DESIGN STUDY REPORT

An Electromagnetic Induction System for Observation of Bulk Magnetization Response of UXO Targets

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TABLE OF CONTENTS

TABLE OF CONTENTS i
LIST OF FIGURES iii
LIST OF TABLES vi
INTRODUCTION AND EXECUTIVE SUMMARY 1
The Problem 1
Goals 2
Deduced Characteristics of the Design to Help Achieve Goals 3
Why Proposed Approach Was Flawed 3
Configurations Studied 4
Methodology to Compare the Configurations 5
Results 6
Conclusions 8
BACKGROUND 10
Field Intensity Units in This Study 10
Primary Rejection Needed 10
Computation of Primary Field at Target 10
Computation of Secondary Field at Receiver 11
Rejection Needed 12
Methods of Primary Rejection / Cancellation 12
Field Bucking 12
Replica Subtraction 13
Directional Nulling 14
Symmetry Subtraction 14
Background or Remainder Subtraction 14
On Primary Reduction, Nulls, Stability, Drift, and Symmetry 15
RESULTS 18
Standard Coils 18
Simple Planar Bucking 19
Full Helmholtz Bucking 22
Partial Helmholtz Bucking 26

Horizontal Pair Symmetry 31
Transmitter Current Replica Subtraction 35
CONCLUSIONS 38
REFERENCES 40
Appendix A: Performance of a Design Using Square Coils 41
Appendix B: Enabling Features of a Primary Rejecting Design 47
Compute B-field Signal Instead of dB/dt Signal: 47
Use Well-Known Linear Digital Filtering Techniques 48
Make a Frequency Domain System Using Software 48

LIST OF FIGURES

Figure 1 Simple Planar Bucking configuration. 4

Figure 2 Full Helmholtz Bucking configuration. 4

Figure 3 Partial Helmholtz Bucking configuration. 5

Figure 4 Horizontal Pair Symmetry configuration 5

Figure 5 Transmitter Current Replica Subtraction configuration. 5

Figure 6 Coordinates and vectors for computation of the field point P for a current in wire segment P1-P2 10

Figure 7 Primary field intensity in vicinity of receiver coil for a standard 1m transmitter loop. 12

Figure 8 Secondary field intensity at the receiver coil as a function of target position. Primary fields are computed as in the previous figure. The target is assumed a 10cm sphere having a polarizability of 1. 12

Figure 9 Geometry of standard transmitter and receiver coils. 18

Figure 10 Dimensions of standard transmitter and receiver coils,. 18

Figure 11 Residual field from a standard loop versus change in receiver coil size. 18

Figure 12 Residual field from a standard loop versus change in both transmitter and receiver coil sizes. 19

Figure 13 Residual field from a standard loop versus change in both receiver and transmitter coil size. . 19

Figure 14 Coil geometry similar to GEM. 19

Figure 15 Vertical and bucking dimensions in coil geometry similar to GEM. 19

Figure 16 Residual total field for the Simple Planar Bucking configuration in the vicinity of the receiver coil. 20

Figure 17 Residual vertical field for the Simple Planar Bucking configuration in the vicinity of the receiver coil. 20

Figure 18 Sensitivity of the Simple Planar configuration to changes in the parameter 'a'. This is equivalent to changes in bucking coil dimensions. 21

Figure 19 Sensitivity of the Simple Planar configuration to changes in transmitter dimensions. 21

Figure 20 Sensitivity of the Simple Planar configuration to changes in receiver dimensions. 21

Figure 21 Sensitivity of the Simple Planar configuration to changes in receiver, transmitter, and bucking coil dimensions 21

Figure 22 Geometry of Full Helmholtz configuration. 22

Figure 23 Receiver coil and bucking coil dimensions of Full Helmholtz configuration. 22

Figure 24 Detailed geometry of bucking coil, top view. 23

Figure 25 Detailed geometry of bucking coil as it would be on a printed circuit board. Each board would have 4 turns on each side. 23

Figure 26 Residual total field for the Helmholtz Bucking configuration in the vicinity of the Rx coil. ... 23

Figure 27 Residual vertical field for the Helmholtz Bucking configuration in the vicinity of the Rx coil. 24

Figure 28 Secondary field intensity at the Rx coil as a function of target position for the Full Helmholtz configuration. 24

Figure 29 Sensitivity of the Full Helmholtz configuration to changes in the parameter 'a'. 25

Figure 30 Sensitivity of the Full Helmholtz configuration to changes in transmitter dimensions. 25

Figure 31 Sensitivity of the Full Helmholtz configuration to changes in dimensions of transmitter, receiver, and bucking coils. 25

Figure 32 Sensitivity of the Full Helmholtz configuration to changes in bucking coil dimensions. 25

Figure 33 Sensitivity of the Full Helmholtz configuration to changes in receiver dimensions. 26

Figure 34 Geometry of the Partial Helmholtz configuration. 26

Figure 35 Residual total field for the Partial Helmholtz Bucking configuration with two turns per bucking coil. 27

Figure 36 Residual total field for the Partial Helmholtz Bucking configuration with four turns per bucking coil. 28

Figure 37 Residual vertical field for the Partial Helmholtz Bucking configuration with two turns per bucking coil. 29

Figure 38 Residual vertical field for the Partial Helmholtz Bucking configuration with four turns per bucking coil. 29

Figure 39 Sensitivity of the Partial Helmholtz configuration to changes in the parameter 'a'. 30

Figure 40 Sensitivity of the Partial Helmholtz configuration to changes in receiver coil dimensions. 30

Figure 41 Sensitivity of the Partial Helmholtz configuration to changes in transmitter coil dimensions... 30

Figure 42 Sensitivity of the Partial Helmholtz configuration to changes in bucking coil dimensions. 30

Figure 43 Sensitivity of the Partial Helmholtz configuration to changes in dimensions of receiver, transmitter, and bucking coils. 30

Figure 44 Geometry of Horizontal Pair configuration, top view. 31

Figure 45 Geometry of Horizontal Pair configuration, front view. 31

Figure 46 Total field between the two inside windings of the two transmitter loops for the Horizontal Pair configuration. 32

Figure 47 Total field for the Horizontal Pair configuration in the vicinity of the receiver coil. 32

Figure 48 Vertical field for the Horizontal Pair configuration in the vicinity of the receiver coil. 32

Figure 49 Sensitivity of the Horizontal Pair configuration to changes in position of the receiver coil. A 1000ppm change in 'a' means a 1mm displacement of the Rx coil. 33

Figure 50 Secondary field intensity at the receiver coil as a function of target position for the Horizontal Pair configuration. 34

Figure 51 Transmitter Current Replica Subtraction configuration. Green is a coil carrying transmitter current. Red is a coil producing a replica subtraction signal. 35

Figure 52 Total field for the Transmitter Current Replica Subtraction configuration. 36

Figure 53 Output of the Transmitter Pickup coil configuration versus change in physical size. 37

LIST OF TABLES

Table 1 Summary of field intensities and stabilities for configurations studied 38

INTRODUCTION AND EXECUTIVE SUMMARY

The Problem

The root of this problem is that the primary field transmitter and the secondary receiver in an EM system are both in vicinity of one another – where *primary* implies the magnetic field produced by a transmitter coil, while *secondary* implies the magnetic field produced by a target, in response to the primary field. It is common knowledge that the primary field, in the vicinity of the receiver coil, is orders of magnitude larger than the secondary field at the receiver. To observe the secondary field, the primary field must be removed from the observation.

This 'problem' is circumvented in time domain EM systems by turning off the primary field and then observing the secondary field that persists after turn-off. The secondary field in this case is the *eddy current* response of the target. However, a target also has a *bulk magnetic* response and that response can only be observed while the primary field is present. The eddy current response is driven by changes in the primary field (dB/dt). The bulk magnetic response is driven directly by the primary field[1]. The bulk-magnetic response is exactly same shape as the primary and is present only while the primary is present.

Thus the objective of this study is to find a way to remove the primary field that is observed by a receiver. This removal must be VERY good, on the order of 5 orders of magnitude or 0.001% or 10ppm in order to observe response from 10cm sphere at depth of 100cm.

A good solution to the problem would be to use some kind of adaptive signal processing so that the measurement system could continually adjust its characteristics to remove the primary field response. But since the primary field and the bulk magnetic response are signals that are identical in every way except magnitude, there is no characteristic of which we are aware that can be used to separate an observed primary signal from an observed secondary signal. They happen at the same time and with the same time domain and frequency domain characteristics.

We are aware of only two basic methods of primary removal.

- The first is placement of a receiver coil at a location where the net primary field sensed by the receiver is small or zero. In the best case scenario this would be because the primary field is small at the location of the receiver. But it can also be because the field changes direction across the area of the receiving loop or because the direction of the field is orthogonal to the plane of the receiving loop. The fundamental characteristic of this method is that magnetic field itself 'subtracts' components such that there is no net voltage induced into the receiving loop.
- The second relies on subtraction of two electronic signals. The signals can be signals from two loops, or signals generated otherwise such as through a transformer or a current-sensing electronic circuit. Commonly a *figure-eight* receiving loop is this type because it is equivalently two separate loops connected in series opposition. The fundamental characteristic of this method is that two electronic signals are 'subtracted' in an electronic circuit.

[1] Another way to say this same thing is that the eddy-current response is a *quadrature* response while the bulk-magnetic response is an *in-phase* response.

Note that both of these fundamental methods rely on subtraction of two large quantities to produce a small quantity. To maintain a small difference, both of the large quantities must be **very** stable, or must vary identically, or must vary predictably.

All of the methods we studied involve physical dimensions of coils. We will show that for success of this method, it is necessary to maintain dimensions that are stable to 10ppm, or 0.001%, or 0.1mm out of 1m, or 0.004in out of 39in. Note that linear expansion coefficients of some applicable materials are on the order of 10 µm/m/°C: wood 3.7, copper 16.6, and fiberglass and plastics >30. Thus to obtain dimensional stability even for the best material, wood, temperature could change by no more than 2.5°C. Alternatively, a complex mechanical design might be possible in which different but predictable temperature coefficients are used such that net effects are offset. For example, an expanding receiver loop increases signal while an expanding transmitter loop decreases signal. This study shows that geometries can be chosen such that identical expansion exactly offset each other (in theory).

Some of the methods involve electronic components. We note that a typical value for temperature stability is 100ppm/°C for normal components or 10ppm/°C for precision components. For an electronic component having 10ppm/°C temperature coefficient, the component's temperature could change by no more than 1°C. Therefore, electronic components have roughly the same temperature stability difficulties as mechanical components.

Goals

In this problem our overall goal is to be able to *observe* a secondary field at a receiver while the primary field is present at the target. This goal contains a few parts:

- Reduce the primary response in the receiver to something less than the secondary response to a 10cm spherical target at 1m depth. We will show that in round figures, the primary response in the receiver must be reduced by 100dB (0.001%, 10ppm).
- Contain drift so that so drift-detecting measurements need to be made no more often than the time to make several measurements. This issue was not directly addressed in this study. However it is indirectly addressed from the view that stability is observed not only for a single measurement, but for successive measurements. We found it out-of-scope[2] to make these computations. At the same time they are essentially time dependent studies of the issues studied herein.
- Derive system configurations that are reasonable for implementation. This is as much a question of economics, as one of capabilities. We studied only systems that could be reasonably designed by G&G Sciences within the scope of this project, as differentiated from systems that could be designed by more skilled mechanical designers. Given enough time and money, we expect that systems actually could be fabricated to solve this problem. So one consequence of this study might be to provide bases for future projects.
- Derive system configurations that are adaptable to multiple sensor configurations. This was a goal but a very difficult one when all considerations are included. For example if multiple receiver coils were used, where each has its own bucking coil, then the design must include consideration of the interaction between bucking coils for individual receiver coils in the vicinity of one another. Although this goal was kept in mind, it was not a requirement.

[2] Or perhaps, beyond capabilities.

Deduced Characteristics of the Design to Help Achieve Goals

In the process of this study we delineated some characteristics that deserve mention.

Field Cancellation Methods

These methods all have a bucking coil. A couple characteristics of bucking coils are important.

- 'Nearness' of receiver coil to both transmitter coil and bucking coil: This dimension is crucial. If the bucking coil is close to the receiver coil, then absolute mechanical tolerances become extremely important. This is important because one characteristic to keep in mind is that field intensity from a wire is proportional to (at least) 1/R distance from the wire. So movements of few ten-thousandths of inch are important when dimensions are an inch or so. We conclude that the receiver coil should be as far as possible from both the transmitter windings and bucking windings. This is similar to saying the resultant field should be uniform over as large volume as possible.
- Geometry must be chosen so that final bucking arrangement can be fine-tuned during fabrication. In the configurations studied, we determined that the observed magnitude of the field in the vicinity of the receiver coil could be reasonably reduced by maybe 60dB. Yet to achieve even this reduction requires tight tolerances. In fact it is likely that mechanical adjustment would be required to achieve even 60dB. To achieve further reduction would require minute adjustment capabilities that this author believes impractical within the scope of this project. The computations show that a mechanical adjustment of just 0.1mm, in a dimension of 10cm, would cause a 1000ppm change. We note that given resources, a design having adequate characteristics might best be outsourced to a mechanical designer/fabricator.

Replica Subtraction Methods

All of these methods have a *pickup coil* in one form or another. A primary signal is sensed in the receiver coil and a *replica* of the primary is sensed by the pickup coil. These methods are absolutely dependent on the stability of the two signals – the signal sensed by the receiver coil and the signal sensed by the pickup coil. It is obvious that the issue is the relative stability of the two signals. Both signals must either be stable or must change equal amounts.

Why Proposed Approach Was Flawed

For this study, we proposed that we would strive to combine two methods of primary field cancellation/subtraction, thinking that the two methods would act in cascade. The thought was that if one of the methods lost its ability to reduce the primary, then the other method would still perform adequately and the null would not be lost. But this is not the case. For example, we can perceive a method where the primary field is bucked away at two symmetric points above and below a Z transmitter coil and a receiver coil is placed at each point. And we could perceive that the final signal is the difference between the signals at the two receiver sensors. Either method alone, if working perfectly, produces a null. However if one of the bucking coils drifts, and produces a non-null signal at one sensor, then the final signal, after subtracting the two sensors will be the same amplitude as the non-null signal. Thus, the two methods have not compensated for each other. Contrastingly, if both bucking coils drift in the same direction by the same amount, then the final answer would still be a null. This leads to the conclusion that using two methods in cascade to stabilize a null can only work if one of the methods drifts symmetrically – i.e. the two values to be subtracted must drift in perfect synchronism. We believe that reaching this goal using two methods is not much different, and perhaps may be harder to achieve, than reaching the goal using just one method. Yet most of the methods we studied rely in some way on symmetry – so the issue of absolute stability or symmetric stability cannot be ignored.

For this study we have considered only separate methods of primary reduction. We note now, as we did in the proposal, that there will always be a secondary method: that is the method of background subtraction – i.e. observing background, then remembering it, and then computationally subtracting it.

Configurations Studied

We studied many methods of primary field bucking, attempting to find one that was novel, perhaps new, and appeared to have a good chance of providing desired results. We found no such method. The methods presented in this study are reasonably descriptive of all of the methods studied.

In each of the methods studied we used a 'standard' receiver coil. That was a 10cm square coil, having ten turns each separated by 1/16 inch.

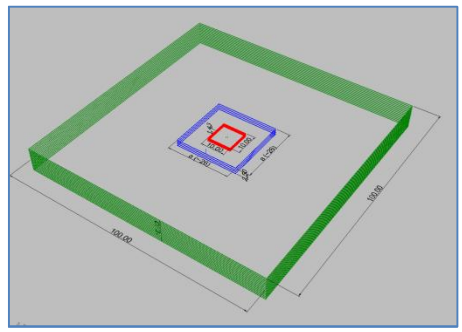

Figure 1 Simple Planar Bucking configuration.

The following are brief descriptions of each method:

- Simple Planar Bucking (Figure 1): This was not a reproduction of a Geophex, Ltd. GEM-3 but was choice of a geometry similar to a GEM-3. In this geometry, a single vertical-axis transmitter coil surrounds a vertical axis bucking coil. The bucking coil surrounds a single vertical-axis receiver coil. Given dimensions for the transmitter coil and the receiver coil, a bucking coil with proper dimensions is chosen. We note here and in the following geometries, that the dimensions of the bucking coil are inversely related to the number of turns in the bucking coil. Defining the bucking requires first choosing its number of turns, and then numerically adjusting its dimensions until a null is found in the receiver coil. The purpose in selecting this geometry was to attempt to understand why the GEM-3 geometry produces 'drift.'
- Full Helmholtz Bucking (Figure 2): This is geometry in which a pair of transmitter coils is separated by standard 'Helmholtz' dimensions: the distance between two identical coils is ½ of their diameter. Then a pair of bucking coils is placed symmetrically between, again with Helmholtz dimensions. Then a receiving coil is placed at the symmetric center. As above, dimensions of the bucking coils are adjusted to achieve a null in the receiver coil.

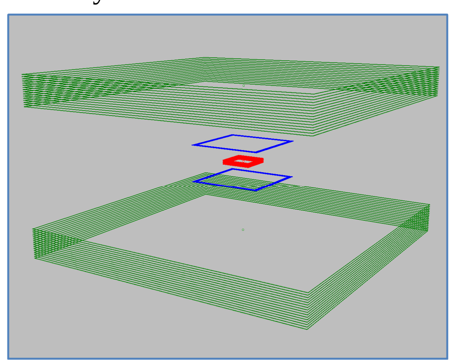

Figure 2 Full Helmholtz Bucking configuration.

- Partial Helmholtz Bucking (Figure 3): This is geometry similar to above except there is only one transmitter coil. The bucking coils are arranged in Helmholtz geometry around a receiver coil, and all are placed at the center of the transmitter coil. This geometry was studied because it is simpler than the full Helmholtz configuration and because it places the receiver coil closer to the target. It has been noted that this is an assembly not completely different than a GEM assembly but that it is thicker and could be more rigid

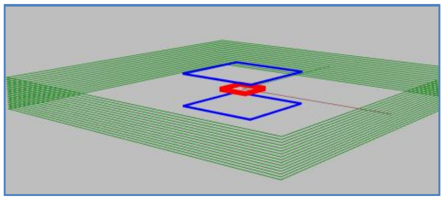

Figure 3 Partial Helmholtz Bucking configuration.

- Horizontal Pair Symmetry (Figure 4): This is geometry in which there are two, vertical-axis transmitter coils placed side by side separated by a distance on the order of a loop diameter. A receiver coil is placed symmetrically between the two. When one transmits a field with upward direction, while the other transmits a field with downward direction, a null field occurs along a line of symmetry between the two. This configuration was studied because it has potential application for array configurations with multiple transmitter and receiver coils.

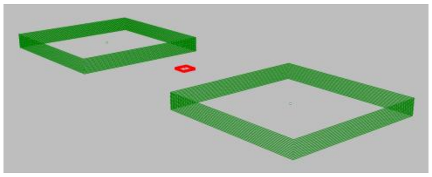

Figure 4 Horizontal Pair Symmetry configuration .

- Transmitter Current Replica Subtraction (Figure 5): This is geometry intended to be used to produce a replica of the voltage seen at the terminals of the receiver coil. The voltage is intended to be subtracted at the input of the first amplifier. The geometry was chosen because it could be implemented through fabrication of coils using traces on a printed circuit board – the green in the figure represents transmitter coils and the red represents receiver coils. Both coils would be connected in opposition so that coupling between the two is maximized, while external field pick-up by the receiver coils is minimized.

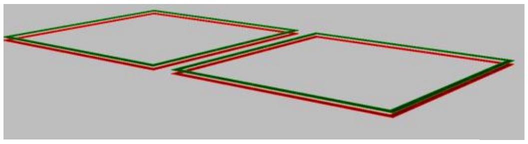

Figure 5 Transmitter Current Replica Subtraction configuration.

Methodology to Compare the Configurations

The field strength numbers presented in this study are presented as dBn. This is taken to mean decibels relative to a magnetic field of 1nT where dBn is computed as $20\log_{10}(f/10^{-9})$ where f is magnetic field strength in Tesla. In this study, transmitted fields were computed as usual. Then voltages appearing at the terminals of a receiver coil were computed by doing a numerical integration across the planar area of a receiver coil. Then this receiver voltage was normalized by the nominal area of the receiver coil to produce an equivalent or average field value at the receiver. Since field strengths are positive numbers while voltages can be positive or negative, we represented field strengths in dBn as either positive or negative numbers where the sign is taken to mean the sign of the received voltage – so large negative numbers for dBn mean large ‘negatively oriented’ fields, not small fields as would normally be the case for logarithmic numbers. Any field strength less than 1nT, regardless of sign, was assigned a value of 0dBn.

Determining a method to model the performance of the different configurations as might be encountered in reality was one of the most difficult parts of this study. There was no good way, in the mind of the author, to realistically decide how these configurations would change, and thus drift. The one obvious concept to study is how the received signal changes when physical dimensions change. One type of dimensional change is studied when dimensional design values are being determined – i.e. when dimensions are being computed to produce a null in the receiver. Another type of dimensional change is studied when dimensions change by small amounts such as that caused by thermal expansion. In this study, we first iteratively determined nominal dimensions such that a null was observed at the receiver. Next we applied dimensional changes to individual or sets of components, and then re-computed the 'signal' that would be observed at the receiver. We allowed that dimensional changes could be separately applied to each component set in the configuration (transmitter coils for one, bucking coils for another, and receiver coils for the last), and to any combination of these components. Interestingly, it was often observed that while individual dimensional effects were substantial, the combination of dimensional affects was miniscule or zero. For example, a transmitter coil that expands combined with a bucking coil that expands, results in an observed field at the receiver that remains near null; while the observed field for expansion of either coil alone results in a substantial reduction of the null.

Results

Substantial detail is presented later. A descriptive review of the results follows .

- For reference, the reader should remember that primary fields at the receiver are about 99dBn while secondary fields at the receiver are about 11dBn (for a 10cm sphere at 1m depth). Thus the secondary field observed at the receiver (in dBn) is 88dB smaller than the primary. Thus to achieve a positive 'signal-to-residual-primary' observation, the primary should be reduced by something more than 88dB. For this study we choose 100dB. This is the depth of the *null* that is required.
- For the Simple Planar Bucking configuration, the fields in the vicinity of the receiver coil have an intensity of about 75dBn. While the concept of a bucking coil is to reduce the primary field by some huge amount so that the receiver can be placed in a region where the ambient primary is small, reality is quite different. In essence the bucking is changing the ambient primary field from a directionally uniform field of 99dBn into a directionally varying (high gradient for each component of the field) field of 75dBn, a reduction of 24dB. To reach a perfect null requires that the receiver coil be placed in this high-gradient field such that it spans an area where positive and negative fields perfectly subtract from one another. For the configuration studied, the receiver coil sees an upward field over most of the central area of the coil) and downward fields over its perimeter. The GEM null is sensitive to drifts because this 'subtraction' across the area of the receiver coil is equivalent to a null of about 75dB. It seems apparent from experience that it is unlikely that one could maintain a null this deep when ambient fields have high gradients that are dependent upon coil geometry. It is more likely that a 20dB null might be obtained reliably producing a 44dB reduction of the primary. Since the goal is achieving a 100dB null, another 54dB would have to be obtained through the process of background subtraction.
- The Full Helmholtz configuration appears to be about 35dB better than the Simple Planar configuration from the perspective of reduction of the ambient primary in the vicinity of the receiver. Total fields in the vicinity of the receiver coil are on the order of 40dBn. Like the Simple Planar configuration, the last 40dB of the null is obtained through in-coil cancellation of upward and downward fields within the receiver coil. However, one might be able to maintain

20dB of cancellation within the receiver coil and 20dB of cancellation through background subtraction. So this configuration appears to make a solution possible.

- We studied configurations of the Partial Helmholtz configuration – for each bucking coil having either 2, or 4 turns. The 2-turn configuration is the most compact, while the 4-turn configuration performs best because the bucking coils are farther from the receiver coil. The four turn configuration is roughly 10dB poorer than the Full Helmholtz configuration -- The residual field in the vicinity of the receiver coil is ~50dBn (a reduction of 45dB) and the remainder of the null (50dB) would be obtained through in-coil cancellation and background subtraction.
- The Horizontal Pair configuration is a simple example of obtaining a null through in-coil cancellation. The residual field in the vicinity of the receiver coil is about 70dBn (a reduction of only 25dB) and the remainder of the null is obtained through in-coil subtraction. In this case, one half of the receiver coil sees upward oriented fields while the other half sees downward oriented fields. It could be expected that the 70dB null needed to cancel the bucked field would be highly sensitive to lateral movement caused by unequal dimensional changes, because the bucked field has its largest values near the edges of the receiver loop. It might be less sensitive to pure flexing or to dimensional changes if those changes are symmetric.
- The Transmitter Current Replica Subtraction configuration is not expected to perform as well as the Full Helmholtz or Partial Helmholtz configurations. In this method, the entire null, 95dB, is obtained through a single subtraction, and that subtraction is one of two signals: the first is the primary field from the transmitter coil as observed by the receiver coil, and the second is the signal produced by this configuration. Dimensional computations indicate that the output of this configuration coil varies directly as dimensional changes. Thus if dimensional changes cannot be held stable to better than ~0.001%, then the null will rapidly deteriorate – and this assumption ignores the stability required in electronic components needed to produce an initial null. So this configuration is not likely to be used alone to meet our goal. However, this configuration, or one that is similar, is a reliable way to produce a background signal that can be subtracted from whatever residual primary signal is observed after application (and drift) of one of the other methods, such as, say, the Partial Helmholtz configuration.

Overall, a final performance note is necessary. Computations for the Simple-Planar and Helmholtz configurations showed that the null of the primary field is directly affected by dimensional changes in either the transmitter coil or the bucking coil(s). However, dimensional changes in both coils together, where dimensional changes are geometrically proportional and symmetric, cancel each other out, and a null can be maintained. This is true even for the Simple Planar configuration that we are reasonably certain will not produce acceptable performance. This means that our modeled computations of drift in the null are insufficiently complex to simulate changes that will occur in reality. To the author of this study, this means that the only real way to make an evaluation is to do it experimentally. At the same time, we believe this study indicates that either of the Helmholtz configurations are significantly better than the GEM configuration. So given that the GEM configuration is capable of producing useful data, albeit not without difficulties in collecting the data, perhaps a Helmholtz configuration could make a useful instrument.

Conclusions

Although this study showed the difficulty in designing an instrument with the desired performance, it is obvious that such an instrument is possible because actual instruments actually exist – the Geophex GEM instruments are an example. The principle need, relative to the existing instruments, is to improve stability by reducing drift.

This study showed that the Helmholtz-like configurations are significantly better than the planar configurations from the perspective that they produce a volume where the residual field is significantly smaller than the same volume using planar configurations. Therefore the configurations should drift less. Furthermore, the Helmholtz-like configurations introduce a *thickness* into the design – this can be used to advantage to design a more rigid and thus stable physical configuration. The partial Helmholtz configuration is one that is physically attractive from the perspective of manufacturability and durability.

The investigations in this study into replica subtraction methods produced a possibility that had not been appreciated beforehand. The replica subtraction method can be used to improve the performance of the usual *background subtraction* computations. Instead of measuring a background signal and remembering it and then subtracting it, this new method use a replica signal to subtract background. A proportionality constant would be determined in a background measurement, and the constant would be used to 'subtract background' in succeeding measurements. Note that this procedure would probably not eliminate the need to 'subtract background.' This procedure would only provide a maximum rejection of the primary signal and/or rejection of any background 'bulk magnetic' response. It would not provide subtraction of background eddy-current responses.

Given that the *cube* receivers have become a proven sensor, and given that this study has shown that a *thick* sensor assembly is desirable, it is natural to contemplate a design that combines these attributes. We believe that a sensor can be fabricated that has acceptable primary rejection characteristics and acceptable drift. Since we believe that a single receiver sensor is difficult enough for the first trial, we believe a hand-held style sensor is the best objective for future efforts. A tentative design and its performance graphs are shown in Appendix A.

Therefore our recommendation for further work on this objective is:

- Design a partial Helmholtz system with transmitter coil diameters on the order of 50cm and a receiver coil diameter of 5 to 8cm. Use more turns per bucking coil in order to avoid a bucking coil that is small with windings near the receiver coil. Although this study was done with 100cm (Metal-Mapper) size coils, we believe that a bulk magnetization system, if it works, will be more useful for hand-held measurements than it would be (even if possible) for either detection or initial characterization surveys. The design presented in Appendix A has these characteristics.
- Use a 3D 'cube' receiver coil inside the Helmholtz bucking coil. The horizontal (axis) components of that coil will offer the best opportunities to observe the bulk magnetization secondary signal and are likely to show little drift and good performance due to the symmetry of the residual field. Yet if the system is stable, the vertical component will likely be observable when corrected with replica subtraction (below).
- Design and fabricate the entire system using wood frames. This is because wood has a small coefficient of linear thermal expansion, has good strength, and is easy to work. However if a

prototype device proves acceptable, then additional funding should be allocated to design a device having similar characteristics, lighter weight, perhaps more durability, and similar performance.

- Allow for shims to be placed between the bucking coil and the receiver coil in order to make final adjustments on the null. Shims could be as thin as pieces of paper.
- Design a Transmitter Current Replica Subtraction coil to be used in the last step of background subtraction. We have contemplated replica subtraction only as a processing step, not as hardware implementation. We envision that 40dB of replica subtraction can be implemented and maintained using digitized signals.

BACKGROUND

Field Intensity Units in This Study

In this paper we often discuss magnetic field intensity. We found it convenient to settle on a value of "dBn" to document and compare field intensities. We define "dBn" to be

$$dBn = \begin{Bmatrix} 20log_{10}\left(\frac{|f|}{10^{-9}}\right), f > 10^{-9} \\ -20log_{10}\left(\frac{|f|}{10^{-9}}\right), f < -10^{-9} \\ 0, otherwise \end{Bmatrix}, \tag{1}$$

where f is field intensity in Tesla. This convention assumes that any field intensity less than 1 nanoTesla is zero, and it preserves the sign of directional components of the field, such as B_z.

This convention made it convenient to compare primary field intensities, secondary field intensities, and resultant equivalent field intensities as observed in receiver coils. In all modeled cases in this study, the 'signal' at the output of the receiver coil was taken to be the apparent field intensity according to the voltage received from a receiver coil divided by the nominal area of the receiver coil, where 'nominal area' means the area of the receiver coil before any dimensional variations were applied.

Primary Rejection Needed

Computation of Primary Field at Target

In this study, all transmitter coils and all bucking coils were modeled as a series of wire segments and all coils were assumed to be square. For example the standard 1m square transmitter coil consisted of 16 turns and each turn consisted of 4 wire segments in a plane. The planes for each turn were separated by a factor typically assumed to be 1/16 inch.

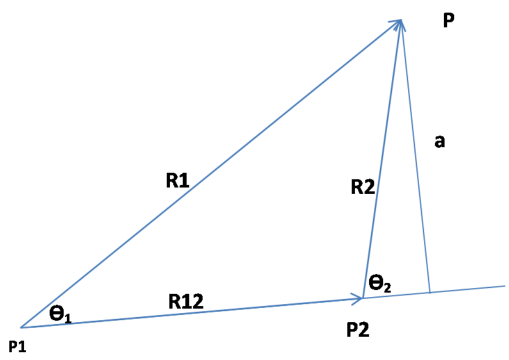

Figure 6 Coordinates and vectors for computation of the field point P for a current in wire segment P1-P2.

Computation of primary fields involved computation of the vector magnetic field from each of the wire segments and adding the results. For a point P and a wire segment P1-P2 in a plane as shown in Figure 6, the B field at point P is perpendicular to the plane and is given by (numerous sources)

$$\boldsymbol{B_p} = \frac{\mu_0 I}{4\pi a}(\cos(\theta_1) - \cos(\theta_2))\boldsymbol{b_p} \tag{2}$$

where $\boldsymbol{R}_1, \boldsymbol{R}_2, \boldsymbol{R}_{12}$ are vectors, R_1, R_2, R_{12} *are magnitudes of* $\boldsymbol{R}_1, \boldsymbol{R}_2, \boldsymbol{R}_{12}$, $\boldsymbol{r}_1 = \frac{\boldsymbol{R}_1}{R_1}, \boldsymbol{r}_2 = \frac{\boldsymbol{R}_2}{R_2}, \boldsymbol{r}_{12} = \frac{\boldsymbol{R}_{12}}{R_{12}}, a = R_1 \sin(\theta_1)$,

$$\sin(\theta_1) = \frac{|\boldsymbol{R_{12}} \otimes \boldsymbol{R_1}|}{R_{12}R_1} = |\boldsymbol{r_{12}} \otimes \boldsymbol{r_1}|, \text{(cross product)} \tag{3}$$

$$\cos(\theta_1) - \cos(\theta_2) = (\boldsymbol{r_1} - \boldsymbol{r_2}) \odot \boldsymbol{r_{12}}, \text{(dot product)} \tag{4}$$

$$\boldsymbol{b_p} = \frac{\boldsymbol{r_{12}} \otimes \boldsymbol{r_1}}{|\boldsymbol{r_{12}} \otimes \boldsymbol{r_1}|} = \frac{\boldsymbol{r_{12}} \otimes \boldsymbol{r_1}}{\sin(\theta_1)} \tag{5}$$

Computation of Secondary Field at Receiver

We first compute the moment of the target according to Bell [1],

$$\boldsymbol{M} = V\kappa\boldsymbol{H}_0 \tag{6}$$

where V is volume of the target (m^3), κ is a polarizability factor ranging from 2 along axis to 0.5 crosswise, and H_0 is the primary field at the target in amp/m. In this formulation we assume the target has a single polarizability that is aligned with the primary field. Then

$$\boldsymbol{M} = V\kappa\frac{\boldsymbol{B}_p}{\mu_0}. \tag{7}$$

Next we compute the field at the receiver from the usual dipole equation, written in matrix notation, where $\boldsymbol{B}_s, \boldsymbol{r}, and\ \boldsymbol{M}$ are column vectors,

$$\boldsymbol{B_s} = \frac{\mu_0}{4\pi R^3}(\boldsymbol{3rr^T} - \boldsymbol{I}]\,\boldsymbol{M}, \tag{8}$$

or substituting Equation (7),

$$\boldsymbol{B_s} = \frac{V\kappa}{4\pi R^3}\left(3\boldsymbol{rr^T} - \boldsymbol{I}\right)\boldsymbol{B_p},$$

where $\boldsymbol{R}$ is a vector from the target to the receiver, R is its magnitude, $\boldsymbol{r} = \frac{\boldsymbol{R}}{R}$, and $\boldsymbol{I}$ is the identity matrix.

For purposes of this study, we assume the target is a 10cm diameter sphere having a volume of 0.00133π m^3 and that $\kappa = 1$, so

$$\boldsymbol{B}_s = \frac{0.00133}{4R^3}\left(3\boldsymbol{rr^T} - \boldsymbol{I}\right)\boldsymbol{B_p} \tag{9}$$

Rejection Needed

Figure 7 shows the primary field in the vicinity of the receiver for our *standard* 1m loop. We note a value of 99dBn. Figure 8 shows the magnitude of the B field, at the receiver, given that the target is located at a position as shown in the figure. The 10cm sphere target at 1m depth in the center of the array produces a signal at the receiver of about 11dBn. Thus the receiver must be able to 'see' an 11dBn signal while exposed to a primary field of 99dBn. This means that the primary must be rejected by something more than 88dB. If the primary were rejected by 100dB, we would expect a 12dB 'signal to primary' ratio at the receiver.

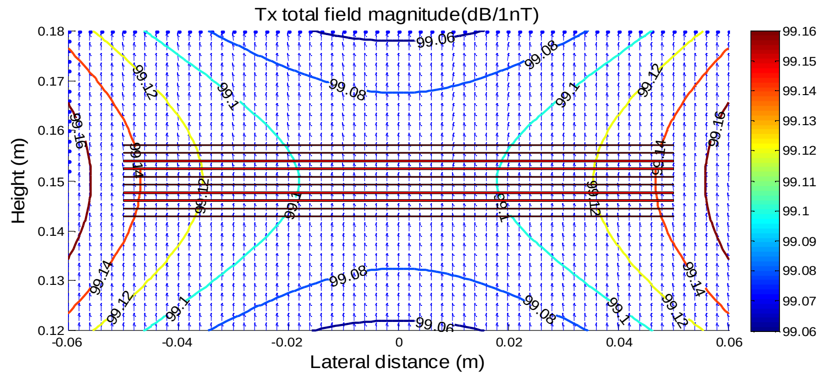

Figure 7 Primary field intensity in vicinity of receiver coil for a standard 1m transmitter loop.

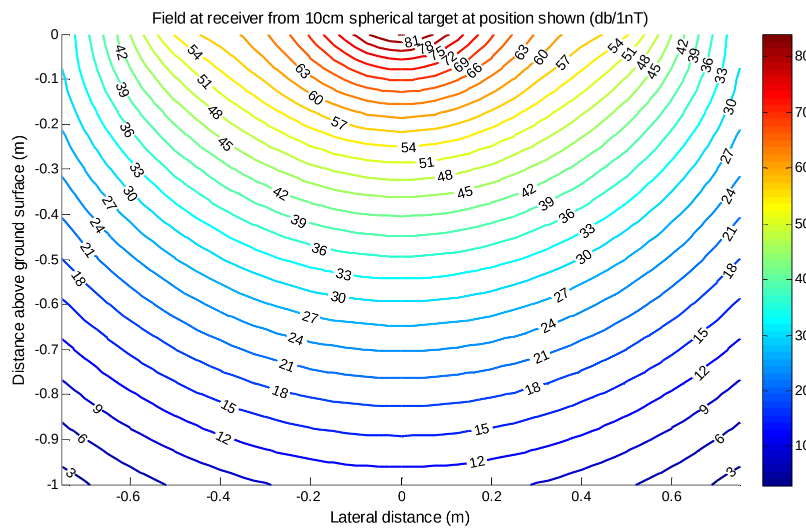

Figure 8 Secondary field intensity at the receiver coil as a function of target position. Primary fields are computed as in the previous figure. The target is assumed a 10cm sphere having a polarizability of 1.

To select a round number as a goal, we chose to strive for a primary rejection of 100dB. Anything much less than this means that only shallower targets will be visible. Anything more than this will means that the system under consideration has a good chance to function adequately.

Methods of Primary Rejection / Cancellation

In the context of this study we have identified five concepts for rejection of the primary signal.

Field Bucking

This technique involves winding a separate coil, or coils, that surround or are otherwise inductively coupled to a receiver coil. The *bucking* coil(s) generate a magnetic field that is in opposition to the primary field in the vicinity of the receiver coil.

The GEM-3 uses this technique, and it is commonly cited in the literature.

The central issue in performance of this method is geometry between the primary coil(s), the receiver coil(s), and the bucking coil(s). The magnetic field resulting from superposition of opposing fields produces a smaller field, but that smaller, *residual* field is likely to have huge spatial gradients in both amplitude and orientation. The residual field is sensitive to geometries of both the transmitter coil(s) and the bucking coil(s).

The residual field is also sensitive to current through any of the coils. A secondary issue is the method used to generate and control current through the bucking coil. This can be done by 1) wiring the coils such that primary current also flows completely through the bucking coil, 2) sampling the current in the primary coil with a current shunt (resistor) and sending that current through the bucking coil, with or without amplification, or c) using ancillary sensing coils and feedback to generate a bucking signal that causes a null (zero) signal to be sensed in the ancillary sensing coils. In this study we assumed and tested only the first method: wiring bucking coils such that current through them is guaranteed to be the same current generating the primary field. Note that the **effective** current in a coil can be a function of frequency and inter-winding capacitance in the coil. We assume in this study that frequency is low enough that winding capacitance is not an issue. However when nulls on the order of 60dB are considered, it is noted that the self-resonant frequency of the coils of interest should be at least 1000 times higher than the frequency being used.

The feedback cancellation technique is attractive because it is like a continuously adjusted null – i.e. it is like a continual adjustment for drift. It is sometimes utilized in Helmholtz coils used to cancel the earth's magnetic field for measurements with magnetometers. However, nearly any method in this class relies on some stable property or some symmetry property of the mechanical configuration, just as all of the other methods. So we did not study feedback cancellation as a way to reduce the primary because we would not expect it to have any performance advantages – see the section below "On Primary Reduction, Nulls, Stability, Drift, and Symmetry."

The bucking technique is different and better than the others that follow from one perspective. That perspective is that the subtraction of large values is taking place in the magnetic fields. The receiver coil is thus exposed to a smaller magnetic field, and the dynamic range requirements on the electronic circuits to follow are reduced. This is compared to the replica subtraction method where individual electronic circuits are both exposed to the full primary signal, and subtraction occurs electronically. We note that for typical EM systems, ferrite core receiver loops cannot be used because of the large **linear** dynamic range and/or bandwidths involved. In this regard, a well-balanced bucking system might allow the designer to use ferrite core receiver loops.

Replica Subtraction

This technique involves electronic subtraction of two large signals. It can be done by purely electronic means, such as subtraction in an operational amplifier circuit. And it can also be done by sensing transmitted current with a coil and wiring that coil's output in opposition to a receiver coil's output – this is the method called the Transmitter Current Replica Subtraction herein. Scott [2] [3] uses a transformer to implement this technique. Importantly in this technique, the receiver coil is exposed to the full amplitude of the primary field, but if coils are wired in series opposition, the first amplifier is not exposed to the large primary signal. This means that both the receiver coil **and** the subtraction coil or signal must have large dynamic range and extreme linearity. Also importantly, these techniques are most likely to be used with analog signals to avoid digitization difficulties.

The replica subtraction method is attractive from the perspective of its relatively easy implementation and its versatility. It can be perceived for example how an antenna array could be fabricated and how replica subtraction could be built in so every receiver coil was 'nulled' with every transmitter coil. This same objective would be more difficult to implement with, say, multiple bucking coils for each receiver.

Directional Nulling

In this technique the receiver coils are aligned with respect to the primary such that they receive zero net primary flux. It is apparent that the output of the receiver coil varies as the sin of the angle between its plane and the magnetic field (assuming of course that the local field is directionally consistent across the receiver coil). Thus maintaining a 60dB null requires controlling angles to 0.05 degrees. With this technique, geometry, particularly bending or warping geometry, is crucial.

Directional nulling was not studied specifically herein. Yet directional nulling is inherently allowed in most of the magnetic field graphics. It is assumed for the most part herein that a receiver coil will have three components. In that regard, eliminating the primary that is in alignment with one of the three coils is the most difficult problem. If that problem can be solved, then it is expected that the directionally nulled coils will perform at least as well.

Symmetry Subtraction

In this technique, two receiver coils are placed at points where a symmetric primary field is (theoretically) the same. The outputs of the two coils are subtracted as replica subtraction above. The BUD system uses this technique to reduce dynamic range requirements at the receiver. And the ALLTEM system uses this technique to cancel the primary. The technique is also referred to as a quadrupole method [3] and often the two symmetric loops are referred to as *figure-eight* loops.

The symmetry subtraction method can be visualized in two variations. In the first it is assumed that the primary field is approximately uniform and is the same across the areas of two separate receiver loops. In this case, each loop measures the full value of the field, and the outputs of the two loops are subtracted. This is similar to the replica subtraction method but differs in the way that the 'subtractive' signal is obtained. For this description we consider a *figure-eight* loop to be two loops wired in series opposition.

In the second variation, the primary field changes direction across the area of the receiver loop, such that there is zero net flux through the loop. The Horizontal Pair Bucking method described later is exactly this method.

Background or Remainder Subtraction

This method is fundamental and is nearly universally applied in addition to any of the other methods. The primary signal and any other constant signals are observed in the receiver by operating the instrument when no target is present. The response is memorized and then subtracted from succeeding measurements. In the framework of this study it is taken to mean that 'background' is simply residual primary such as the primary observed after nulling the primary and then experiencing drift. But in practice this method also removes other secondary signals that are produced for example by metallic items, e.g. wires, in the vicinity of the coil structure.

The process of 'removing' background is not as simple as implied. The act of memorizing a background and then subtracting it assumes that the background remains constant over the time span between two measurements. When examining the background contributed by the primary signal alone, there is an implicit assumption that the current through the transmitter coil remains constant or can be accurately measured. And further, we always measure ‘background’ as a time-dependent transient, so background subtraction **also** assumes implicitly that the time dependency of the background remains constant.

Our experience with removal of background has been that neither of these assumptions is very good. Transmitter current is likely to change by huge amounts when ‘huge’ is framed in the realm that 1000ppm is huge. And the time dependence of the background is likely to vary from pulse to pulse as well as from measurement to measurement.

On Primary Reduction, Nulls, Stability, Drift, and Symmetry

It seems obvious in retrospect, but the goal of achieving and maintaining primary reduction is not much different than a goal of maintaining absolute precision and stability. If one is able to maintain stability in two measurements to very precise and stable values, then the two measurements can be subtracted, and small changes between them can be observed. All of the methods studied herein rely on some method of subtracting two values, whether they are magnetic fields or electronic signals. In a simplified sense, we can think of ‘primary reduction’ as a study of finding ways to making two very precise and stable measurements.

This concept is more commonly discussed by examining the observed value after subtraction and comparing it to the two values before subtraction. The amount the result is reduced is measured as the *null*. It is the residual compared to the values being subtracted, assuming of course that the values being subtracted are essentially the same.

It is common to assert that maintaining a null of 40dB is reasonable and that maintaining a null of 60dB is possible for very stable systems, but that maintenance of nulls greater than 60dB is unrealistic. Maintenance of a null of 60dB is equivalent to maintaining stability of the two entities being subtracted to an accuracy of 0.1% or 1000ppm. This implies that our goal of achieving primary rejection of 100dB might be unreachable because that implies making two measurements, both stable and precise to 10ppm. However in practice, the question of *maintenance* of a null often becomes one of including a time scale. Nulls of 100dB can achieved for short time periods but they usually don’t persist – that is they *drift*. So a secondary question is the one of drift and this question is again related to the question of precise stability, where stability is considered on a time scale.

We note now that a null of 100dB is equivalent to a stability of 10ppm in each of two entities. The coefficient of thermal linear expansion for applicable materials ranges from 4ppm/°C for wood to ~30ppm/°C for plastics [5]. Thus temperature changes of even just a few degrees are likely to produce changes in physical size greater than 10ppm. . It is also worth noting that 10ppm is equivalent to a dimensional change of only 10^{-5} m or 0.001mm or 0.04 thousandths of an inch over a dimension of 1m. This positional tolerance is even smaller for shorter dimensions. From a mechanical engineering perspective, these requirements are daunting.

Furthermore, precision electronic components, like resistors, commonly have absolute values specified to a tolerance of only 0.01% to 0.1% and have temperature coefficients of 10ppm /°C (for the stable ones!). So again it seems unlikely that we could achieve 10ppm stability. Yet, in electronics, it is common to rely on matched temperature coefficients such that expected temperature drifts are acceptable if they happen to two or more components simultaneously. It is also common to procure components having opposite temperature drift characteristics such as resistors with negative temperature coefficients.

This discussion indicates just how hard it is to achieve a 100dB null. Indeed, in modeling the coil configurations studied herein, we often found ourselves needing to specify dimensions having six or seven significant figures in order achieve numerical nulls of 100dB. Furthermore, both mechanical stability and electronic stability must be present. Since we know that fabricating and maintaining mechanical and electronic tolerances with this much precision and stability is unlikely to happen, we might conclude that achieving our goal is unlikely.

Yet when the issue is framed in the realm of drift versus time, especially reasonably short times, it might be possible to reach our goal for short time periods. For example, if the system were stable to 10ppm over a time period, just long enough to make two observations, we could likely succeed by applying a procedural method, no matter what method of primary rejection is used. This method is inspired by the method used by Sternberg [6]. The user could make two measurements at physically different positions near a target. Then the two measurements can be subtracted. Since the coupling of the primary signal is the same for both measurements (assuming no geometric or electronic drift), the primary signal will cancel. But the secondary signal should be different for the two measurements, so the resultant signal is the response of the target. Of course this method again is at the mercy of stability (and precision) of the system versus time. For example, if transmitter current is different between the two measurements, then it must be known very precisely for both measurements. This same concept is occasionally used by many investigators where *background* observations and *target* observation are made on a one-to-one basis.

That said, we adopted a process in this study where we achieve some initial null through adjustment of physical parameters (commonly the parameter ‘a’). We observe the residual primary signal, expressed as an apparent field, as it would be received by the receiver coil. For most methods, we decided that a “null” was observation of a field intensity of 1nT or less. However, we note that in reality we would probably not be able to physically adjust any parameter to the level of precision we used numerically. In reality we would adjust the parameter to obtain an initial null, say something more than 60dB. Then we would make a measurement when no target is present and record the observed value as ‘background.’ Then we would subtract this background from succeeding observations.

Note that for this study we divided the problem into two parts. The first part is reduction of the observed primary through some physical subtraction process involving coil geometries or pairs of signals. The second part is further reduction through the more usual process of making two sequential measurements and subtracting them. Our goal was to use the first part to get a 60dB null through physical means and to then allow for an additional 40dB to 60dB null that could be attained via procedural/numerical means. This means that the goal of this study is to maintain a 60dB or better null for all time scales. Then to reach the overall goal, we allow that an additional 40dB to 60dB could be obtained via background subtraction.

In our proposal leading to this work, we claimed we would use two methods of reducing the primary in the hopes that each method would complement the other. For example, we proposed reducing the primary field through a bucking process and then further reducing the primary through a symmetry subtraction process (or alternatively an orthogonal coil orientation process). We reasoned that either method alone would produce an acceptable result, so both methods together should be substantially better. We do now not expect that this approach will work as was conceived. This approach could be valid, but only to the extent that the first method produces a field that remains symmetric and/or directionally stable. This is because the final *null* is more likely to be the level of the poorer of the two methods, instead of being a cascade of both methods. Both methods act 'in series' but a drift in either method (meaning a subtraction that does not result in a small number) will produce a result that is like the poorest of either method.

It was common in this study to rely on some symmetry property of the magnetic field, and or on some symmetry property of electronic signals. By this, we mean something like *point symmetry* where there are two measurements, perhaps with different devices, at two physically different positions where the field or the signals are large and expected to be identical in both orientation and magnitude. We then subtract the two observations. Differential receivers or figure-eight receiver loops are good examples.

But there is a different kind of *symmetry* with which we became familiar in this study. It is symmetry in terms of the signals induced into a receiver coil when considered over the whole area of a receiver coil. Most of the bucking methods we studied produce a difference field that is smaller than the primary. It is smaller by a moderate amount, like 20 to 40dB. But this field is neither uniform in direction nor uniform in amplitude across the area of the receiver coil. In fact, if a null is to be observed at the output of the receiver coil, then fields in one direction through one part of the coil must offset fields in the other direction through the rest of the coil. When one observes this difference field across the receiver coil, it becomes obvious why it is so difficult to achieve stable nulls – the field has huge amplitude and directional gradients so the receiver output is likely to change by large amounts for tiny changes in geometry.

RESULTS

In this section we show computational and graphic results. Over the time frame of this study we pondered and briefly tested many different conceptual configurations and methods. We present here a subset that is chosen for demonstrative purposes and for purposes of indicating possible *solutions* where we judge a *possible solution* as one that has relatively reasonable performance **and** would be economical to implement.

Standard Coils

The geometry for our *standard* coils is shown in Figure 9 and Figure 10. The transmitter coil is modeled as 1m on each side and having 16 turns spread over a width of 10cm. The transmitter coil is modeled as 10cm on each side with 10 turns spread over a width of 1.43cm.

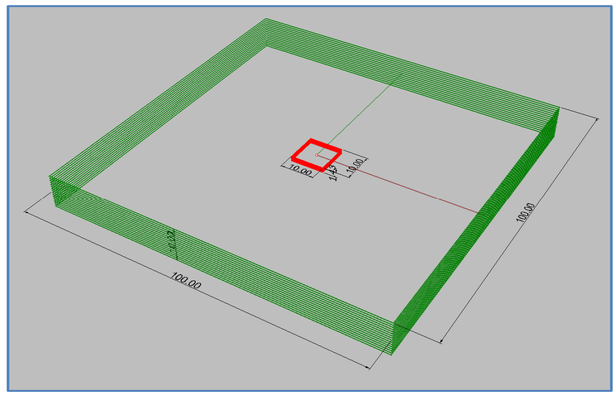

Figure 9 Geometry of standard transmitter and receiver coils.

This configuration has no provisions for rejection of the primary other than background subtraction. This geometry is used extensively as part of the complete geometry in system configurations below. However, it can be studied in terms of stability.

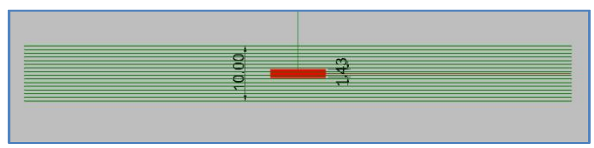

Figure 10 Dimensions of standard transmitter and receiver coils,.

The primary field as observed at the receiver was shown in Figure 7. Across the area of the receiver coil, the field is uniform to about 0.06dB or 0.6% or 6000ppm.

If this coil were used in a background subtraction mode, the resultant null would be as shown in Figure 11, Figure 12, and Figure 13. As might be expected, the output increases by about 200ppm for a 100ppm change in receiver coil size, because the output is a function of receiver coil area. The output decreases by about 100ppm for a 100ppm change in transmitter coil size because the received is primarily a function of 1/R distance from each transmitter winding. If both the receiver coil and the transmitter coil change size jointly, the output increases about 100ppm for each 100ppm.

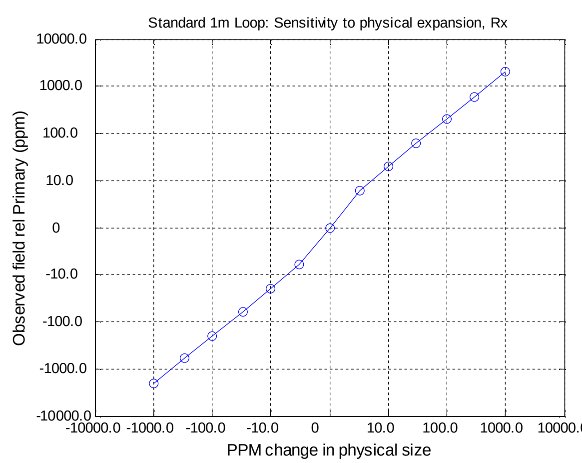

Figure 11 Residual field from a standard loop versus change in receiver coil size.

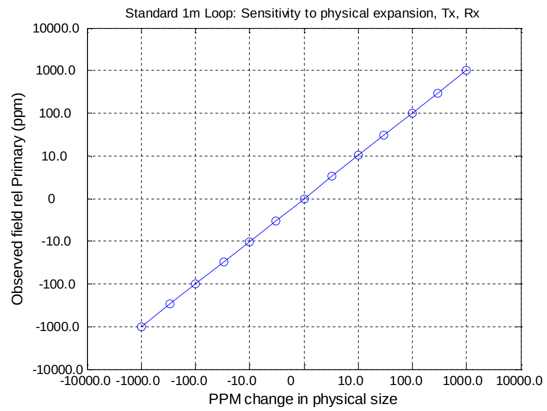

Figure 12 Residual field from a standard loop versus change in both transmitter and receiver coil sizes.

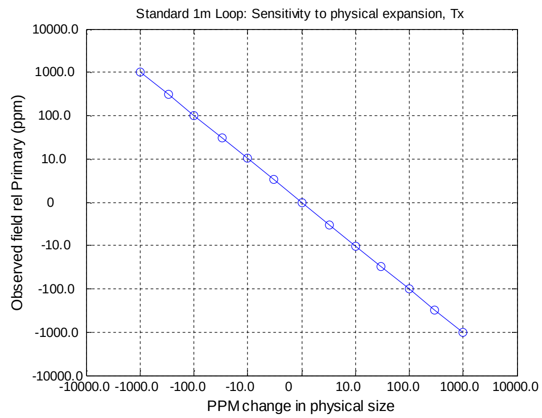

Figure 13 Residual field from a standard loop versus change in both receiver and transmitter coil size.

Simple Planar Bucking

This configuration is similar to the well-known Geophex Inc. GEM-3 system. It consists of a single transmitter coil surrounding a single bucking coil surrounding a single receiver coil (Figure 14). The configuration is not a reproduction in any way other than coincidence of the GEM-3 geometry. In this configuration, the transmitter and receiver coils are as described for the standard coil configuration. The bucking coil is first chosen to have 4 turns distributed across the same vertical dimension as the receiver coil, 1.43cm. To achieve a null, the bucking coil must have a side dimension of 26.5518cm per side (Figure 14 and Figure 15). For purposes of assessing the results, note that the primary coil produces a positive signal in the receiver coil, while the bucking coil produces a negative signal.

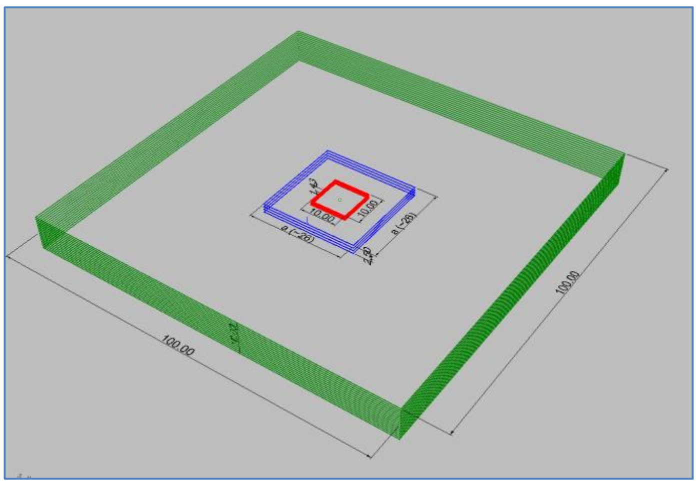

Figure 14 Coil geometry similar to GEM.

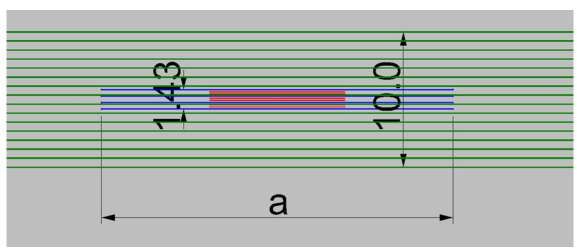

Figure 15 Vertical and bucking dimensions in coil geometry similar to GEM.

Figure 16 and Figure 17 show the residual magnetic field in the vicinity of the receiver coil. The contours in Figure 16 make it appear the field is rather uniform at a level of 70 or 75dBn. But note the two small *eyes* near the edges of the coil. These are actually compressed contour lines where the total field is not only maintaining a rather significant amplitude (more than 45 to 65dBn except in the very small centers of the 'eyes') but is changing direction rapidly from up to down. This is shown more clearly in Figure 17, which is the vertical component. Note that this configuration achieves *null* by receiving a positive field over most of the center portion of the receiver coil while receiving a negative field over most of the outer portion. It would seem 'by eyeball' that this configuration would be very sensitive to the positioning of the bucking and receiver coils, especially to the size or position of the receiver coil, because most the perimeter contributes most to the area of the coil. However, the computations refute this expectation and produce an unexpected result.

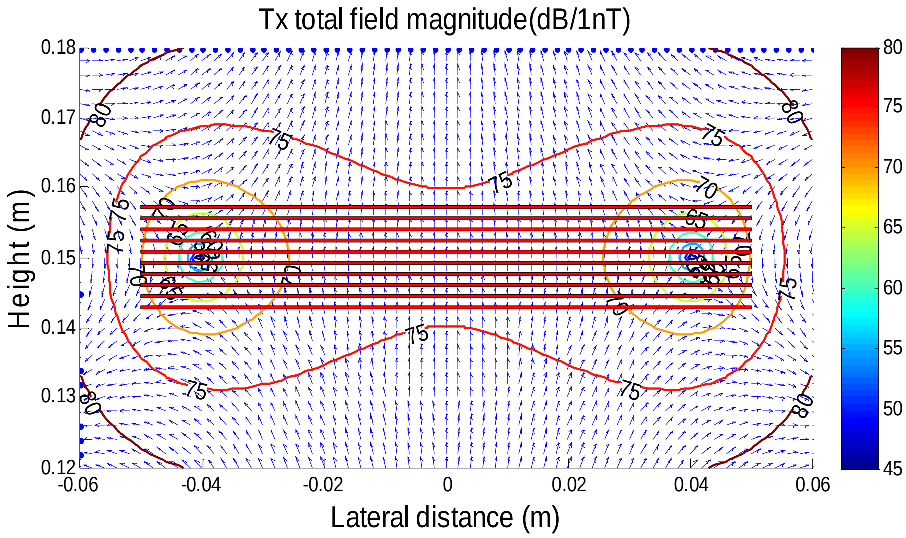

Figure 16 Residual total field for the Simple Planar Bucking configuration in the vicinity of the receiver coil.

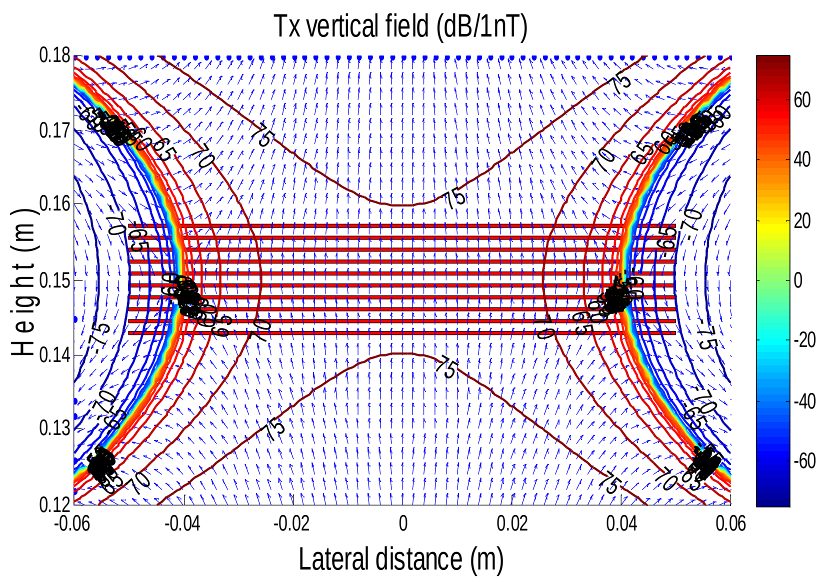

Figure 17 Residual vertical field for the Simple Planar Bucking configuration in the vicinity of the receiver coil.

Changes in the size of the bucking coil are shown in Figure 18. This result would be expected, because if the bucking coil is too small, the receiver coil sees a ‘negative’ field and vice versa. Similarly, a transmitter coil that is too small produces a positive residual field (Figure 19). Also, as expected, a receiver coil that is too small sees mostly the upward field in the center of Figure 16. The receiver coil is less sensitive to changes than for the other coils. For a 1000ppm change in receiver coil size, the null is reduced by only 100ppm (Figure 20). This is because the bucking coil already reduces the size of the *ambient* field surrounding the receiver coil, so changes in receiver coil geometry are less important. We expect this change and, in fact, the one objective of using a bucking field is to cause this insensitivity.

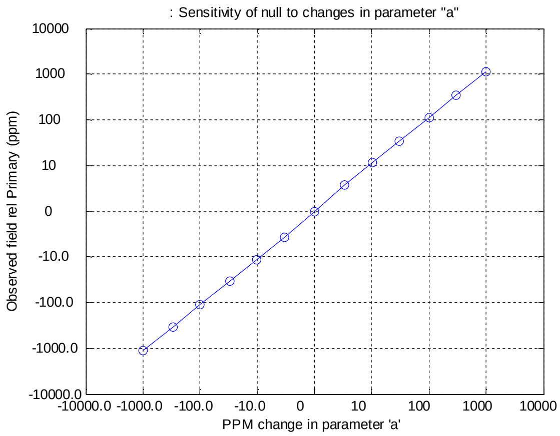

Figure 18 Sensitivity of the Simple Planar configuration to changes in the parameter ‘a’. This is equivalent to changes in bucking coil dimensions.

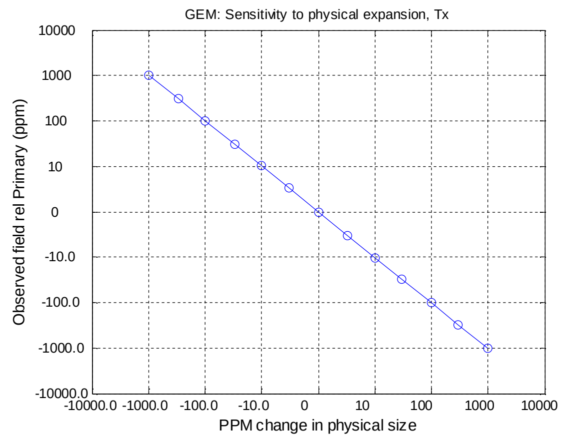

Figure 19 Sensitivity of the Simple Planar configuration to changes in transmitter dimensions.

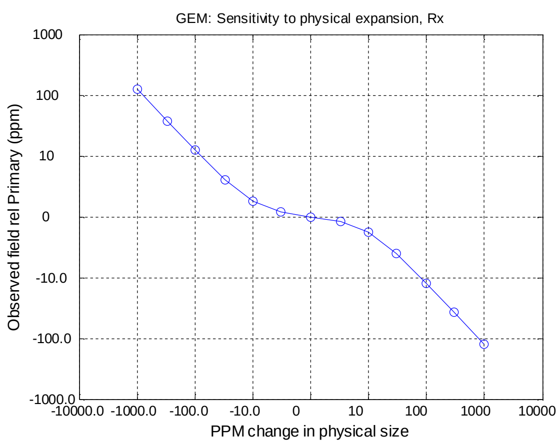

Figure 20 Sensitivity of the Simple Planar configuration to changes in receiver dimensions.

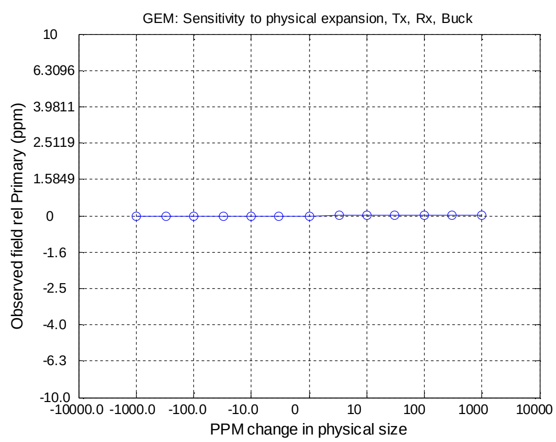

Figure 21 Sensitivity of the Simple Planar configuration to changes in receiver, transmitter, and bucking coil dimensions.

But the unexpected result is found when all three coils are allowed to expand or contract in unison. All of the size changes offset one another and the net effect is no change (Figure 21)! This result means that physical designs can allow for changes in physical size, as long as those physical changes happen in unison to all three coils.

Full Helmholtz Bucking

A Helmholtz coil has two coils that, for circular coils, are spaced one radius apart. The Helmholtz coil is well known (numerous references) to produce a *uniform* magnetic field within the volume between the pair of coils. It is attractive for this application because we know that if we can produce a uniform primary field and a uniform bucking field, and if we can subtract them reliably, we should be able to produce a volume of small residual field.

This configuration was studied because we believed it would provide the best result even though it has some drawbacks. The first drawback is that it requires two transmitter coils, thus complicating the mechanical design. The second drawback is that its geometry seems unfavorable -- the receiver coil must be higher above the ground than the other systems that have all coils in some sort of a near-planar configuration.

The geometry of the configuration studied is shown in Figure 22 and Figure 23. The transmitter coils are chosen to be spaced 50cm apart, one-half the side dimension. The receiving coil is placed at the center. The bucking coils are chosen to have a side dimension of ‘4*a’ cm and to be spaced a cm apart in the Helmholtz geometry. The parameter ‘a’ is adjusted to achieve a null in the receiving coil. The value of ‘a’ depends on the ratio of the number of turns in each bucking coil to the number of turns in each transmitting coil. In our computations, both the number of turns in the transmitting coil and the number of turns in the bucking coil were arbitrarily chosen. Then the value of ‘a’ needed to produce a null was computed iteratively. For the Helmholtz configuration with 16 turns in each transmit coil and 8 turns in each bucking coil, the parameter ‘a’ must be 0.12532. This result implies that the bucking coils must be roughly 50cm on each side and are spaced roughly 25cm. Of course this result makes sense intuitively.

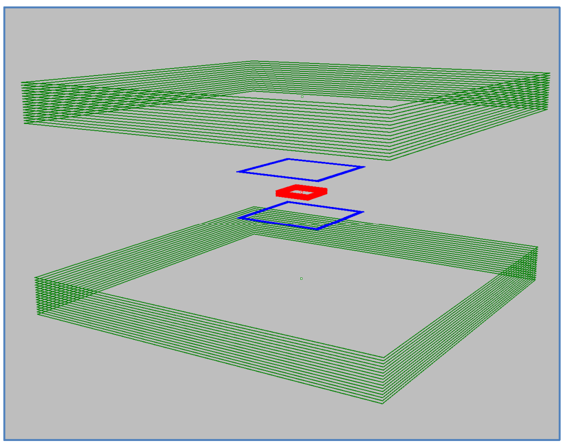

Figure 22 Geometry of Full Helmholtz configuration.

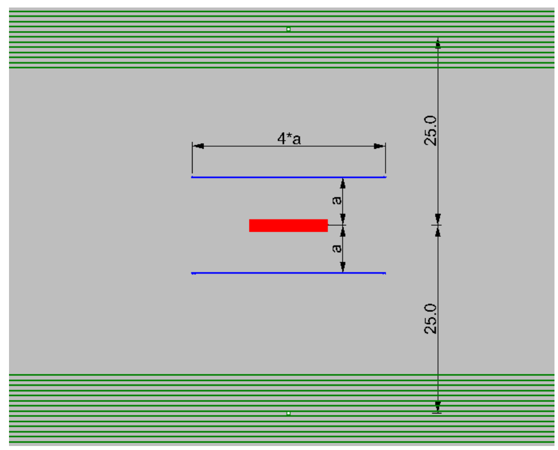

Figure 23 Receiver coil and bucking coil dimensions of Full Helmholtz configuration.

The detailed configuration of the bucking coils was chosen to mimic a configuration that could be implemented with printed circuit boards. The concept is to procure circuit boards with correct dimensions (as nearly as printed circuit-board houses normally provide) and to install those above and below a given receiver coil. Details are shown in Figure 24 and Figure 25.

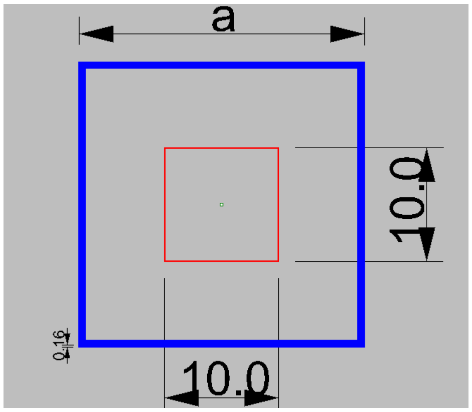

Figure 24 Detailed geometry of bucking coil, top view.

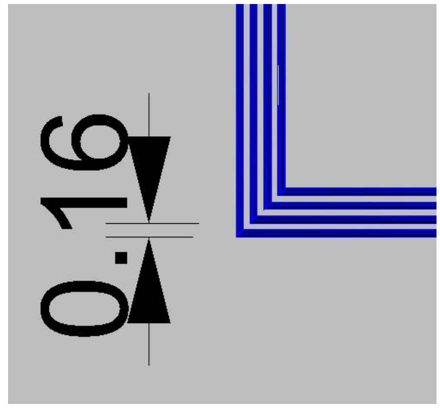

Figure 25 Detailed geometry of bucking coil as it would be on a printed circuit board. Each board would have 4 turns on each side.

In numerical computations, the value of 'a' determines both the size and spacing of the bucking coils. In practice the size of the bucking coils would be chosen as a design specification as would be the spacing of the bucking coils. But after fabrication, the spacing between receiver coils would be adjusted with shims, in order to optimize the null immediately after fabrication.

For this configuration, the residual field in the vicinity of the receiver coil is shown in Figure 26 and Figure 27. The residual field magnitude is no greater than about 45dBn. This is a nice reduction of about 57dB from the ambient primary field which is about 102dBn for this configuration. The remainder of the null, from 45dBn to 0dBn, is a result of the residual field having opposing directional components across the area of the receiving loop -- see Figure 27

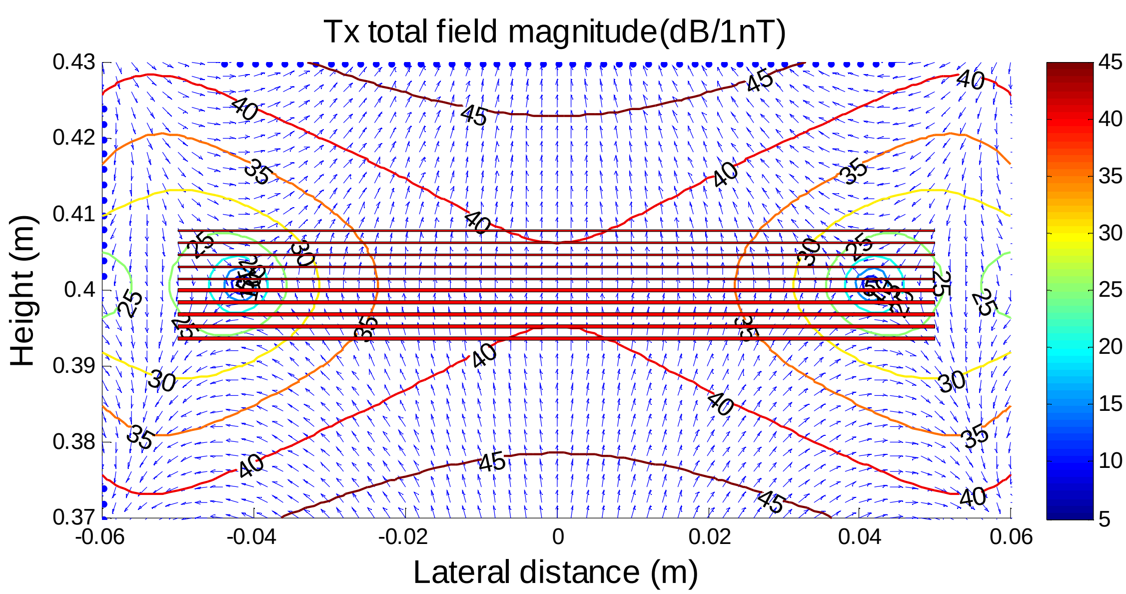

Figure 26 Residual total field for the Helmholtz Bucking configuration in the vicinity of the Rx coil.

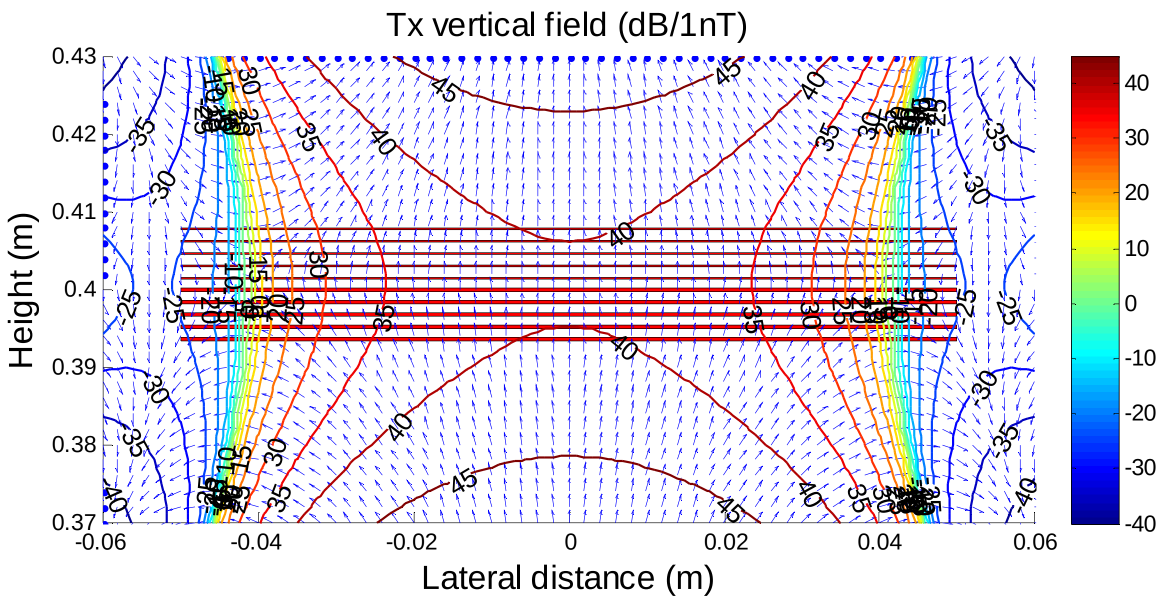

Figure 27 Residual vertical field for the Helmholtz Bucking configuration in the vicinity of the Rx coil.

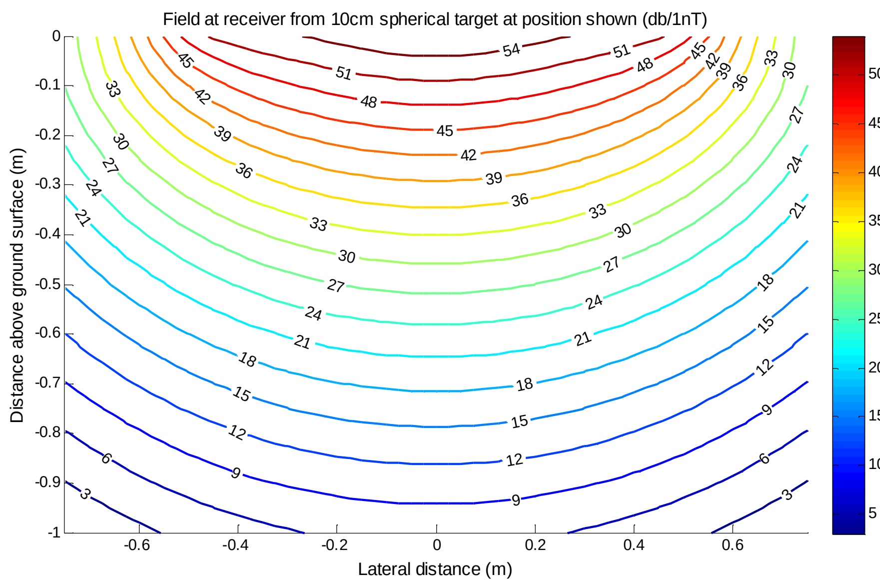

Figure 28 Secondary field intensity at the Rx coil as a function of target position for the Full Helmholtz configuration.

We had an expectation that the Full Helmholtz configuration would produce a smaller signal than the others, because the receiver coil would be farther from the target. This is only partly confirmed in Figure 28. The field at depth is only about 3dB less than the Standard configuration. This ‘less than expected’ value is partly due to the fact that the Full Helmholtz configuration has two transmitter coils.

Sensitivities to changes in dimensions for this configuration are shown in Figure 29, Figure 30, Figure 31, Figure 32, and Figure 33. This configuration loses null to about 60dB for a 1000ppm change in physical dimensions. But note that the loss of null for physical changes in size of the receiver coil alone is small. This means that if the transmitter and bucking dimensions can be held constant and stable, that the dimensional stability of the receiver alone is unimportant. However, since the transmitter and bucking coils are larger than the receiver coil, it is not likely that they would be dimensionally stable while the receiver coil was not. However, the outstanding result is that, like the Simple Planar configuration, if the transmitter, receiver, and bucking coils all change dimensions in unison, that there is no loss of null at all.

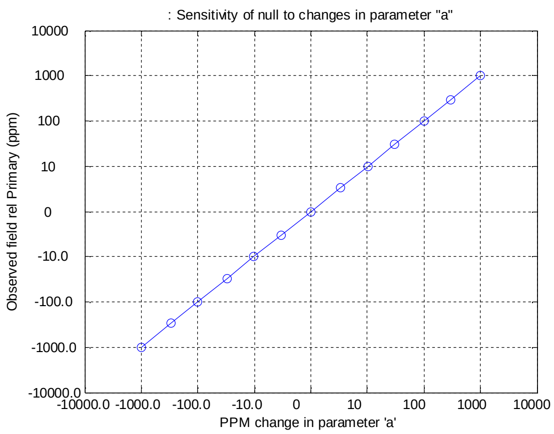

Figure 29 Sensitivity of the Full Helmholtz configuration to changes in the parameter 'a'.

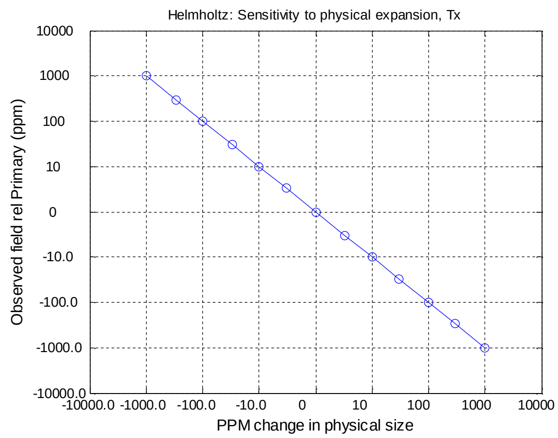

Figure 30 Sensitivity of the Full Helmholtz configuration to changes in transmitter dimensions.

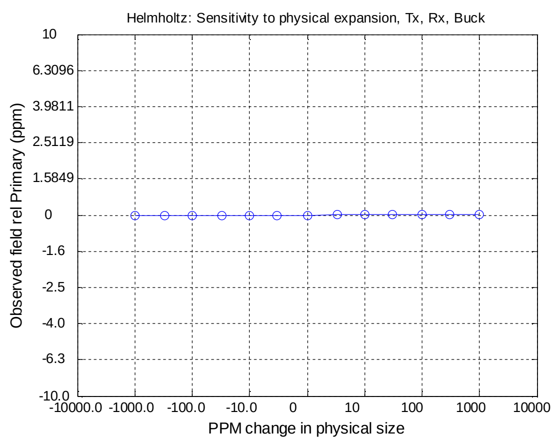

Figure 31 Sensitivity of the Full Helmholtz configuration to changes in dimensions of transmitter, receiver, and bucking coils.

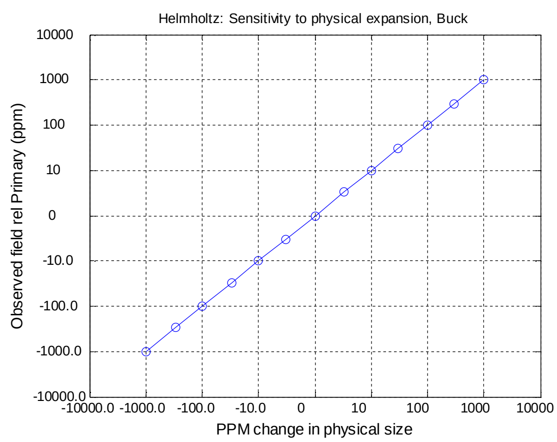

Figure 32 Sensitivity of the Full Helmholtz configuration to changes in bucking coil dimensions.

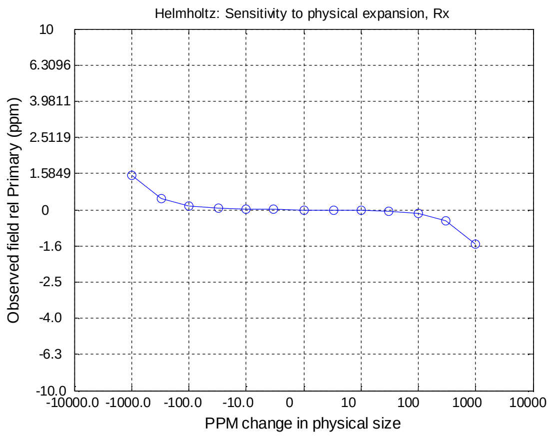

Figure 33 Sensitivity of the Full Helmholtz configuration to changes in receiver dimensions.

This configuration is attractive from the point of view that it does a good job of bucking the primary field over a reasonably large volume. With a larger volume we could hope that it would remain relatively more stable than the other configurations. And further, because of its configuration it might maintain symmetry in the residual field better than the other configurations. If it holds symmetry there is always the opportunity to use two receiver coils to obtain a final null. Given that symmetry might be a result easier to maintain than a small residual field, we expect that any receiver configuration that makes use of symmetry or orthogonality might offer the very best opportunity to fabricate an EM system that is capable of reliably observing the bulk magnetization effect.

Partial Helmholtz Bucking

This configuration uses bucking coils around the receiver that are similar to the Full Helmholtz configuration. The important difference is that the Partial Helmholtz configuration uses only one transmitter coil, and all coils can be vertically centered about a single horizontal plane. A geometry of the configuration is shown in Figure 34. The bucking coils and the receiver coils are the same as described for the Full Helmholtz configuration with one exception. The exception is that we studied performance of the Partial Helmholtz configuration when the bucking coils each had 4 turns or 2 turns instead of eight

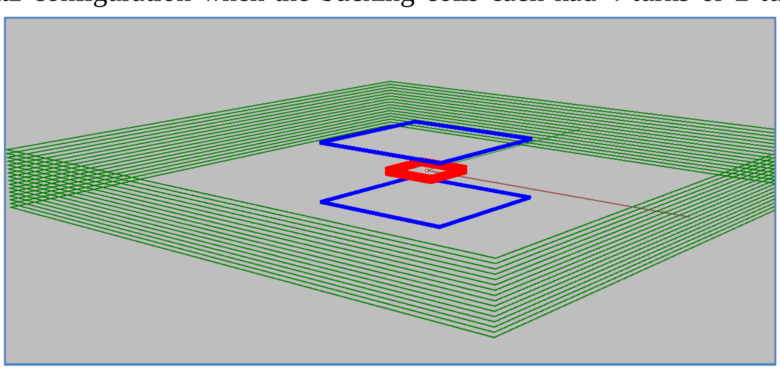

Figure 34 Geometry of the Partial Helmholtz configuration.

turns like the full Helmholtz configuration. Like previous configurations, the size and spacing of the bucking coils is a function of the number of turns. The 2-turn case is compact. It requires the parameter ‘a’ to be 0.04657225 meaning that the bucking coils are placed about 4.7cm above and below the center of the receiver coil and would be about 19cm on a side. With these dimensions, the total vertical dimension of the receiver and bucking coils would be less than 10cm; it would all fit in the 10cm high volume of a standard Metal-Mapper transmitter coil. And the sizes might allow for use of multiple receiver coils within one transmitter coil. For reference, the value of the parameter ‘a’ for 4 turns is 0.09421341. Therefore the bucking coils would be about 19cm apart and would have a side dimension of about 38cm.

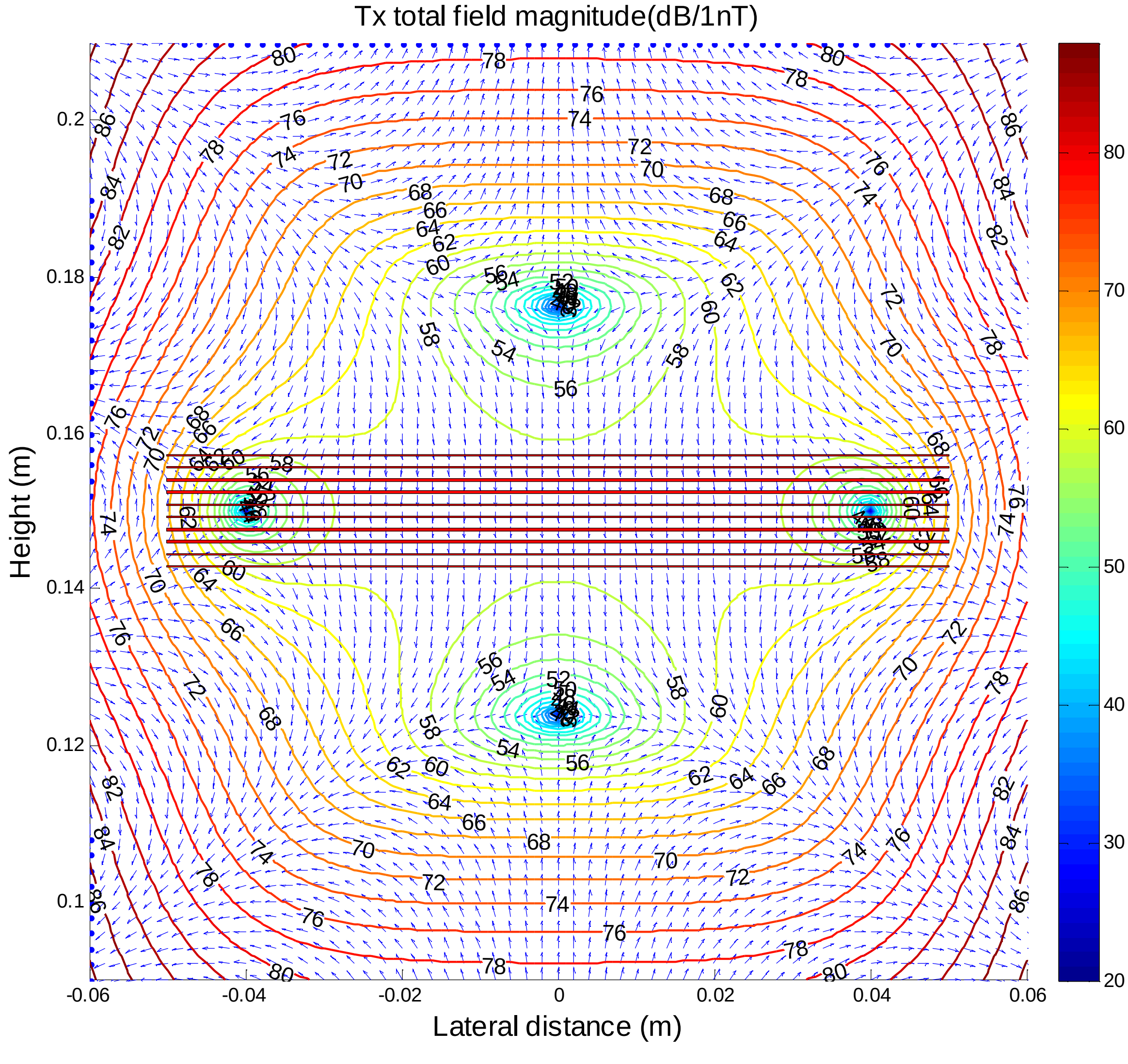

Figure 35 Residual total field for the Partial Helmholtz Bucking configuration with two turns per bucking coil.

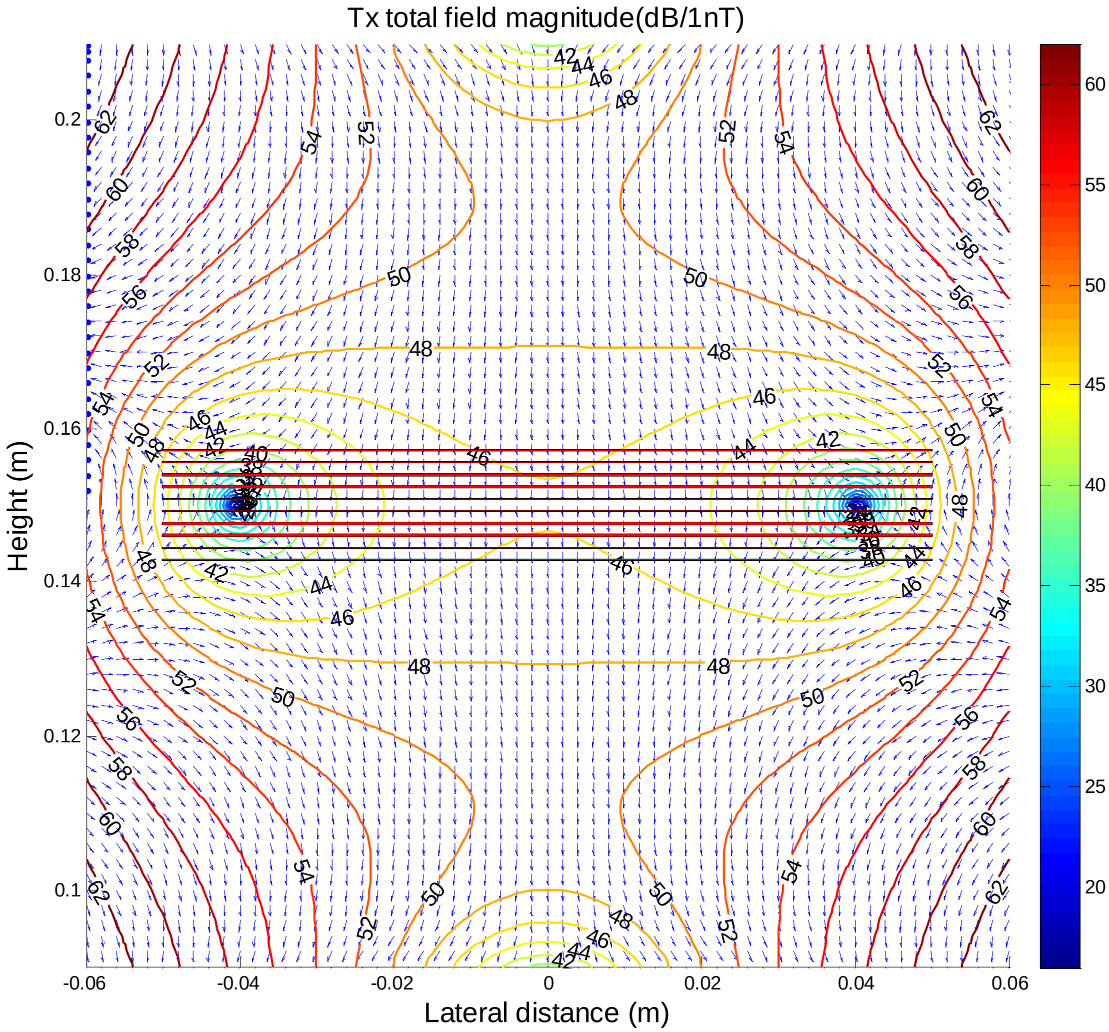

Figure 36 Residual total field for the Partial Helmholtz Bucking configuration with four turns per bucking coil.

The residual total field is shown in Figure 35 and Figure 36, and the residual vertical field is shown in Figure 37 and Figure 38. The total field in the vicinity of the receiver coil is 58dBn for two turns and 46dBn for four turns. This indicates that four turns will likely perform significantly better than two turns. Gradients for the two turn case are even more apparent in Figure 37. Note in Figure 35 for the two-turn case that there are four small 'eyes' in the pattern. These are local nulls in the field and they are indicative of changes in direction of the residual field. Within a centimeter of each of the eyes, the total field amplitude is back up to ~55 or 60dBn so these local nulls are not very useful.

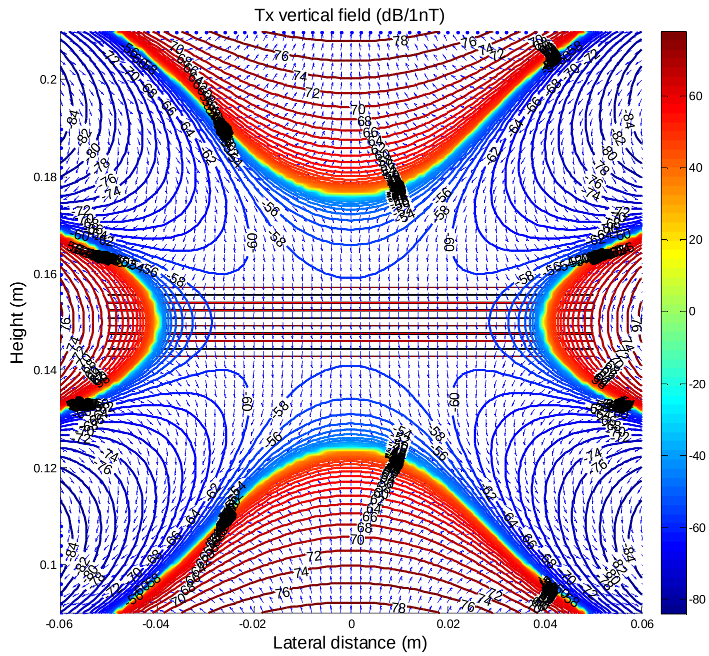

Figure 37 Residual vertical field for the Partial Helmholtz Bucking configuration with two turns per bucking coil.

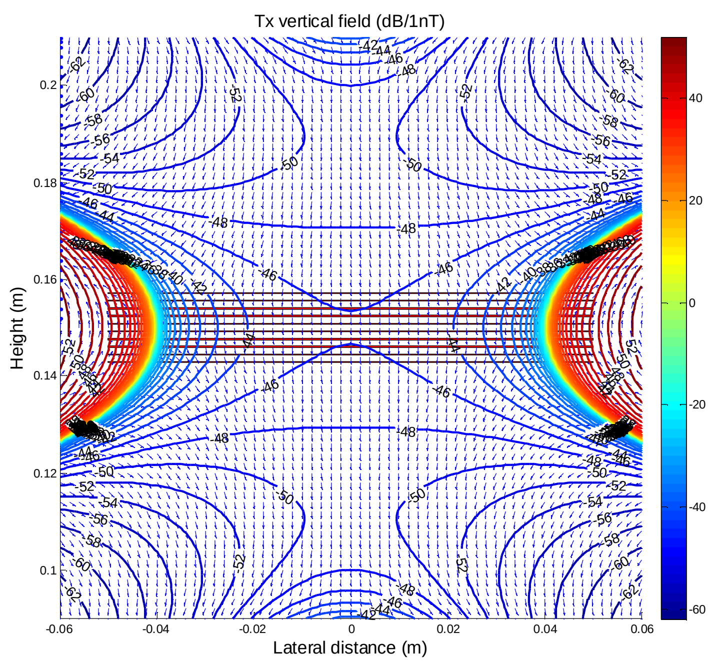

Figure 38 Residual vertical field for the Partial Helmholtz Bucking configuration with four turns per bucking coil.

Residual observations versus changes in physical parameters are shown for the four turn case in Figure 39, Figure 40, Figure 41, Figure 42, and Figure 43. Residual observations for the two turn case are nearly identical, with one small exception, so are not shown. The exception is that the two turn case is more sensitive to changes in receiver coil size. However since both configurations are proportionally sensitive to changes in transmitter coil and bucking coil, there may be no substantial difference.

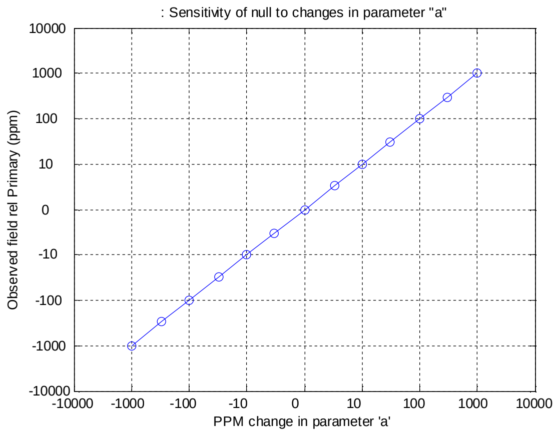

Figure 39 Sensitivity of the Partial Helmholtz configuration to changes in the parameter 'a'.

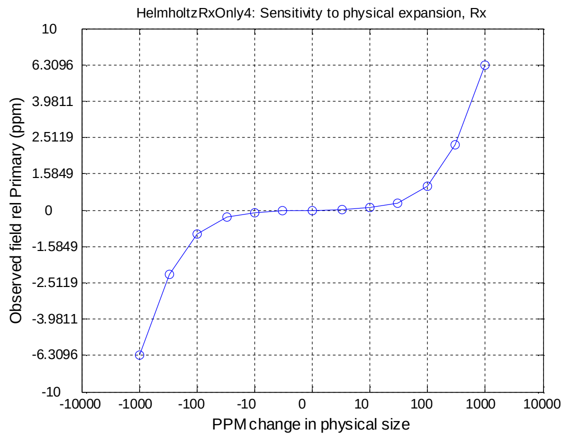

Figure 40 Sensitivity of the Partial Helmholtz configuration to changes in receiver coil dimensions.

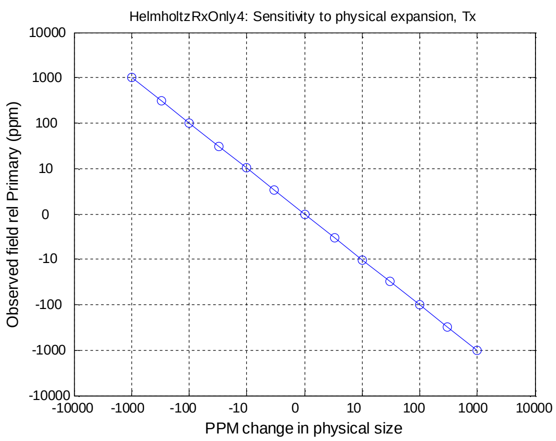

Figure 41 Sensitivity of the Partial Helmholtz configuration to changes in transmitter coil dimensions.

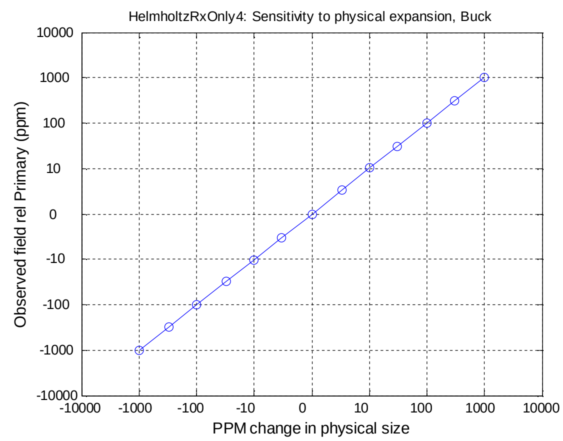

Figure 42 Sensitivity of the Partial Helmholtz configuration to changes in bucking coil dimensions.

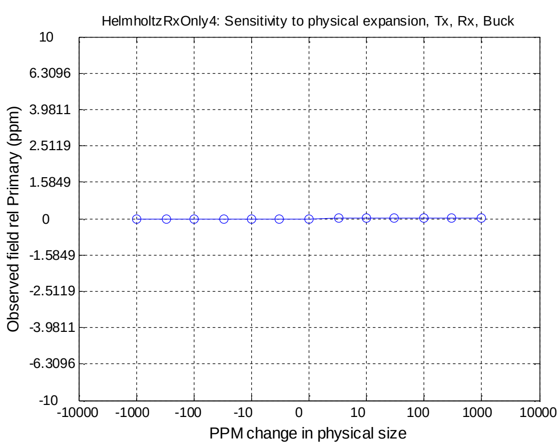

Figure 43 Sensitivity of the Partial Helmholtz configuration to changes in dimensions of receiver, transmitter, and bucking coils.

Like the other configurations, this configuration shows absolute stability when all components expand or contract by the same amount, Figure 43. Thus if both the transmitter coil and the bucking coils can be made proportionally stable, then the configuration may offer good performance.

Horizontal Pair Symmetry

This configuration is shown in Figure 44 and Figure 45. It is inspired because it is a simple configuration that could be fabricated from existing components and would allow use of multiple receivers. It is also would allow simple balancing, just by moving the receiver coil slightly closer to one or the other transmitter coils. It requires two transmitter coils wired in series and wired so that their polarities are 'opposing' – that is one transmits an upward field while the other transmits a downward field. With this configuration, the field below the ground surface will be mostly horizontal, and there will be a fine line midway between the two antennas where the fields will subtract and provide a null. For this study, the two transmitter loops were placed 200cm apart, center to center.

In addition, we also briefly studied a configuration similar to this in which two transmitter loops are placed upright (axes horizontal). If these two coils transmit in the same direction at the same time, there will be a null directly between them located outside the coils by some amount depending on the spacing. This configuration could be attractive because the receivers would be closer to the ground than the transmitters and because multiple receivers could be used. However, the configuration is judged a little unwieldy, and initial study indicated its performance was not exceptional, so is not presented here.

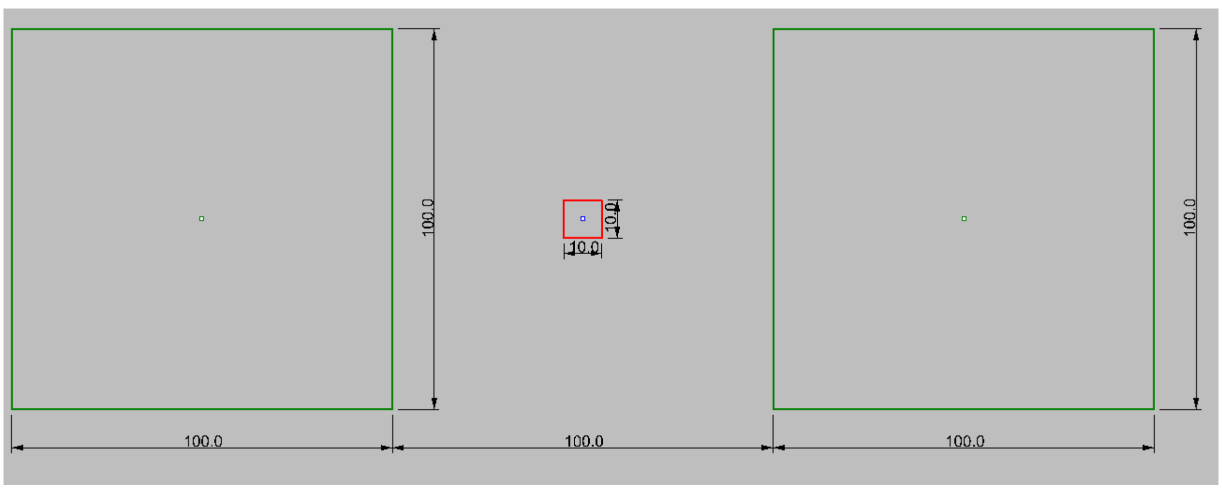

Figure 44 Geometry of Horizontal Pair configuration, top view.

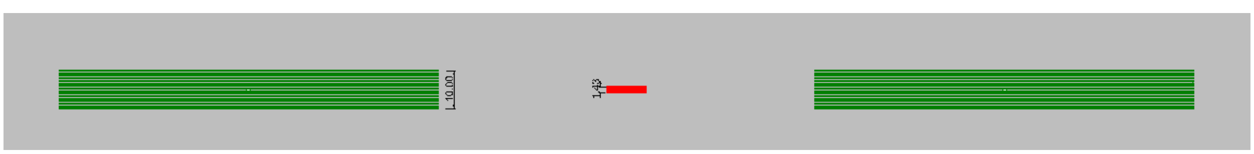

Figure 45 Geometry of Horizontal Pair configuration, front view.

The total field is shown in Figure 46 for the entire distance between the two transmitter coils. The total field is also shown in Figure 47 for the vicinity of the receiver coil, and the vertical field is shown in Figure 48. It is apparent that the receiver is immersed in a field with a magnitude of roughly 70dBn and that null is achieved by very careful placement of the receiver right and left between the two coils.

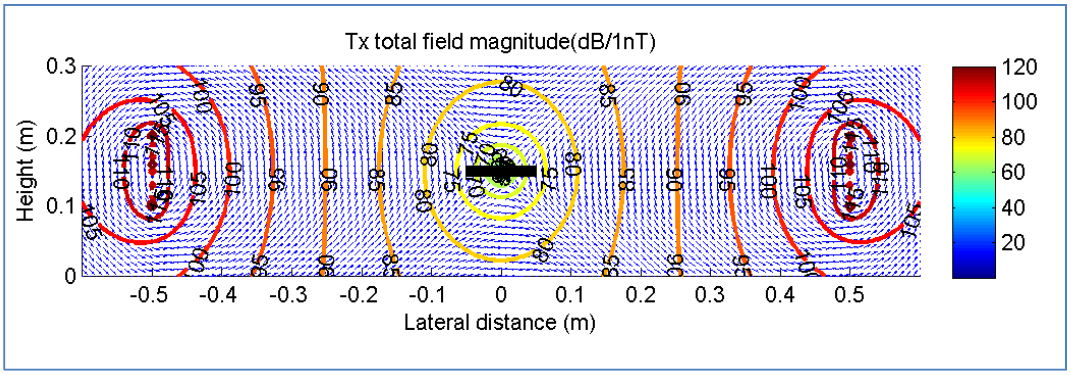

Figure 46 Total field between the two inside windings of the two transmitter loops for the Horizontal Pair configuration.

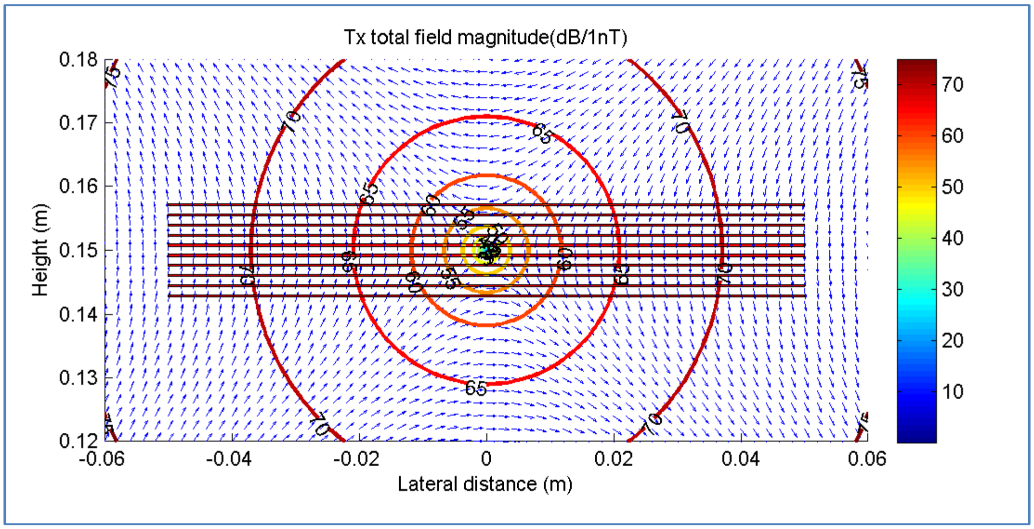

Figure 47 Total field for the Horizontal Pair configuration in the vicinity of the receiver coil.

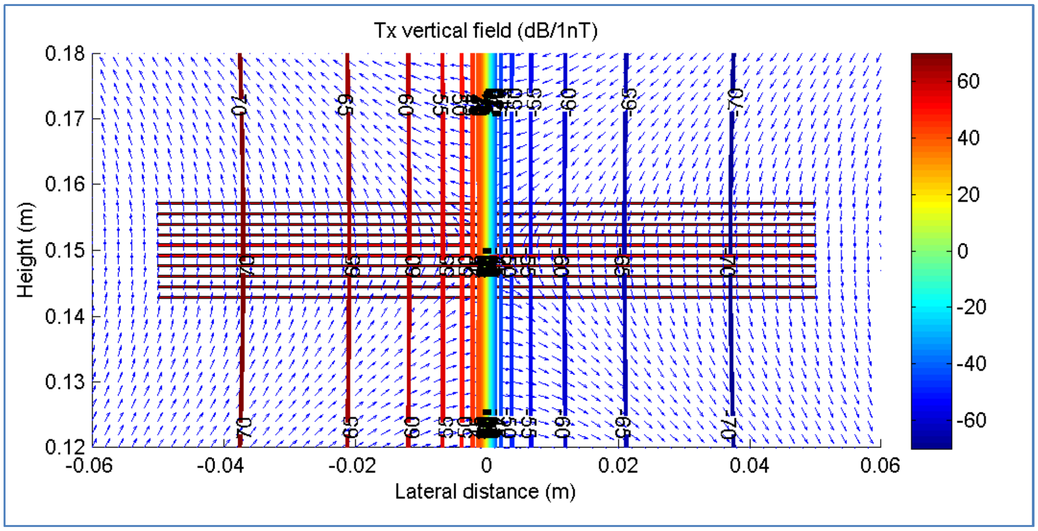

Figure 48 Vertical field for the Horizontal Pair configuration in the vicinity of the receiver coil.

Results of expansion or contraction of this method are not shown because any expansion or contraction that is symmetric does not reduce the null. Instead, the sensitivity of this method is shown as a displacement of the horizontal placement of the receiver coil. A 1mm displacement (1000ppm over a distance of 1m) results in an observed signal change of 10,000ppm (Figure 49).

The sensitivity to dimensional changes, particularly the placement of the receiver coil in this configuration is somewhat worse than the sensitivity of the other methods. And the method is different from the others in that it activates the target with a horizontal field instead of a near vertical field.

Sensitivity to a target is shown in Figure 50. Compare Figure 50 to Figure 8. This configuration is about 6dB poorer than a standard 1m loop. This is because first, there are only two coil sides effectively contributing to the signal below ground, and secondly a horizontally activated target produces a horizontal dipole that gives a signal that is only half of the same dipole oriented vertically.

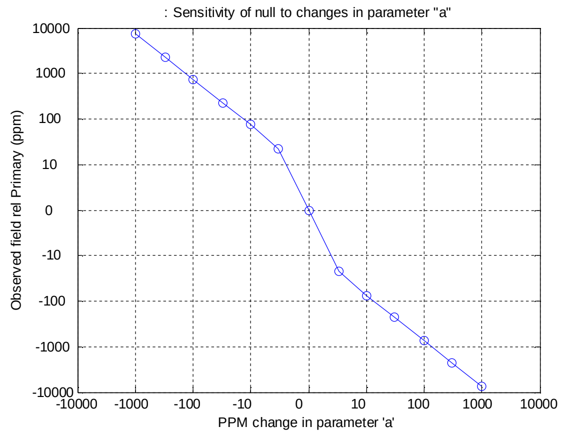

Figure 49 Sensitivity of the Horizontal Pair configuration to changes in position of the receiver coil. A 1000ppm change in 'a' means a 1mm displacement of the Rx coil.

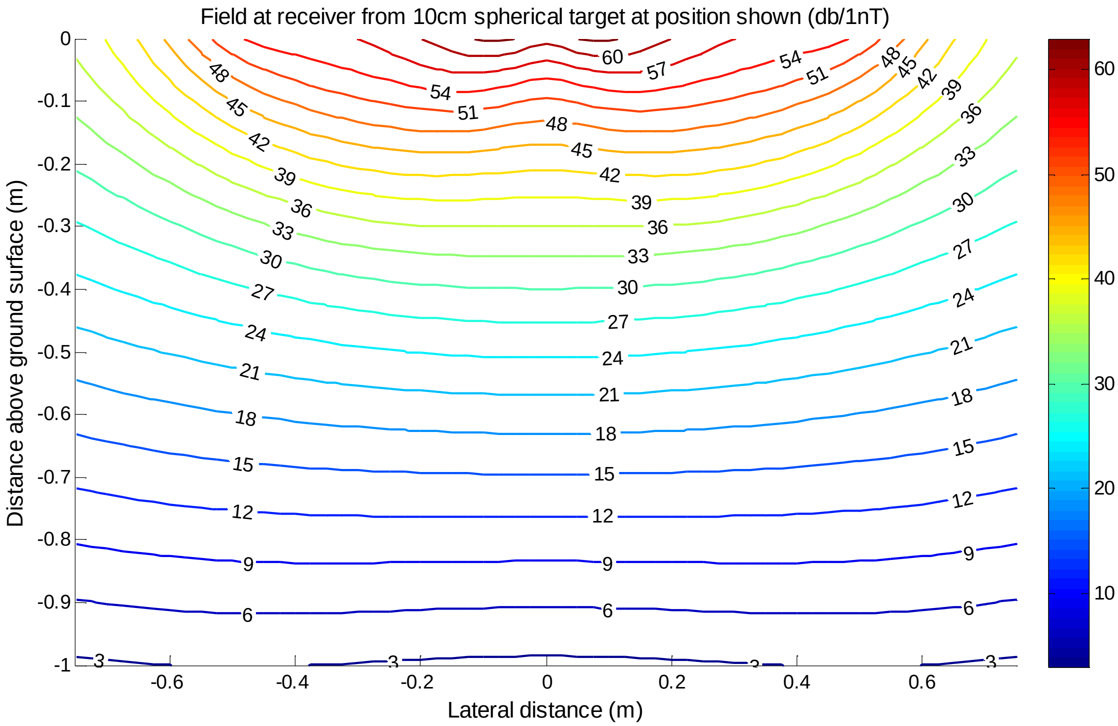

Figure 50 Secondary field intensity at the receiver coil as a function of target position for the Horizontal Pair configuration.

Transmitter Current Replica Subtraction

This coil configuration is used to produce an electronic signal that has 'exactly' the same shape as a signal, due to the primary alone, from the receiver coil. For this configuration we assume that the primary field is exactly the same shape as the current entering the transmitter coil terminals even though we know this might not be precisely true. The objective here is to place a small coil in series with the transmitter coil and to produce a signal that can be subtracted from the signal produced by the receiver coil. The objective is, in essence, to make a receiver coil that senses only the primary field.

There is much literature to this generalized problem of producing a signal proportional to the current in a wire. An interesting device is known as a 'Rogowski coil.' When used for current sensing it is wrapped around a conductor and becomes essentially indistinguishable from a 'toroid.' Much of the literature is concerned with integrating the output of the coil so that the signal represents the actual current in the wire. Our application does not require that step – since the receiver senses the derivative of the primary field, we are happy to sense the derivative of the primary current.

For this study we chose a simple configuration. Our concept is to design a 'pickup coil' that is electrically isolated and produces a stable signal. This signal would then be wired in series with the receiver coil, and thus the receiver electronics would amplify only the difference signal. This concept requires an implied calibration wherein the sensitivity of the pickup coil exactly balances the sensitivity of the receiver coil. Rather than studying methods to produce this calibration, we studied stabilities, thus avoiding the issue for now. This configuration is not completely different from a concept of simply using two identical receiver coils and wiring them in series opposition. The challenge is finding a place to put the second receiver coil so that it picks up only primary field (and no secondary field).

For this task we made initial computations of several configurations. But none appeared to be substantially different or better than any other. We tried closely coupled configurations such as the one described below, and loosely coupled ones, where the pickup coil is a different size than the inducing (transmit) coil. We briefly tried configurations where, for example, two pickup coils were located on each side of the winding along one side of the transmitter coil – this would help assure that the sensed field is the same as the primary field. But in the final analysis we chose just one configuration for study – one that offered simple and perhaps stable fabrication techniques.

The configuration chosen for study is shown in Figure 51. This configuration represents a coil pair that could be fabricated from printed circuit boards. The green coils represent coils that are wired in series and carry full transmitter current. The coils are wired so that they produce opposite polarities, up in one and down in the other. The red coils are coils are wired in series like the green coils. They produce a voltage that could be subtracted from a receiver-coil voltage. Polarities are set this way so that the receiver coils become less sensitive to external fields. Any field that is planar across the areas of the two receiver coils will cancel. The coils were chosen to be nominally 10cm per side.

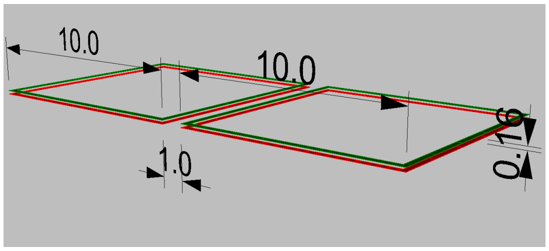

Figure 51 Transmitter Current Replica Subtraction configuration. Green is a coil carrying transmitter current. Red is a coil producing a replica subtraction signal.

At first view, this configuration might be considered to be a transformer with almost unity coupling. So one would think its output would be stable. But for our purposes, "stable" means 10ppm drift or less. So this configuration is subjected to the same computations as the previous configurations.

The total field produced by the transmitter-current coils is shown in Figure 52. This figure provides no significant insights other than to indicate the magnitude of the fields involved. Since the fields are of magnitudes similar to the primary field at the center of the main transmitter coil (Figure 7), and since the field at the center of the transmitter coil is the minimum field inside the transmitter coil, the placement of this coil becomes an issue. It must be placed where the primary field is small or where the primary is essentially uniform.

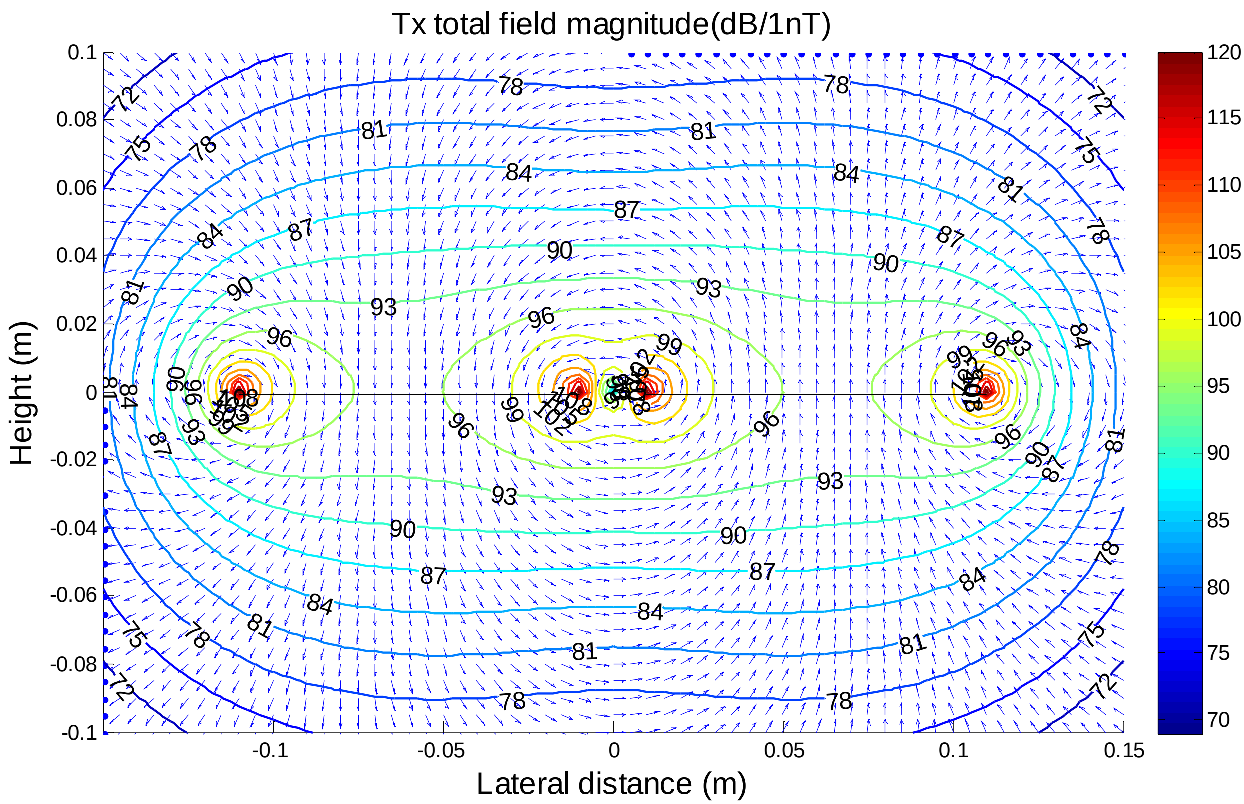

Figure 52 Total field for the Transmitter Current Replica Subtraction configuration.

The only stability issue that was studied for this configuration was physical expansion. Given that the wires would be placed on a circuit board, the whole board would change size proportionately. The results are shown in Figure 53.

Figure 53 indicates that the output of this coil would change 200ppm for a 100ppm change in physical size. However, we expected that a configuration could be created such that the expansion of the transmitter coil would offset the expansion of the receiver coil to produce a small net effect. We were unable to find such a configuration. We believe the reason that the bucking coil configurations become dimensionally stable even when dimensions are varying is because the changes in the transmitter and bucking coils are changing in the same direction by the same amount so the net subtraction remains zero. Such is not the case for this pickup coil configuration because we are not sensing a null.

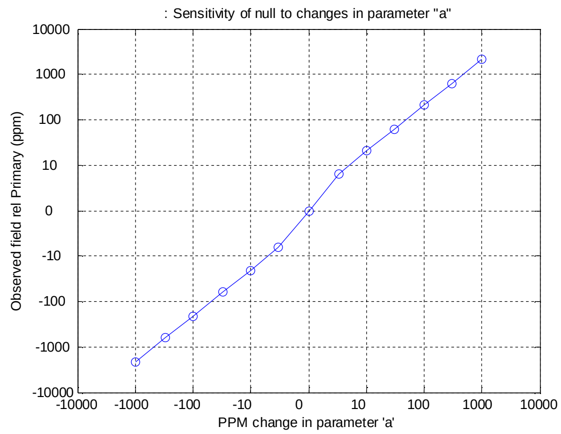

Figure 53 Output of the Transmitter Pickup coil configuration versus change in physical size.

CONCLUSIONS

After substantial study, the conclusions of this study seem insignificant. In general, it can be said that if a user wants a null that is stable to 100dB or 10ppm, that dimensional and electronic stabilities must be stable to 10ppm. But this statement can be taken in the context that physical stability does not have to be absolute; it has only to change such that the ratio of dimensions or electronics parameters stays constant. The table below shows a summary of the field values and stabilities for each of the configuration studied.

Table 1 Summary of field intensities and stabilities for configurations studied

	Approximate residual field intensity in a volume containing the receiver coil.	Change in residual field intensity for a 100ppm change in physical dimensions	Secondary field intensity, 10cm sphere, 1m deep
Standard Metal Mapper Coils	99dBn	N/A	12dBn
Simple Planar Bucking coil	70dBn	100ppm Transmitter or Buck alone. 0ppm Transmitter and Buck together.	12dBn
Full Helmholtz Bucking	40dBn	100ppm Transmitter or Buck alone. 0ppm Transmitter and Buck together.	9dBn
Partial Helmholtz Bucking, 4 turns	46dBn	100ppm Transmitter or Buck alone. 0ppm Transmitter and Buck together.	12dBn
Partial Helmholtz Bucking, 2 turns	68dBn	100ppm Transmitter or Buck alone. 0ppm Transmitter and Buck together.	12dBn
Horizontal Pair Symmetry	73dBn	900ppm for 100ppm movement of receiver coil.	3dBn
Transmitter Current Replica Subtraction	96dBn	200ppm	NA

The objective of this study was to determine a configuration that would be tested experimentally. We are not pleased with the results of this study in that we found no configuration we thought would meet our goal consistently. However, we learned that the two Helmholtz configurations might function well enough – that is drift might be small enough so that reasonable measurements could be made in production field use.

In this study we also developed an appreciation for geometries and parameters that most affect performance and developed a deeper understanding of background subtraction in the context of subtracting away the primary response. Therefore a significant conclusion is that not only should the system be stable in terms of permanently rejecting the primary but also the system should provide 'new' or improved methods of remembering and subtracting background.

We recommend the following system:

- Design a partial Helmholtz system with transmitter coil diameters on the order of 50cm and a receiver coil diameter of 5 to 8cm. Use more turns per bucking coil in order to maximize the distance from bucking coil windings to receiver coil windings. Although this study was done with 100cm (Metal-Mapper) size coils, we suspect that a bulk magnetization system will be more useful for hand-held measurements than it would be for either detection or initial characterization surveys.
- Use a 3D 'cube' receiver coil inside the Helmholtz bucking coil. The horizontal (axis) components of that coil will offer the best opportunities to observe the bulk magnetization secondary signal and are likely to show less drift and better performance due to the symmetry of the residual field. Yet if the system is stable, the vertical component will likely be observable when corrected with replica subtraction (below).
- Design and fabricate the entire system using wood frames. This is because wood has a small coefficient of linear thermal expansion, has good strength, and is easy to work. However if a prototype device proves acceptable, then additional funding should be allocated to design a device having similar characteristics, lighter weight, perhaps more durability, and similar performance.
- Allow for shims to be placed between the bucking coil and the receiver coil in order to make final adjustments on the null. Shims could be as thin as pieces of paper.
- Design a Transmitter Current Replica Subtraction coil to be used in the last step of background subtraction. In this context we recommend replica subtraction be implemented as a processing step, not as hardware implementation. That is we recommend that a special sensor be fabricated to produce a replica signal and that this signal be digitized and used to subtract residual primary signal from received signals. We envision that 40dB of replica subtraction can be implemented and maintained using digitized signals.

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Appendix A: Performance of a Design Using Square Coils

This appendix presents the computed performance of a tentative design for a sensor/system. This design is the starting point for a system that could be fabricated to test the lessons learned in the study..

In this design we have chosen certain parameters. First we limited the vertical dimension of bucking coils to be the same as the vertical dimension of a *standard* transmitter coil (10cm). Second we limited the bucking coils to have geometry similar to the transmitter coil, assuming both would be wound with the same wire and both would be wound on similar forms. We experimented briefly with bucking coils that were equally distributed across the 10cm allowable space but found, not surprisingly, that *Helmholtz-like* coils provided best performance. So we settled upon dimensions that are similar to cubes used in MetalMapper and TEMTADS. In particular we spaced turns of the bucking coil by the same spacing used for the transmitter coil, assuming they would be wound with the same wire (perhaps even the same continuous wire) as the main transmitter coil. Results are shown below where discussions are provided primarily in figure captions.

Finally it was apparent in this study that one part of the problem was establishing a small residual field over the volume of a 10cm cube. When we prepared the graphs in this appendix, we found that the residual field was larger than previous calculations – this is because we previously used a 100cm transmitter loop while here we used a 50cm transmitter loop. So we scaled the size of the receiver sensor by the same ratio meaning that we assumed a 5cm cube.

Results are shown for this system in a manner similar to those in the body of the report. The geometry of the system is shown in Figure A-1, Figure A-2, and Figure A-3. The transmitter coil is 50cm per side, the bucking coils are 19.2cm per side, and the receiver coil is 5cm per side. The bucking coils are marginally taller in the vertical dimension than the transmitter coil. This was necessary to achieve the good null around the receiver as shown below.

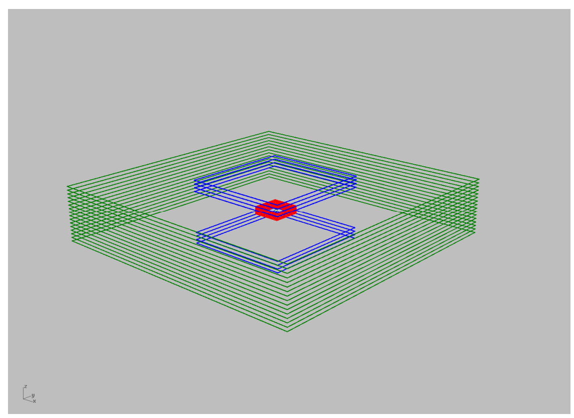

Figure A-2 Isometric view of the configuration.

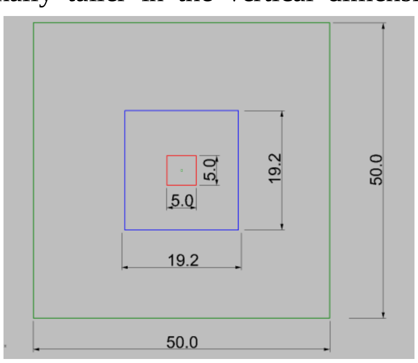

Figure A-3 Plan view of the configuration.

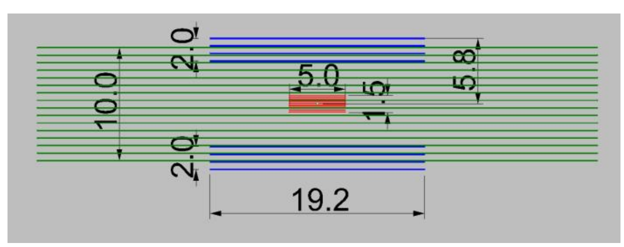

Figure A-1 Front view of the configuration

An overall view of the total residual field is shown in Figure A-4. This figure is not useful for studying the field in the vicinity of the receiver coil – for that see Figure A-5. Figure A-4 shows the magnitude of the field just below the coils. We worried that such a configuration would produce a spatial *hole* in the overall sensitivity when the target is directly beneath the center of the array, because the bucking coil would reduce the primary field. However, Figure A-4 shows that the field remains with good amplitude even at 10cm below the center of the array.

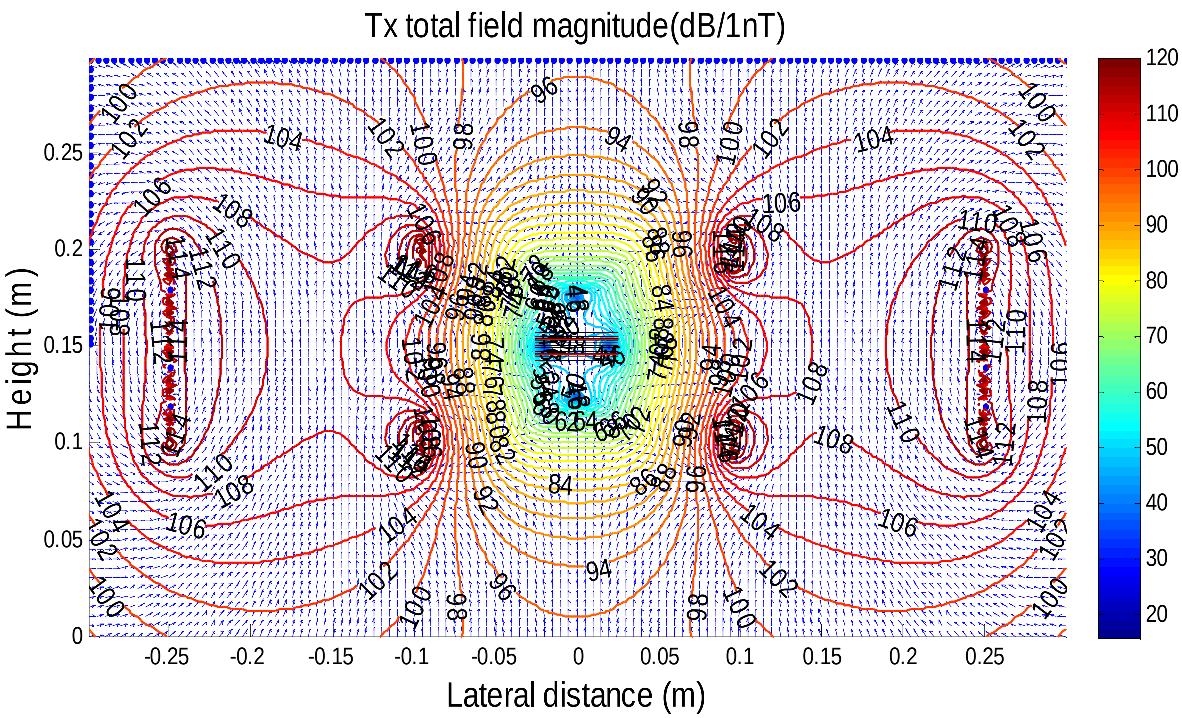

Figure A-4 Total field overview.

Figure A-5 shows the nicest aspect of this design. There are four local minima in the vicinity of the receiver coil and the maximum effective value of the residual field is about 52dBn. Given that the primary field before bucking is about 105dBn for this configuration, the bucking coils are providing a reduction of 53dB. The four minima do a reasonable job of covering an entire receiver volume of 5cm by 5cm. This means that the receiver X and Y coils should show a very small residual field that could very well remain stable. The Z coil is susceptible to dimensional changes because, as with all previous designs, the primary field is reduced to only about 52dBn. The rest of the ‘null’ in the coil is due to positive Z fields around the edges of the coil and negative Z fields in the middle (Figure A-6).

This configuration shows a little bit better sensitivity to dimensional changes than those shown previously. As with other configurations, the system in moderately insensitive to changes in receiver coil dimensions – see Figure A-7. However, in contrast to other configurations, this configuration is moderately less sensitive than the others to changes in both transmitter coil or bucking coil dimensions – see Figure A-8 and Figure A-9. But finally and most importantly, like other configurations this one compensates for simultaneous dimensional changes in all coils, having almost perfect stability as shown in Figure A-10.

For comparison with the larger coils, the secondary field intensity, as a function of position of a target, is shown in Figure A-11. This configuration has almost the same response to shallow targets as a 1m transmitter. But because it is a smaller configuration, it of course produces smaller signals at depth. This configuration produces about the same signal for a target at 75cm depth as a 1m size system produces for a target at 1m depth. Given that we expect this system to be most useful for characterization of nearer (meaning shallower) targets, this tradeoff seems acceptable.

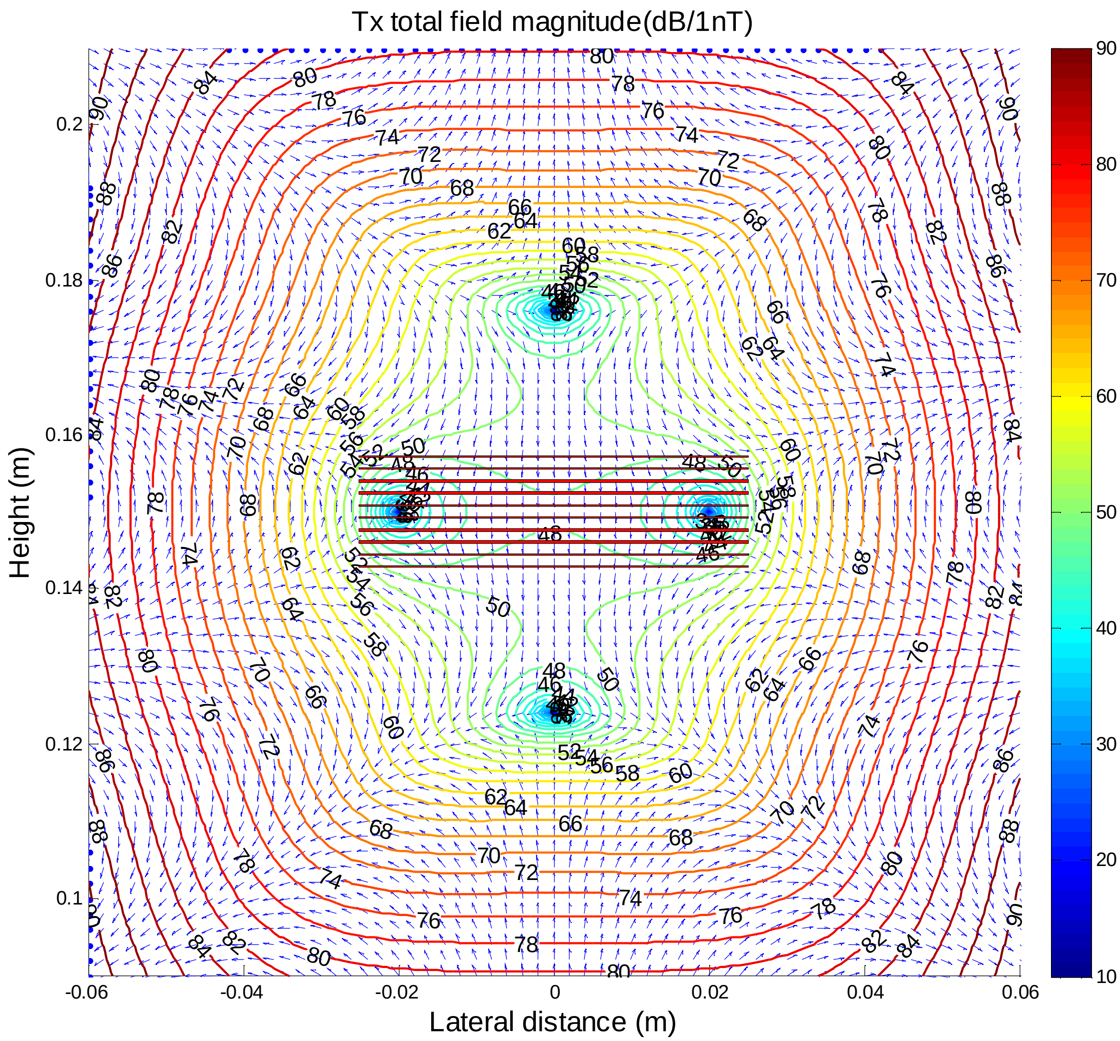

Figure A-5 Total field in the vicinity of the receiver coil.

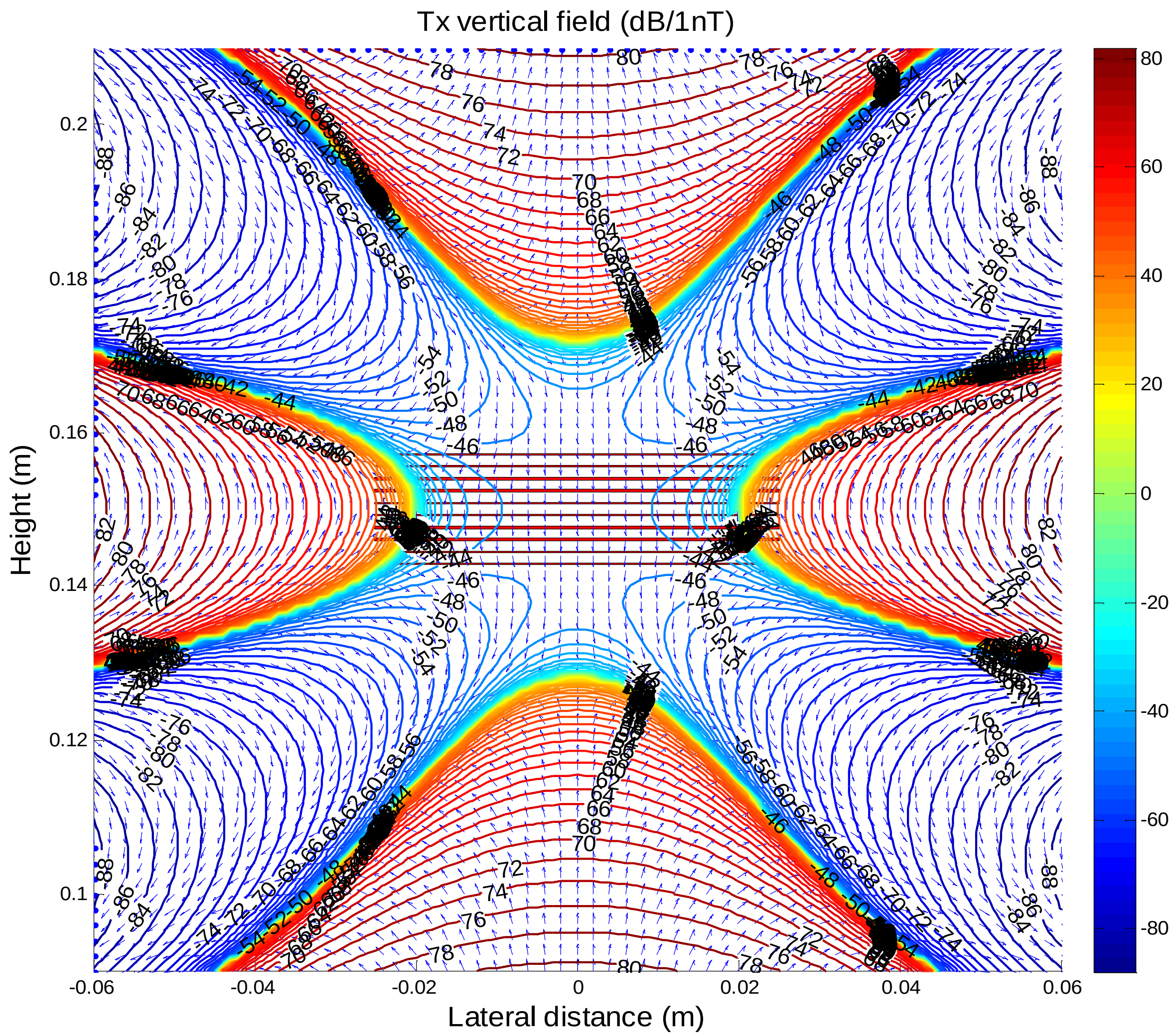

Figure A-6 Vertical component of the residual field in the vicinity of the receiver coil.

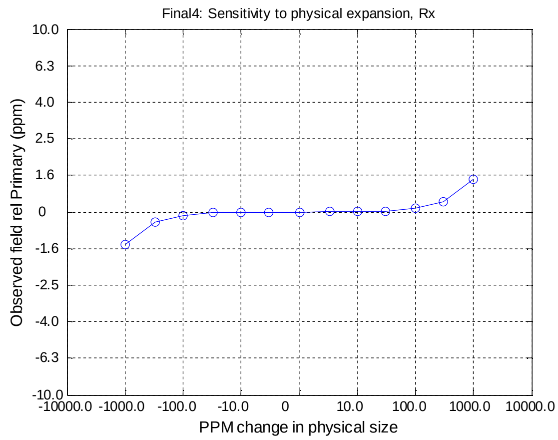

Figure A-7 Sensitivity of the design configuration to changes in receiver coil dimensions.

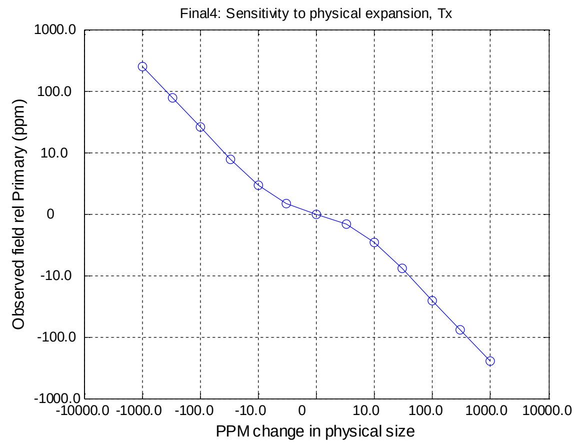

Figure A-8 Sensitivity of the design configuration to changes in transmitter coil dimensions.

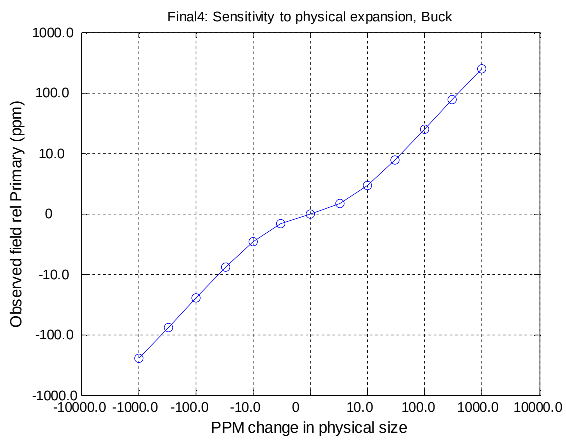

Figure A-9 Sensitivity of the design configuration to changes in bucking coil dimensions.

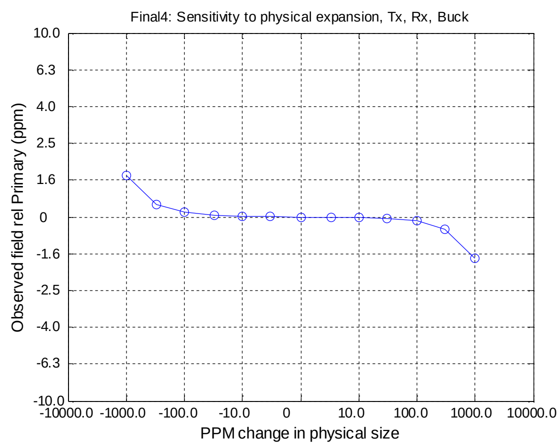

Figure A-10 Sensitivity of the design configuration to simultaneous changes in dimensions of all coils.

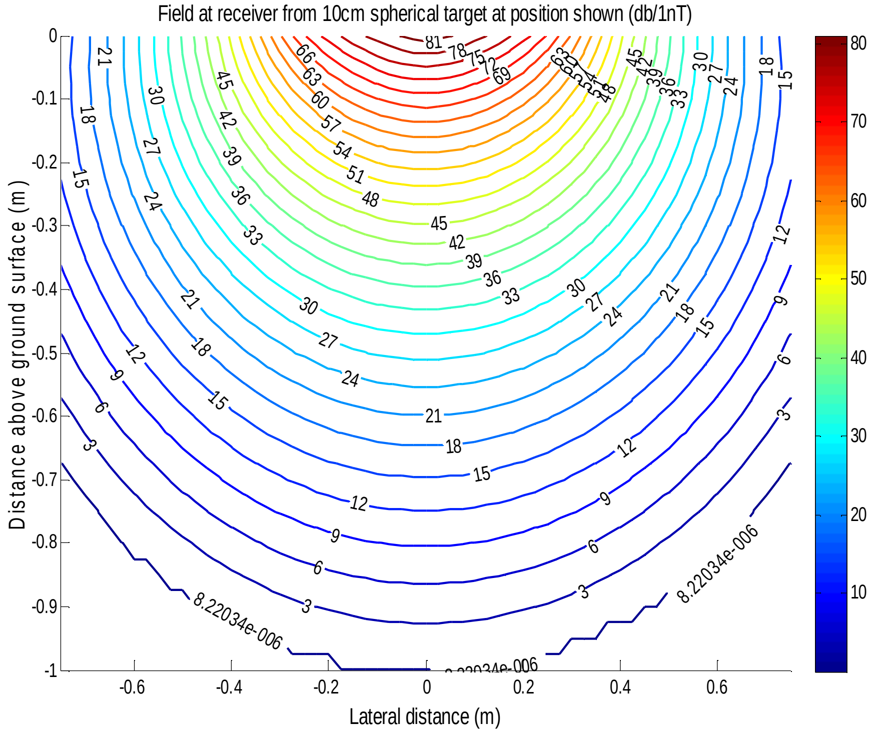

Figure A-11 Secondary field intensity for the design configuration.

Appendix B: Enabling Features of a Primary Rejecting Design

This appendix is included because the author believes it important to delineate some of the measurement techniques that are possible once we have established a system configuration that eliminates, or at least greatly reduces, the primary signal. All of these techniques become possible because a primary-rejection system can be a **linear** system whereas most time-domain systems that are in use are **nonlinear** systems. In particular, the existing time domain systems must clip the primary signal if there is any hope of maintaining a dynamic range that is capable of seeing secondary signals.

The existing systems that are acutely familiar to this author (TEMTADS, MetalMapper, MPV) provide time-based samples of received signals at a high sampling rate. Normally a nice digital-sample stream would open up opportunities to digitally filter signals to achieve any of many different objectives. But since the input signal is clipped (meaning nonlinear), most of the well-known digital filtering possibilities are eliminated. This includes especially, any techniques that rely on the shape of the primary signal – for example cross correlations or cross-power-spectral densities. But it also eliminates most linear filtering schemes because all of those rely on a time-history of the input signal to compute a filtered output signal.

Therefore, this appendix is included in this report to point out those techniques the author believes could be easily implemented in a system that is linear. All of these arguments assume that the system uses an induction sensor (i.e. a dB/dt sensor).

Compute B-field Signal Instead of dB/dt Signal:

At the outset of investigations that lead to the first generation Advanced Ordnance Locator (AOL), it was proposed that the AOL would produce a B-field signal rather than a dB/dt signal. After serious efforts the attempts were fruitless because the **linear** dynamic range that was needed was impossible to implement (economically if not fundamentally). Therefore the idea was abandoned.

Sensing a B-field signal instead of a dB/dt field signal has two substantial advantages. First, the dynamic range required for sensing the target response is reduced to the extent that target responses have speed differences. A B-field sensor produces the same signal for fast or slow fields while a dB/dt field sensor produces different amplitude signals for fast or slow fields. Second, the effective bandwidth of a B-field sensor is smaller than the effective bandwidth of a dB/dt sensor, thus reducing noise. Without getting into a dissertation, this is similar to the common knowledge that differentiation of a signal widens bandwidth and increases noise.

In a time-domain dB/dt system the basic difficulty in converting the received dB/dt signal into a B signal, is that the dB/dt transient received at the time the transmitter is turned off is **huge** compared to the signals of interest. Two things make it huge: first the primary field is much larger than signals of interest, and second the speed of the primary turn-off transient is much faster than most signals of interest. Since transient speed by itself induces a dynamic range requirement into the receiver, the combination of large dynamic range between primary and secondary plus large dynamic range caused by speed differences between primary and secondary, results in a huge dynamic range. The combination of this huge dynamic range and a required wide bandwidth, makes it impossible to implement this dynamic range as a **linear** dynamic range.

A primary-rejected system will reduce dynamic-range requirements and will allow implementation of a completely linear receiver. Producing a B-field signal from a dB/dt signal is a 'simple' matter of integrating the received signal (meaning a 'running sum'). This is already done in existing MetalMapper software as an optional plotting technique – but any integration produces an arbitrary constant. This constant is actually the area of the primary turn-off dB/dt transient. But for conventional systems this transient is clipped in order to implement the required dynamic range as a non-linear dynamic range. Therefore, the constant is unavailable and must be estimated by other means.

Use Well-Known Linear Digital Filtering Techniques

The breadth of this possibility is too wide to allow offering specific techniques here. A good example of this technique would be to design and implement a notch filter to reduce interference of power-line signals. Other techniques could be used to perform specific functions given ancillary requirements – such as emphasizing some facet of a target response that is well-defined. But digital filtering techniques are well-known and widely available. For example, Matlab offers digital-filtering toolboxes so digital filters can be designed without a thorough understanding of the underlying concepts.

Perhaps an important aspect of digital filtering for the problem studied herein is correlation of the primary signal with received (secondary) signals. As used here, *correlation* is equivalent to the more common term *matched filter*. In this idea, the bulk-magnetization signal could be measured using matched-filter techniques.

Make a Frequency Domain System Using Software

Once the system is reduced to a linear system, many *system-response* techniques become available. Since the transmitters in the MetalMapper, TEMTADS, and MPV are all controlled by software, frequency-domain techniques become available via reasonably simple software modifications. For example, a pseudo-random sequence could be used to drive the transmitter (instead of a standard time-domain signal) and a cross-correlated system frequency-response could be computed. Or a stepped, frequency ramp could be used and the received signal could be cross-correlated to produce a frequency response.

One facet of the MetalMapper/TEMTADS/MPV systems is that the transmitter is digital, i.e. that it is capable only of transmitting square waves, where *square* means on a time basis that is substantially slower than the rise/fall time of transmitter current. This limits some of the frequency domain possibilities – for example, we could not use a white noise driving function. Yet any digital function is available. And since the receiver is linear, compensating corrections can be made for the fact that the frequency response of the transmitter is not completely wide band. A good example is use of a pseudo-random sequence – the received response would be normalized by the pre-measured transmitter response, in the frequency domain, to produce the system response.

The bottom line is that we believe that a linear system will offer a frequency-domain-like capability to be implemented into the MetalMapper/TEMTADS/MPV systems in addition to the usual time-domain capabilities. Importantly, if the primary-rejection system is implemented, any of these possibilities could be available via software, with no change in hardware.