FINAL REPORT

ON

IMPROVED AEROMAGNETIC COMPENSATION

for

Ontario Mineral Exploration Technology Program
Project # P02-03-043

A New Aircraft Compensation System for Magnetic Terrains

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SUMMARY

Leliak's system of equations, first published over 30 years ago for served magnetometers, remains today the standard for aeromagnetic compensation using multiple strapdown sensors. This project examines the fundamentals of Leliak's system of equations to gain understanding into aeromagnetic compensation. Software was developed using Leliak's equations, and several different numerical solvers were tested. The data used consisted of data supplied by the Ontario Geological Survey, test data supplied by Pico Envirotec and data collected for the project. In conjunction with the above, different high pass filters, required to obtain good compensation coefficients, were tested in the compensation routines. Building on the EMIGMA simulation platform of PetRos EiKon, various multi-block models of aircraft were simulated using combinations of induced and permanent magnetic characteristics as well as conductive portions of the model. This synthetic data was also used in the testing of the compensation routines and has proven valuable in gaining insight into all aspects of the compensation process. Aeromagnetic compensation requires knowledge of the aircraft attitude, now typically measured with a three component vector fluxgate magnetometer. In areas where the Earth's magnetic field is not uniform, such as in magnetic terrains, the attitude measured in this fashion is erroneous. Three GPS sensors were installed onto an aircraft and GPS data was collected at 10 Hz, the same sampling rate as the fluxgate sensors. Test flights were conducted to gather data for compensation testing and to determine if aircraft orientations obtained by the GPS is accurate enough for compensation. The results of compensating one box using attitudes obtained by GPS and by the vector fluxgates show that with proper processing, the methods yield similarly good results. The GPS data has the added advantage of being free of the magnetic variations in the Earth.

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OMET PROGRAM

1.   SCOPE

The scope of this report covers the work performed as part of an Ontario Minerals Exploration Technology (OMET) Project P02-03-043, A New Aircraft Compensation System for Magnetic Terrains. The proponents of the project are Bob Lo, P.Eng., and Dr. Ross Groom of PetRos EiKon, with the lead researcher being Dr. John Jia of PetRos EiKon. The project officially commenced in August of 2003 and ended in February of 2004.

The rationale for studying aeromagnetic compensation is introduced by the proponents of this project who believe that Aeromagnetic compensation is now the limiting factor in obtaining significantly better aeromagnetic data. It is envisaged that better aeromagnetic data will allow for the interpretation of deep targets, will allow for more confident of aeromagnetic signature of small magnetic bodies in complex magnetic terrains. There are a number of reasons of why aeromagnetic compensation can be improved as a result of new technology. For example, alternate devices for measuring aircraft attitude are now available. Such issues are discussed further below.

The authors have found that the fundamentals of aeromagnetic compensation are not well understood by the general exploration community. Therefore, discussion is provided on the methodology of performing compensation flights and the system of equations that are used to solve for the coefficients to be used in compensation.

As the system of equations, first proposed by Leliak (1961) is fundamental to this research, it is examined in some detail by Dr. Jia and presented in an appendix in this report. The researchers at PetRos EiKon developed software to apply Leliak's system of equations and studied the use of a number of different numerical solvers to solve these equations. In addition, the filtering of the data, a required procedure, was examined. This work is covered in Sections 3.1 to 3.4.

In addition to the interference effects addressed by Leliak, there are noise from moving parts on the aircraft such as the rudder, EM effects from the aircraft flying through a large magnetic gradient, EM effects from the MT field, and varying EM signals from electronic components and electrical use. This project does not attempt to address all these factors.

The standard approach to solving the magnetic compensation system of equations is to fly at high altitude, a series of maneouvers while collecting data. These maneouvers provide data for the system of equations that are then solved to determine a set of coefficients that are utilized to remove aircraft effects during the actual survey. These coefficients are only estimates of the required coefficients as they are due to aircraft effects at high altitude. We had proposed to extend our research to include techniques for in-flight and post-flight improvement of the coefficients and to determine which coefficients can be improved with actual survey data. Due to time and budget restraints, this aspect of the research was not conducted.

To gain insight into the behaviour of Leliak's equation and of how the various components of Leliak's system of equations (i.e. terms for induced, remanent, and certain EM effects) behaved and interacted with each other, PetRos EiKon developed synthetic simulations of simple block representations of an aircraft, and used the simulated results to analyze the suitability of Leliak's equations, the accuracy of solutions and the application of filters. This work was not initially envisaged in the project, but has proven invaluable in helping the proponents understand aeromagnetic compensation. The authors are also not aware of any other groups who have published on this work.

As mentioned earlier, one of the processes in the compensation methodology is filter the data to enhance the signals from the high altitude maneouvers prior to calculating the compensation coefficients. The concept of reducing the geological noise leakage into the compensation flight via other methods, such as via its removal by direct calculation and subtraction was investigated. This was done using the data supplied as in-kind contribution by the Ontario Geological Survey. This is reported in section 3.6 and in an appendix to this report.

A large component of the OMET project was to conduct test flights into using three GPS sensors to measure aircraft attitude. Geodetic grade GPS's capable of 10 Hz sampling were rented and installed into Terraquest Ltd.'s Navajo survey aircraft. Section 3.7 describes the installation, and section 3.8 describes the test flights which were conducted and the rationale behind these flights.

The accuracy of the differentially processed GPS data proved to be a surprise in that it was significantly less than the manufacturer's stated specifications. Processing using Waypoint Consulting's GravMov software to obtain the relative heading information between two moving GPS receivers proved to yield acceptable results. The analysis of the GPS data to obtain aircraft attitude can be found in section 3.9.

To quickly assess the GPS data, fluxgate data were simulated using the orientations provided by the GPS's. These simulated fluxgate data were inputted into the existing compensation program to obtain compensation results. The results are as good as the results from fluxgate data. This successful result demonstrates that it is possible to use GPS or other orientation devices to measure aircraft orientation for aeromagnetic compensation. To the authors' knowledge, this is the first case of using GPS attitude to compensate for the magnetic effects of a survey aircraft. Section 3.10 describes the analysis and process used in obtaining this compensated result.

Finally, Section 4 of this report provides the details of how this project has benefited exploration in Ontario as it is the mandate of the OMET Programme to fund such projects. The authors believe that these results are definitely of benefit to exploration in Ontario and beyond. This is described in subsections on benefits to the proponents, to Ontario Airborne Surveying Companies. The technology transfer of this research is also summarized in this section.

This project would not be possible without the contributions and support, whether in funding, in-kind, or in cooperation and understanding by the subcontractors and supporters of this project. The authors are indebted to these individuals and organizations and they are acknowledged in the ACKNOWLEDGEMENTS Section.

1.1   Development Overview

We intended to develop a comprehensive solver for the system of equations under all situations and to investigate, in general, the suitability of different numerical solvers and the resulting mathematical and physical limitations of their implementation. These intentions would be studied as they related to particular aircraft magnetic noise and individual magnetic sensors. The research performed starts from the basic physical model and extends the system to be more general. In addition, the capability to simulate the aircraft effects was developed thus enabling the direct testing of the suitability of the equations and the resulting practical limitations of the physical model.

Magnetic compensation algorithms require the knowledge of the attitude of the aircraft, normally measured with a three-component fluxgate sensor. In fact, traditionally, the algorithms are not implemented such that the attitude is actually determined but rather the fluxgate data is simply used as a deterministic variable in the equations. It is appropriate to extend the compensation techniques to use "attitudes" derived from GPS measurements. At the present time, the absolute positioning of a location through GPS should be sufficiently accurate with a base station receiver and at least 2 frequencies being received from the satellite. However, in practice this was not possible and a different means had to be developed to utilize the multiple GPS measurements. The fluxgate data is also affected by the magnetic noise of the aircraft while the GPS is far less influenced by the electromagnetic noise of the aircraft. Thus, comparison of compensation by GPS and fluxgate attitude information is extremely insightful.

1.2   Software Components

1)   The System of Equations and Its Solution

1a)   The System of equations:

1a- i)   Study of the mathematical system,

A mathematical and physical analyses of the traditional Leliak system with an aim to extensions to provide more generality and thus better numerical solutions was attempted. Experimentation of hypothesized systems with synthetic data was undertaken with fruitful results. A thorough study of the terms in Leliak system was undertaken both from the view point of synthetic data and from the flight data.

1a -ii) Study the conditioning of the matrix system

A mathematical analyses of the mathematical systems for their conditioning characteristics. Conditioning is a mathematical term implying solvability and stability. This aspect is related to the filters applied to the data and the maneouvers performed during the box flights , the magnetic noise of the aircraft as well as individual sensor characteristics.

1a -iii) Study the solution techniques for the mathematical system

A study of the solution capability of more modern mathematical solvers for the hypothesized systems. Solution of the system, with the use of both synthetic and "real" data, was studied with 4 different techniques. These being the

standard SVD where the number of eigenvalues may be chosen, Ridge Regression, Conjugate Gradient and a Symmetric Matrix approach.

1a -iv)   Study the dependency on physical factors and attitude

An examination of the dependency of the solution on specific physical factors and specific attitude information. This was initially undertaken with synthetic data and then we undertook to recover the attitude of the aircraft from the fluxgates and GPS measurements and re-study these aspects.

1a-v)   Develop synthetic data

Simulation of aircraft effects and the utilization of the synthetic data to enable the analyses of sections 1a-1) through 1a-iii)..

We developed the ability to place several permanent and soft magnetic components on the plane as well as to have several types of so-called EM noise effects and then have the plane actually fly the maneouvers of a real flight box.

1a-vi)   Apply historical data

After the use of synthetic data for study, the detailed analyses of the previous aspects with historical data was undertaken including studying the conditioning of the mathematical systems for specific sections of the historical boxes.

1b)   Software Implementation:

1b-i)   For 3-axis fluxgate sensors

Implement the mathematical techniques for fluxgate attitude information for processing.

1b-ii)   For 3 GPS receivers

Implement the mathematical techniques for GPS attitude information for processing.

1b-iii)   Software Architecture

Suitable software architecture to allow flexible application of filters, solution for coefficients with high altitude data was developed.

1c)   Testing with High Altitude Boxes

Testing of the resulting software with new high altitude flight patterns designed to augment the mathematical system and to investigate specific issues arising from the previous studies.

2)   In-Flight Feedback Filters for Coefficient Improvement

2a)   Research of Appropriate Techniques

Study various techniques for in-flight improvement of the high altitude coefficients.

2b)   Software Implementation

2b-i)   For 3-axis Fluxgate sensors

Implement the most promising techniques for in flight improvements for fluxgate sensors.

2b-ii) For 3 GPS sensors

Implement the most promising techniques for in flight improvements for GPS sensors.

2b-iii) Software Architechture

Development of appropriate overall software application to implement the improvement filters.

2c)   Testing with Survey Lines

Testing of in-flight improvements with short low altitude survey lines over test sites.

3)   Post-Flight Improvements and Corrections

A second round of corrections determined from the test results.

1.3   Survey Components

1)   Identify survey suitable survey aircraft (Terraquest or Brucelandair),

1i)   negotiate a suitable contract with the airborne contractor,

1ii)   If suitable geophysical and ancilliary equipment is not installed, then obtain suitable geophysical and ancilliary equipment either from other survey contractors or from equipment rental companies (i.e. Scintrex Ltd.),

1iii)   Identify suitable GPS equipment (Devtec or Haltech or GPS manufacturers),

1iv)   Identify ancilliary equipment as required, i.e. laptop logging computers, base station magnetometers, etc.

2)   Installation of GPS antennae on aircraft

2i)   Identify suitable locations for GPS antennae, using when possible, pre-existing mounting plates, mounting brackets, magnetometer wingtip pods or tail stingers,

2ii)   design and manufacture mounting brackets for installation (only wingtip backet and minor modifications to the tail stinger was eventually required)

2iii)   open up wingtip fuselage inspection panels, run low loss coax cabling from data acquisition unit to antennae on wingtip and on top of fuselage,

2iv)   remove tail stinger from aircraft and run low loss coax cabling from halfway along stinger to data acquisition unit,

3)   Installation of GPS receivers and laptop data loggers,

3i)   devise method of mounting GPS receivers and laptops on available working surface (they were velcro'ed on),

3ii)   modify power supplies and distribution to yield sufficient power and distribution outlets to supply power to GPS receivers and antennae and laptops,

4)   Ground and airborne testing

4i)   check to see that magnetometers are not unduely affected by the GPS sensors,

4ii)   ground test to determine GPS antennae can see enough satellites,properly,

4iii)   verification that GPS receivers are outputting data to laptops and that laptops are logging,

4iv)   check that GPS positions change when aircraft is moved,

4v)   check that all instruments still work when airborne, and that equipment is secure.

5)   Field Testing

5i)   Identify suitable survey area

5ii)   obtain public domain aeromagnetic datasets over it,

5iii)   design tests to determine background and heading effects,

5iv)   design tests to obtain compensation boxes,

5v)   design tests to demonstrate the utility of GPS compensation (i.e. over magnetic features),

5vi)   programming the above into the navigation system,

5vii)   obtaining replacement parts or fixing any equipment problems as required,

5viii)   obtaining and coordinating GPS and magnetometer base stations,

5ix)   ensuring that the proper aircrew is in place for the tests and that the pilot is aware of rationale behind the non-standard tests,

5x)   conduct test flights while monitor survey progress and costs,

6)   De – Installation

6i)   Remove as much of the wiring as Terraquest wishes,

6ii)   Remove GPS antennae and brackets, and seal up any new holes,

6iii)   Remove GPS receivers, laptop computers, etc.

7)   GPS Processing

7i)   try base station differential processing

7ii)   do relative heading process with GravMov

7iii)   develop enhanced relative position processing suitable compensation with GPS

2.   INTRODUCTION

2.1   Rational for Studying Aeromagnetic compensation

The objective of this project are easy to state: "To reduce the noise to signal levels for an aeromagnetic survey by a factor of 10!" This would simply be a platitude if its relevance were not so important to exploration in Ontario. The increase in the signal-to-noise ratio will provide greater confidence in the interpretation of aeromagnetic data in those tough or complex geological situations where the highest sensitivity data is required. Where are these tough or complex situations?

1) Exploration underneath the Paleozoic cover: Better aeromagnetic data will provide for better detection of magnetic targets under the Paleozoic cover. In this situation, the geological response of the Archean basement originates 100's of metres beneath an almost magnetically transparent Paleozoic cover. This large separation between the aircraft and the crystalline basement results in a significantly reduced magnetic signature. Thus, the confidence level of the geological interpretation of the aeromagnetic data is simply and directly related, to a signal to noise issue.

2) Exploration in magnetic environments: The more difficult issue is the detection of subtle features in a magnetically complex environment. For example, it is well known that there is a good correlation between the abundance of gold and the abundance of iron. This iron is often in the form of very magnetic iron formations. The response from the iron formation is so strong, that it violates one of the assumptions of aeromagnetic compensation, which leads to higher noise levels near iron formations. And the magnetic signature of gold deposits may be very subtle, for example, caused by magnetic destruction in the alteration zone surrounding the deposit. Quite subtle changes in the magnetic environment of the iron formation may be important. In Western Ontario where there is an abundance of iron formations, this implies that for gold exploration the aeromagnetic data quality is adversely affected by the iron formations. Thus, for gold exploration, quite subtle changes in the magnetic environment of the iron formation may be important. This example is a case for a different and improved method of compensation, and thus for the requirement for low noise levels even within very magnetic environments.

As an example, a quick review of the OGS data as part of their in-kind contribution to this project has confirmed the hypothesis that the compensation is affected by a strong magnetic signature. Figure 1 and Figure2 show the raw magnetometer data and the compensation that was applied to the data. The compensation for the most part has no correlation with the raw TMI as expected. But in the vicinity of an BIF, the compensation terms dramatically changes, perhaps showing that the magnetic effects of the BIF is causing a spurious orientation calculation in the fluxgate orientation device. Additionally, the two adjacent lines were flown in opposite directions. Note how much

different the compensation is for the different directions. Admittedly, these are obvious examples, but it is a demonstration that there will be occasions when the assumptions of compensation fail.
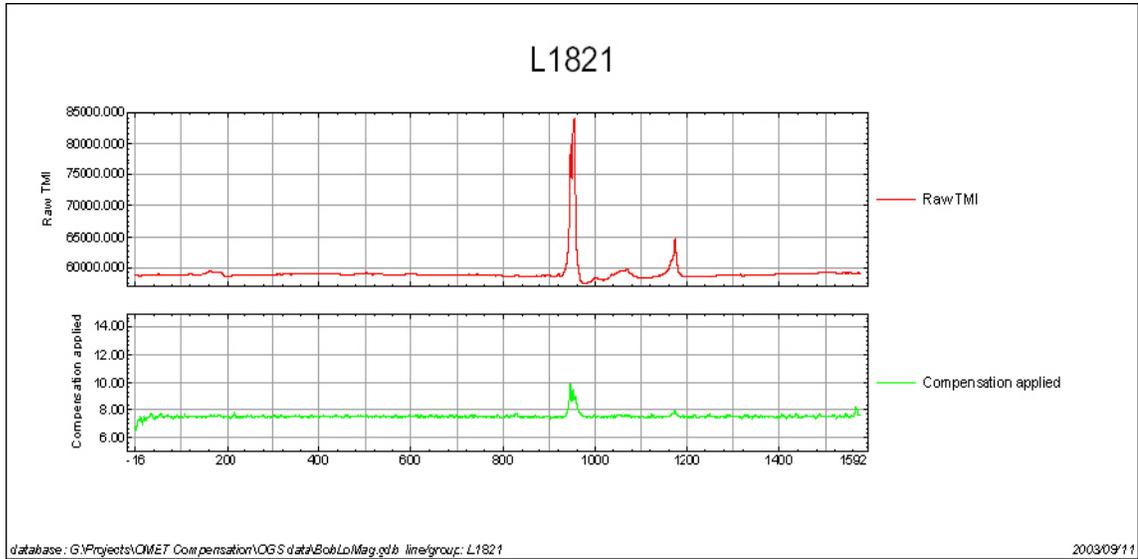
Figure 1: Plots of Raw TMI and the compensation applied to the data over a very magnetic source. Fight direction is approximately south to north.
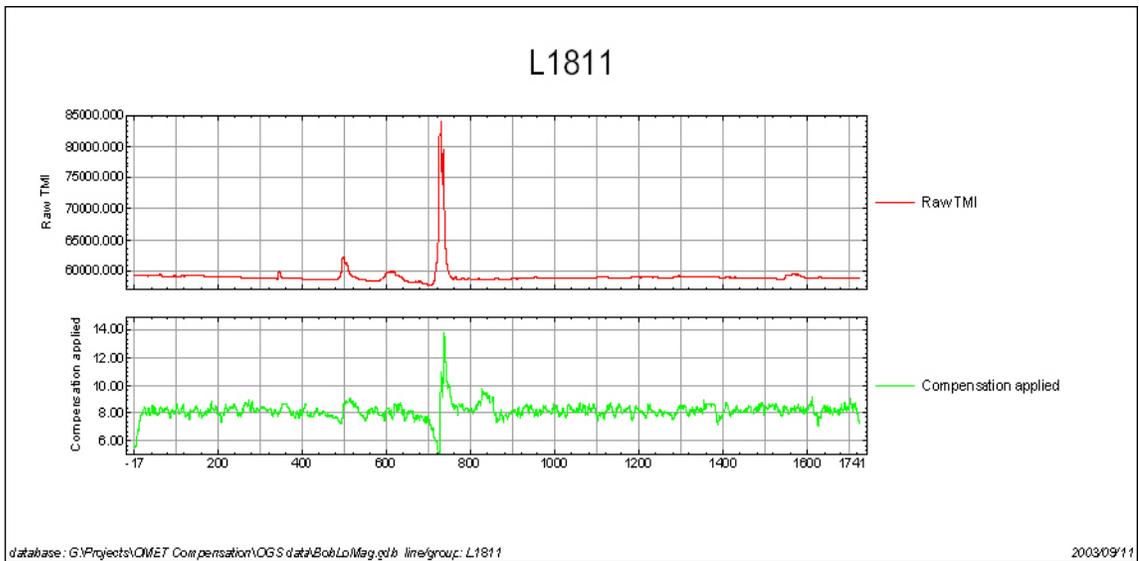
Figure 2: Plots of Raw TMI and the compensation applied to the data over the same very magnetic source as L1821. Fight direction is approximately north to south.

3) Exploration for kimberlites in the presence of dyke swarms:

This case is similar to Case 2, above. Dyke swarms are prevalent in Ontario. Many kimberlite pipes are found in the midst of dyke swarms or adjacent to dykes. Dykes, like iron formations, produce a strong magnetic response that leads to higher aeromagnetic noise levels near the dyke. Kimberlite pipes can be magnetic to non-magnetic and

given their small size, a weakly magnetic pipe may easily be missed near a dyke due to the higher magnetic noise. Once again, having better aeromagnetic signal-to-noise ratios will help in this exploration scenario.

In summary and in our opinion, one of the major drawbacks associated with modern aeromagnetic surveys is the use of a magnetic device to measure parameters to correct for magnetic readings - namely the fluxgate magnetometers. This is a critical circular argument. But what does this imply? Simply that there will be situations where the assumptions of aeromagnetic data correction are not correct and these situations will lead to erroneous "final processed" TMI and gradient products. Examples of these situations are near the presence of iron formations and near dyke swarms as described above.

Of course, it is relatively easy to describe some obvious situations where modern compensation will lead to interpretation problems but there may be many, many other situations, which are buried underneath our data limitations. With the advent of a new generation of magnetometers and data acquisition systems, surely a re-examination is required of the first stage in data processing and that stage is "the magnetic compensation processing techniques".

2.2   Why examine aeromagnetic compensation?

Aeromagnetic data has been fundamental for mineral exploration in Ontario for decades. Over the last two decades, there have been dramatic advances in many aspects of this geophysical technique as well as the geological interpretation of this data. There have been radical developments in two primary aspects of the technique: hardware or data acquisition and software or interpretation capabilities. From a hardware perspective, there have been significant improvements in the basic sensors and the data acquisition hardware. New sensor and data acquisition developments provide not only significantly increased sensitivity as well as higher sampling rates but also improved data positioning and time synchronizing. From the software perspective, we have not only seen dramatic strides in data processing, gridding and display but also significant breakthroughs in structural imaging through inversion and depth estimation techniques.

However, there is a least one weak link in the entire process, magnetic compensation, which is now a limiting factor in data improvement. Consequently, advances in hardware and software have reduced significance due to this limitation. For example, the residual noise from the aircraft movement after compensation is still 100's of times larger than the noise capabilities of a modern cesium sensor. Although, the aeromagnetic data acquisition capabilities are much improved, they are also able to better detect the magnetic effects of the aircraft. If the correction or compensation of the aircraft is of limited accuracy then the interpretation of the data cannot go beyond this limitation. Users who require highly accurate data for interpretation of subtle features can utilize acquisition systems capable of the required sensitivity and software capable of utilizing the required sensitivity but the final data is flawed by relatively high noise from the aircraft movement effects. In addition, there are noise problems from moving parts on the aircraft such as the rudder and varying EM signals from electronic components and electrical use. This project does not attempt to address these factors.

30 years ago, the primary cause of noise from aircraft movement was due to relatively large, non-linear responses caused by the changing alignment of the magnetic sensor

with the total magnetic field. This was improved significantly with the development of so-called "servo" techniques. With this instrumentation, the sensor was constantly oriented to align with the direction of the Earth's magnetic field. Later, this was no longer required as multi-cell sensors were developed, and as the operational zone of the magnetic sensors became wider and more linear. Apart from this aspect, the fundamentals of magnetic compensation have not changed for over 20 years. These fundamentals are based on a physical model postulated in 1961 by Paul Leliak (1) that was commercially implemented until some 20 years ago. Leliak did his research for the US Navy for submarine detection and for some years his work was classified. It is almost for certain that his publication only revealed a small part of his work. Presently, the world's military are researching aeromagnetic compensation but much of their work is unavailable to the exploration industry.

The basis of Leliak's physical model is expressed in a relatively simple set of equations which are obviously too simply for the true effects of the aircraft. Secondly, the normal approaches taken to solve these systems of equations are taken from that era and and from the early speed limitations of microprocessors. With the advances both in processing power and in operating systems, there are now no real barriers to using the most advanced techniques for solving this set of equations and extending his equations to be more complete.

We proposed to begin our research from the basic physical model and extend the system to be more general. In addition, as we wished to develop the capability to simulate the aircraft effects, we proposed to directly test the suitability of our equations and the resulting practical limitations of using our physical model. We explored the solution technique for the equations and, in general, experimented with the suitability of a variety of solvers and the resulting mathematical and physical limitations of their implementation.

Magnetic compensations algorithms require knowledge of the attitude of the aircraft, now measured with a three component fluxgate sensor. It is appropriate to extend the compensation techniques to use attitudes derived from GPS measurements. At the present time, the absolute positioning of a location through GPS may not be sufficiently accurate without a base station receiver and at least 2 frequencies. However, it may be possible to determine the relative locations of the sensors sufficiently accurately to perform the attitude estimates. This research direction is useful for a variety of reasons. First of all, it will improve the compensation when there are strong effects on the fluxgate sensors from magnetic rocks but also when smaller more subtle features are the object of the surveys. In not so strong magnetic terrains, it would allow to compensate by two techniques and allow comparison of the two methods. This comparison will provide invaluable information towards developing better physical and mathematical models for the aircraft effects. Thirdly, for gradient data collection, GPS-based compensation will in principle allow for accurate determination of magnetic gradients. Fourthly, it is quite probable that GPS development will out-pace fluxgate development (or other vector sensors) and thus it seems prudent to at least begin development of compensation based on GPS measurements. Finally, the compensation of vector magnetic data is, of course, desireable, as the vector data may be even more useful than gradient data. Compensation of vector data with vector data may be somewhat circular even if compensating squid data with fluxgate data and compensation with GPS attitude determination may be more suitable and cheaper than attitude determination from inertial guidance systems.

Finally, even when the effects of aircraft movement are accurately estimated at high altitude and these effects are correctly removed, these estimates will only address the first term in the sources of these effects. When the aircraft flies at lower altitudes for surveying, it may then be moving through a geomagnetic field of significant gradient and these effects will not have been estimated from the higher altitude box path flights. Eventually, it will be necessary to determine the second order effects on the sensors due to aircraft movement in the gradient fields. Attempts have been made to do this by using correlation techniques that attempt to investigate the correlation between response and movement and remove well correlated changes in the measured magnetic field with aircraft movement. This aspect of improvements was intended to be investigated.

2.3   Leliak's system of equations

Leliak developed a set of linear equations to represent the magnetic and electromagnetic effects of an magnetic and conductive aircraft flying through the Earth's field. At the time when Leliak developed these equations, the magnetic sensors were oriented sensors. Servo motors maintained the magnetic sensor's orientation relative to the Earth's magnetic field. This is an assumption built into Leliak's formulation of the magnetic compensation problem.

Leliak proposed an 18 term compensation model derived from, permanent, induced, and EM or eddy current effects. A set of directional cosines can be defined such that the aircraft attitude relative to the Earth's magnetic field vector can be described. Leliak demonstrates that the interference effects can be defined as a function of the directional cosines, the Earth's field, and the time derivatives of the directional cosines.

Due to two trigonometric identities, and with certain assumptions the 18 terms can be reduced to 16 terms if the directional cosines are exact.

Dr. John Jia has summarized the system of equations developed by Leliak and how to apply them numerically in an internal memorandum. Rather than essentially reproducing that report with the mathematical formulations, it is included in Appendix A.

Leliak's equations are the basis for the compensation routines that are commercially available. Therefore, it was decided to re-code the numerical algorithms to allow for the study of compensation theory and its applications.

2.4   Compensation or FOM flights

The standard approach to solving Leliak's system of equations is to fly a high altitude series of maneouvers while collecting data. These are sometimes called FOM flights. The authors are aware of three common variants of the FOM flights. The simplest and typical set of aircraft maneouvers are +/- 5 degree pitches, +/- 10 degree rolls and +/- 5 degree yaws, on four different tracks at 90 degrees to each other and parallel to the survey and tie lines directions. This is the type commonly flown by users of RMS Instruments' compensator. The second variant has the addition of two additional tracks per box side at +/- 10 degrees from the main headings producing a 12 sided figure. Users of Picodas, Pico Envirotec, and Fugro's proprietary FAS DAS Compensator

commonly fly this box. Our experiments, and testing by PetRos EiKon prior to this project has shown that the 12 sided "box" is not necessary to produce a valid set of compensation coefficients. The reasons why the extra two legs per side was added are not known to the authors. The last variant was introduced to the authors by Bradley Nelson of the NRC. It is essentially the first box, but with the diagonals flown as well to check the solutions. This is the box style flown in this project and we have termed the style – a "Nelson Compensation Box". The purpose of the Nelson Box may well be the same as the purpose of the 12-sided box. The compensation coefficients are highly dependent on the heading of the aircraft. In earlier years, this may have been interpreted as heading issues with the Cesium sensors. Although, this was certainly part of the problem in the past, today the sensors are less and less sensitive to heading. However, what still remains is that the nature of the Leliak mathematical model for compensation still delivers coefficients highly dependent on heading and this is expected from physical fundamentals.

All three variants of the box flights yield good directional information for the horizontal attitude related coefficients, but lacks some of the vertical orientation information. This is one of the reasons for the ill conditioning of the matrix used in solving the 18 equations. There are rules of thumb for where these FOM flights are to be undertaken. They have to be reasonably close to the survey area so that the Earth's field direction and the magnetic intensity are more or less the same in both the FOM flight area and in the survey area. The flights are typically flown at 10,000 feet above the ground as this is roughly the altitude limit of unpressurized aircraft used for geophysical surveying. The FOM flights are flown high to remove the magnetic response of the ground from getting into the maneuver data. These maneouvers provide data for the system of equations that are then solved to determine a set of coefficients that are utilized to remove aircraft effects during the actual survey. These coefficients are only estimates of the required coefficients as they are due to aircraft effects at high altitude and calculated for a somewhat arbitrary set of aircraft maneuvers over a relatively short period of time.

Some of the approaches that could improve the removal of the aircraft effects on the data include the overall mathematical technique used to solve for the compensation coefficients, more appropriate high pass filtering to correlate the data to the box maneouvers to better condition the matrix system, extension to additional terms to remove heading and gradient effects. The calculation of coefficients of aircraft attitude from non-magnetic sensors as the latter sensors are also susceptible to aircraft magnetic noise and geological gradients.

3. THE PROJECT

The project differs slightly from the proposed project due to a) information gained during the project which shifted research emphasis, b) to instrument problems which caused the loss of GPS data from one sensor during the second flight trials, and c) to the complexity of the problems in compensation that were not apparent before the start of the project.

Below is a Summary of Reseach Activities:

i)   Software coding of various versions of Leliak's equations

ii)   Development of different mathematical solvers for the system

iii)   Experimentation with highpass filters

iv)   Development of algorithms and techniques to simulate aircraft magnetic noise

v)   Testing of systems, solvers and filters on synthetic and actual aircraft flight boxes

vi)   Experimentation to remove low order geological noise

vii)   Research folklore and attempt to explain theoretically

viii)   Experimented with Nelson boxes – Why diagonals?

ix)   Experimented with Random maneuvers – Why?

x)   Experimented with different amplitude maneuvers – synthetic and real

xi)   Installed three additional GPS's on survey aircraft

xii)   Test flying of those GPS's

xiii)   Analysis of the GPS data

xiv)   Using GPS to calculate aircraft orientation

xv)   As a test or demonstration, used the aircraft orientation from GPS to calculate synthetic fluxgates as input to the compensation routines

xvi)   Obtained compensated results from GPS

3.1   Literature search and research

The literature search began with some fairly recent publications on the subject of aeromagnetic gradiometry compensation papers by Doug Hardwick (Hardwick, 1984 and Hardwick, undated) who began with an introduction into aeromagnetic compensation. In Hardwick's papers was the reference to the original published paper on aeromagnetic compensation by Leliak(1961). Leliak's original paper was obtained through the NRC iner-library search and a valuable internal publications by B. Leach (Leach, 1979a and 1979b) and a paper by B.Nelson (Nelson, 2000) were also

obtained through library searches. In addition, a paper by Slack *et. al.* (1967) was very useful

Our continued literature search keyed in on two researchers at the National Research Laboratories (Dr. Barry Leach and Brad Nelson) who had, or are working on aeromagnetic compensation for military purposes. Contact was made with these individuals and a meeting setup on September 25 in Ottawa to exchange ideas on aeromagnetic compensation. They were quite helpful, but often ran into confidentiality issues when trying to answer our questions. Out of this meeting we had obtained several more insights into the compensation issues. These are, the approximation of the direction of the anomalous field's impact on the equations, flying the compensation boxes in a different manner, testing the amount of geological signal leakage into the compensation data prior to coefficient calculation, introducing slight maneouvers along the survey line to help in adaptively changing the solutions and the use of a newly developed commercial product of an integrated Inertial Measurement Unit and a GPS which yields attitude information suitable for input into the compensation algorithms.

Dr. John Jia has maintained contact with Dr. Leach with e-mail discussions on aeromagnetic compensation issues during the duration of the project.

3.2   Software coding of Leliak's system of equations

Dr. Jia's memorandum on the mathematics of calculating the coefficients was the start for the re-coding of the Leliak based compensation software. To avoid the overhead and burden of coding up an Graphical interface and database access functions, the compensation code was embedded into PetRos EiKon's EMIGMA software.

Both the 16 term and 18 term compensation routines were implemented. The 16 term compensation routine is slightly easier to use. The 16 term compensation assumes an orthogonality in the fluxgate measurements which appears to be reasonable for the instruments now being used. Errors in the non-orthogonality of the fluxgates are probably below the noise level of the data thus the 18-term and 16-term solutions are essentially equivalent for all the data utilized in this project.

3.3   Addition of different solvers

As mentioned above, the system of equations is large and can be ill-conditioned. It was decided that different solvers would be implemented to determine if using different solvers would yield better results for given situations. Four different solvers, each with user controllable parameters were implemented. These were the SVD, Ridge Regression, Symmetric Inverse, and Conjugate Gradient solvers. The solvers and the parameters were tested using compensation boxes taken from Terraquest's compensation flights, flown for the OGS or supplied by Pico Envirotec.

Based on many testing results, the following points were noticed:

i) The safest possible accurate linear equation system solver for a non-specialist is a truncated singular value decomposition (TSVD) with only the first 10 eigenvalues utilized (the dimension of the matrix is of 16 by 16). More eigenvalues can provide more accurate compensation but requires careful use.

ii) Ridge regression with all 16 terms is always a safe solution but always produces a less accurate solution than the best eigenvalue solution.

iii) Conjugate Gradient generates the same results as standard 16-term SVD, even though the initial guess of solution is set to an independent unit vector individually.

iv) Other solvers, such as generalized inverse matrix, inverse real symmetric definite matrix by eigenvector solution generates the same results as a standard SVD.

v) The most efficient and promising method to improve the magnetic compensation coefficients computation is probably ridge regression but requires proper application of the correct ridge matrix.

vi) Numerical C++ SVD generates the same results as does the Fortran IMSL SVD indicating that strict numerical accuracy is not a dominating factor. Many other aspects of our work also confirmed this issue.

Figure 3 below shows the track of a twelve sided compensation box flown with a modern data acquisition system utilizing an up-to-date Cesium sensor. There are 4 lines with approximate NS, SN ,EW, WE headings.
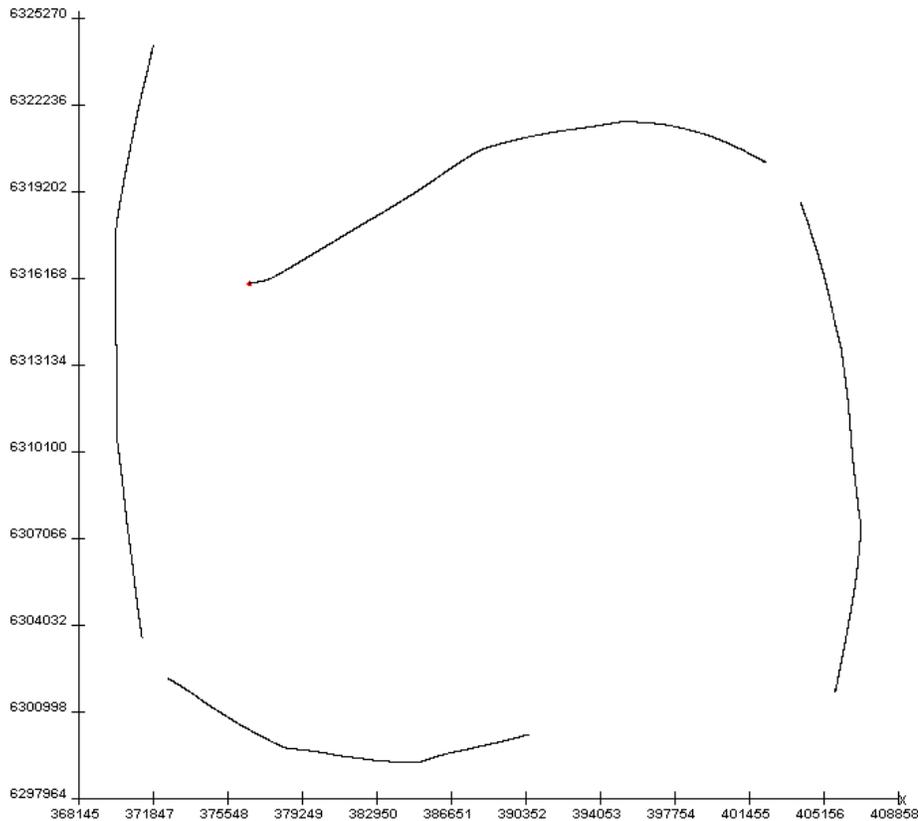
Figure 3: Plan view of the flight path of the compensation box used in the following solver testing

Figure 4 shows the flight path of the test line which is used for testing of the different solvers. The compensation coefficients used for the testing were obtained from the box shown in Figure 3. Note that the X and Y scales in Figure 4 are not the same. The flight direction is nominally north to south.
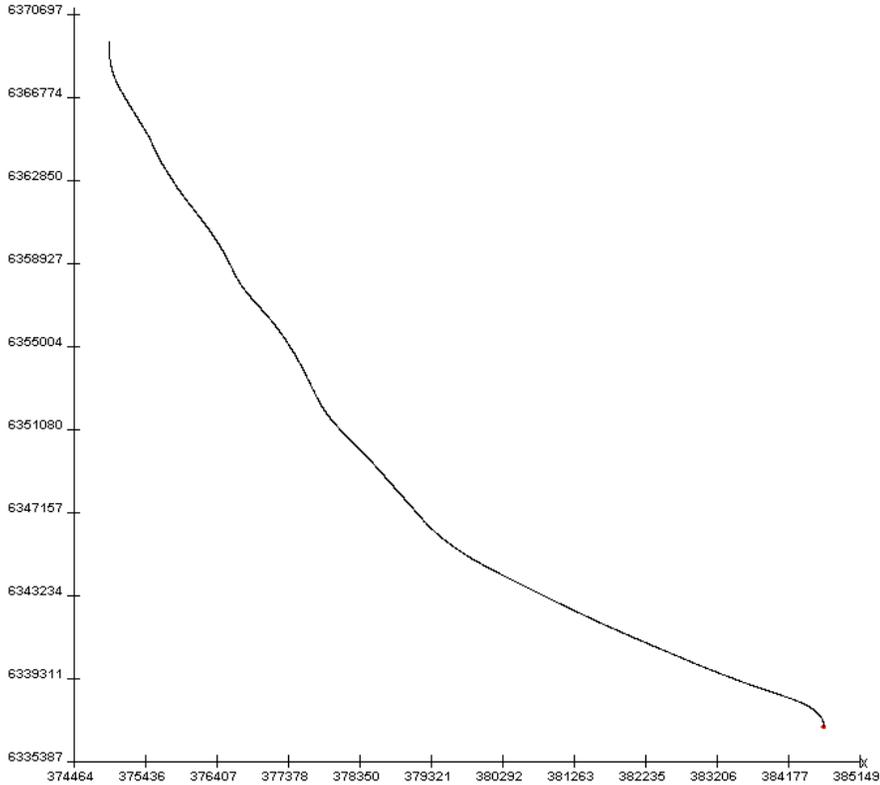
Figure 4: Survey data profile to be compensated for

The eigenvalues of the 16 by 16 symmetric positive definite coefficient matrix are listed in table 1:

Number	eigenvalue
1	46.041340
2	2.730461
3	1.407049
4	0.650389
5	0.023333
6	0.021161
7	0.012276
8	0.010162

9	0.003641
10	0.000540
11	0.000141
12	0.000091
13	0.000076
14	0.000037
15	0.000007
16	0.000002

Table 1: Eigenvalues obtained from solving the box in Figure 3

It should be noted that the eigenvalues decrease very rapidly in magnitude with the 9th eigenvalue 4 orders of magnitude smaller than the first eigenvalue.

The compensated and uncompensated results are shown in Figure 5.
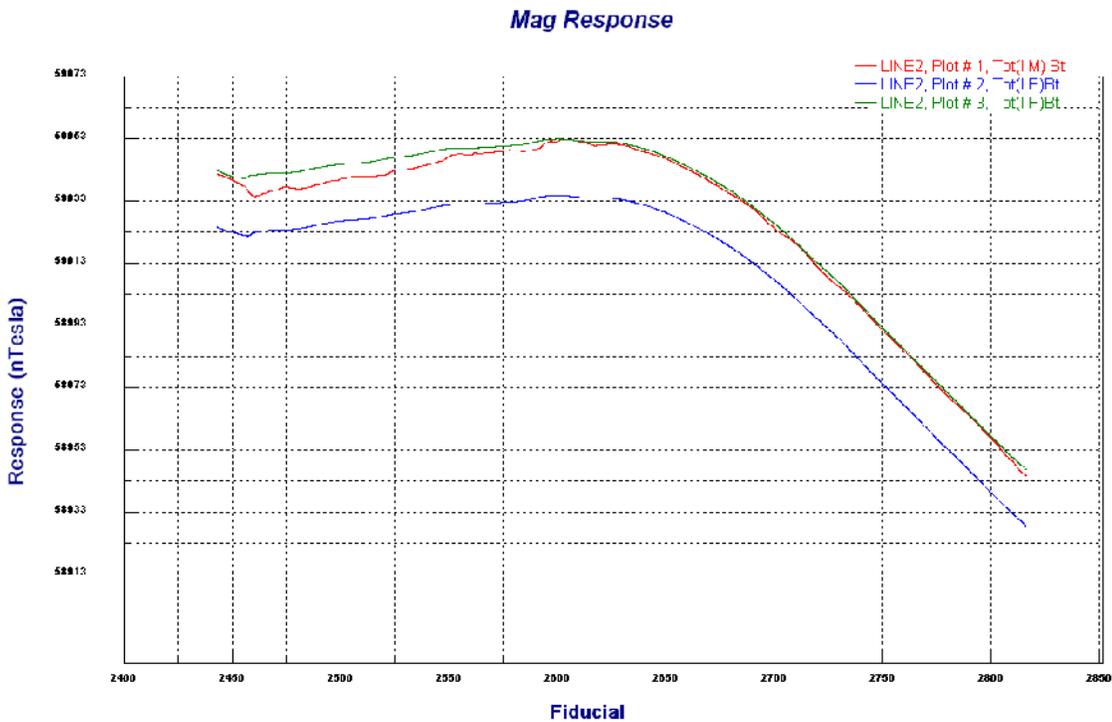
Figure 5: Compensated and Uncompensated Data: Red- original uncompensated data, Blue – Compensated data with no truncation (i.e. 16 eigenvalues); Green- Truncation, first 10 eigenvalues/eigenvectors utilized.

The reader will note that the utilization of the 6 smallest eigenvalues produces a very large DC shift between the compensated and uncompensated data. In fact, this shift is

not between compensated and uncompensated as one of the large eigenvalues removes a gradient and the shift is from this solution.

In Figure 6, we demonstrate the relationship between the solution technique and the DC shift. Here, we compare SVD with 10 eigenvalues to ridge regression with a ridge amplitude larger than the 9th eigenvalue. Application of a ridge (diagonal covariance matrix) essentially cuts out certain eigenvalues from the solution.
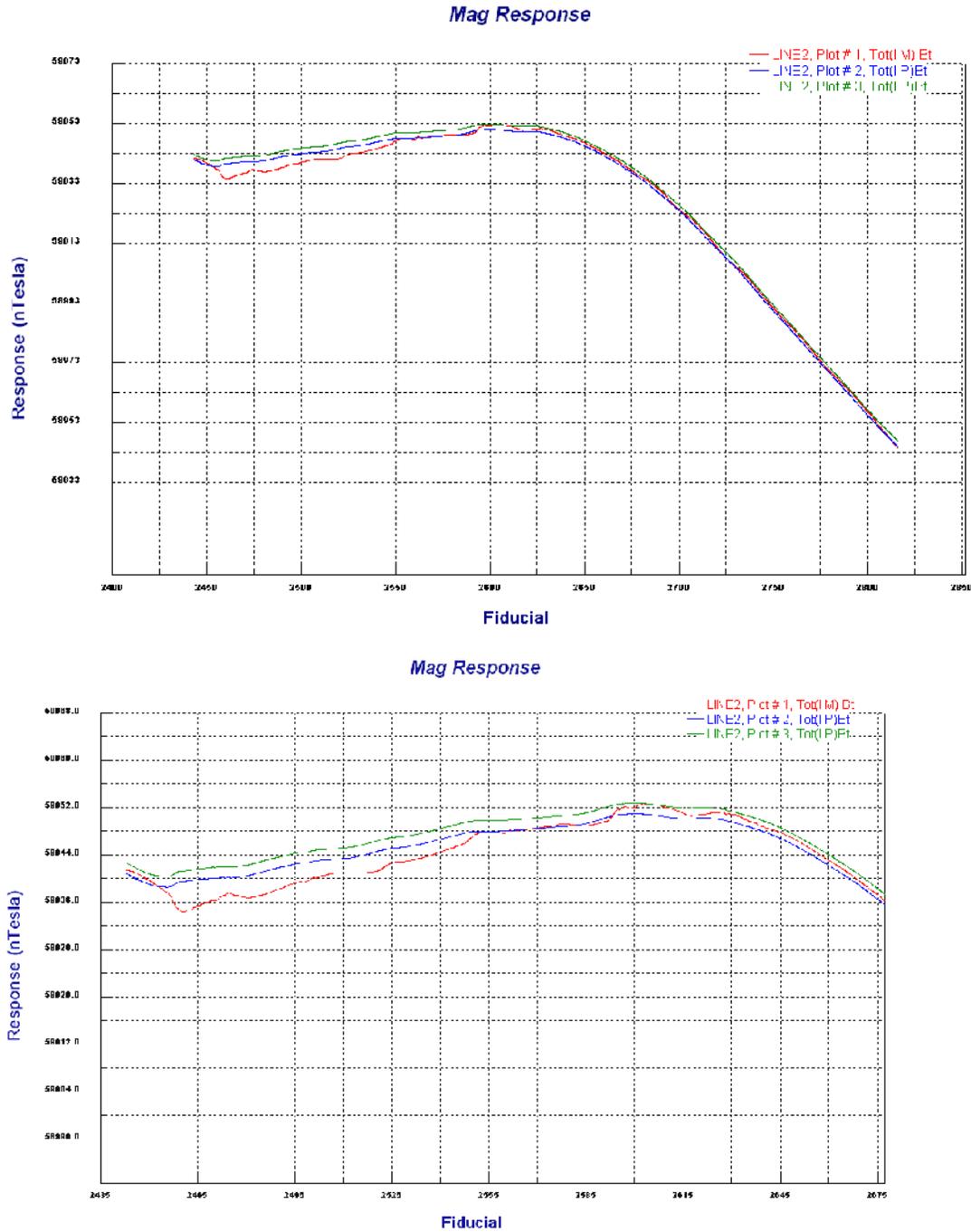
Figure 6: DC shift as a function of solution technique.Top: whole profile, Bottom: enlarged portion, Red- original measured, Blue-ridge regression with k = 0.006, Green- current version, truncation, first ten eigenvalues are kept (NO -solvers VS. shift)

In Figure 7, we compare ridge regression solutions with different ridge amplitudes.
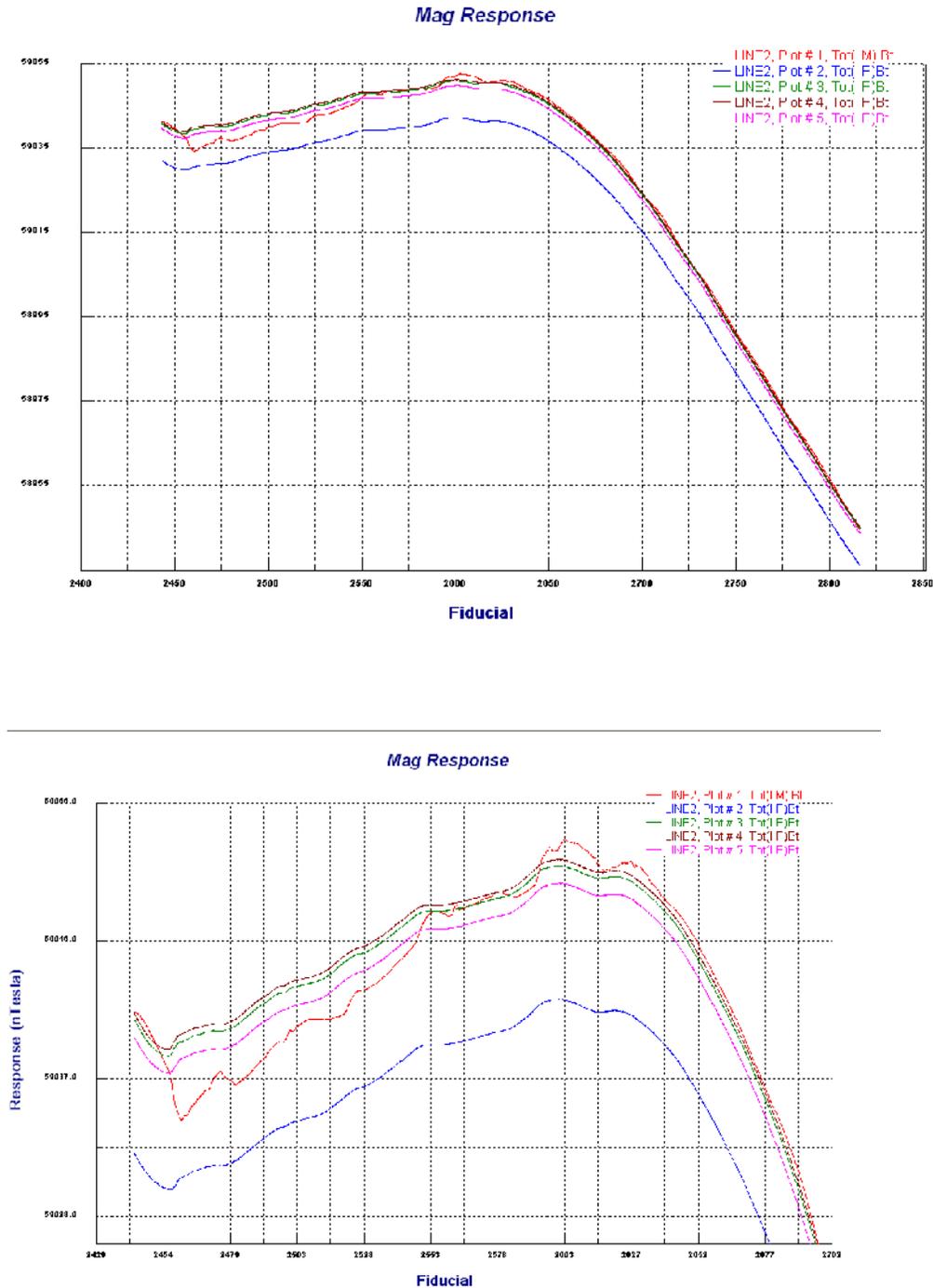
Figure 7: Comparison of ridge regression solutions. Top curves: whole profile, Bottom curves: enlarged portion. Red- original measured, Blue-ridge regression with k = 0.00006, Green- ridge regression with k = 0.0006, Brown- ridge regression with k = 0.006, Pink- ridge regression with k = 0.06

Note in Figure 7, that the largest ridge (pink) removes a gradient in the data and the other ridge solutions have DC shifts in amplitude from this solution.

Figure 8 compares SVD solutions with 14,15 and 16 eigenvalues.

Figure 8: SVD Comparisons: Red- original uncompensated, Blue-SVD with all 16 eigenvalues kept, Green- SVD with first 15 eigenvalues kept, Brown- SVD with first 14 eigenvalues kept
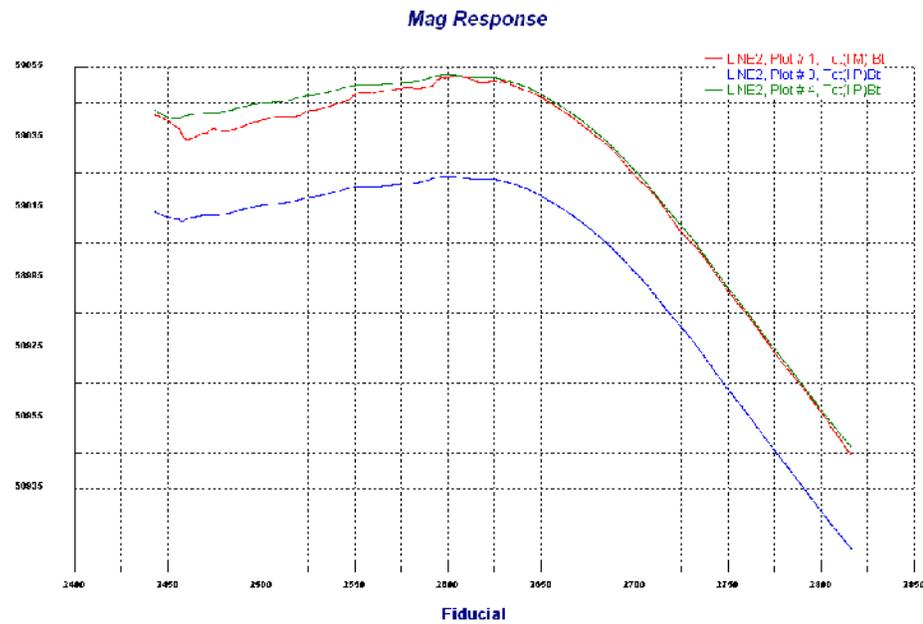
Figure 9: SVD Comparisons with sharp DC shift: Red- original uncompensated Blue-SVD with first 14 eigenvalues kept, Green- SVD with first 13 eigenvalues kept

Figure 9 indicates that by adding the 14 eigenvalue a large DC shift is included but increasing to 15 or 16 eigenvalues only adds small additional shifts.
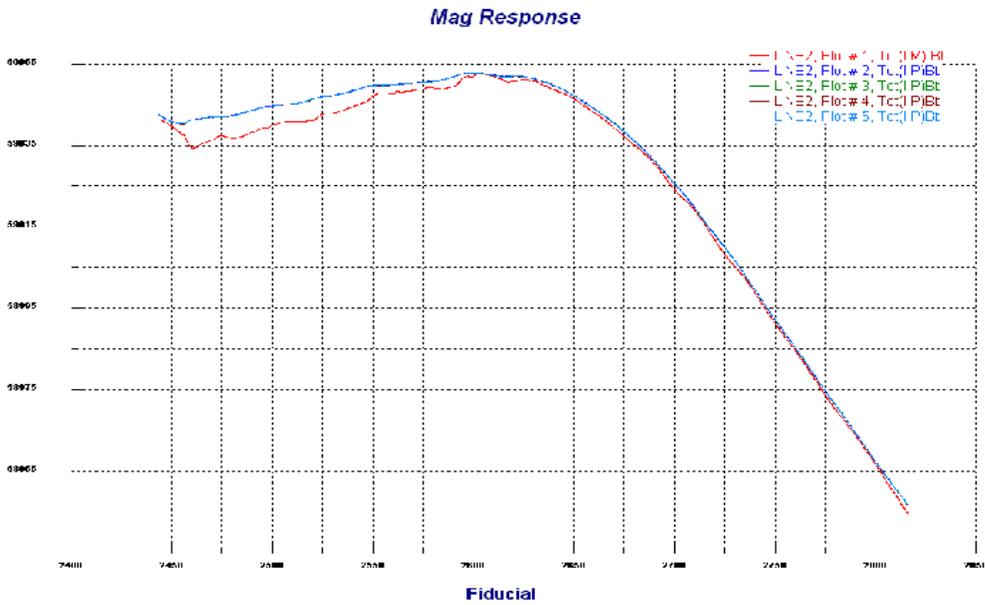
Figure 10: Red- original uncompensated, Solutions generated with first 9, 10 11, 12 eigenvalues overlay.
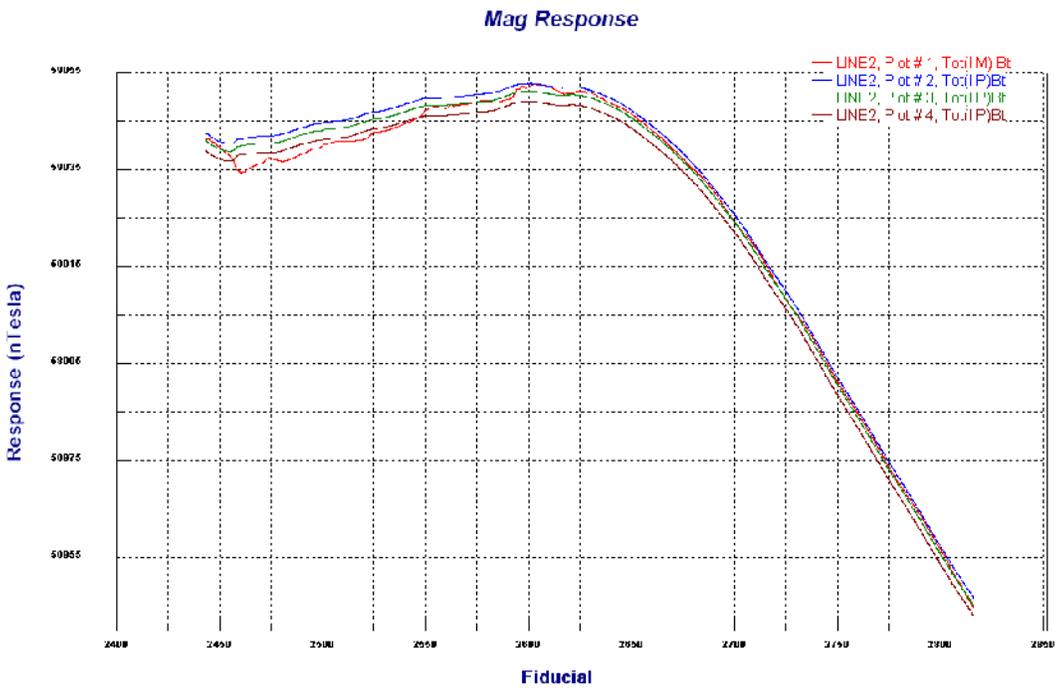
Figure 11: Red- original uncompensated. Blue-SVD with first 8 eigenvalues kept, Green- SVD with first 7 eigenvalues kept, Brown- SVD with first 6 eigenvalues kept
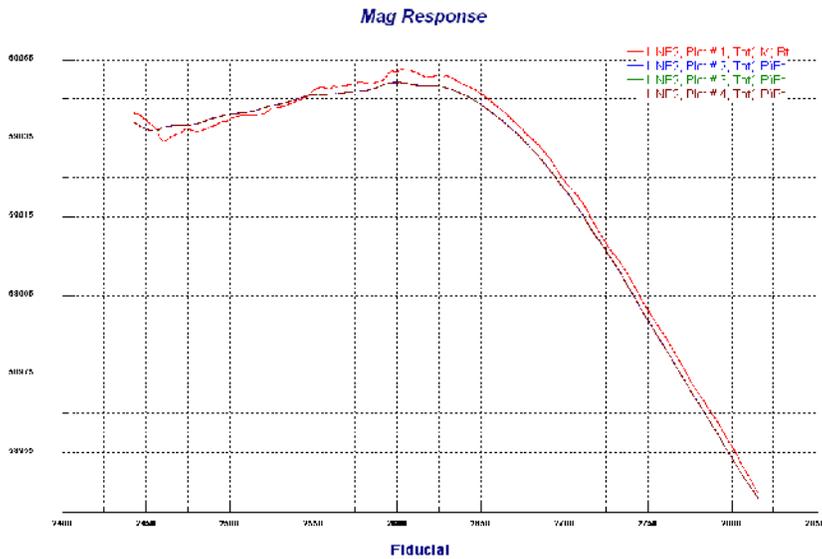
Figure 12: Red- original uncompensated: Coincidental are those generated with first 3, 4, 5 eigenvalues (blue,green,purple).
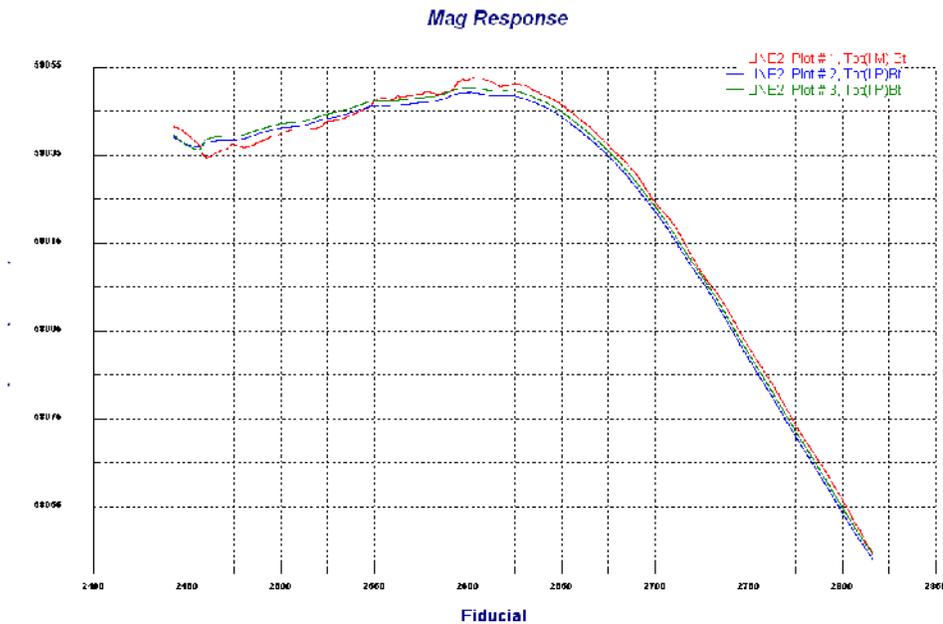
Figure 13: Red- original uncompensated, Blue-SVD with first 3 eigenvalues kept, Green- SVD with first 2 eigenvalues kept.

Again note that in Figure 12, by the 3rd eigenvalue a gradient has been removed and the other higher eigenvalue solutions have DC shifts from this level. The gradient is actually removed in this case by the 2nd eigenvalue and the 1st eigenvalue does very little.
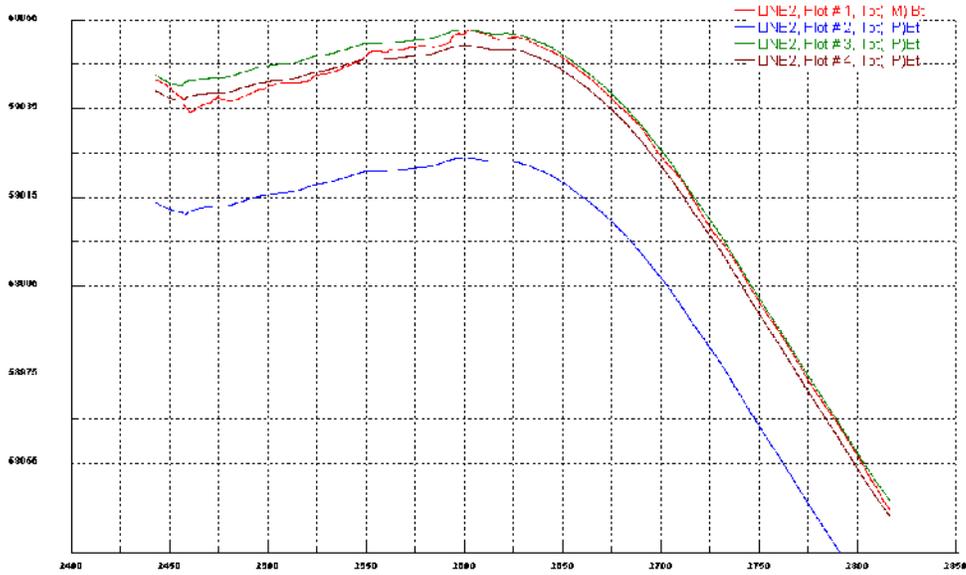
Figure 14: Red- original measured, Blue-SVD with first 14 eigenvalues kept, Green- SVD with first 10 eigenvalues kept, Brown- SVD with first 3 eigenvalues kept.
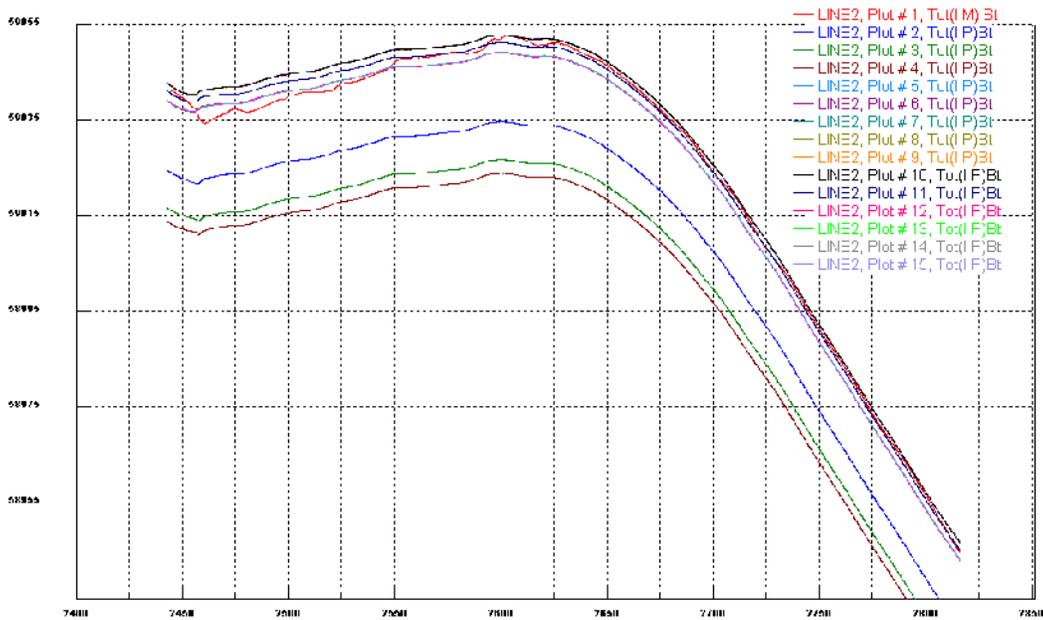
Figure 15: Red- original measured, Results generated with SVD using first 3-16 eigenvalues
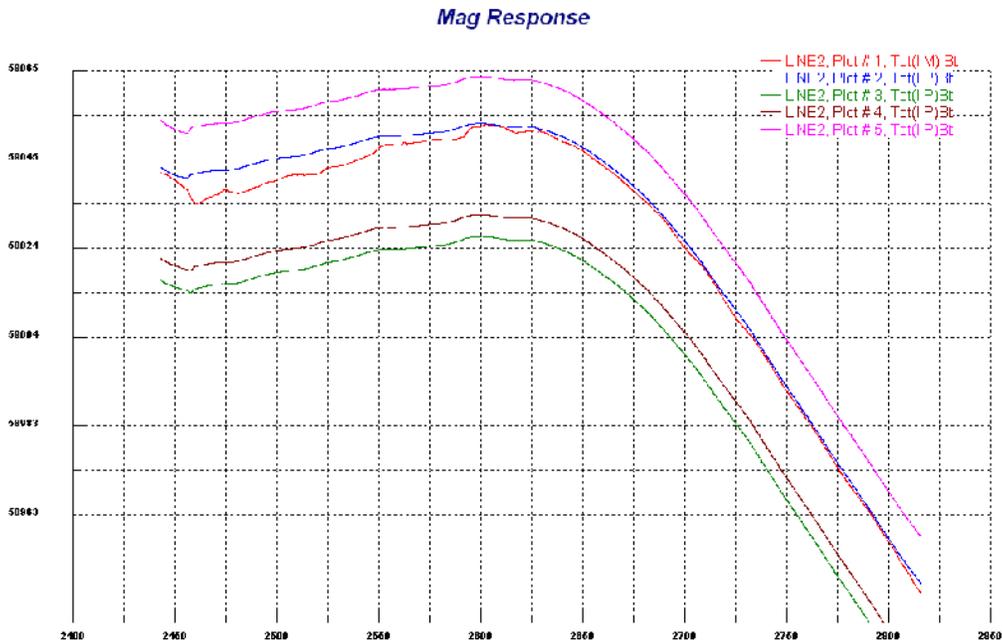
Figure 16: Red- original measured, Blue-SVD with first 13 eigenvalues kept, Green- SVD with all but the 16th eigenvalue, Brown- SVD with all but the 15th eigenvalue, Pink- SVD with all but the 14th eigenvalue

The results in Figure 16 indicate again that a a very strong DC shift is caused by 14th, 15th and 16th components corresponding to the eigenvalues 14,15, and16.

We also note that the first 3 (or even 2) components generate fairly good results in a broad sense.

3.4   Highpass Filtering

In real airborne survey, there are many background noises of various types affecting the compensation process such as local gradient of total field, geologic noise, and micropulsations. The data has to be filtered in order to restrict the frequency range of the data, for the compensation process, to a band of frequencies centered around the primary frequency modes for the aircraft maneuvers. As a result, the signal-to-noise ratio is greatly enhanced for the aircraft maneuver interference that is generated in the magnetic signal. Usually the filtering process involves either high-pass or band-pass filtering.

To achieve this, Leach (B. W. Leach, 1979a, 1979b) suggested that the sampled data quantities, that is, each column of A and the column vector Y in (2 in appendices), have identical filtering. In other words, filtering is applied to the matrices A and Y rather than to measured total field and fluxgate data. For various reasons, we were unsatisfied with this approach and thus implemented Leach's approach to filtering the operator but also pre-filtering both the TMI and fluxgate data prior to compensation.

Regretably, we our work concurs with Leach and we generally do filter the operator rather than the data. However, we (R.Jia,R.Groom) have not given up on the issue of filtering the data.

In this example, we utilize somewhat more difficult data collected from a helicopter.

Line 3:

Mag Response
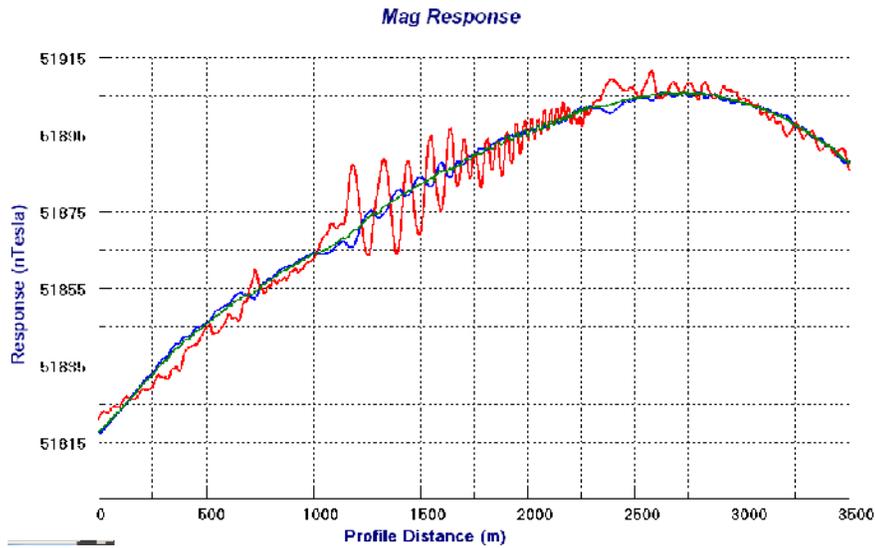
Figure 17: Red: original uncompensated data, Blue: compensation results with SVD10 and Gaussian filter with lag = 4, Green: compensation results with SVD10 and Gaussian filter with lag = 31

Mag Response
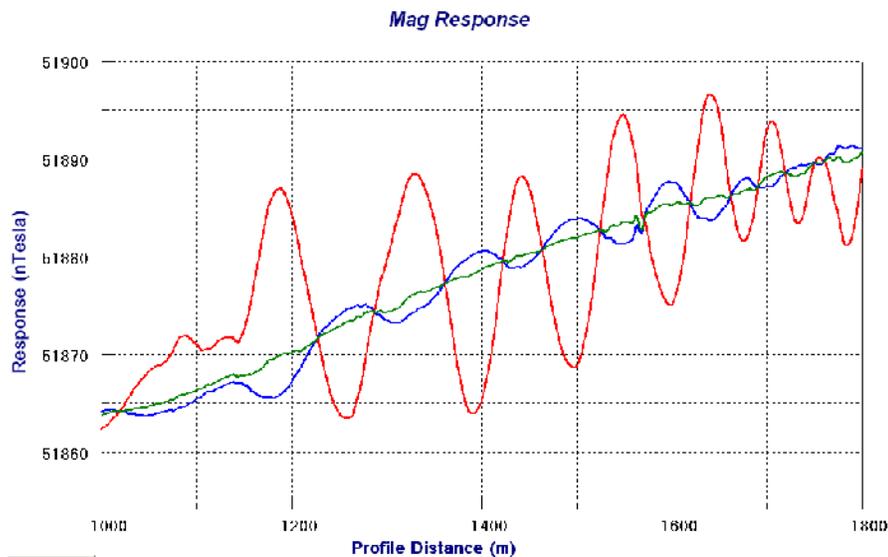
Figure 18: Enlarged portion of the above diagram, Red: original total field data
Blue: compensation results with SVD10 and Gaussian filter with lag = 4, Green: compensation results with SVD10 and Gaussian filter with lag = 31
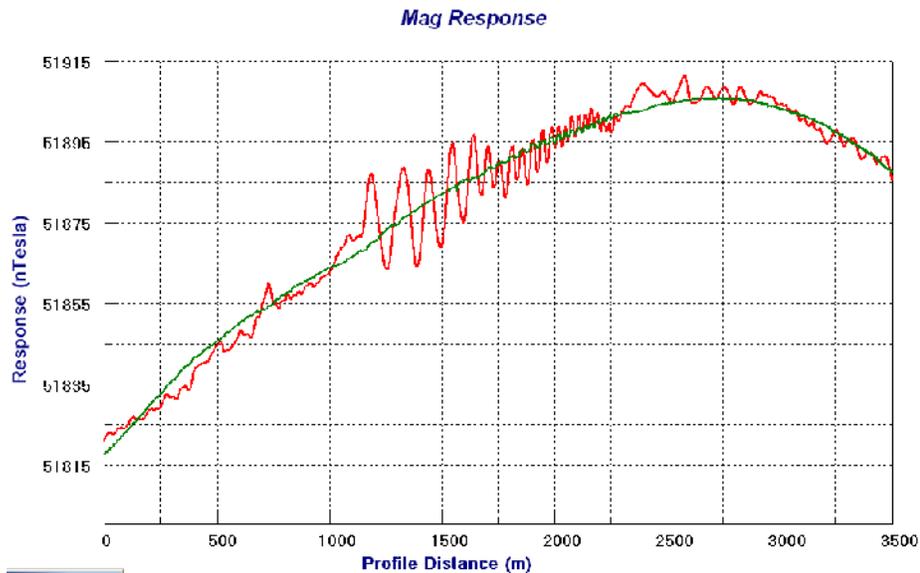
Figure 19: Red: original total field data, Green: compensation results with SVD10 and Gaussian filter with lag = 31

Various filters were experimented with. The most promising appear to be the Gaussian filter. The above examples show the effects of compensation when using different Gaussian filters. In the above examples, it is clear that a Gaussian filter of lag =31 produces better compensation than when a lag of 4 (which has similar characteristics to some of the standard filters used in compensation) is used. Based on our experiments with synthetic model as well as real compensation boxes. it is concluded that a good set of interference coefficients in a predictive model can be produced by first applying a Gaussian high-pass filter directly to both the data and the fluxgate data and then adding a DC value (average value) to the filtered data. It is evident that adding DC values is essential as they specify the aircraft's orientation including the heading direction along which a particular flight path is flown.

3.5   Synthetic models

To study the mathematical aspects of compensation more rigorously, and to evaluate the results, we have developed the ability to generate synthetic data of the aircraft's effects on the magnetic measurements. For these examples, the simulated aircraft is given a variety of magnetic noise features including permanent ("hard") magnetic material and induced ("soft") magnetic material as well as low frequency electromagnetic characteristics. The simulated aircraft can be flown through simulated maneouvers or to its actual flight patterns over a specified geological model and the effects on the sensor(s) are calculated numerically.

Figure 20: Perspective view of a sample block model of the "aircraft" used to generate synthetic data fo[...]manent magnet[...]
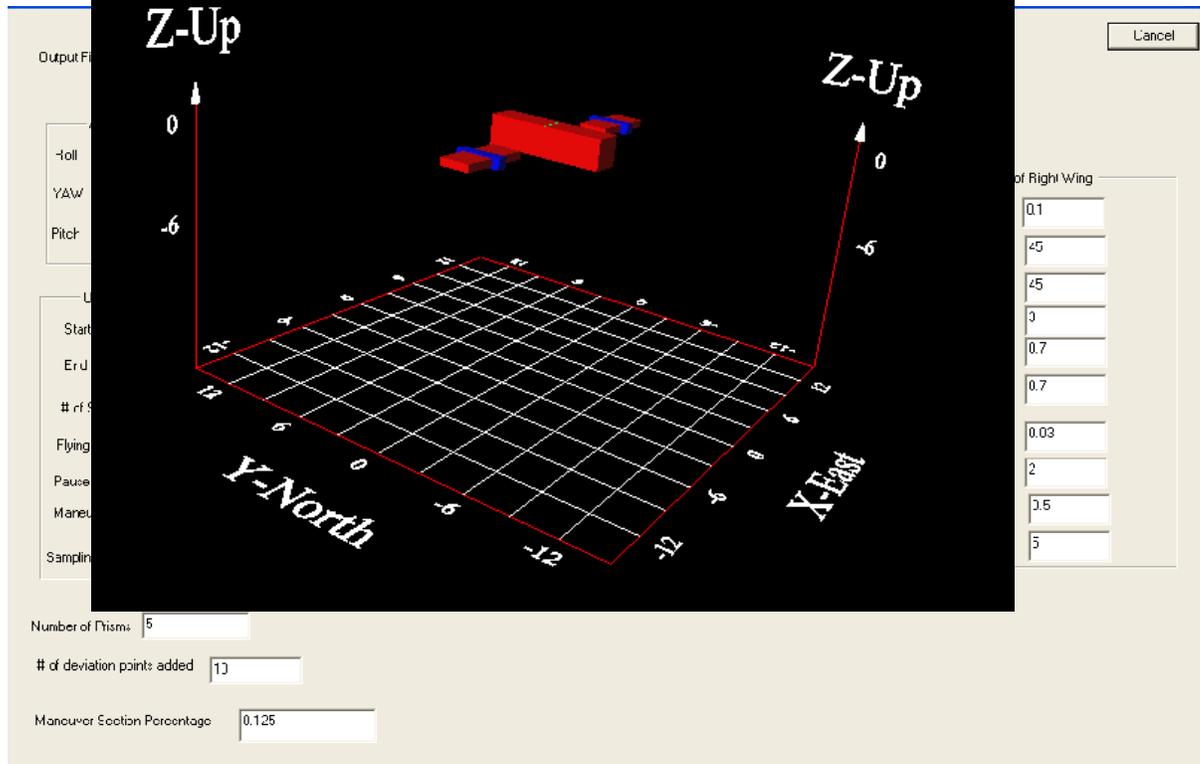
Figure 21: Screen capture of the executable interface used to generate the synthetic examples.

The executable interface (Figure 21) specifies the setting for aircraft's flying route and maneuvers (pitching roll, yaw), Magnetic and physical structures of the aircraft, background earth's field information.

We have developed the ability to generate a synthetic model of the aircraft's magnetic effects. Here, for example, we simulate the sources of the permanent magnetic field in the aircraft with the use two magnetic dipoles, one on each wing. The sources of the induced magnetic field of the aircraft were simulated with 2 thin rectangular prisms representing the two wings and another long box type prism to represent the fuselage of the aircraft. We also simulated the eddy-current magnetic fields caused by the aircraft's conductive structures moving in the earth's magnetic field by calculating the time variation of the coupling of these prism structures with the earth's field. Here, the synthetic compensation box consists of 4 lines, each having a length of 14km, and are flown along EW and NS directions. The flight altitude of the box was set 9500 feet and the data was collected every 0.05 s or the sampling rate is 20 Hz. The maneuvers of the aircraft were simulated with pitch ($\pm 5°$), roll ($\pm 5°$) and yaw ($\pm 10°$). The earth field is set to be inclined at 75 degrees to the horizontal and oriented 5 degrees to the north and has strength of 55500 nT. The 4 box lines are illustrated in Figure 22 as red, blue, green and brown lines. A survey line (pink line) was simulated at altitude of 650 feet with pitch ($\pm 5°$), roll ($\pm 5°$) and yaw ($\pm 10°$). Four local magnetic anomalies were

inserted in the eastern part of the survey region to simulate a regional gradient in the average earth's field.
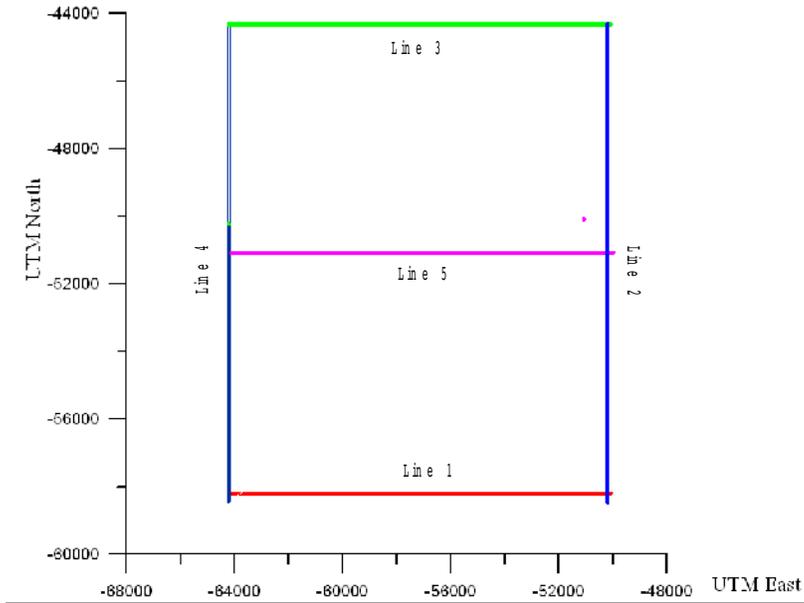
Figure 22: Synthetic compensation box and survey Line

Simulated fluxgate data versus maneuvers

The order of the maneuvers for the aircraft is pitch ($\pm 5°$), roll ($\pm 5°$) and yaw ($\pm 10°$). In simulating the fluxgate data, the X axis (i.e. Bx) is parallel to the transverse axis of the aircraft. The Y axis (By) is parallel to the longitudinal axis of the aircraft. The Z axis (thus Bz) is parallel to the vertical axis of the aircraft.

With Line 1

Change in Bx:

From Figure 23 we can see that pitch does not cause any change in Bx because X axis does not move at all. Note that the earth field is inclined at 75 degrees to the horizontal and oriented 5 degrees to the north. It follows from this that the roll causes the biggest change in Bx. Yaw motion also causes little change in Bx.

Change in By:

Pitch(5 degree) causes as much change in By as Yaw (10 degree) does. Roll does not cause any change in By because the local Y axis does not move at all.

Change in Bz:

Yaw does not cause any change in Bz because the Z axis does not move at all. Pitch causes very little change in Bz because Z axis is kept nearly perpendicular to the earth field while pitching. The biggest change in Bz comes from rolling.
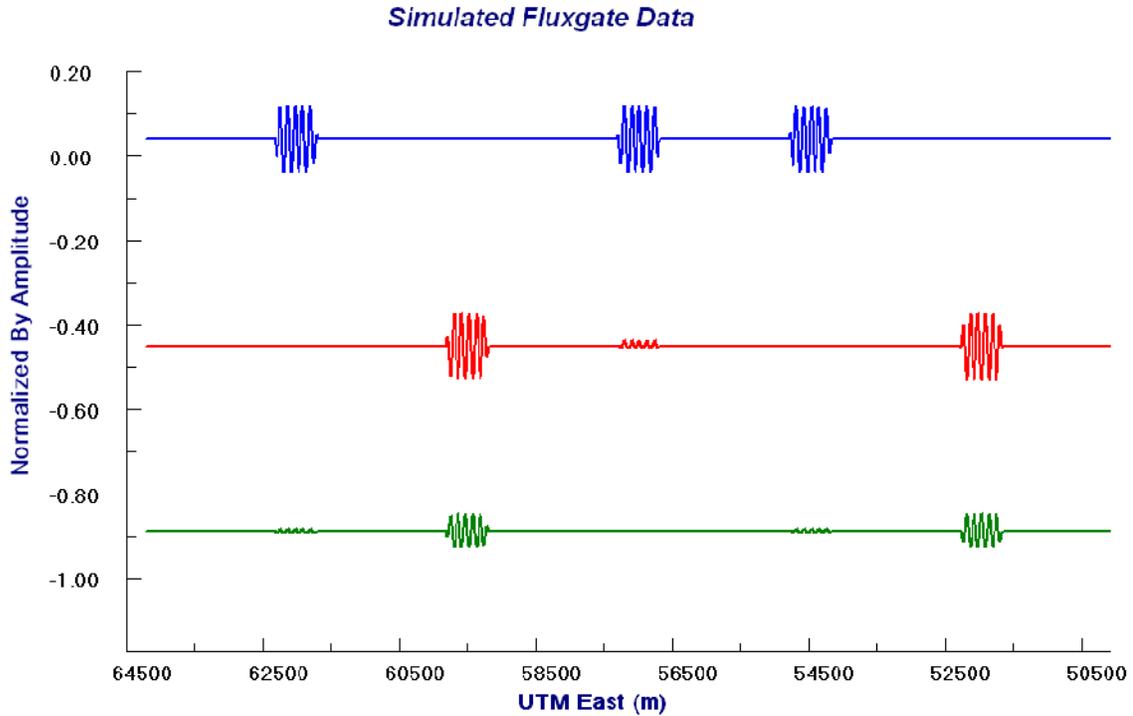
Figure 23: Line 1, Simulated Fluxgate Data which is normalized by its amplitude, Red: Bx. Blue: By. Green: Bz

With Line 2: (Figure 24)

Note that the aircraft flies from south to north and the order of the maneuvers for the aircraft is still: pitch ($\pm 5°$), roll ($\pm 5°$) and yaw ($\pm 10°$).

Change in Bx:

From Figure 24, we can see that pitch does not cause any change in Bx because X axis does not move at all. Note that the earth field is inclined at 75 degrees to the horizontal and oriented 5 degrees to the north. Roll (5 degree) causes as much change in Bx as Yaw (10 degree) does.

Change in By:

Pitch causes the biggest change in By. Yaw (5 degrees) causes very little change in By. Roll does not cause any change in By because the Y axis does not move at all.

Change in Bz:

Yaw does not cause any change in Bz because the Z axis does not move at all. Roll causes very little change in Bz because Z axis is kept nearly perpendicular to the earth field while rolling. The biggest change in Bz comes from pitch.

Figure 24: Line 2, Simulated Fluxgate Data which is normalized by its amplitude, Red: Bx. Blue: By. Green: Bz

With Line 3

Note that the aircraft flies from east to west and the order of the maneuvers for the aircraft is still: pitch ($\pm 5°$), roll ($\pm 5°$) and yaw ($\pm 10°$).

Change in Bx:

From Figure 25, we can see that pitch does not cause any change in Bx because X axis does not move at all. Note that the earth field is inclined at 75 degrees to the horizontal and oriented 5 degrees to the north. It follows from this that the roll causes the biggest change in Bx. Yaw motion also causes a little change in Bx.

Change in By:

Pitch(5 degree) causes as much change in By as Yaw (10 degree) does. Roll does not cause any change in By because the Y axis does not move at all.

Change in Bz:

Yaw does not cause any change in Bz because the Z axis does not move at all. Pitch causes very little change in Bz because Z axis is kept nearly perpendicular to the earth field while pitching. The biggest change in Bz comes from rolling.
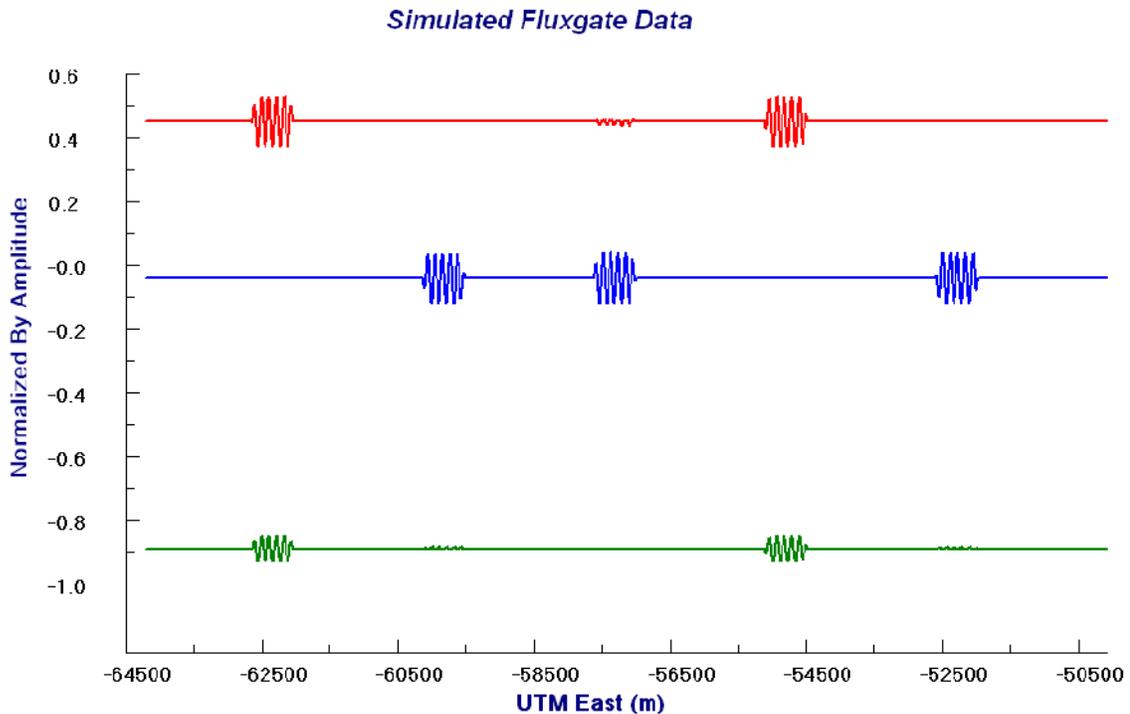
Figure 25: Line 3, Simulated Fluxgate Data which is normalized by its amplitude, Red: Bx. Blue: By. Green: Bz

With Line 4

Note that the aircraft flies from north to south and the order of the maneuvers for the aircraft is still: pitch ($\pm 5^\circ$), roll ($\pm 5^\circ$) and yaw ($\pm 10^\circ$).

Change in Bx:

From Figure 26, we can see that pitch does not cause any change in Bx because X axis does not move at all. Note that the earth field is inclined at 75 degrees to the horizontal and oriented 5 degrees to the north. Roll(5 degree) causes as much change in Bx as Yaw (10 degree) does.

Change in By:

Pitch causes the biggest change in By. Yaw (5 degrees) causes very little change in By. Roll does not cause any change in By because the Y axis does not move at all.

Change in Bz:

Yaw does not cause any change in Bz because the Z axis does not move at all. Roll causes very little change in Bz because Z axis is kept nearly perpendicular to the earth field while rolling. The biggest change in Bz comes from pitch.

Figure 26: Line 4, Simulated Fluxgate Data which is normalized by its amplitude, Red: Bx. Blue:
By. Green: Bz

Compensation Results for Synthetic Data

In Figures 27-34, we illustrate the compensation results with standard (16 terms) SVD
as well as truncated SVD having the first 10 components (TSVD). The results are
produced for all lines except Line 2, which will be dealt with separately in the following
section. Note that the compensated curves are shifted to account for an DC shift from
the compensation. A Gaussian filter with lag 4 was utilized during the compensation.
There is little difference between the compensation results generated with standard
SVD and the compensation results generated with TSVD having the first 10
components (e.g. Figure 31) other than the DC shift of the compensated data. It is
indicated that there is no noticeable linear dependence among the terms. (Note: Some
authors refer to this a multicolinearities). Please refer to next section for more details.
By line-to-line compensation we mean compensation of the data of a box line using the
data from itself. Figures 27-34 shows that good compensation results were obtained by
compensating the simulated real survey line (Line 5) with the coefficients from Line 1
that has the same heading as Line 5.
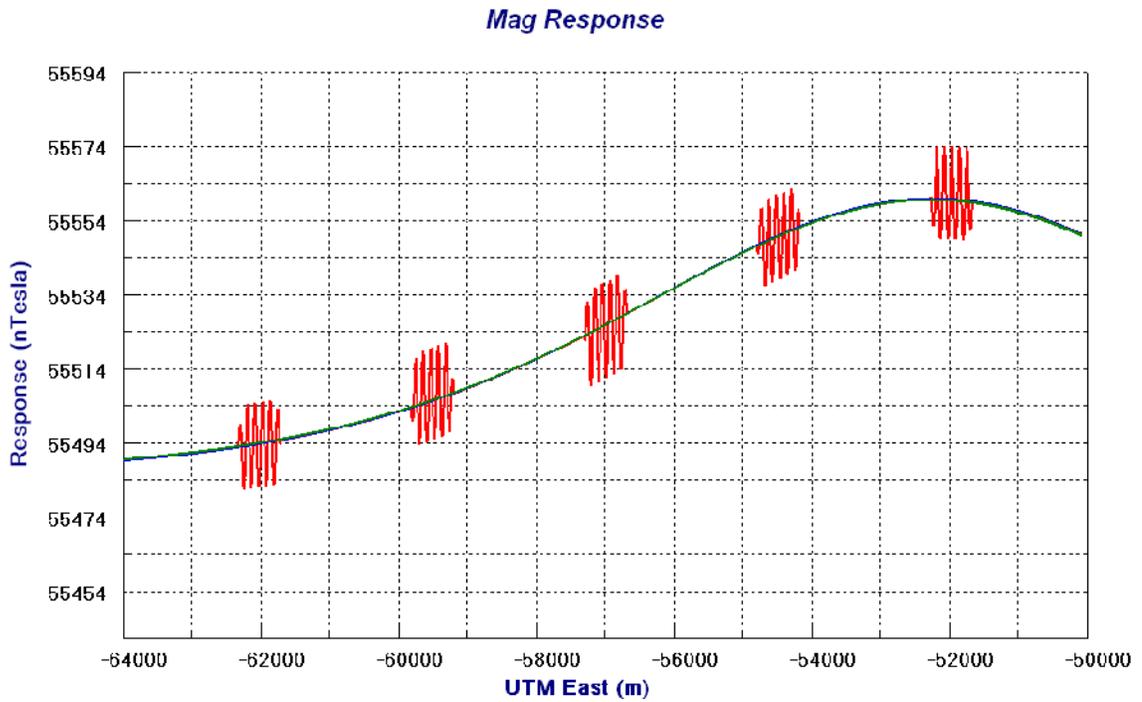
Figure 27: Line 1 (line-to-line compensation, ie, utilized the data from line 1 to compensate the data of Line 1), Red: original uncompensated data, Blue: compensated with TSVD with the first 10 components, Green: compensated with SVD with all the 16 components
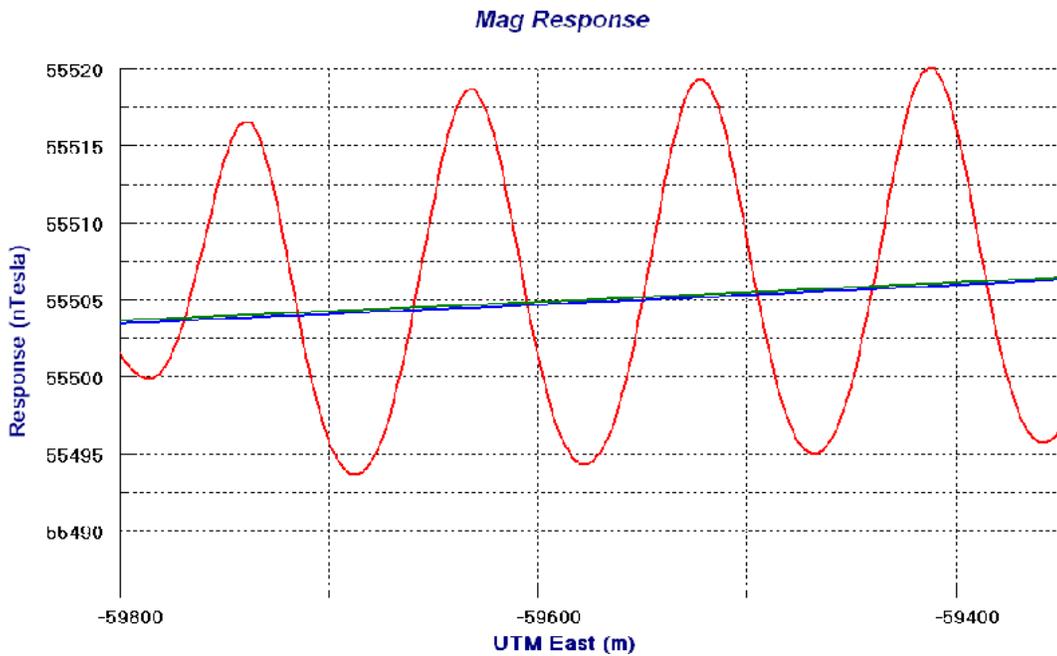
Figure 28: Line 1 (line-to-line compensation) Enlarged portion, Red: original uncompensated data, Blue: compensated with TSVD with the first 10 components, Green: compensated with SVD with all the 16 components
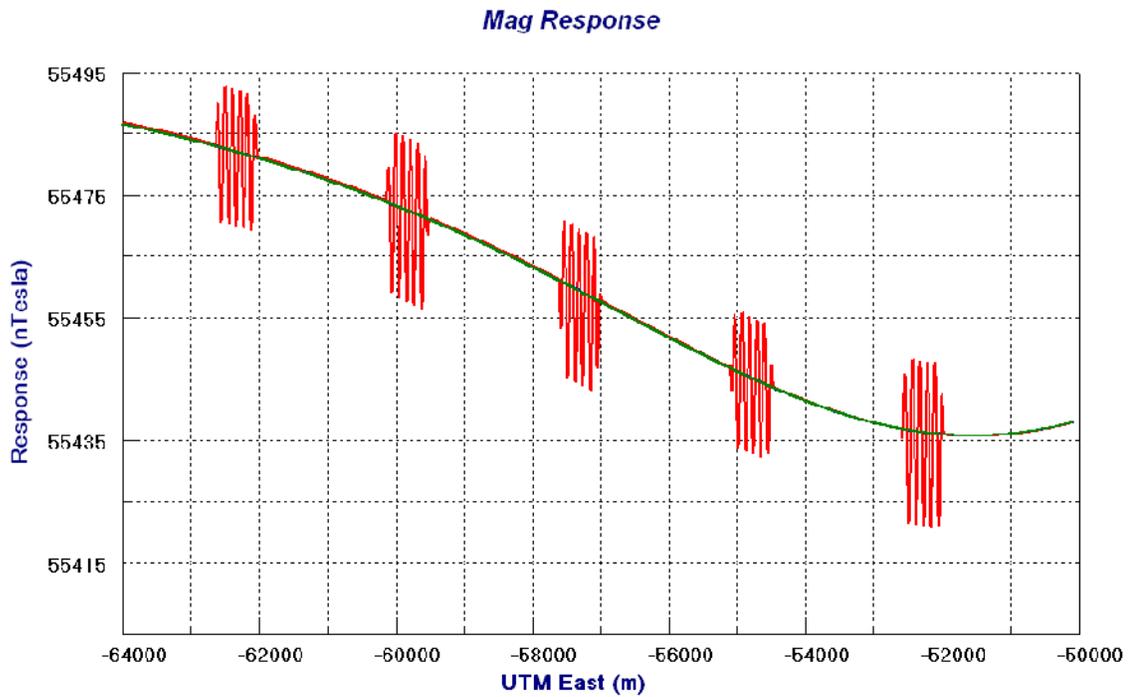
Figure 29: Line 3 (line-to-line compensation), Red: original total field, Blue: compensated with TSVD with the first 10 components, Green: compensated with SVD with all the 16 components
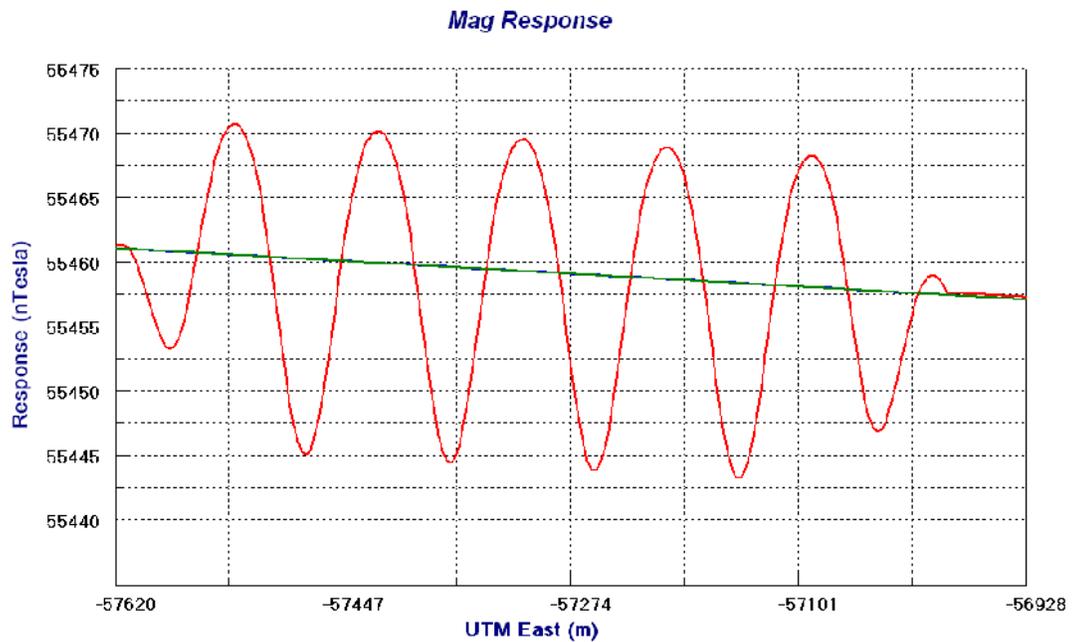
Figure 30: Line 3 (line-to-line compensation) Enlarged portion, Red: original total field Blue: compensated with TSVD with the first 10 components, Green: compensated with SVD with all the 16 components
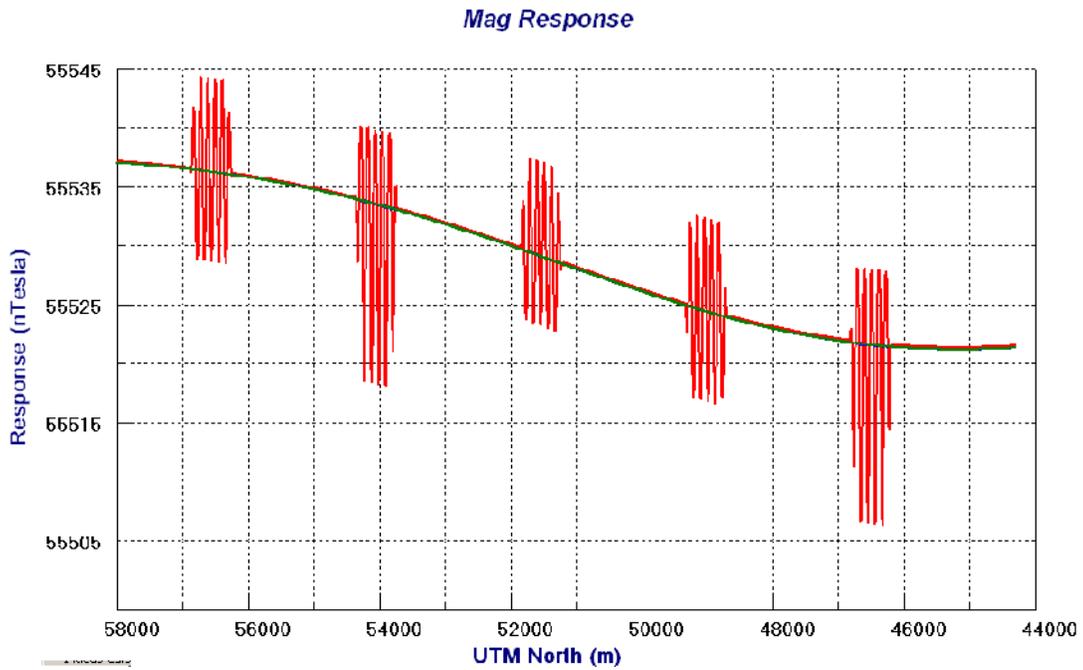
Figure 31: Line 4 (line-to-line compensation) Enlarged portion, Red: original total field Blue: compensated with TSVD with the first 10 components, Green: compensated with SVD with all the 16 components
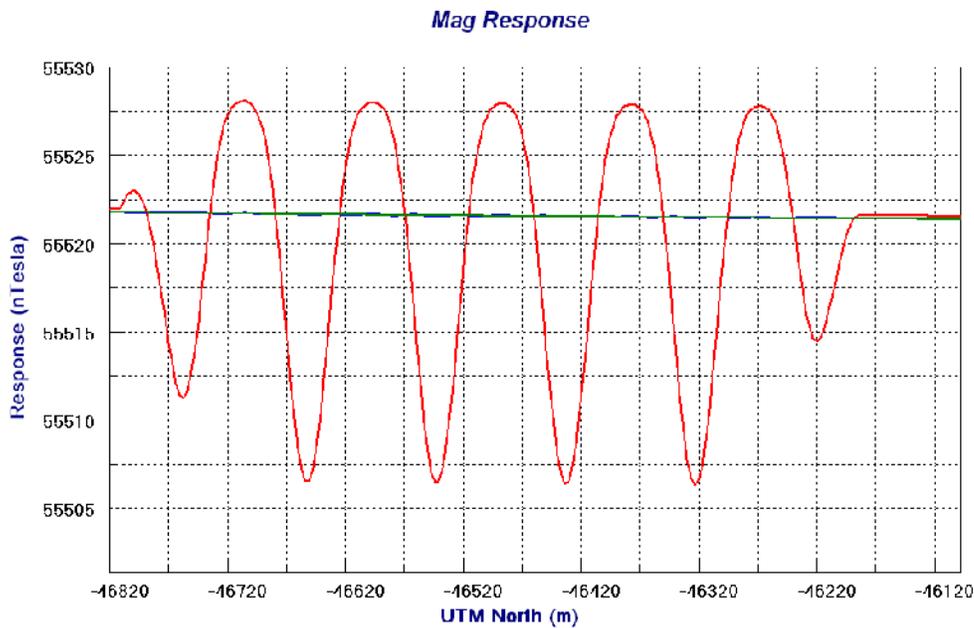
Figure 32: Line 4 (line-to-line compensation), Red: original total field, Blue: compensated with TSVD with the first 10 components, Green: compensated with SVD with all the 16 components
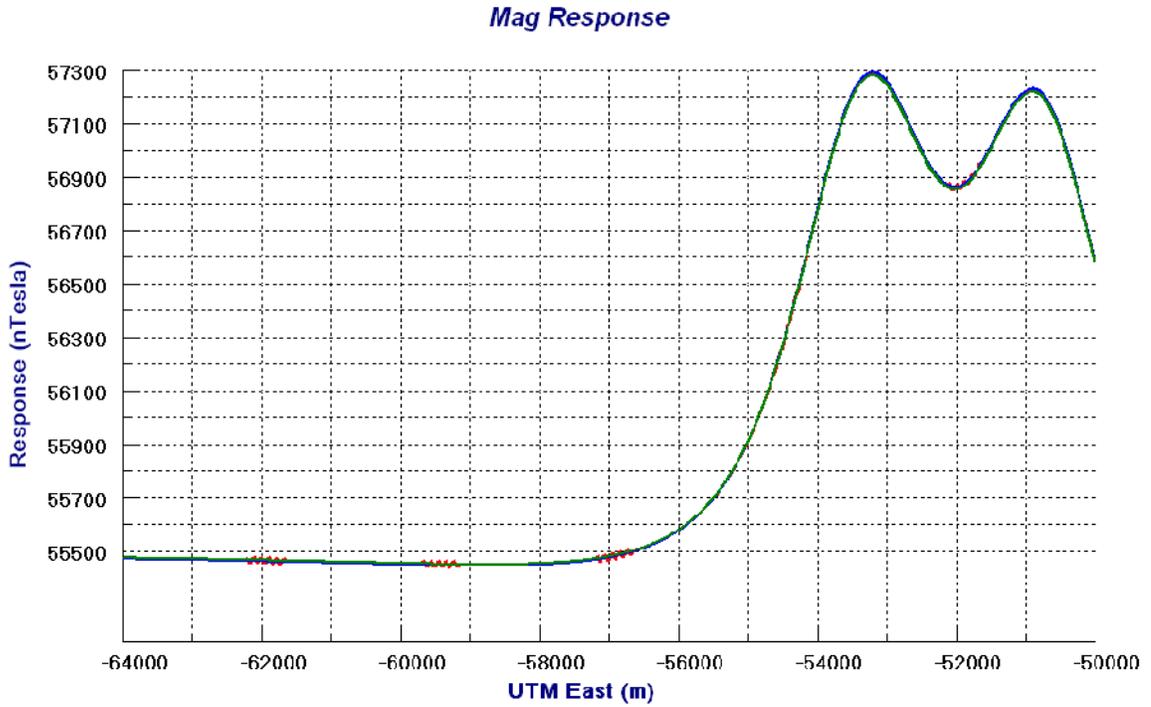
Figure 33: Line 5 (compensation by Line 1), Red: original total field, Blue: compensated with TSVD with the first 10 components, Green: compensated with SVD with all the 16 components
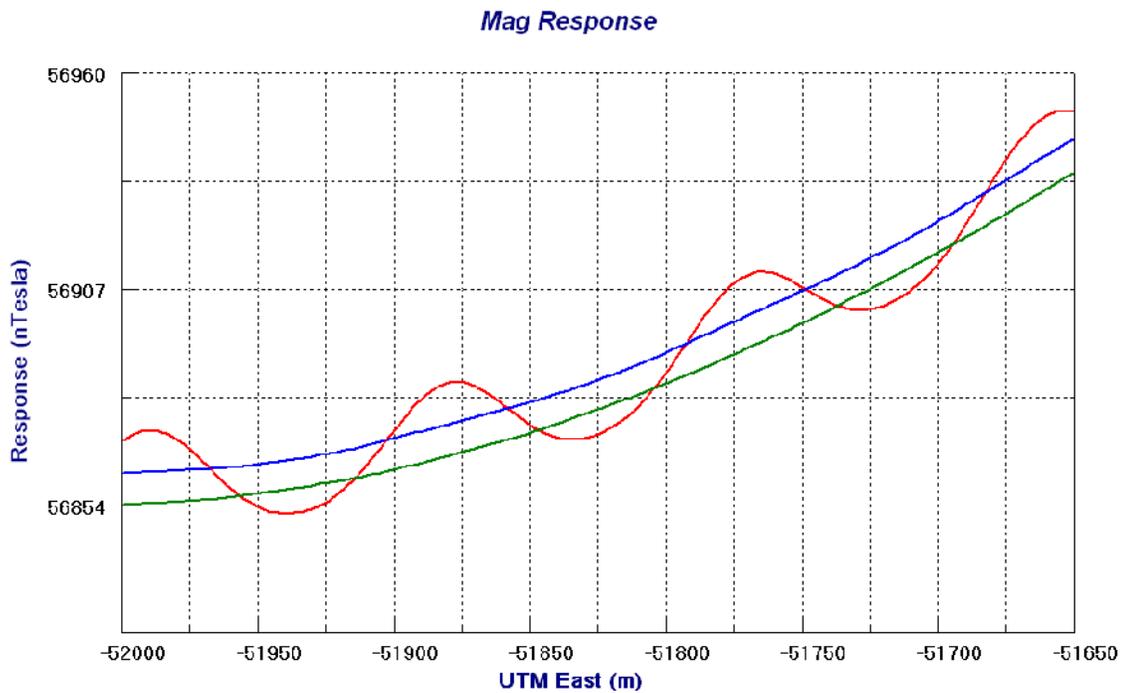
Figure 34: Line 5 (compensation by Line 1) Enlarged portion, Red: original total field, Blue: compensated with TSVD with the first 10 components, Green: compensated with SVD with all the 16 components

Effect of Filtering and Solvers on Compensation

We utilize Line 2 as special case since there exists a strong linear dependence among the columns of the operator that are 16 or 18 terms (functions) of the data and fluxgate data. This causes the compensation results with standard SVD to be distorted (see Figure 35). However, this multicolinearity (linear dependence) can be removed by either

I) selecting the appropriate solver, or

II) applying an appropriate filtering

during the process for computing the coefficients.

Solver VS Compensation

Figures 35-36 show the effect of solvers on removing multicolinearity. By TSVD with the first 10 components good results were produced (Figures 35 & 36). SVD with all 16 terms is not correct (Figure 35&36). This indicates that the multicolinearity is related to the last 6 components. TSVD with the first 15 components generated good results (Figure 37); we further conclude that the last component causes the multicolinearity.
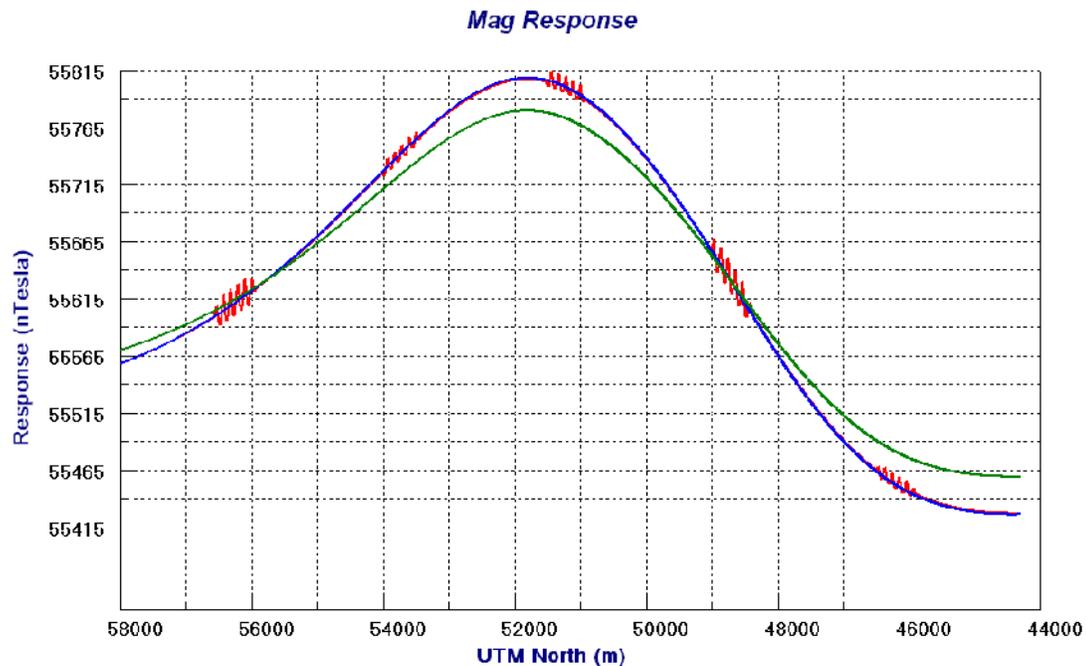
Figure 35: Line 2 (line-to-line compensation), Red: original uncompensated data, Blue: compensated with TSVD with the first 10 components, Green: compensated with SVD with all

the 16 components, Gaussian filter with lag 4 was used, The distorted results by SVD-16 are caused by Multi-correlations among the terms.
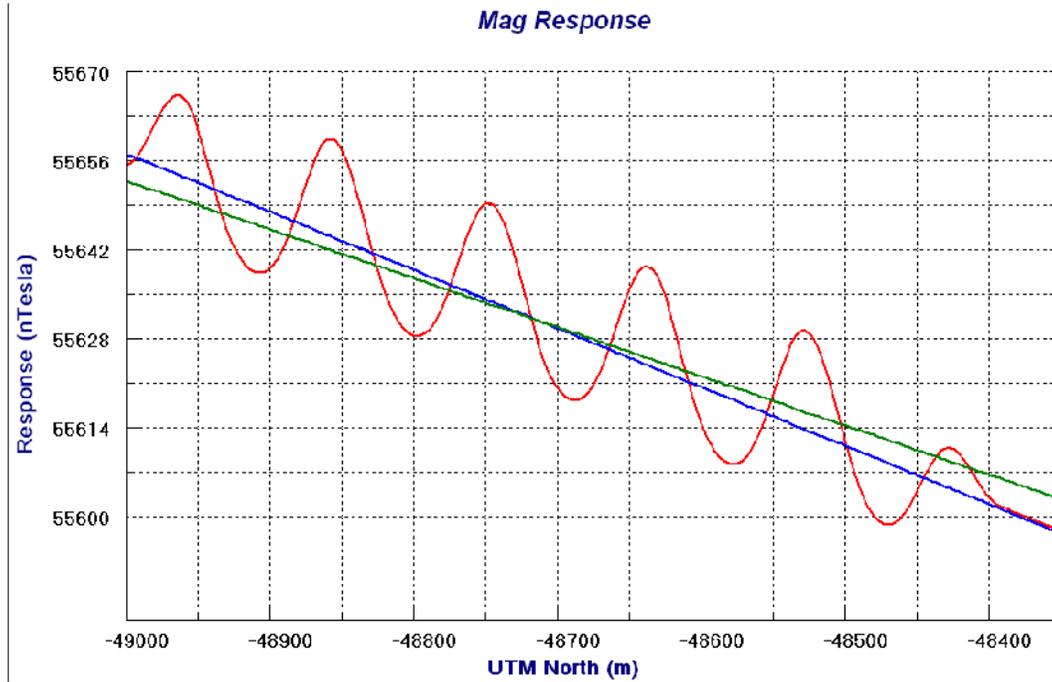
Figure 36: Line 2 (line-to-line compensation) Enlarged portion, Red: original total field, Blue: compensated with TSVD with the first 10 components, Green: compensated with SVD with all the 16 components.
Gaussian filter with lag 4 was used.
The distorted results by SVD-16 are caused by Multi-correlations among the terms.
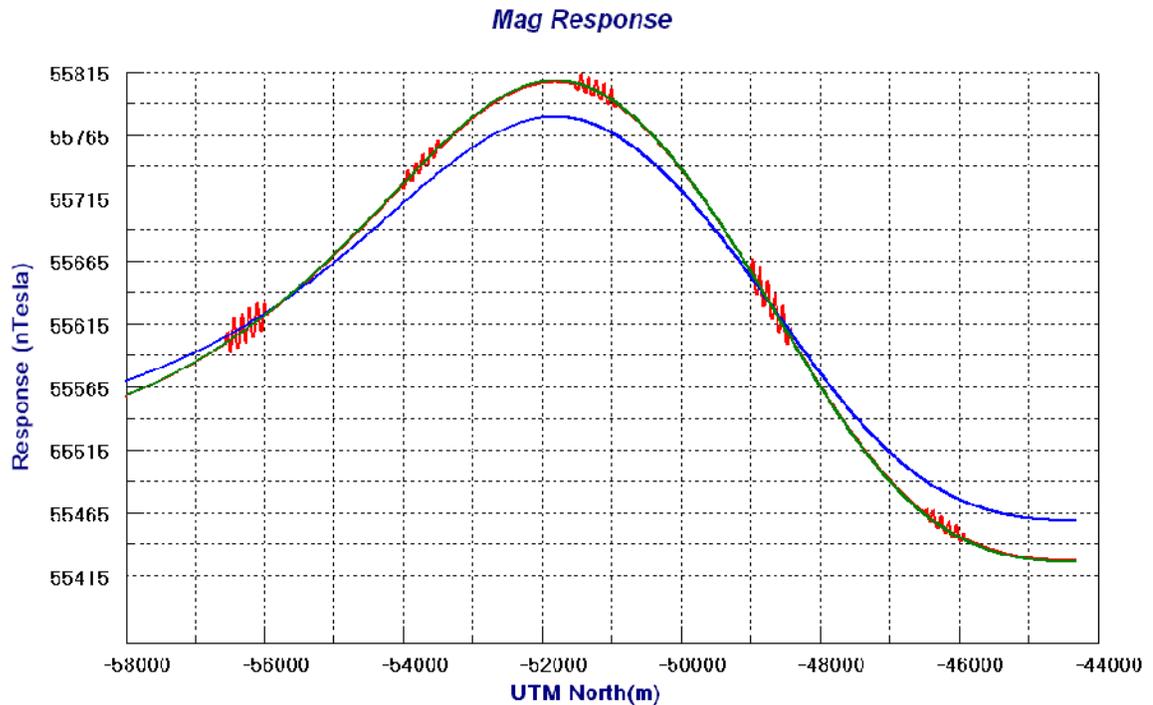
Figure 37: Line 2 (line-to-line compensation), Red: original total field, Blue: compensated with SVD with all the 16 components, Green: compensated with TSVD with the first 15 components Gaussian filter with lag 4 was used, The distorted results by SVD-16 are caused by Multi-correlations among the terms.

Filtering VS Compensation

We now show how the filtering can affect the compensation. Here, we utilize a Gaussian filter with lag 2, 3, or 4. Note that the smaller the lag value is then the tighter the filter that is applied or the higher the cut-off frequency of the highpass filter. Figures 38-39 illustrates that a tight filter can remove the multicolinearity in this case.
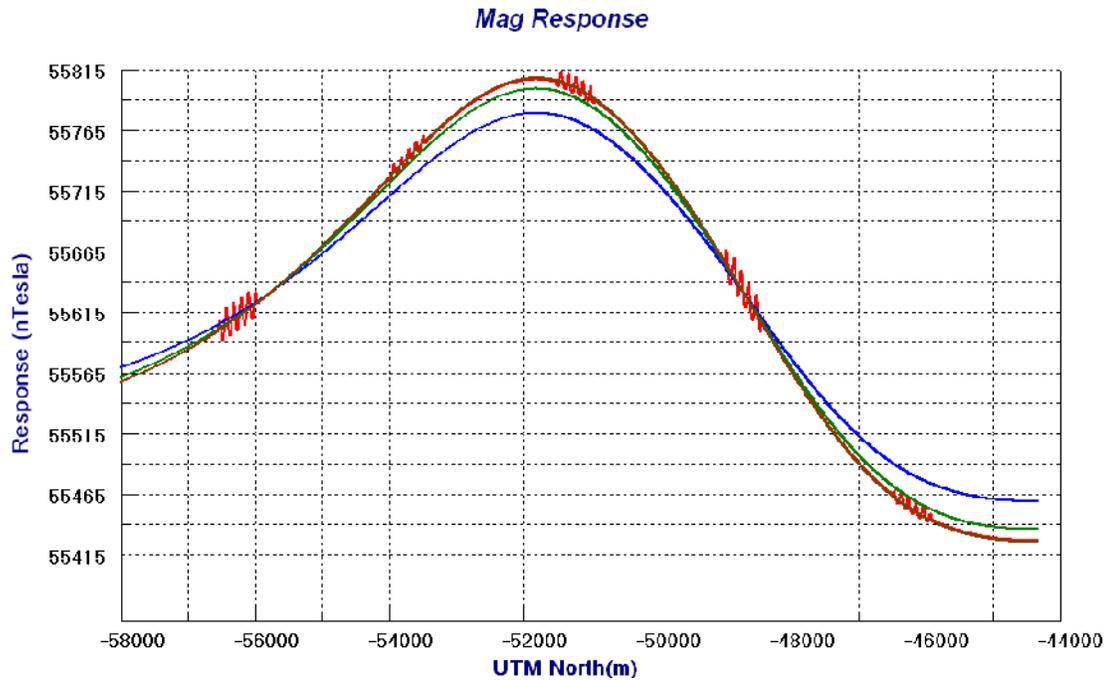
Figure 38: Line 2 (line-to-line compensation),Red: original total field, Blue: compensated with standard SVD and Gaussian filter having lag 4, Green: compensated with standard SVD and Gaussian filter having lag 3
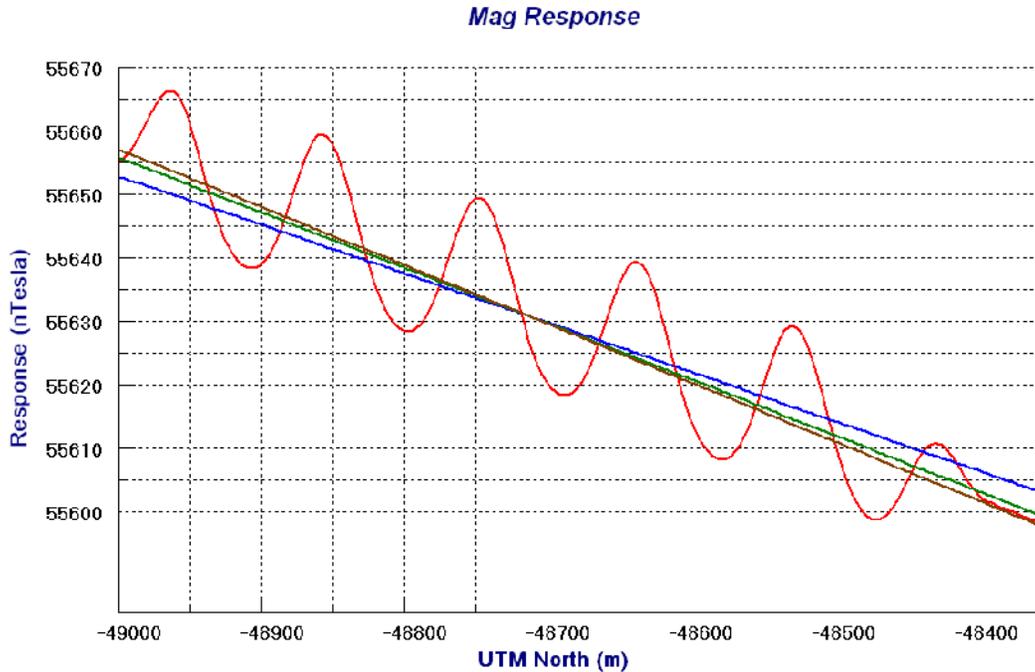
Figure 39: Line 2 (line-to-line compensation) Enlarged portion:Red: original total field. Blue: compensated with standard SVD and Gaussian filter having lag 4, Green: compensated with standard SVD and Gaussian filter having lag 3

Conclusion

Our capability to generate synthetic models enables us to study various issues regarding magnetic compensation such as the use of different solvers and different data filtering operations prior to calculating the compensation coefficients.

If the wrong filter is utilized during the coefficient calculation, the frequency range of the filtered data, for the compensation process, exceeds the primary frequency modes for the aircraft maneuvers. This eventually leads to a multicolinearity which can severely distort the compensation results (see Figure 35). However, this multicolinearity problem could be resolved by selecting a appropriate solver (Figure 35).

An appropriate filter can restrict the frequency range of the data, for the compensation process, to a band of frequencies centered around the primary frequency modes for the aircraft maneuvers. Therefore it can resolve the issue of multicolinearity (Figure 37).

3.6   Reduction of Geological noise

The usual practice in flying a compensation box is to fly high (around 10,000') in an "magnetically" quiet area. This removes or reduces the high spatial frequency of geological character. Here, during the compensation flight, the aircraft magnetic noise is the signal that one wishes to increase as the input into the compensation algorithms.

But in many areas of the world, such as shield areas, conducting a compensation flight in a magnetically quiet area is not logistically possible. So some geological noise leaks into the system even after high-pass filtering of the data.

Also, during the pitch maneuver of the compensation flight, the aircraft has a tendency to slightly increase and decrease in altitude as the aircraft noses up or down for the maneuver. This altitude creates a change in the TMI due to the vertical gradient of the Earth's magnetic field. This variation in the TMI is directly correlated with the maneuvers which means that it can not be removed with the highpass filters that are applied to the data.

To determine if removing the geological noise would result in a better compensation solution, the data collected by Terraquest for the OGS was used. Compensation Box 217 was flown entirely within the survey area. This provided a high-resolution data set which can be upward continued to the nominal height of the compensation box. The geological signal was then extracted from the grid, and subtracted from the compensation data. As a first approximation of to the altitude variations of the Earth's Main Magnetic Field, the IGRF was also removed from the compensation data. This pre-processed compensation data, was then, freed of the effects of geology, and altitude variations.

Examination of the FOM shows that the regularly compensated FOM and the pre-processed compensated FOM's were virtually identical. This means that the filtering which is done on the data is very effective in eliminating geological noise and that altitude variations are a minor error term in the compensation process.

3.7   GPS installation

Terraquest had an aircraft available in Toronto for the week of September 28 to October 4 as it transited through their home base of Buttonville airport between two surveys. The aircraft is a twin engine Piper Navajo, registration CF-XKS and is fully equipped with an airborne gradiometer installation. This was also the same aircraft that was used to collect the Fort Hope data that the OGS has contributed in-kind to this project. Development of the numerical code was sufficiently advanced that testing of the code on various compensation boxes could be done and it was felt that the GPS inputs could be implemented relatively quickly.

Figure 40 – Picture of the Terraquest's twin-engine Navajo survey aircraft

The logistical consideration was that the opportunity to use the aircraft at that time, when daylight hours are longer, should not be wasted. Considerable effort was put into the installation of the three extra GPS sensors and to negotiate the contract with Terraquest. Two electronics technicians were placed on the task, and the installation was essentially completed in four days time.

GPS antennas were installed in the wingtip of the port wing, on the fuselage above the mid point of the wings, and half-way along the tail stinger. The wing-inspection panels

were opened and low loss coaxial cables were run from inside the fuselage, treaded through the wing spars to the wingtip where a bracket held the antenna in-place inside the molding of the wingtip. The fuselage antenna was mounted on an external mounting plate which was already in-place. The tail stinger installation involved the removal of the tail stinger from the fuselage to thread wires from the GPS back to the fuselage and the mounting of the antenna onto the stinger. The stinger GPS was half way back of stinger as the antenna had to be kept away from CS-2 magnetometer, but as far back of the aircraft as possible to avoid interference with rudder. The distances between the sensors were measured using a survey tape measure. The distances are: tail – fuselage: 22 feet 8.25 inches, tail – wing: 32 feet 3 inches, and wing to fuselage as 20 feet. In addition, the wing antenna is 2 feet 3 inches aft of the fuselage antennas. The vertical and horizontal distances were not measured as it was too difficult due to the antenna not being on a horizontal plane.

Three Novatel Millenium, geodetic grade, dual frequency GPS's (OEM-3's in Propak enclosures) from Devtec were rented and installed. As well, three notebook computers with serial ports were installed into the aircraft to be used with each GPS receiever.

Figure 41 – picture of the three GPS receivers and one of the laptop computers used for datalogging.

The flight testing took place in two stages, the first immediately following the GPS installation, and the second at the end of January when the aircraft returned to base from another commitment and after its engine change. These first tests will acquire data on different headings to help resolve the issue of perhaps solving for the gradient and amplitude from Leliak's equations to eliminate the need for an initial high-pass filter, and perhaps to allow for flying compensation boxes at lower heights, flying compensation boxes in the modified manner as suggested by Nelson at the NRC, boxes in 30 degree increments to obtain a more evenly spaced heading direction, and to fly using different amplitudes of pitch, roll and yaw.GPS's on fuselage, port wing and tail stinger

3.8   The Physical Survey

First Flight Test

The first flight tests were designed to establish a proper baseline for subsequent tests, to measure the magnetic effects of heading, to determine if the addition of diagonal lines to the compensation box (as suggested by Bradley Nelson) would improve the compensation. And it was to test some of the folklore of the Figure of Merit being affected by the amplitude of the pilot's maneuvers. And it was to test the concept that good quality GPS sensors would be able to adequately measure the aircraft's attitude. Terraquest mobilised an experienced survey pilot and flight-testing was scheduled to start on Saturday Oct. 4, 2003. But due to weather conditions, only a short flight was

accomplished on Oct. 6. The flight on Oct. 6 started late, and the operator returned to base as he notices higher than usual noise on one of the magnetometer sensors on the wingtip. In fact, this should not have been cause for a return to base as the wingtip magnetometers were not the primary sensors. Nevertheless, this short flight proved that the instrumentation that was installed was working.

Oct. 7 was the production flight in which most of the scheduled tests were flown. Only one flight was obtained as weather moved in to prevent a second flight for the day. Most of the scheduled flying was completed, except for about two hours worth of compensation box flights. With two days of standby used up already, and with an unfavourable weather forecast, it was decided to wait until the aircraft returned from its small job at LG4, Quebec. This also gave the researchers time to evaluate the data and to make modifications.

The first survey location was chosen as it is Terraquest's testing area. It is located to the east of Lake Simcoe and is relatively close to Buttonville Airport base. The OGS Ontario Aeromagnetic Master Grid shows that the area is reasonably quiet magneticly. Figure 42 shows the flight paths of the test lines on a windowed portion of the OGS Master Grid which has been upward continued to 9,500 feet.
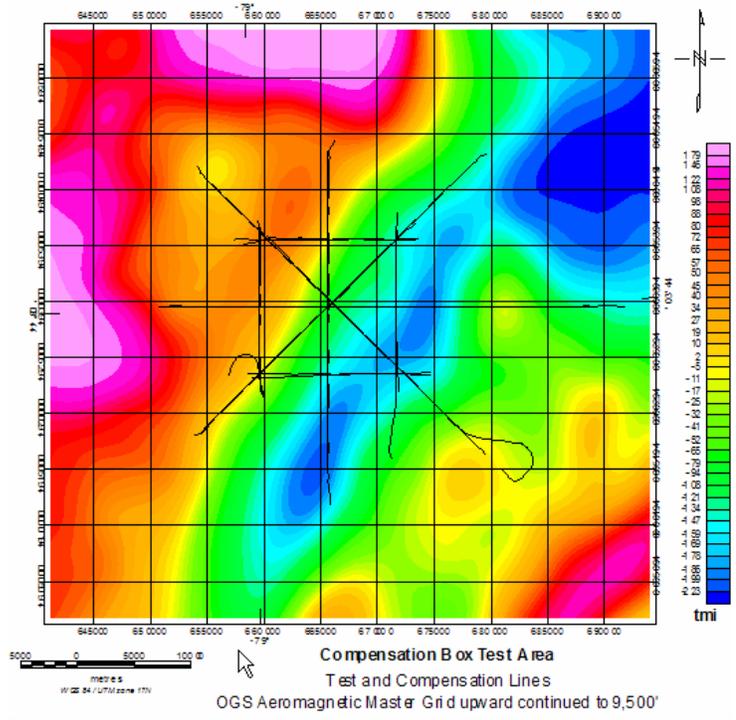
Figure 42: Flight path of the first test flight

The data collected in this test is supplied with the accompanying CD ROM which also has documentation on the file formats.

The first test consisted of 4 tracks oriented 45 degrees from each other and intersecting at a common point. These tracks were flown in reciprocal directions at 9,500 feet ASL and were approximately 24 kms long. The pilot was asked fly the lines as smoothly as possible. The "star" pattern was flown to help determine the heading

effects of the aircraft and ceasium cells, to provide an estimate of the regional gradient, and to provide a long time sampling at each direction for possible calibration of the GPS sensors and their results.

In addition, a set of two crisscrossing lines was flown at 8000' ASL, below the north-south, east-west lines. These second lines were to check on the vertical gradient of the magnetic field in the test area and perhaps to test to see if it may be possible to fly compensation boxes at lower altitudes.

Two compensation boxes with the diagonal lines added (termed Nelson's boxes in this report) were also flown. Unlike normal surveys where the aircrew decide nominally where to fly the compensation boxes along tracks which are not preprogrammed, the lines of these boxes were programmed so that experiments with compensation boxes can be compared.

The first box was flown without maneuvers while the second box was flown with normal maneuvers. Additional boxes and variants of compensation flights were planned, but after the first two days of airborne tests, and with incoming bad weather, it was decided to assess the data first before proceeding. Also a factor in delaying the second set of tests was Terraquest's cooperation in allowing the GPS antenna and wiring to remain onboard the aircraft until the second test.

Approximately 618 kms of data were collected in the first set of tests.

Second Flight Test

The aircraft was scheduled to return in the late October or early November timeframe for the balance of the flight-testing. Instead, due to an increase in exploration activity at the end of 2003, the aircraft was kept busy until a scheduled engine change had to be performed, forcing the aircraft to return to its home base. The engine change started in the last part of December 2003 and was supposed to be completed in the first week of January, 2004, at which time it was scheduled to be available to the project for one or two days of test flying. The engine change took longer than expected as the aviation maintenance shop shut down for the holiday season and other smaller mechanical issues delayed the aircraft from being airworthy again.

The remainder of testing was to complete the compensation box testing, to gather data for testing the post flight adaptive filtering techniques, and to fly over a magnetic feature to demonstrate the advantages of GPS orientation devices.

The magnetic feature choosen was one of iron deposits in the Marmora area. An OGS survey conducted by Kenting in 1983 exists for the area (GDS 1018 – Revised) and will provide for target selection and data comparison. Initially, the Wanapetei Anomaly east of Sudbury was considered, but due to the distances involved, requiring a mobilisation to Sudbury, it was decided to use the less magnetic, but much closer Marmora anomalies. The Marmora anomalies have the added advantage of having a relatively modern, digitally recorded aeromagnetic survey over it.

The second set of flight tests were much more problematic than the first. After the aircraft was ready, one of the airborne GPS antenna's was overdue from its rental on another of Devtec's clients, necessitating borrowing one from Gedex Inc. Then the power supply on one of the GPS receivers failed, and a spare GPS receiver had to be

rented. Worse, soon into the test flight, one of the laptop computers stopped and so GPS data from the wing was lost. This means that the demonstration of advantages of the GPS orientation data over the vector fluxgate data has not been demonstrated, although the authors feel that it is obvious.

The data collected in this test is also supplied with the accompanying CD ROM which also contains the documentation on the data formats.

3.9   GPS processing

It was envisaged that the three x, y, z positions of the airborne GPS receivers can be used to derive the pitch, roll and yaw of the aircraft as an input into the compensation routines. There were a number of GPS processing issues encountered by this survey.

The plan was that the GPS data can be processed using the GravMov software by WayPoint Consulting in Calgary, a provider of high-end GPS processing software. GravMov differs from other base station correction packages in that it uses a moving basestation to compute relative heading and pitch. This can yield better heading and pitch information that obtaining them via the absolute x, y, z locations.

To see if GravMov was really required and in an attempt to reduce costs, and as a test, the data collected by the airborne Novatel Millenium GPS's were post flight differentially processed in the traditional manner of using a Novatel Millenium base station situated in Newmarket, some 40 to 50 kms from the test area. A second GPS base station was operated as a backup by Terraquest during the first tests. But it was only a single frequency receiver sampled at 1 Hz and the differential processing used the Novatel Millenium basestation. The processed data at 10 Hz was substantially poorer than the stated accuracies of receivers.
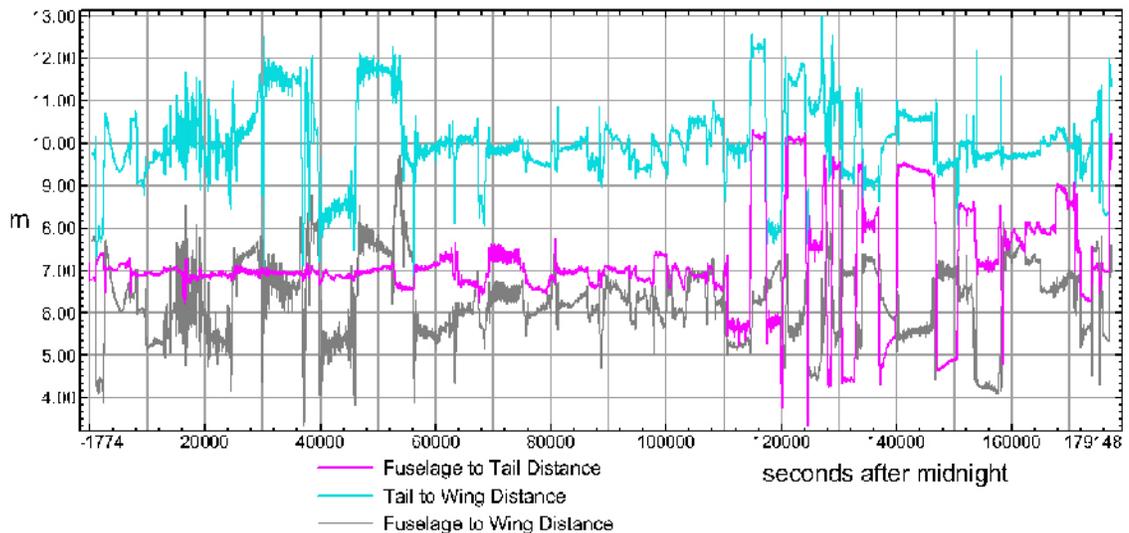
Figure 43 – plot of the distances between the GPS antennae versus time for flight 4

Figure 43 displays the distances between GPS antennae as calculated from the processed positions of the antennae. These are shown as a function of time. Examination of the plots in Figure 43 demonstrate that the errors and drift in positioning were almost an order of magnitude higher than the quoted values of the GPS receivers. The differentially processed data were apparently more accurate than the raw data, but the relative differences between the three receivers had problems in the long term drift and had sudden jumps of up to 1 or 2 metres. Long wavelength errors in the three positions were also noted.

The data was sent to WayPoint Consulting in Calgary, for their analysis and comments. They pointed out that during flight, the number of satellites tracked seemed to drop from the 6 or 7 seen on the ground, to in some cases, three satellites. There does not seem to be a reason for this. Perhaps it was the operation of the GPS's at 10 Hz on a relatively fast moving platform which caused the loss of satellites. This may be one of the causes for the errors.

WayPoint also suggested that the data be processed using their GravMov software and the data which has been processed in this manner looks much better. GravMov processes the airborne GPS data in pairs, to obtain the relative orientation of one from the other. Three pairs, fuselage to wing, fuselage to stinger, and stinger to wing were processed in this manner. The errors in relative positions of the airborne antennae are about twice of what the quoted values would be. This error should be small enough such that good orientations of the aircraft can be obtained with the GPS's.

Research then began on how to use the GPS relative vectors to compensate the data. In more detailed analysis of the GravMov processed data, it was felt that the error in position still was not small enough to provide sufficiently accurate orientations. However, GravMov's processing solved for the relative orientation between any two GPS receivers, and the relative distance was a secondary, and less accurate output. Dr Groom devised several processing and statistical techniques to utilize the 3 combinations of relative vectors between antennae. The GPS relative vectors were integrated with the magnetic data through GPS time.

GPS Data Quality Check

As a check on the data quality of the GPS orientations, we note that the three GPS antenna are rigidly mounted on the aircraft and therefore, in principle, any two pairs of GPS sensors, or any two direction vectors can be used to derive the third vector. This was done by calculating the SW(stinger-wing) vector using the FW(fuselage-wing) and FS(fuselage-stinger) .

Figures 44, 45 and 46, we show, as an example, the absolute error in the x-component of the SW vector between the "measured" and calculated vector after statistical "bootstrapping" analyses. Note: Measured is after GravMov processing.
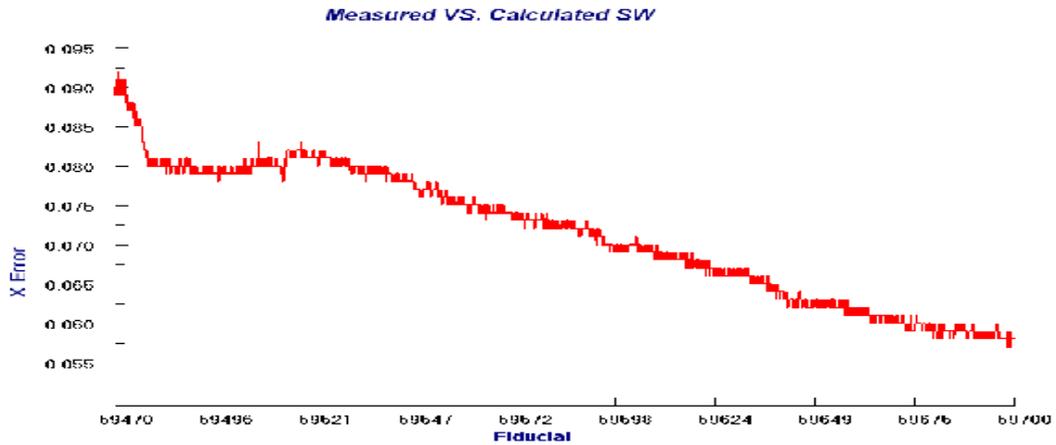
Figure 44: Line 1090, The absolute error between the x-component of measured SW vector and the x-component of calculated SW vector
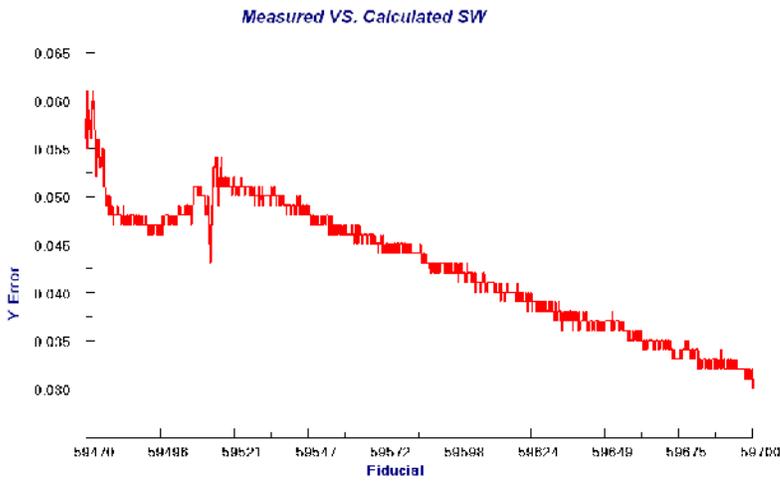
Figure 45: Line 1090, The absolute error between the y-component of measured SW vector and the y-component of calculated SW vector after bootstrapping.
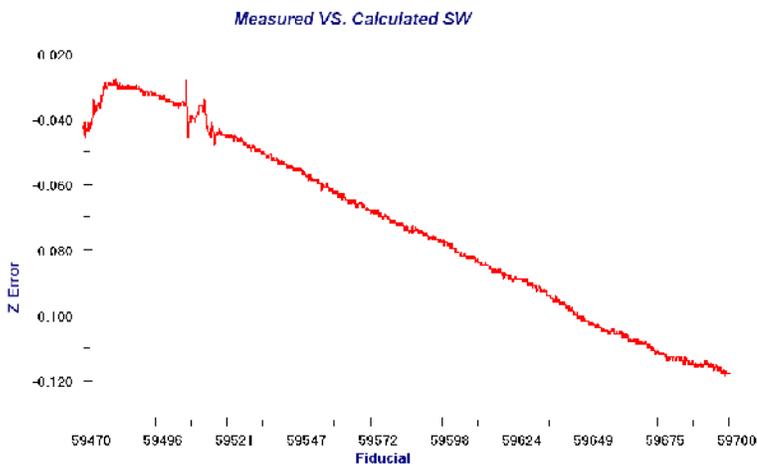
Figure 46: Line 1090, The absolute error between the z-component of measured SW vector and the z-component of calculated SW vector after bootstrapping.

The difference in the X, Y and Z errors are small, showing that the GPS data is consistent, and that any two GPS pairs can be used for input into compensation.

3.10 GPS compensation

In this subsection, magnetic compensation using the GPS orientation was demonstrated using data from Line 1090 of Box 2 of the first test flight. The line is an east-west line taken from a Nelson's box in the test area. The file containing the data for this line is in: FLTS4AB \\ b3100716_p03.xyz.

In order to quickly test the GPS orientation data, it was decided to use the available interfaces to rapidly gain access to the compensation software. The strategy was to use the GPS orientation and information about the Earth's main magnetic field to simulate a set of GPS derived fluxgate data as input into the compensation routines.
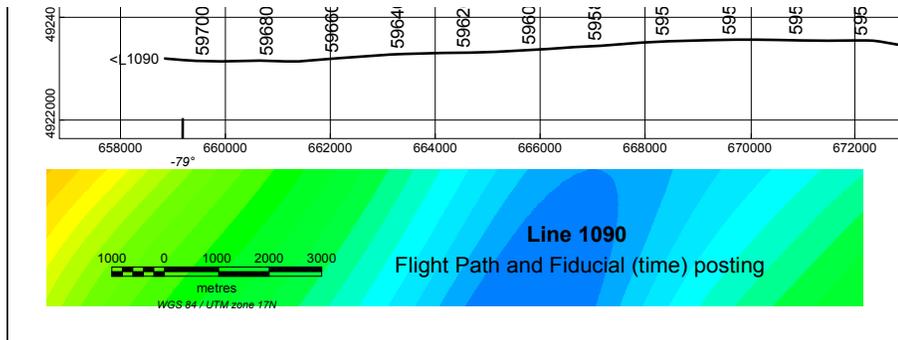
Figure 47: Flight Path of Line 1090 with Fiducial posting along the east to west flight path overlain on a TMI image upward continued to 9,500 feet.

Figure 47 shows track of line 1090 with Fiducial posting along the line for reference with the following plots in this subsection. The line is flown east to west and the flight path is overlain on a TMI image upward continued to 9,500 feet.
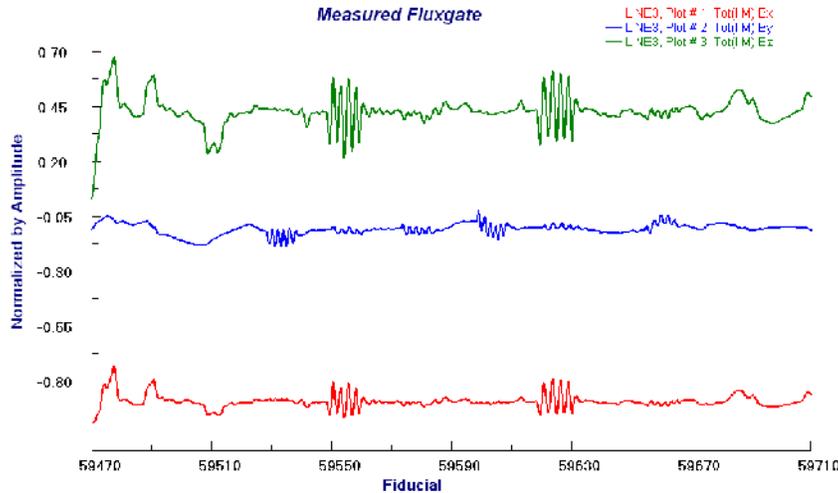
Figure 48: Normalized Measured Fluxgate Data

Figure 48 shows the three component fluxgate data collected along line 1090 normalized to unit amplitude. Note that the Earth's regional magnetic field (IGRF) in the survey region has an inclination of 71.7^O and declination of 11.6^O degrees West and has strength of 55785 nT. The declination changes a total of only 0.16 degrees between the ends of lines. The UTM grid north is 1.46 degrees west of true north in the survey area. The flight altitude is 9500 feet, or 2895 m.

Simulated Fluxgate Data

Prior to simulating the fluxgate data from the GPS attitudes, some analysis of the GPS data had to be done and a methodology developed. This was due to the lack of information on how the fluxgates are mounted on the aircraft. Compensation routines have become relatively robust, so that nowadays, the exact orientation of the fluxgates is not a concern. For the Terraquest aircraft, the fluxgates were mounted deep inside the tailstinger and removing it to determine the orientation met with resistance from the technicians who did not want to tamper too much with a working installation.

In the following, we will refer to O-XYZ as the local coordinate system of the fluxgates.

Utilizing the measured fluxgate data, we can see that for this instrument configuration on this particular aircraft and along Line 1090 that

1. the fluxgate X-component is vertical and positive upward,
2. the fluxgate Y-component is along UTM East,
3. the fluxgate Z-component is along UTM North.

The details of how this was figured out are provided below.

The fluxgate data are normalized by their amplitude. The actual outputs of the fluxgate as measured by the data acquisition system are in milli-volts from which we need only to convert to directional cosines.

The average values of the components of normalized fluxgate data along the entire profile are as below (see Figure 44 above):

$$\bar{Bx} = -0.9 \text{ , } \bar{By} = -0.12 \text{ , } \bar{Bz} = 0.42$$

From this, we can calculate the actual inclination and declination of the magnetic earth field as:

Inclination = 63.9 degrees.

declination to local UTM North = 15.9 degrees West.

Recall that IGRF in the survey region is inclined at 71.7 degrees to the horizontal. The YZ- plane of the fluxgate reference system (O-XYZ) is oriented horizontally as defined by the average directional cosines. Therefore, the X-component is vertical and positive upward as demonstrated by the average fluxgate directional cosines as indicated above.

Furthermore, the magnetic earth's field in the survey region is oriented 11.6 degrees West of north (IGRF) and the UTM grid north is 1.46 degrees west of true north in the survey area. We may conclude that the Y component of measured fluxgate is about 5.8 degrees south of East and the Z component is 5.8 degrees East of North.

Figure 49: Heading of Line 1090, from east to west

We now define an derived (imaginary) fluxgate reference system O-X'Y'Z'. The derived data is calculated from the GPS instruments. It is assumed that the processed relative distance vectors between the GPS sensors are in the UTM co-ordinate system.

In the processing the GPS data from GravMov, three vectors are generated:

In the following :

$\vec{fw}$ represents the vector from fuselage to wing,

$\vec{fs}$ stands for the vector from fuselage to stinger,

$\vec{sw}$ stands for the vector from stinger to wing.

We further suppose that the coordinates of these three vectors in the imaginary fluxgate reference system O-X'Y'Z' are:

$$\vec{fw} = (-1.25, -5.20, -3)$$

$$\vec{fs} = (6.93, -0.25, -0.36)$$

$$\vec{sw} = (-8.09, -4.9, -2.68) \cdot$$

We also assume that the initial position (the first position of the profile) of this fluxgate reference system O-X'Y'Z' is coincidental with the UTM coordinate system. In other words, this fluxgate reference system O-X'Y'Z' is approximately orientated along the UTM coordinate system. Based on this, the fluxgate channels are produced for the setting. Roughly speaking, our X' channels corresponds to Y channels of measured fluxgate, our Y' channels corresponds to Z channels of measured fluxgate, and our Z' channels corresponds to X channels of measured fluxgate.

We also noticed that there is approximately 2.8 second GPS time lag between the two sets of data. This time lag was eliminated when importing the data.

Any two pairs of the three vectors can be independently used to simulate fluxgate channels. There is no significant difference between the results generated with these pairs (see Figures 50, 51, 52).
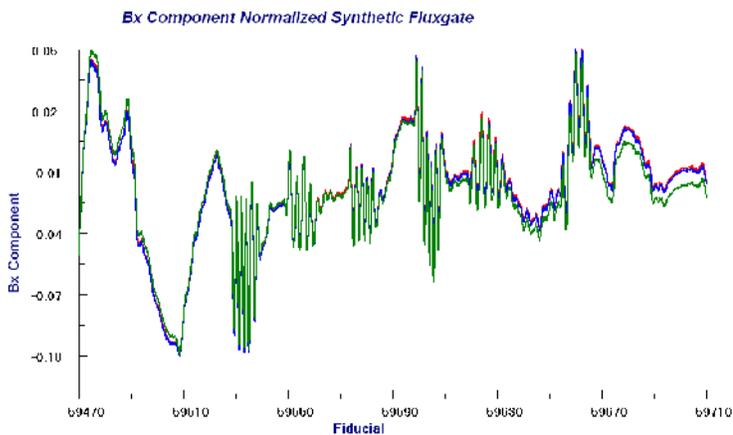
Figure 50: Line 1090: Simulated Fluxgate channel Bx (10Hz data), Red: by FW and FS, Blue: by SW and FS, Green: by SW and FW
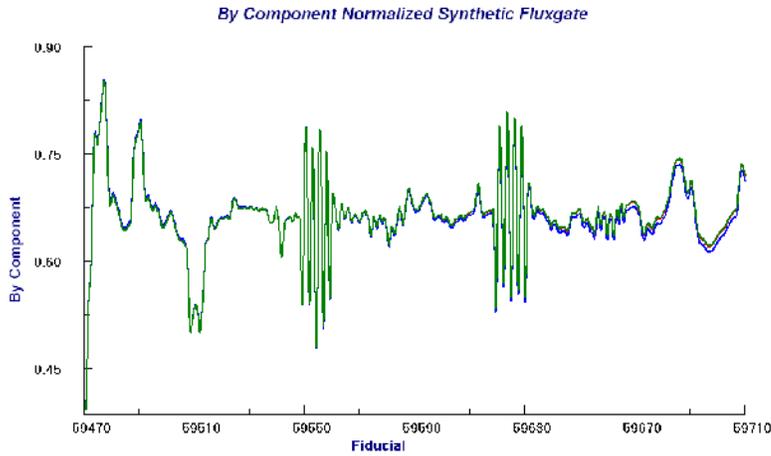
Figure 51: Line 1090, Simulated Fluxgate channel By (10 Hz data), Red: by FW and FS, Blue: by SW and FS, Green: by SW and FW
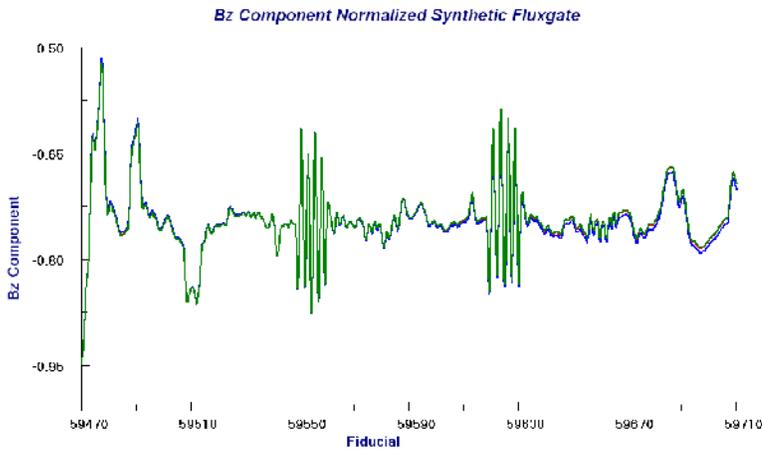
Figure 52: Line 1090, Simulated Fluxgate channel Bz, Red: by FW and FS, Blue: by SW and FS, Green: by SW and FW

There is little difference between the simulated fluxgate channels with each individual pair of GPS vectors, therefore the compensation results generated with three pair of GPS vectors are nearly identical. (see Figure 56).
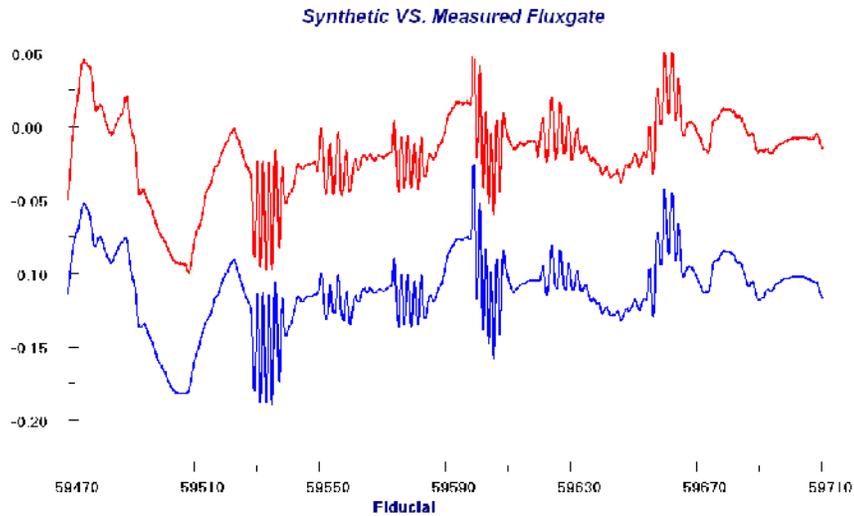
Figure 53: Line 1090, Simulated VS. Measured Fluxgate Channel, Red: simulated Bx'
Blue: measured By
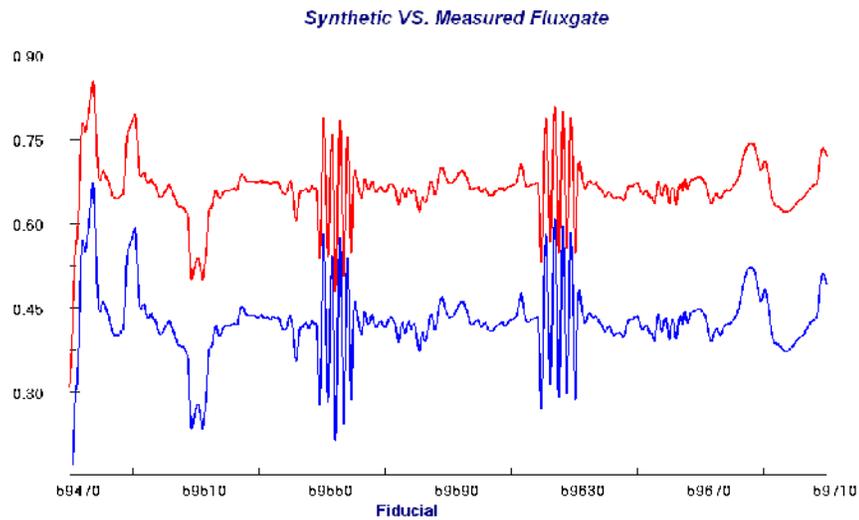
Figure 54: Line 1090: Simulated VS. Measured Fluxgate Channel, Red: simulated By'
Blue: measured Bz

Figure 55: Line 1090: Simulated VS. Measured Fluxgate Channel, Red: simulated Bz'
Blue: measured Bx

The patterns of the simulated fluxgate channels are very similar to the patterns of the measured fluxgate channels. (see Figures 53, 54, 55). The difference between the amplitudes may be due to the different fluxgate orientation (our XY-plane is less dipped).

The GPS derived fluxgate data was then inputted into the compensation routines and the compensation results are shown below.
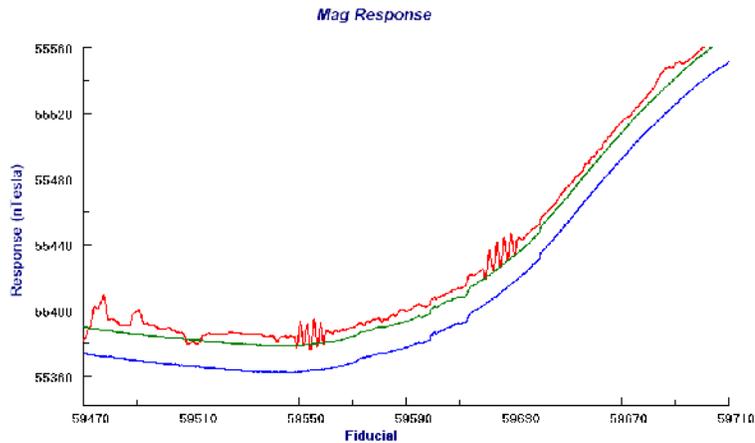
Figure 56: Line 1090 (10 Hz data): Compensation results with vectors VS. Compensation results with measured Fluxgate data, Red: measured Btotal, Blue: compensated total field with FW and FS vectors, Green: compensated total field with measured Fluxgate Channels, Blue and green curves were not shifted
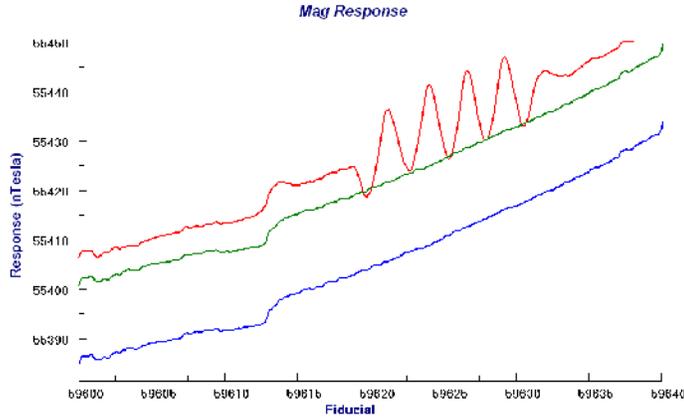
Figure 57: Line 1090 (10 Hz data, enlarged portion of Figure 56 above) Compensation results with vectors VS. Compensation results with measured Fluxgate data, Red: measured Btotal Blue: compensated total field with FW and FS vectors, Green: compensated total field with measured Fluxgate Channels, Blue and green curves were not shifted
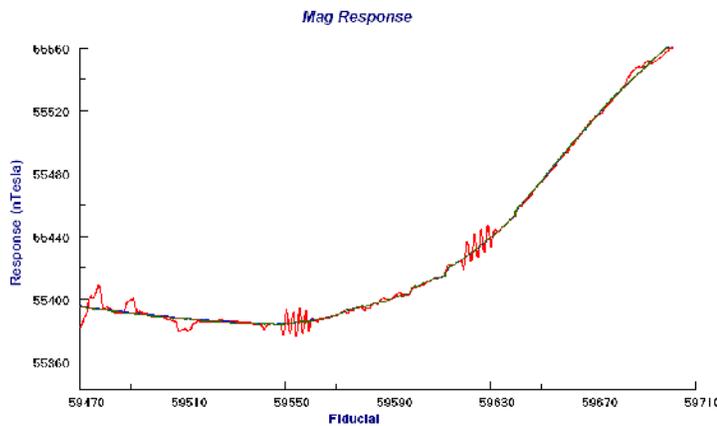
Figure 58: Line 1090 (10 Hz data) - Compensation results with Each Individual pair of vectors, Red: measured Btotal, Blue: compensated total field with FW and FS vectors, Green: compensated total field with SW and FS vectors, Brown: compensated total field with SW and FW vectors
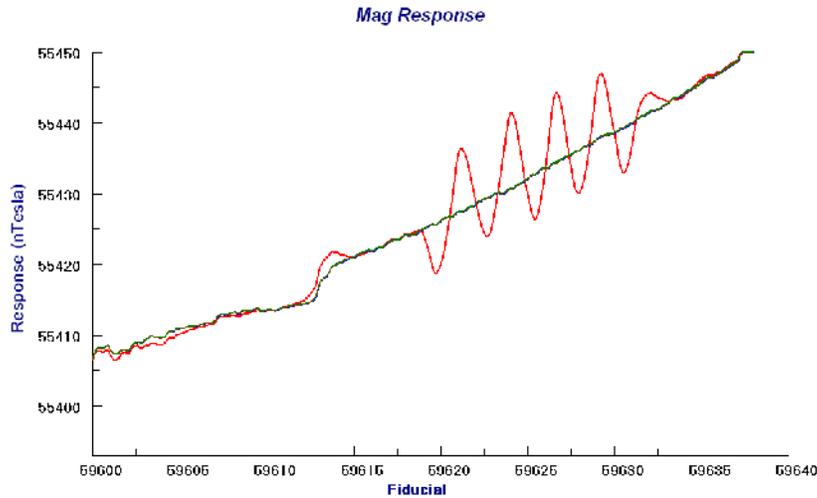
Figure 59: Line 1090 (10 Hz data, enlarged portion of Figure 58 above): Compensation results with Each Individual pair of vectors, Red: measured Btotal, Blue: compensated total field with FW and FS vectors, Green: compensated total field with SW and FS vectors, Brown: compensated total field with SW and FW vectors

The results are always the same no matter which pair of vectors are utilized. This is due to good quality of GPS data (see Figures 58, 59).

Note that the compensation results between the measured fluxgate orientations and the GPS derived orientation are indistinguishable on these plots when the DC offset is removed.

20 Hz magnetometer data

The data acquisition system used on these tests was a modern system, capable of acquiring data at 20 Hz. The magnetometers were also outputting a magnetometer value at 20 Hz. As an extension to the work above, the 10Hz GPS data was interpolated to yield 20 Hz data simulating the sampling rate of the rest of the data. Figure 56 below shows that the 10 Hz GPS data interpolated to 20 Hz still provides sufficient information on the aircraft orientation to provide adequate aeromagnetic compensation.
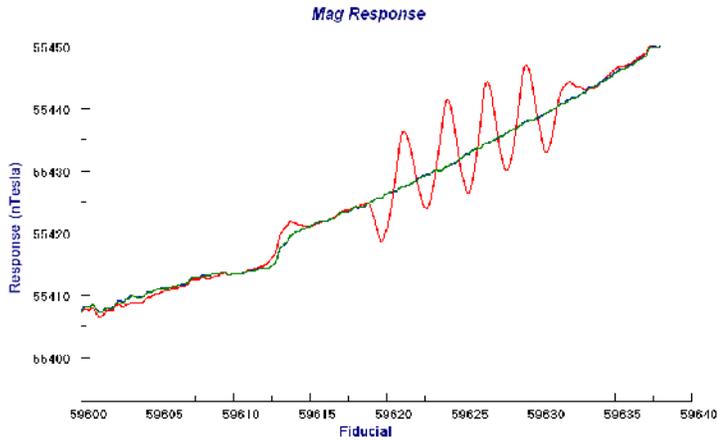
Figure 60: Line 1090 (20 Hz data) Compensation results with vectors VS. Compensation results with measured Fluxgate data, Red: measured Btotal, Blue: compensated total field with FW and FS vectors, Green: compensated total field with measured Fluxgate Channels, The blue and green curves were shifted upward.

There is little difference between the compensation results with GPS data and the compensation results with measured Fluxgate data (see Figures 56 and 57).

4.   BENEFITS TO EXPLORATION IN ONTARIO

The results of this research reaches beyond Ontario, but it is instructive to review the benefits of the results of this research project to exploration in Ontario.

Closer collaboration between Bob Lo, P.Eng. (BHL Earth Sciences) and PetRos EiKon was established for this project. While the two proponents had previously worked on other projects, none was as large in scope and funding as this Aeromagnetic Compensation Project. The working relationship established a link between someone with emphasis on geophysical consulting (Bob Lo) and a group with emphasis on research and software development for the earth sciences. Good feedback from the users' or clients' point point of view was obtained by PetRos EiKon for the workings and implementation of the software. In addition, many of the airborne industries' quirks and folklore concerning the methodology and practise of airborne surveying was supplied by Bob Lo. Bob Lo also had the industry contacts and skills to organize the airborne tests. PetRos EiKon had the research and development capabilities to investigate the mathematics behind the compensation software, to then code up the compensation software, to quickly develop the simulation software to test the software, to advance the software via the implementation of better pre-filtering of the data and more advanced numerical solvers, and to make use of the GPS data collected in the test flights to compensate the data. Without PetRos EiKon's EMIGMA software platform, this project would have been more difficult and a commercial product, partially stemming from some of the research results of this project would either not have been possible, or would be substantially delayed. This closer collaboration has been recognized by the industry in general. The two proponents have sought other projects from the senior mining firms such as BHP and De Beers to extend the traditional aeromagnetic compensation process of scalar, cesium vapour magnetometers, to vector fluxgate or vector SQUID magnetometers, using IMU's or GPS's.

Closer collaboration between the two proponents and Terraquest was established as Terraquest supplied the geophysically equipped aircraft for the flight testing. As a result, Terraquest understands more of the issues of compensation. Their Navajo survey aircraft is now wired for three GPS to be quickly installed, if the need arises. This wiring is now proving to be beneficial as another survey company, Goldak announced that they were installing three GPS's on their survey aircraft at the request of a large diamond exploration and mining company, for the purpose of being able to de-rotate the magnetic fields. They had not thought about using the fluxgate data to compensate the magnetometers, but upon hearing of this work, will consider it.

Closer collaboration between the proponents and Gedex was established after we found out that we both had similar problems trying to get GPS positions to the stated accuracies of the manufacturer. The airborne data collected in the first test was forwarded to Gedex as they are interested in aircraft motions. And when we needed a replacement GPS antenna, Gedex supplied the one that they were not using.

Benefits to the Proponents

1. Quicker development of a commercial compensation routine and better and more reliable compensation results. More thorough understanding of how to obtain the best results is now available to the proponents.

2. More options written into the compensation codes to allow for improvements in the compensation via more judicious pre-filtering, selection of solvers, selection of parameters in the solvers.

3. More testing of the commercial routine to make it robust via testing of the data collected.

4. Better understanding of the aeromagnetic compensation routines

Benefits to Ontario airborne surveying companies

There are five small surveying firms based in Ontario that operate in Ontario and Internationally. These are Terraquest Ltd., Aeroquest Ltd., Geotech Ltd., McPhar Geosurveys, and Flux Geophysics. None conduct any research into aeromagnetic compensation. Thus, to have an Ontario firm conduct research into the fundamentals of the technology that they use and depend upon is of benefit to them whenever they have to compete against larger, and perhaps technologically more advanced competitors.

Technology Transfer

As part of the technology transfer, a booth at the OEGS conference was booked and people were informed of the OMET Project. A talk was also presented, the Power Point presentation of which is included in the digital archive of the data. The talk summarized the progress to date and noted that were surprises in the GPS data and that the expected and quoted accuracies were not obtained. This comment garnered followed up by two individuals. The first, by Bob Komarechka suggested that we investigate using FOG (fiber optic gyroscopes). The second, by Brian Main of Gedex resulted in a very useful comparison of GPS results. It also resulted in a small collaboration between the groups in that (with OMET approval) the GPS and accelerometer data collected by this project was forwarded to GEDEX to help with their analysis of aircraft motions.

In addition to the talk at OEGS, an abstract for an oral paper was submitted to 2004's SAGEEP meeting in Colorado. It was been accepted and the talk presented by Ross Groom.

An extended abstract on the use of GPS receivers for orientation was written and submitted to the 2004 Annual Meeting of the Society of Exploration Geophysicists.

5.   CONCLUSIONS

Software was developed to implement both Leliak's 16 and 18 term linear systems for aeromagnetic compensation. In addition, to more general implementation of a traditional polynomial high pass filter, a Gaussian highpass filter was developed which enabled better control of the filtering process utilized prior to coefficient computation. It is concluded that good compensation coefficients can be generated by applying filtering to total field and fluxgate data rather than to the linear operator matrices.

We also concluded that good interference coefficients can be generated from all lines from a compensation "box".   More precisely, in some cases, a single set of coefficients can be generated from the entire box to be utilized with data collected on any heading. However, in general, coefficients must be calculated which are heading dependent or more particularly in is useful to use diagonals in the "compensation box".

Our capability for building synthetic models of the aircraft noise is invaluable to reveal the relationship between the mathematical theory and physical factors and thus providing useful guidelines for our work. We have demonstrated that ridge regression analysis and truncated singular value decomposition are very effective techniques to improve the predicative power of the 16-term and 18-term interference models, particularly in the case that there exists linear dependence in the interference terms. The variation of solutions of the linear systems with different mathematical techniques as well as the use of GPS orientation information have been investigated and has been presented.

Experiments with different highpass filters with different filter characteristics and with different numerical solvers on real and synthetic data indicate that the best possible compensation can only be accomplished via good selection of filters and solvers. While a single filter and solver combination can be robust in producing a useable set of compensation coefficients, we believe that no single filter or solver can produce the best possible compensation. However, we do believe that it is possible to build into compensation software the capability to optimize automatically for the best possible results.

This work has demonstrated that aeromagnetic compensation can be accomplished using three GPS sensors judicious mounted on the survey aircraft. The attitude input for compensation is accomplished at the present time by generating synthetic fluxgate data for post-flight input into the compensation routines developed at PetRos EiKon Inc.   It is envisaged that this work can be expanded to include other aircraft orientation devices such as Inertial Measurement Units. With the use of the GPS orientation, noise resulting from erroneous fluxgate attitudes over magnetic terrains will be avoided. This still has to be proven in airborne tests. De-rotation of gradient magnetometer readings, although not done yet, can be implemented relatively easily with the GPS orientation.

Future work will consist of developing compensation routines for vector magnetometer data using the GPS or other non-magnetic field based orientation devices such as IMU's, to avoid the circular arguments mentioned earlier.

Finally, the work performed in this project has benefited exploration in Ontario by creating better collaboration between the proponents, via the demonstration that GPS sensors can be used for compensation so that better aeromagnetic data can be obtained in the magnetic

terrains of Western Ontario, and via the technology transfer of this research to the small, mostly Ontario based aeromagnetic acquisition contractor who cannot otherwise conduct research into this subject.

ACKNOWLEDGEMENTS

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