Calibration Report

For Magnetic, Radiometric and Elevation Surveys

It is the responsibility of the Contractor to demonstrate that the Data have been acquired in accordance with the Technical Specifications outlined in Schedule 3 of the Deed (Schedule 3: 1.4a).

Technical Specifications related to the acquisition equipment and its calibration are to be documented in a calibration report and provided to Geoscience Australia prior to survey mobilisation (Schedule 8: 1.1a).

All calibration tests are to be completed within 12 months prior to survey mobilisation (Schedule 3: 1.12j).

1 Survey Details

This calibration report relates to the Survey in Table 1.1.

Table 1.1: Summary of survey details.

Geoscience Australia Project Number	P5003
Geoscience Australia Project Name	Tasmanian Tiers Airborne Magnetic & Radiometric Survey
Contractor Company Name	MAGSPEC Airborne Surveys
Contractor Job Number	1181
Acquisition Start Date	TBC

2 Aircraft

Table 2.1 lists the aircraft that will be used to acquire data for the Survey and Figure 2.1 shows the location of the sensors on the aircraft. Aircraft performance specifications are listed in Schedule 3:1.1a of the Deed.

Table 2.1: Details of the aircraft used to acquire data for the survey.

Make and Model	Cessna 210M
Call Sign	VH-HHJ

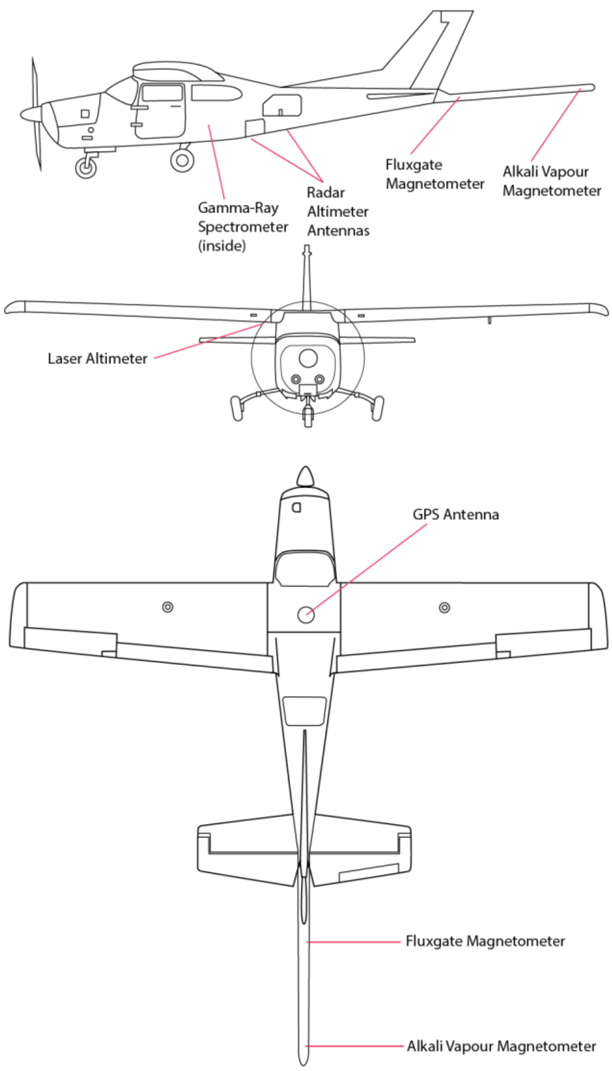


Figure 2.1: Example Only – A figure or photo of the survey aircraft showing the location of the sensors (e.g. alkali vapour magnetometer; Schedule 3: 1.9a), fluxgate magnetometer (Schedule 3: 1.9a), gamma-ray spectrometer, radar altimeter, laser altimeter, GNSS antennas) is required. Please label the distance and height between sensors.

3 Equipment Specifications

Table 3.1: Definitions related to equipment specifications.

Term	Definition
Sensitivity	The least change in a quantity which a detector is able to perceive.
Resolution	The minimum separation of two bodies before their individual identities are lost.
Accuracy	The total error compared to the true value (i.e. how close a measurement is to the true value).
Precision	The repeatability of an instrument measured by the mean deviation of a set of measurements from the average value.

Table 3.2: Specifications of the equipment used in the survey.

Total Field Magnetometer Schedule 3: 1.9	Make and Model	Geometrics G823a
	Type (e.g. caesium vapour)	Caesium Vapour
	Sampling Rate (Hz)	20
	Sensitivity at Sampling Rate (nT)	0.004/√Hz
	Resolution (nT)	0.001
	Absolute Accuracy (nT)	< 3
	Dynamic Range (nT)	20,000 – 100,000
	Serial Number	V4924
Three-Component Fluxgate Magnetometer Schedule 3: 1.9	Make and Model	Billingsley TFM100G2
	Sampling Rate (Hz)	20
	Sensitivity at Sampling Rate (nT)	100µV/nT
	Resolution (nT)	0.01
	Absolute Accuracy (nT)	+/- 0.5 % of full scale
	Dynamic Range (nT)	+/-100,000
	Serial Number	1400
Base Station Magnetometer Schedule 3: 1.10	Make and Model	GEM GSM-19
	Type	Overhauser
	Sampling Rate (Hz)	1
	Sensitivity at Sampling Rate (nT)	0.022
	Resolution (nT)	0.01
	Absolute Accuracy (nT)	0.1
	Dynamic Range (nT)	20,000 – 120,000
	Serial Number	9058299

Gamma-Ray Spectrometer Schedule 3: 1.12	Make and Model	RSI RS-500
	Detector Geometry (e.g. tabular/12 crystals in 3 x 4 configuration)	Tabular 4x crystals per pack
	Integration Interval (seconds)	1.0 or 0.5
	No. Channels	1024 (256 recorded)
	Energy Range (keV)	0-3,000
	Downward Detector Volume (litres)	32 (2x 16)
	Live Time Accuracy (%)	99.5 (“zero” dead time)
	Overall System Resolution (%)	<5.0
	Self-Stabilising?	Yes
	Serial Number	6018
Radar Altimeter Schedule 3: 1.6	Make and Model	Honeywell KRA-405B
	Sampling Rate (Hz)	20
	Operating Range (m)	0-762
	Absolute Accuracy (cm)	91
	Precision (cm)	10
	Serial Number	5759
Laser Altimeter Schedule 3: 1.6	Make and Model	Renishaw ILM-500R
	Sampling Rate (Hz)	20
	Operating Range (m)	0-250
	Absolute Accuracy (cm)	10
	Precision (cm)	8
	Serial Number	9300116102
Acquisition System Schedule 3: 1.2	Make and Model	GeoResults ZDAS DX2
	Oversampling?	N/A
	Options available (switches or on the fly corrections/processing)	gradiometer
	Fiducial Precision	0.05 sec
	Serial Number	Z209
Global Navigation Satellite System (GNSS) Schedule 3: 1.5	Make and Model	Novatel OEM719
	Sampling Rate (Hz)	2
	Differential Mode?	Y
	Horizontal Accuracy (cm)	40
	Vertical Accuracy (cm)	40
	Serial Number	DMGW18050179E

Barometer Schedule 3: 1.7	Make and Model	Setra 276
	Sampling Rate (Hz)	20
	Air Pressure Precision (mbar)	0.01
	Temperature Precision (°C)	0.1
	Serial Number	N/A

4 Altimeter Calibration

4.1 Parallax

A parallax correction must be applied with respect to the magnetic, gamma-ray spectrometric and elevation Data. The navigation Data positions must be interpolated rather than interpolating the geophysical Data (Schedule 3: 1.8b).

Description of Method
After GPS positions are interpolated due to parallax (see Section 5.1), a test line is flown in opposite directions over a topographic feature. A parallax correction of +2 fids was determined and applied to radar altimeter data, and +2.9 fids to laser altimeter data.

4.2 Linearity Test

Altimeter linearity should be verified before commencement of Survey operations by flying over a level airstrip on barometric instruments at terrain clearances of 30, 60, 80, 100, 150 and 300 m approximately (Schedule 3: 1.6b-c).

Table 4.1: Details of the linearity test.

Date	4th February 2021
Location	Emerald airport, Emerald, Queensland
Aircraft Call Sign	VH-HHJ
Vertical Datum Recorded by GNSS	GRS80
Calibration Range Height (m) - Relative to Vertical Datum of GNSS	190.41 – 1.95 = 188.46
Vertical Offset Between the GNSS and the Laser Altimeter (m)	0.20
Vertical Offset Between the GNSS and the Radar Altimeter (m)	1.45

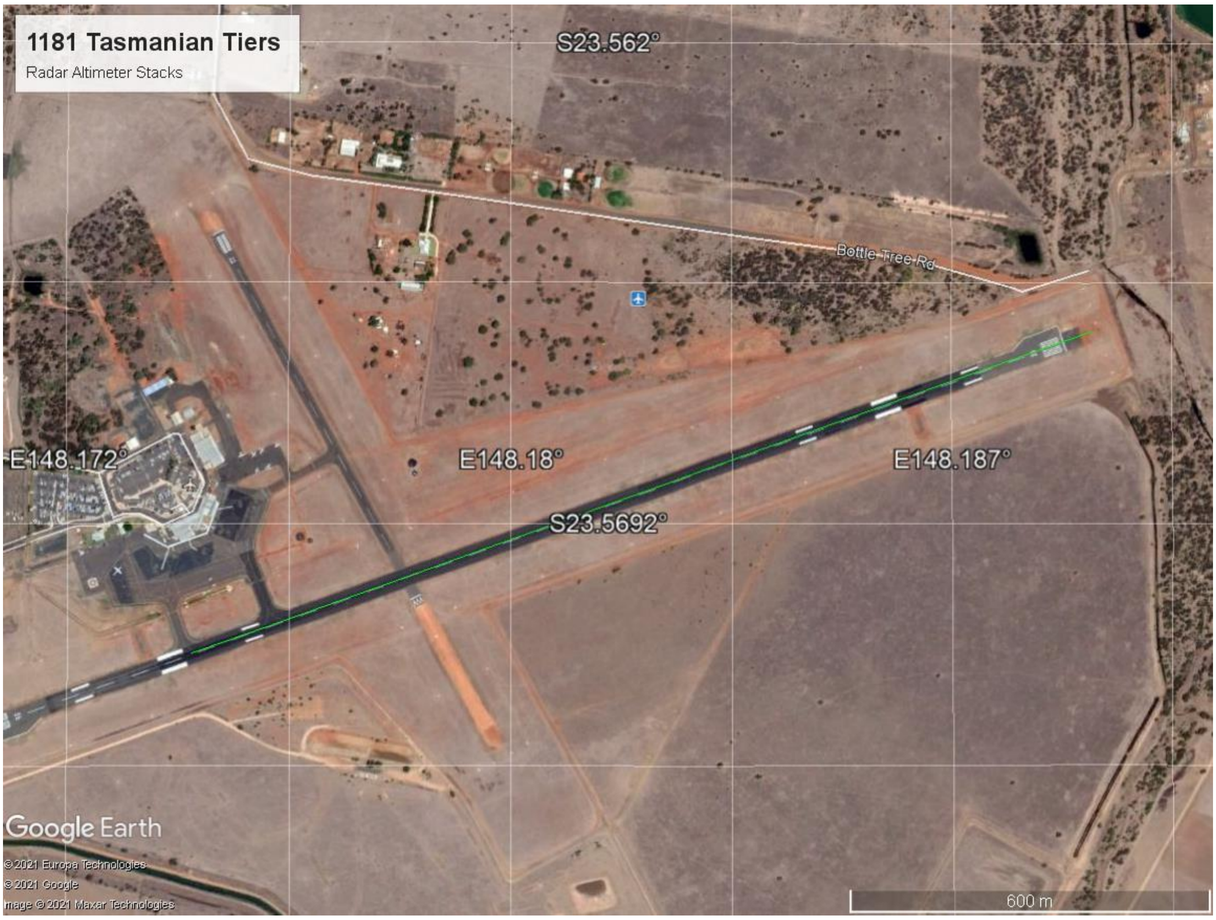


Figure 4.1: Map view showing the location of the calibration range where the linearity test was performed.

Description of Method

On 3rd February 2021, height stacks were performed over the Emerald, Qld airstrip to check and calibrate the radar and laser altimeters. The GPS height of the airstrip was removed from the GPS height. Physical offsets between the GPS, radar altimeter and laser altimeter sensors were taken into account.

GPS to airstrip (m)	1.95
Laser to airstrip (m)	1.75
GPS to Laser (m)	0.20
GPS to Radar (m)	1.45

Table 4.2: Definitions related to the linearity test.

Term	Definition
Calibration Range Height	The vertical height of the calibration range shown above (i.e. mean ground level) determined by the method noted in Table 4.1.
Approx. Terrain Clearance	The approximate heights above the calibration range at which the linearity test is to be applied.

GNSS Height	Raw	The measured output of the GNSS relative to the vertical datum specified in Table 4.1.
	Mean Ground Level	'GNSS Height Raw' minus the 'Calibration Range Height' to achieve a value relative to the mean ground level.
Laser Altimeter	Raw	The measured output of the laser altimeter in metres.
	Vertically Corrected	The values in 'Laser Altimeter Height Raw' adjusted to account for the vertical offset between the GNSS and the altimeter on the aircraft.
	Calibrated	The values in 'Laser Altimeter Vertically Corrected' calibrated using the 'GNSS Height Mean Ground Level' values.
Radar Altimeter	Raw	The measured output of the radar altimeter in metres.
	Vertically Corrected	The values in 'Radar Altimeter Height Raw' adjusted to account for the vertical offset between the GNSS and the altimeter on the aircraft.
	Calibrated	The values in 'Radar Altimeter Vertically Corrected' calibrated using the 'GNSS Height Mean Ground Level' values.

Table 4.3: GNSS, radar and laser measurements (raw, corrected and calibrated) relative to the vertical datum specified in Table 4.1.

Approx. Terrain Clearance (m)	GNSS Height (m)		Laser Altimeter Height (m)			Radar Altimeter Height (m)		
	Raw	Mean Ground Level	Raw	Vertically Corrected	Calibrated	Raw	Vertically Corrected	Calibrated
30	221.54	221.54 - 188.46= 33.08	33.07	33.07+ 0.2= 33.27	33.27-33.08 =0.19	31.86	31.86+1.45= 33.31	33.31- 33.08= -0.23
60	250.55	62.09	62.49	62.69	-0.60	61.13	62.59	-0.50
80	270.07	81.61	81.18	81.38	0.23	80.63	82.08	-0.47
100	290.20	101.74	101.08	101.28	0.46	100.82	102.27	-0.53
150	339.16	150.71	148.40	148.60	2.11	150.04	151.49	-0.79
300	489.00	300.54	-	-	-	300.98	302.44	-1.90

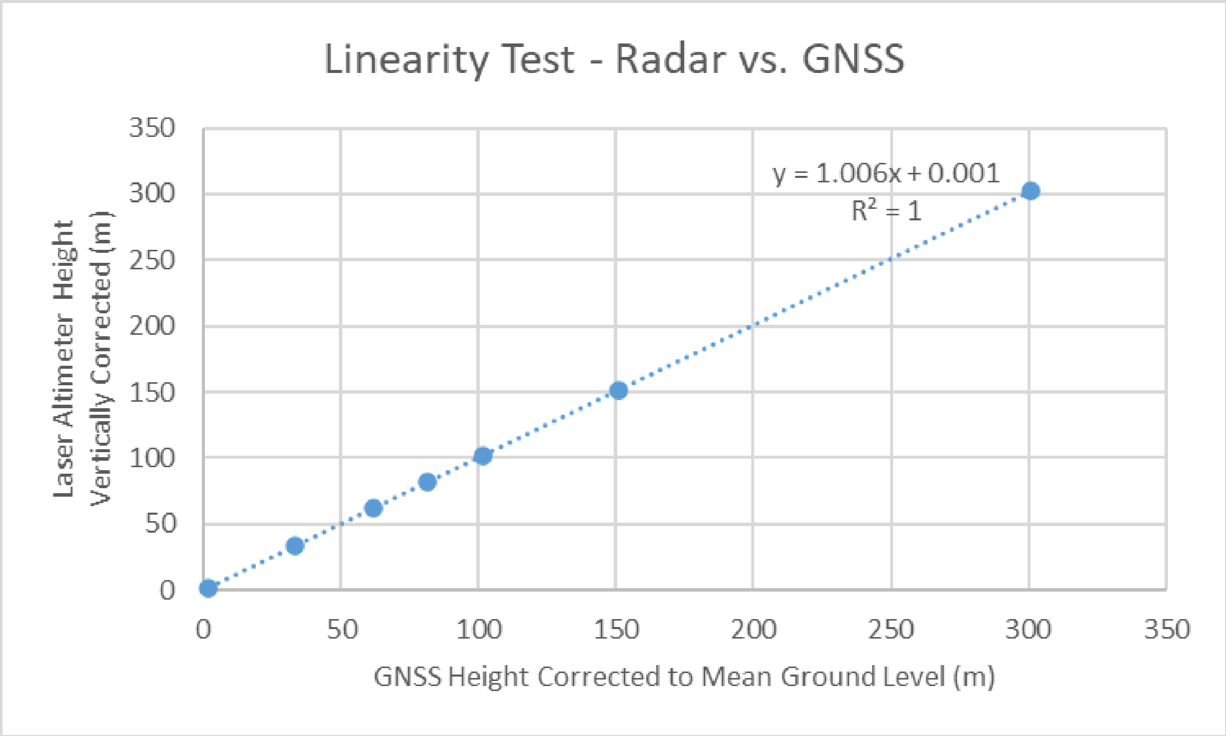


Figure 4.2: Example Only - Radar Altimeter Height Vertically Corrected vs GNSS Height Corrected to Mean Ground Level from Table 4.2 showing the regression line, equation and R^2 value.

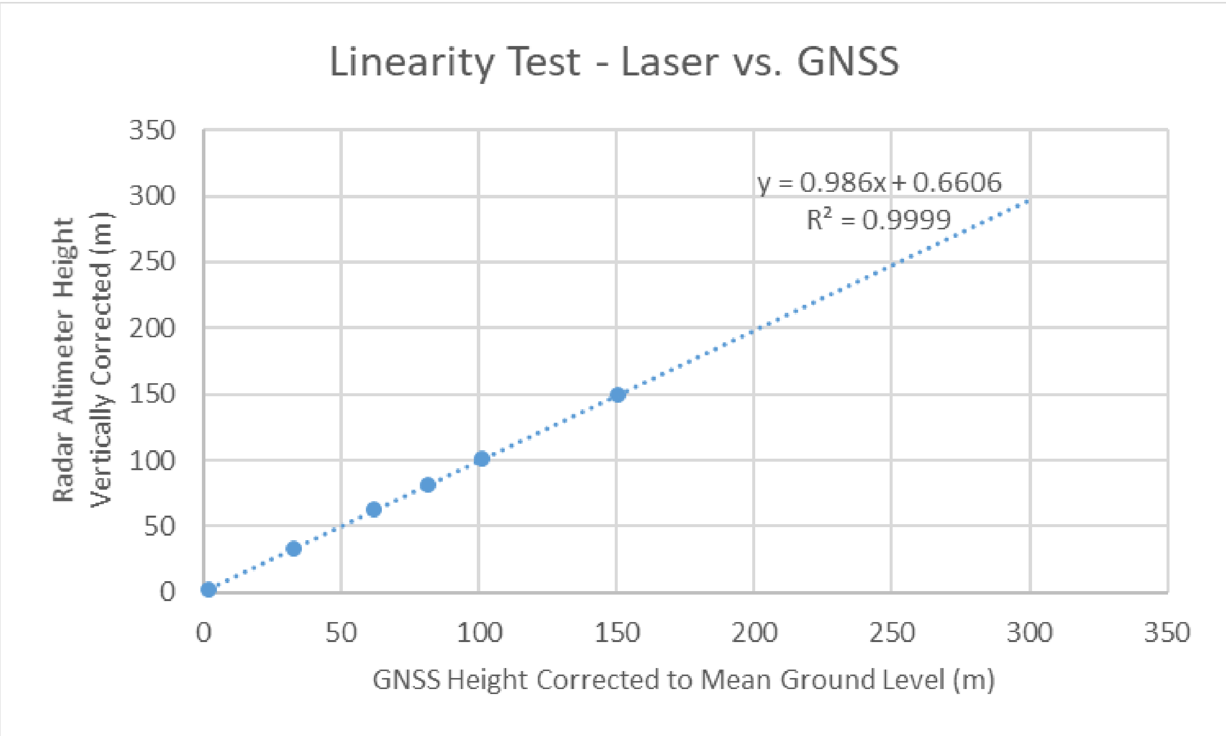


Figure 4.3: Example Only - Laser Altimeter Height Vertically Corrected vs GNSS Height Corrected to Mean Ground Level from Table 4.2 showing the regression line, equation and R^2 value.

Please indicate if the altimeter has been calibrated in accordance with the Deed: YES ☑ / NO ☐

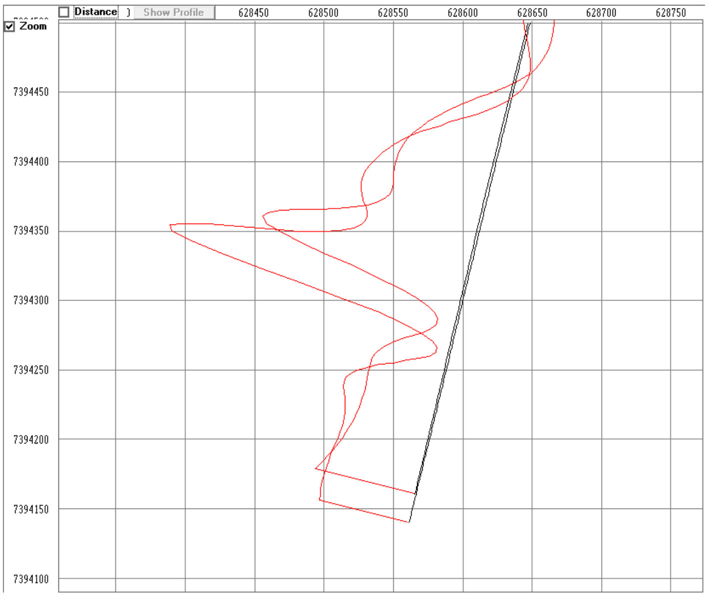
5 Magnetometer Calibration

5.1 Parallax

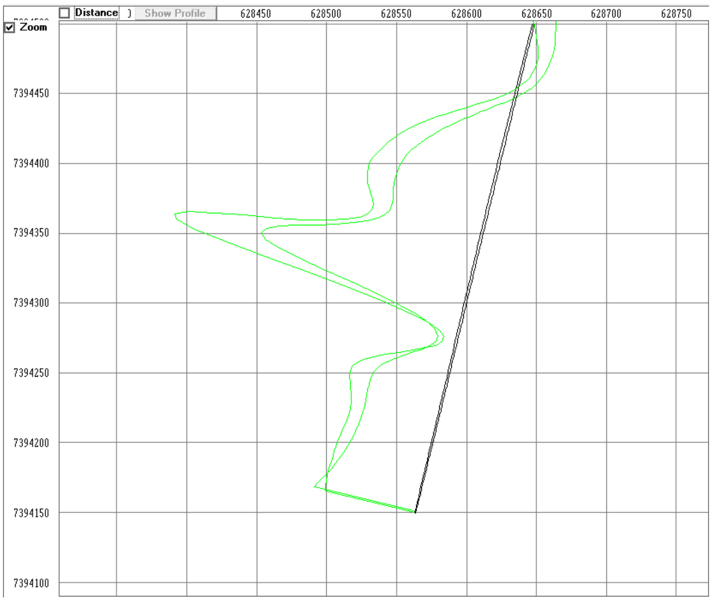
A parallax correction must be applied with respect to the magnetic, gamma-ray spectrometric and elevation Data. The navigation Data positions must be interpolated rather than interpolating the geophysical Data (Schedule 3: 1.8b).

Description of Method

On 3rd February 2021, a magnetometer parallax test was conducted by flying the same line in opposite directions over a railway line. Magnetic profiles of the test are shown below, with the parallax correction determined to be 2.7 fiducials: -



Magnetic profiles before parallax application



Magnetic profiles after parallax application

5.2 Manoeuvre Noise Test

Manoeuvre noise must be compensated to less than 0.2 nT peak to peak for manoeuvres with 10° rolls, 5° pitches and 5° yaws (Schedule 3: 1.9e).

Magnetometer manoeuvre noise tests must be performed by flying a test line 2500 m above ground level, or higher, in an area of low magnetic gradient. The test line must consist of line segments flown on all headings on which that particular Aircraft will be conducting Survey flying. Whilst flying each line segment of the test line, the Aircraft shall perform a series of 10° rolls, and 5° pitches and yaws. Each manoeuvre type shall have a minimum duration of 30 s. The digital records of the manoeuvre tests must be suitably annotated and available to Geoscience Australia for inspection (Schedule 3: 1.9i).

Table 5.1: Details of the manoeuvre noise test.

Date	13th February 2021
Location	Tasmania
Aircraft Call Sign	VH-HHJ

Description of Method
On 13th February 2021, a compbox was flown off the coast of Tasmania to check and calibrate magnetic compensation. The compbox was flown at 10,000 ft, on cardinal directions, north, west, south, and east, respectively. The manoeuvres were flown in the order, pitch, roll, and yaw. The magnetic data is post compensated using a 16-point solution. A 0.125 Hz high pass filter was applied to compensated magnetic data. The average, absolute minimum and maximum peak were summed for a peak to peak difference.

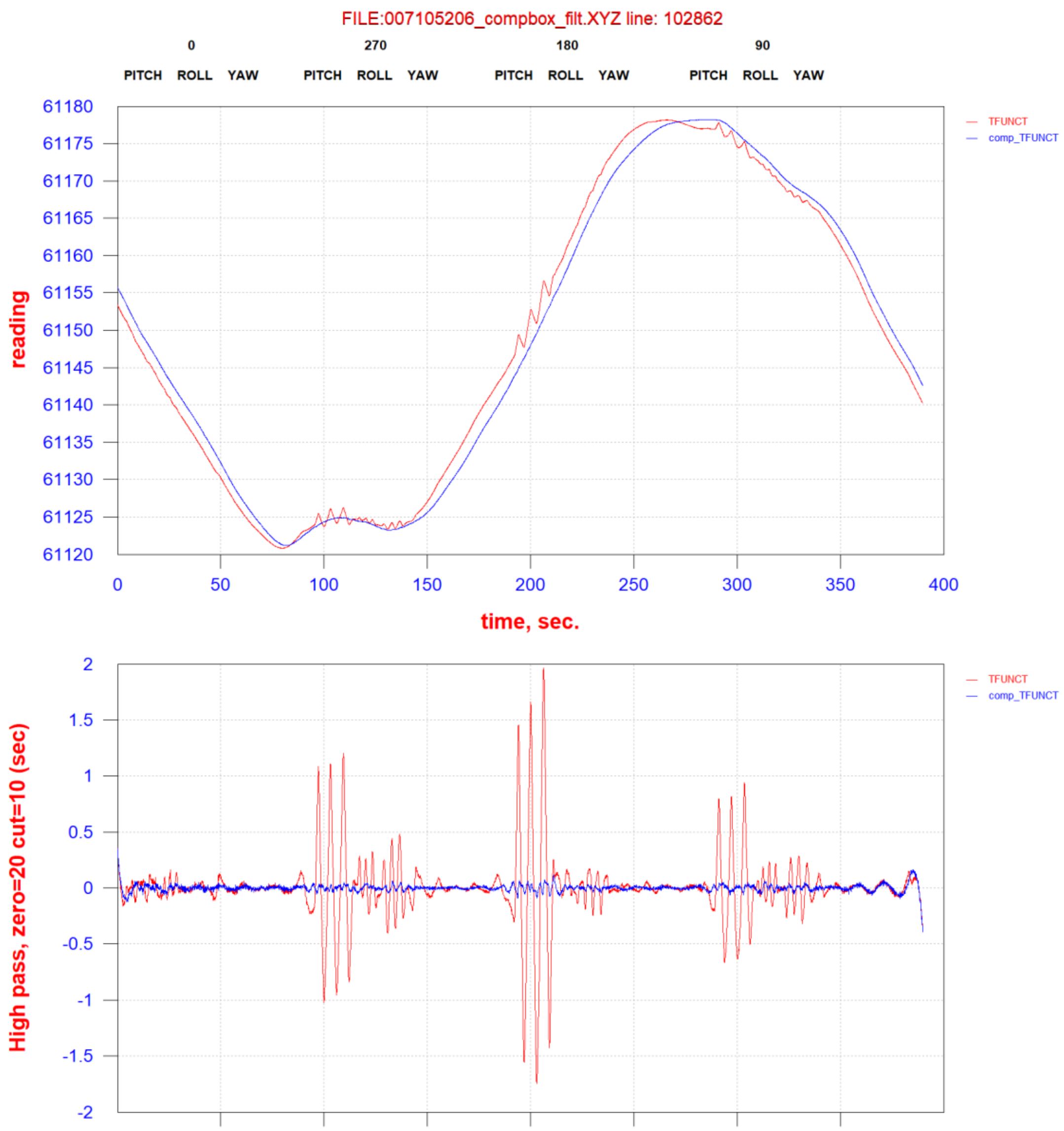


Figure 5.1: Graph of total magnetic intensity/high-pass filtered data (nT) vs. time (seconds) with roll, pitch and yaw manoeuvres and flight direction annotated.

Table 5.2: Recorded compensation values for various manoeuvres.

Flight Direction (°)	Compensation values (nT)		
	10° Pitch	5° Roll	5° Yaw
000	0.0606	0.0419	0.0389
090	0.0453	0.0577	0.0501
180	0.0855	0.0340	0.0461
270	0.0488	0.0346	0.0518

Please indicate if the manoeuvre noise test is within specification: YES ☑ / NO ☐

5.3 Heading Error Test

Heading error must be compensated to ±1 nT or less (Schedule 3: 1.9f).

Magnetometer heading error test lines should be flown at 2500 m in a cloverleaf pattern in an area of low magnetic gradient, with the lines passing over a common ground point. Listings of fiducial numbers and magnetic readings for the common ground point are required for all headings on which that particular Aircraft will be conducting Survey flying, together with coordinates computed as for Survey Data. Due allowance should be made for heading errors in final Data reductions (Schedule 3: 1.9j).

Table 5.3: Details of the heading error test.

Date	03/02/2021
Location	Emerald
Aircraft Call Sign	VH-HHJ

Description of Method
On 3rd February 2021, a heading error test was conducted by flying a cloverleaf pattern over a lone tree, in an empty paddock. The area selected is within a low magnetic gradient. The magnetic reading at a central point in each cardinal direction indicate the heading error of the aircraft. Two heading error values are determined by calculating the difference in the corrected total magnetic field flown in opposite directions.

Figure 5.2: Location of bi-directional survey lines flown at 2500 metres.

Direction (°T)	Fiducial #	Time (seconds past midnight)	X (m)	Y (m)	GNSS Height (GRS80; m)	Magnetic Total Field Compensated (nT)	Magnetic Total Field Compensated + Diurnal/IGRF/ Parallax Corrected (nT)	Heading Error (nT)
000	475100	22501.1	644197.8	7397583.1	215.972	51102.321	-331.421	+/-0.660
180	395500	22421.5	644199.1	7397582.0	216.49	51102.567	-330.761	+/-0.661
090	640300	22666.3	644198.2	7397583.7	215.582	51102.930	-331.153	+/-0.425
270	568300	22594.3	644197.3	7397583.4	217.874	51103.206	-330.728	+/-0.425

Table 5.4: Results of the magnetometer heading error test highlighting the crossover point.

Please indicate if the heading error test is within specification: YES ☑ / NO ☐

6 Gamma-Ray Spectrometer Calibration

6.1 Parallax

A parallax correction must be applied with respect to the magnetic, gamma-ray spectrometric and elevation Data. The navigation Data positions must be interpolated rather than interpolating the geophysical Data (Schedule 3: 1.8b).

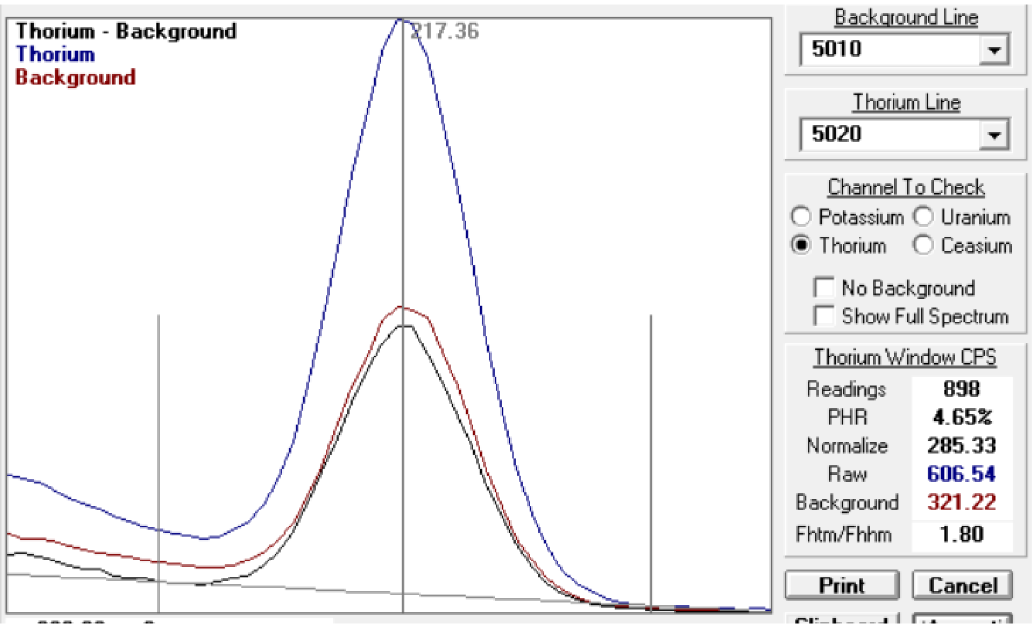
Description of Method
Low level flight over the Carnamah Test Range in opposite directions was flown on 30/10/20. At 1.0 second sampling, a parallax of -0.5 fiducials was determined from visual inspection of the profile data.

6.2 Full-Width Half Maximum

Prior to the commencement of the Survey, or any calibration procedure, the overall system resolution must be better than 7% based on the full-width half maximum of the ^{208}Tl peak at 2615 keV (Schedule 3: 1.12f).

Description of Method and %FWHM

On 18/09/20, the aircraft was positioned on the apron at Jandakot Airport. Background counts were measured over 15 minutes, followed by the thorium pad (extended thorium test).



Peak	PHR	Raw	Background	Normalised Thorium	Fhtm/Fhhm	Readings
217.3649	4.654843	606.5435	321.2177	285.3259	1.803443	898

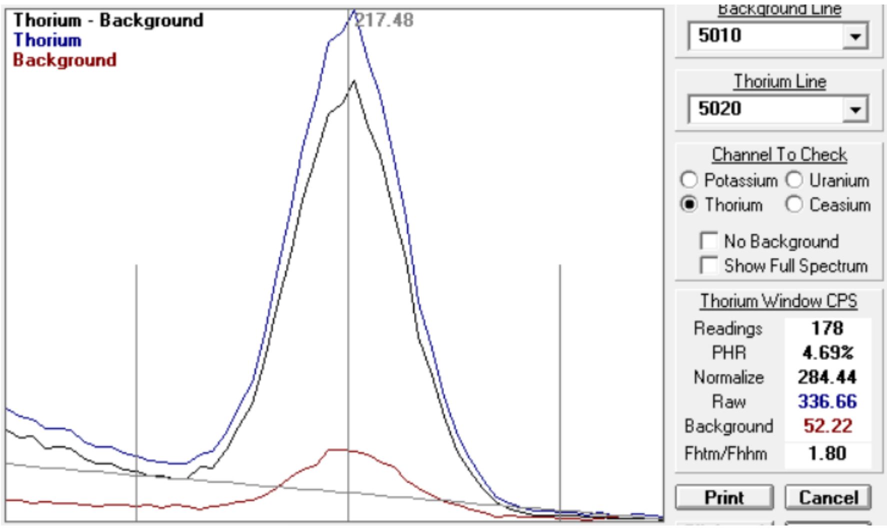
Overall system resolution was 4.65% (PHR)

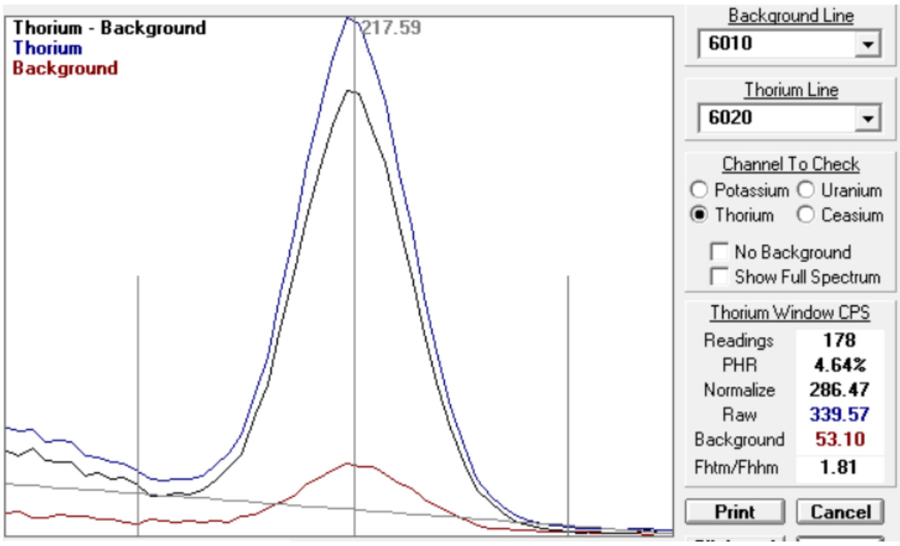
6.3 Thorium Source Test

Before and after every calibration, thorium source tests must be performed to establish that the system sensitivity has not changed during the calibration. The average of the dead time and background-corrected thorium window count rate from the thorium source must be calculated. If the pre- and post-calibration source checks differ by >3 %, the calibration must be repeated (Schedule 3: 1.12).

Description of Method

Aircraft was positioned on airstrip and system counts measured for 180 seconds with a thorium source positioned near the spectrometer as required, followed by background readings. These were conducted before and after survey flying (pre- and post- calibration checks).





Peak	PHR	Raw	Background	Normalised Thorium	Fhtm/Fhhm	Readings	Running Mean Th	%Diff
217.48	4.69	336.66	52.22	284.44	1.80	178.00	284.44	-0.20
217.59	4.64	339.57	53.10	286.47	1.81	178.00	285.45	0.51

Difference in normalise thorium less than 3%.

Please indicate if the gamma-ray spectrometer calibration is within specification: YES ☑ / NO ☐

6.4 Cosmic and Aircraft Background

Cosmic and aircraft background calibrations must be performed by flying a series of five or more stacks over the sea at heights ranging between 1000 and 3000 m above mean sea level at 250 m intervals (choosing a minimum of 5 heights in this range). The flying time at each altitude should be a minimum of 10 minutes (Schedule 3: 1.12).

Table 6.1: Details of the cosmic and aircraft background calibration.

Date	12 February 2021
Location	Offshore Tasmania
Aircraft Call Sign	VH-HHJ

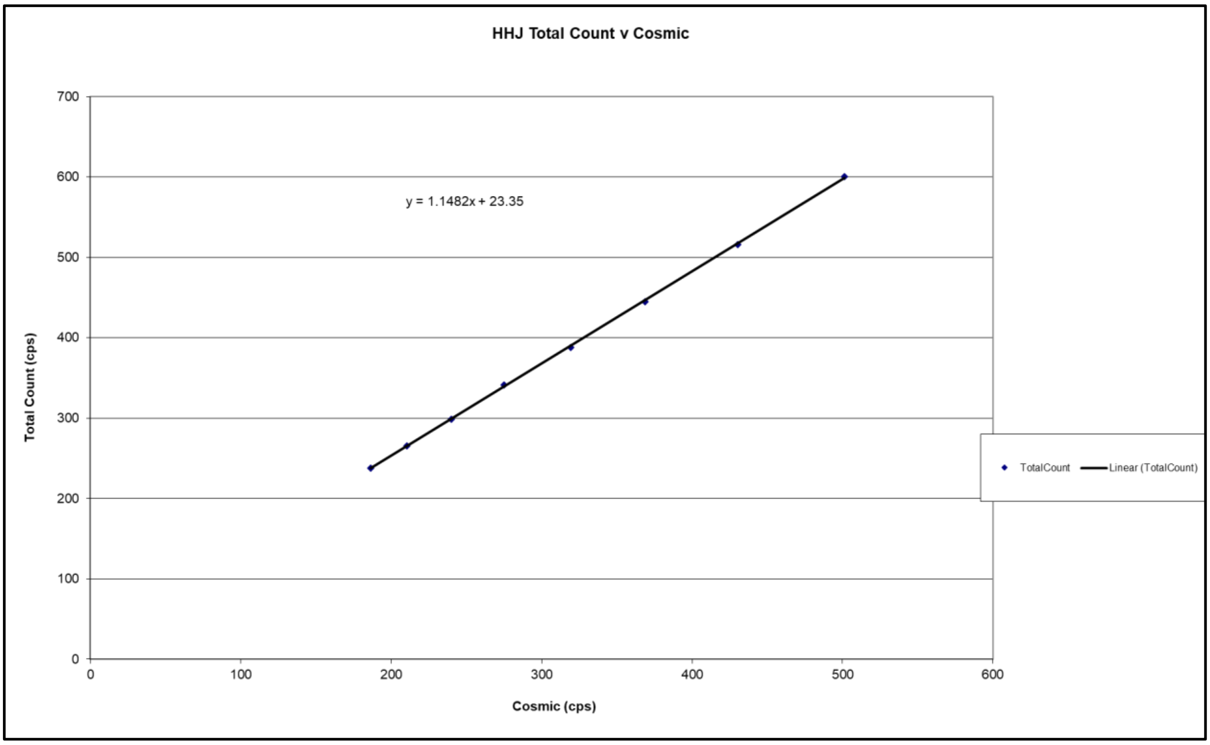
Description of Method
On 12th February 2021 the aircraft was flown offshore at various heights (300m – 3000m) with the system recording.

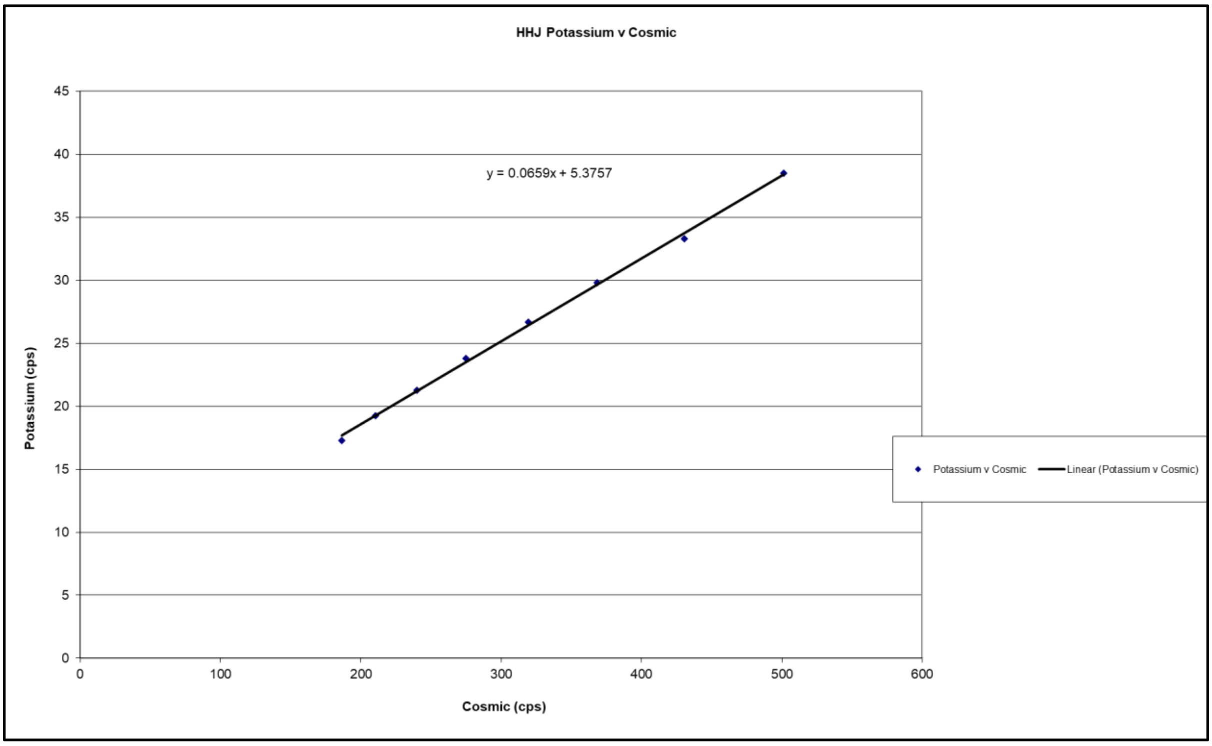
Table 6.2: Cosmic and aircraft background calibration results.

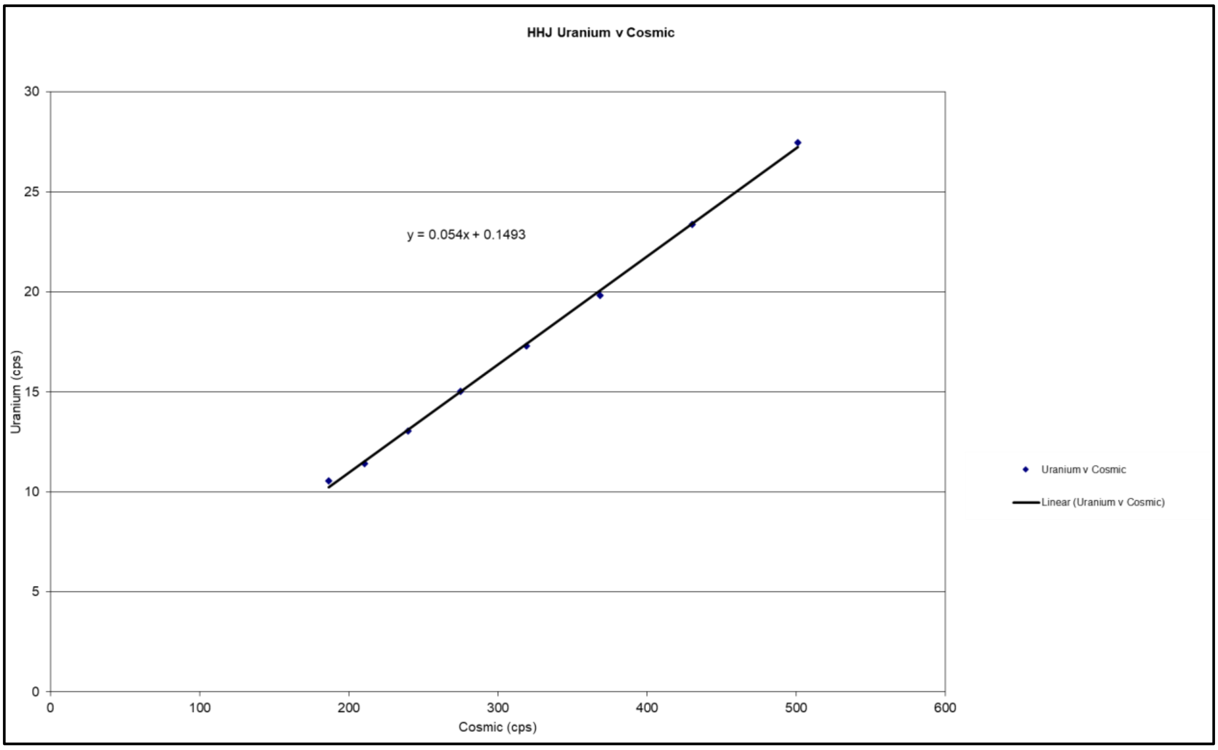
Flying Height	210	263	19	12	11
1000	240	296	21	14	13
1250	275	339	23	15	15
1500	369	442	29	20	21
2000	430	513	33	24	25
2500	210	263	19	12	11

Table 6.3: Calculated aircraft and cosmic background results.

	TC (cps)	K (cps)	U (cps)	Th (cps)
Calculated aircraft background	23.35	5.3757	0.1493	0.00
Calculated cosmic background	1.1482	0.0659	0.054	0.064


HHJ Total Count v Cosmic
y = 1.1482x + 23.35
Total Count (cps)
Cosmic (cps)
0
100
200
300
400
500
600
700
0
100
200
300
400
500
600
TotalCount
Linear (TotalCount)


HHJ Potassium v Cosmic
y = 0.0659x + 5.3757
Potassium (cps)
Cosmic (cps)
0
5
10
15
20
25
30
35
40
45
0
100
200
300
400
500
600
Potassium v Cosmic
Linear (Potassium v Cosmic)



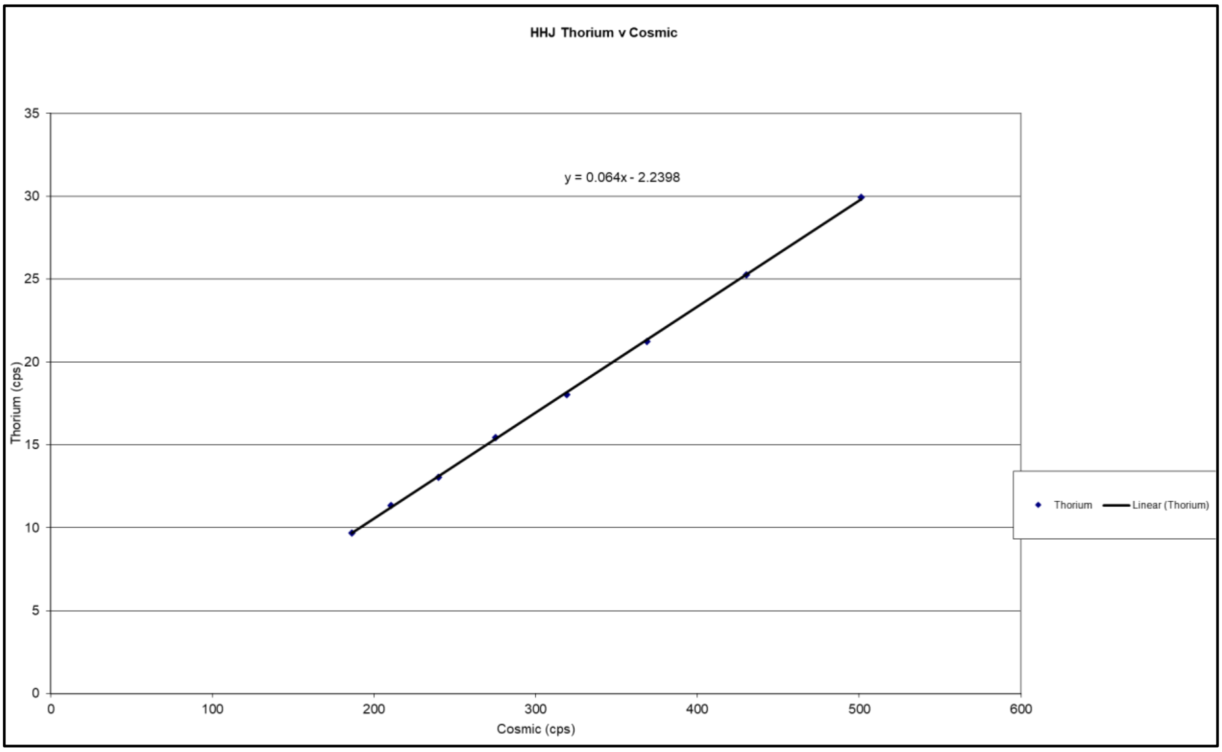


Figure 6.1: High-altitude regression plots for aircraft and cosmic background.

Please indicate whether the cosmic and aircraft background calibration is within specification:

YES ☑ / NO ☐

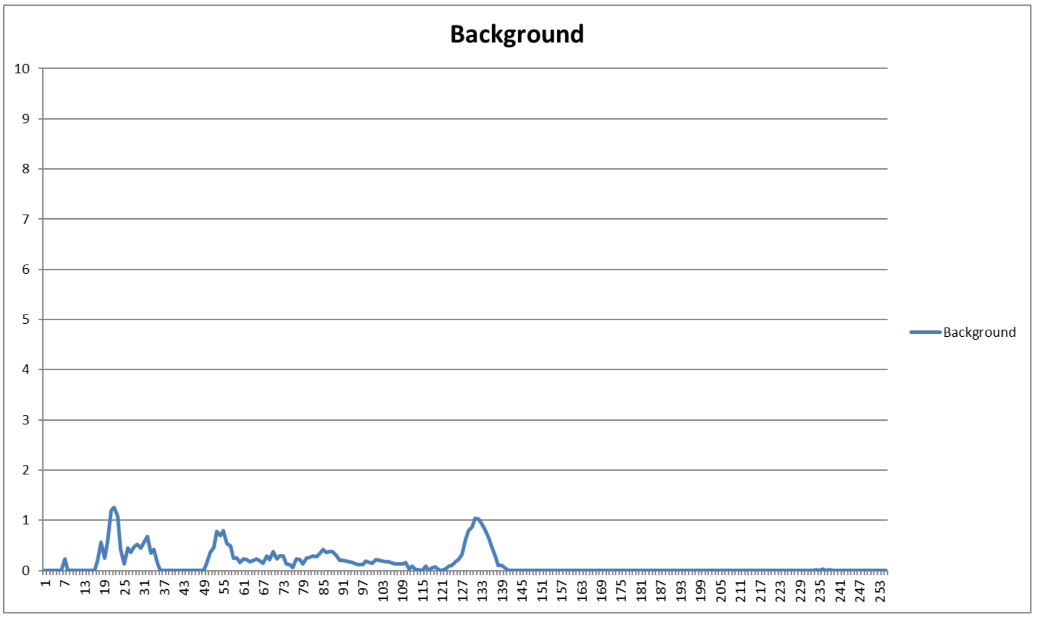
6.5 Radon Background

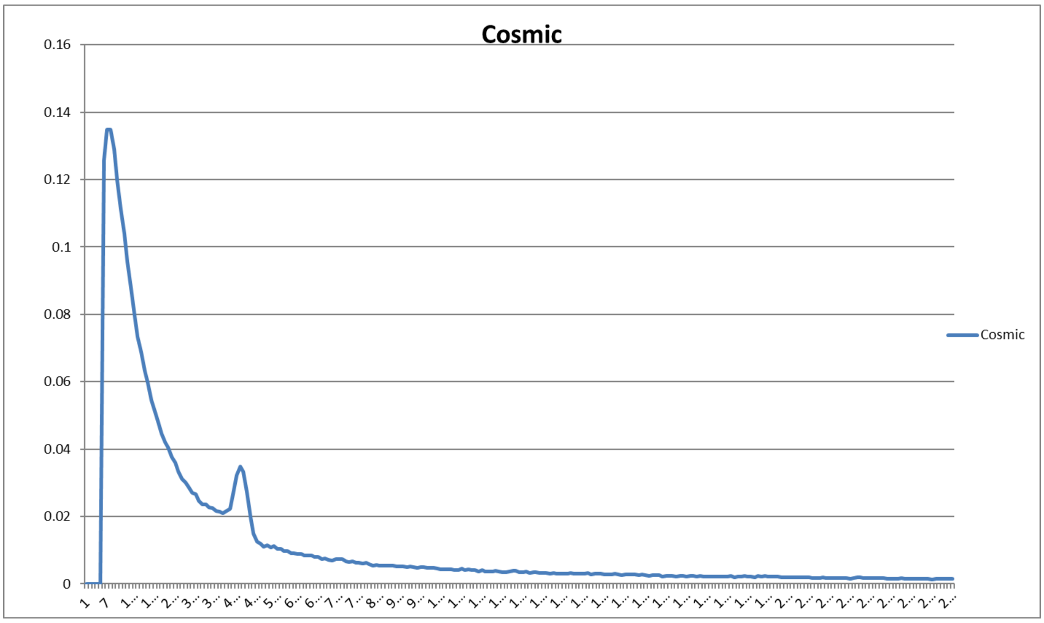
The gamma-ray spectrometer system must be calibrated to remove radon background effects using the spectral-ratio or full–spectrum methods described by Minty (1998), or the upward-looking detector method (IAEA, 2003). A Radon spectrum can be obtained by flying over after in the presence of atmospheric radon and then subtracting the aircraft and cosmic components (Schedule 3: 1.12).

Table 6.4: Details of the radon background calibration.

Date	30/10/20
Location	Offshore Western Australia
Aircraft Call Sign	VH-HHJ

Description of Method
On 30/10/20, the aircraft was flown offshore Western Australia. The spectra recorded had the cosmic and background components removed to reveal the radon component (see plots below).





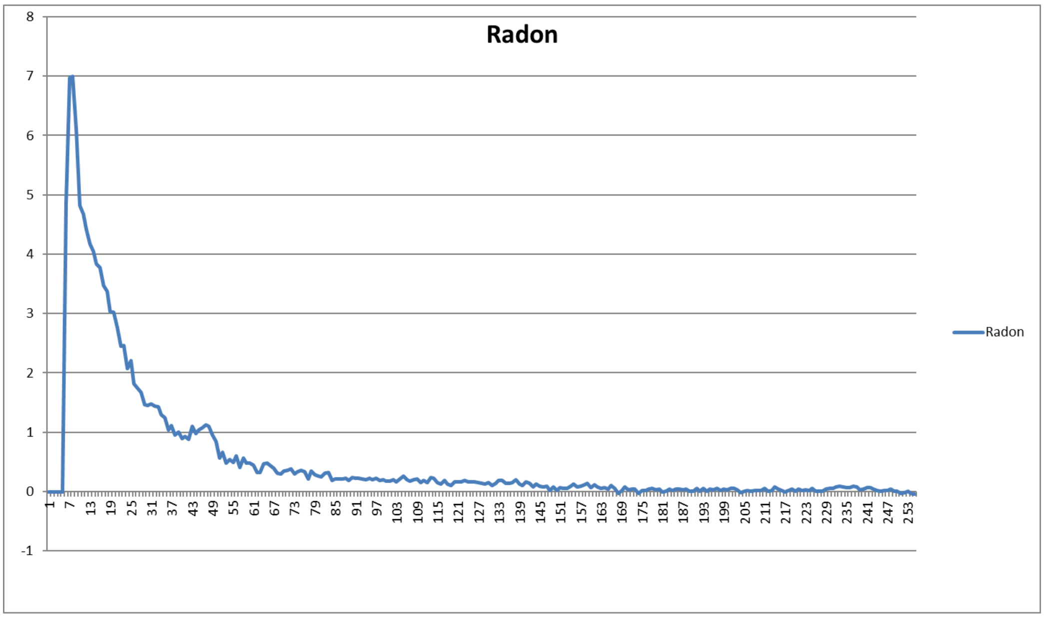


Figure 6.2: Background, Cosmic and Radon component spectra.

Please indicate if the radon background calibration is within specification: YES ☑ / NO ☐

6.6 Stripping Ratios

The airborne gamma-ray spectrometer system must be calibrated for stripping ratios on a set of calibration pads approved by Geoscience Australia for this purpose (Schedule 3: 1.12).

Table 6.5: Details of the stripping ratio calibration.

Date	18/09/20
Location	Jandakot, WA
Aircraft Call Sign	VH-HHJ

Description of Method
The aircraft is positioned on the apron of the airport. Calibrated concrete pads (Background, Potassium, Uranium, Thorium) are separately positioned under the aircraft and system counts recorded in accordance with procedures. Stripping ratios are derived for: Alpha (thorium into uranium), Beta (thorium into potassium), Gamma (uranium into potassium) and “a” (uranium into thorium).

Table 6.6: Stripping ratio coefficients.

Detector ID No.	Alpha (α)	Beta (β)	Gamma (γ)	Constant (a)
Average	0.2875	0.4483	0.7943	0.0523

Please indicate if the stripping ratio calibration is within specification: YES ☑ / NO ☐

6.7 Height Attenuation Coefficients and Window Sensitivities

A series of flights must be made over a calibration range, approved by Geoscience Australia, to estimate system sensitivities and height attenuation coefficients. The calibration range must be surveyed with a calibrated portable spectrometer on the same day as the calibration flights are flown. The portable spectrometer should record spectra with a minimum of 256 channels in the energy range 0 to 3000 keV (Schedule 3: 1.12).

Table 6.7: Details of the height attenuation coefficients and window sensitivities calibration.

Date	30/10/20
Location	Carnamah Test Range
Aircraft Call Sign	VH-HHJ

6.7.1 Calibration Range Results

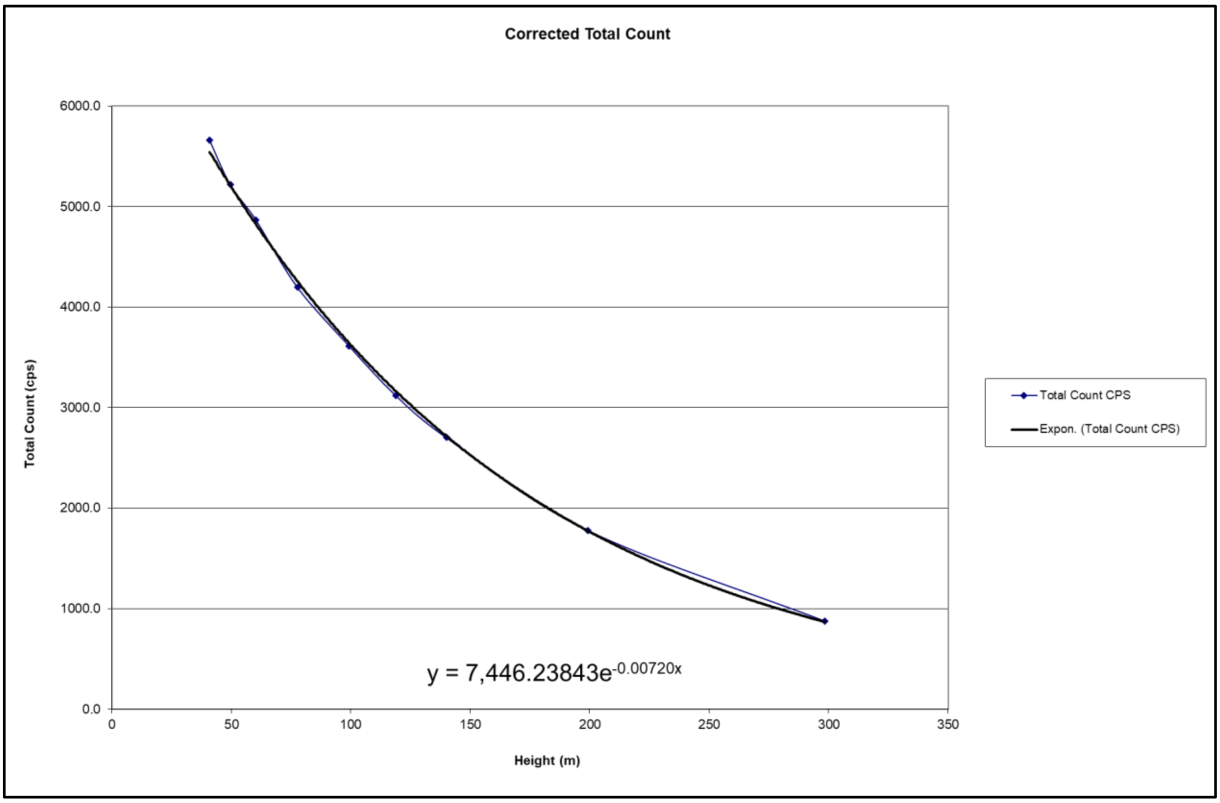


Figure 6.3: Plot of Height versus Total Count (Carnamah Range – 30/10/2020).

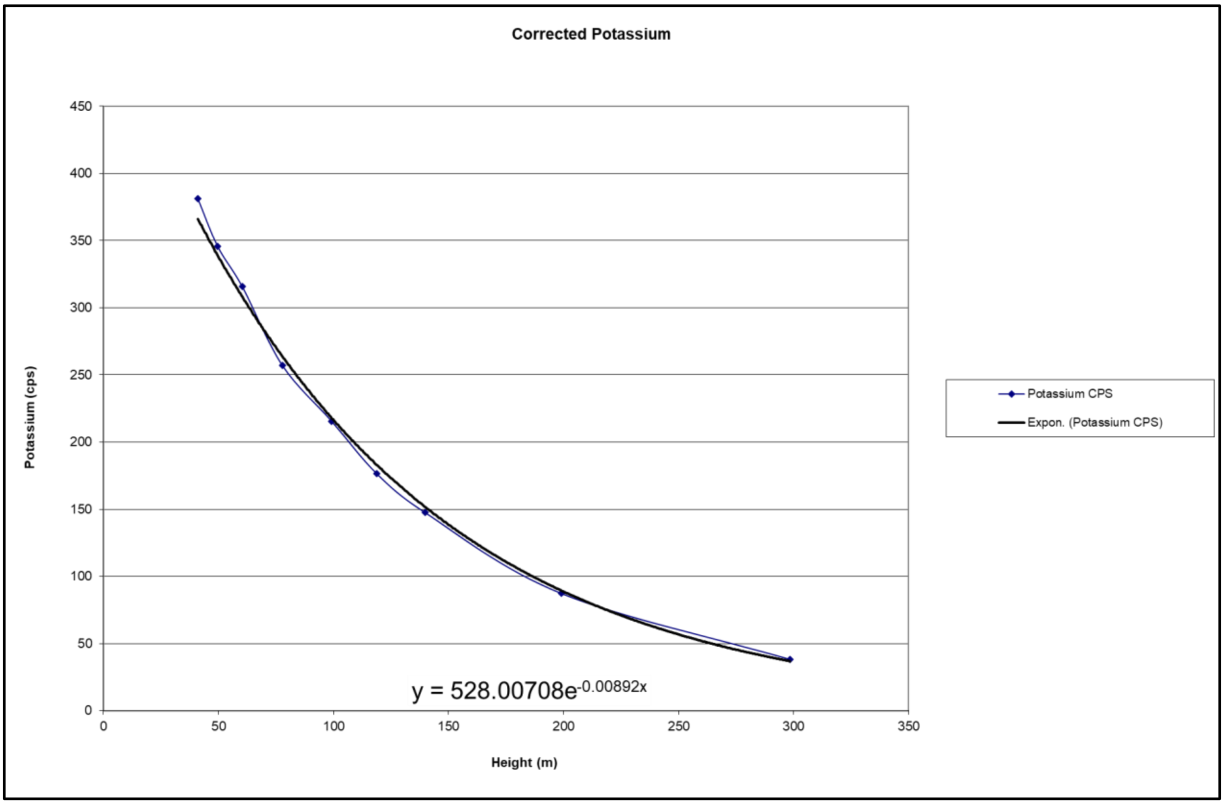


Figure 6.5: Plot of Height versus Potassium Count (Carnamah Range – 30/10/2020).

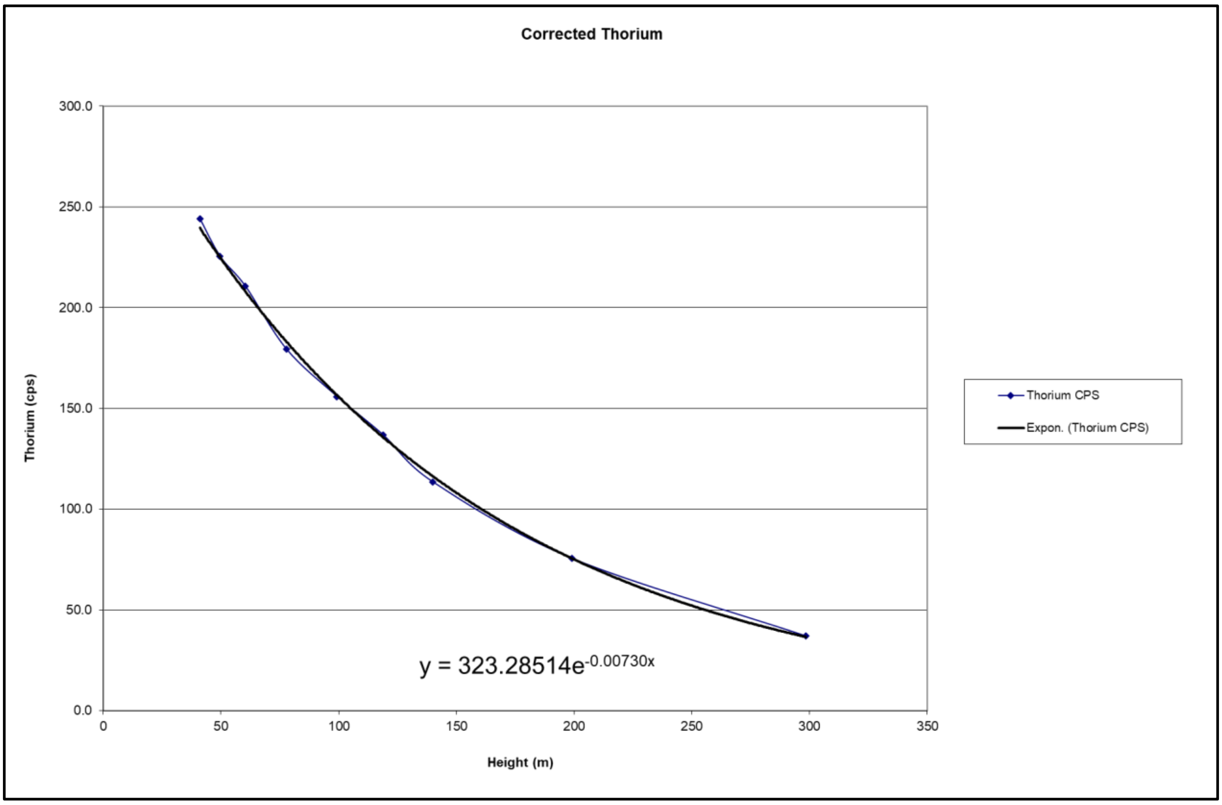


Figure 6.6: Plot of Height versus Thorium Count (Carnamah Range – 30/10/2020).

Table 6.8: Ground station readings from the calibration range (e.g. Carnamah Test Range).

Station Number	K (%)	U (ppm)	Th (ppm)
1	4.69	6.95	55.58
2	3.79	2.95	19.37
3	3.56	3.46	31.74
4	3.06	3.46	29.82
5	3.12	3.43	35.54
6	3.72	3.90	36.53
7	3.09	6.58	51.52
8	4.26	4.36	27.67
9	4.05	3.93	29.74
10	4.30	4.52	25.76
11	3.82	3.27	27.37
12	2.30	5.35	29.94
13	2.96	5.27	25.72
14	4.60	6.23	40.48
15	3.16	4.22	27.14
16	3.04	4.03	32.31
17	2.48	8.03	74.68
18	2.05	6.23	68.01
19	2.68	2.70	26.70
20	2.05	4.98	64.77
21	2.48	6.35	52.83
22	2.20	4.29	48.29
23	2.28	5.37	34.64
24	2.63	3.73	23.49
25	1.99	3.70	25.46
Average	3.14	4.69*	37.80

*n.b. a standard “dry” value of 4.05 ppm is used for the uranium concentration.

6.7.2 Height Attenuation Coefficients

Description of Method
On 30/10/20, the aircraft flew over the Carnamah Test Range in Western Australia at different heights (40m – 300m terrain clearance). The system counts were recorded and average windowed values calculated for each height.

Note: Theoretical values may be used for the height attenuation coefficient if the measured values are significantly different to the theoretical values. However, the measured values and their respective regression plots must still be displayed in this report.

Table 6.9: Results of the height attenuation coefficients.

	Total Count	Potassium	Uranium	Thorium
Height Attenuation Coefficient	0.0072	0.0089	0.0085	0.0073

6.7.3 Sensitivity Coefficients

Description of Method

Sensitivity coefficients are derived from dividing the windowed counts at the average ground range concentrations: -

k%	3.14
U ppm	4.05*
Th ppm	37.80
A	164.75

Table 6.10: Sensitivity coefficients calculated using the average background-corrected and stripped count rate at the nominal survey height divided by the respective radioelement ground concentration shown in Table 6.11 (above).

Nominal Height (m)	K (cps)	K sensitivity	U (cps)	U sensitivity	Th (cps)	Th sensitivity	TC (cps)	TC sensitivity
40	360.8641	115.1	55.3	13.7	244.1	6.5	5659.6	34.4
50	328.7543	104.9	47.9	11.8	225.5	6.0	5218.5	31.7
60	298.1636	95.1	46.8	11.6	210.7	5.6	4867.4	29.5
80	244.0942	77.9	40.2	9.9	179.5	4.7	4195.9	25.5
100	203.9974	65.1	32.5	8.0	155.9	4.1	3613.5	21.9
120	164.7276	52.5	27.7	6.8	136.9	3.6	3119.8	18.9
140	137.237	43.8	24.4	6.0	113.5	3.0	2701.6	16.4
200	81.1126	25.9	15.5	3.8	75.5	2.0	1777.9	10.8
300	33.4267	10.7	5.8	1.4	37.0	1.0	875.4	5.3
40	360.8641	115.1	55.3	13.7	244.1	6.5	5659.6	34.4

Please indicate if the height attenuation and sensitivity coefficients are within specification:

YES ☑ / NO ☐