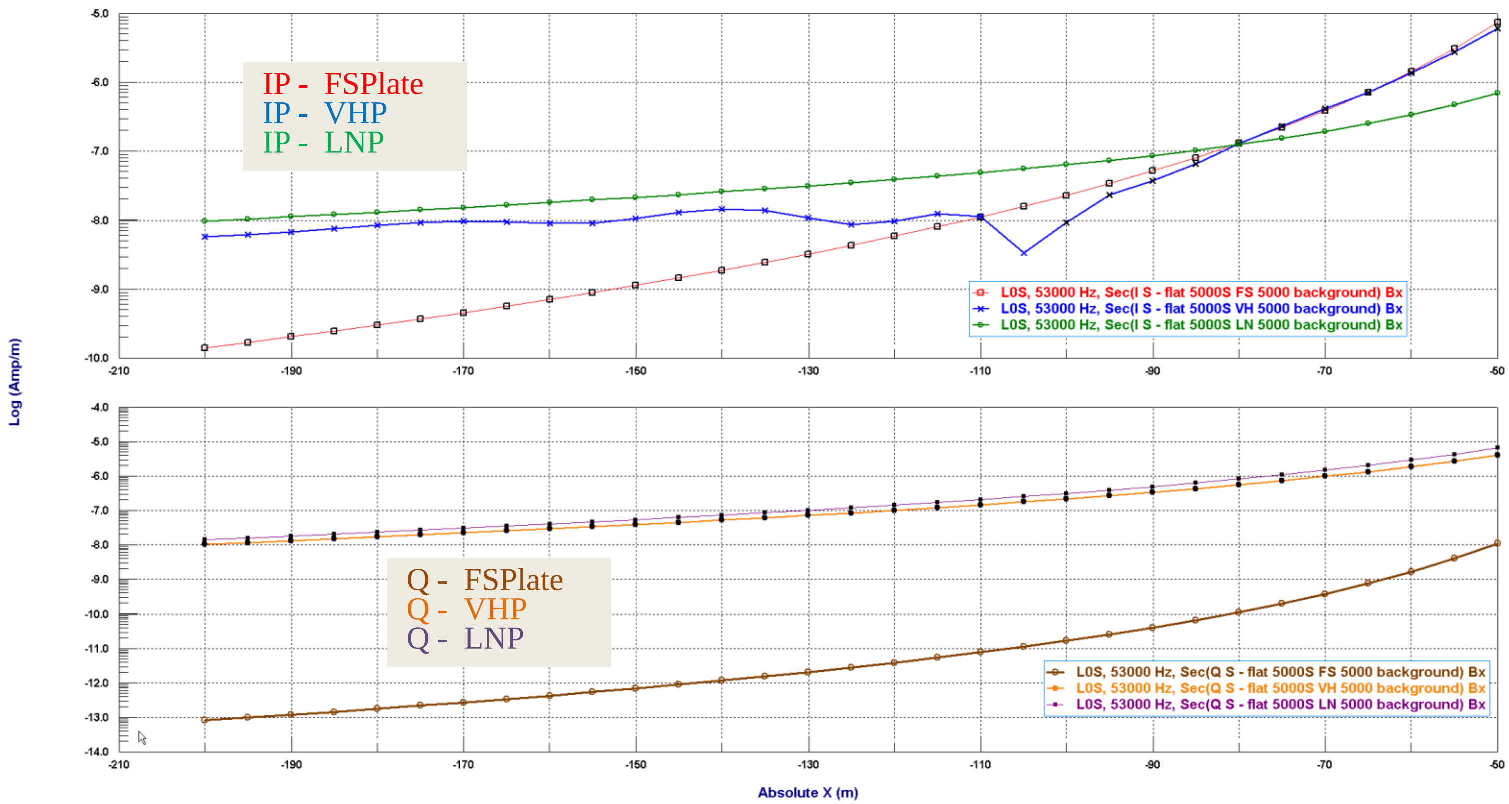
CASE 1: Project 1: Survey ID:1

53000 Hz, outside loop, HX, Secondary (Scattered) Field ONLY

Example 5: HX Offset
Plate: 50m x 50m, oriented NS-EW, no dip
Depth to Top: 5m
Conductance: 1500 and 5000 Siemens
Background: 5000 Ohm-m
Algorithms: FSP, VHP, LNP
Components: Hx (Units Amps/m)

Each algorithm was developed with specific objectives in mind to represent EM scattering. Below, we see the same model now for the Hx component well outside the loop. The effects of the electric field are now evident even in this extreme resistivity background. In the IN phase, the inductive response falls off from the loop quickly while the effects of the electric field excitation fall off much more slowly. The VHP algorithm begins to struggle as move farther away from the source due to the increase in the gradients of the source fields. The LNP algorithm is extremely stable and very accurate but does not reproduce induction.

For the quadrature, the response is dominated by the electric field effects but VHP and LNP do not agree exactly but certainly are within typical noise levels for data this far removed from the source. The VHP and LNP responses have a different sign to the inductive response.

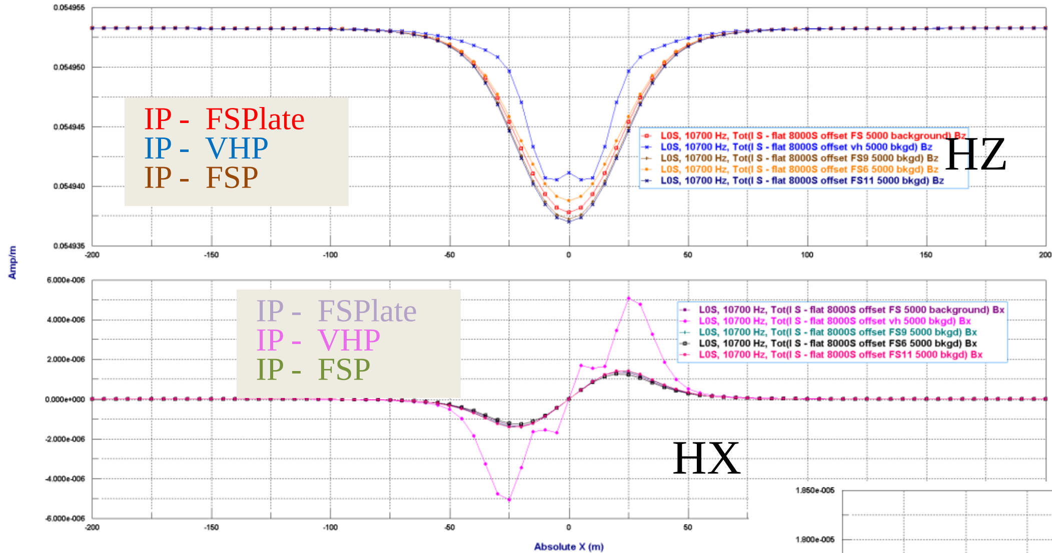


10,700Hz, HZ, HX, Secondary (Scattered) Field ONLY

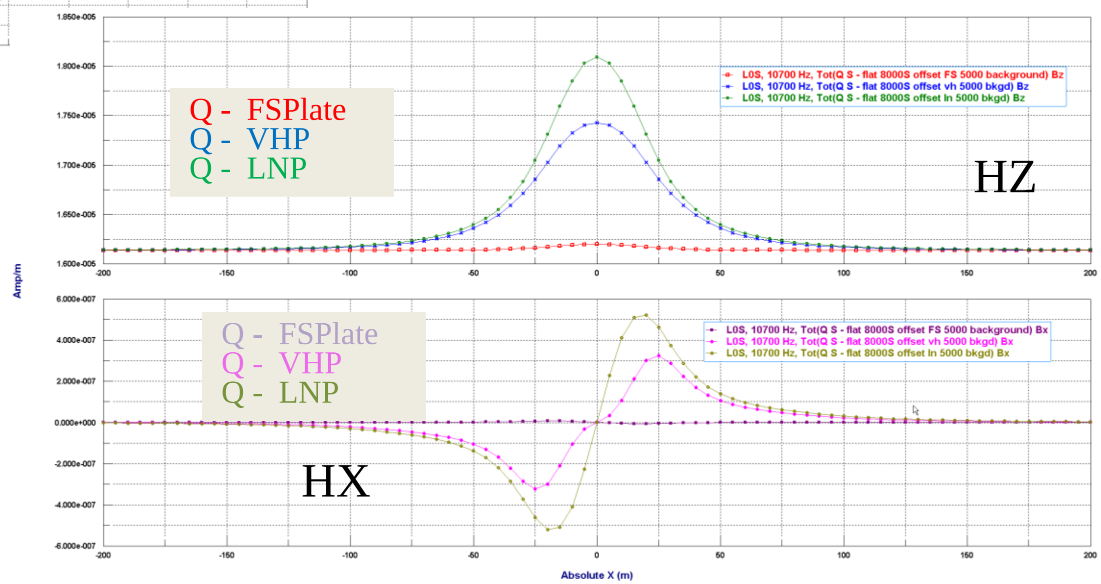
CASE 2: Project 1: Survey ID:1

Example 6: HX,HZ – TARGET OFFSET
Plate: 50m x 50m, oriented NS-EW, no dip, offset
Depth to Top: 5m
Conductance: 1500 and 5000 Siemens
Background: 5000 Ohm-m
Algorithms: FSP, VHP, LNP
Components: Hx (Units Amps/m)

This example is for the same loop and receiver configuration, but in this case, the model is not centered on the profile but the plate center is offset 50m (plate dimension) from the profile. Here, we show one single frequency (10.7Khz). The IN phase response of VHP for HZ has a sharper fall off than the FSP. The FSP response is shown for 4 different settings of eigenvalues (7,9,6 and 11). In this case, the response of FSP appear to converge as the number of eigenvalues increases. However, the mathematical eigenvalue problem solved here is not guaranteed to converge. The response for IN phase, HX for the two algorithms are quite different.



For the quadrature, with the plate at this distance and at this frequency, the electric field effects dominate the induction effects. Limitations can be seen in the VHP algorithm.

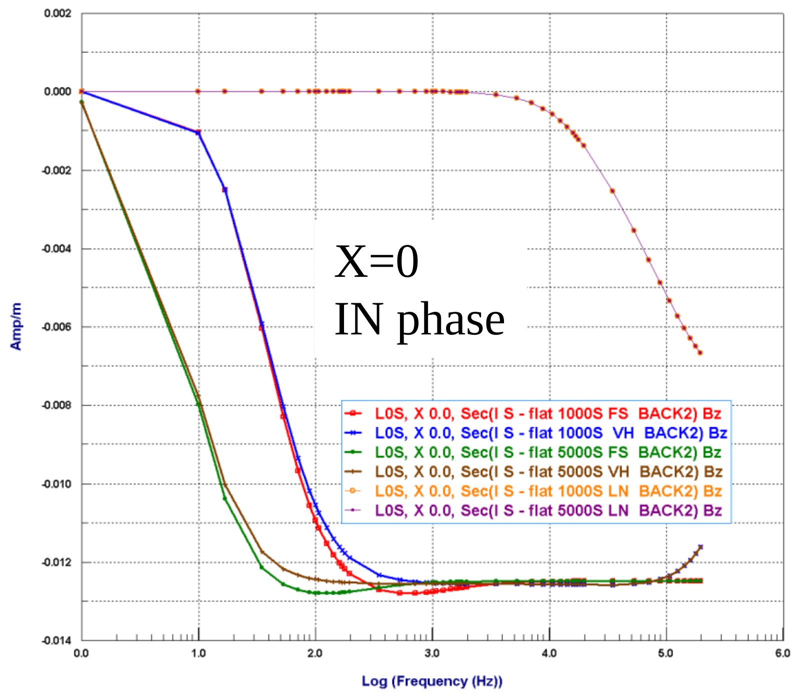


CASE 3: Project 3: Survey ID:3

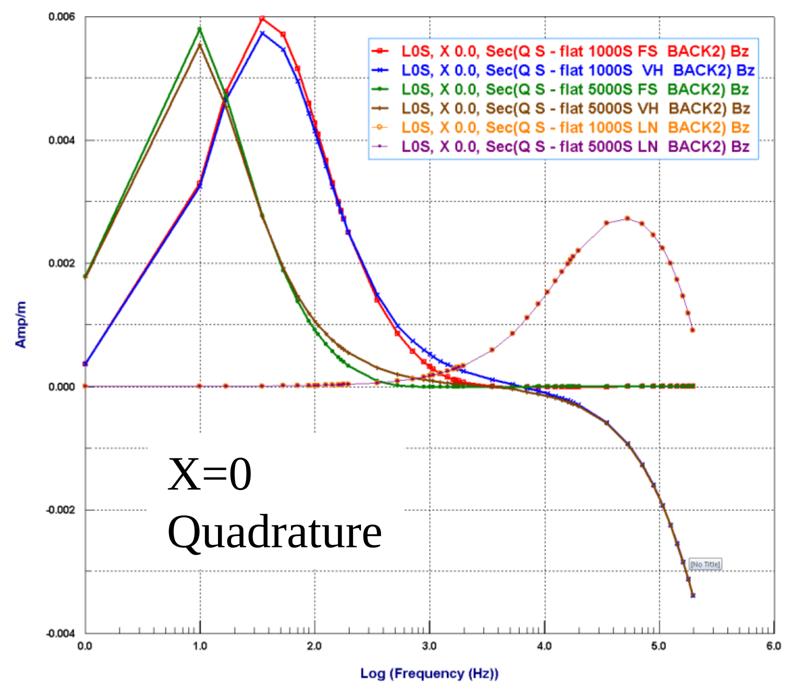
Sprectral Response, HZ, HX, Secondary (Scattered) Field ONLY

Example 7: HZ – Characteristic Background
Plate: 50m x 50m, oriented NS-EW, no dip, no offset
Depth to Top: 5m
Conductance: 1000 and 5000 Siemens
Background: 2 Layers over halfspace
Algorithms: FSP, VHP, LNP
Components: Hz (Units Amps/m)

We turn to a more realizable resistive environment. This background resistivity is fairly representative of mining exploration in both the Canadian and US Northwest and is actually taken from a study in northern Manitoba. Northern Ontario and Quebec as well as Scandinavia have slightly higher underlying resistivities although the resistivity of the weathered cover can be lower. Australia is similar although some areas are very conductive. Note: Only the secondary field is shown here with the background response removed for clarity.



Now that we are in a more realizable background materials, we see the problem becomes much more complicated than the simple conditions of an unrealizable high resistivity background. We show the response for two flat conductors 1000S and 5000S respectively. For the Inphase response, the VHP and FSP agree at low frequency and reach the same high frequency limit before electric field effects begin to occur. At high frequencies, the two conductors cannot be distinguished. Above 100KHz, the VHP deviates from FSP but the direction of deviation disagrees with the more accurate LNP algorithm.



Again, the VHP and FSP agree reasonably well at low frequencies but the electric field effects begin to increase rapidly just below 1KHz. Again, the VHP and LNP results do not agree at higher frequencies but in both cases the effects of the electric fields in the quadrature becomes significant relative to the Inphase response.

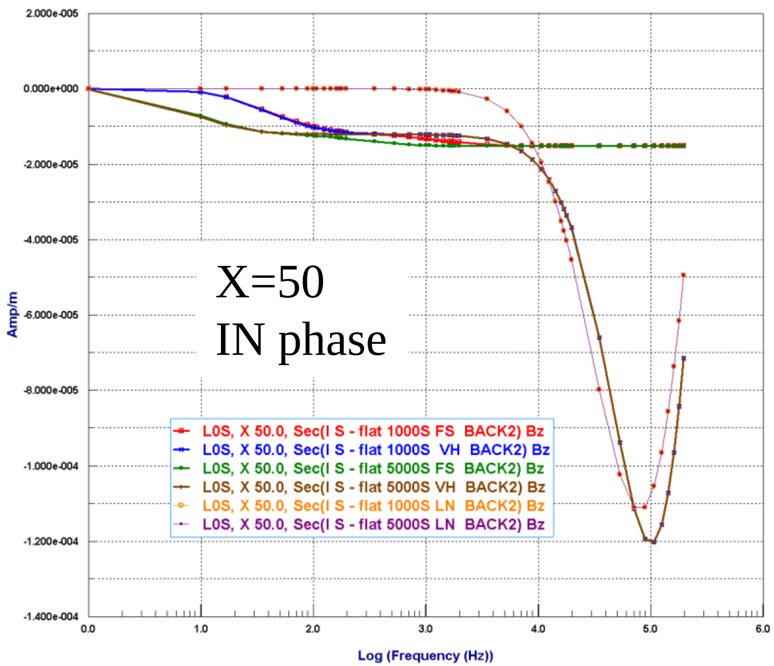
Sprectral Response, HZ, HX, Secondary (Scattered) Field ONLY

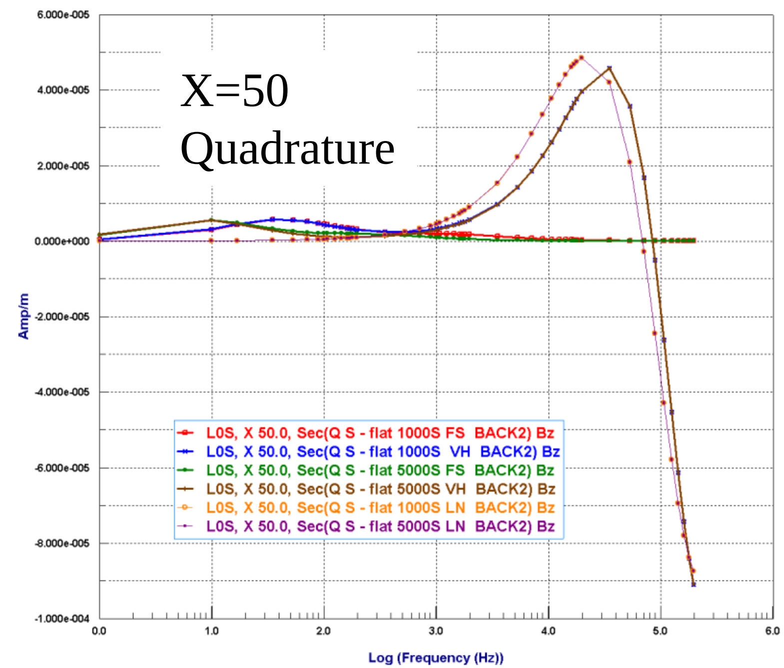
CASE 3: Project 3: Survey ID:3

Example 8: HZ – Characteristic Background
Plate: 50m x 50m, oriented NS-EW, no dip, 50m offset
Depth to Top: 5m
Conductance: 1000 and 5000 Siemens
Background: 2 Layers over halfspace
Algorithms: FSP, VHP, LNP
Components: Hz (Units Amps/m)

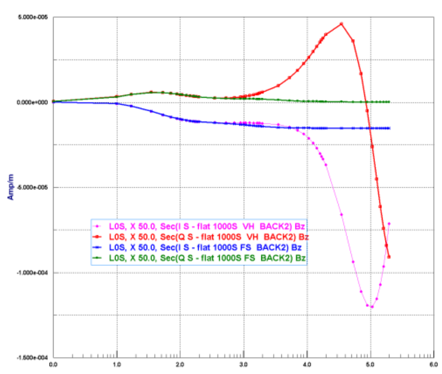
As we move away from the target in this environment, the electric field effects significantly increase in their importance. In the case below, the Rx is at x=50 only 25m from the conductor's edge. Hz is examined. This example shows clearly the fallacy of the inductive limit hypothesis for realizable conductors and resistive backgrounds.

For the Inphase, VHP and FSP agree up to about 200Hz. By 2Khz, FSP response for both conductors have converged to their inductive limit. VHP reaches its inductive limit at a much lower frequency. At 10Khz, the electric field effects begin to increase rapidly and dominate by 100KHz. VHP and LNP produce similar electric effects on the magnetic field but LNP lags VHP in frequency slightly. However, the VHP algorithm includes interaction between the two currents produced in the plate (magnetic induction and electric field effects).





In the quadrature, the electric field effects dominate beginning at 1Khz. In FSP inductive limit in the Inphase is $1.53x10^{-5}$ while the quadrature reaches above $4x10^{-5}$. The figure on the right shows, IP and Q for VHP and FSP for the 1000S conductor.

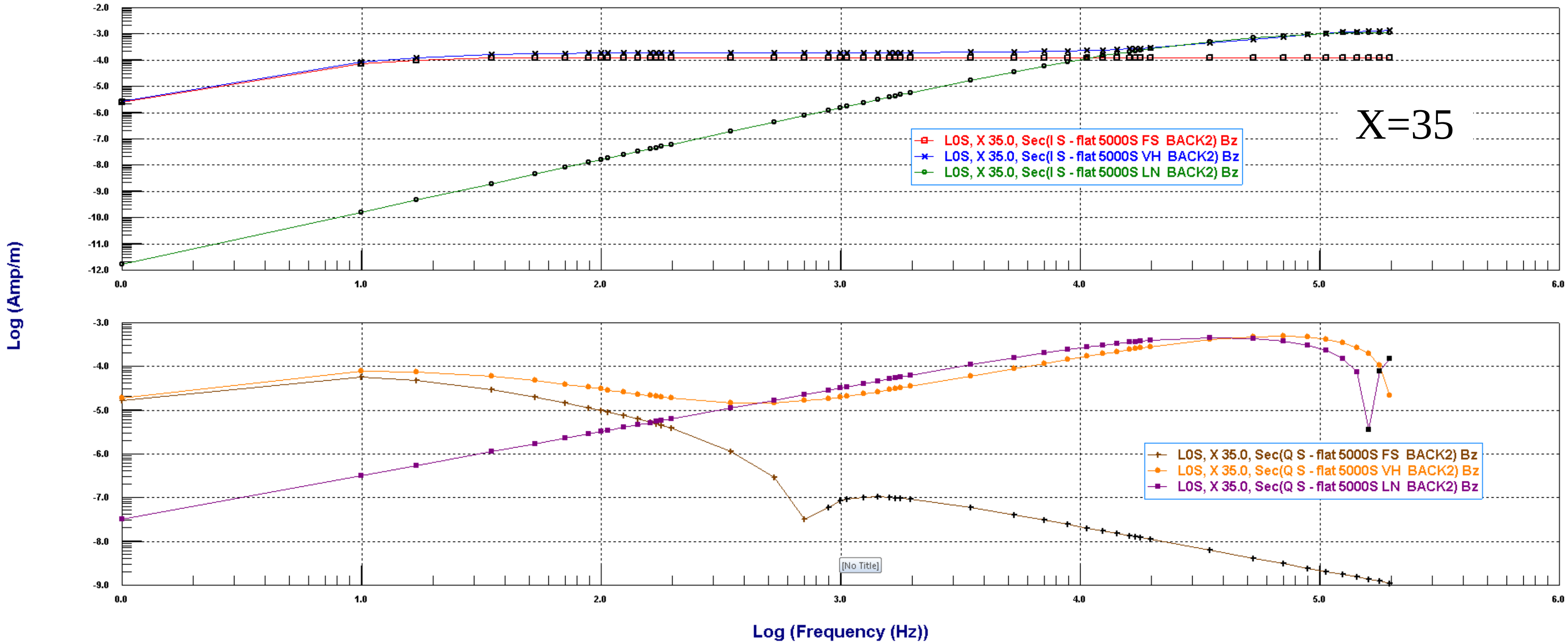


CASE 3: Project 3: Survey ID:3

Example 9: HZ – Characteristic Background
Plate: 50m x 50m, oriented NS-EW, no dip, 35m offset
Depth to Top: 5m
Conductance: 5000 Siemens
Background: 2 Layers over halfspace
Algorithms: FSP, VHP, LNP
Components: Hz (Units Amps/m)

Sprectral Response, HZ, Secondary (Scattered) Field ONLY

For the example below, the Rx is just outside the plate at x=35m. The 3 algorithm results are shown for just the 5000S model but both IP and quadrature. The two algorithms reach slightly different inductive limits at a low frequency. The Inphase separates at about 10Khz where it meets the LNP results for electric field effects only. The quadrature response of the two plate algorithms separate again at a low frequency. The VHP quadrature meets the LNP response just below 1Khz but the LNP goes through its sign change before the VHP algorithm. The sign change is a current channeling effects as the currents in the host change sign.

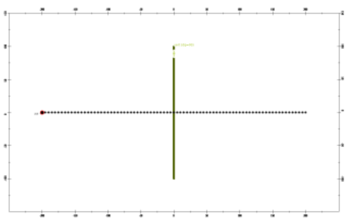


SIMULATED AIRBORNE, Sprectral Response, HZ, HX Secondary

CASE 4: Project 2: Survey ID: 2

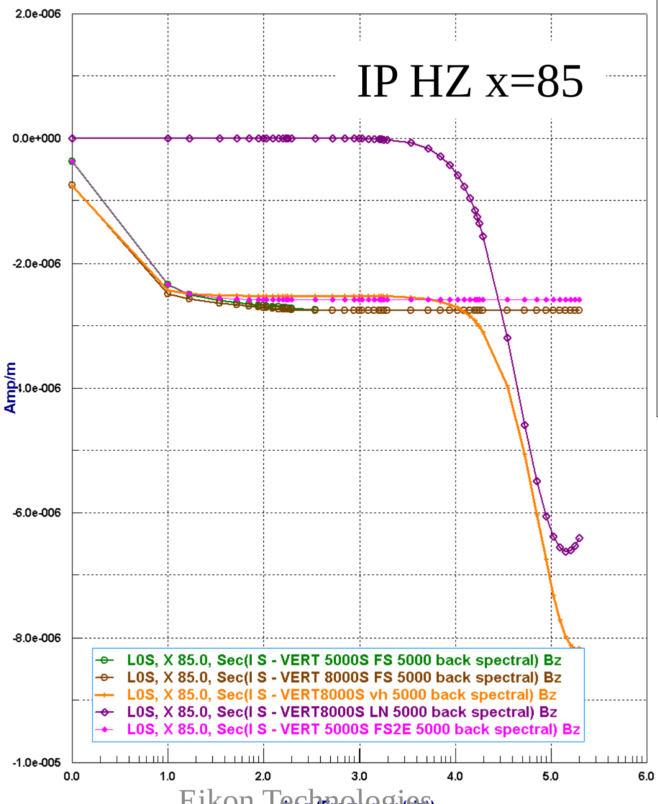
Example 10: HZ,HX – very resistive background
Instrument: 30m above ground, 900m^2, in loop Rx
Plate: 200m x 100m, oriented NS, vertical dip,
Depth to Top: 10m
Conductance: 5000 Siemens
Background: 5000 Ohm-m
Algorithms: FSP, VHP, LNP
Components: Hz (Units Amps/m)

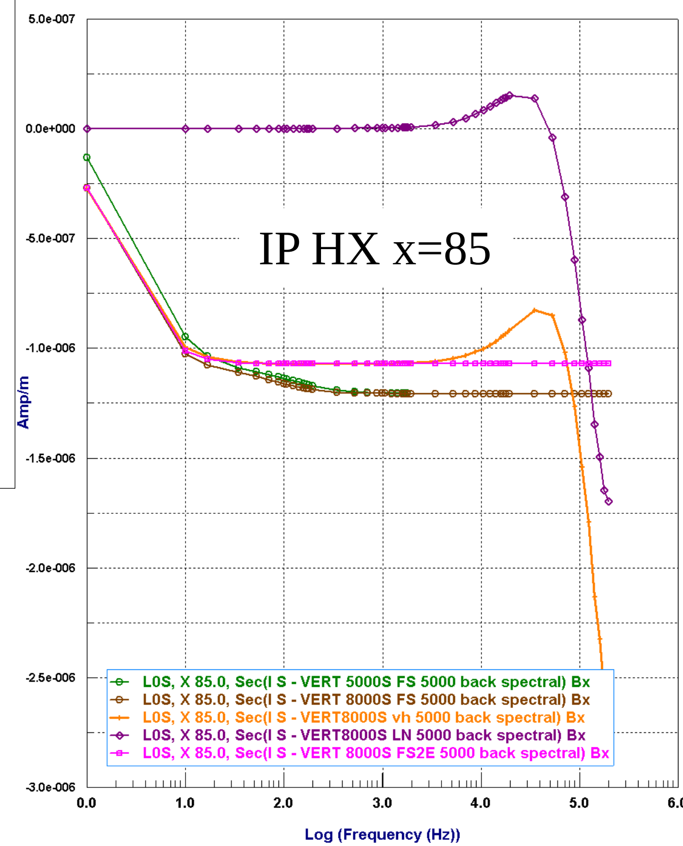
This example, increases the loop size to something typical of an airborne TDEM system and puts the instrument at 30m above ground which is a typical height for such systems. Again, we measure in loop. For this example, we stick to an extremely resistive background rock. This situation is more difficult for the simulation algorithms as the gradients in the exciting magnetic field have increased as the depth of the conductor is from 10 to 110m below ground and extends from inside the Tx loop out to 85m beyond the loop. Replicating the EM effects of a conductor from a loop due to high source gradients is a much more difficult task than dealing with extreme conductivities. All three algorithms are designed to include the non-linearity of the responses and the full extent of the currents inside the conductors. This design is quite different than FD and FE techniques which focus on only the self-scattering of each cell and often only reproduce linear or Born .



On the left is IP HZ at x=85 and on the right, IP HX. The first two responses are the vertical plate at 5000S and 8000S respectively for FSP with 7 eigenvalues. The third response (orange) is the VHP for 8000S while the last (pink) is FSP with 2 eigenvalues. The LNP shows the effect of the electric field response which begin at around 5KHz but become the dominate response by the highest frequency.

Note that the FSP for a given number of eigenvalues saturates by about 300Hz. Also note that the 2 eigenvalue simulated FSP responses match the VHP response.



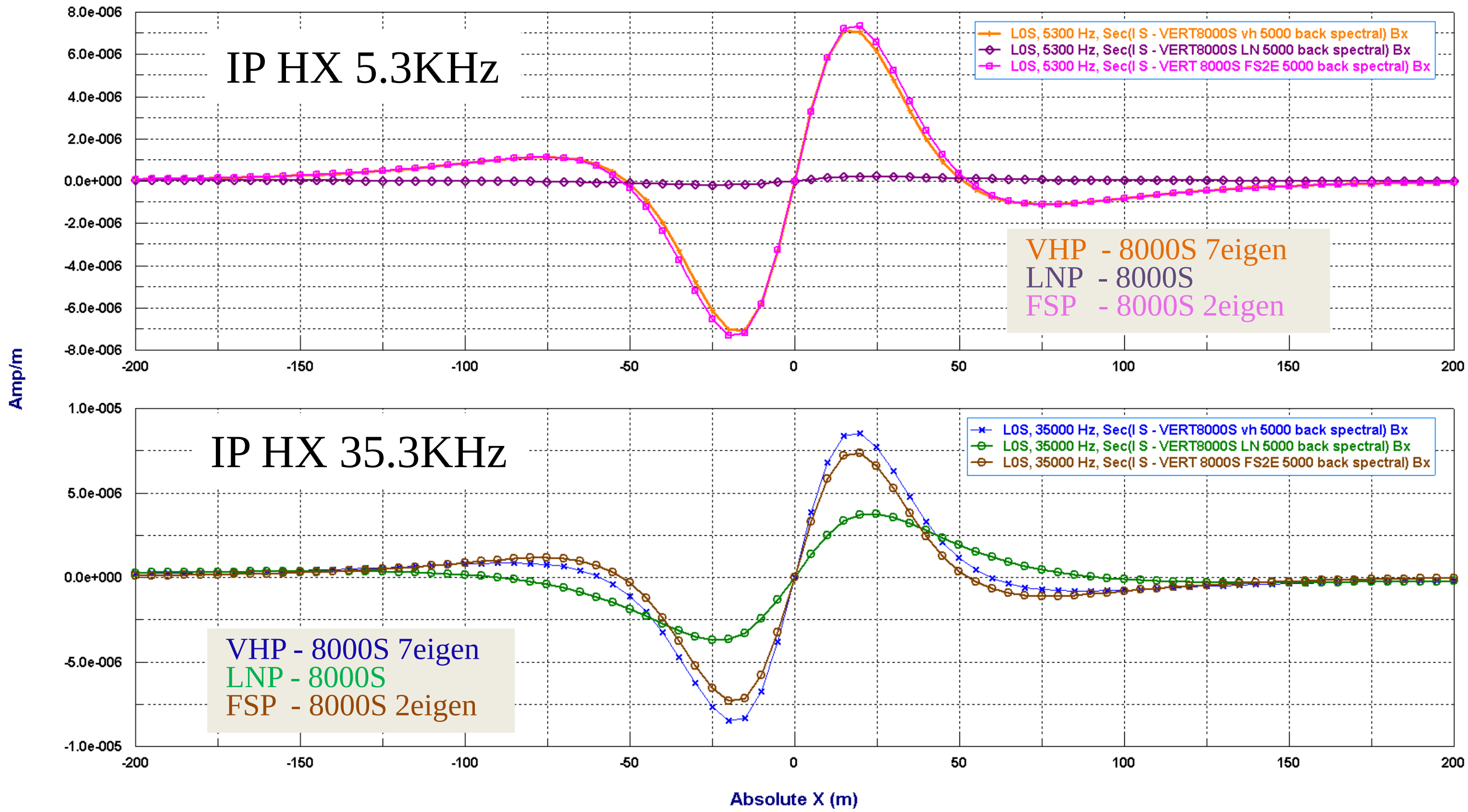


CASE 4: Project 2: Survey ID: 2

Sprectral Response, HX Secondary (Scattered) Field ONLY

Example 11: HX – very resistive background
Instrument: 30m above ground, 900m^2, in loop Rx
Plate: 200m x 100m, oriented NS, vertical dip,
Depth to Top: 10m
Conductance: 5000 Siemens
Background: 5000 Ohm-m
Algorithms: FSP, VHP, LNP
Components: Hz (Units Amps/m)

This is the same simulation study as the previous page. Here, we show only Hz IP at 2 frequencies along the entire profile. Only the responses for FSP with 2 eigenfunctions, VHP and LNP are shown. This demonstrates again the significant effects of the electric field sources on the magnetic field as the frequency increases even for this inductive source.

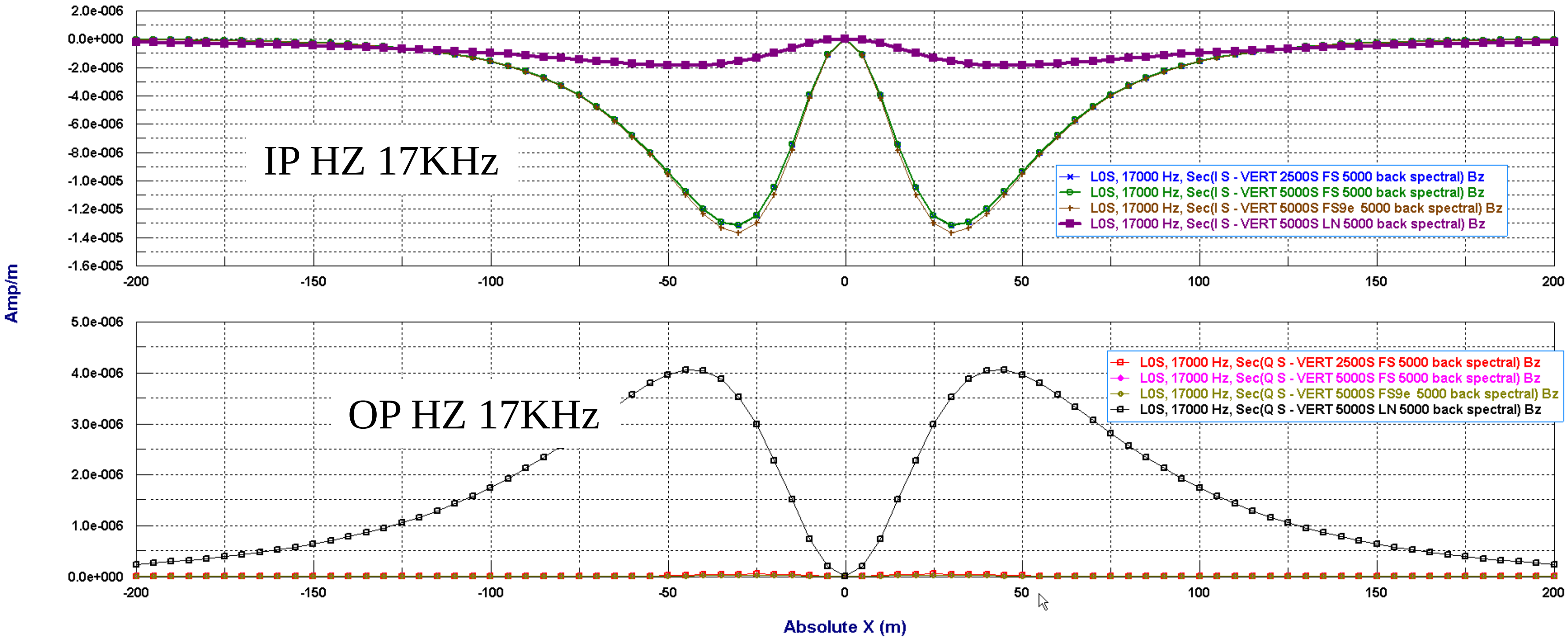


CASE 5: Project 2: Survey ID: 2

Sprectral Response, HZ Secondary (Scattered) Field ONLY

Example 12: HZ – very resistive background
Instrument: 30m above ground, 900m^2, in loop Rx
Plate: 200m x 100m, oriented NS, vertical dip,
Depth to Top: 10m
Conductance: 5000 Siemens
Background: 5000 Ohm-m
Algorithms: FSP, VHP, LNP
Components: Hz (Units Amps/m)

Another look at the same models, here IP and OP HZ at 17KHz. The electric field effects are just beginning to be significant in the IP at this frequency but dominate completely the OP. The peak of the electric source field effects in the OP is about 1/3 that of the peak of the magnetic source field effects in the IP.



Some Issues in the Time Domain

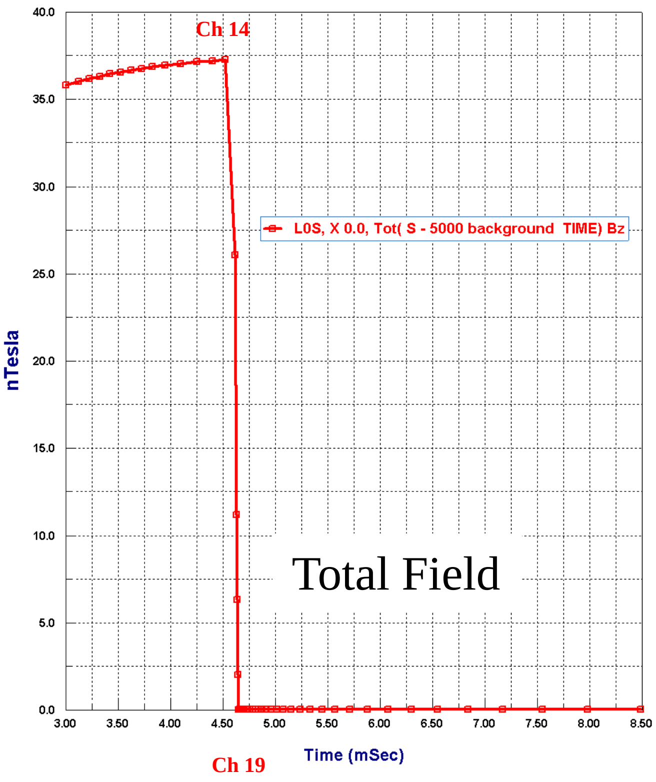
CASE 6: Project 2: Survey Id 15

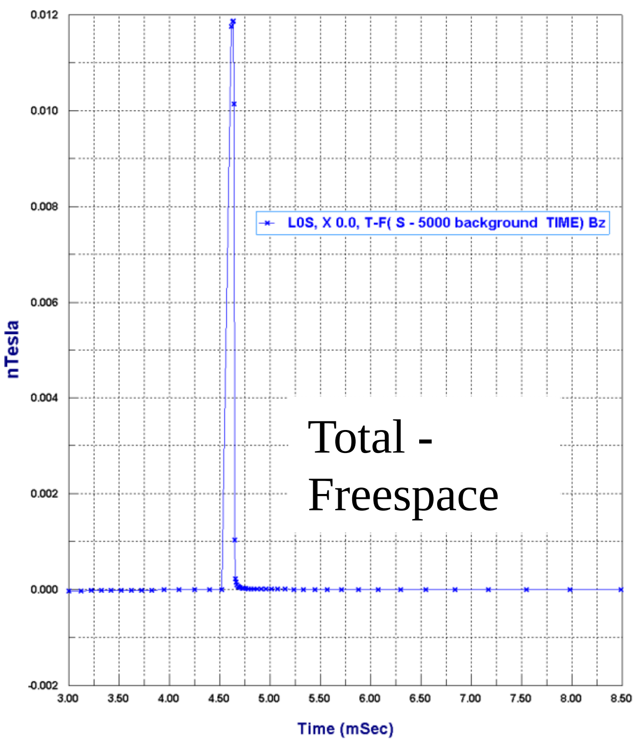
Example 13: HX, HZ – very resistive background
Instrument: 30m above ground, 900m^2, in loop Rx

Background: 5000 Ohm-m
Algorithms: Layered Earth
Components: Hz (nTesla)

Time Domain EM systems are not impulse responses. The main issue is that they are all periodic systems with data collected during normally a bipolar waveform and collected and stacked over many cycles. The resulting data is thus the impulse response of the ground convolved with the current waveform as well as the system response of the transmitter and the receiver. The current waveform is almost always some form of a square wave with different duty cycles depending upon the system. There have been developed a few systems with somewhat different waveforms principally to provide data during the ON time but these systems are not discussed here.

Two significant issues relate to our discussions made here on the impulse responses of a conductor. First, the periodicity of the TX current means that the contribution of each harmonic drops off at approximately 1/N. Thus, for a 30Hz current, 3030Hz is the 101st harmonic for example. Secondly, there are two types of receivers in today's world for TDEM, coils and magnetometers. Coils must be low passed even if they do not contain susceptible cores as there quickly become non-linear in the output phase. Magnetometers generally have a relatively low bandwidth to remain linear systems.





Shown here at the responses of the 5000Ωm halfspace or background from shortly before the beginning of turn OFF, through the RAMP and for several msecs into the OFF time.

We have used a precise linear ramp although only two ground systems have a well defined ramp turn off.

Typically ground systems produce as output the TOTAL measured field while airborne systems typically have the freespace or direct wave removed either by bucking or numerical post processing.

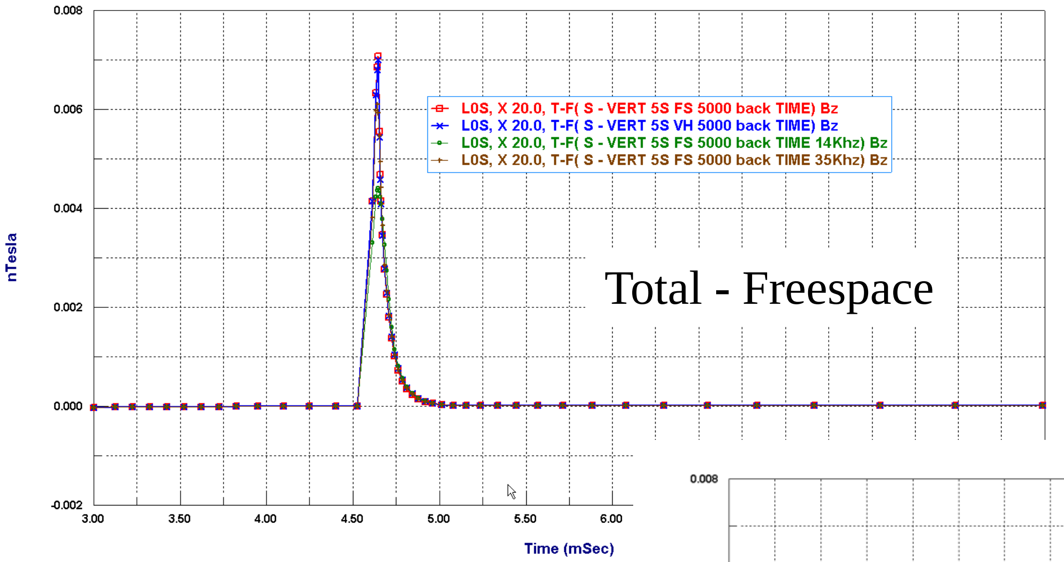
BASEFREQUENCY: 30Hz
ON TIME: 4.6msec
TURN OFF: 0.05msec
OFFTIME: 12.016 msec
Upper Bandwidth: 180KHz

Some Issues in the Time Domain

CASE 6: Project 2: Survey Id 15

Example 14: HX, HZ – very resistive background
Instrument: 30m above ground, 900m^2, in loop Rx
Plate: 200m x 100m, oriented NS, vertical dip,
Depth to Top: 10m
Conductance: 5 Siemens
Background: 5000 Ohm-m
Algorithms: FSP, VHP
Components: Hz (Units nTesla)

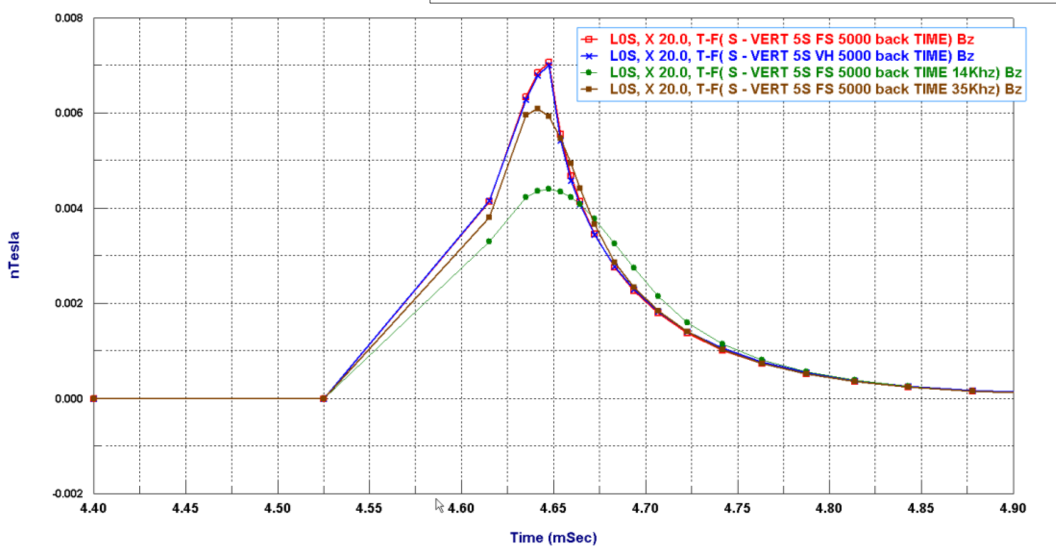
For the purposes of simplicity, we show the Total field response minus the freespace (direct wave). Most airborne systems either have the direct wave bucked out by the use of a sensor or the direct wave is calculated and removed. For airborne systems this is important as the bandwidth is limited and the RX and TX are close to each other relative to the ground similar to ground FDEM systems. Most airborne systems do not measure during the turn OFF. However, in this example we display channels before, through and after turn OFF. All computations are contained in Survey 15 in the database.



Total - Freespace

This is the same TX-RX configuration and model as in the previous spectral responses. We have simply transformed to the time domain, the spectral responses previously calculated. In this example, the Tx is at X=20 and we have computed the FSP response for 5S using an upper bandwidth of 180, 35 and 14 KHz respectively. The VHP is computed using 180KHz.

Using an upper bandwidth of 180KHz, there is virtually no difference between FSP and VHP indicating that the differences in the responses of the two algorithms caused by the electric source effects have almost no effect on the results in the time domain for the reasons explained on the previous page. The blowup below before, during and after the turn off ramp show the effects of the low pass filters applied to the systems due to the Rx antennae characteristics.



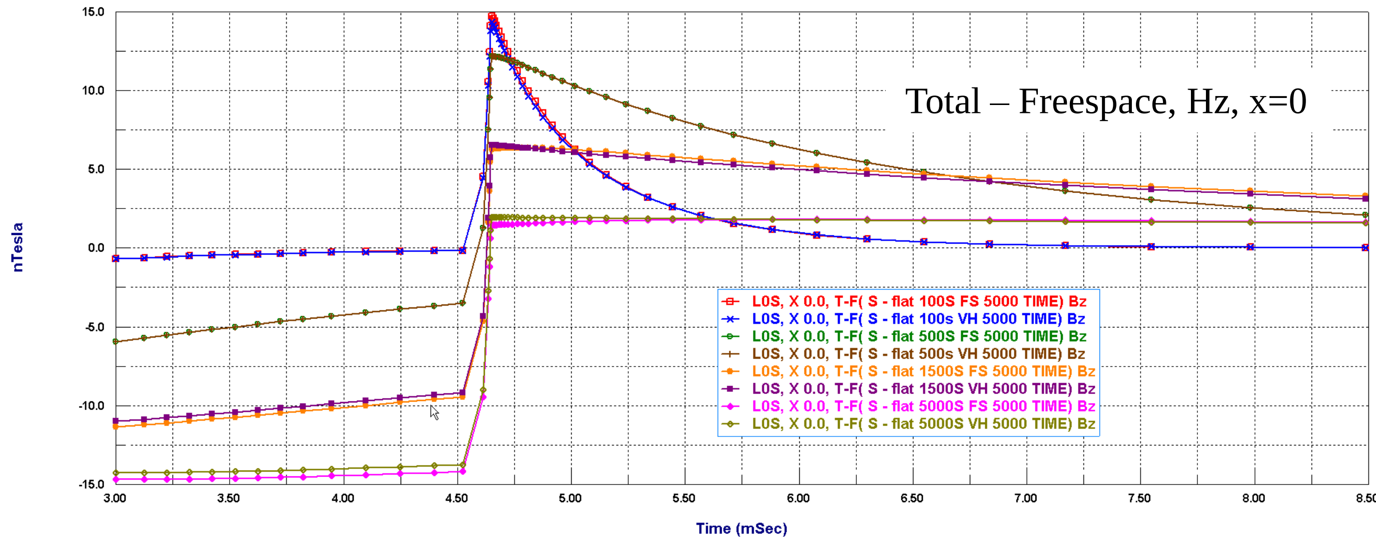
BASEFREQUENCY: 30Hz, T/2 = 16.6666msec
ON TIME: 4.6msec
TURN OFF: 0.05msec
START of "OFF TIME": 4.65 msec
OFFTIME: 12.016 msec

Some Issues in the Time Domain

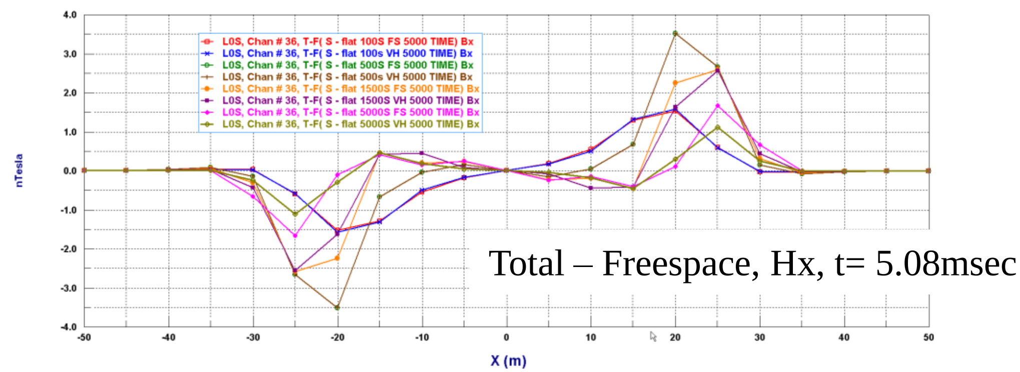
CASE 7: Project 1: Survey Id 20

Example 15: BZ, BX – very resistive background
Instrument: 1m above ground, 266m², in loop Rx
Plate: 50m x 50m, oriented NS, No Dip,
Depth to Top: 5m
Conductance: 100,500, 1500, 50005 Siemens
Background: 5000 Ohm-m
Algorithms: FSP, VHP
Components: Bz, Bx (Units nTesla)

We return to the previous flat plate model to examine the responses in the time domain to compare the algorithms. The utilized bandwidth goes up to under 190KHz in this example which is well above most TDEM systems. The waveform settings are below and we show the response both in the ON time and the off time but not the full waveform. Of course, as the conductance increases the secondary response increases in the ON time and decreases in the OFF time. We show BZ at the peak location (x=0). There is slight discrepancies in the two algorithms for 1500S and 5000S but well within typical data errors. For BX we compare the responses at Ch36 (5.08msec) just after the end of the turn off. We chose this display as there are large spatial variations in BX and interpreting data will have to consider these spatial variations. The 100S and 500S results are very close at all stations. The 1500S results differ a little at two stations . Differences in the 5000S are slightly larger and occur at 6 stations primarily at the edges of the plate.



BASEFREQUENCY: 30Hz, T/2 = 16.6666msec
ON TIME: 4.6msec
TURN OFF: 0.05msec
START of “OFF TIME”: 4.65 msec
OFFTIME: 12.016 msec
Upper Bandwidth: 190KHz



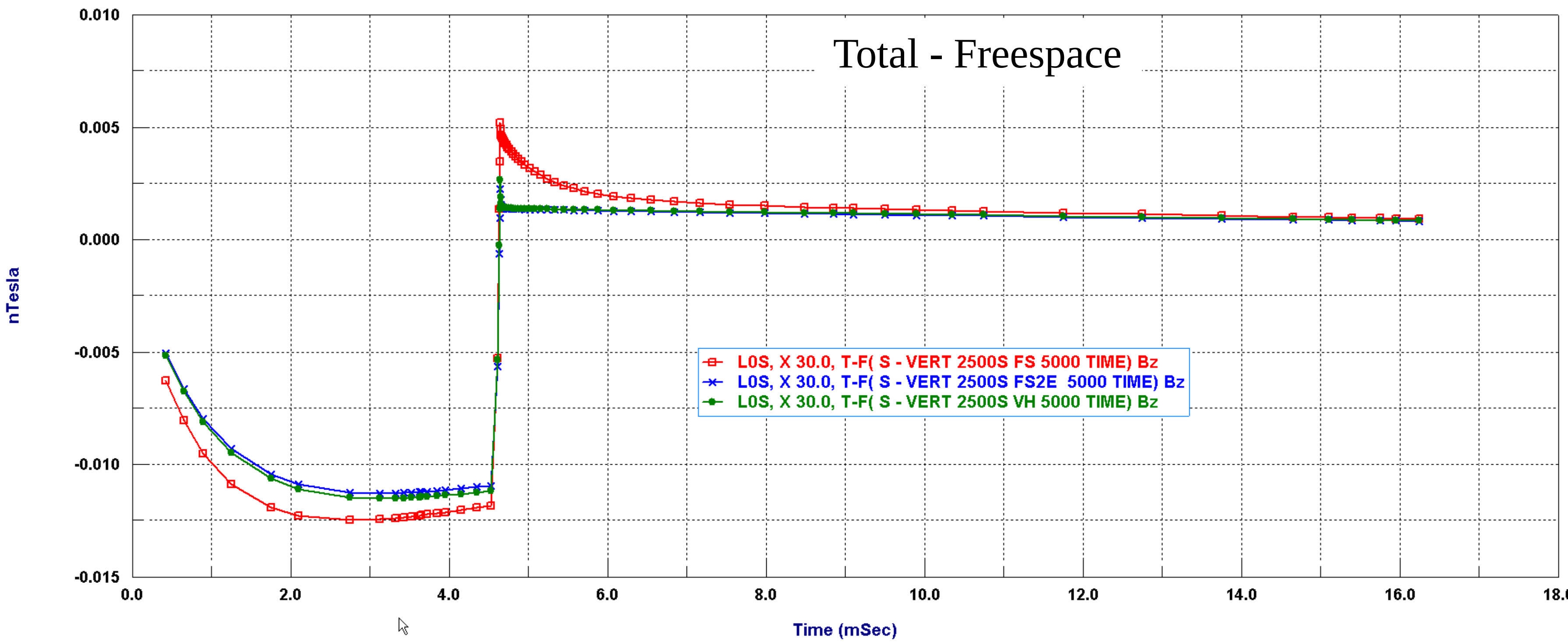
Some Issues in the Time Domain

CASE 6: Project 2: Survey Id 18

Example 16: HZ – very resistive background
Instrument: 30m above ground, 900m^2, in loop Rx
Plate: 200m x 100m, oriented NS, vertical dip,
Depth to Top: 10m
Conductance:2500 Siemens
Background: 5000 Ohm-m
Algorithms: FSP, VHP
Components: Hz (Units nTesla)

We return to example 6 with a vertical plate but now widening the time windows calculated from 0.425msec from the ON time beginning to 16.25msec or about 11msec after the end of the turn OFF. For all the simulated responses, we use a bandwidth up to 180Khz not to introduce the issue of bandwidth into the discussion here. Again only secondary response (T-F) is shown. Below, is shown the decay of Bz at its peak along the profile.

At least two issues are of relevance in the figure below. First, the FSP response for 2500S with 7 eigenvalues does not match the VHP algorithm but rather the FSP with 2 eigenvalues does agree with VHP. The first eigenpotential (eigencurrent) of FSP is a dipolar response while the 2nd eigencurrent is a quadrapole. However, at late time, the responses all converge which they will do with other commercial algorithms (MultiLoop, & EMIT). The other factor is that the responses will not decay by the end of the offtime at 16.667 msec which means that there will be run on into the next cycle which means the ON time response will not decay to ZERO at T=0msec. The system is periodic and not causal.



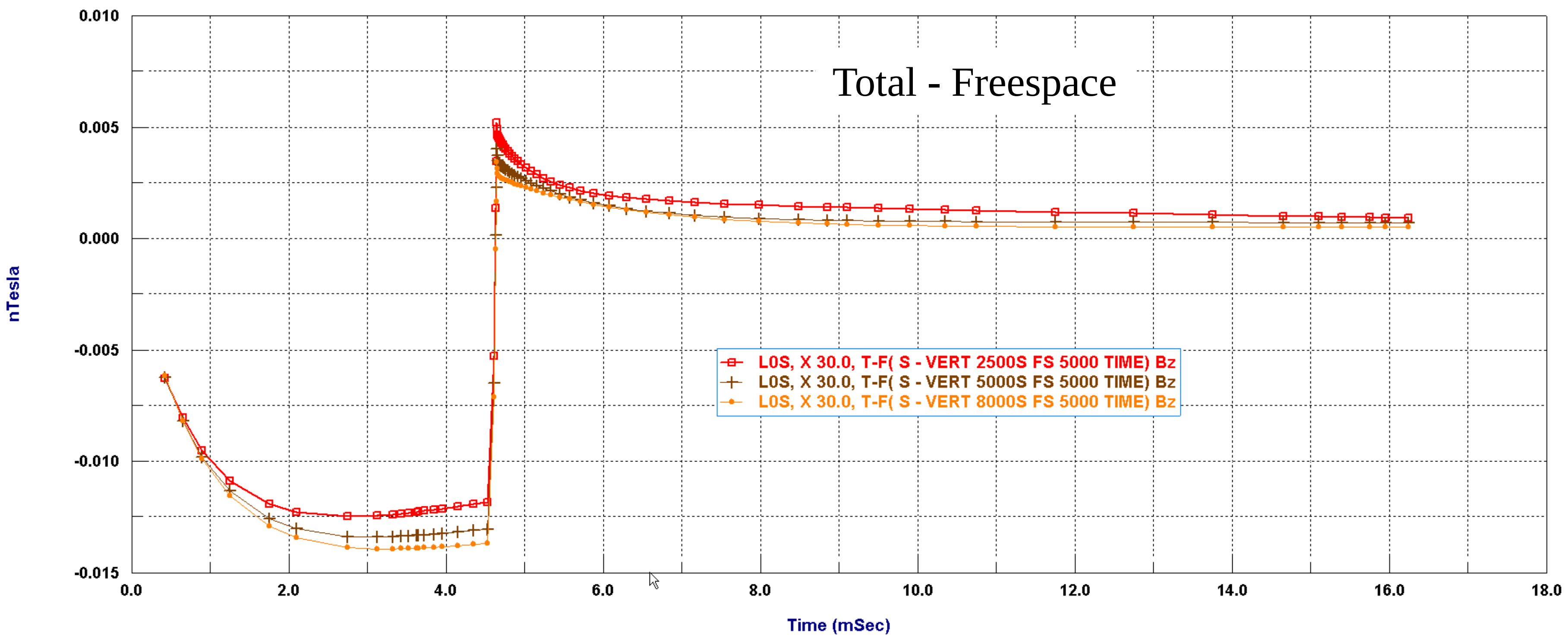
BASEFREQUENCY: 30Hz, T/2 = 16.6666msec
ON TIME: 4.6msec
TURN OFF: 0.05msec
START of “OFF TIME”: 4.65 msec
OFFTIME: 12.016 msec
Upper Bandwidth: 190Khz

Some Issues in the Time Domain

CASE 6: Project 2: Survey Id 18

Example 17: HZ – very resistive background
Instrument: 30m above ground, 900m^2, in loop Rx
Plate: 200m x 100m, oriented NS, vertical dip,
Depth to Top: 10m
Conductance: 2500, 5000, 8000 Siemens
Background: 5000 Ohm-m
Algorithms: FSP
Components: Hz (Units nTesla)

Again with the same system, plate , waveform and windows but now comparing 3 high conductance response using FSP. There is a constant decrease in the early OFF time and late ON time with increasing conductance. However, the responses of the 3 models converge both in the OFF time and towards the start of the cycle. The late OFF time results are not exactly the same but are within a reasonable data error.



BASEFREQUENCY: 30Hz, T/2 = 16.6666msec
ON TIME: 4.6msec
TURN OFF: 0.05msec
START of “OFF TIME”: 4.65 msec
OFFTIME: 12.016 msec
Upper bandwidth: 190Khz

Some Issues in the Time Domain

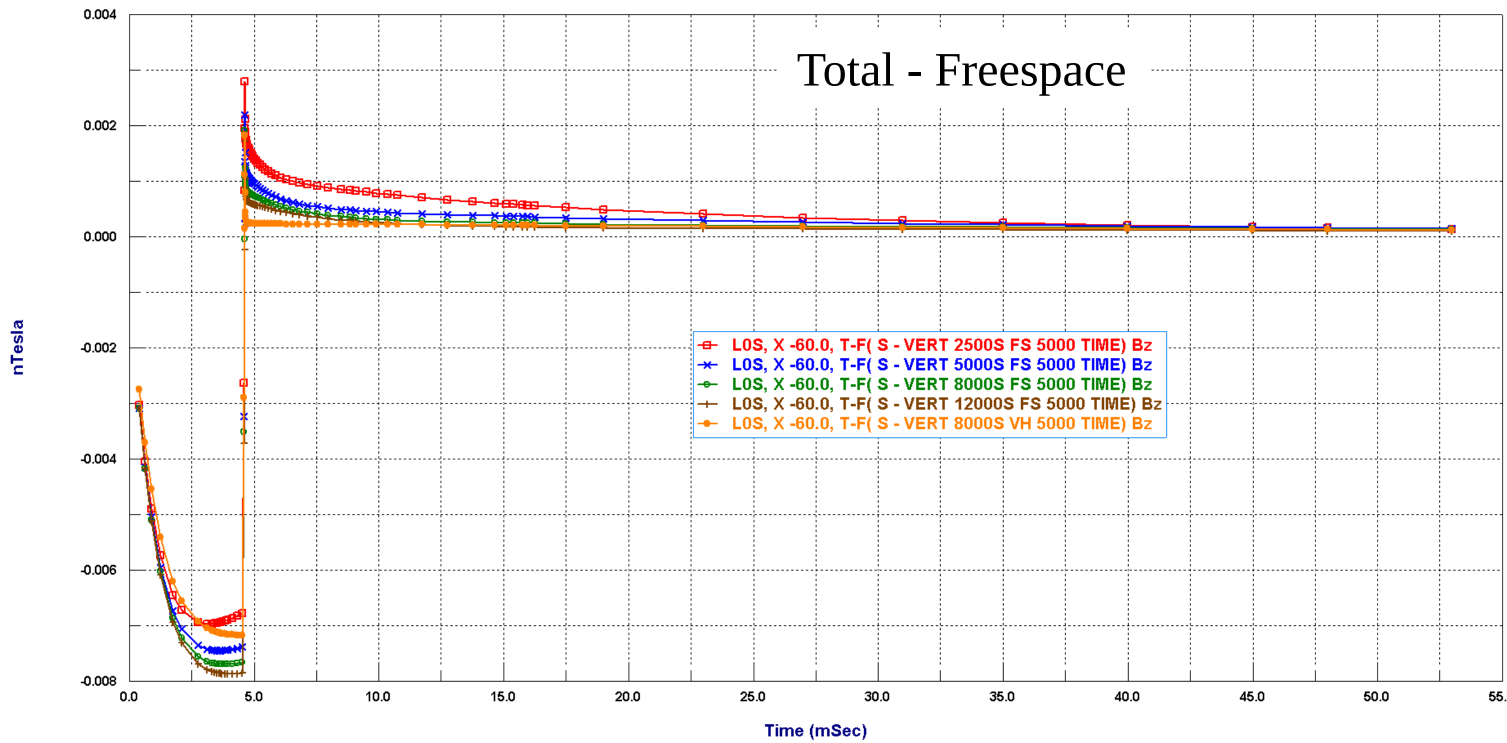
CASE 7: Project 2: Survey Id 19

Example 18: HZ – very resistive background
Instrument: 30m above ground, 900m^2, in loop Rx
Plate: 200m x 100m, oriented NS, vertical dip,
Depth to Top: 10m
Conductance: 2500, 5000, 8000 Siemens
Background: 5000 Ohm-m
Algorithms: FSP
Components: Hz (Units nTesla)

This is the same vertical plate with the same system configuration but now the base frequency has been reduced to 8Hz. This reduction is typical when looking at strong conductors in order to collect data later in time. The waveform settings are given below.

If you look closely at the 8Hz and 30Hz synthetic data, you will see particularly in the late OFF time and early ON time that the results are slightly different. This is due to the low frequency content differences in the two base frequencies but also the effect on RUN on into the next cycle which is predicted by Fourier theory.

Late OFF time offers very little in differentiating the conductors and while the ON time is more discriminatory in this regard, few systems offer ON time measurements. Exceptions to this are UTEM and SPECTREM which do not turn OFF the current and AeroTEM which is now defunct.



BASEFREQUENCY: 8Hz, T/2 = 62.5msec
ON TIME: 4.6msec
TURN OFF: 0.05msec
START of “OFF TIME”: 4.65 msec
OFFTIME: 57.85 msec
Upper bandwidth: 190Khz

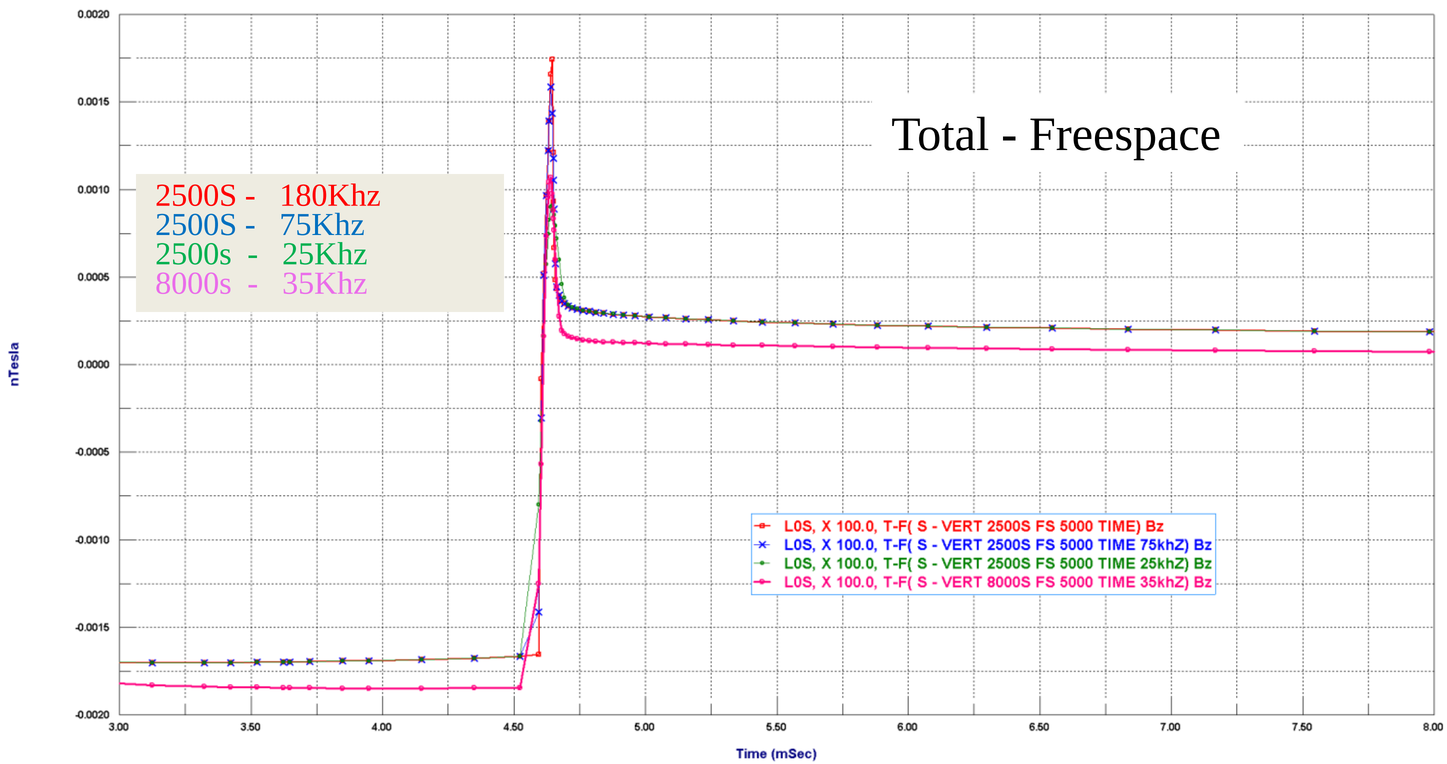
Some Issues in the Time Domain

CASE 8: Project 2: Survey Id 23

Example 19: BZ – very resistive background
Instrument: 30m above ground, 900m^2, in loop Rx
Plate: 200m x 100m, oriented NS, vertical dip,
Depth to Top: 10m
Conductance: 2500, 8000 Siemens
Background: 5000 Ohm-m
Algorithms: FSP
Components: Bz (Units nTesla)

This example is again for a 8Hz basefrequency. In this case, the station is 100m removed from the center of the conductor. Again, we are in a very resistive background and we show the Total response with the Freespace removed for late ON time, Ramp Turn OFF time and OFF time. While the higher conductance does reduce the OFF time response observing a stronger conductance than 8000S is very rare and even at this high conductance there still remains a late time response.

Of course, measuring in the ON time would be of strong benefit but removing the direct wave (freespace) is extremely difficult in the ON time due to the magnitude of this response when compared to the secondary response. Some instruments are designed to measure during the Turn-OFF but this is difficult to interpret accurately as seen on the next page.



BASEFREQUENCY: 8Hz, T/2 = 62.5msec
ON TIME: 4.6msec
TURN OFF: 0.05msec
START of “OFF TIME”: 4.65 msec
OFFTIME: 57.85 msec
Bandwidth: Variable

Some Issues in the Time Domain

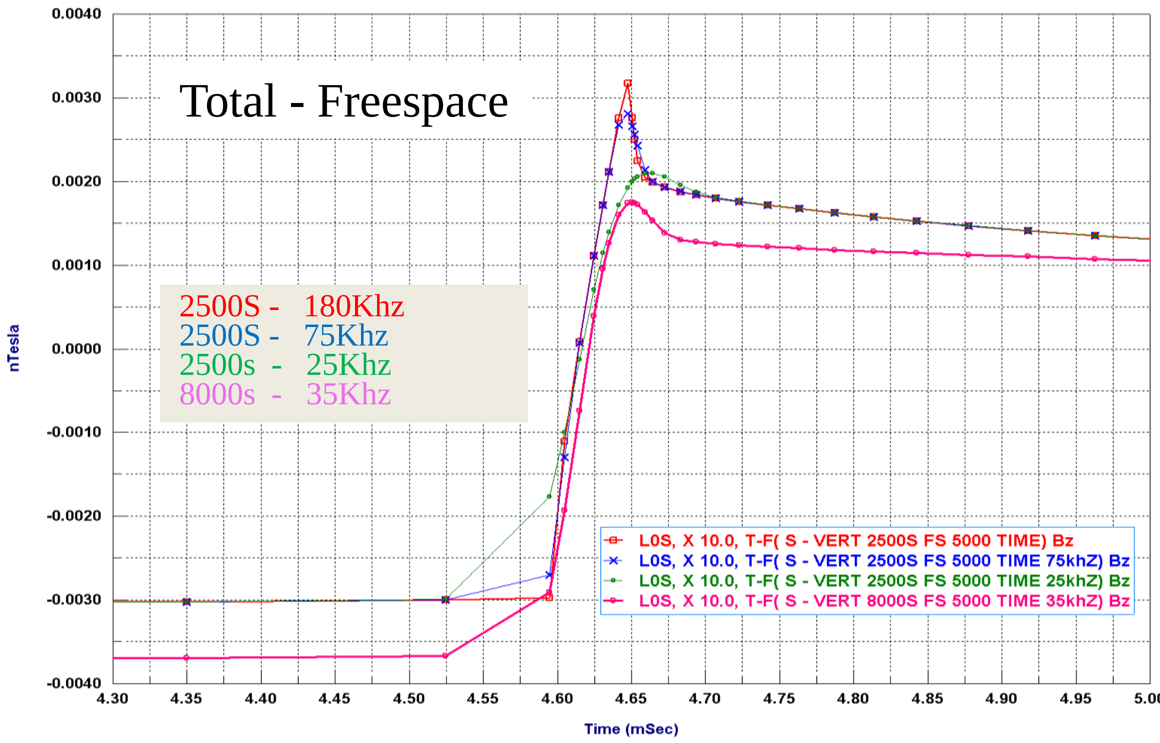
CASE 8: Project 2: Survey Id 23

Example 20: BZ – very resistive background
Instrument: 30m above ground, 900m^2, in loop Rx
Plate: 200m x 100m, oriented NS, vertical dip,
Depth to Top: 10m
Conductance: 2500, 8000 Siemens
Background: 5000 Ohm-m
Algorithms: FSP
Components: Bz (Units nTesla)

Measuring during the Turn Off is a technique employed by some instruments. However, simulating accurately during the Turn Off requires very good knowledge of the impulse spectrum of the instrument and in particular the bandwidth of the receiver including the antennae.

Most ground based systems today use either magnetometers or coils containing magnetic cores. These antennae must be band limited to avoid rotation in the output phase . Some manufacturers do provide coils which are linear to higher frequencies.

Below, we see that the ON time is a very clear discriminatory of conductance and has a negligible bandwidth issue. Modern airborne systems tend to measure only in the OFF time and at some distance in time from the end of the current turn off. A few airborne systems measure in the OFF time and then process to a 100% duty cycle. We have not examine this issue here.



BASEFREQUENCY: 8Hz, T/2 = 62.5msec
ON TIME: 4.6msec
TURN OFF: 0.05msec
START of “OFF TIME”: 4.65 msec
OFFTIME: 57.85 msec
Bandwidth: Variable

SUMMARY

Determining the accuracy of any algorithm which intends to simulate a model to an EM instrument (system) from low to moderately high frequencies is a very complicated issue. There are various scattering processes involved in EM at these frequencies and the mathematics for these processes and for the interaction of these processes are not trivial and indeed not all the mathematics are known today. Some aspects of these processes and the mathematics behind them are only discovered when attempting to develop algorithms.

In this study, we approach these questions primarily in regard to:

1) Strong conductors by geophysics standard
2) The inductive response as governed by Faraday's equation
3) An ungrounded current loop as source *(inductive source*)
4) The bandwidth between 17Hz and 180KHz
5) The use of thin-sheet algorithms
6) Frequency domain impulse responses
7) Effect of current waveform on time domain responses

Secondarily, we consider the effects of the electric fields incident upon the conductors

A) The effects of currents induced in the background host rocks
B) Electric field pickup by the conductors at higher frequencies

December 1, 2024
R. W. Groom