The use of GPS sensors and numerical improvements in Aeromagnetic Compensation

Ruizhong Jia, PetRos EiKon, Concord, Ontario, Canada
R. W. Groom, PetRos EiKon, Concord, Ontario, Canada*
Bob Lo, BHL Earth Sciences, Thornhill, Ontario, Canada

Summary

Aeromagnetic compensation for the magnetic effects (noise) of the aircraft is now a significant limiting factor in the final data quality. Fundamentally, the residual noise from the aircraft movement after compensation is still 100's of times larger than the signal to noise capabilities of a modern cesium sensor. 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.

Surveys over magnetic terrains face the additional problem that the aircraft attitude required for the compensation techniques are often incorrect. This is due to the measurement of the aircraft attitude via the use of a vector fluxgate magnetometer and the assumption that the Earth's field is uniform. This problem is envisaged to increase as surveying heights get lower and lower, increasing the anomalous magnetic field sensed by both the vector fluxgate and the airborne magnetometer. Non-magnetic orientation devices, such as the use of three GPS receivers on the aircraft are an obvious solution to this problem.

The results of this work demonstrates that it is possible to use three well spaced GPS receivers on an aircraft to measure the aircraft attitude to the precision required to compensate for the aircraft effects.

The experiments with the different highpass filters used on the data and with the different solvers indicate that with the proper selection of filters and solvers, better compensation results can be obtained.

Introduction

In 1961, Leliak (1961) published a paper outlining a mathematical technique for estimating and removing the effects of an aircraft from magnetic data collected from a served total field magnetometer. The basis of this technique is a system of linear equations which attempts to represent the permanent and induced magnetization, and the electromagnetic effects due to an aircraft as a function of the attitude. The standard approach to solving the magnetic compensation system of equations is to fly a high altitude series of pitch, roll and yaw maneouvers in a "compensation box" while collecting aircraft attitude and magnetometer data. The data from these flight paths are then used to determine up to 18 coefficients relating to the motions and the linear equation system is then usually solved with a least-squares method. The resulting coefficients are then used to remove the aircraft's effects from survey data flown at a lower survey altitude. The attitude of the aircraft is usually determined from strapdown, three-component vector fluxgate magnetometers on the aircraft. Leliak's system of equations has been the basis of commercial compensation systems to the present time.

Using the vector fluxgates to measure the aircraft attitude results in several problems which may be solved via GPS or other attitude inputs. Obtaining the aircraft attitude with fluxgate measurements assumes that the Earth's magnetic field is more or less uniform over the survey area. In magnetic terrains, where local variations in the magnetic field intensity and direction can be significant, erroneous attitude and therefore erroneous compensation results will occur. If vector magnetic data, such as SQUID magnetometers are used to measure magnetic data, the compensation of vector SQUID data with vector fluxgate data may be somewhat circular. Thirdly, for gradient data collection, GPS-based compensation will allow for accurate determination of magnetic gradients and its de-rotation into a global frame of reference.

As part of the process of determining compensation coefficients from the flight box data, it is generally considered necessary to highpass the data to remove the lower frequency information from the data to provide more accurate and stable solutions. We have implemented the Gaussian high pass filter which enables us to better control the filtration process utilized in the coefficients 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 as is traditionally done. We also concluded that good interference coefficients can be generated with all the box lines.

We have been studying the suitability of the basic equations through the use of synthetic data, the variation of solutions with different mathematical techniques for solving the equations as well as the use of GPS orientation information. In particular 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, especially in the case that there exist multicolinearities in the interference parameters .

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Later papers by Leach (1979a, 1979b) discussed the variety of factors affecting the accuracy of the so-called “compensation” of the aircraft including the non-orthogonality of the fluxgate sensors, the effects of regional gradients as well as techniques for solving the equations for the coefficients. Leach studied the sensitivity of the coefficients as a function of band pass filtering and introduced 3 gradient terms into the 18-term model to establish a complete interference model involving 21 terms. To improve the computation of the coefficients, he experimented with various techniques to solve 16 and 18-term linear equation system, such as, stepwise regression analysis, rank deficient singular value decomposition, and ridge regression analysis. It has been demonstrated that application of ridge regression analysis permits useful and stable compensation results.

Filtering and Coefficients Computation

In a real airborne compensation flight, 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.

Based on our experiments with synthetic models 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.

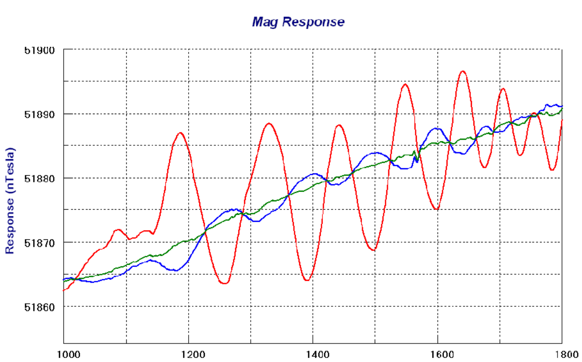

Figure 1: Example of different Gaussian filters on compensating data: Red - original total field data, Blue - compensation results with SVD10 and Gaussian filter with lag = 4, Green - compensation results with SVD10 and Gaussian filter with lag = 31

The system of equations is large and may be ill-conditioned. It was decided that different solvers would be implemented in the compensation routines to determine if using different solvers would yield better results. 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 flown for the OGS.

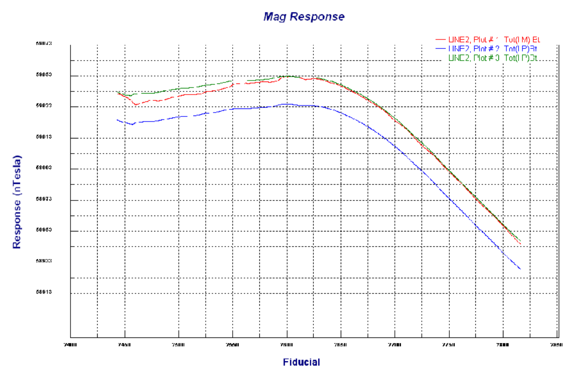

Figure 2: Example of using different number of eigenvalues/eigenvectors in a SVD solver. Red- original measured, Blue-no truncation, Green - first 10 eigenvalues/eigenvectors are kept

Figure 2 above shows that a DC shift in the compensated data is introduced by one of the last eighenvalue terms. Other than the DC shift, there are very minute changes in the compensated values between SVD solver that use different numbers of terms. Further tests show that Conjugate Gradient generates more or less the same results as standard SVD, even though the initial guess of solution is set to a independent unit vector individually.

Other solvers, such as generalized inverse matrix, inverse real symmetric definite matrix, eigenvalues and eigenvectors of real symmetric matrix generates the same results as standard SVD.

The most promising method to improve the magnetic compensation coefficients computation is probably a Truncated SVD. Ridge regression appears to be the safest.

Compensation with GPS sensors for aircraft attitude

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To measure the attitude of the aircraft, three GPS antennas were installed in Terraquest Ltd.'s twin engine Piper Navajo, registration CF-XKS, which was fully equipped with an airborne gradiometer installation. Low loss coaxial cables were run from inside the fuselage, treaded through the wing spars to the port 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.

Three Novatel Millenium, geodetic grade, dual frequency GPS's from Devtec were rented and installed inside the aircraft cabin. As well, three notebook computers with serial ports were installed into the aircraft to be used with each GPS receiver. Figure 2 shows the three Millenium receivers and one of the laptop data loggers inside the Navajo aircraft.

Figure 3: – picture of the three GPS receivers and one of the laptop computers used for datalogging.

For the test flights, a fourth Novatel Millenium receiver was used as a base station, some 40 to 50 kms from the test area. The GPS was recorded at 10 Hz, the same sampling rate as the vector fluxgate. At first, the base station data was used to differentially process the GPS to yield the X, Y, Z positions from the three antennae, which can be used to determine aircraft attitude. However, the positions in the three GPS receivers recovered in this manner had relative errors of several metres and was deemed to be not accurate enough for input into the compensation routines.

GPS processing then used a specialized commercial routine which processed for the relative orientation between two GPS moving GPS antennas. Three vectors are generated and are termed: the vector from fuselage to wing (FW), the vector from fuselage to stinger (FS), and the vector from stinger to wing (SW).

The strategy to quickly use the GPS vectors for this research was to simulate the fluxgate channels for input into the compensation routine. Any two pairs of the three vectors can be independently used to simulate fluxgate channels.

Figure 3 shows simulated fluxgate channel, Bx, from the three possible pairs of GPS vectors. There is no significant difference between the results generated with any of these pairs demonstrating a robustness to this method and the relative accuracy of the GPS measurements.

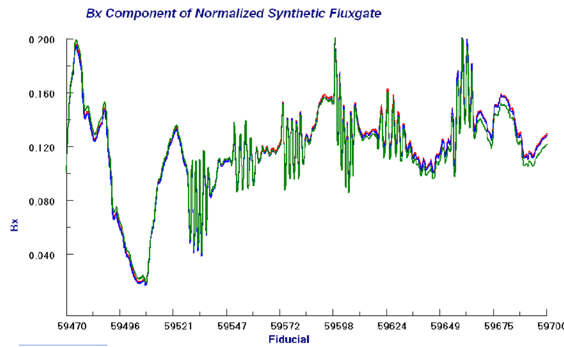

Figure 4: Line 1090: Simulated Fluxgate channel Bx, Red: by FW and FS, Blue: by SW and FS, Green: by SW and FW.

Figure 5 shows the measured fluxgate channel, Bx versus the simulated Bx. The plot shows that the relative variations of the simulated fluxgate channels are very similar to the patterns of the measured fluxgate channels. The difference between the amplitudes may be due to either fluxgate calibration issues, or an orientation of the fluxgate which is slightly different than assumed.

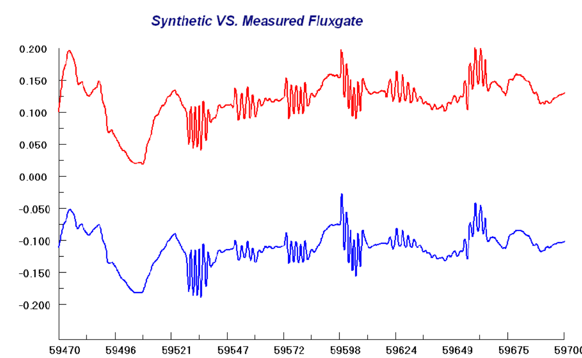

Figure 5: Line 1090 - Simulated VS. Measured Fluxgate Channel, Red: simulated Bx, Blue: measured Bx.

We were then able to use the simulated, fluxgate data as input into the compensation routines. Figure 6 shows the entire line 1090 compensated using the measured fluxgates and the simulated fluxgates. The differences between the two methods can not be seem in Figure 5.

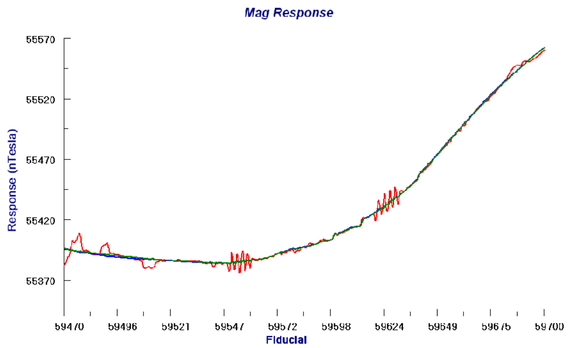

Figure 6: Line 1090 – Comparison of compensation results, Red: measured Btotal, Blue: compensated total field with GPS vectors FW and FS vectors, Green: compensated total field with measured Fluxgate Channels.

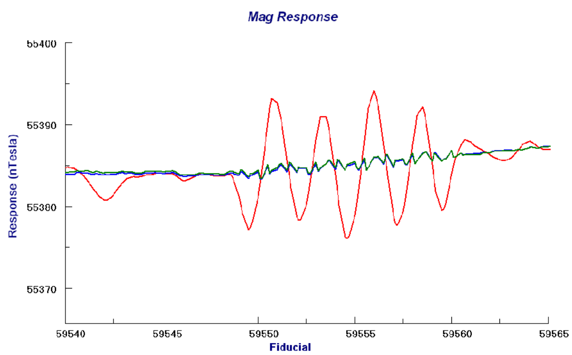

Figure 7: Portion of line 1090 above – Expanded view of the comparison of compensation results, Red: measured Btotal, Blue: compensated total field with GPS vectors FW and FS vectors, Green: compensated total field with measured Fluxgate Channels.

Figure 7 is a portion of 1090 with expanded scales to show the maneouver signal and its removal via the measured fluxgates and the GPS. As with the previous figure, the differences between the two methods can not be seen showing that compensation with the GPS devrived attitudes in this case are as good as compensation using the fluxgates.

Conclusions

This work has demonstrated that aeromagnetic compensation can be accomplished using three GPS sensors, judicious mounted on the survey aircraft. This is accomplished at the present time by generating synthetic fluxgate data for post-flight input into the compensation routines developed at PetRos Eikon. 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.

Experiments with different highpass filters of 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 one single filter or solver can produce the best possible compensation.

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