Recent Advances in Aeromagnetic Compensation

G. Noriega
RMS Instruments
1-6877 Goreway Dr., Mississauga, ON, Canada, L4V 1L9, g.noriega@rmsinst.com

Abstract– Aeromagnetic compensation plays an important role in most airborne geophysical exploration programs, dealing with the modelling and elimination of interference effects generated by the aircraft flying in the Earth's magnetic field. The subject has received considerable attention throughout the last few decades, with significant advances in areas such as modelling, algorithms, performance analysis, and implementation issues. This work discusses broadly recent developments on adaptive compensation (which allows continuous optimization of the solution through a recursive algorithm), real-time compensation of on-board electronic systems (whose effects are not captured by the conventional model), attitude-reference sensors, compensation of UAV platforms, and various modelling issues.

Resumen– La compensación aeromagnética juega un papel importante en la mayoría de los programas de exploración geofísica aérea, tratando con el modelado y la eliminación de los efectos de interferencia generados por la aeronave volando en el campo magnético de la Tierra. El tema ha recibido atención considerable a lo largo de las últimas décadas, con avances significativos en áreas tales como modelado, algoritmos, análisis de desempeño, y cuestiones de implementación. Este artículo analiza desarrollos recientes en compensación adaptativa (que permite la optimización continua de la solución mediante un algoritmo recursivo), la compensación en tiempo real de sistemas electrónicos de a bordo (cuyos efectos no son captados por el modelo convencional), sensores de referencia de orientación, compensación de plataformas de UAV, y varios aspectos de modelado.

Keywords – Aeromagnetic compensation, magnetometry.

Introduction

Airborne magnetic surveys have been used routinely and effectively for decades for geological mapping, mineral and oil/gas exploration, environmental surveys, and magnetic anomaly detection (Hood, 2007). Aeromagnetic compensation plays a critical role in eliminating interference effects generated by the maneuvering of the aircraft flying in the Earth's magnetic field. Historically, the evolution from active compensation techniques to advanced automatic (digital) compensation systems facilitated important advances (Hood, 2007) – e.g., the use of high-sensitivity magnetometers in aircraft stingers and/or wing-pods, thus avoiding the multitude of problems and risks inherent in towed-bird systems. Most importantly, aeromagnetic compensation has allowed the exploitation of the high sensitivity of modern optically-pumped magnetometers, especially in gradiometer configurations.

The subject has been studied extensively since the introduction of the original compensation model (Tolles and Lawson, 1950; Leliak, 1961), which accounts for aircraft interference from permanent, induced, and eddy-current sources. For context, we list only a few representative examples of work in key areas: modelling and algorithms (Williams, 1993; Gu et al., 2013; Dou et al., 2016), performance analysis (Noriega, 2013, 2015), implementation (Hardwick, 1984; Nelson, 2003), attitude reference (Jia et al., 2004; Liu et al., 2016), and novel applications (Nelson et al., 2003; Versteeg et al., 2007; Argast et al., 2010).

The present work discusses recent developments, some of which have been successfully implemented in advanced compensation systems for some time (e.g., adaptive compensation and real-time compensation of on-board electronics), while others are still in early experimental stages (e.g., compensation of UAV platforms and SQUID systems).

Adaptive Compensation

The traditional approach in aeromagnetic compensation involves a calibration flight at high-altitude, away from geological effects, which leads to a mathematical model representative of the aircraft's magnetic signature. The computation of the set of *solution* coefficients is based on the entire data set collected, and entails use of some form of least-squares algorithm to solve the large (often ill-conditioned) set of linear equations involved.

Adaptive compensation, first introduced in advanced commercial systems in the mid-2000's, permits a fundamentally different approach by using a recursive algorithm to solve the least-squares problem. The system continuously adapts solution coefficients for optimum compensation. The recursive algorithm has important computational advantages, avoiding some of the more severe numerical issues with the conventional approach. Furthermore, new calibrations build upon the established "knowledge" of the aircraft's signature from previous calibrations. The technology substantially eases calibration procedures: simple sets of *trim maneuvers* at reasonably low altitude may be carried out on a regular basis (e.g., en route to the survey area), thus continuously improving on a sound initial solution.

We have studied in detail the performance of adaptive compensation using data sets from an extensive collection of archival records from actual production survey aircraft, and a comprehensive (proprietary) set of simulation tools. Let CAL denote a conventional calibration flight – 4 orthogonal headings, with 4 maneuvers of each type (rolls, pitches, yaws) per heading –, flown at nominal altitude A_o = 3000 m, and TRIM represent the series of trim-maneuvers to be flown in adaptive-compensation mode. We characterize TRIM through a series of parameters: (a) type (T*ij* denotes the flight path for the trim maneuvers segment, with *i* the number of orthogonal headings flown, and *j* the number of maneuvers of each type per heading); (b) fractional degradation of the original solution (δ, which characterizes the severity of the aircraft's magnetic signature change); (c) altitude (defined as a fraction of A_o); and (d) geological effects (modelled through parameter K_G, such that K_G=2 yields effects ≈ 50 nT p-p at $A_o/3$ altitude). To assess performance we concentrate, for brevity, on the ratio $R = \mathrm{IR}_{adp}/\mathrm{IR}_{nad}$, where IR_{adp} is the improvement ratio obtained with the adaptive solution, and IR_{nad} the one obtained with the original (non-adaptive) solution.

Figure 1 summarizes performance as a function of the type of trim-maneuvers segment, T*ij*, with i = {1, 2, 3, 4} and j = {2, 4}. Other parameters are set to nominal values (δ=1.0%; $A=A_o/3$; K_G=2). The results shown are for 31 trials. There is no significant difference in performance between 3- and 4-heading segments for a given number of maneuvers. On the other hand, there are significant differences (p < 0.001) between 2- and 3-heading segments, and between 1- and 2-heading segments. Note that inter-group differences (i.e., 4 vs. 2 maneuvers) are always significant. These results suggest that 2-heading segments offer a good compromise: they do not impose a major burden on operations, and with 2–4 maneuvers of each type they will typically yield improvements between 15 and 25%. Notice that single-heading segments typically yield only modest improvements, and potentially (with only 2 maneuvers) may actually result in poorer performance after adaptation (R < 1).

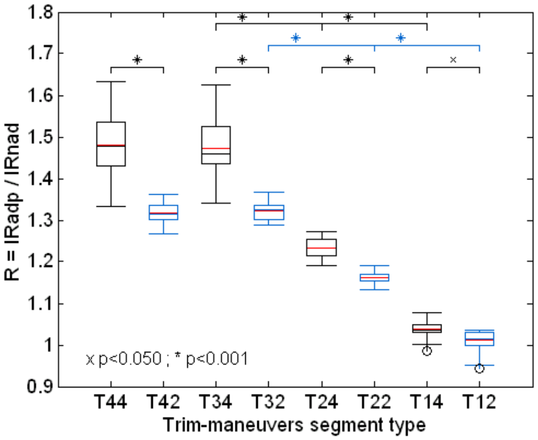

Figure 1 – Relative improvement ratio vs. trim-maneuvers: T*ij* denotes TRIM with *i* headings and *j* maneuvers of each type per heading. Statistical analysis: ANOVA, *N* = 31 trials per case; LSD method for comparison of pairs of treatment means. Significant differences ('x' at *p*=0.05, '*' at *p*=0.001) shown thus (bottom-to-top): inter-group, intra-group (adjacent 2-mnvr. cases), and intra-group (adjacent 4-mnvr. cases).

The altitude at which TRIM is flown is clearly critical. An analysis similar to the one above shows that for $A_o/2 \le A \le A_o$ (T_{22}, δ=1.0%, K_G=2), $R(A)$ is slightly below 1.2, with no statistically significant differences across the range. A drop in altitude from $A_o/2$ to $A_o/3$ does show a significant decrease in performance (p < 0.05), as does one from $A_o/3$ to $A_o/4$ (p < 0.001). Thus, the range $A_o/4 \le A \le A_o/3$ is recommended.

Geological effects along TRIM also play a fundamental role. For $K_G \leq 2$ (T_{22}, δ=1.0%, $A=A_o/3$) performance does not change significantly. On the other hand, for $K_G > 2$ performance decreases rapidly; with K_G=8 (4X its nominal value), the analysis yields a large span of values for $R(K_G)$, with mean and median below unity. Essentially, with fairly substantial geology along TRIM, and a relatively low altitude, the performance of adaptive compensation is rather unpredictable.

Dynamic Compensation of On-Board Electronic (OBE) Systems

Real-time compensation of the effects of currents from OBE systems (such as radios, avionics, hydraulic pumps, intercoms, and other instrumentation) eliminates interference which is not accounted for by the conventional compensation model.

The model is augmented by suitable terms calculated from a simple *OBE calibration*, which may be conducted on the ground or in the air, by cyclically engaging and disengaging the OBE systems to be compensated. During real-time operation analog signals monitor the status of the OBE devices. For devices with constant current draw, OBE compensation works in *discrete mode*: compensation automatically switches on/off, as the status signal crosses some threshold. For systems with variable current draw OBE compensation operates in *continuous mode*: the status signal is proportional to the current drawn by the device, and thus, the model provides compensation proportional to the varying magnetic interference.

OBE interference is thus modeled as

$$H_{\mathrm{OBE}}(k) = \sum_{i=1}^{N_O} \sum_{j=1}^{N_F} \beta_{i,j}(k) F_j(k) \ ,$$

where N_O is the number of OBE devices modeled, $F_j(k)$ are the (N_F) basis functions (based on direction cosines), and k denotes discrete time. The terms $\beta_{i,j}(k)$ are adjusted in real-time, based on the solution coefficients obtained from the OBE calibration, and the OBE status signals.

OBE compensation is complementary to conventional real-time compensation. It provides robust tolerance of electrical interferences and simplifies post-processing.

Modelling Issues

While based on the same principles of the original model (Tolles and Lawson, 1950; Leliak, 1961), the underlying (proprietary) models and algorithms in current high-performance compensation systems are substantially different, addressing efficiently important issues such as, for example, solution robustness and muti-colinearities. These are subjects that continue being studied (Dou et al., 2016; Noriega, 2013).

Under certain conditions, incorporation of third-order spherical terms has proven effective, in particular in the compensation of gradients. This has also been applied in efforts to compensate full-tensor SQUID gradiometer systems. Reasonably good improvement ratios (≈ 4–12) have been achieved in the compensation of the *balanced* gradients in a helicopter-boom installation (RMS Instruments, unpublished internal documents). However, there remain highly non-stationary inherent non-linearities that need further investigation. The balancing process (to decorrelate tensor and parasitic field components) also plays a critical role in the performance of the subsequent compensation.

Attitude Reference

Fluxgate magnetometers have performed the role of attitude reference remarkably well throughout the years in both total-field and gradiometer applications. We have studied their potential effects on compensation performance using comprehensive data sets from production survey aircraft. The dominant factor is the quality and effective resolution of the analog-to-digital conversion system: a minimum 16-bit resolution is required for optimum performance, with no significant improvements beyond that. With high-performance, state-of-the-art fluxgate sensors, worst-case contributions to compensated residual errors due to noise and non-orthogonalities are well under 1 pT. Non-linearities, crosstalk, and bias errors do not introduce statistically significant differences.

Nonetheless, this area is a natural candidate for potential improvements when magnetic anomalies at very low altitudes may interfere with the fluxgate sensor. Interesting efforts have been made using multiple GPS receivers (Jia et al., 2004), and modelling fluxgate errors (Vasconcelos, 2011), but neither appears to offer compelling benefits. High-resolution inertial measurement systems may be a good alternative (or complement): while in our experience they do not impact compensation performance significantly, they may be advantageous under the effect of large gradients.

Compensation of UAV Platforms

The use of unmanned aerial vehicles (UAVs) for aeromagnetic surveying has seen an interesting resurgence after early attempts in the mid-2000's (Anderson and Pita, 2005). This has been fueled, undoubtedly, by the multitude of reasonably cost-effective platforms available.

The success of any endeavour on UAV usage for airborne magnetometry is contingent on many factors (Versteeg et al., 2007). Ultimately, it is fundamental that high-quality data be generated, comparable to that of conventional aircraft. Compensation plays a central role in this, as the close proximity of the magnetometer sensor(s) to the various sources of interference is inevitable.

In our experience (RMS Instruments, unpublished internal documents), an installation on a < 25-Kg (MTOF weight) helicopter UAV, with a Cs magnetometer sensor mounted on a 1.5-m boom, has achieved good initial results, with compensation yielding improvement ratios slightly above 10, with residual errors of the order of 40–50 pT (1.6-Hz bandwidth, 10-Hz sampling). The results are quite positive, even when compared to typical performance in conventional aircraft (stinger-mounted sensors). Residual errors are on the high-end of the performance range, but the improvement ratio is in-line with typical performance. The analysis of solution robustness has also yielded good results: cross-calibration indexes (Noriega, 2013) consistently below 1.2.

Conclusions

The field of aeromagnetic compensation has evolved significantly over the last few decades. While much of the work has either been confined to academic circles, or otherwise remains proprietary because of commercial considerations, substantial practical advancements have been achieved and are well documented. The subject will remain relevant as new applications in areas such as UAVs and SQUID systems develop.

References

Anderson, D.E. and Pita, A.C. [2005] Geophysical surveying with GeoRanger UAV. *American Institute of Aeronautics and Astronautics*, **50**, 67–78.

Argast, D., FitzGerald, D., Holstein, H., Stolz, R., and Chwala, A. [2010] Compensation of the full magnetic tensor gradient signal. *ASEG 21st Int. Geophysical Conference and Exhibition*, Sydney, 2010.

Dou, Z., Han, Q., Niu, X., Peng, X., Guo, H. [2016] An adaptive filter for aeromagnetic compensation based on wavelet multiresolution analysis. *IEEE Geosci. Remote Sens. Lett.*, **13**, 1069–1073.

Gu, B., Li, Q., Liu, H. [2013] Aeromagnetic compensation based on truncated singular value decomposition with an improved parameter-choice algorithm. *Proc. Int. Cong. Image & Signal Proc.*, 1545–1551.

Hardwick, C.D. [1984] Important design considerations for inboard airborne magnetic gradiometers. *Geophysics*, **49**, 2004–2018.

Hood, P.J. [2007] History of aeromagnetic surveying in Canada. *The Leading Edge*, **26**, 1384–1392.

Jia, J.R., Groom, R.W., Lo, B. [2004] The use of GPS sensors and numerical improvements in aeromagnetic compensation. *Annual Meeting Society Exploration Geophysicists*, Denver, CO, USA, 2004.

Leliak, P. [1961] Identification and evaluation of magnetic field sources of magnetic airborne detector equipped aircraft. *IRE Transactions on Aerospace and Navigational Electronics*, **8**, 95–105.

Liu, Z., Pang, H., Pan, M. and Wan, C. [2016] Calibration and compensation of geomagnetic vector measurement system and improvement of magnetic anomaly detection. *IEEE Geosci. Remote Sens. Lett.*, **13**, 447–451.

Nelson, J.B. [2003] Aeromagnetic noise from magnetometers and data acquisition systems. *8th Int. Congr. Brazilian Geoph. Soc.*, Rio de Janeiro, 2003.

Nelson, B., Stolz, R., Schulz, M., Chwala, A. Rothenbach, M and Meyer, H.-G. [2003] The German Airborne SQUID Tensor Magnetic Gradiometer. *8th Int. Congr. Brazilian Geoph. Soc.*, Rio de Janeiro, 2003.

Noriega, G. [2013] Model stability and robustness in aeromagnetic compensation. *First Break*, **31**, 73–79.

Noriega, G. [2015] Aeromagnetic compensation in gradiometry-performance, model stability, and robustness. *IEEE Geosci. Remote Sens. Lett.*, **12**, 117–121.

Tolles W.E. and Lawson, J.D. [1950] *Magnetic compensation of MAD equipped aircraft*. Airborne Instruments Lab. Inc., Mineola, N.Y., Rep.201-1.

Vasconcelos, J.F., Elkaim, G., Silvestre, C., Oliveira, P., and Cardeira, B. [2011] Geometric approach to strapdown magnetometer calibration in sensor frame. *IEEE Trans. Aerosp. Elec. Sys.*, **47**, 1293–1306.

Versteeg, R., McKay, M., Anderson, M., Johnson, R., Selfridge, B., and Bennett, J. [2007] Feasibility study for an autonomous UAV – magnetometer system. *INL/EXT-07-13386, SERDP SEED 1509:2206*.

Williams, P.M. [1993] Aeromagnetic compensation using neural networks. *Neural Computing & Applications*, **1**, 207–214.