Compensation of the full magnetic tensor gradient signal

Dominik Argast
Intrepid Geophysics
Brighton, Victoria, Australia
dominik@intrepid-geophysics.com

Des FitzGerald
Intrepid Geophysics
Brighton, Victoria, Australia
des@intrepid-geophysics.com

Horst Holstein
University of Aberystwyth
Aberystwyth, Wales, UK
hoh@aber.ac.uk

Ronny Stolz
Institute for Physical High-Technology
Jena, Germany
ronny.solz@ipht-jena.de

Andreas Chwala
Institute for Physical High-Technology
Jena, Germany
andreas.chwala@ipht-jena.de

SUMMARY

In recent developments a full tensor magnetic gradient system has been deployed in South Africa. The instrument is made by IPHT (Institute of Photonic Technology, Jena, Germany) and flown by helicopter. In developing a 'custom' solution for taking the raw signal through to a final located geophysically sound data base, one of the biggest challenges has proven to be the compensation of aircraft / bird rotational movements, so that the reported magnetic curvature gradients in the world co-ordinate system are as free of these rotational errors as possible.

Issues that arise include drift correction of the Euler Angles from the INS (Inertial Navigation System), removal of flux jumps from the SQUID and recovering the three components of the 'B' field.

Compensation issues are limiting the achievable resolution of the field gradients.

A novel least-squares rotational adjustment of the tensor signal in a moving window is proposed as an extra compensation step to achieve higher spatial coherency of the curvature gradients.

Key words: Euler angles, INS, tensor gradients, quaternions

INTRODUCTION

Aeromagnetic compensation requires knowledge of the aircraft attitude, i.e. the state of the three rotational degrees of freedom. This is also known as the Euler angles or roll, pitch and yaw of the aircraft or sensing bird - see figure 1.

Instrumentation advances in recent years prompted the development of 'off the shelf' options to deduce these quantities in a satisfactory and reliable manner for traditional TMI systems. However, we find that the best quality inertial navigation systems that do not have International Traffic In Arms Regulation (ITAR) restrictions, do not return Euler angles after Kalman filtering to better than one degree RMS. Up until now, it has probably been next to impossible to verify the typical long term errors from an INS, as what other independent means do we have that is going to be better than this?

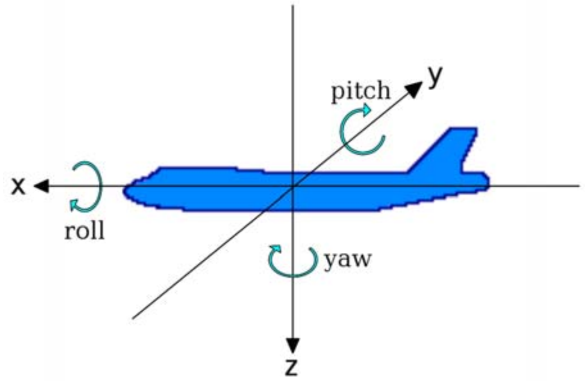

Figure 1. Schematic showing Euler Angles, Roll, Pitch and Yaw

In different parts of the globe, gradient and full vector magnetic field measuring systems are deployed with good results, still using traditional compensation techniques (Leliak, 1961). Questions have been raised about compensation being the limiting factor holding back a fundamental breakthrough in reducing signal to noise ratios and opening up the magnetic method to more exacting and subtle influences (Jia et al 2004).

This paper goes right past all thoughts of being able to use the traditional methods as we come face to face with Low Temperature SQUID magnetic gradient measuring devices. All efforts to develop processing steps and methods that parallel the Leliak work, have proven fruitless for some of the reasons anticipated by Jia et al. For example, "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." (Jia et al, 2004)

As is sometimes the case, the measured magnetic tensor processed to return its world coordinate form, points us to the conclusion that there are obvious "heading" errors still in the signal. At this point in its evolution, the sensitivity of the delivered and processed SQUID Magnetic Gradient tensor signal is more sensitive compared to what is considered by some as the best low flying gradient system (MIDAS) which measures the rotational invariant TMI of the magnetic field but often proved to be sensitive against yaw angle changes as well.
So we are left with the weak link in getting super high quality deliverable signal from next generation SQUID magnetic

tensor systems. This is the problem of improving on magnetic compensation and the estimation of the Euler angles themselves. Furthermore, SQUIDs do not measure the absolute value of the gradient components which will mix in noise during the process of georeferencing or derotating using Euler angles.

DISCUSSION

Leliak's system of equations

Leliak (1961) based his work on a postulated physical model in the context of submarine detection for the US Navy. The basis of Leliak's physical model is expressed in a relatively simple set of equations to capture electromagnetic effects of a magnetic and conductive aircraft flying through the Earth's field. These errors, once modelled, are then removed by a decorrelation technique.

Leliak proposed an 18 term compensation model derived from, permanent, induced, and EM or eddy current effects. He 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. The method developed, uses first and second order Taylor series terms to derive the 18 coefficients. It requires an aircraft pilot to perform a series of single axis sinusoidal maneuvers. This was commercially implemented by RMS some 20 years ago in an off the shelf custom hardware box. This remains the standard for aeromagnetic compensation.

Hardwick, (1984) investigates the subject of aeromagnetic gradiometry compensation. The most prominent outcome of his work was the so-called Tri-Ax gradient system flown commercially by Geodas in the Republic of South Africa.

Jia et al (2004) revisits the original work and looks to modern solvers and a mathematical notation that is more compact. Standard principal component analysis is seen as the safest and easiest to understand for a non-specialist. Only the first 10 eigenvalues appear to be needed for the coefficients to be calculated. This implies that some of the terms in the original equations have little influence. He also points to an original limitation with the magnetic sensors of 1961 (inability to guarantee orthogonality of components) that no longer applies, thus reducing the number of equations to 16. Furthermore, he raises the basic issue that the aeromagnetic method dividends are fundamentally hampered by the lack of work by the exploration industry on this subject. This is not the only place where very little engineering research is directed thus negating or hampering the more glamorous "inversion" projects.

The IPHT magnetic tensor system

The engineering specifications and progress reports from various surveys for this instrumentation system have started to be made public by Stolz et al. (2006), Stolz (2009) and Rompel (2009). FitzGerald (2009) gives details of processing technology that has evolved. Since 2008, the towed bird shown in Figure 2, is used to carry in separate packs, the cryogenic chamber maintained at 4.2 degrees Kelvin, in which all the SQUID instruments are deployed, and a second smaller pack in the rear with the data acquisition unit, optical fibre or WLAN communications unit, GPS, inertial navigation system etc. Various sampling rates are used, with the high rate being 1000Hz. This bird has proven to be quite stable aerodynamically, but there remain various modes of accelerations and rotations that need to be dealt with.

Figure 2. Current generation towed bird for the magnetic tensor system developed jointly by Spectrem and IPHT

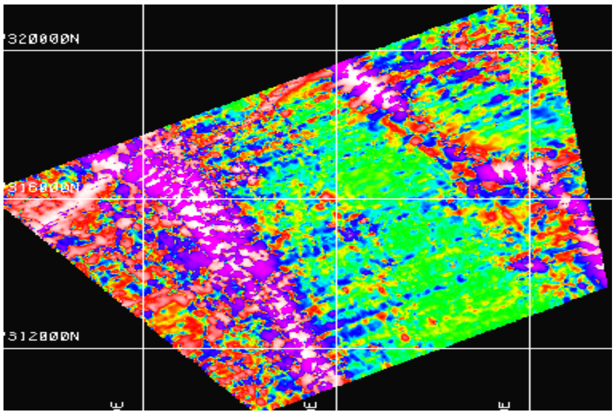

Figure 3. Part of a magnetic tensor survey, partially processed, assuming the attitude is correctly estimated by the INS. The signal is the cube root of the second invariant of the tensor with units in nT/m. The clearly visible striping is reminiscent of traditional heading errors

A vital step in forming the magnetic gradient tensor from the measured data is the removal of the dominant and inherent parasitic leakage of the "B" field into the measured mixed gradients. The system is highly over-determined, which allows the calculation of the balancing coefficients in regions where the magnetic gradients are zero and no regional long wavelength gradient components are present. The balancing coefficients are then averaged over all lines flown in the same direction and are used to remove the parasitic B field from the measured mixed gradients.

In a subsequent step, the measured gradients are unmixed to recover the full magnetic gradient tensor with respect to a coordinate system fixed to the measurement instrument (the so-called body system). Finally, the attitude of the instrument has to be estimated to convert the tensor as measured in the body system to a world coordinate reference frame.

What looks like a conventional heading error appears after applying these processing steps. This is clearly visible as striping in Figure 3. The figure shows the cube root of the second invariant of the tensor gradient with units in nT/m.

This quantity is a measure of the magnitude of the signal and is independent of the coordinate reference frame. Note, that the data in Figure 3 has not been corrected for altitude variations along and between lines, which accounts for some of the striping visible.

The attitude errors are grouped in this method since all lines flown in each of the cardinal directions of a traditional rectangular survey plan are grouped together. Whilst this works well to first order, the fundamental reason why this systematic error appears at all, together with why all attempts at using high altitude pattern flying to deduce traditional compensation coefficients or something that acts like these have failed, remains an open issue. This has lead to an extensive investigation into the engineering and behavior of gyros, Kalman filters, and how the on-board GPS and accelerometers might also be used to stabilize and improve attitude determinations.

Attitude Measurement Systems

A prime example for accurately estimating Euler angles is the Ørsted satellite mission. The in-flight calibration methods used to estimate Euler angles for the Ørsted satellite assume that the magnetic field is given by a spherical harmonic model of the Earth's main field, which is estimated simultaneously with the three Euler angles. The accuracy of the Euler angles derived for this mission is quoted to be of the order of 30 arcsec. In a real atmosphere, with a towed bird, we cannot get close to this confidence in our estimates.

The INS onboard the IPHT instrument is the highest quality before ITAR restrictions are invoked. There are three fiber-optical gyroscopes and three MEMS type acceleration sensors that are measuring angular velocities and accelerations, respectively. These are integrated from the initial known state of zero to give the three Euler angles at each sample interval. This data is down sampled and smoothed to 10Hz. In practice, the pitch has a long term drift that must be corrected (see Figure 4). A typical method of doing this is to use a Kalman filter as supplied by the University of Calgary. The yaw is more easily checked as there is the readily available GPS heading estimate. The roll estimate derived from the simple integration is typically much better behaved.

Generally it is considered acceptable if the estimated angles are within about one degree of apparent reality. However, this is not accurate enough for magnetic tensor gradient systems. The curvature gradients, especially in a quickly varying anomalous field, are very sharp. Thus, the source of our "heading error" is the full Euler angle errors, not just the yaw.

The IPHT system provides measures of the three components of acceleration and also four measures of relative components of the B field via other SQUIDs. A method to recover the absolute components of the B field has been developed. The acceleration vector and the absolute B field vector as measured in the body system can be compared to the known corresponding quantities in the local NED (north-east-down) coordinate reference frame. The B field vector in the NED system is assumed to be given by the IGRF model and the gravity vector is simply the vertical gravity. From the angles between these vectors an independent estimate of the Euler angles of the instrument system can be derived. This is schematically shown in Figure 5.

The attitude estimate derived this way is not accurate enough for our purposes. However, it is a useful independent measurement of the Euler angles that serves to guide the integration of the gyro angular rates to obtain the attitude of the instrument system. A method to blend the INS attitude estimate and the independent attitude estimate has been developed. In our work, as with most current developments of this nature, sensor fusion is achieved by an extended Kalman filter using quaternions to carry the attitude estimate. This method is extensively documented in the literature (e.g. Crassidis 2005) and is similar to the requirement for many strap down navigation systems that combine INS, components of accelerations and magnetic fluxgate measure to blend in real time and stabilize the attitude determination. It is suggested that in a future configuration the deployment of two GPS units to get a real-time vector of attitude of the plane would also improve our ability to derive the Euler angles with the necessary accuracy.

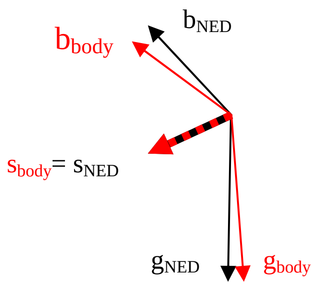

Figure 5. Schematic showing a scheme to blend to estimates of the attitude

Model Simulations

Extensive model studies have been undertaken to demonstrate methods of blending the two estimates of the Euler angles. Employing a Kalman filter is necessary if this type of work is to be done in real-time. This is not a necessary step if post-processing is acceptable.

Also in this study we introduced some known errors in Roll, Pitch and Yaw for an aircraft to see what happens to the signal and then a first attempt at a method to remove the known systematic error. It is these model studies which demonstrate the sensitivity of a magnetic tensor gradient to small errors in measured attitude.

CONCLUSIONS

One of the major drawbacks associated with modern aeromagnetic surveys is the use of fluxgate magnetometers to measure parameters that are used to correct the magnetic gradient readings. This is a critical circular argument as there is a known parasitic leakage of the B field into the mixed gradients.

Furthermore, the balancing coefficients are calculated in regions of small or zero magnetic gradients, but it is not known what amount of geological signal is leaked into the compensation data prior to coefficient calculation.

An improvement in estimating the attitude of a magnetic tensor gradient instrument is essential to derive high quality magnetic tensor gradient data.

There may be better current INS systems, but it is likely that a second independent measure of attitude involving GPS antennae will be needed. Vector components and tensor magnetic gradients of the anomalous induced field are much more sensitive to attitude than scalar TMI. A real-time solution is not necessary at this stage.

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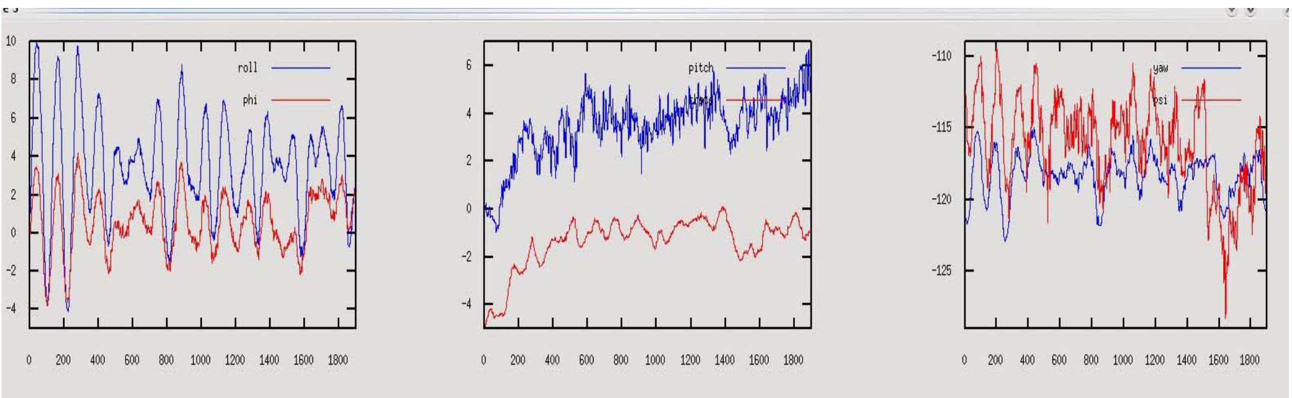

Figure 4. The two measures of the Euler angles from the system. The Blue is from the INS before Kalman filtering and the Red is estimated from the B field and acceleration vector. Note the separation in the estimates as well as the amplitude differences.