AusAEM Year 1: Some aspects of quality control and calibration

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SUMMARY

For the AusAEM Year 1 survey an inertial measurement unit (IMU) was installed for the first time on the TEMPEST receiver bird to measure its orientation and to augment GPS derived positioning of the receiver. This has given us the opportunity to develop better quality control and calibration procedures, which would otherwise not be possible.

Theoretical modelling of the primary field on high altitude zero-lines, using the full position/orientation information, revealed discrepancies between observed and modelled data. It alerted us to time-lag parallaxes between EM and bird position/orientation data, some spurious IMU data on many pre-flight zero-lines, and a coordinate system sign convention inconsistency.

The modelling also revealed systematic differences that we could attribute to the calibration of the receiver pitch and EM data scaling. We developed an inversion algorithm to solve for a receiver pitch offset and an EM scaling calibration parameter, for each zero-line, which minimised the systematic discrepancies. It eventuated that the calibration parameters fell into five distinct populations explicable by significant equipment changes. This gave us the confidence to use the medians of these populations as parameters to calibrate the data.

The work shows the value of the new receiver bird orientation data and the importance of accurate IMU calibration after any modification. It shows the practical utility of quantitative modelling in the quality control workflow. It also demonstrates how modelling and inversion procedure can be used to successfully diagnose calibration issues in fixed-wing AEM data.

Key words: AusAEM, TEMPEST, airborne, electromagnetic, calibration, AEM,

INTRODUCTION

During 2017 and 2018 Geoscience Australia, and its partners the Geological Surveys of Queensland and the Northern Territory, commissioned the AusAEM Year 1 Airborne Electromagnetic Survey in the Northern Territory and Queensland (Ley-Cooper and Richardson, 2018). The survey is part of Geoscience Australia's Exploring for the Future programme. This four-year initiative of the Australian Government is aimed at enhancing the geoscientific information available to support resource exploration and to showcase Australia as a destination for investment opportunities.

The AusAEM Year 1 survey was a large regional survey of 60,000 line kilometres, predominantly flown on 20 km spaced lines, with some infill flying. CGG Aviation (Australia) Pty Ltd was contracted to acquire and process the data. The TEMPEST airborne electromagnetic (AEM) system was used. Due to the large areal extent and remote setting the survey had to be flown from ten different survey bases. The scale and logistical complexity meant that it took twelve months of elapsed time to complete the acquisition. A lightning strike on the system, a receiver bird loss, and the elapsed time meant that significant equipment changes during the survey were inevitable.

This survey represented the first production survey that an inertial measurement unit (IMU) had been installed in the receiver bird of a fixed-wing AEM system. This development completes the program for monitoring all nine degrees of freedom of the system's transmitter-receiver geometry. Previously this had not been successfully achieved due to electromagnetic noise created by the IMU device being close to the receiver coils. The IMU measures the orientation (roll, pitch and yaw) of the receiver coils, which is an important input into the quantitative modelling of AEM data. We expect that the receiver coil IMU data will improve the fidelity and reduce the uncertainty in inversion products resulting from the survey. It was thus an important milestone in the evolution of fixed-wing AEM acquisition.

As an incidental benefit, we have found that the new receiver bird IMU data have permitted the development of new and improved quality control and calibration procedures. This abstract will discuss how Geoscience Australia and CGG Aviation (CGG) calibrated and made use of the new IMU data from high altitude zero-lines to make various quality control checks, and to calibrate the scaling of AEM data, including accounting for variations due to the inevitable equipment changes on this long survey.

METHOD AND RESULTS

In this analysis, we use the high-altitude zero-line data that were recorded before and after each production flight. Each zero-line is approximately 60-80 s in duration and is flown at greater than 1,000 m above ground level. At this height there is negligible secondary field ground response. Therefore we can expect that the primary field estimated from the TEMPEST data processing is accurate and that they should match theoretically modelled primary field data.

To model the theoretical primary field we used a 16 sided polygon approximation of the transmitter loop shape. The magnetic B-field effect, at the receiver coils, of each polygonal edge was calculated using the Biot-Savart-Laplace law, calculations which were then integrated around the transmitter loop. The fully measured geometry, which consists of the orientation (roll, pitch and yaw) of the transmitter loop and the receiver coils, plus the GPS measured transmitter to receiver separations, was used in the calculation.

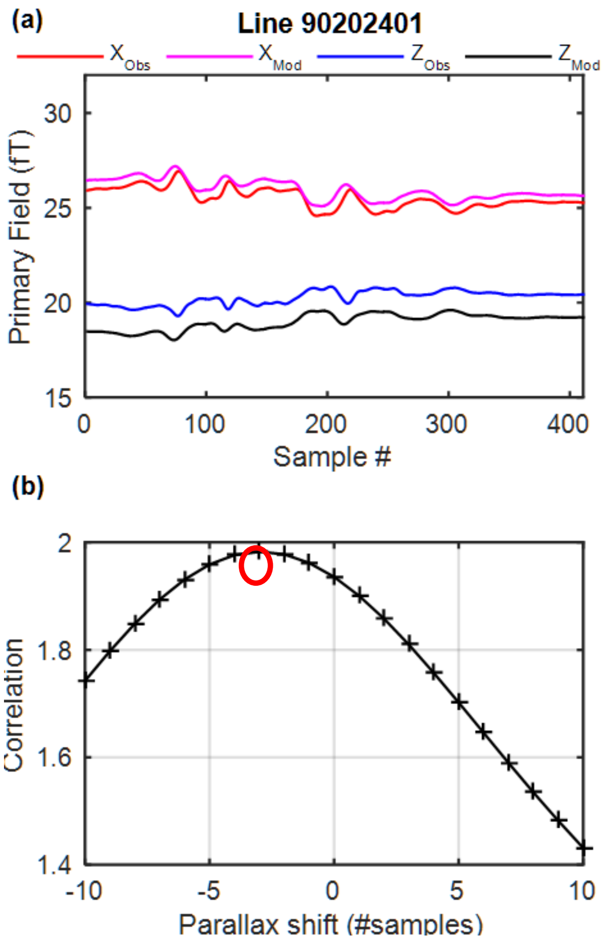

Figure 1. An early field quality control version of high altitude zero-line 90202401 showing, (a) the observed and theoretically modelled X and Z-component primary field data, and (b) the cross correlation between the observed and modelled data which indicates a three-sample parallax shift.

Figure 1(a) shows the observed versus the theoretically modelled X- and Z-component primary field data from an early field quality control version of the dataset for zero-line 90202402. Clearly there are discrepancies between the observed and modelled primary field for both components, which will be discussed later. As well there is an apparent time-lag displacement known as a parallax. We ran a cross-correlation between the observed and modelled profiles on both components separately and summed the result. For this line, we found that the maximum correlation occurred for a lag of three (0.2 s) samples or a total shift of 0.6 s, as shown in Figure 1(b). This indicated that there was a 0.6 s synchronisation difference between the EM instrumentation and the geometry (GPS and IMU) monitoring instrumentation.

It eventuated that this modelling was a valuable quality control check that identified different time-lag parallaxes for each flight in the early phases of the survey. These lags were subsequently rectified. The check is now integrated into CGG's TEMPEST quality control workflow. We have attempted similar correlation checks on previous TEMPEST surveys, however without using the receiver bird IMU data to correctly model the theoretical primary field, those checks could never be definitive because true lags between the transmitter and receiver bird motion could not be totally accounted for, thus obscuring the results.

After the timing parallax was rectified, and on further investigation of unusually large discrepancies on some pre-flight zero-lines, we found that the receiver bird IMU data was spurious on many of the pre-flight zero-lines, but that it always appeared to be reliable for the post-flight zero lines. This alerted CGG to the cause, which was that the receiver bird and IMU were powered down for a system cross-talk calibration line run just prior to the pre-flight zero-line and the IMU having insufficient time to reinitialise before the zero-line started. In future this will be averted by allowing more time for the IMU to reinitialise.

The discrepancy checks between the observed and modelled primary field data also proved to be useful in identifying that the sign of the horizontal-transverse transmitter to receiver separation was opposite to what had previously been understood.

After dealing with the issues discussed above we can begin to investigate the reasons for the remaining discrepancy between the observed and modelled primary field data. Figure 2 shows, in (a) cross-plot and (b) profile fashion, a comparison between the observed and modelled data for a later preliminary iteration of the AusAEM dataset on post-flight zero-line 90504301. There is no longer an obvious parallax shift between the profiles in Figure 2(b), but a clear level (or amplitude) difference is observed.

The cross-plot shows that the modelled X-component data are consistently larger amplitude than the observed, and vice versa for the Z-component. This was also the case for line 90202402 shown (in Figure 1(a)).

One simple hypothesis to explain this discrepancy is that the receiver pitch is systematically offset from the true value, since a small rotation of the receiver coils in the X-Z plane increases the X-component data and decreases the Z-component data. A small systematic error in the receiver pitch is entirely feasible because the axes of the IMU instrument cannot necessarily be physically aligned perfectly with the axes of the receiver coils.

There are other possible explanations for the lower than expected X-component data and larger than expected Z-component data. These could include; (a) a transmitter pitch offset, (b) a different effective area or gain of the X and Z coil windings, and (c) systematic error in the transmitter to receiver horizontal and vertical separations measured by GPS.

The transmitter pitch offset calibration was determined by CGG by physically measuring the transmitter loop tilt on the tarmac (tape measure) while recording the transmitter IMU data and then taking the difference. There was no engineering reason to suspect that the X- and Z-coils had different gains because they are identically machine wound. Nor did we have reason to suspect a systematic (rather than random) error from flight to flight in the GPS measured transmitter to receiver separations.

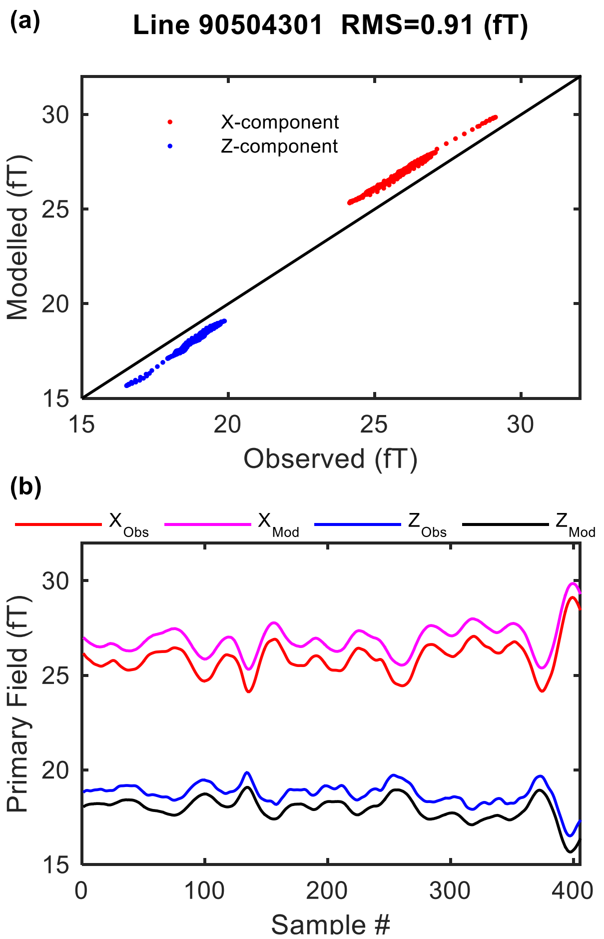

Figure 2. A preliminary version of high altitude zero-line 90504301 showing the discrepancy between the observed and modelled data in (a) cross-plot and (b) profile form.

We developed an iterative gradient-based least-squares regularised inversion algorithm to solve for these two calibration parameters. The algorithm was run on each zero-line separately, inputting the (~400) X- and Z-component observed primary field values as data. We used a starting/reference model value of 1.0 and 0.0 degrees for the EM scaling factor and the receiver pitch offset respectively, with assigned uncertainties of 0.1 and 5 degrees.

Figure 3 shows a comparison of the observed and modelled data for the same zero-line as in Figure 2 after applying the calibration values determined by our inversion algorithm for this line, which were 1.012 for the EM scaling factor and 2.18 degrees for the receiver pitch offset.

We ran the inversion algorithm for every zero-line flown for this survey (282 lines), to solve for an EM scaling factor and receiver pitch offset. The results are presented in Figure 4. It is evident that different values are resolved for each zero-line. We were not confident to apply different calibration values for each individual flight because there was no plausible reason to do so. However, it did emerge that there were five distinct populations of calibration values present.

On Figure 4. the five populations are designated as Bird A, Bird B1, Bird B2, Bird B3 and Bird C, which aligned to different phases of the survey with contiguous receiver bird status. The AusAEM Year 1 survey lasted 12 months in duration. The first receiver bird, Bird A, was used until the system was struck by lightning and rebuilt. After this Bird B was used until it had to be ejected for safety reasons, after which Bird C was used. There are three populations for Bird B because the shell had to be opened for maintenance after flight 91 and the transmitter electronics switches were upgraded for 12.5 Hz testing after flight 128.

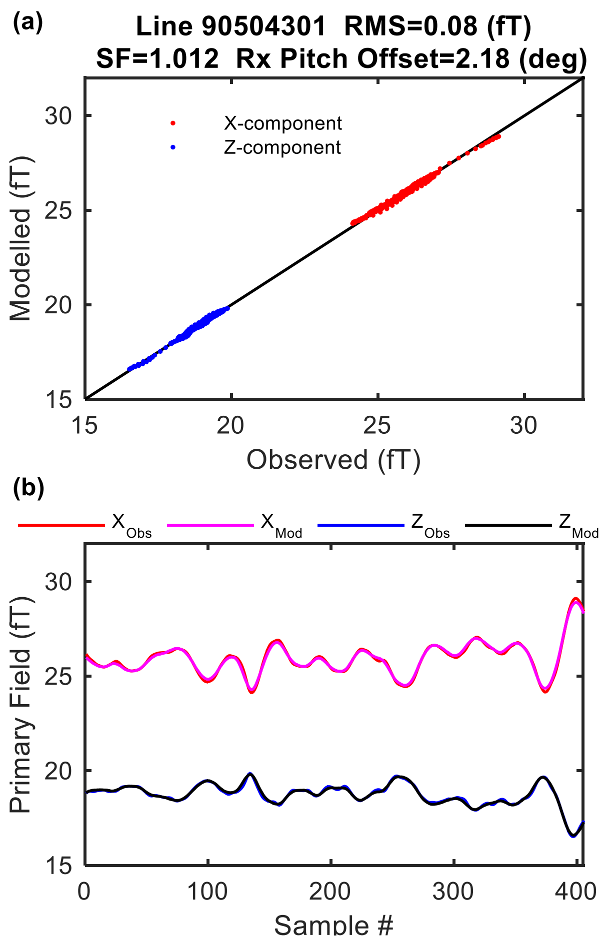

Figure 3. High altitude zero-line 90504301 after calibration with EM scale factor 1.012 and receiver pitch offset 2.18 degrees. It shows improved agreement between the observed and modelled data in (a) cross-plot and (b) profile form.

We observe in Figure 4. that Bird B1 and B2 flights appear to exhibit the same EM scaling factor (Figure 4a) but different receiver pitch offset values (Figure 4b). This is consistent with the relative alignment of the receiver coils and the IMU being changed slightly during the maintenance but which would not affect the gain. On the other hand, the Bird B2 and B3 flights appear to exhibit different EM scaling values (Figure 4a) but the same receiver pitch offset values (Figure 4b). This is consistent with the transmitter switches having being modified (introducing a slightly different overall system gain), but which would not affect the receiver pitch offset. Naturally we would expect, and do observe, different values for both calibration parameters between Birds A-B and Birds B-C since they were totally different instruments.

Since we had plausible physical explanations, we were quite comfortable applying the median value of each of the five populations of calibration values to all the EM (primary and secondary) and receiver pitch data over the associated range of flights. Table 1 shows the calibration values that were determined for each phase from the median of each population and subsequently applied to the AusAEM Year 1 dataset. The observed EM data were multiplied by the EM scaling factors, and the receiver pitch offsets were added to the measured receiver pitch data.

Table 1. Calibration values that were applied to each phase of the AusAEM Year 1 data. The five sets of calibration factors are consistent with the number of significant equipment changes.

Phase	Flight numbers	EM scaling factor	Receiver pitch offset (deg)
Bird A	8-70	1.012	+2.2
lightning strike			
Bird B1	74-91	1.000	+1.6
bird shell opened for maintenance			
Bird B2	94-128	1.000	+2.7
transmitter switch upgrade			
Bird B3	141-192	0.986	+2.7
bird loss			
Bird C	201-211	0.974	+0.9

To avoid possible future confusion, we note that the EM scale factor values in Table 1 differ from those stated in Table 18 of the logistics and processing report (CGG, 2018). This is because the authors were applying the calibrations to a dataset to which scaling factors (as effective receiver area) had previously been applied, which was not the case for the dataset used to generate the figures and tables in this abstract.

CONCLUSIONS

We have used the theoretical forward modelling of primary field AEM to check the agreement between observed and modelled data. Through lack of agreement, this quality control measure revealed time-lag parallaxes between the EM and ancillary position/orientation data. It also alerted us to an error in the coordinate system sign and to the spurious IMU data on many pre-flight zero-lines. Without the installation of the new receiver bird IMU data in TEMPEST these problems may well have gone unnoticed, or at the very least they would have been difficult to confidently diagnose.

We hypothesised various reasons that could potentially explain the discrepancy between the observed and modelled primary field data. We tested our favoured hypothesis by developing a least squares inversion algorithm to solve for the calibration parameters on each zero-line, being an EM scaling factor and a receiver pitch offset. We judged the results to be plausible because we could observe five distinct populations of calibration values associated with particular phases of the survey partitioned by significant equipment changes. These calibration values were used to calibrate all the survey data.

The results show the value of the receiver bird IMU data. It reinforces the, already known, fact that measured responses are extremely sensitive to receiver pitch. They show that accurate calibration of the alignment of the IMU instruments is required and that they should be re-calibrated after equipment changes. They also show the value of using quantitative modelling to investigate and diagnose discrepancies between observed and modelled data. The modelling and inversion approach that we have outlined will become a routine part of the quality control and calibration workflow for fixed-wing AEM.

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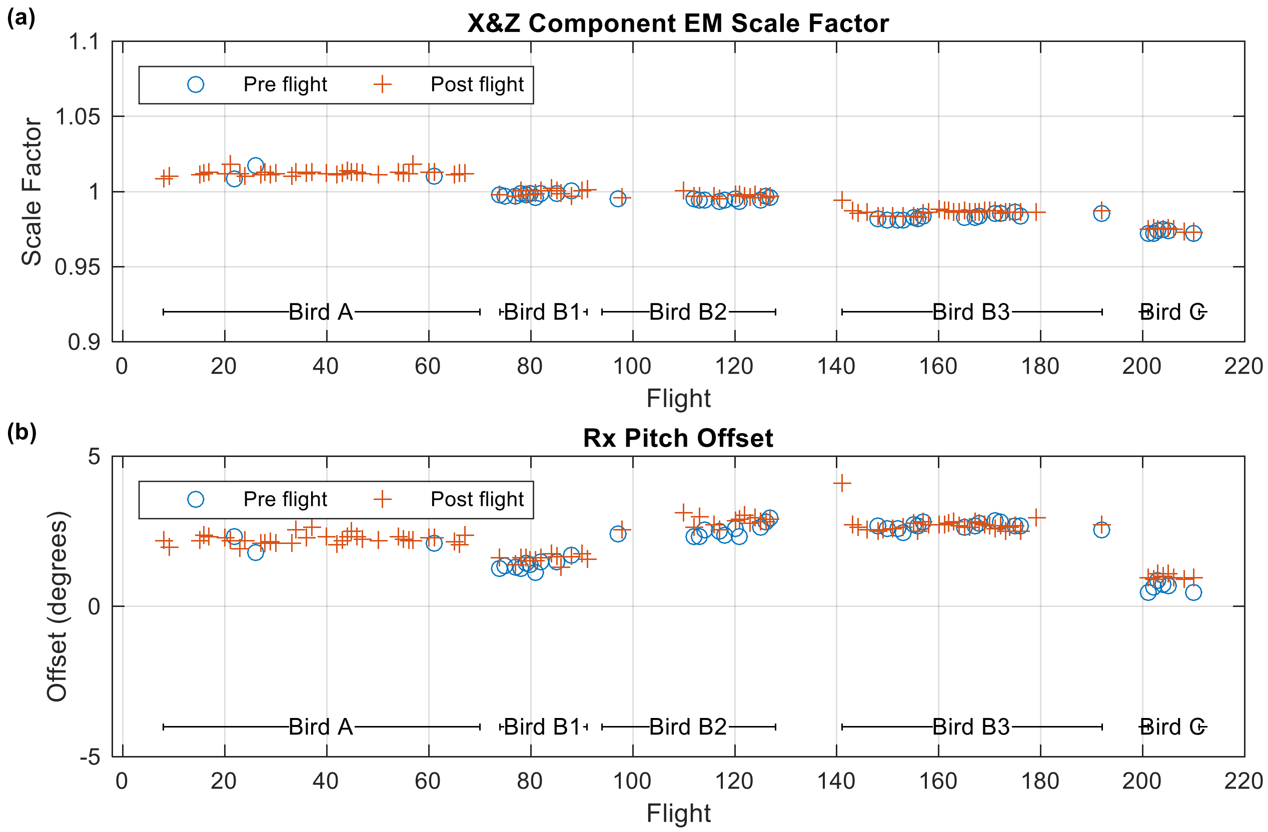

Figure 4. Summary of the (a) EM scaling factor and (b) receiver pitch offset calibration values that were estimated by our inversion algorithm for each high altitude zero-line over the duration of the survey. The median of each of the five populations (Bird A, B1, B2, B3, and C) are used as the calibration values that are applied to the dataset. Note that many pre-flight zero-lines are not included because they have suspect receiver bird IMU data as noted in the text.