
Part 1: Data acquisition and quality control

Introduction

A total of 15 600 line kilometres of regional helicopter electromagnetic (HEM) data were acquired in four separate survey areas during 2001–2002 (fig. 1.1) as part of the Western Tasmanian Regional Minerals Program (WTRMP). The survey areas are prospective for a wide range of mineralisation styles, including Palaeozoic VHMS, replacement tin, skarns, vein lead-zinc-silver, gold, nickel and copper.

This report describes quality control of the HEM surveys during data acquisition, and presents initial regional-scale geological interpretations for the Balfour, Dolcoath, Meredith and Mount Read Volcanics survey areas.

Data acquisition

Data were acquired using a Geotech Hummingbird HEM system. The survey contractors were GeoInstruments Ltd (January 2001) and Fugro Airborne Surveys (late 2001–2002).

The Hummingbird HEM system employs both horizontal coplanar (HCP) and vertical coaxial (VCX) transmitter-receiver geometries – typical system parameters are listed in Table 1.1. Nominal bird height for the survey was 30 m, although actual heights were often greater than this due to the rugged and heavily-forested terrain. Flight line and tie line spacings were 200 m and 1500 m respectively. Flight lines were directed north-south in the Dolcoath area, and east-west in the other areas.

The severe terrain and dense vegetation within the survey areas unfortunately resulted in two survey birds being destroyed or irreparably damaged during the survey. Specifications and dates of operation of the three birds used for the survey are given in the data acquisition report from Fugro Airborne Surveys (TAS_HEM_Readme.txt). The Dolcoath survey was flown entirely using Bird 2, and the Balfour survey using Bird 3. The Meredith survey was flown using both Birds 2 and 3 (fig. 1.2), and the Mount Read Volcanics survey using all three birds (fig. 1.3).

Resistivities within the survey areas are high, typically ranging between a few hundred and a few thousand ohm-metres. These high resistivities have generally resulted in very low signal strengths at 880 Hz and 980 Hz, although strong responses are observed at these frequencies over mineralisation and conductive lithologies such as Tertiary basalts and carbonaceous shale.

The maximum depth of investigation for the Hummingbird system has been estimated theoretically at around 150 m (Reid, 2002). However, the depth of investigation decreases significantly in

areas of conductive cover (e.g. Tertiary basalts and Quaternary alluvium), and may be less than 50 m in very conductive areas. The practical depth of investigation determined from conductivity-depth transformation of the HEM data has been further reduced due to widespread data quality problems at the lowest frequency (See *Levelling Errors* section).

Data processing

Conductivity-depth transformation

Levelled inphase and quadrature HEM data supplied by the contractor have been transformed to conductivity vs depth using EMFlow v3.2 (Macnae *et al.*, 1998) and the Sengpiel method (Sengpiel, 1988). Conductivity-depth sections produced using EMFlow are referred to in this report as ‘conductivity-depth images’ (CDIs), and those produced using the Sengpiel method as ‘Sengpiel sections’ (e.g. fig. 2.9). These conductivity-depth transformations, although similar, have specific advantages and disadvantages. The Sengpiel transformation is relatively simple, but is known to underestimate the actual depth of investigation of HEM data, and to overestimate the thickness of conductive layers within the earth. The EMFlow CDI process is very complex, but can produce conductivity-depth sections with superior depth resolution to those from the Sengpiel transformation.

EMFlow and Sengpiel conductivity-depth data have also been used to produce plan slices of conductivity at fixed depths below the surface (e.g. fig. 2.13–2.15). In contrast to the EMFlow CDI process, the Sengpiel conductivity-depth transformation yields only one conductivity and depth per frequency, i.e. a maximum of five conductivity-depth pairs at each location. The sparseness of the resulting conductivity-depth data means that Sengpiel depth slices have inferior spatial resolution to their EMFlow counterparts, and are suitable only for large-scale interpretation (e.g. Griggs, 2002). Only the conductivity-depth slices produced using EMFlow are discussed in this report.

The quality of the CDIs, conductivity-depth slices and Sengpiel sections is highly variable, and depends in turn on the quality of the levelled inphase and quadrature data (see *Quality Control* section). In many parts of the WTRMP survey, the EMFlow CDI and Sengpiel transformations have produced consistent results, and data quality in these areas is considered to be reasonable. However, the CDI and Sengpiel methods can produce strikingly different results in some cases. In particular, the CDIs contain widespread deep conductive artifacts in resistive areas (e.g. granites), where measured HEM responses are very close to or below the noise level. These artifacts typically occur most strongly at depths in excess of the

depth of investigation of the Hummingbird HEM system, but also affect conductivities calculated at shallower depths. EMFlow CDI and Sengpiel sections occasionally show quite dissimilar results in areas where the signal strength is above the noise level (e.g. Balfour Line 11271, fig. 2.12). These differences are thought to result from drift or other levelling errors in the data, as conductive features in the Sengpiel sections (which are not evident in the EMFlow CDIs) often occur immediately adjacent to areas where responses fall below the noise level. The relative insensitivity of the EMFlow CDIs to these errors is likely to be due to weighting out of the inphase and VCX responses during the deconvolution process (Reid, 2002).

Deep conductivity-depth slices produced from the CDI data have been found to be of limited use, due to the difficulty of discriminating geological features and processing artifacts. It has however been possible to obtain some useful geological information from the depth slices, particularly those from Balfour and Meredith. The poorer quality of the depth slices from the Mount Read Volcanics and Dolcoath surveys is presumably due to the difficulties of acquiring and levelling HEM data in areas of severe topography and complex geology.

Multiplots showing raw HEM responses, TMI, radar altimeter, and CDI and Sengpiel sections have been found to be the most valuable interpretation product. Processing artifacts in the EMFlow CDIs can be immediately recognised by comparison with the Sengpiel sections – areas of ‘no data’ in the Sengpiel sections correspond to measured responses below the nominal noise level for the survey (Reid, 2002).

Anomaly picking

Confined bedrock conductors (i.e. HEM anomalies with a strong response at 880 Hz and 980 Hz), and conductors with coincident magnetic anomalies have been manually picked from the Balfour HEM data (fig. 2.8). Anomalies considered too wide to be due to mineralisation, and those corresponding to radar altimeter spikes, were excluded during the picking process. Anomaly picking has not been performed for the Dolcoath, Mount Read Volcanics and Meredith areas, but is strongly recommended in order to identify responses potentially associated with mineralisation.

Quality control

The primary quality control for the WTRMP surveys was a daily repeat test flight line. The location of the test flight for each survey area was chosen by the contractor in order that test flights would cause minimum inconvenience to production surveying. A different test line was flown in each survey area, and test line lengths ranged from <1 km to ≈4 km. Test flight data have been used to assess the general repeatability of HEM data acquired on different days (or using different birds) during the survey.

Assessment of noise levels for the survey based on the test flight data has been complicated by large ‘DC shifts’ or biases in the measured inphase and quadrature responses from individual flights.

Analysis of test line data during the survey identified a calibration problem affecting data acquired using Bird 2. This error resulted from incorrect positioning of the Q-coil used for daily calibration of the 34 kHz coil pair. An empirical correction factor was applied to the incorrectly-calibrated data by the contractor, as described in the data acquisition report (TAS_HEM_Readme.txt). The validity of this correction, and the possible effect of the calibration error on CDI and Sengpiel sections, have not yet been assessed.

A basic check on the HEM data quality was provided by data acquired on two test flights over seawater. These seawater test flights produced apparent resistivities in the range 0.2 ohm-m to 0.4 ohm-m at the higher frequencies, consistent with those expected for seawater. A quantitative analysis of the seawater test flight data was not undertaken, due to a lack of information on bathymetry and seawater temperature.

Levelling errors

Data quality from production flights was initially assessed using maps of apparent resistivity at each frequency. These were calculated by the contractor using the amplitude-altitude algorithm, which assumes a purely conductive (non-magnetic) earth (Huang and Fraser, 2000). The amplitude-altitude algorithm has the disadvantage that it requires the bird altitude as an input. Radar altitudes are frequently in error over heavily-forested survey areas due to returns from the tree canopy.

By convention, inphase and quadrature Hummingbird HEM responses over purely-conductive earths are expected to be positive for the HCP geometry, and negative for VCX. Negative inphase responses are however observed at low frequency over near-surface magnetic sources (Huang and Fraser, 2000; fig. 1.4). A data quality issue identified via analysis of test flight and production data has been a widespread negative 880 Hz inphase response of up to ≈10 ppm in levelled data acquired over resistive, nonmagnetic lithologies (D’Andrea, 2001; fig. 1.5). This negative response exceeds the nominal noise level of the survey, and is large in comparison with the signal strengths expected at 880 Hz in resistive areas (e.g. Table 1.2). Negative low-frequency responses are most likely to be due to incorrect levelling of the data, due to use of the amplitude-altitude algorithm for calculation of apparent resistivities during the levelling process. The amplitude-altitude algorithm yields an (incorrect) conductivity estimate even from data in which either (or both) inphase or quadrature responses are of opposite sign to that expected from a purely-conductive earth. The inphase-quadrature algorithm,

which does not depend on bird altitude, and which is more sensitive to data quality, should be preferred for future HEM surveys in heavily-forested survey areas.

Estimation of errors from test flight data

Measurement errors for the Hummingbird system have been estimated by analysis of data from five survey flights over the Zeehan airstrip test line using Bird 1 (Table 1.1). The test flight data were acquired over a period of three days in January 2001. The test line is topographically flat with little vegetation, and measured radar altitudes are considered to be reliable. Zeehan airstrip is constructed on Quaternary alluvium overlying Devonian Bell Shale (Brown *et al.*, 1994).

Drift was removed from the test line data by the contractor, using zero levels determined from high altitude data acquired at the start and end of each test line. No other data levelling was performed. An example of drift-corrected observed data from test flight 1 (7004 Hz and 880 Hz) is given in Figure 1.6.

Table 1.1

Hummingbird system parameters

<i>Frequency (Hz)</i>	<i>Coil separation (m)</i>	<i>Orientation</i>
34 111	5.10	HCP
7 004	6.29	VCX
6 600	6.29	HCP
985	6.03	VCX
880	6.03	HCP

Ground truth for the test line was provided by transient electromagnetic (TEM) and direct-current (DC) resistivity soundings at the intersection between the north-south and east-west runways at Zeehan airstrip (henceforth referred to as the 'cross-strip'). The 'average' ground truth model was a two-layered earth with parameters:

Layer 1 thickness = 24.9 m
 Layer 1 conductivity = 0.006825 S/m (147 Ωm)
 Layer 2 conductivity = 0.0004753 S/m (2104 Ωm)

This model was determined from independent layered-earth inversions of the DC resistivity and TEM data. Frequency-domain (EM-34) vertical coplanar (VCP) and horizontal coplanar (HCP) profiles along the entire airstrip indicate that near-surface conductivities (30–40 m) are low and reasonably uniform, with conductivities ranging between 1 to 6 mS/m (HCP) and 1 to 9 mS/m (VCP). Transmitter-receiver separation for the EM-34 survey was 40 metres.

The initial step in processing was to calculate the distance from the cross-strip of each point on each of the five test flight lines. A 100 m segment of data (50 m either side of the cross-strip) was extracted from each flight line.

The height-compensated response of the ground truth model was then calculated for each flight line, using the observed radar altimeter reading at each observation point on each flight line as an input to the forward model. The response of the ground truth model is different for each test flight due to differences in flight height. Representative signal magnitudes for the ground truth model are listed in Table 1.2.

Table 1.2

Response of the ground truth model for test flight 1, calculated using the actual survey altitude (37.5 m) at the receiver position closest to the cross-strip

<i>Frequency (Hz)</i>	<i>Inphase (ppm)</i>	<i>Quadrature (ppm)</i>
34 111	125	125
7 004	8.6	27
6 600	31	104
985	0.3	4
880	1	14

When the observed data and the height-compensated theoretical data were compared, they were found to be significantly different in amplitude due to large 'DC offsets' or biases in the measured data. Figure 1.7 shows calculated differences between the observed and ground-truth responses for the inphase component at 6600 Hz.

An attempt was then made to calculate calibration corrections for the flight line data, using the least-squares inversion process described by Deszcz-Pan *et al.* (1998). This involved calculation of an amplitude scaling (gain) factor for each frequency (five total), daily phase correction factors for each frequency (15 total – 5 frequencies × 3 days), and inphase and quadrature biases for each flight and each frequency (50 total – 10 components × 5 flights). Observed data from three locations on each test line (-50 m, 0 m, and +50 m from the cross-strip), and actual observed radar altitudes, were used in the inversion for calibration corrections. Corrected data showed an excellent fit to the observed data from each test flight. However, calculated amplitude, phase and bias corrections showed very large ranges and were considered to have implausible magnitudes in many cases (e.g. phase corrections of several radians).

As calculation of amplitude and phase corrections was found to be unstable, best-fit bias corrections were calculated by fixing the amplitude scaling factor = 1, and all phase correction factors at 0. The same three observation points from each test line (-50 m, 0 m and +50 m) were used for calculation of the bias correction. The best-fit inphase and quadrature bias corrections at each frequency are given in Table 1.3. Biases are expressed as the response in ppm which must be **added** to the observed data in order for it to approximately match the response of the cross-strip ground truth model.

Some of the biases listed in Table 1.3 are of comparable magnitude to the theoretical response of the ground truth model (e.g. Table 1.2). It should be noted that Deszcz-Pan *et al.* (1998) have reported bias corrections of up to 1400 ppm for DIGHEM HEM data.

The next step in processing was to calculate a residual response for each line and frequency. For a given component (inphase or quadrature), the residual response (RR) at any point on a test line is given by

$$RR(x,f) = OR(x,f,h) - TR(x,f,h) + B(f,h) \quad (1.1)$$

where $OR(x,f,h)$ = observed response at position x , frequency f and height h .

$TR(x,f,h)$ = theoretical response of the ground truth model at position x , frequency f and height h .

$B(f)$ = computed bias for test flight at frequency f (Table 1.3).

Table 1.3

Computed inphase and quadrature biases for each frequency for each test line flight, calculated with amplitude factor fixed = 1, and phase corrections fixed = 0. The actual flight number is given in brackets in column 1 – the first two digits of the flight number are the Julian Day (Year 2001), and the second two are the survey flight number on which the test line was flown.

Test flight number	Frequency (Hz)	Inphase bias (ppm)	Quadrature bias (ppm)
1 (3505)	34,111	64.5	41.0
1	7,004	-2.44	-6.77
1	6,600	-7.05	24.84
1	985	-0.12	-3.16
1	880	7.84	4.46
2 (3506)	34,111	3.44	-96.6
2	7,004	2.98	7.98
2	6,600	-13.07	6.17
2	985	0.70	-0.8
2	880	7.73	-1.94
3 (3608)	34,111	-24.7	-106.8
3	7,004	-4.5	1.91
3	6,600	-15.09	9.88
3	985	-4.90	-1.67
3	880	12.02	3.17
4 (3710)	34,111	60.6	32.3
4	7,004	-0.62	2.31
4	6,600	-15.91	8.93
4	985	-0.94	-0.69
4	880	9.31	-5.05
5 (3711)	34,111	69.9	21.8
5	7,004	2.12	6.74
5	6,600	-17.73	-0.85
5	985	1.12	-0.58
5	880	9.73	-7.29

Residual responses for each flight, frequency and component are shown in Figures 1.8 and 1.9. General trends can be seen in the calculated residual responses – the HCP residuals increase from $x = -50$ m to $x = +50$, while the VCX residuals decrease. Because these basic trends can be seen on all flight lines and at all frequencies, they are considered to be of geological origin.

The envelope of the responses shown in Figures 1.8 and 1.9 can be used to determine representative inphase and quadrature measurement errors at each frequency (Table 1.4). These errors are considered to arise mainly due to errors in data levelling (i.e. during estimation of bias corrections). Levelling errors for 34 kHz inphase and quadrature, and 6600 Hz quadrature exceed the nominal noise levels for the survey (2.5 ppm). Errors could be considerably larger in routine survey data, where data levelling is not constrained by ground truth, or may not correctly consider inter-frequency or inphase–quadrature amplitude relationships.

Table 1.4

Estimated levelling errors for WTRMP test flight data

Frequency (Hz)	Inphase error (ppm)	Quadrature error (ppm)
34 111	10	12
7 004	1	2.5
6 600	2.25	8
985	0.6	0.4
880	1.2	0.9

Figure 1.10 shows Sengpiel sections calculated from test flights 1 and 5 before and after application of bias corrections. The uncorrected sections (a and c) are strikingly dissimilar, and are in poor agreement with ground truth data. Corrected sections show close agreement with each other, particularly within the upper 100 m, and are consistent with the ground truth model.

Noise levels

The high ground resistivities on the test line mean that there is very little geological signal at 985 Hz or for the inphase component at 880 Hz (e.g. Table 1.2). Noise levels for these components have been directly estimated from the residual responses in Figures 1.8 and 1.9, and are within ± 2.5 ppm for all five test flights.

Drift errors

The levelling error and noise analysis described in the preceding sections does not fully include the effects of drift, which can be a significant source of error in HEM surveys (Huang and Fraser, 1999). Each of the test flights shown in Figures 1.8 and 1.9 was flown in 20–25 seconds, and zero levels for drift correction of the data were determined from high-altitude flights immediately before and after each test flight. This

situation is considerably different to production surveying, where high-altitude flights are made only every half hour. Nonlinear drift of the system response between high-altitude flights is impossible to recognise, and incorrect drift removal can result in large errors in the data (Valleau, 2000).

Figure 1.11 shows 34 kHz and 6600 Hz zero levels measured at high altitude during a single WTRMP survey flight. Drifts are clearly nonlinear, and have magnitudes of up to several hundred ppm. These large variations are probably partly the result of unavoidable temperature changes due to the very large elevation ranges (700 m+) within the survey area. The measured drifts are very large in comparison with HEM responses expected over resistive lithologies (e.g. Table 1.2): this suggests that inaccurate drift correction could be a very serious source of error in the WTRMP survey data.

Summary

Accurate conductivity-depth transformation of HEM data is strongly dependent on the reliability of the levelled inphase and quadrature responses. Analysis of WTRMP test flight data has demonstrated the low noise levels of the Hummingbird HEM data, and has shown that data constrained by ground truth can be used to generate repeatable, geologically valid conductivity-depth sections. However, test lines were usually located outside the survey areas, and were not levelled or drift-corrected in the same manner as the

rest of the survey data. Accordingly, test flight data cannot be used to estimate levelling or drift errors in the production survey data delivered by the contractor.

Analysis of survey data has indicated that some significant levelling errors are present in the final data, e.g. relatively large negative inphase responses at 880 Hz over non-magnetic lithologies. Levelling errors may also be present at the higher frequencies, but are difficult to recognise due to the larger signal strengths. Systematic levelling errors at these frequencies can only be recognised by comparison of the HEM data with geophysical ground truth (e.g. TEM and DC soundings and borehole conductivity logs). Acquisition of appropriate ground truth data over the very large and inaccessible WTRMP survey area has been beyond the scope of this project.

Conductivity-depth sections and depth slices presented in this report have been calculated from levelled data supplied by the survey contractor, and have not been verified by ground geophysical measurements or drillhole data. Ground truth data should be used wherever possible to confirm interpretations presented in the following sections. Ground-truth constrained re-levelling of the HEM data, as has been described for the Zeehan test line data, would undoubtedly improve the quality of conductivity-depth sections generated from the production survey data.

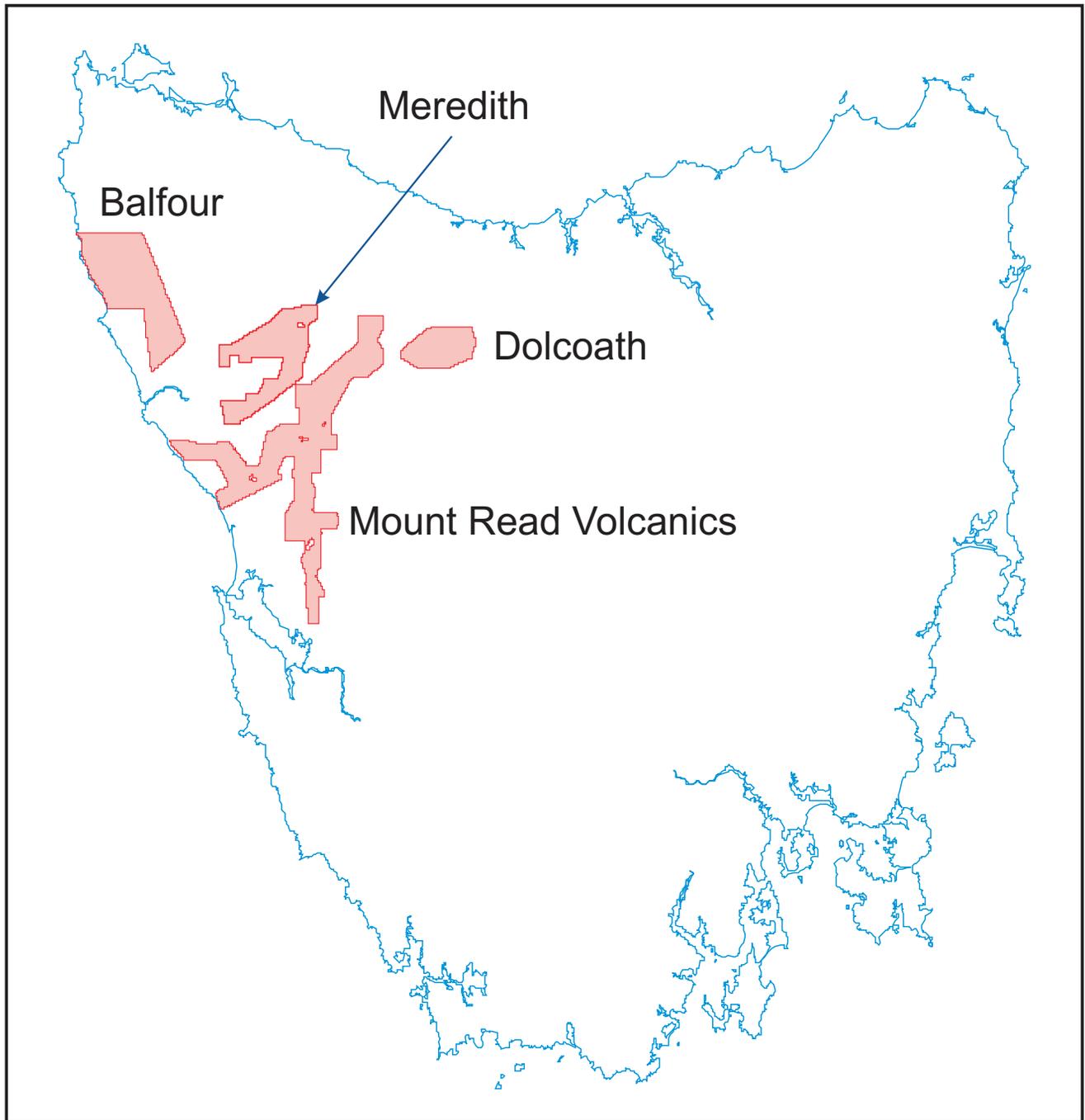


Figure 1.1
Locations of the 2001/2002 WTRMP Hummingbird HEM surveys.

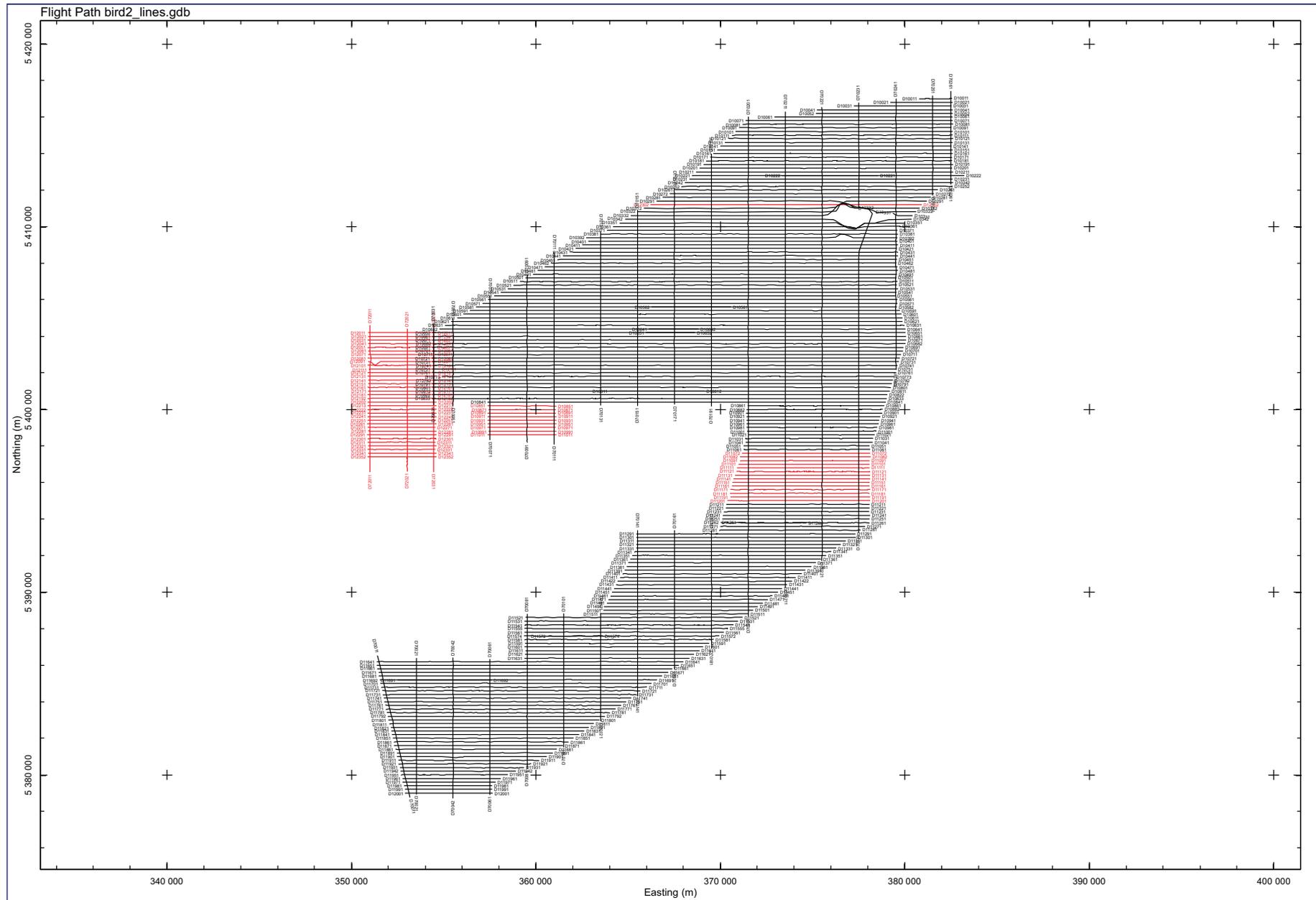


Figure 1.2. Meredith survey flight path map, showing lines flown with Bird 2 (black) and Bird 3 (red).

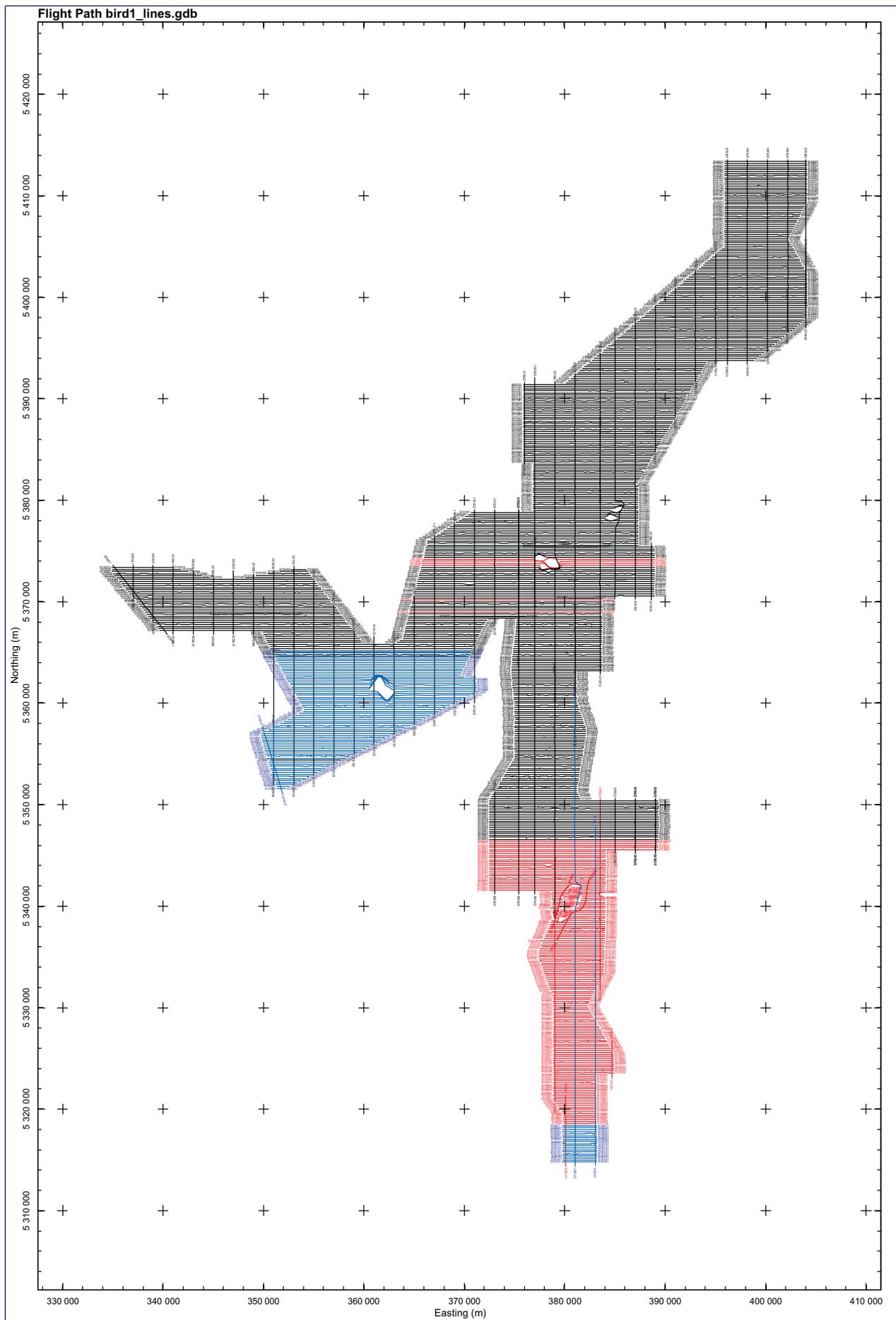


Figure 1.3

Mt Read Volcanics flight path map, showing lines flown with Bird 1(blue), Bird 2 (black) and Bird 3 (red).

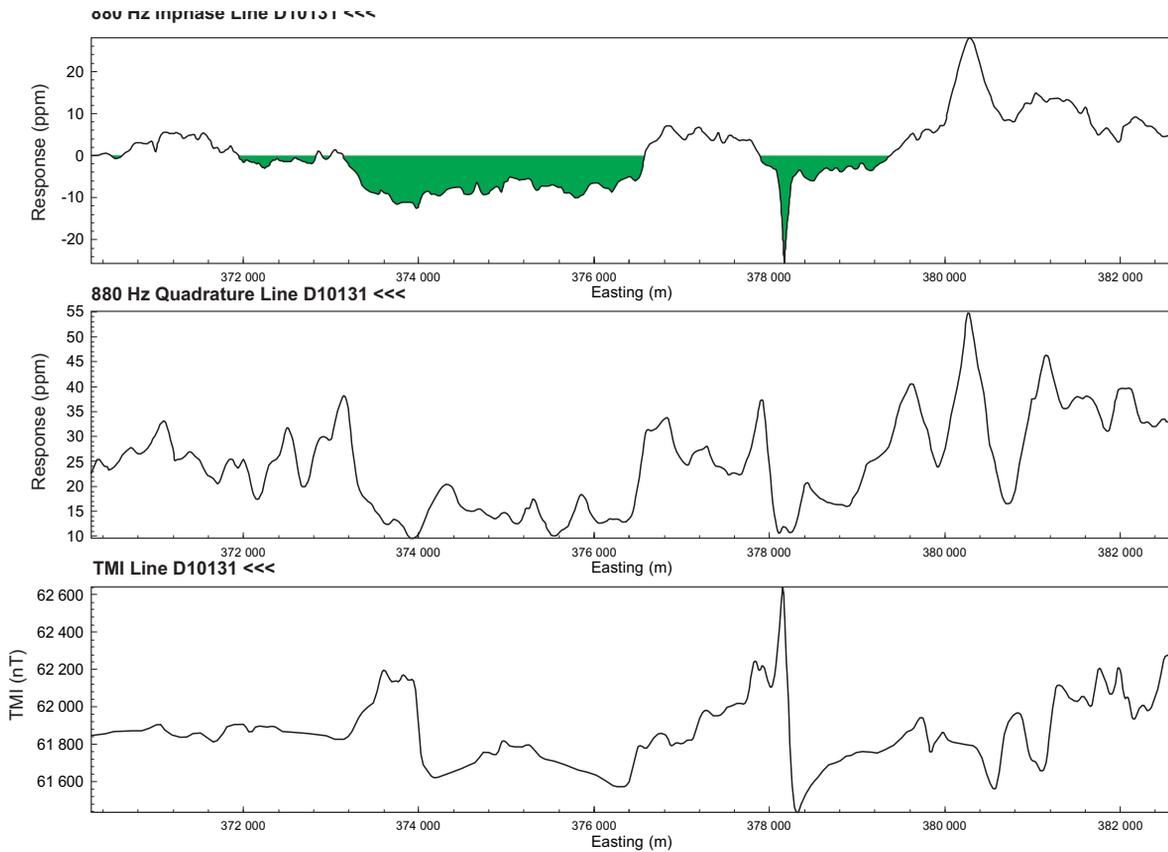


Figure 1.4

Multiplot showing 880 Hz and TMI responses from Line 10301 of the Meredith survey. Areas of negative inphase EM response are shaded. The negative inphase spike corresponds to a shallow 400 nT magnetic anomaly, and is due to magnetic polarisation of the response.

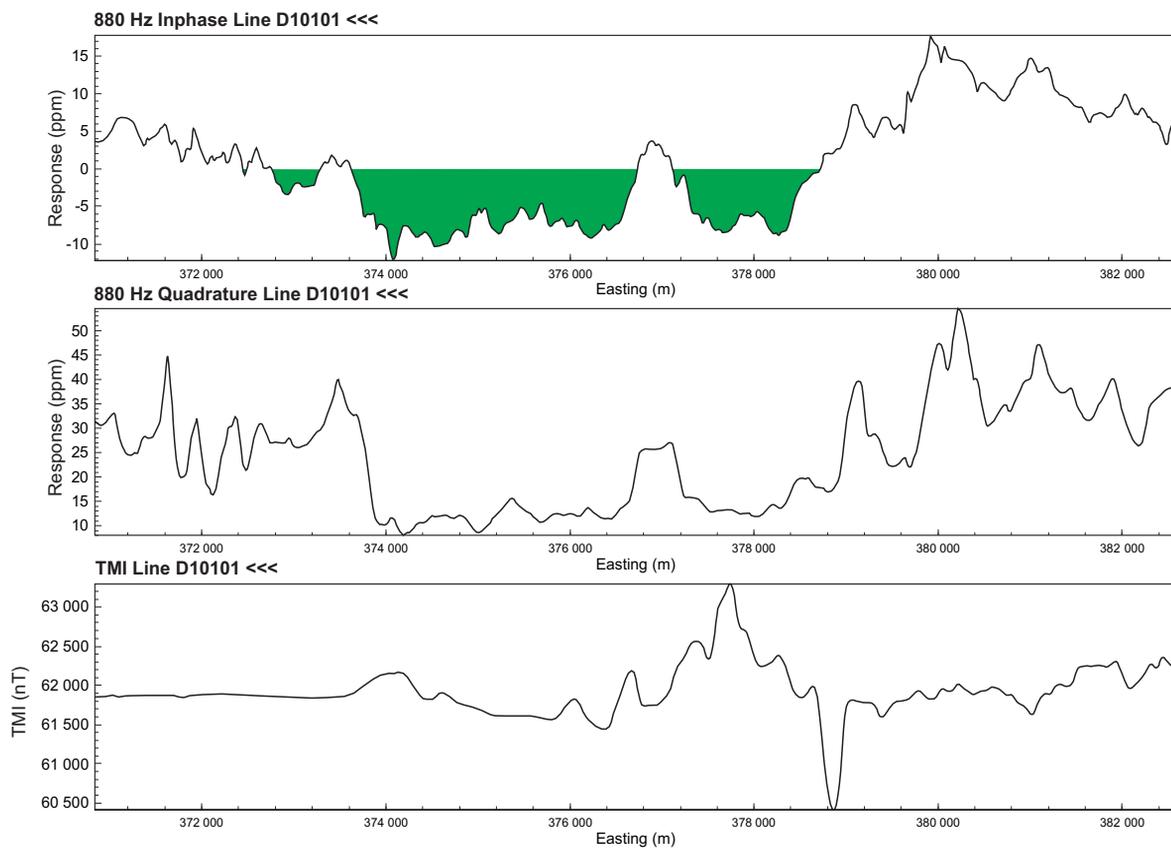


Figure 1.5

Multiplot showing 880 Hz and TMI responses from Line 10101 of the Meredith survey. Areas of negative inphase EM response are shaded.

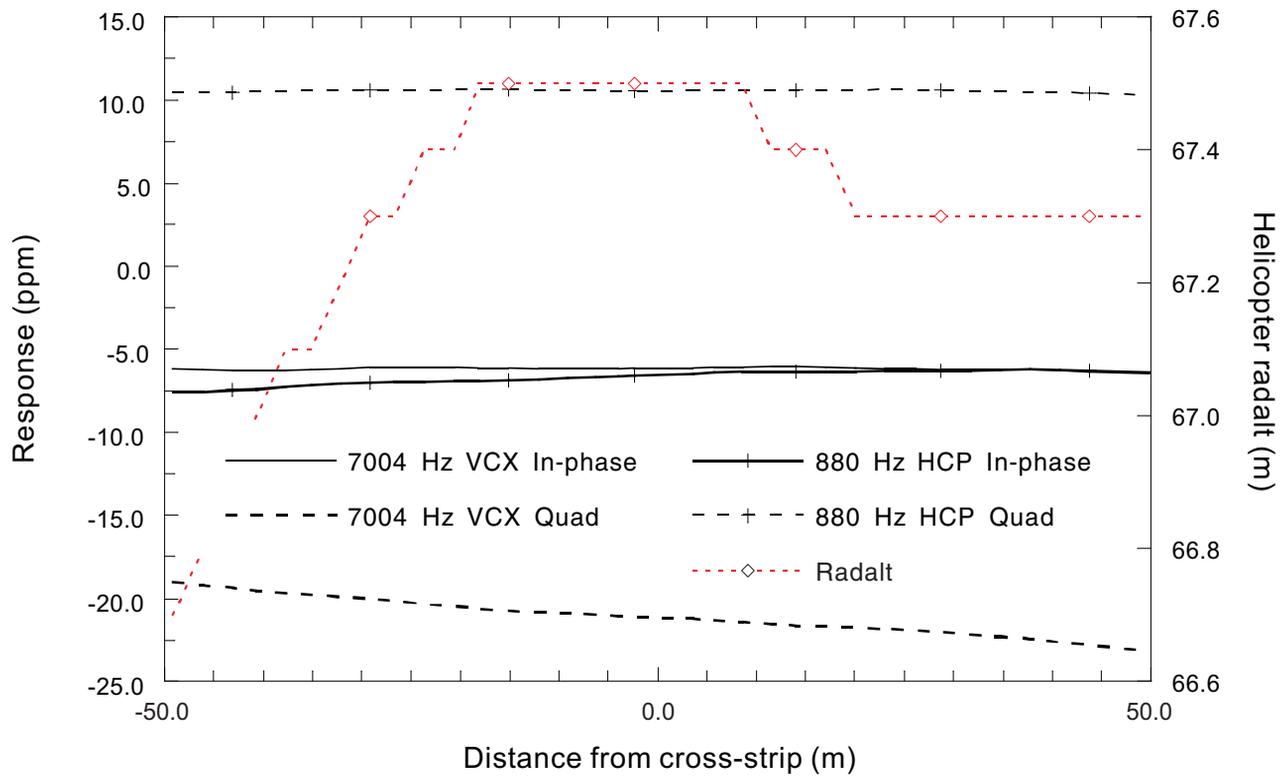


Figure 1.6
Observed data from Zeehan airstrip test flight 1 (February 2001).

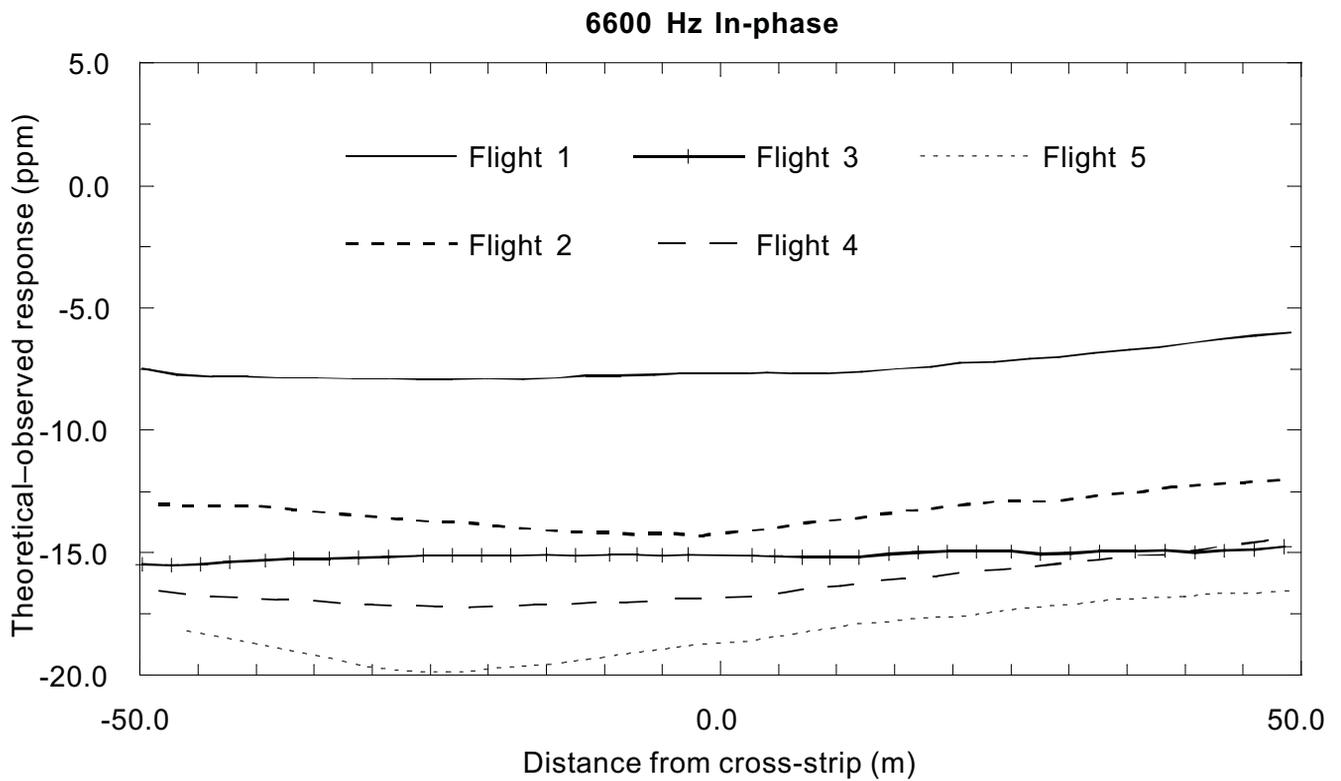
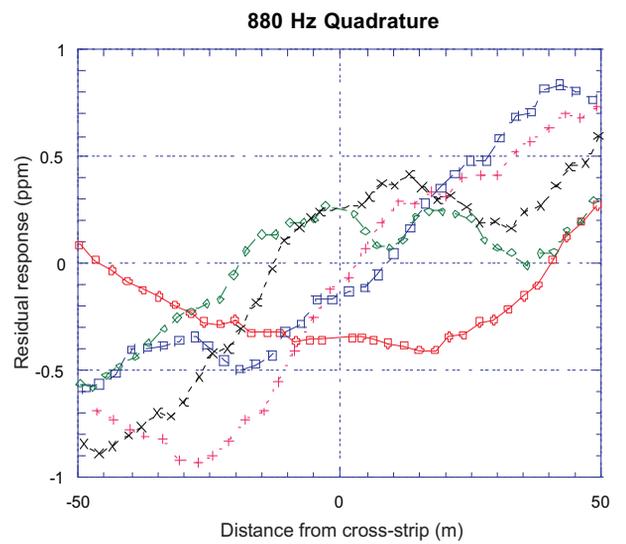
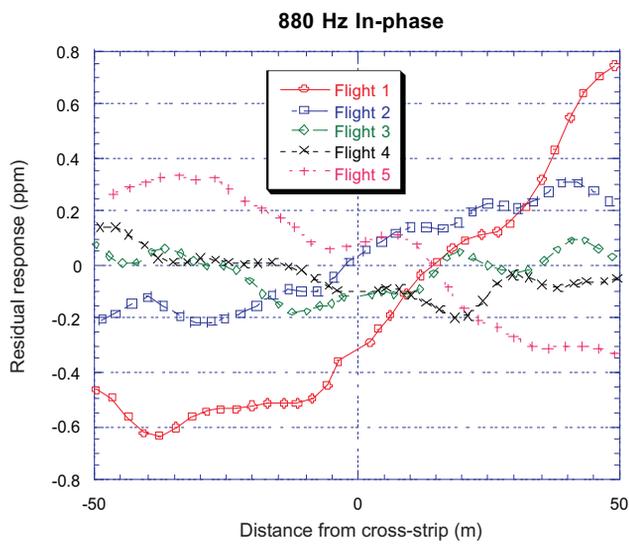
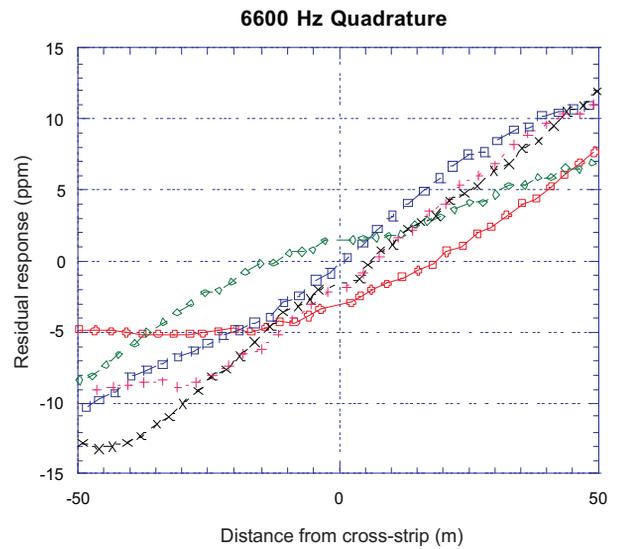
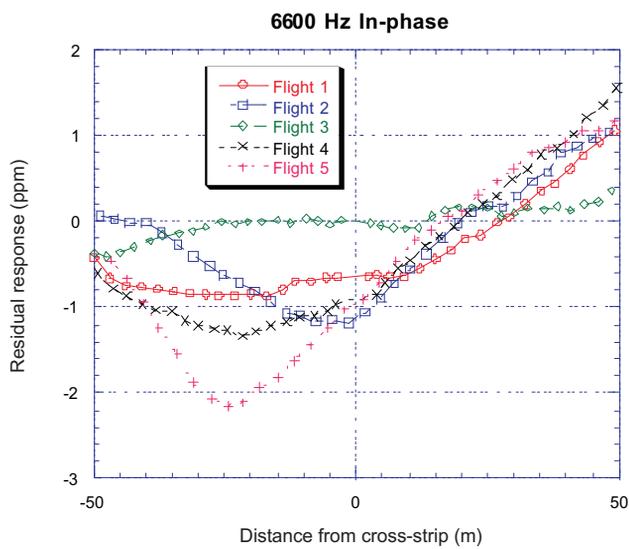
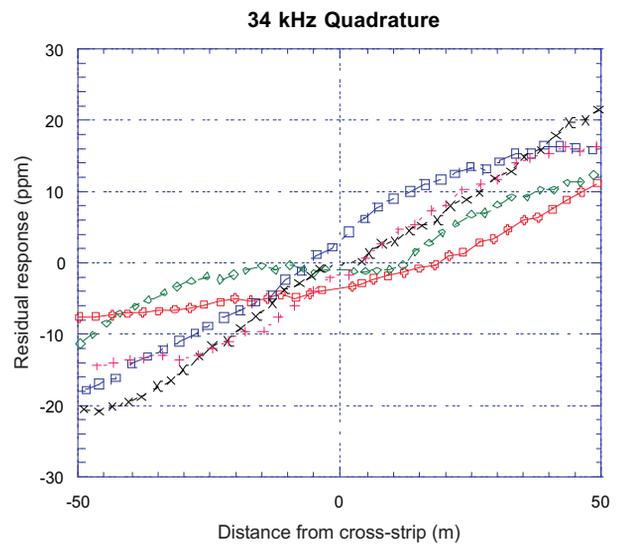
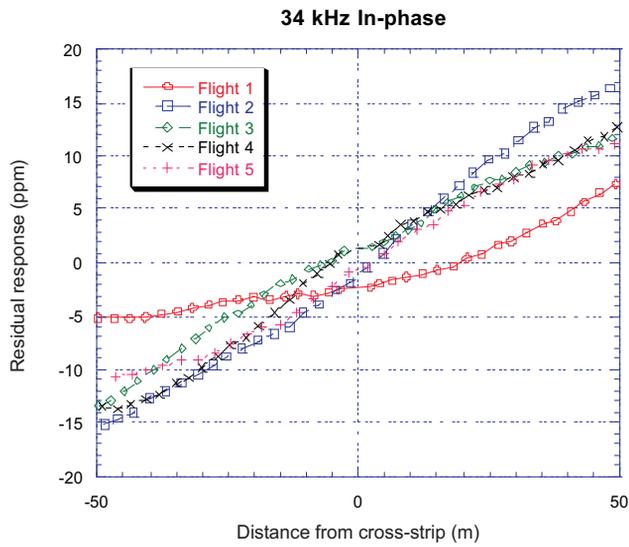


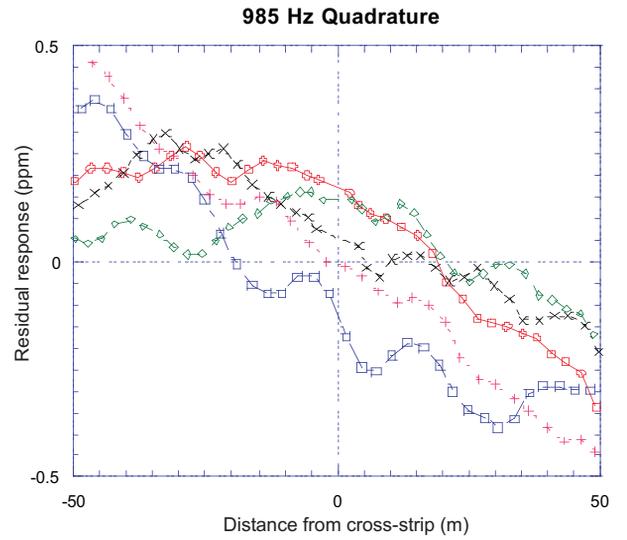
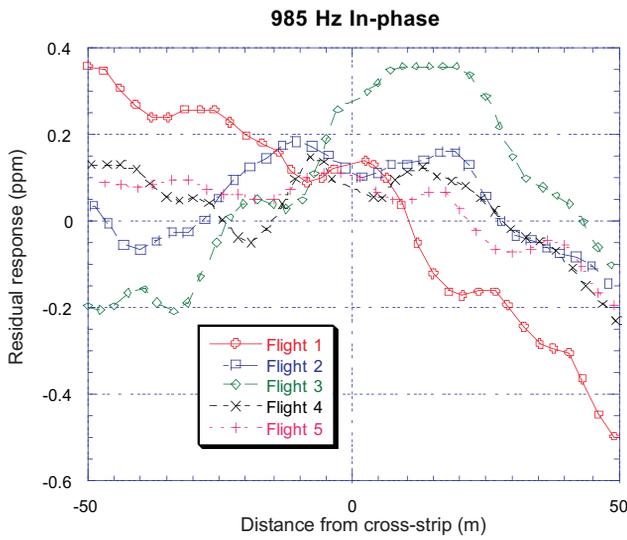
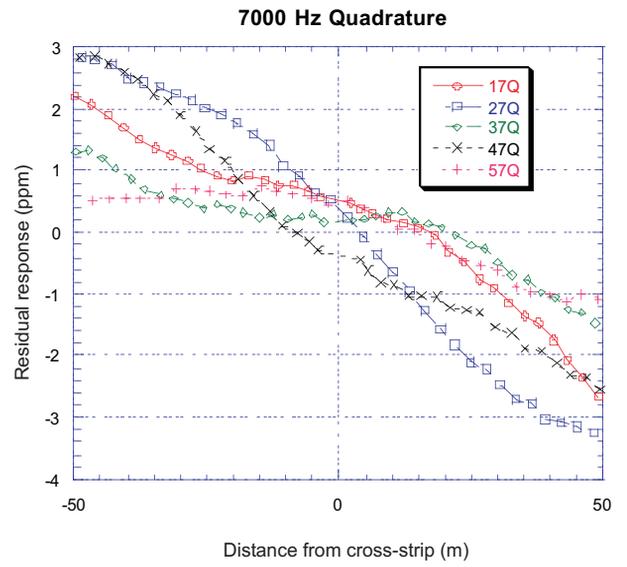
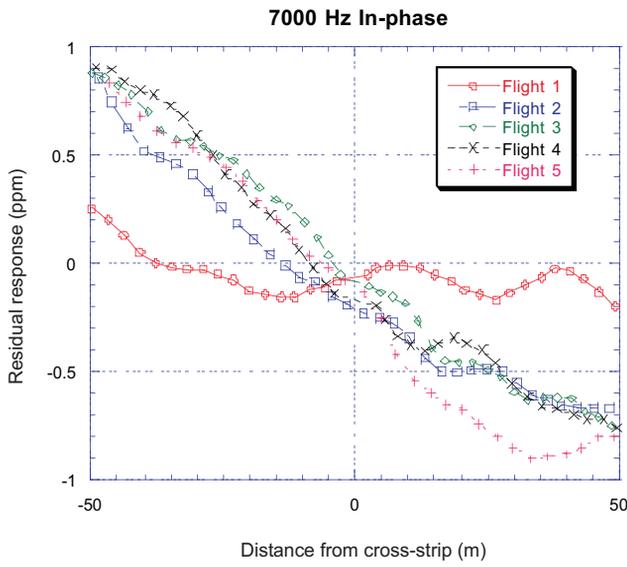
Figure 1.7
Differences between the 6600 Hz inphase response of the ground truth model and observed response for five Zeehan airstrip test flights.



Residual response = Observed – height-corrected theoretical – bias

Figure 1.8

Inphase and quadrature residual responses for 34 kHz, 6600 Hz and 880 Hz HcP data from five test flights at Zeehan airstrip.



Residual response = Observed – height-corrected theoretical – bias

Figure 1.9

Inphase and quadrature residual responses for 7004 Hz and 985 Hz VCX data from five test flights at Zeehan airstrip.

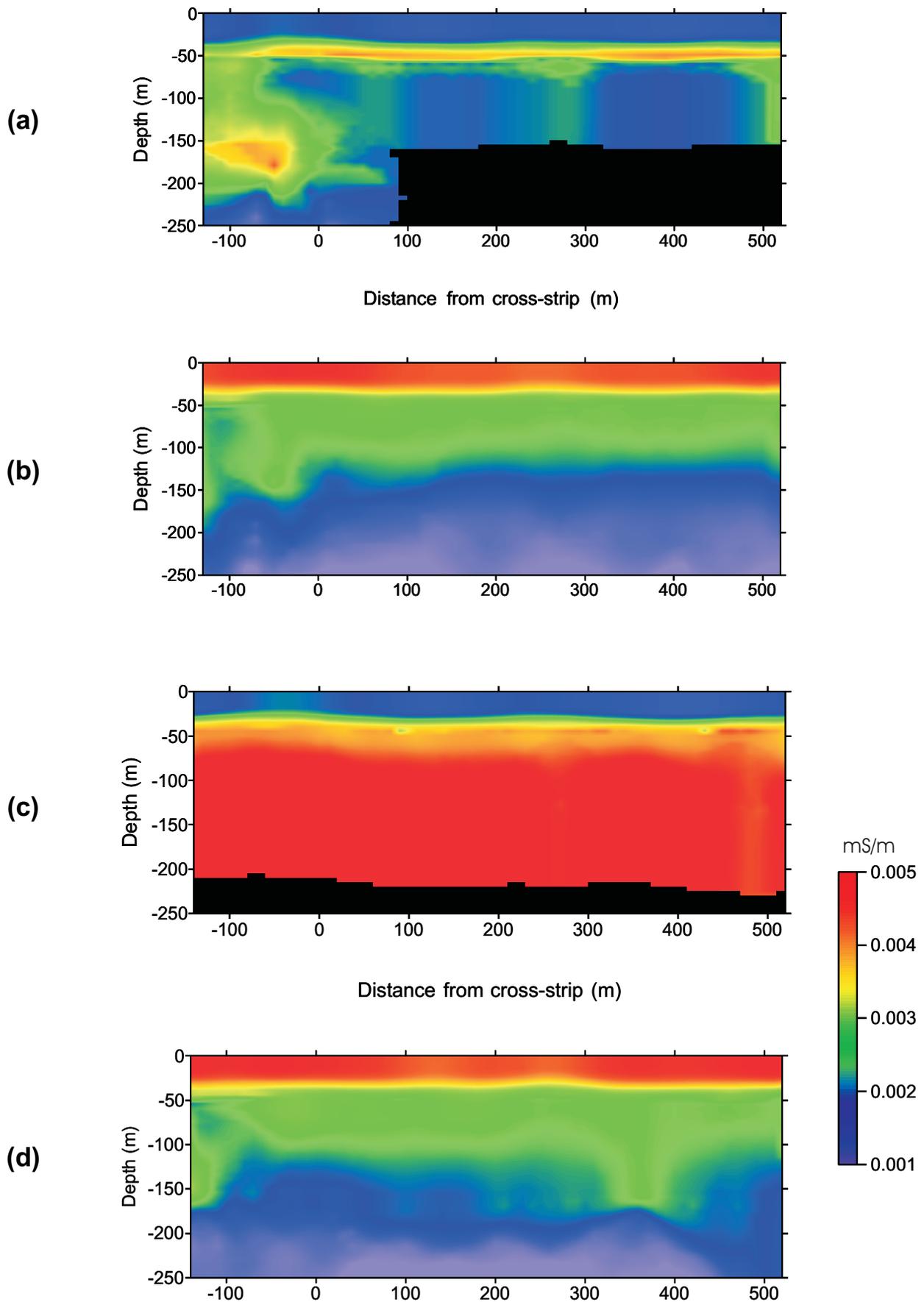


Figure 1.10

Sengpiel sections calculated from: (a) raw data from Zeehan test flight 1; (b) data from test flight 1 with bias corrections applied; (c) raw data from Zeehan test flight 5; and (d) data from test flight 5 with bias corrections applied.

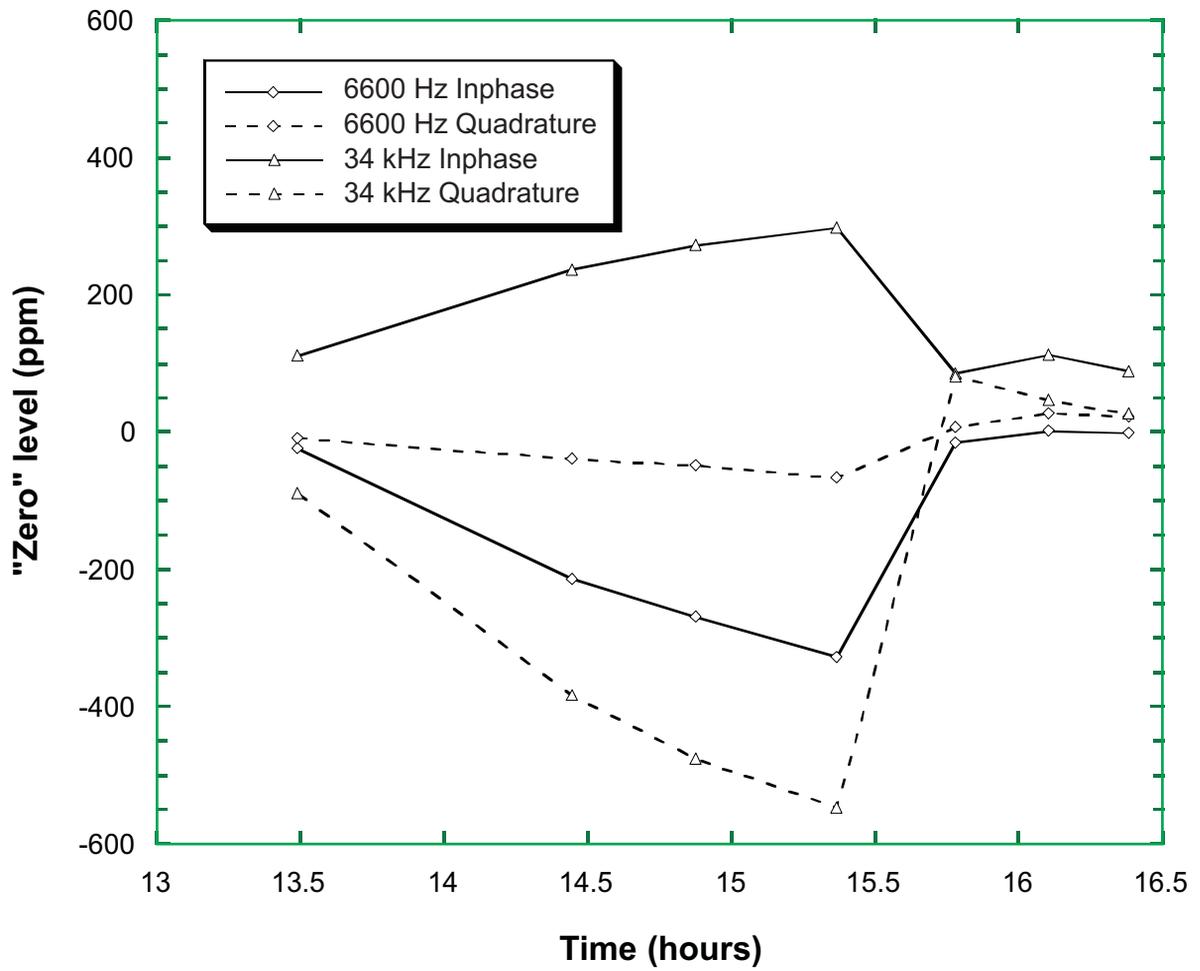


Figure 1.11

Inphase and quadrature 'zero' levels at 6600 Hz and 34 kHz, measured at high altitude during Flight 10 of the Mt Read Volcanics survey (February 2001).