The USGS High-Altitude Magnetic Mission – Instrumentation Challenges

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Abstract

The United States Geological Survey (USGS) is embarking on an ambitious program to carry out a high-altitude areomagnetic survey of the continental U.S. and Alaska, using a modified Canberra bomber aircraft, to be flown at an altitude of 15 km (50,000 feet) with a line spacing of approximately 16 km. The main purpose of the survey is to bridge the wavelength gap between numerous low-altitude surveys and the orbital-altitude Magsat data.

The areomagnetic mapping is to be carried out simultaneously in the aircraft with a NASA-funded radar mapping project, aimed at producing high accuracy elevation data and high resolution surface imagery.

Two flight tests with a cesium magnetometer mounted in a stub at the tail of the Canberra showed that the bare aircraft can be compensated by conventional methods, albeit with some difficulties, and that with a proposed 12 foot (3.66 m) tail boom, good compensation should be assured. However, the radar instrumentation will consist of three transmitter/receivers, one in each wingtip and one in the belly, each of which could require up to 125 amperes of non-stationary DC power! The varying magnetic fields associated with these power systems could create an enormous problem for the magnetics system, possible completely masking the low-level geologic signals seen by the magnetometer. A related problem is that compensation will have to be carried out with the radar system in full operating mode and it is expected that to avoid danger of exposure to high levels of EM radiation on the ground, compensation may have to be carried out at survey altitude. At high altitudes, the aircraft's manoeuvrability is quite limited and the necessarily slow compensation manoeuvres will have some of the same frequency content as the long-wavelength anomaly signals expected at these altitudes. These anomaly signals can be expected to degrade the compensation results.

This paper explains some of the compensation problems and shows a compensation result from the bare aircraft. I will also show the results of a study done on another aircraft, in which magnetic interference pulses from VHF radio transmissions are compensated, with the hope that the technique involved can be extended to be helpful in compensating the variable magnetic effects of the radar supply currents.

Introduction

The High-Altitude Magnetic Mission (HAMM), scheduled to start late in 2003, funding permitting, will provide data that will benefit a number of areas of study in crustal geophysics, lithoshperic studies, continental-scale structures and geological tectonic processes, to name but a few Ref. (1). It will also form a reference field for joining hundreds of low-altitude surveys taken over many years, at diverse altitudes with varying standards for instrumentation and navigation, into a very useful, coherent database. The HAMM is to be flown concurrently with a NASA-sponsored radar survey, IFSAR, standing for "Interferometric Synthetic Aperture Radar"; this concurrency will make the magnetic survey affordable. The specifications of the survey are mostly defined by the radar project, such as the survey altitude of 15.24 km (50,000 feet), with line spacing of approximately 16 km (8.6 nm), but these specifications turn out to be very satisfactory for bridging the gap between the low-level surveys and the orbital-altitude data from Magsat and Oersted missions. The survey lines will be long, each covering roughly half of the continental United States, starting first with the western half. The USGS would like to extend the lines to include 300 km of the coastal margins, which would be beyond the IFSAR mapping; this will be done if additional funding can be secured.

This magnetic survey will be different from just about every other survey done to date. In the conventional areomagnetic survey, where the anomaly total field is of prime interest, usually the regional value of the field is removed early in the process. However, in this case it is the absolute value (or "DC" value) of the field that is required. To make this type of measurement accurately and consistently from flight to flight is difficult and is seldom undertaken. In support of the creation of the North American Magnetic Map in the 1980's, the National Research Council of Canada's Convair 580 flew a few continental-scale lines roughly in the north-south direction, using an observatory test point near Ottawa (Bourget ,ON) to establish calibration of the aircraft's magnetic instrumentation. Maintaining this calibration from flight to flight was a challenge and a significant source of error. Another source of error was the scarcity of ground magnetometers or magnetic observatories along the flight lines to estimate the diurnal variations. These same challenges must be met on the HAMM.

The survey aircraft will be a modified 1950-vintage Canberra bomber, built by English Electric, owned and operated by Air Power Inc. of Lakewood, California (Figure 1). With a service ceiling of 60,000 feet and a survey true air speed of 400 knots (741 km/h), it is well suited for the project, although as can be expected there are magnetic challenges associated with the airframe and systems.

This paper discuses the general challenges facing the project and then focuses on instrumentation and compensation

The Challenges

1. Tracking the Diurnal Magnetic Variations

Long-period secular variations of the earth's magnetic field and shorter-period variations caused by ionospheric events are loosely classed as "diurnal". The wavelengths involved most certainly fall into the spectrum of the anomalies to be measured at 16 km altitude and will cause significant errors if not accurately measured and tracked. The International Geomagnetic Reference Field (IGRF) is inadequate for the short-period, dynamic prediction required for this survey. NASA studies based on Magsat and POGO satellite data have resulted in a "Comprehensive Model" of the near-earth magnetic field that unifies earth-core current models with solar-induced and other ionospheric models. Known as "CM-3", it will be essential to the HAMM, but considerable further development is required to introduce surface observation data to supplement the satellite data on which CM-3 is based. The distribution of dedicated magnetic observatories in the US and Alaska is far too sparse for HAMM and a series of movable ground stations has been proposed for the survey. An along-line spacing of 300 km is considered optimum, but 600 km is a more likely compromise. All ground data will go into refining CM-3. This will be a tremendous development effort and will take place *as the survey is flown*. Further development will be required to extend the data from earth surface to the survey altitude.

The network of ground stations is itself a challenge. It is expected that along-track universities will be the key to operating these stations. The logistic questions of equipment supply, quiet-site selection, time synchronization, data transmission and quality control, will have to be addressed.

2. Compensation and DC Calibration

These two items can be discussed under the same heading, but the difference must be clearly understood. Compensation consists of modelling the magnetic signature of the aircraft and based on the coefficients of the model, cancelling the corresponding interference in the magnetometer signal. This is critical to recovering good geophysical data because the interference signals, which are generated by magnetic and conductive material relatively close to the magnetometer, can completely mask the distant magnetic anomaly signals that fall of as the third or fourth power of distance. The interference signals are a complex mixture of the sum of permanent and induced magnetic sources, as well as eddy current sources (from large conductive surfaces), plus certain non-linear effects. They are generated by motion about the aircraft axes and have spectral content from about twice the aircraft's natural frequencies, right down to DC. It is this DC component that is particularly important for the absolute-value measurement of field as in the HAMM.

Data to solve for the coefficients of the interference model are collected by flying the aircraft through its normal attitude operating envelope, (constrained by the attitude operating limits of the magnetometer), with representative pitch, roll and yaw manoeuvres. In solving for the coefficients, the DC value of the total field must be removed from the data; we do not want to model out the desired signal! This can be done in two ways:

a) By modelling the ambient total field experienced along the flight path during the compensation data collection and subtracting it from the data. This has to be an iterative process to separate interference influences from the ambient field that we are trying to model. The method has the disadvantage that even with a higher-order power model of the field, the separation is not complete and the l results are not good in terms minimizing the residual.

b)The DC value of the total field can be removed by high-pass filtering the signal at a frequency below the lowest natural manoeuvre frequency of the aircraft. This results in a very low residual, often as low as 10 to 20 pT and is the usual and preferred method. It has the disadvantage that the DC accuracy of the compensated signal is lost. However, a combination of experience, flights over calibrated reference points and the use of ridge regression in the solution (Ref. 3), have resulted in compensations where the DC value is close to correct Having the correct (or almost correct) DC value means that the "near DC" signals, which include the errors with changes of heading, are also close to correct, i.e. the errors at these low frequencies are minimized.

For an absolute-value survey, "nearly correct" DC value is just not good enough. Furthermore, very few aircraft maintain their DC calibration from flight to flight. There are a number of reasons for this, such as shock-magnetizing of the undercarriage on landing, the high fields associated with starter currents causing hysteresis effects in permanent magnetic components, thermal magnetization and demagnetization in engine components, certain maintenance procedures carried out with non-demagnetized tools etc. The more complex the aircraft systems suite, the greater the chance of DC variability in the magnetic signature, and the Canberra, with its complex array of radars, will be a very complex system.

2.1 DC Calibration. With the uncertainty of the DC calibration point after conventional compensation and the much greater uncertainty from flight to flight, the only way to establish a measurement reference is to fly the aircraft over a known point that is "tied" to a magnetic reference station on the ground, which in turn, is tied to the reference system for the survey, the Comprehensive model or the IGRF. All systems have to be operating exactly as they would be on the survey, including the full IFSAR suite. To do this sort of calibration in a conventional survey aircraft at low altitude, as for example, over the Ottawa Bourget test point, is straightforward. However, it is not clear if the IFSAR can be safely operated at low altitude, meaning that the DC calibration (and the compensation) may have to be done at high altitude, possibly as high as the survey altitude. At whatever altitude, the point will have to be established by another survey aircraft whose DC calibration is well defined. This will be a problem if the calibration point and the compensation area have to be above the service ceiling of conventional survey aircraft. The flying of the point would have to be very accurate with good DGPS guidance and it would have to be in a very low gradient area in order to minimize small positioning errors. This low-gradient area should be on the transit path between the aircraft base and the start of the survey lines in order to minimize flying time, which will be very costly.

An alternative to flying calibrated point might be to establish a short line (again, on the transit path) that has a recognizable anomaly structure. This line would be flown for each flight and the DC *difference* from flight to flight would be known, once the diurnal was taken into account. This would avoid the necessity of an absolutely-determined calibration point and perhaps after all data have been processed, somehow a final DC datum can be selected. In any case, for each flight, whether the method be absolute value or relative DC shift, some calibration flying will have to be done.

2.2 Compensation. The necessary manoeuvres may have to be done at a high altitude, for the reasons given above. The pitch, roll and yaw manoeuvres are normally done on four headings in a square pattern, in as low-gradient area as can be found, Low gradient is especially important for the Canberra because its manoeuvre envelope is quite limited at altitude and the manoeuvres have to be very slow, e.g. 25 seconds for a ± 5^o roll. The wavelength of such manoeuvres is approaching that of the anomalies expected at the survey altitude. The compensation high-pass has to be set to a very low, 0.02 Hz, to accommodate the slow manoeuvres but it will not exclude the all the ambient field anomalies, which will bias the compensation solution and lead to degraded results. (In conventional aircraft compensation, with faster manoeuvres, the high-pass can around 0.1 Hz, which excludes all but the very longest wavelength anomalies). If as expected, the compensations have to be done at high altitude, the low gradient area will be mandatory.

The compensation procedure takes about fifteen minutes in the Canberra, Changes in the magnetic signature of the aircraft from flight to flight, will cause degraded compensation and manoeuvre noise in the data. Fortunately, compensation does not have to be done for each flight; small errors in compensation can be corrected by a "trim-up" procedure, consisting of several small pitches and rolls on the run-in to the survey line, which adjusts the compensation coefficients without changing the DC calibration point.

3. Variable Radar Supply Currents. This is by far the greatest challenge faced by the project. In a magnetic survey aircraft, DC currents must be absolutely stable during compensation and survey flying. Even the smallest change in the power configuration, such as turning on a cabin light, can cause a significant change in the DC calibration of the magnetometer signal, as well as degraded compensation. The three radar transmitters will be powered by its own inverter, each of which may use up to 125 Amperes of DC current. Such currents will have an enormous effect on the magnetometer signal. The effects could be lessened if the DC power were supplied with positive and negative in wires as twisted pairs. This has been requested, but there is no assurance that such a modification is feasible. As presently proposed, the negative power returns from the inverters will be through the airframe, which cannot be considered as a stable path. Furthermore, it is highly unlikely that the current requirements of the radar systems will be constant throughout a survey flight.

The only foreseeable solution to the problem of variable currents is to have current monitors on each of the three supply lines and to modify the compensation coefficients based on the measured currents. DC currents can be viewed as "permanent" magnetic sources and therefore, only the three permanent compensation terms should be affected. It is hoped that a) for each inverter, the changes to the permanent terms will be a linear function of current and b) that the linear relationship for each inverter will hold when all three are operating together (i.e. there is no magnetic "cross talk" between the inverter currents).

To solve for the permanent term changes for each inverter, the aircraft will have to be flown through compensation manoeuvres in its final survey configuration with the radars in full operation. For each inverter, there will have to be at least two distinctly different current values on each of four headings in order to solve for coefficient changes and to establish the linear relationships. This will require a considerable amount of careful flying..

4. The Error Budget. The targets set are for the magnetic measurement is 1.2 nT rms (or 5 nT peak-to-peak for a sine wave). The same error values are the target for the error in diurnal measurement as given by the Comprehensive Model when finally developed. Given the challenges outlined above, achieving errors within these bounds will represent an unprecedented achievement.

Results to Date

1. Compensation. In October of 2002, the Canberra did a short test flight that consisted of a four-heading compensation and two short lines flown in reciprocal directions on roughly similar paths. The flight altitude was 17000 feet. The instrumentation consisted of a cesium magnetometer mounted in a stub, or bubble at the tail of the Canberra and of a vector magnetometer mounted in the aircraft's belly. A data system recorded data at 40 Hz. After the flight, a number of ground tests were done on the aircraft to clarify findings from the flight. Certain magnetic disturbances seen in flight were reproduced on the ground and their effect was measured at a distance of 12 feet behind the tail to simulate the signal that would be expected with the proposed 12-foot tail boom.

The most noticeable artifacts in the data were short disturbances of from 20 to 80 nT, lasting for about one second, occurring every couple of minutes throughout the flight. These turned out to be from the pilot's pitch trim system. In the Canberra, the whole, massive horizontal stabilizer is moved by a large electric motor to achieve pitch trim. In ground testing, the magnetic disturbance was greatly reduced by providing twisted pair wiring for the motor power and the activating relays. There was a small amount of magnetic hysteresis as the stabilizer moved from one position to another, but at the twelve-foot position, it was greatly reduced'

The trim glitches were removed by interpolation across the intervals of the disturbances and the coefficients of a 28-term compensation model were solved for the four-heading, twelve-minute compensation. The compensation statistics were

Stdev UC	Stdev CMP	IR
34.801	7.9140	4.397

where the first two numbers are standard deviations in nT, uncompensated and uncompensated respectively, and the improvement ratio (IR) is the ratio of these two numbers. Figure 2 shows the compensation results. The two positive-going "humps" in the compensated residual are local field anomalies; no attempt to find a low-gradient area for the compensation was possible given the shortness of the flight. The manoeuvres can be clearly seen in the uncompensated trace and they are only about half the wavelengths of the humps. The compensation high-pass used was 0.02 Hz, giving a bandwidth broad enough to include the manoeuvres, but not tight enough to discriminate against the background anomalies. This illustrates the point made in Section 2 above, that a low-gradient area is essential for achieving good compensation with the Canberra at high altitude. In Figure 3, the IGRF for the area is plotted with the compensated residual, showing that in a low-gradient area, a quite respectable compensation could be obtained.

Figure 4 shows the compensations applied to the two short test lines. It is clear that the compensation is effective, especially during the turn between the lines. The arrows mark the extent of the lines. The lines should be more level in the DC sense, but the pilot was not using GPS to ensure track repeatability. For neither trace were the trim glitches removed, nor was the noise swath in the compensated trace, which was due to noise from the vector magnetometer. The real message from this phase of the flight is that the coefficients from the compensation are robust.

2. Compensation of an Electric Current Disturbance. Using data from the NRC Convair 580 research aircraft, I did a study that might lead to methods of mitigating the effects of variable radar currents in the Canberra aircraft. In the Convair, VHF radio transmissions always produce "glitches" or pulses in the aircraft's magnetometers. It was determined that the source was simply the 28 volt DC current to the transmitter(s). Thus, the glitches should be compensatable by adjusting just permanent coefficients.

In searching through a long aeromagnetics flight, I found 15 "pulses of opportunity". Figure 5 shows a cluster of six such pulses.To put the pulses on a level baseline, the total field was de-trended by subtracting from it a low-passed version of itself (a 500-point boxcar, sample rate 32 Hz). The amplitude of the onset of the pulses was measured graphically and the values are shown in Figure 5. The onset occurred over three data points, at the approximate centre of which, the three field values of the vector magnetometer were recorded. This gave sufficient data for a compensation. Most of the pulses occurred on magnetic headings between 270^o and 330^o, which would not lead to a very robust solution, but fortunately, four occurred during a turn from $72\,^o$ to $30\,^o$ (the negative-going values in Figure 6). A three-term compensation (permanent terms only) produced the compensated residual shown in green. It can be seen to be pleasingly low. The corresponding permanent coefficients (Lateral, Transverse and Vertical) in nT were

L	T	V
1.30237	1.70536	-0.02465

These values were added to the normal permanent coefficients during the whole duration of the pulse disturbances. The result for one cluster of pulses is shown in Figure 7.

It should be noted that in this study, the pulses were the result of a *constant* DC current. To test the method for a variable current source, a dedicated experiment would have to be carried out with accurate measurement of the DC current and with data taken at least at tow different current values, over a wide range of headings, in order to prove that the changes to the coefficients are linear functions of the current.

Summary and Conclusions

The HAMM project is is its very early stage of development and there have only been three magnetometer test flights with the Canberra aircraft. The technical challenges facing the project are tremendous, especially the joint operation of the magnetics system with the high power radars and the likely complication of having to do all test flying at a very high altitude. However, a great deal has been learned from the testing to date. We do know that the aircraft is compensatable, as illustrated in this paper. Ground tests show that magnetic data artefacts will be minimized by the use of a 12-foot tail boom. Theory and experiment indicate that variable current effects can be accommodated, although with the sheer size of the radar currents, measurement accuracy may become an issue. Finally, I emphasize the importance establishing the DC reference for each flight and the necessity of doing compensation in a low gradient, anomaly-free area.

References

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Acknowledgements

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Figure 1 -

The Canberra Aircraft

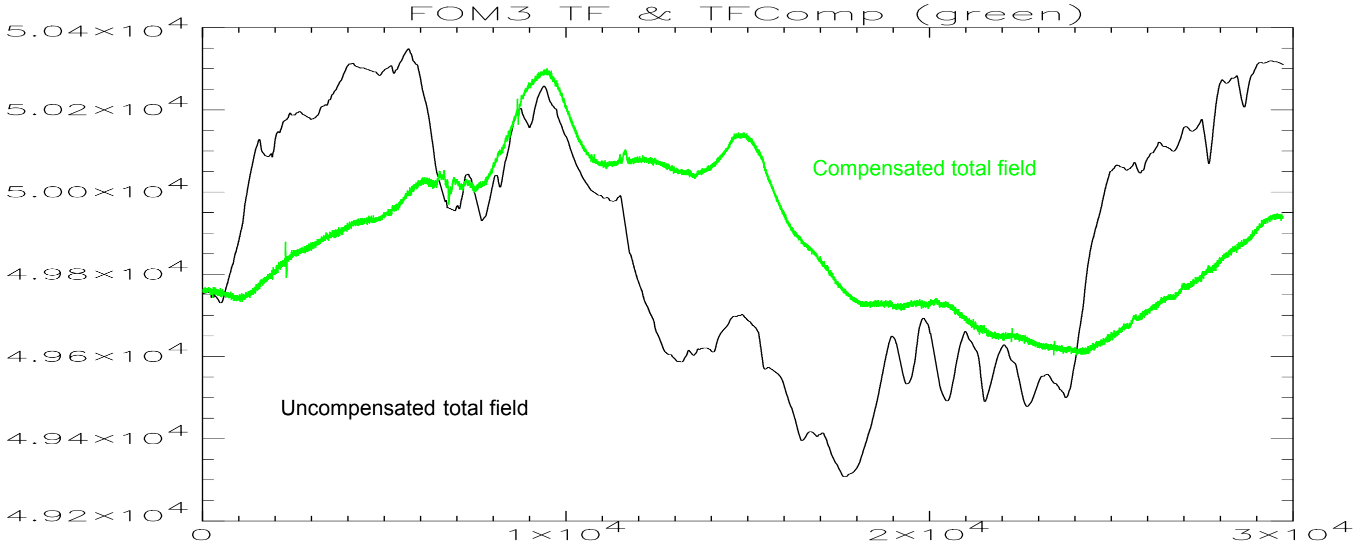

Figure 2 – Compensation Result

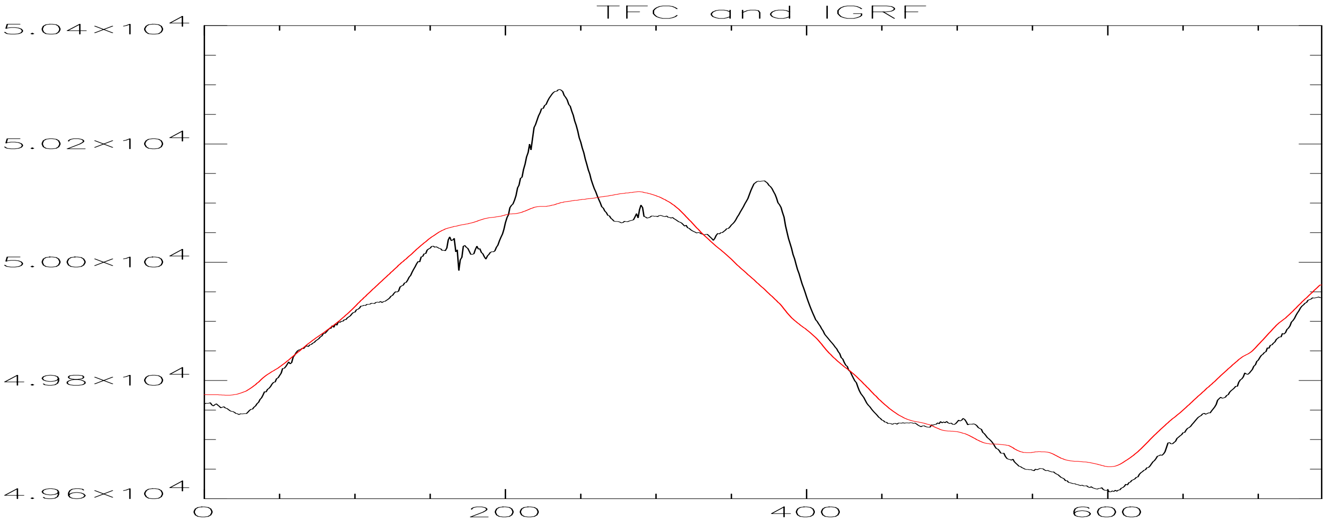

Figure 3- Compensated Total Field vs. IGRF

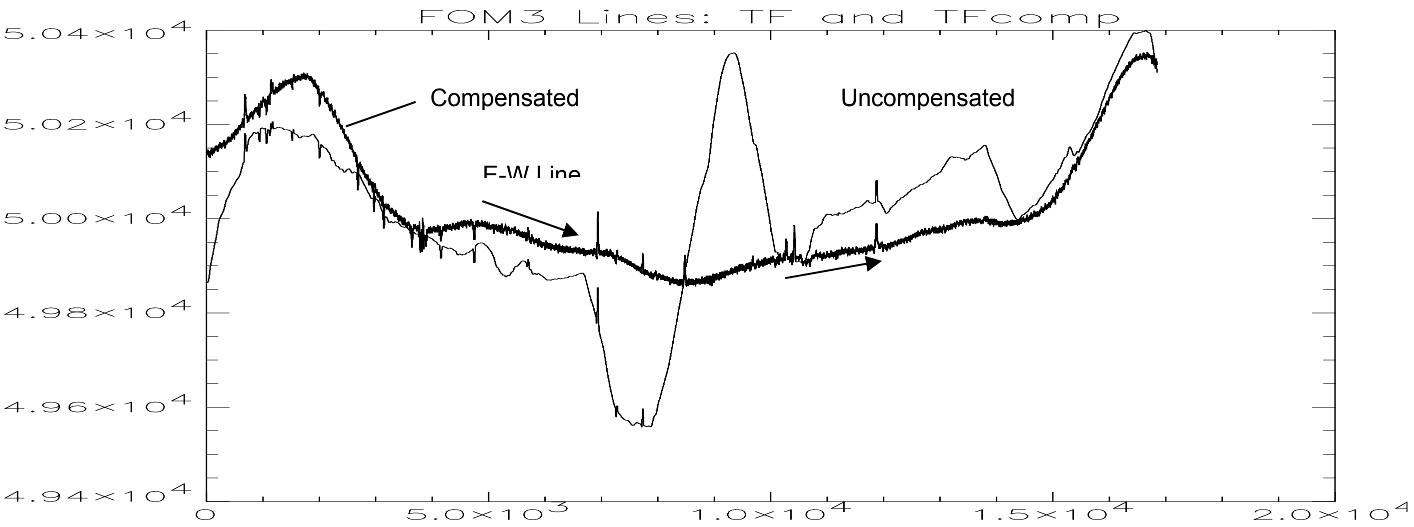

Figure 4- Two Test Lines

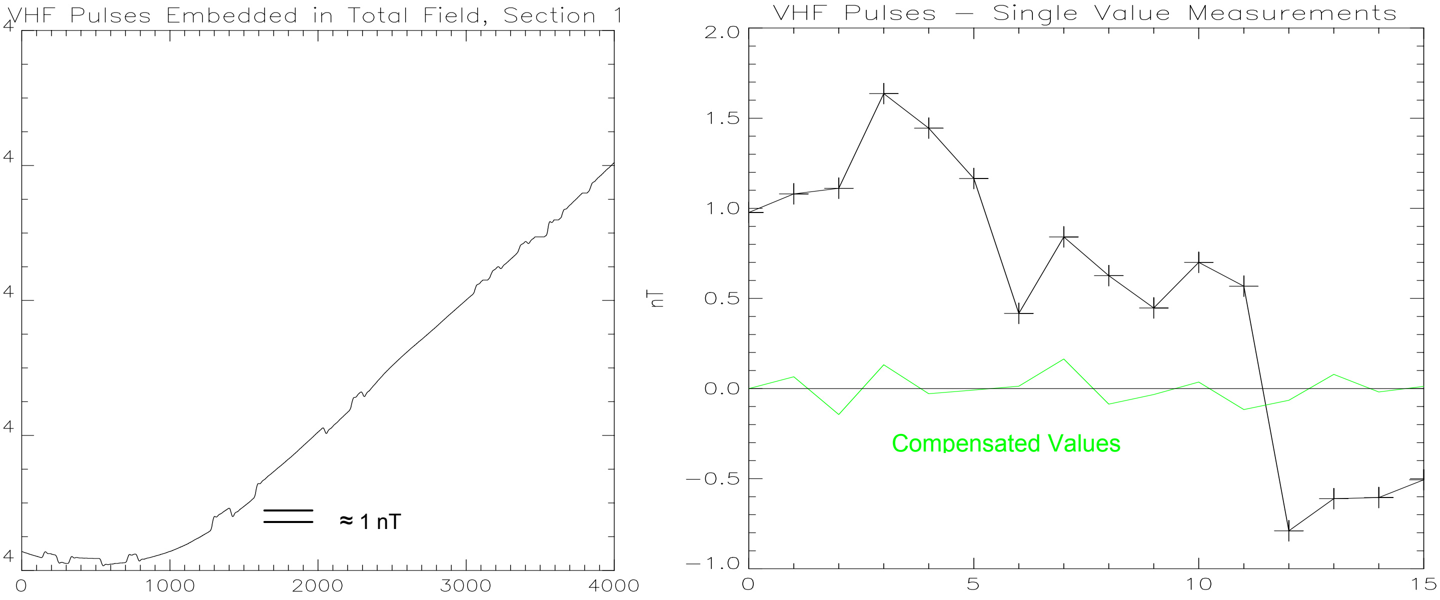

Figure 5 – VHF Pulses in Total Field

Figure 6 – VHF Pulse Step Onset Values

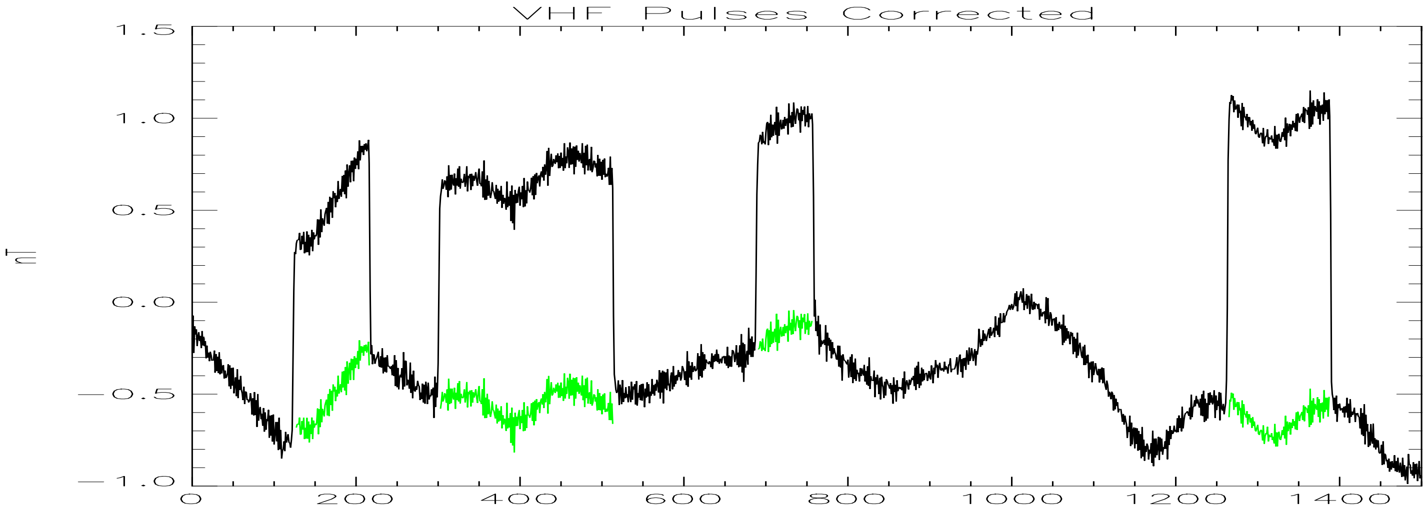

Figure 7 – VHF Pulses Removed from Total Field