Magnetic Compensation of Survey Aircraft; a poor man's approach and some re-imagination

D.J.FitzGerald, J.Perrin, Intrepid Geophysics, BRGM

_____

Abstract

A magnetic survey aircraft is always undergoing small changes in its rotational attitude, as the survey is conducted, due to turbulence and the demands of real-time flying. The roll, pitch and yaw angles, also known as Euler angles,(see figure 1) are the appropriate measures of this attitude. Real time measures of the aircraft attitude are therefore required and are typically measured with a three component vector fluxgate magnetometer.

The angular changes cause an overall magnetic response, called manoeuvre noise, which needs to be estimated and removed. Leliak first proposed an engineered solution to this problem. This solution, involving 16 hypothetical magnets, has proven remarkably robust and enduring. Efforts to improve on this have done little but tweak the edges. We revisit the original work and show how these ideas can be simply expressed as a workflow in a modern geophysical toolkit, such as Intrepid, with very few special considerations. The case study is from France and involved a not particularly well demagnetised aircraft. Post survey compensation achieved using this simplified procedure, drove the noise to an acceptable error below 0.2 nT.

The limitations of this original solution to the more challenging acquisition of vector and tensor magnetic gradients are becoming well known. For an industry to more fully embrace the world of potential field vector and tensor gradient measures of the magnetic field, a re-imagination of the survey aircraft's manoeuvre responses is required. We make some suggestions.

Introduction

The methodology and instrumentation for airborne magnetic surveys have progressed greatly over the last 60 years. Industry now collects high-resolution magnetic data at a sample interval of about 7m and from as low as 20m above the ground. Safety and operational factors limit lower flying heights.

The Earth's magnetic field, at any particular location, varies with time. Several causes of variation can occur, with periods of a few seconds to days. The long-period daily variation (diurnal) of the field varies smoothly, with the amplitude dependent on magnetic latitude and increasing towards the magnetic poles. The daily variation can typically be 40 nT.

In contrast, there can be severe magnetic storms, during which the magnetic field may change by several hundred nT and be affected for several days. Short wave-length magnetic disturbances, known as geomagnetic pulsations or micropulsations, occur randomly and may have a period of less than 1 second to more than 2 minutes. with amplitudes 0.12 nT for the higher frequency to about 5 nT for those with longer periods. In general, only pulsations with periods of 20-40s, classed as P3 pulsations, with amplitudes of 1-4 nT, occur during daylight hours, when most surveying occurs.

Magnetic surveys should not be flown during a period of magnetic storms. To reliably map the magnetic anomalies due to geological sources, it is necessary to monitor the non-geological effects outlined above, using a base station. This base station is positioned as close as possible to the survey area, in an area of low magnetic gradient and away from the influences of cultural effects. Typically, a GPS receiver is located at the base station, to enable an accurate time series record, so that readings on the ground and in the air, can be synchronized.
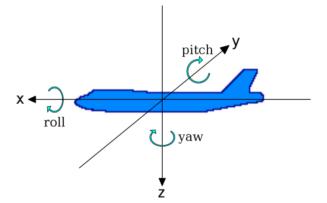

Figure1. The Euler angles, Roll, Pitch and Yaw.

Prior to magnetic compensation, the recorded diurnal signal is also removed from the aircraft measured signal, to isolate the 'manoeuvre noise'. Also magnetic manoeuvre noises have to be considered. This manoeuvre noise derives from the metal on the survey aircraft 1) acting as a permanent magnet, 2) inducing magnetic response while moving through a magnetic field, 3) and also having time dependent eddy currents from the skin of the aircraft. As the surveying system as a whole, does not change its shape or physical properties, it can be treated as an object in a rotating reference frame that has various responses to the Earth's magnetic field.

Leliak 1961, first proposed a method of modelling the response of the survey system, to solve for a linear set of

coefficients to account for these effects. This has been termed magnetic compensation.

Magnetic compensation must be undertaken at the start of a survey and after any modification or maintenance has been performed on the aircraft or system. An appropriate standard set of procedures must be developed and complied with to achieve the best compensation. A typical magnetic-compensation procedure is as follows:

Aircraft must be in normal operating mode;

All equipment operating;

All equipment for survey on board;

For efficiency, the area where the compensation is to be performed should be close to the survey area;

Perform the compensation at an altitude of 2500m above ground level or higher, in a region of low magnetic gradient;

Perform a series of aircraft manoeuvres; (+/-10 degrees of roll, +/- 5 degrees of pitch and +/- 5 degrees of yaw for each of the 4 cardinal directions;

Perform a second set of check manoeuvres to verify the data quality can be achieved;

Make a final check on the field data processing system;

Method

The poor man's implementation of the traditional algorithm follows the original nomenclature. The body coordinates of the aircraft, together with the direction cosine angles X,Y,Z are shown in figure 3. The terms of the polynomial are made up of the 3 contributing factors and amount to 16 independent terms, even though 18 were first proposed. Each line direction in a Figure of Merit survey (FOM) involves say 6 seconds of Roll, 6 seconds of Pitch, then 6 seconds of Yaw.

The first thing to do is to transform the data into Leliak's linear equation system, equation 1.

$$A.C = M \quad (1)$$

where M denotes the manoeuvre noise vector , C the Leliak coefficients and the A matrix for the Leliak magnetic terms.

If you have a fluxgate magnetometer to use as your measure of the rotational state, a conversion to the required body coordinate system is required. In the example survey, the delivered fluxgate has the conventions

FGX in line >0 to North;

FGY transverse positive to right;

FGZ vertical positive downward.

The first step is one of re-orientation to map these to the convention for X body, Y body and Z body as shown in figure 2.

The data is filtered with an initial moving average 7 point filter, followed by a highpass Fuller filter to get the Bx, By and Bz as proxies for the primary rotational attitude of the aircraft relative to the IGRF vector.
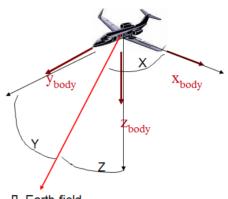
This process gets a well-conditioned, not too noise signal for the correlations to work. The total field from the fluxgate is also required to estimate the direction cosines. We also need the base offset for each direction.

With these estimates, the A matrix for every sample point for the FOM, is easily built, using the fact that X can also be assumed to be just Bx/TotalField etc. (See table 1).

The magnetometer reading from a FOM flight is the signal recorded with just manoeuvre noise, so this, after similar filtering, forms the right hand side term.

Leliak convention

Figure 2. The body coordinate convention first proposed by Leliak, with the origin at the centre of the plane. Note the unusual definition of X,Y,Z as angles of the principal directions of the plane, from the IGRF field direction.

Simple batch processing job files are used to automate this workflow.

The process of solving for a set of 16 independent coefficients that capture all the orientation effects can be accomplished by a range of solvers. As this is not a large computational task, a simple SVD has been used here. In the spirit of a poor man's solution, a batch job file takes the A matrix and the observed magnetic manoeuvre noise vector and solves for these terms. A typical output is shown in table 2.

Coefficient Number	Traditional Nomenclature	Rotational component	Comment
1	T	X	Permanent, scalar
2	L	Y	Direction cosines
3	V	Z	
4	TT - LL	X.X	induced
5	LT + TL	X.Y	
6	TV + VT	X.Z	
7	0	Y.Y	
8	LV + VL	Y.Z	
9	VV - LL	Z.Z	
10	tt - ll	dX/dTime.X	Eddy, tensor, time variant
11	lt	dY/dTime.X	
12	vt	dZ/dTime.X	
13	tl	dX/dTime.Y	
14	0	dY/dTime.Y	
15	vl	dZ/dTime.Y	
16	tv	dX/dTime.Z	
17	lv	dY/dTime.Z	
18	vv - ll	dZ/dTime.Z	

Table 1. The original 18 terms in the Leliak equation, showing the original nomenclature for the permanent magnet, induced magnetization and eddy current terms. X,Y,Z refer to included direction cosine angles.

Examples

Figure 3 shows a typical set of Figure of Merit lines flown for the purpose of deducing the compensation coefficients.
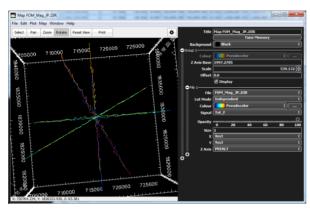

Figure3. The figure of Merit patterns, showing the stacked profiles of the magnetic signal. There are 4 lines flown for up/back, for each of two rotational patterns.

C1	=	9.03378927	C10	=	0.00010766
C2	=	-40.38791294	C11	=	0.00004787
C3	=	0.31585390	C12	=	-0.00005460
C4	=	-0.00021560	C13	=	0.00001926
C5	=	-0.00000139	C14	=	-0.00036131
C6	=	-0.00003946	C15	=	-0.00010920
C7	=	0.00001678	C16	=	-0.00023076
C8	=	0.00002713	C17	=	0.00070803
C9	=	0.0	C18 = 0		

Table 2. A sample set of coefficients from the solution of the A matrix with the manoeuvre noise vector.
The final piece of the puzzle is to now create a magnetically compensated channel from the observed Raw magnetic field data. This is easily achieved using a simple script with a calculated field that manipulates the running Roll, Pitch and Yaw observations for the survey, as from before, and multiplies each of these monitors with the corresponding coefficient- see figure 4.

Verification Step

The typical experimentation and verification steps to be used here involve selection of all the FOM data, or just those lines that correspond to the survey line direction that you are processing. Recovery of a TMI can also be accomplished, by looking at a cross-over point for all FOM lines, to see firstly that the error is reduced to an acceptable figure. In the test case used for this example, the initial mis-fit is 7 nT and this is reduced to 0.7 nT. The other verification step is to try the newly derived coefficients on the second FOM dataset, to verify that the manoeuvre noise is reduced to less than say 0.2 nT.

To the raw reading by a series of subtractions

"$CompMag = $RawMagAno -($C1*$A1 + $C2*$A2 + $C3*$A3 + $C4*$A4 + $C5*$A5 + $C6*$A6 + $C7*$A7 + $C8*$A8 + $C10*$A10 + $C11*$A11 + $C12*$A12 + $C13*$A13 + $C14*$A14 + $C15*$A15 + $C16*$A16 + $C17*$A17) "

Filter output with Fuller 301 points in window

longer gives better compensation, but to show the results a smaller one allow to focus on the manoeuvre noise or residual

Figure 4. The compensation equation is a subtraction of the coefficient weights for each factor, from the observed survey Roll, Pitch and Yaw states.

Re-imagination

Leliak proposed a model for magnetic compensation using harmonic analysis and based upon the first and third Maxwell equation, assuming the displacement current was zero. We propose a new statement of the equation, in a more terse classical form, equation 3. The second term is the standard magnetic field term (LaPlace) in phase with the manoeuvre angle and the first term is the curl term for just the conductive current, on the aircraft surface, out of phase. We expand each term into 8 contributing factors using a second order approximation of an harmonic time series for the orientations. Equation 2 uses the quaternion notation, which is simply derived from the Euler angles, scaled by maximum angular deviation.

$Rotation$: $q(\varphi/\varphi max, \phi/\phi max, \theta/\theta max, 0)$ (2)

$$Noise: \quad f(q,t) = \sum_{n=1}^{2} q^n (\nabla \times H - i\nabla \cdot B)e^{inwt} \quad (3)$$

Leliak imagines that the measurement system is spatially insensitive, so ignores any displacement effects and just considers the three orientation variations in time. In the expanded form, the first eight terms are really just the vector and tensor orientation terms, minus any amplitude information. The B field as a vector has the 3 direction cosine terms, and the magnetic tensor has 5 independent components whose orientations follow the nomenclature that Leliak develops for the induced magnetic terms, though not in any conventional sense. Interestingly, the reason the third diagonal term is not necessary, follows from the orthorgonality of the eigenvectors. This can also be expressed as equation 4

$$cosX.cosX + cosY.cosY + cosZ.cosZ = 1 \quad (4)$$

For a potential field, the LaPlace equation provides the necessary reduction from 6 to 5 terms for the tensor. To put some sort of physical meaning to these first 8 terms, 3 simple dipole magnets, plus 5 quadrupoles can be thought to summarise the effects, and these are labelled T,L,V etc.
We now turn to the question of extensions to this method for magnetic vector/ tensor measuring systems. Increasingly, geologists have a fascination with also being given access to the magnetization direction for each magnetic anomaly. This is a proxy for the emplacement

date of the source of the magnetic anomaly. In regional surveying work, this extra piece of information can greatly reduce the uncertainty and assist the choice of which anomalies to follow up. In Brazil, with low equatorial latitudes, the issue of careful recovery of the magnetization direction is especially difficult. The *Backus effect* can be largely overcome by also recovering the magnetic vector, even if this is of lesser quality than the main TMI measure. (Khokhlov et. Al. 1997) One challenge for the industry is to improve our surveying technology so this becomes routine. The minimum requirement for this is reliable B field vector measures, and for better resolution, magnetic tensor gradients. Originally, fluxgate instruments always provided a vector, but due to instability, have been largely ignored, expect as a source of orientation information. Remanent magnetic anomalies interfere with a fluxgate's ability to provide that orientation, so I would advocate a shift to inertial navigation instrumentation to ascertain the 3 attitude measures, without reference to the magnetic field.

It should be acknowledged that there have been many attempts to just use the Leliak method directly on vector and magnetic gradiometer measures, with little success. Typically, high altitude derived coefficients just do not work when applied to survey height measures.
For an instrument that is sensitive enough to measure magnetic variations and gradients to 10 pT/m, it will be moving through a geomagnetic field of significant gradient that these effects will not have been estimated from the higher altitude Figure of Merit flights. It is necessary to determine the second order effects on the sensors due to aircraft movement in the gradient fields.
The original paper also alludes to ignoring the vertical gradient terms for the pitch corrections.

The Eddy current terms are also arguably deficient. Jia et al, 2004 states "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."
Argast et al, 2010, details many of the processing steps needed to create a coherent magnetic tensor survey signal for the IPHT, SQUID based system. I followed this work, FitzGerald, 2013, with an update that foreshadows some of the work in this paper. The IPHT instrument has further difficulties, in that the B field components are also reporting in the raw gradient measures, due to manufacturing tolerances on the gradiometer sensor.
Leaving these difficulties aside, and imagining that other viable magnetic tensor gradiometer systems are just around the corner, there is a need to revisit the basics of this compensation technology, and add to the original Leliak model, so that it can serve the purpose for removing manoeuvre noise from magnetic tensor survey measurements.
Given the basis for the original derivation of the model, what can be done to address its deficiencies?
Third order orientation terms can be added, to make allowance for higher order curvatures This is already needed when honouring the curvature gradients during full tensor gridding for instance.

It has also emerged that the LaPlace term, should use harmonics in the horizontal plane, and decay exponentially in the vertical direction. This is a deficiency in the context of the Leliak derivation, as the vertical is also treated harmonically, Sanchez et al, 2005. The only vertical term originally considered, was for the pitch correction.

Conclusions
The original Leliak method proposed for magnetic compensation for aircraft manoeuvre noise, whilst surveying, has proven remarkably useful. The engineering approximations employed have ensured that for standard TMI surveys, coherent results can be achieved without obvious artefacts from the aircraft and the acquisition activity.
We revisit this original work and demonstrate that a very simple workflow can be easily achieved by following the guidelines originally set out, and post-processing Figure of Merit data, deriving the 16 monitor coefficients to correct for orientation effects. We then apply these to the actual survey lines to achieve a result that approaches best practise. Of course, the existing engineered "black box" solutions will generally do a better job, as these have been refined over many years.
The quest for new magnetic survey systems to routinely provide not only magnetic anomaly magnitudes, but also magnetization direction requires an improvement in the routine systems used for surveying. Some suggestions

- Exponential decay should be considered for the vertical terms, rather than the current harmonic treatment.
- At least some of the third order orientation terms for the B field third order tensor can be added.

Acknowledgments
The permission of the BRGM to make reference to internal procedures and test work is acknowledged.

References
Argast, D, FitzGerald, D., Holstein, H., 2010, Compensation of the full magnetic tensor gradient signal: 21st ASEG Conference, Sydney

FitzGerald, D., 2013 Full Tensor Magnetic Gradiometry : 13th SAGA Conference, Kruger Park

Khokhlov, A.,G. Hulot G.,J.-L. Le Mouel, 1997 On The Bachus Effect –I, Geophys. J. Int. (1997) 130 (3):701-703.

Jia, J., Lo, R., Groom, R., 2004, A new aircraft compensation system for magnetic terrains. Final report on improved aeromagnetic compensation: OMET Program Report#P02-03-043, 70p.

Leliak P., 1961, Identification and evaluation of magnetic field sources of magnetic airborne detector MAD equipped aircraft: IRA Transactions on airspace and navigational electronics, Volume 8, P.95-105

Sanchez, V, Sinex, D, Li, Y, Nabighian, M, David Wright, D,vonG Smith D, 2005, Processing and Inversion of Magnetic Gradient Tensor Data for Uxo Applications, 18th EEGS Symposium on the Application of Geophysics to Engineering and Environmental Problems