Tellus A3 & A4 (2017) Airborne Geophysical Technical Report

(Operations, Logistics and Data Merging)

Geological Survey Ireland is a division of the Department of Communications, Climate Action & Environment.

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The Tellus Project

Tellus is a national programme to gather geochemical and geophysical data across the island of Ireland. The survey examines the chemical and physical properties of our soils, rocks and waters to inform the management of Ireland's environment and natural resources. The project is managed by the Geological Survey, Ireland and is funded by the Department of Communications, Climate Action and Environment (DCCAE).

For more information on the Tellus Project please visit www.tellus.ie

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Executive Summary

Tellus is a national airborne geophysics mapping programme of Ireland and follows on from the Tellus Survey of Northern Ireland in 2005-2006 with the first survey carried out in Ireland in 2011. Since then annual survey blocks have generally progressed southwards through the country. The latest phase of the Tellus programme collected new airborne data over County Mayo and the northwestern part of County Donegal, in Ireland and is collectively referred to as blocks A3 and A4 respectively. Surveying was carried out between 27 April 2017 and 30 September 2017 by Sander Geophysics Ltd (SGL). Previous airborne geophysical surveys were carried out across Northern Ireland (Tellus) in 2005 and 2006 (Beamish *et. al*, 2006), parts of counties Cavan and Monaghan in the ROI (Kurimo*,* 2006), counties Donegal, Leitrim, Sligo, Cavan, Monaghan and Louth as part of the EU INTERREG IVA-funded Tellus Border Project (Hodgson and Ture, 2012), across counties Roscommon, Longford and Westmeath as part of the Tellus North Midlands project (Hodgson and Ture 2015), across parts of counties Meath, Dublin, Kildare, Offaly, Laois an Wicklow (Block A1) in the east of the country in 2015 (Hodgson and Ture 2016) and across County Galway (Block A2) in 2016 (Hodgson and Ture 2017). All surveys measured magnetic field, electrical conductivity and gamma-ray spectrometer data (primarily potassium, thorium and uranium). This report summarizes the main operations from the latest A3 and A4 surveys and discusses the processing of the acquired data and its merger with existing datasets to produce seamless merged geophysical datasets.

Acknowledgements

During the operation of the survey Emma Scanlon, Aoife Brady, Peter Heath, Jim Hodgson, Kate Knights and Judith Mather, along with Morrow Communications all helped with the successful undertaking of the outreach programme. The crew of SGL are thanked for the hard work throughout the duration of the survey.

Table of Contents

List of Figures

List of Tables

1. Tellus Geophysical Surveys

1.1 Overview of Tellus Project and previous Tellus airborne Geophysical surveys

The Tellus Block A3 survey over County Mayo and Block A4 survey over County Donegal follow on from previous airborne surveys carried out under the Tellus Programme. This includes the original Tellus survey of Northern Ireland (2005-2006) and the EU INTERREG IVA-funded cross border survey of the border region of Ireland (2011-2012), the Tellus North Midlands survey (2014-2015) along with the survey of Block A1 (2015) in the east of the country and a survey of county Waterford (2016) in the south of the country and Block A2 over county Galway (2016). All airborne surveys comprised the collection of low-altitude magnetic, gamma-ray spectrometry and electromagnetic data. However, for the North Midlands survey Time-Domain Electromagnetic (TEM) data was collected in contrast to Frequency-domain EM (FEM) data which was collected for the other surveys. This latest surveys (A3 and A4 Blocks) of the Tellus Programme were carried out by Sander Geophysics Ltd (TR-849A3-2017-000 [2017a] and TR-849A4-2017-000 [2017b]), who employed the same FEM system used in earlier phases. The survey aircraft was based at Sligo Airport which is located between the two blocks (A3 & A4) in the northwest of the country. Following the completion of this latest phase over 50% of Ireland and nearly two thirds of the island of Ireland (Ireland & Northern Ireland) have now been surveyed.

2. A3 & A4 Survey Operations & Specifications

The nominal survey areas are shown in Figures 1 & 2. Block A3 covers the majority of County Mayo in the northwest of Ireland. Topography and land-use in the area is a mix of low-lying peat bog and undulating grass farmland with significant topography in the central and western parts. Croaghaun Sea Cliffs on Achill Island to the far west of the survey area are some of the highest in Europe extending 688 m from sea level.

Block A4 covers the central and western parts of County Donegal. Significant topography is found throughout the survey area, the highest point is Mount Errigal at 751m. Upland areas are primarily overlain with blanket peat, with lower lying areas predominantly grassland or scrub.

The surveys were flown together from the field base at Sligo airport which lies between the two survey blocks. The survey areas were designed to allow an overlap with the Tellus A2 and Tellus Border surveys, which would assist the merging of the data. The survey was also designed within the context of a national survey and to complete 50% of this national survey by the end of 2017. The different survey blocks discussed in this report are outlined in Figure 3.

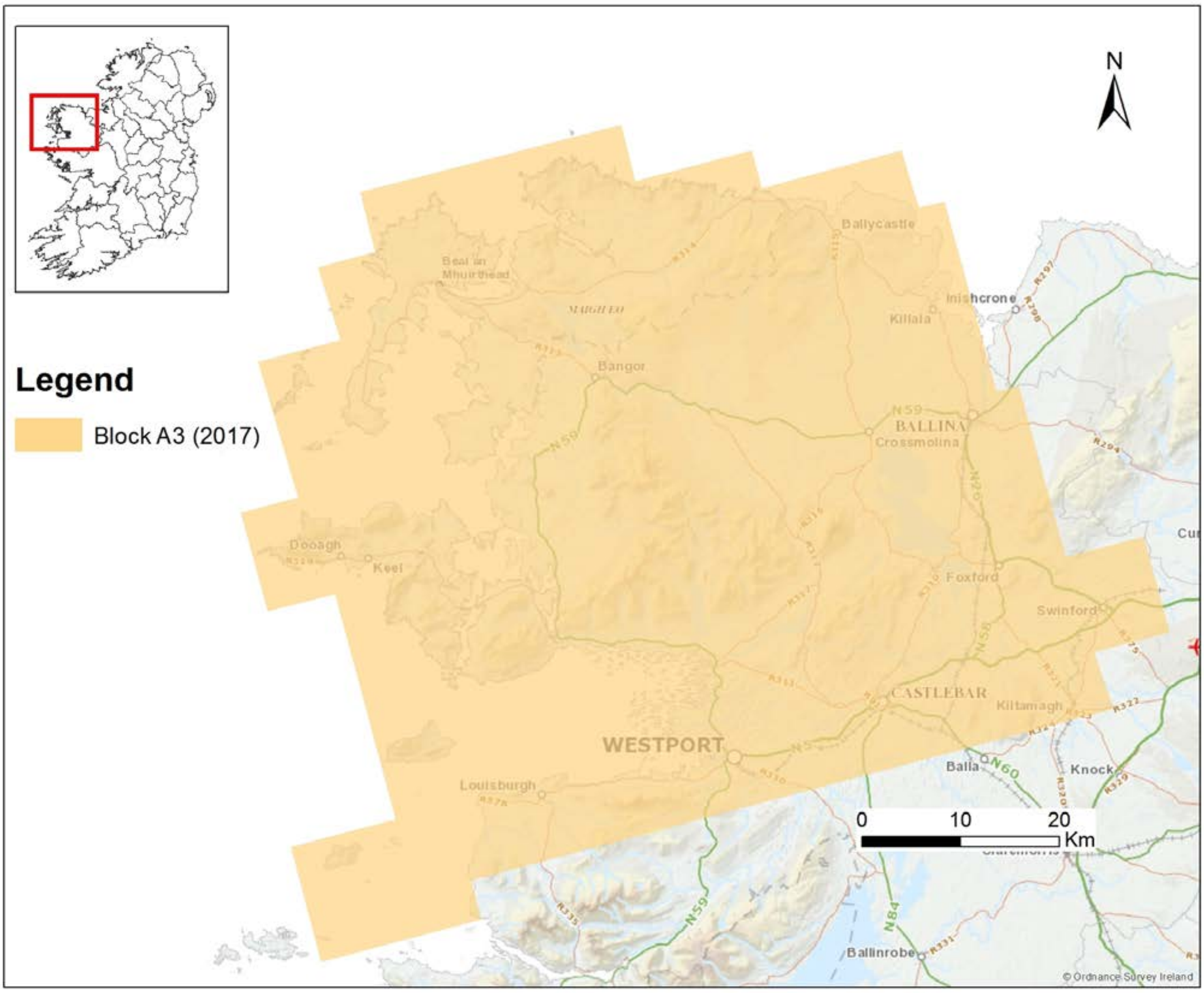

Figure 1: Tellus A3 block survey area over County Mayo

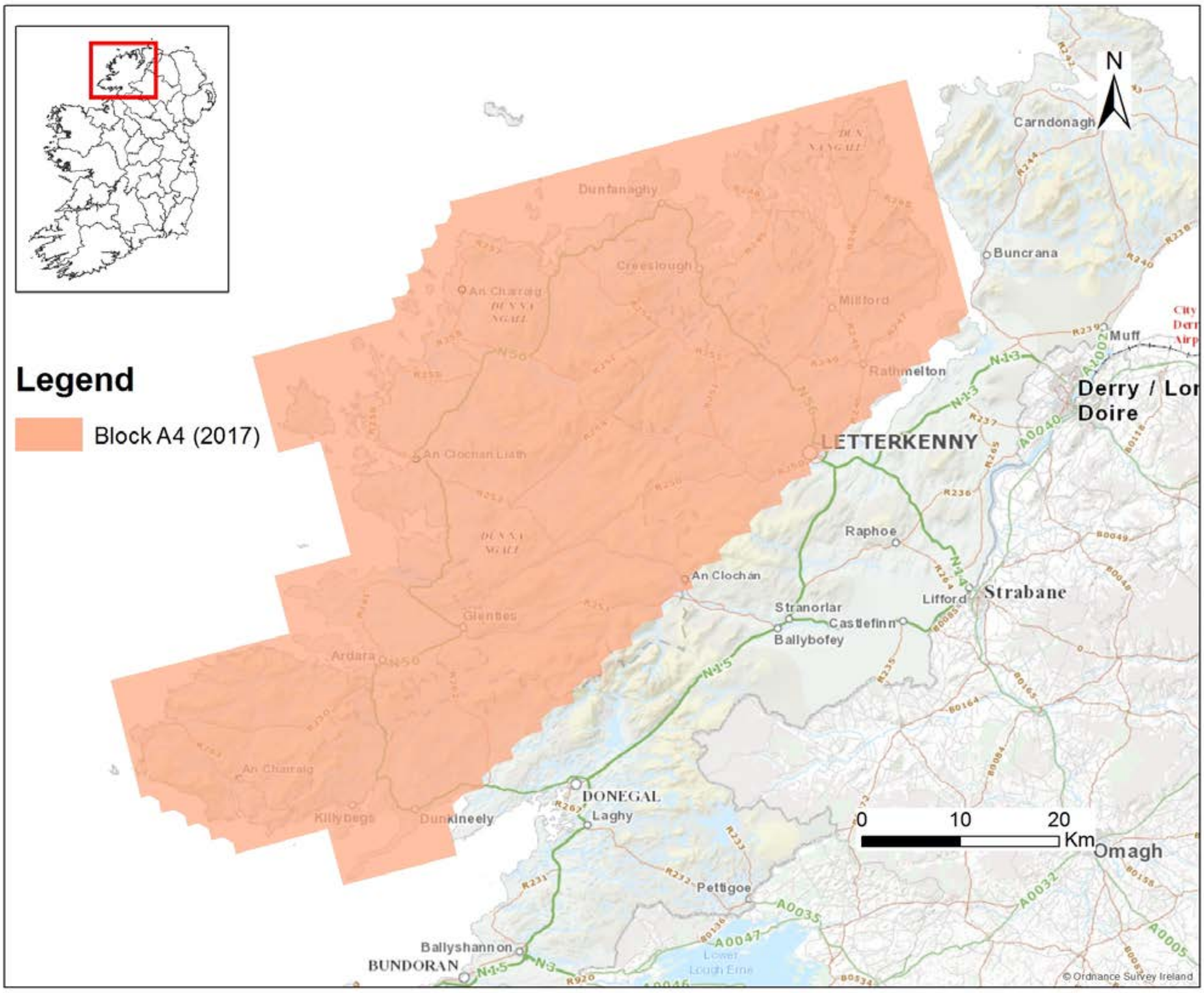

Figure 2: Tellus A4 block survey area over County Donegal

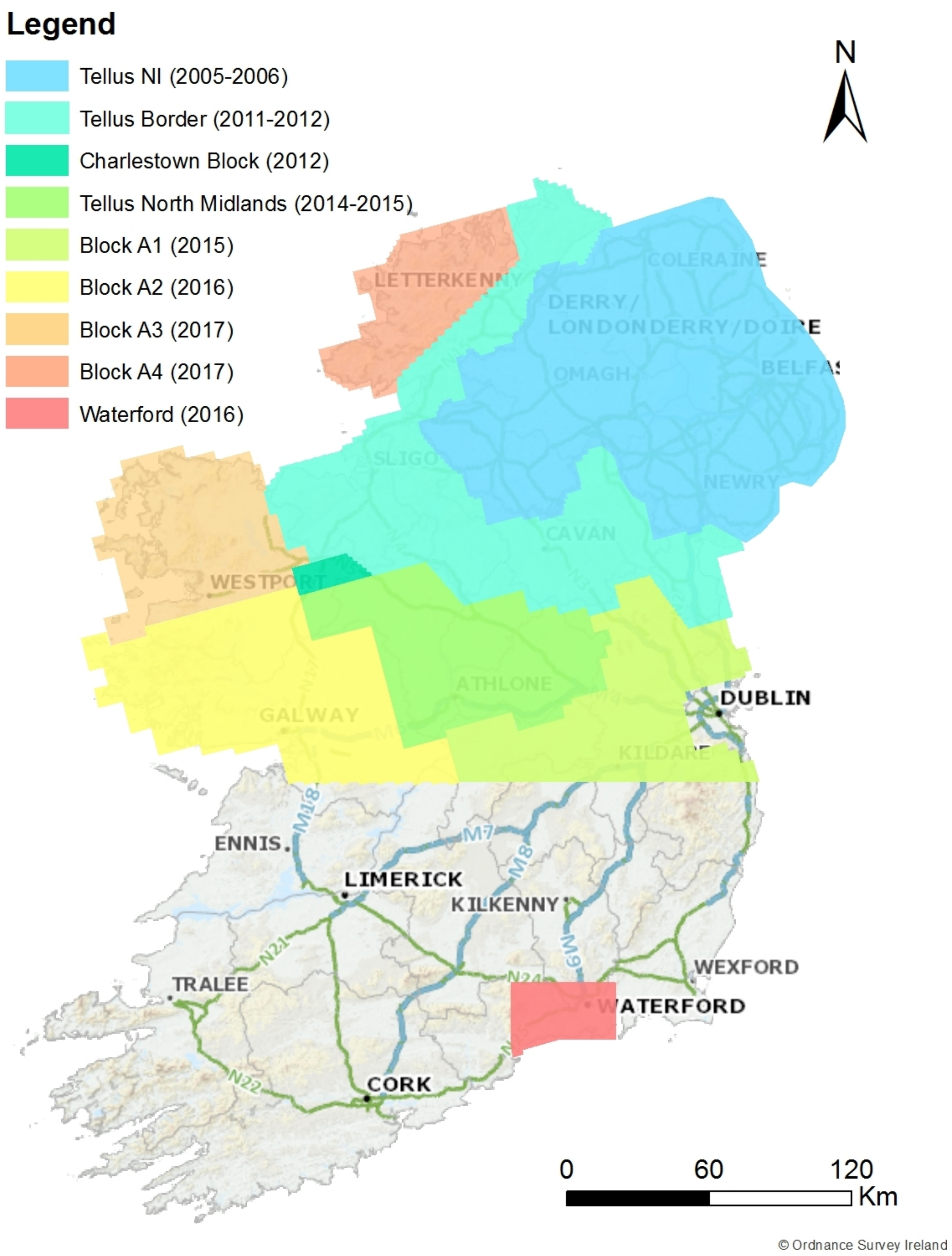

Figure 3: Tellus survey blocks 2005 - 2017

2.1 Flight characteristics and survey pattern

The flight pattern is described in Table 1 below.

Table 1: Flight Pattern

Traverse Line Spacing	200m
Tie Line Spacing	2000m
Traverse Line Heading	165/ 345^{0}
Tie-Line Heading	75/ 255^{0}
Flying Height (rural / urban)	60/ 240m subject to pilot's discretion
Projection / Datum	Irish Transverse Mercator

A repeat test calibration line was established close to the town of Bundoran, Co. Donegal in the northwest of Ireland. The test line was the same line as flown during the Tellus Border, North Midlands and A1 and A2 Surveys, allowing comparisons to be made between surveys. The line was flown twice during the A3 and A4 surveys, at the beginning and towards the end of the survey season. The test line is 6km in length and was flown at six different elevations during each run. The line ran from off-shore to on-shore and was selected based on variable bedrock and superficial geological aspects, and is discussed further in Section 3.6.

2.2 Flight permits

The contractor (Sander Geophysics Ltd.) received the required Irish Aviation Authority (IAA) flight permits (low flying permission number 03/2016) for its aircraft C-GSGF to conduct a low-level survey in Ireland.

2.3 Geographic projection

Final data was referenced to the Irish Transverse Mercator as defined in Table 2.

Table 2: Irish Transverse Mercator Geographic Projection

IRISH TRANSVERSE MERCATOR	
Reference Ellipsoid:	GRS80
Central Meridian	08° 00' 00" West
Vertical Datum:	Malin Head
Map Projection:	Transverse Mercator (Gauss Conformal)
True origin:	53° 30' 00" North, 08° 00' 00" West
False origin:	600 km west, 750 km south of true origin
Scale factor on Central Meridian:	0.999820

2.4 Re-flight conditions

Data was received from the contractor on a weekly basis for quality assessment. The following re-flight conditions were enforced during the survey:

- Where flight line deviation for traverse-lines is greater than 45m from the planned line over a distance of 2.5km or more, or greater than 90m from the planned line over any distance (except where ground conditions dictate otherwise, for example to avoid radio-masts etc.).
- Where flight line deviation for tie-lines is greater than 100m from the planned line over a distance of 2.5km or more, or any deviation greater than 200m from the planned line over any distance.
- Where terrain clearance exceeds +/- 20 metres from the nominal survey height for more than 5 continuous kilometres or 40m of nominal survey height at any time on any line, unless local topography makes this unavoidable.
- Where the nominal survey flying speed (60m/s) is exceeded by more than 30% (78 m/s) for more than 5 continuous kilometres.
- Where the noise envelope of the magnetic records exceeds 0.1nT as determined by the normalised fourth difference.
- If, during data acquisition, magnetic variations recorded at the local base magnetometer exceed 12nT over any 3 minute chord or exceed 2nT over any 30 second chord, on flight lines or tie lines. The base magnetometer must be fully operational during all on-line data collection.
- Where the average line gamma spectra for any line appears anomalous by comparison with previously acquired data then the data of that line will be investigated in detail and re-flown if necessary.
- If the calibration of the EM system deviates significantly from the norm.
- If both primary and secondary GPS base stations fail to record for 30 minutes or more, simultaneously.
- If both primary and secondary magnetic base stations fail to record for 30 minutes or more, simultaneously.

These conditions may be exceeded without re-flight where such constraints would breach air safety regulations, or in the opinion of the pilot, put the aircraft and crew at risk. All such exceptions were logged and a log of all flights can be found in the technical report produced by SGL (SGL, 2016). Data typically met the required specifications although some altitude deviations were encountered; these were often related to client enforced high fly zones due to urban areas, stud farms, radio masts and pilot safety requirements.

2.5 Survey equipment and aircraft systems

2.5.1 Survey Aircraft

The contractor, Sander Geophysics Ltd., used a De Havilland DHC-6 twin Otter (registration number C-GSGF) for all survey work. The same aircraft was used in the Tellus survey of Northern Ireland (2005-6), under the registration OH-KOG. During this survey it was operated by JAC (Joint Airborne-geoscience capability), which was a partnership between the Geological Survey of Finland and the British Geological Survey. The aircraft was also used under its current registration for the Tellus Border Survey (2011-2012), A1 and A2 Surveys (2015 & 2016). This aircraft is an all metal, fixed-wing, twin-engine, short take-off and landing aircraft (Figure 4). The aircraft can be flown at speeds from 80 to 160 knots (41 to 82 m/s). The Twin Otter is equipped with airborne magnetic, radiometric and frequency-domain electromagnetic (FEM) systems as outlined by Hautaniemi *et al*., 2005. The aircraft houses two magnetometers; one attached to a rear boom and one in the left wing tip pod. The four frequency EM transmitter was housed in the right wing tip pod and the receiver in the left wing tip pod. The GR spectrometer crystal packs were housed in the rear of the aircraft (Figure 5) and also in the undercarriage to accommodate additional crystal packs.

The NavDAS system developed by SGL was used for airborne navigation and data acquisition. The system displays all incoming data on a flat panel screen for real-time monitoring.

Figure 4: Survey Aircraft – De Havilland Twin Otter

2.5.2 Geophysical Instrumentation

Table 3 below outlines the survey equipment used by SGL during the project. Further detail of the instrumentation is given by SGL (2016).

Table 3: Survey Equipment

Survey Method	Equipment used
Magnetometer	Aircraft: 2 x Geometrics G-822A, optically pumped Caesium split beam sensors, tail stinger and wing tip, sampling rate:10 Hz Base station: 2 x Geometrics G-822A SGComp, post-flight compensation
EM system	SGFEM: Four frequency (0.9, 3, 12 and 25 kHz), sampling 10 Hz. Wingtip coils
Gamma-ray spectrometer	Radiation Solution RS-501 gamma-ray spectrometer 1024-channels, self-calibrating, 67.2 litres downward, 12.6 litres upward looking, pressure and temperature sensors, sampling rate 1 Hz.
Altimeter	Collins radar altimeter (AL-101), sampling 10 Hz SGLas-P Riegl laser rangefinder altimeter LD90-3300VHS-FLP, 20Hz

	sampling rate Honeywell Barometric Pressure sensor, 10Hz sampling rate Omega RTD-805 Outside air temperature probe
GPS	SGRef system, DGPS receiver (10 Hz) NovAtel Millenium 12 channel dual frequency
Video	SGDIS – Digital imaging system (avi format)
Data location system	Post-process DGPS based on NovAtel OEM-V receivers in aircraft and at base.
Data transfer medium	Solid state hard drives and FTP

Magnetometers

Geometrics G-822A and optically pumped Caesium split beam magnetometers, were used for both ground and aircraft sensors respectively. The Caesium magnetometres were housed on the left wing pod and within a rear tail stinger. The two base station magnetometers were located close to the field base. All magnetometers had a sensitivity of 0.005nT and range of 20,000 to 100,000nT with a sensor noise less than 0.02nT. Measurements were delivered at 10 Hz intervals.

Spectrometers

The Gamma Ray spectrometer system used was Radiation Solutions RS-501 with Crystal Detector packs RS5557, RS5558, RS5444, RS5632, with 1024 channels. The system used 16 x 4.2 litre downward looking and 3 x 4.2 litre upwards looking NaI crystals of total volume of 67.2 and 12.6 litres respectively. Data was collected at a sampling rate of 1 second in 1024 channel spectral mode. The system was calibrated at the Geological Survey of Canada's test range at Breckenridge, Quebec, along with ground calibration pad test in Ottawa, Canada before departure to Ireland. Hand sample checks were run on the gamma ray spectrometer before or after each day's flying to check spectral stability and system sensitivity. Relative count rates were measured to achieve background rates that were within two standard deviations of the average sample checks for the survey.

Frequency-domain electromagnetic system

The SGFEM system used four frequencies, 912, 3005, 11962 and 24510 Hz with a transmitter-receiver coil separation of 21.4m. The transmitter-receiver coil pairs were mounted in a vertical-coplanar orientation which helped reduce noise by minimising coupling with the wingtip surface. A 50/60Hz power line monitor was also employed to help identify cultural interference. Data was sampled at 40Hz and later decimated to 10Hz by the contractor during processing of the data.

Figure 5: Radiation Solution spectrometer housed in the aircraft.

2.5.3 Altimeter system

Four types of altimeter were employed on the aircraft. These were:

- SGLas-P – Riegl LD90-3300VHS-FLP Laser Rangefinder: This laser altimeter has a range of 338 m and a resolution of 0.01m with an accuracy of 5cm and a sample rate of 20Hz data rate later decimated to 10Hz.
- Collins AL-101 Radar Altimeter: This radar altimeter has a resolution of 0.5m, an accuracy of 5%, a range of 0 to 408 and was sampled at 10Hz.

- Honeywell Barometric Pressure Sensor: Measures static pressure to accuracy of ± 4m with a resolution of up to 2m over range of 0 to 9,144m above sea level. Barometric pressure is sampled at 10Hz.
- Omega RTD-805 Outside Air-temperature probe: Sampled at 10Hz with a resolution of 0.1 ^{0}C with a range of +/- 100 ^{0}C and an accuracy of ± 0.2^{0}C.

2.5.4 Magnetic Base Station

Two magnetic reference stations were installed for blocks A3 and A4 in 2017. GND1 was located at Sligo Airport near DME building south of the runway. GND2 was setup on private property and moved to new location and designated as GND3. The two Geometrics G-822A, magnetometers were used to measure the daily diurnal variation during the survey. The co-ordinates for the two base stations are given below:

Table 4: Co-ordinates of magnetic base stations used during the A3 and A4 surveys

Station	Easting	Northing	Projection	Elevation
Base A (GND1)	W08°36’01.5817’’	N54°16’ 45.8805’’	WGS84	64.3026 m
Base B (GND2)	W08°32’23.5928’’	N54°14’ 20.7008’’	WGS84	96.4091 m
Base C (GND3)	W08°34’52.8214’’	N54°18’ 04.1443’’	WGS84	64.8091 m
Base A (GND1)	560897.13 m	836901.50 m	ITM	
Base B (GND2)	564806.17 m	832381.64 m	ITM	
Base C (GND3)	562160.92 m	839310.49 m	ITM	

3. Start-up Calibrations & Mobilisation

3.1 Calibrations Introduction

The airborne geophysical equipment system calibrations and tests prior to mobilization were carried out in Ottawa, Canada, as well as at the Geological Survey of Canada's Breckenridge Calibration Range in Quebec; further calibrations were also conducted on site in Ireland. The details of all these tests were reported by SGL and are also outlined in the SGL Technical Report 2017. The main calibrations, which were carried out as part of the survey, are summarized below.

3.2 Magnetic Compensation

Two magnetic flights were performed at high altitude (approximately 10,000ft) within the survey area. The compensation flights were flown on survey line headings. A series of pitch (+/- 5 deg), roll (+/- 10 deg) and yaw (+/- 5 deg) manoeuvers were performed along two headings and the largest peak to peak differences (P2P) in the compensated magnetic signal for each maneuver on each heading (total of 6 measurements) were summed to compute the Figure Of Merit (FOM). The contract specification required a compensation figure below 3nT for a combination of 12 manoeuvres. The flight flown on March 2nd 2017 recorded Figure of Merit (FOM) value of 1nT for tail magnetometer in Ottawa within the required specifications. A compensation test flight was also performed in Ireland on April 26, 2017 and FOM of 0.78 was attained

3.3 Heading Error Determination

A heading test was performed prior to the aircraft leaving Ottawa. A test was flown on March 2nd , 2017 for the tail magnetometer in the same flight in which the compensation test was performed and the results of the average heading error are 0.53 and -0.46 nT for N-S and E-W respectively.

The Heading test was also flown on 21st September 2017 over Coney Island near Sligo. The test consists of flying a set of 2 orthogonal lines (N-S and E-W) crossing each other at the midpoint. The error based on the heading direction can be established by comparing the magnetic values at the midpoint between the lines flown in reciprocal directions e.g. North v South. The average results of the heading test were 0.9 nT and 0.73 nT for the north-south and east-west directions respectively.

3.4 Lag and Parallax Test

The lag in the magnetic data is a function of two components, a static lag due to signal processing and a speed-dependent dynamic lag due to the physical offset of the magnetometer and the GPS antenna. Both elements of the lag are well-known. The static lag is known to be 0.244 s from the filters applied during signal processing. The dynamic lag is equal to the offset of the GPS sensor (located on the aircraft tail for this survey) to the tail magnetometer as measured along the long axis of the aircraft, known to be 4.27 m, divided by the flying speed. For a speed of 60 m/s the dynamic tail magnetometer lag will average 0.071 s, for a total lag of 0.32 s.

The antenna location was changed in the field and no formal lag test was performed. A test of this configuration will be provided during pre-survey calibrations for the survey to be conducted in 2018.

3.5 Radiometric Calibrations

Mobilisation in Ireland was completed on 23rd April 2017, with the completion of a series of calibrations. The radiometric equipment was stored in Ireland over the winter therefore not all the standard radiometric calibrations were performed at the Geological Survey of Canada's Breckenridge Calibration Range in Quebec. Instead the previous calibration used for 2016 were used (30th March 2016). These results were then reevaluated in respect of the new data collected in 2017 along with, the repeated test line and calibrations carried out at the end of the survey, Full details of these tests were reported by SGL, are contained in SGL technical Report 2017 and summarised in Table 5. Calibrations are carried out based on guidelines set out in (IAEA, 2003) and (Grasty and Minty, 1995).

Table 5: Spectrometer Processing Parameters for A3 and A4 blocks

Spectrometer Processing Parameter – Spectrometer Radiation Solutions Model RS-501 NaI (Tl) crystals 67.2L, Down, 12.6L Up. At 60m survey altitude.		
Window	**Cosmic Stripping Ratio (b)**	**Aircraft Background (a)**
Total	*1.2696*	*11.2210*
Potassium	*0.0707*	*18.7296*
Uranium	*0.0326*	*1.0200*
Thorium	*0.0475*	*0.1300*

Upward	*0.0067*	*0.0000*
Radon Correction	**Radon Ratio (a)**	**(b)**
Total (Ir)	*14.1819*	*8.3200*
Potassium	*0.8417*	*1.4543*
Thorium(Tr)	*0.0578*	*1.3396*
Upward Uranium(Ur)	*0.2224*	*0.0000*
Ground component	*a1*	*a2*
Up (ug)	*0.04055*	*0.01683*
Stripping Ratios	**Contribution on the ground**	**Effective height adjustment**
α	*0.2760*	*0.00049*
β	*0.4208*	*0.00065*
γ	*0.7702*	*0.00069*
a	*0.0442*	*0*
b	*0.0004*	*0*
g	*0.0009*	0
	Attenuation Coefficients	
Total	-0.006227	
Potassium	*-0.007960*	
Uranium	*-0.005123*	
Thorium	*-0.005838*	
	Sensitivities at 60m	
Total Count		
Potassium	*176.25 cps/%*	
Uranium	*23.39 cps/eU ppm*	
Thorium	*9.37 cps/eTh ppm*	

3.6 EM System Orthogonality

Prior to each flight, the phase shift between the in-phase and quadrature parts of the EM response is verified and adjusted if required. For each frequency, two pulses of constant amplitude are artificially generated, the first being perfectly in-phase with the primary field, and the second being phase shifted by 90 degrees. Therefore, when the phase orthogonality is properly adjusted, no quadrature response should be observed during the first pulse, and vice versa during the second. This test is usually performed above 300m to avoid any EM response from the ground and to minimize cultural interference. The compensation of the primary field is verified, enabling EM data to be recorded with reference to an arbitrary zero-level low enough to ensure that the full range of the receiving device can be utilized. This ensures the system is functioning properly. The orthogonality check is also performed following each production flight, while ferrying back to the base.

3.7 EM Over-Seawater Calibration

The frequency domain electromagnetic system was calibrated following procedures described by Hautaniemi *et al.* (2005). A test site was chosen over Donegal Bay, in an area where water conductivity and temperature have been measured several times over the years, at every meter from surface to sea floor, by the Irish Marine Institute. The water depth reaches over 60m, ensuring that the bottom sediments do not contribute to the EM response. Conductivity data from two different stations taken from three different years were analysed, showing conductivity profiles to be essentially consistent at the two stations, and therefore data can be considered constant between the stations. The calibration line location (in red) and the two sampling stations (CE10003_056 and CE10003_057) are shown in Figure 6.

Figure 6: Location of overwater calibration line and sampling locations

The conductivity data was analysed to estimate the conductivity variation with depth. Conductivity changes with respect to temperature were analysed over three different years. Full details of these tests were reported by SGL (2017a, b). The 4.5km long calibration line was flown on May 26^{th} 2017 at several heights from 50 to 120 m. Surface water temperature measured on the same day as the calibration flight also took place (12.236 °C, published by the Irish Marine Institute) enabling the estimation of the water conductivity close to surface.

[0.089 S/m°C x 13.36 °C] + 12.236 S/m = 4.004 S/m [1]

Based on the average conductivity decrease with depth observed over the three years and the result from Equation 1 above, it was possible to estimate the water conductivity at a depth of 30 m ([-0.0025 S/m2 * 30m] + 4.004 S/m =3.929 S/m), and the average conductivity between the surface and a depth of 30m at the calibration site (3.929 S/m). Slight changes in conductivity below 30m are negligible. This conductivity was used to create a single layer model (half-space), which was employed to calculate the EM response for each component of each frequency, for the range of altitudes covered during the calibration flight. The calculation was performed with the software Airbeo, developed by AMIRA (SGL 2012, SGL 2016, SGL 2017a, b).

3.8 Altimeter Calibration

The altimeter calibration test is carried out to ensure proper functioning of the aircraft altimeters. This is done by flying over a flat surface (runway) at a series of different elevations. A correlation coefficient can then be calculated with values greater than 0.97 indicating an accurate calibration result. Results achieved a value of 1 indicating a good result. This test was performed on March 5^{th} 2017 over the runway at Gatineau Airport, near Ottawa. Six passes were conducted over the runway at heights from 0 to 300 m above ground at various levels. The altimeter values were compared to the post-flight differentially corrected GPS altitude information for calibration. An ideal altimeter would yield a slope of 1 and an intercept of 0. The Collins radar altimeter slope was 1.0176 and the intercept -0.5349 m. The laser altimeter slope was 1.0024 and the intercept was 0.1904 m. These results are within the expected accuracy of the altimeters.

3.9 Mobilisation

The A3 and A4 surveys form part of a 3 year contract award to Sander Geophysics Ltd (SGL), signed on 26^{th} May 2015. The contract runs from 2015 to 2017 and includes the surveying of Tellus airborne survey blocks A1, A2, A3 and A4. The A1 block was flown in 2015, A2 block in 2016 and block A3 and A4 were flown in 2017. Completion of these blocks along with previous Tellus surveys will see more than 50% of the Republic of Ireland completed. Alison McCleary was appointed as SGL party chief and arrived in Ireland on 24th March 2017 along with the chief pilot Steve Gebhardt. Alison McCleary met with project staff at the GSI on Monday 27th March 2017. Configuration of instrumentation on the aircraft along with testing continued until the 23rd April 2017, the first production flight took place for the Donegal survey block on 27th April. F Sligo Airport was used as the field base for the duration of the project.

3.10 Test Line

As part of on-going calibration testing and to help with the integration of different datasets collected during different seasonal conditions a test line was developed. This test line was flown twice during the survey. The line is located close to the town of Bundoran in county Donegal, in the northwest of the country (Figure 7) and runs from the sea to onshore. The test line extends from Irish Transverse Mercator grid Co-ordinates E577142.64m, N859106.47m to E578701.96m, N853314.3m. The line was flown at four different altitudes (60m, 90m, 120m and 150m), plus two additional lines 100m either side of the test line at 60m altitude. The test line is 6km in length. The test line was chosen to include areas of variable bedrock and superficial geology as well as coastal transition zone and sea water. C-GSGF's first test line flight was on 26th April 2017, and a second flight on 19th September 2017. The test line was also flown as part of the Tellus Border, North Midlands, A1 and A2 surveys.

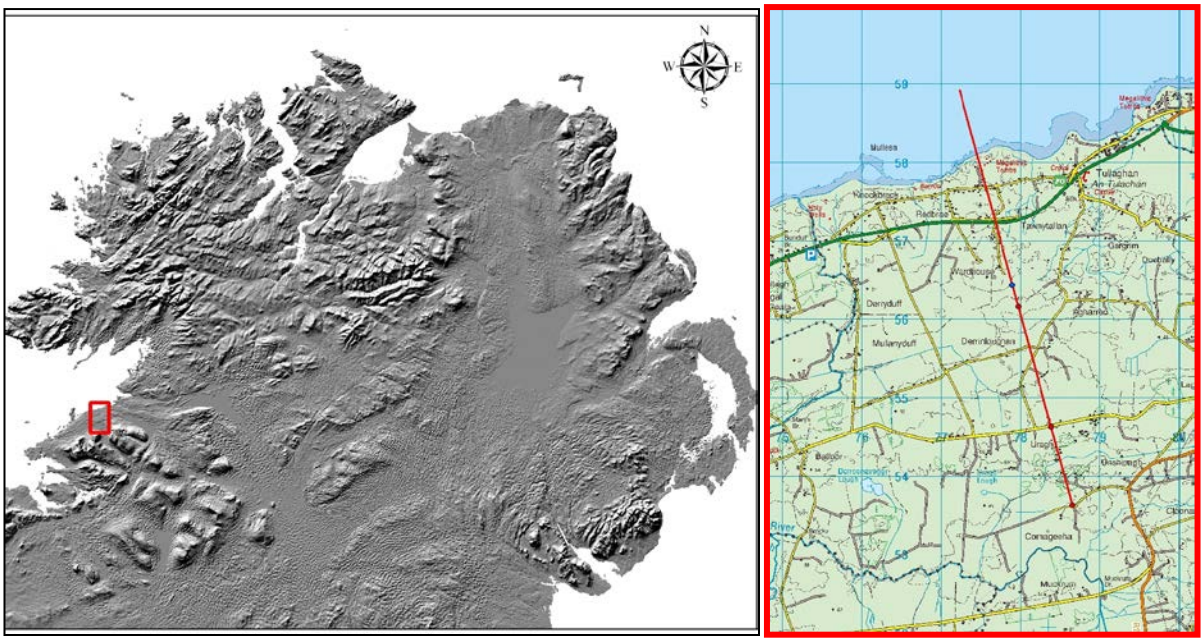

Figure 7: Test line location (in red)

3.11 Personnel

Members from both SGL and the Tellus team were involved in the airborne geophysics operations, the main personnel are listed below in Table 6 and 7.

Table 6: SGL Field Crew

Field Personnel	Name
Operations Manager	Alex Pritchard (offsite)
Crew Chief	Alison McCleary
Data Processor	Diana Kuiper, Cameron McKee
Chief Pilot	Steve Gebhardt
Pilots	Charles Dicks, Jason Thomas, Andre La Fontaine, George Sakgaev, Todd Svarckopf
Technicians	Craig McMahan,

Table 7: GSI Tellus Team

Field Personnel	Name
Head of Programme / GSI Principal Geologist	Ray Scanlon
Project Manager	Dr. Aoife Brady
Geophysical Programme Manager	Dr. James Hodgson
Geophysicist	Mohammednur Desissa Ture
Communications Assistant	Emma Scanlon
GIS and Data Manager	Peter Heath

4. Outreach Programme

4.1 Tellus Public Relations

Due to the low flying nature of the survey (nominal survey altitude of 60m) the distribution of population centres and land use within the survey area an extensive outreach programme was undertaken. This comprised a comprehensive information campaign including meeting with local stakeholders, interviews on local radio and articles in both national and local newspapers. Approximately 130,000 information fliers were posted to land owners within the survey area. State agencies including; local authorities, An Garda Síochána and Local Authorities were also contacted and regularly updated on the progress of the survey. Of particular significance was the bloodstock sector with notifications given through the Weatherby's Organisation (thoroughbred horse registrations) and the Irish Thoroughbred Breeders Association along with individual visits.

As part of this outreach programme a web-based, data management software program was developed internally within the Department. This software, called the Tellus Comms Viewer (TCV), was used to log all enquiries and record all communications with landowners and different stakeholders. Following the outreach programme any land owners, particularly livestock owners, who required notification of the survey in their area were contacted and their land holding digitised within the TCV. The TCV could then be used to determine which flight lines intersected which landholdings and which people may be affected by the flight. Before each flight a Tellus team member would contact the SGL party chief and identify any land owners who required notification. These people where then contacted, and their responses logged. This allowed stock to be moved or in some cases, a high fly zone (240m) to be flown above these properties.

High fly zones were also introduced over urban areas (populations greater than 2500) as required under the permit. During survey activities, an "on-call rota" was established to make sure that there was a team member on duty at all times seven-days a week, to deal with urgent enquiries relating to the airborne survey. A free-phone information line (1800 303 516) was in operation and was managed by Morrow Communications in order to take enquiries about the airborne survey. The line was manned during office hours by Morrow Communications and out of hours by the Tellus communications representative on call. All calls were logged in the TCV managed by the communication assistance and project manager.

5. Quality Assessment

5.1 QA/QC

During the survey operation, data was supplied to the Tellus geophysicists via FTP from SGL on a weekly basis. The data was checked to determine whether it conformed to the required specifications/re-flight requirements as outlined in Section 2.4. The following checks were carried out on all data:

- Terrain clearance and altitude deviations
- Flight line accuracy
- Magnetometer noise
- Ground speed
- Magnetic base station – diurnal variations
- Magnetic noise – Fourth difference/noise
- Gamma ray stability
- EM - noise level, conformity and orthogonality

Weekly QC reports were filed and discussed with the SGL party chief and any required re-flights scheduled into the new flight plan. The weekly QC reports have been collated and can be found as an internal GSI document. Overall technical specifications were adhered to by the contractor. High altitude deviations, mainly the result of the severe topography in the west, along with induced high fly zones due to urban areas or sensitive livestock areas, were a constant issue.

6. Survey Outputs & Statistics

6.1 Survey Production

The survey consisted of a total of 27,620 and 18737 km for blocks A3 and A4 respectively. There were 549/32 (traverse/tie lines) for A4 block and 552/38 (traverse/tie) lines for Block A3. A full list of all flight logs and a flight line summary is contained within the SGL Technical Report (SGL, 2017).

Table 8: Survey Operation overview

Airborne Survey Contractor	Sander Geophysics Ltd.
Survey Aircraft:	De-Havilland DHC-6 Twin Otter (C-GSGF)
Survey Base:	Sligo Airport
Aircraft arrival:	4th April 2017 (Sligo Airport)
Flying dates:	27th April 2017 –30th September
Total no of Flights Productions, re-flights and test flights):	61 flights for A4 block and 101 flights for Block A3.
Date of demobilisation:	5th October 2017
Total Production km's flown:	27,620 and 18,737 km for blocks A3 and A4 respectively.

The airborne survey operated 7 days a week over 24 weeks. Production was steady throughout with number of delays due to mainly weather and few delays related instrumentation or aircraft issues. The survey was completed on schedule. The average production across the survey period was 2,015 km per week; a decrease of the 140 km on the weekly average in comparison to the A2 block survey carried out in 2016. Significant weekly average was attained from week 12 to week 14 (July 3 to 17/2017) with average weekly reached 2800 km. The highest weekly total of 5,051 km in week 13 was observed. The lowest weekly total was 374.6 km, on week 21 (September 4) caused by bad weather.

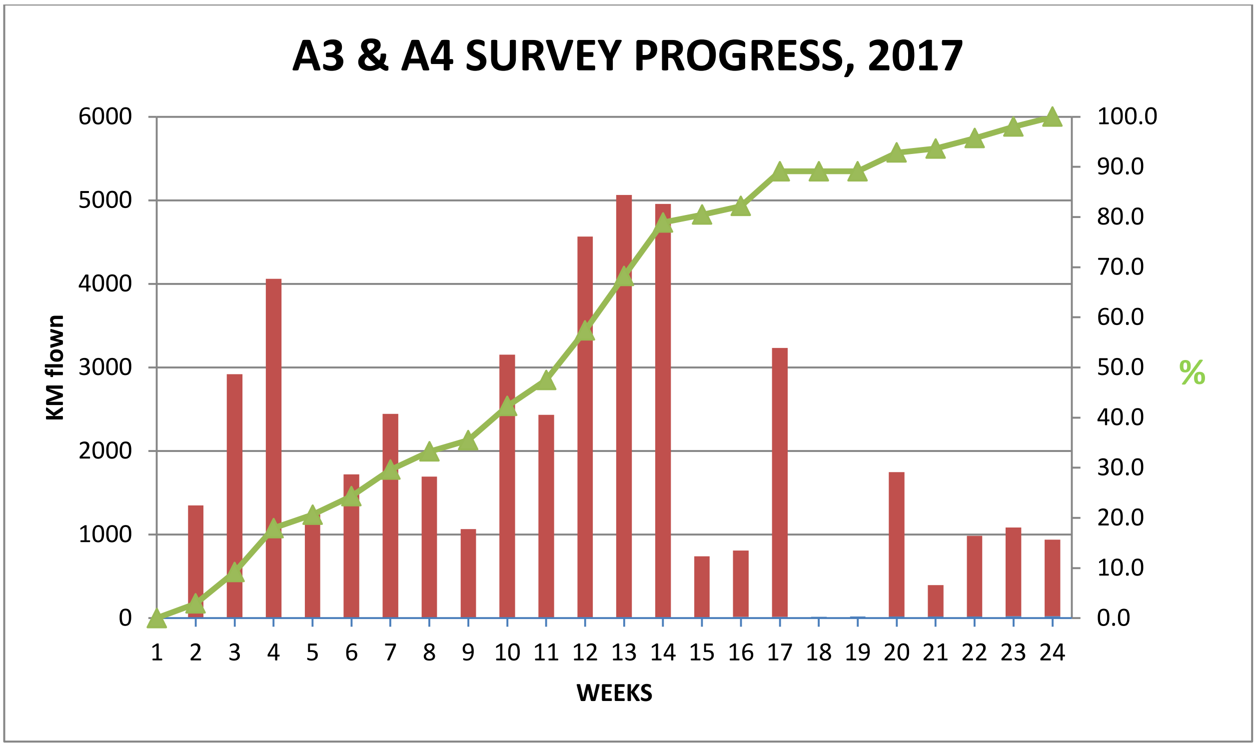

Figure 8: Weekly survey production in line km for A3 and A4 Surveys

6.2 Altitude

The survey specifications set a survey altitude of 60m over rural areas and 240m over urban areas. Topography and land-use in the area (A3 & A4) is a mix of low-lying peat bog and undulating grass farmland with significant topography in the central and western parts. Croaghaun Sea Cliffs on Achill Island to the far west of the survey area are some of the highest in Europe extend 688 m from sea level Table 9 shows altitude variation of Blocks A3 and A4.

Table 9. Altitude variations for survey blocks A3 and A4

Block	Altitude range	max	Mean	SD	# data	%
A3	Less than 100 m	99.90	67.71	9.47	3,465,208	75.73
	100-120 m	119.90	109.33	5.79	183,030	4.00
	120-130	129.90	124.86	2.86	71,336	1.55
	130-150	149.90	139.65	5.72	116,158	2.53
	Greater than150	404.70	274.94	87.72	736,432	16.09
A4	Less than 100 m	99.90 m	70.84	11.32	2,113,574	68.21
	100-120 m	119.90 m	109.27	5.84	235,876	7.61
	120-130	129.9 m	124.82	2.9	89,186	2.87
	130-150	149.9 m	139.45	5.77	140,778	4.54
	Greater than150	403.70 m	234.70	73.27	518,859	16.74

The Tellus A3 & A4 project operated an extensive outreach programme within the survey area in particular identifying livestock owners, stud farms and farmers to make them aware of the low flying survey. A number of livestock/horse owners requested that the high fly altitude of 240m be carried out over their lands. Along with these zones, high fly zones were also identified over towns with populations greater than 2,500. This resulted in a number of high fly (240m) zones throughout the survey area. The high fly zone greater than 150 m covers about 16% of the survey area (Table 9). Numerous other altitude deviations were encountered, generally relating to steep terrain over the mountains in the survey area. These high fly zones have had a significant impact in the overall altitude values across the survey (Figure 9).

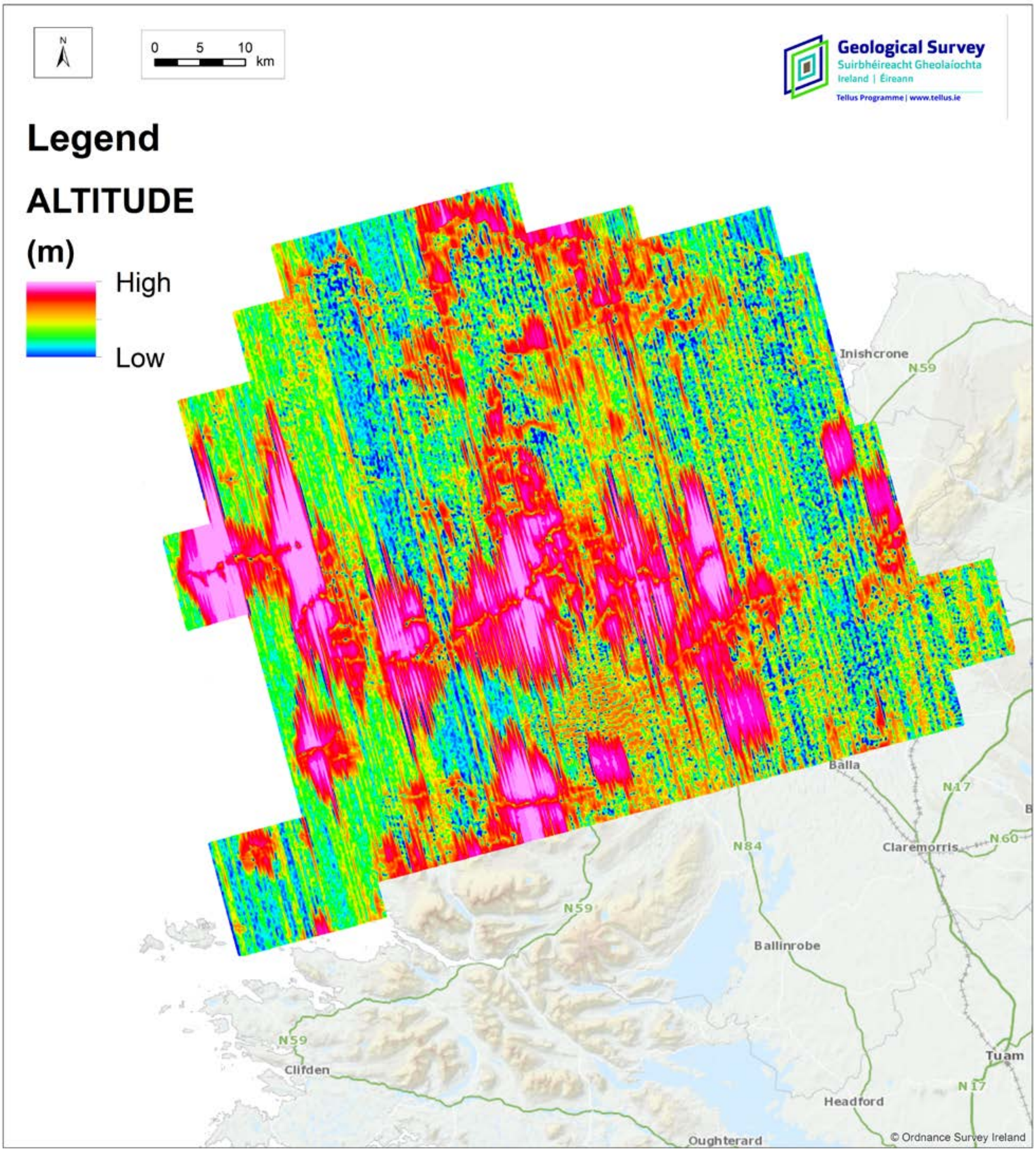

Figure 9: Survey altitude in metres above ground level for Block A3

As can be seen from Figure 9, obvious high altitude (pink) zones are observed across the survey area; these are associated with towns and requested high fly zones but mainly over the hilly terrains. The maximum survey altitude recorded was 1090 m over A3 block while the mean over this block is about 110 m with a standard deviation of 105.35 with approximately 16% of measurements greater than a survey height of 150m. As can be seen from Figure 10, obvious high altitude (pink) zones are observed across the A4 survey area; these are associated with towns and requested high fly zones but mainly over the hilly terrains. The maximum survey altitude recorded was 668 m over A4 block while the mean over this block is about 105 m with a standard deviation of 70.77 with approximately 16.7% of measurements greater than a survey height of 150m

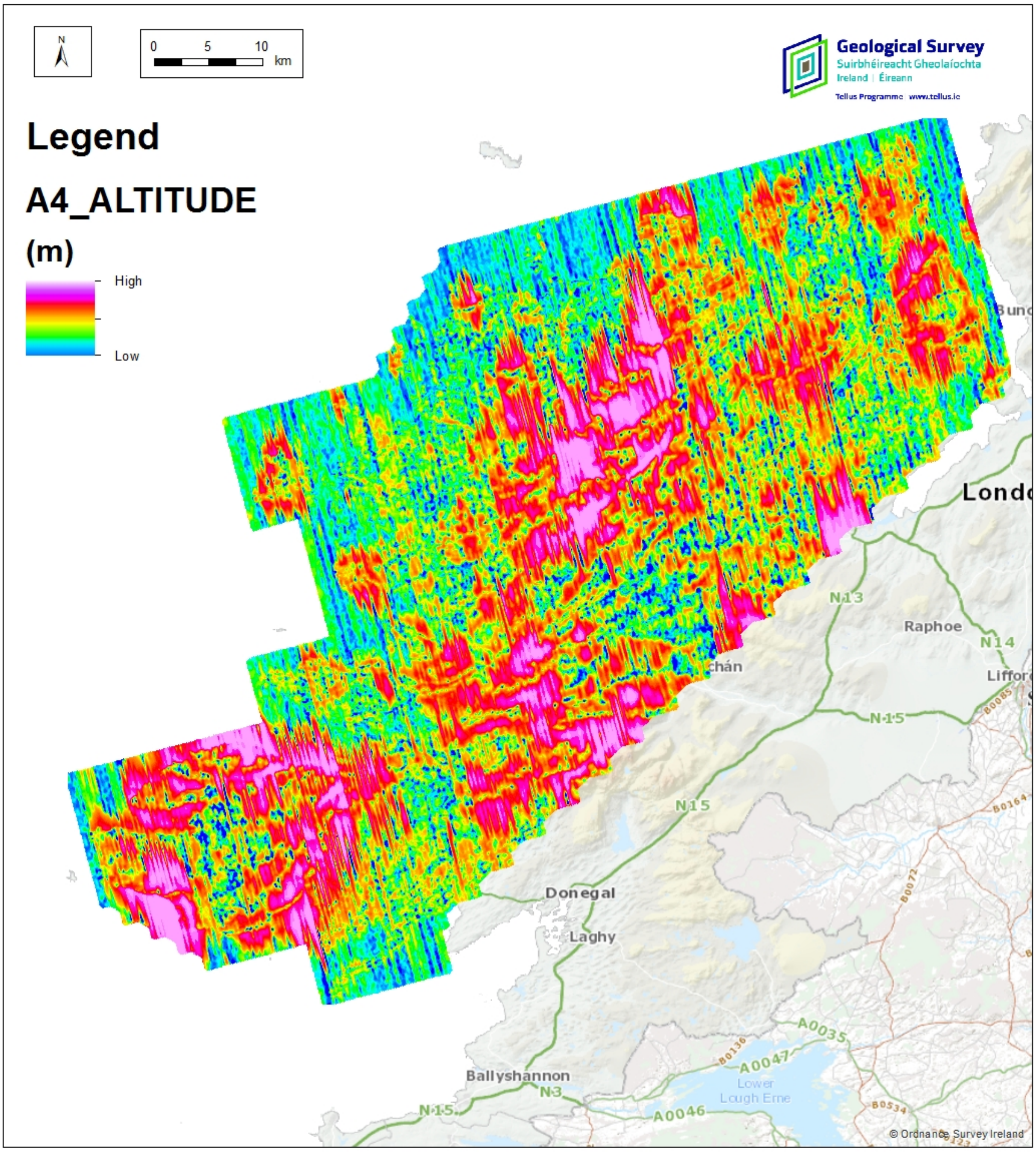

Figure 10: Survey altitude in metres above ground level for Block A4

6.3 Magnetic Data Summary

For the magnetic data a total of 4.572 and 3.099 million data points were collect at a sample rate of 10 Hz respectively for blocks A4 and A3. The main statistics for the raw and corrected data are summaries below in Tables 10 &11.

Table 10: Raw magnetometer summary statistics for A3 and A4 blocks

BLOCK	DESCRIPTION	NUMBER
A3	No data points:	4,572,279
	Sample rate:	10 Hz or 0.1 sec
	Minimum value:	47512.76 nT
	Maximum value:	50952.32 nT
	Mean value:	49322.02 nT
	Standard Deviation	106.27
A4	No data points:	3,099,797 nT
	Sample rate:	10 Hz or 0.1 sec
	Minimum value:	49162.92nT
	Maximum value:	50217.95nT
	Mean value:	49637.60nT
	Standard Deviation	74.14

Table 11: Compensated, IGRF subtracted and levelled tail magnetometer summary statistics A3 and A4 blocks

BLOCK	DESCRIPTION	NUMBER
A3	No data points:	4,572,279
	Sample rate:	10 Hz or 0.1 sec
	Minimum value:	47508.15nT
	Maximum value:	50946.65 nT
	Mean value:	49322.09 nT
	Standard Deviation	106.15
A4	No data points:	3099797
	Sample rate:	10 Hz or 0.1 sec
	Minimum value:	49158.64 nT
	Maximum value:	50221.81 nT
	Mean value:	49637.60nT
	Standard Deviation	74.01

A grid of the resultant magnetic anomaly for A3 and A4 blocks are shown in Figures 11 & 12 respectively. Data is gridded using the minimum curvature method and a grid cell size of 50m. Slight difference in the gridded minimum and maximum exist due to grid expansion effects.

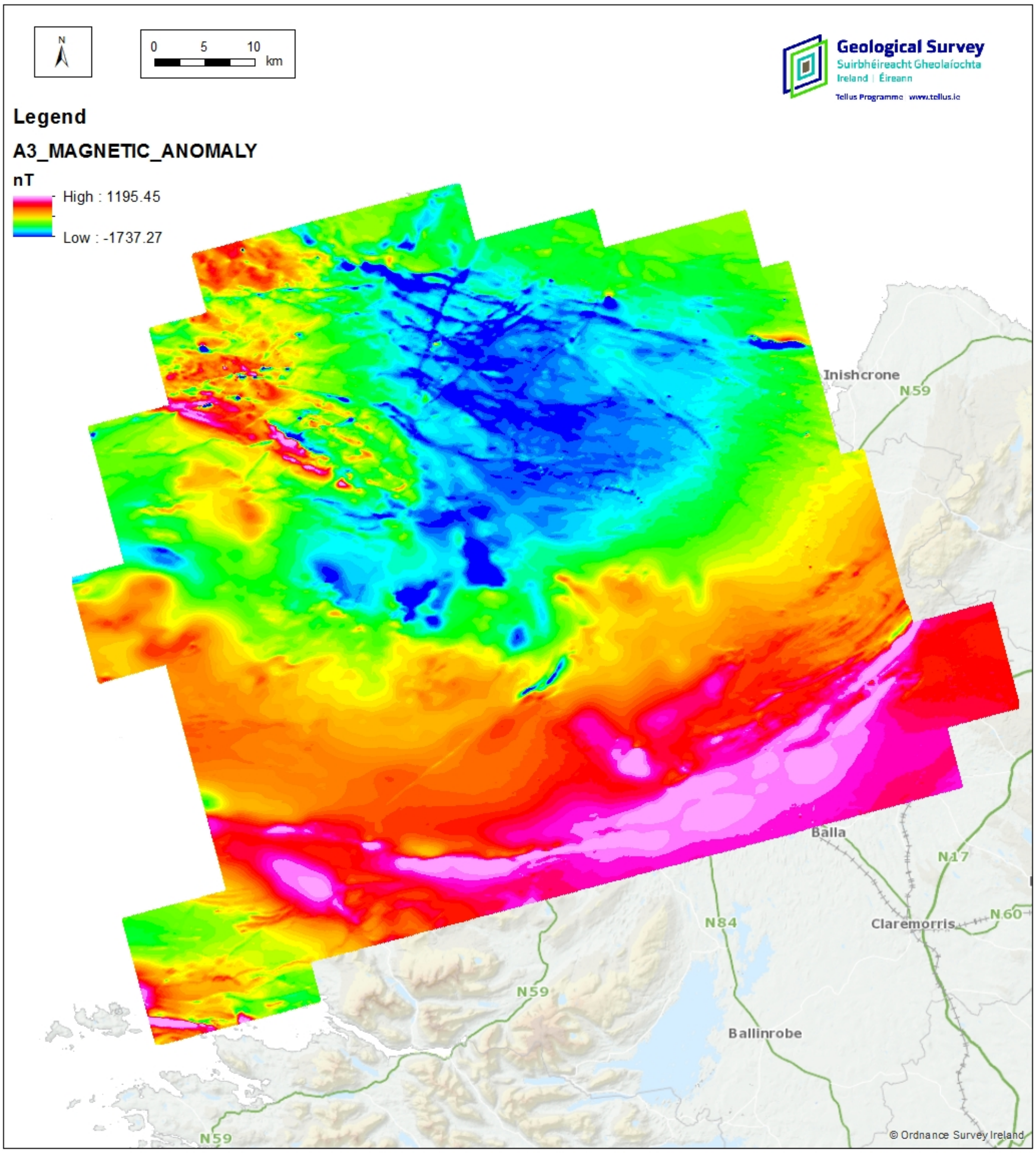

Figure 11: Residual magnetic anomaly for the A3 block

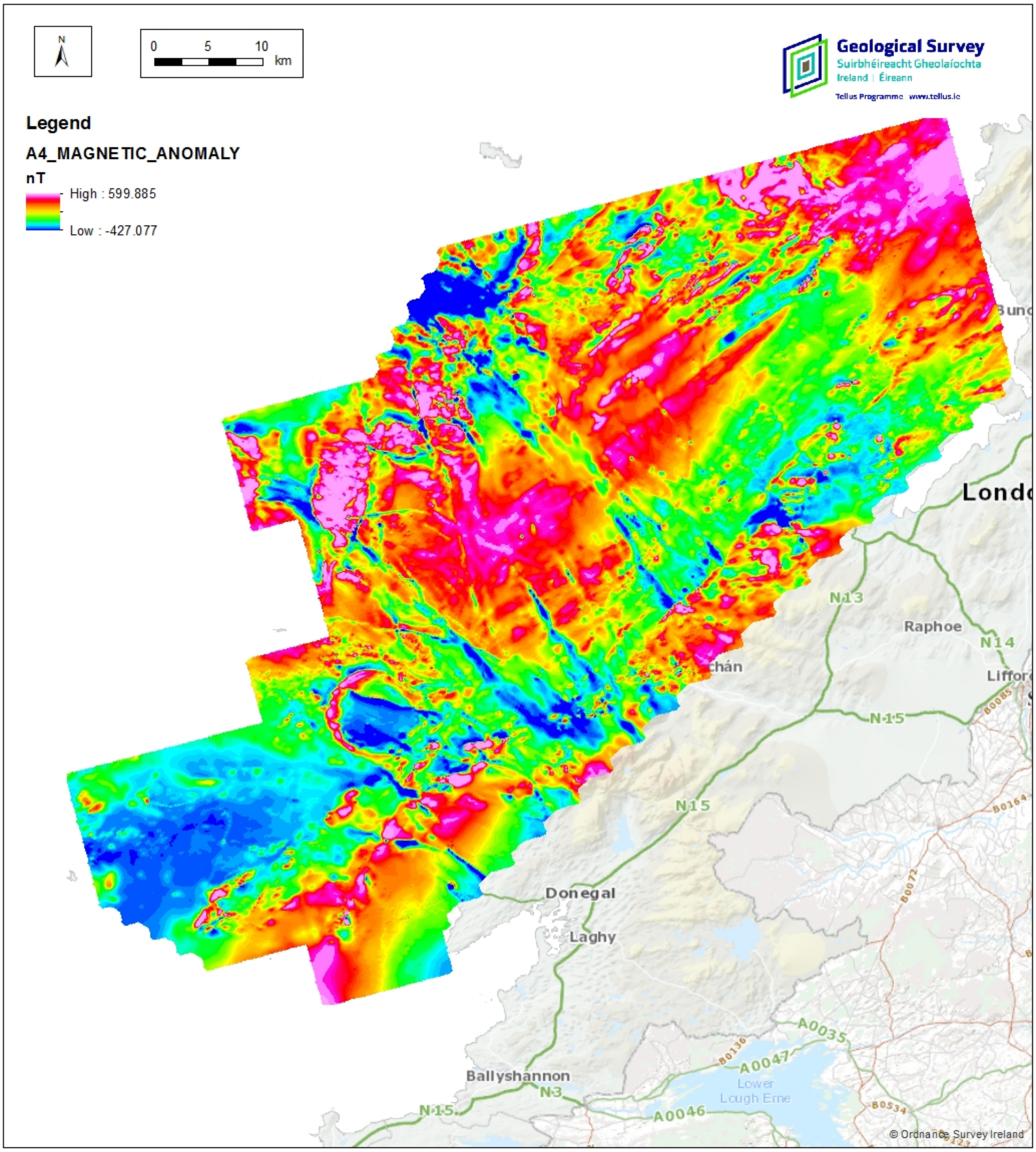

Figure 12: Residual magnetic anomaly for the A4 block

6.4 Radiometric Data Summary

For the radiometric data a total of 415,880 and 281,582 data points (excluding tie lines) were collected at a sample rate of 1 Hz for blocks A3 and A4 respectively. The main statistics for each element are summaries below in Table 12, all data has been corrected and therefore some negative values result in areas of low response primarily over water bodies, data has not been limited to zero..

Table 12: Corrected radiometric data summary statistics

Block	No. data	Element	Min	Max	Mean	SD
A3	415,880	Total Count (cps)	-332	7027	840.82	851.35
		Potassium (%)	-0.35	5.78	0.42	0.47
		e Thorium (ppm)	-1.48	14.88	1.34	1.57
		e Uranium (ppm)	-1.07	5.71	0.37	0.52
		Temp (deg. C)	3.2	25.3	15.52	3.15
A4	281,582	Total Count (cps)	-333	7066	1109.2	966.45
		Potassium (%)	-0.43	5.69	0.53	0.51
		e Thorium (ppm)	-1.49	17.39	2.21	2.21
		e Uranium (ppm)	-0.65	3.73	0.39	0.44
		Temp (deg. C)	6.7	25.1	14.38	3.15

Grids of total counts, percentage potassium, equivalent thorium and equivalent uranium are shown below in figures 13-16 for blocks A3 and A4. Data is gridded using the Inverse Distance Weighted Gridding method and a grid cell size of 50 m. Slight difference in the gridded minimum and maximum exist due to grid expansion effects or clipping of erroneous points. No clipping of data due to high fly altitudes has been carried out.

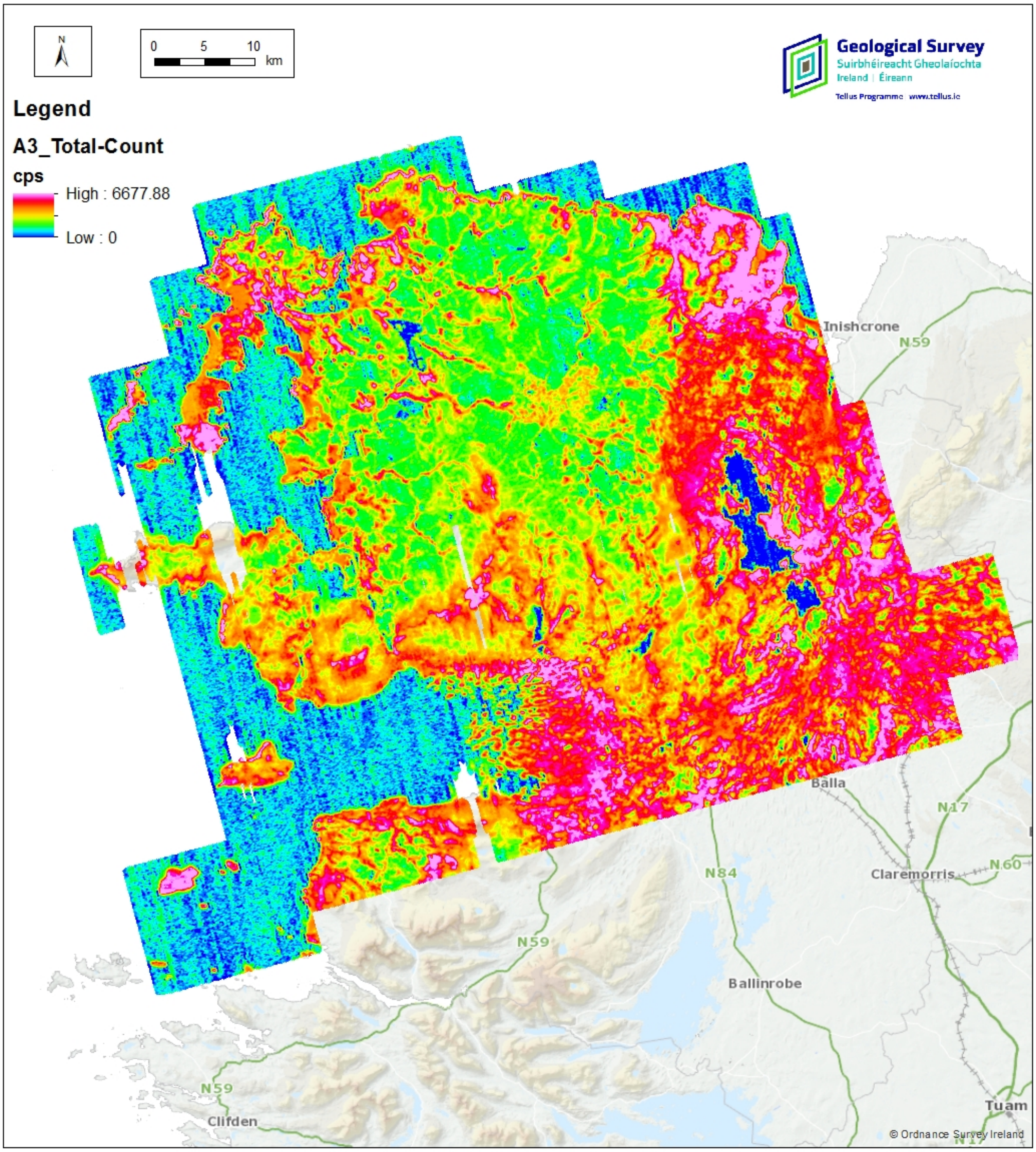

Figure 13: Corrected total count values for the A3 block in counts per second

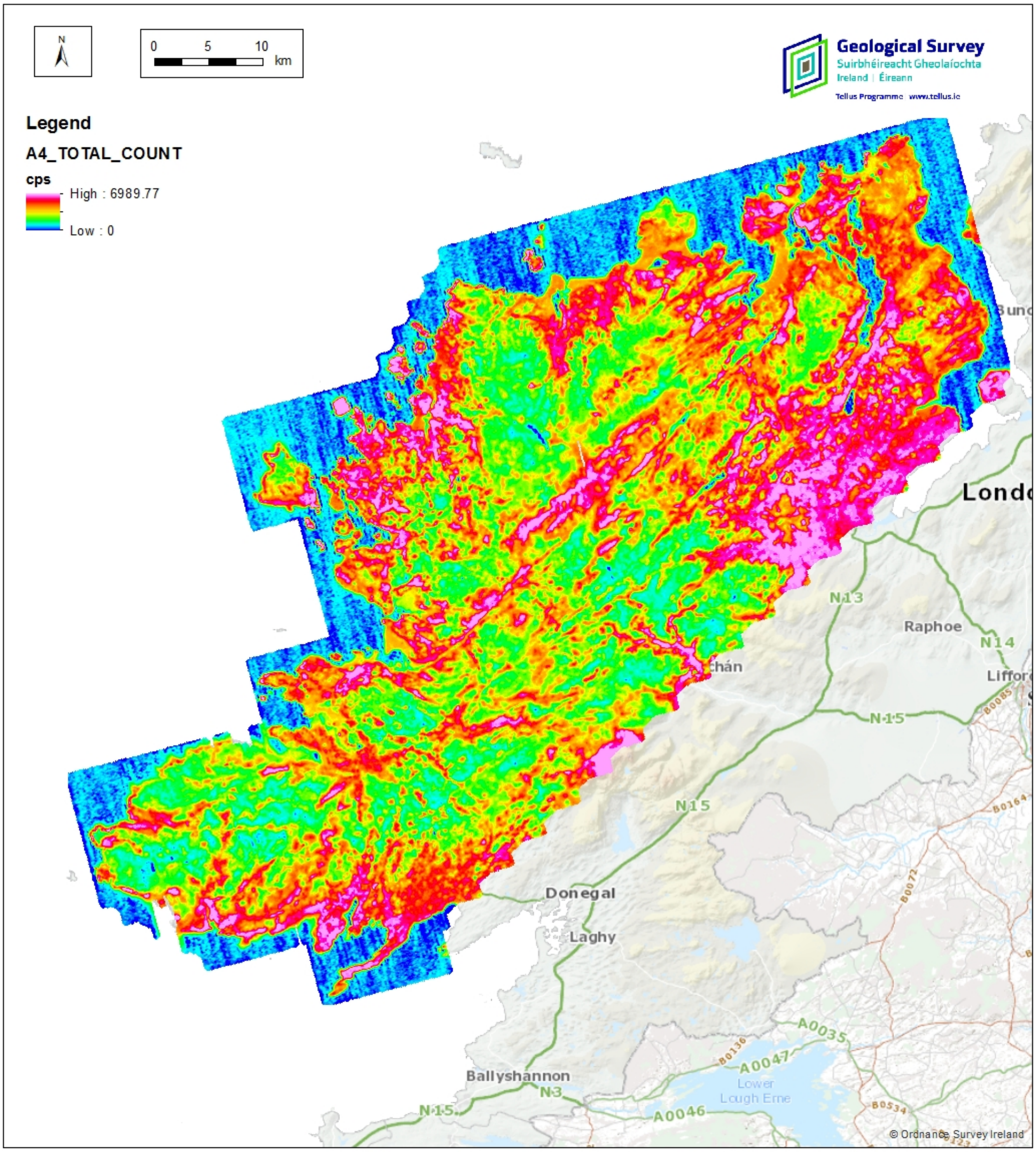

Figure 14: Corrected total count values for the A4 block in counts per second.

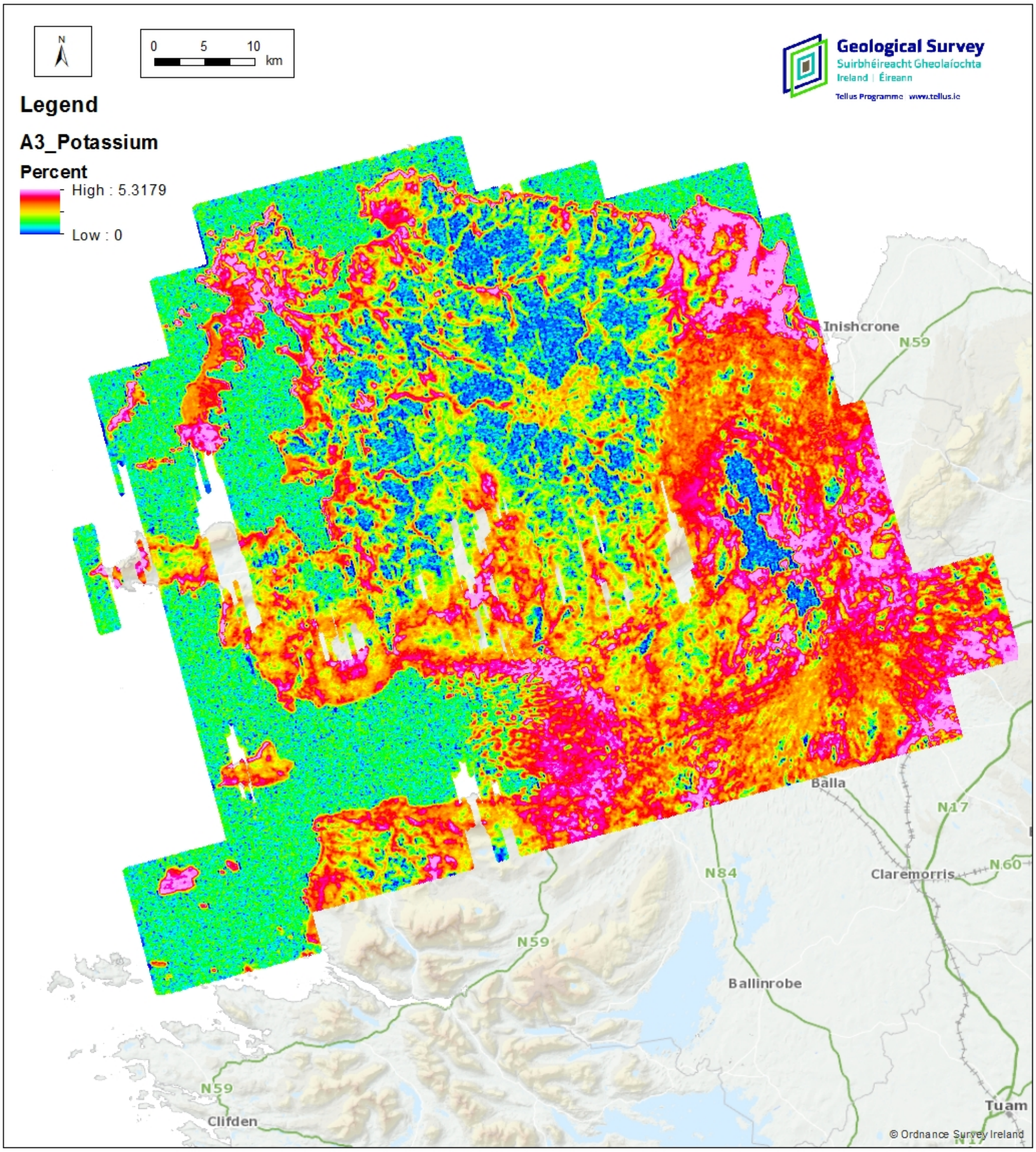

Figure 15: Corrected potassium values for the A3 block as percentage.

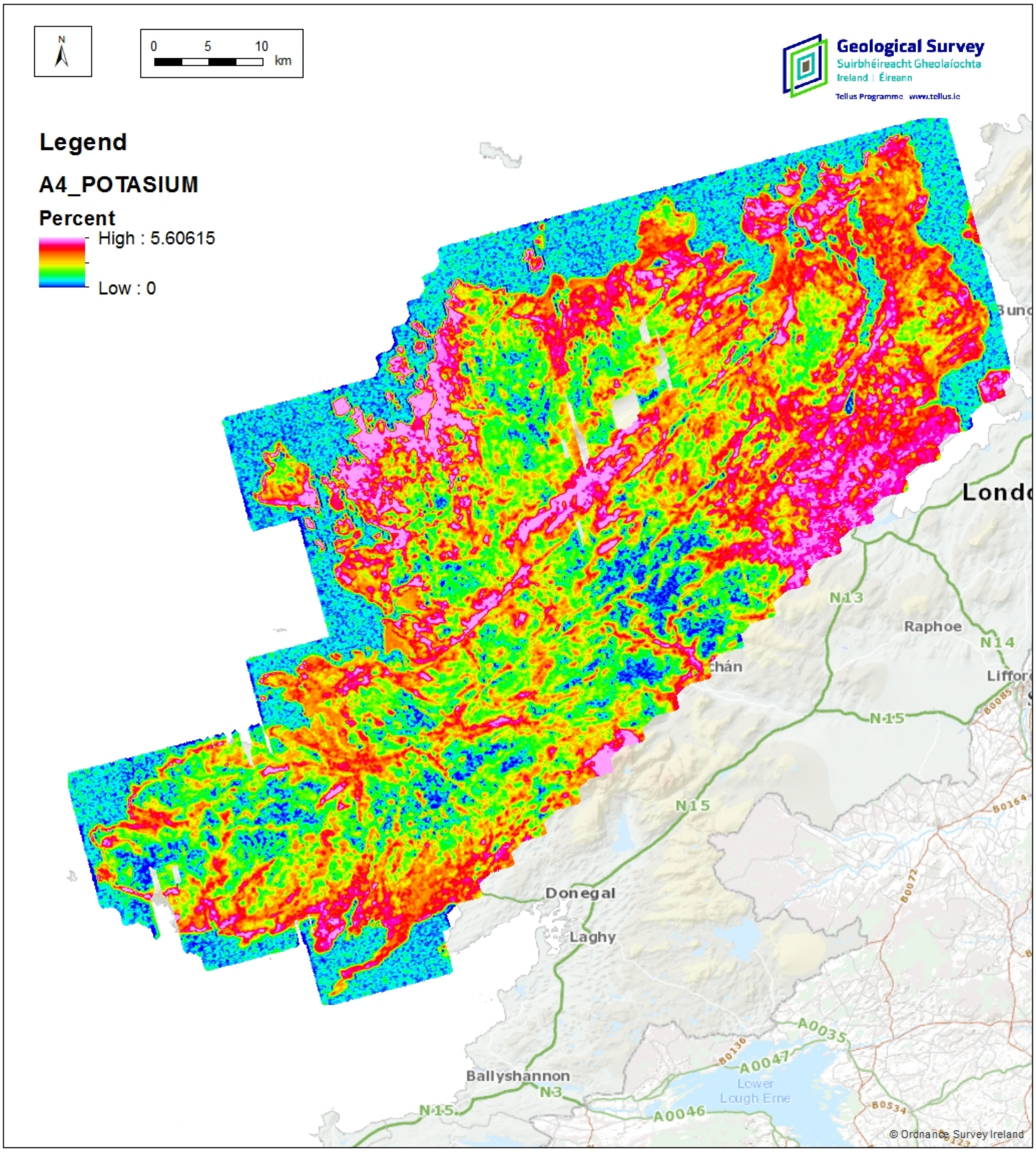

Figure 16. Corrected potassium values for the A4 block as percentage

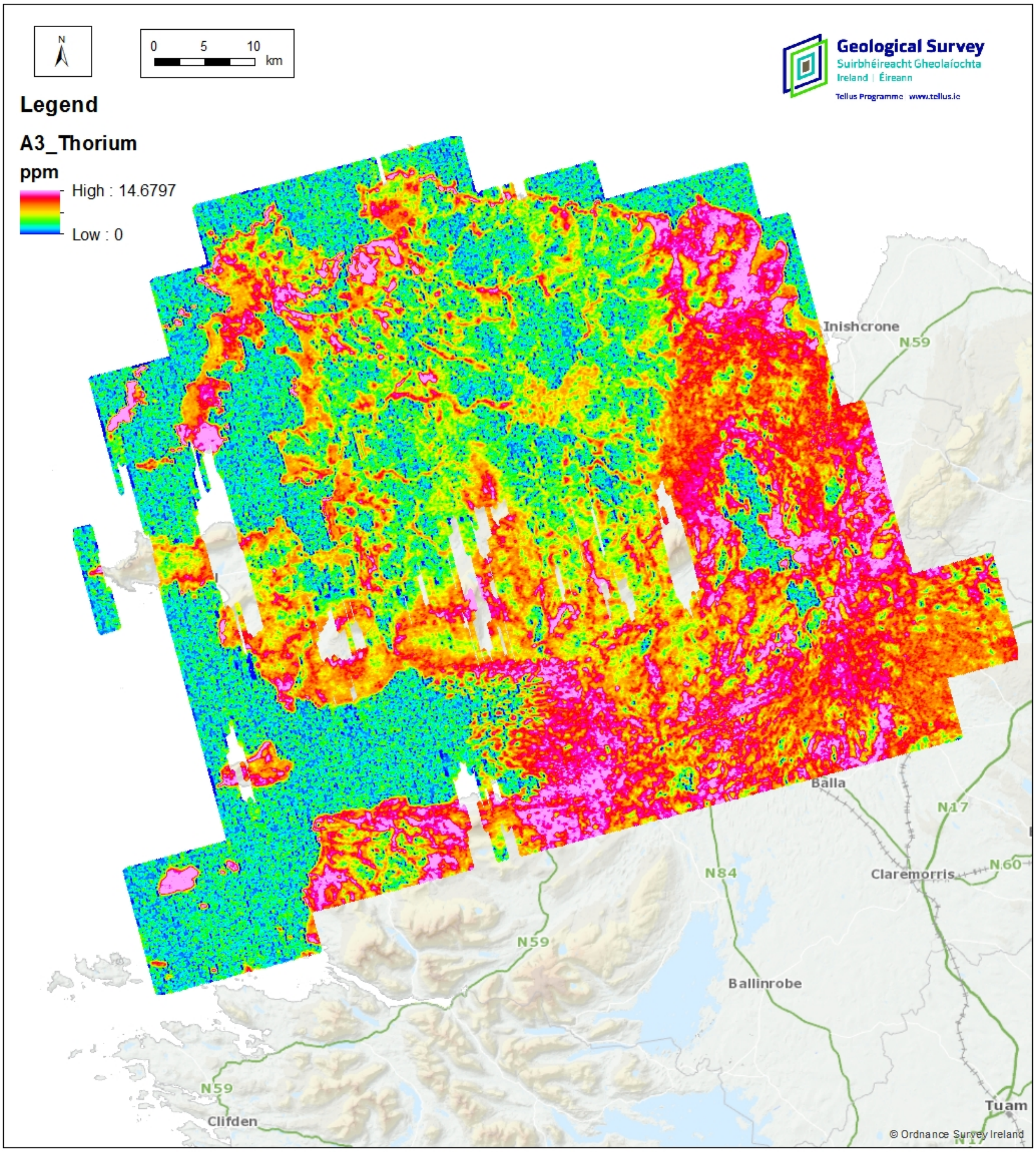

Figure 17: Corrected equivalent Thorium values for the A3 block in parts per million

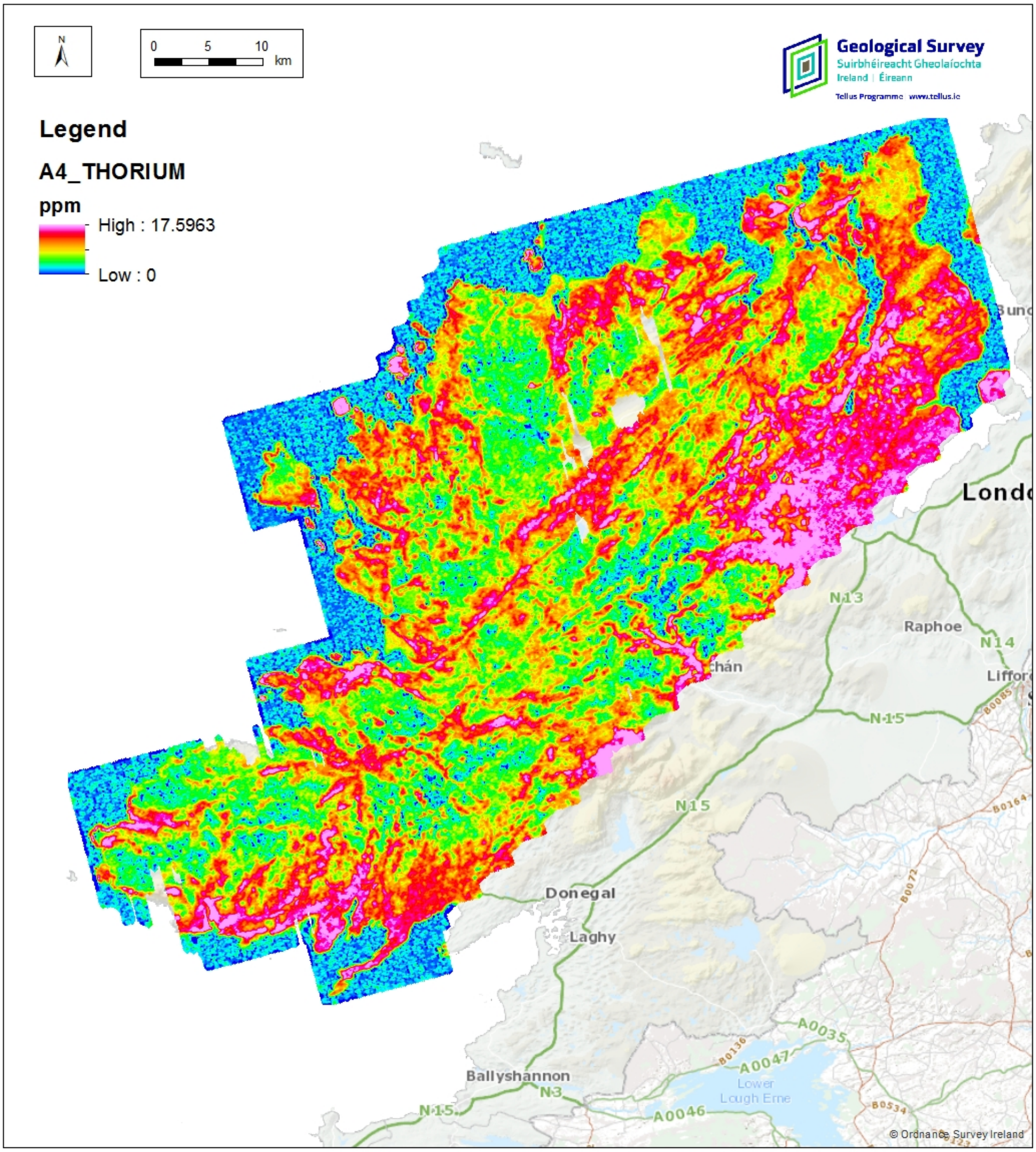

Figure 18: Corrected equivalent Thorium for the A4 in parts per million

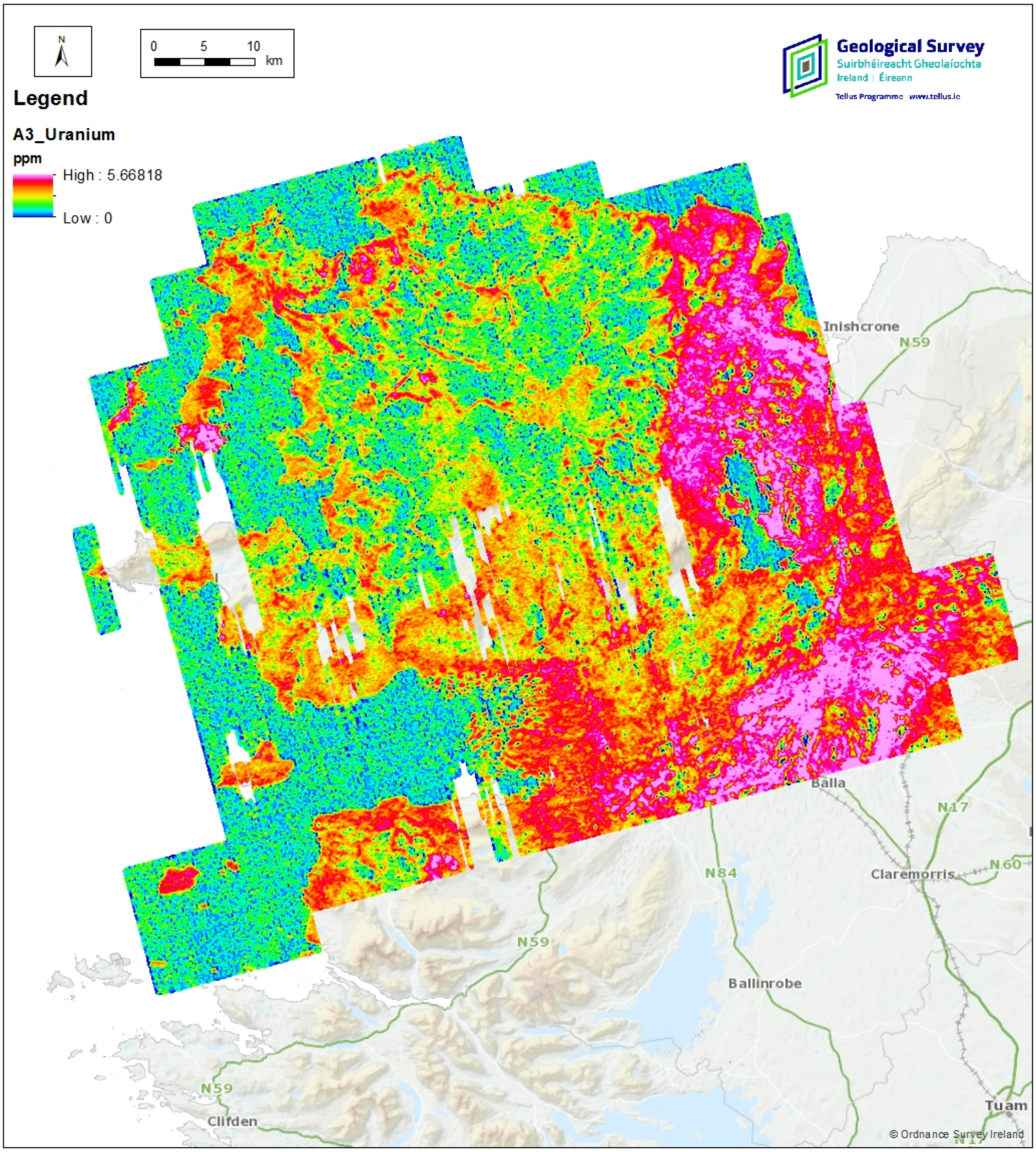

Figure 19: Corrected equivalent Uranium values for the A3 block in parts per million.

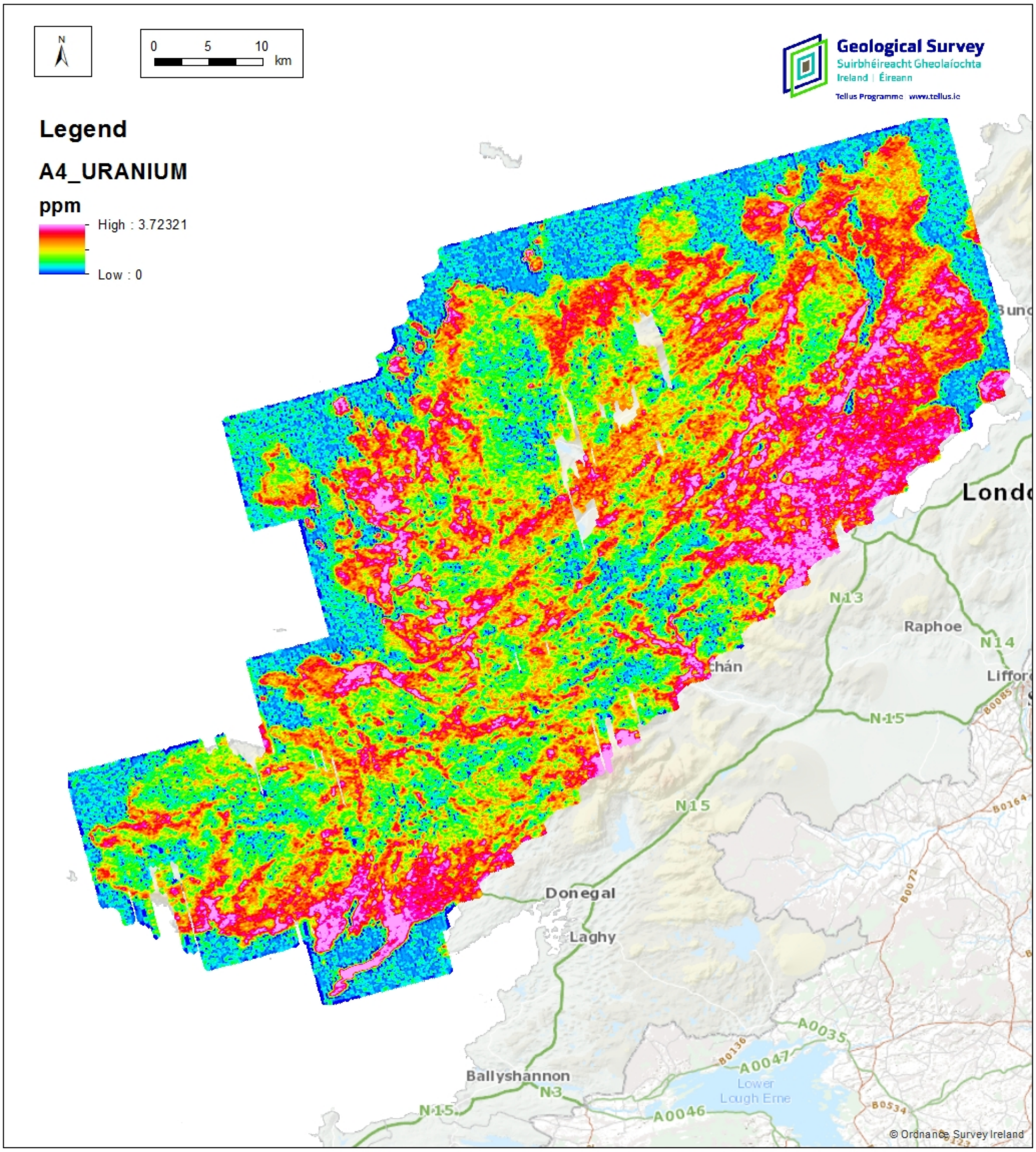

Figure 20: Corrected equivalent Uranium values for the A4 block in parts per million

6.5 Frequency Domain Electromagnetic (FEM) Data Summary

For FEM data a total of 4,572,669 and 3,099,657 data points were collected respectively for blocks A3 and A4 including tie lines at a sample rate of 10 Hz, i.e., measurements at approximately 6m intervals along flight lines. In EM processing the tie line data are not used since EM is a focused signal and is directionally dependent. When tie lines are excluded the numbers of data points on standard traverse lines are 4,140,959 and 2,812,800 respectively for A3 and A4 blocks and these data points were used in the final processing. High fly zones significantly affect the quality of the data. Approximately 16% of the data were measured at a survey altitude greater than 150 m (Table 9) and therefore may be of limited use. Raw, filtered and levelled in-phase and quadrature component data for each of the 4 frequency channels were delivered for each location. Apparent resistivities delivered by the contractor were determined using the Nomogram (look-up table) method, which uses the in-phase and quadrature responses to calculate apparent resistivity and an associate apparent height of the sensor over an assumed conductive, homogeneous half-space. When deriving the resistivity values minimum in-phase and quadrature values of 20-50 ppm are used to avoid erroneous results from data below the noise threshold. If the minimum limit is reached the value is capped at half the frequency, i.e., 456 Ohm-m for 912 HZ data. Data is also limited to 0.1 Ohm. Finally, levelling and micro-levelling of the apparent resistivities is carried out. Full details of the processing of the delivered FEM data for the A3 and A4 blocks can be found in SGL (2017a,b). The main statistics for contractor supplied FEM are summarised below in Table 13.

Table 13: Unfiltered in-phase, quadrature and apparent resistivity summary statistics for A3 and A4 blocks (traverse lines only)

Block		Mean ppm values		Apparent resistivities (ohm-m)		
	Freq Hz	In-phase	quadrature	Min	Max	Mean
A3	912	821.69	231.71	0.1	456.0	132.59
	3005	927.67	230.34	0.1	1503.0	294.16
	11962	1108.29	535.74	0.1	5981.0	714.89
	24510	1488.05	480.72	0.1	12255.0	329.97
A4	912	691.93	186.31	0.1	456.0	187.12
	3005	744.49	164.17	0.1	1503.0	680.77
	11962	908.76	370.80	0.1	5981.0	1843.74
	24510	1031.73	312.15	0.1	12255.0	3612.48

As can be seen from Table 13, the mean of resistivity for 25 KHz is lower than the others, which may be due to the effect of conductive sea water as many flight were flown over sea water. Date has not been clipped to coastal areas.

Figures 21 &22 below show the grids of apparent resistivity from the 3 kHz channel for block A3 and A4. Data is gridded using the minimum curvature method using a grid cell size of 50m.

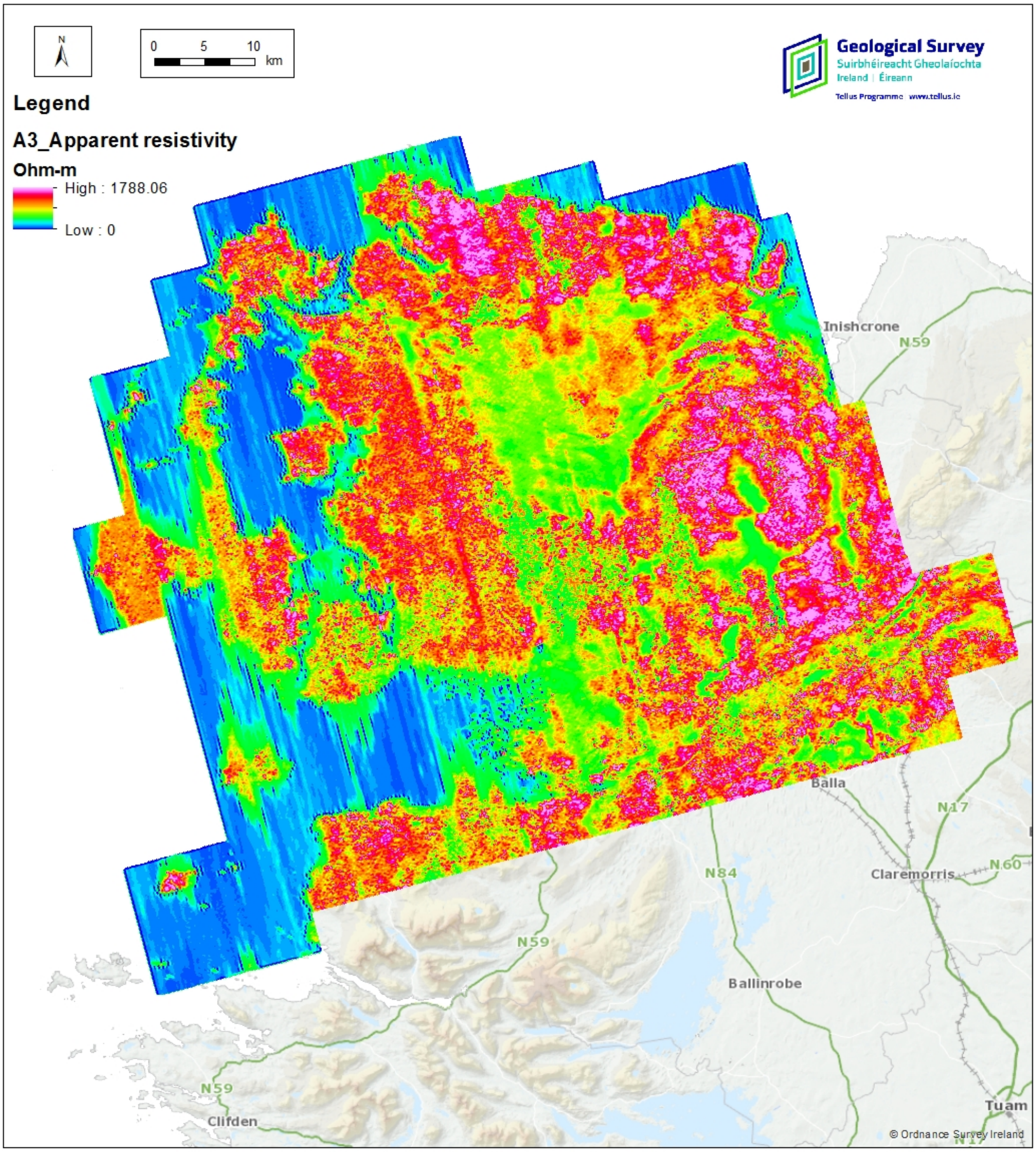

Figure 21: Apparent resistivity (contractor) derived from 3 KHz for block A3 in Ohm-m.

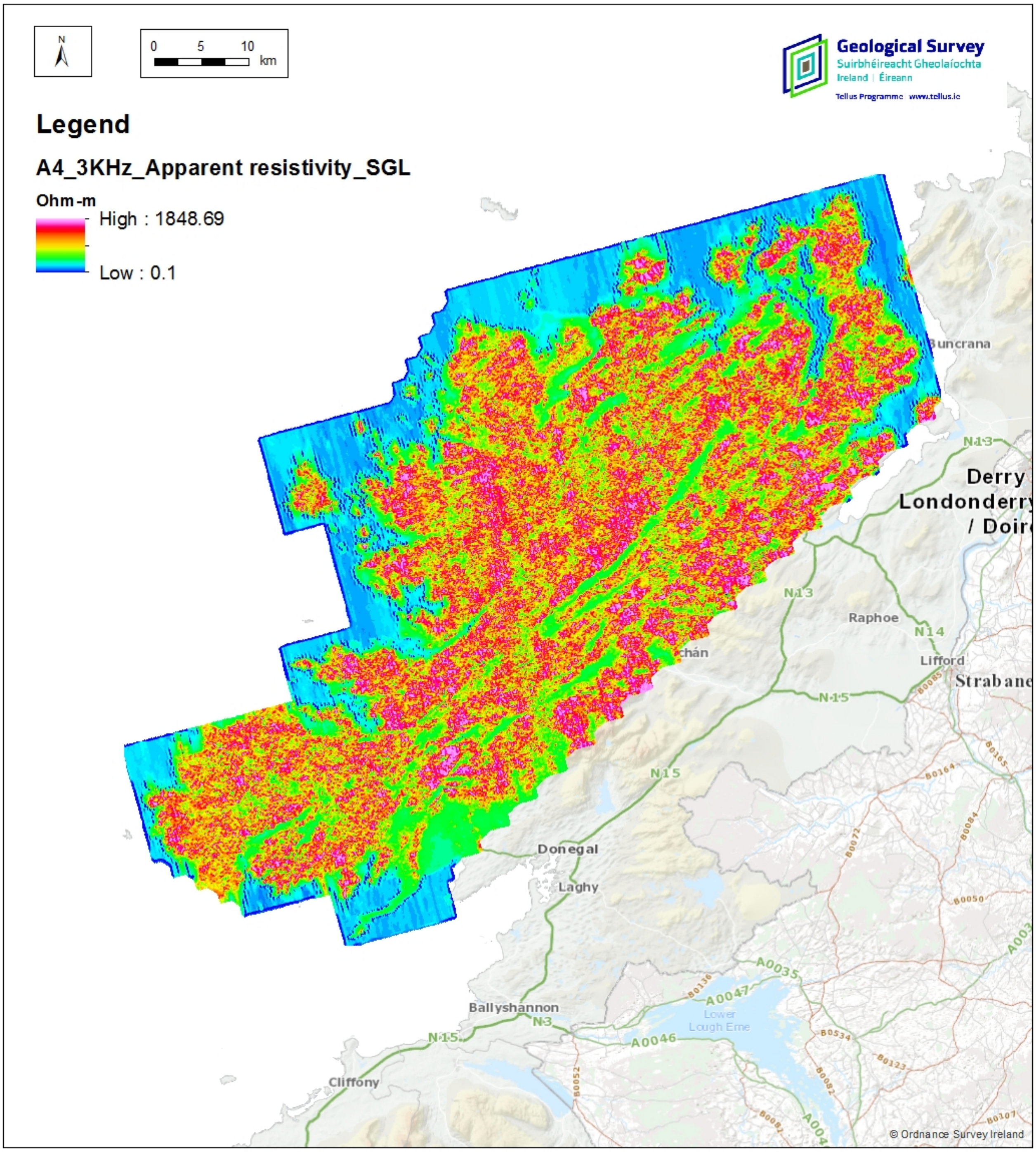

Figure 22: Apparent resistivity (contractor) derived from 3 KHz for block A4 in Ohm-m

7. Data Processing

7.1 Introduction

Standard processing was carried out on all three datasets (1: Magnetics, 2: Radiometrics and 3: EM) by the contractor and are discussed in detail by SGL (2017a, b). The same processing was adopted as was carried out for previous survey's, outlined in Beamish *et al*., 2006 and reviewed in Hodgson and Ture (2013), (2015). The contractors supplied data in ASCII.xyz and Geosoft grid format. However, along with the standard processing of the Frequency Domain EM (FEM) data carried out by the contractor (SGL 2017) additional processing was required to allow the data to be merged with previous EM data collected as part of the Tellus Programme, included Time-Domain EM (TEM) data.

One of the potential issues associated with the EM data is low signal-to-noise ratios of in-phase and quadrature measurements, which can result from high fly altitudes, cultural noise or strong magnetic susceptibilities effects. Owing to small temperature variations the zero level of the system can drift and therefore a drift correction is applied to all data. The applied drift correction to the in-phase and quadrature data results in negative values in areas of low signal-to-noise. Approximately 10% and 5% respectively of low frequency in-phase data collected as part of the A3 and A4 surveys were negative. The in-phase component is more significantly affected than its quadrature counter parts for low frequency. However, due to changes in the drift protocols used between the different surveys over the course of the different tellus survey 2011 to 2017, this affects the different surveys to varying degrees.

One of the peculiarities of EM data of blocks A3 and A4 in 2017 is the higher number of negative values in the quadrature component of the high frequencies, 12 and 25 KHz. The number of negative values in the quadrature components of block A3 reaches 14.4% and 20.8& for 12 and 25 KHz frequencies respectively. The amounts of negative values for block A4 are 8.4% and 16.7% for 12 and 25 KHz frequencies. The highest negative values in quadrature components of frequencies are seen associated with conductive see water. The in-phase component attains the highest values over conductive sea water whereas the quadrature component reaches its inductive limit, causing its value to drop. This is the reason why quadrature components have large number of negative values. The effect of power lines looks minimal on A3 and A4 data due to rural nature of the area and less population.

Along with variations in drift correction affects between survey blocks, variations in derived apparent resistivities along with differences between time domain and frequency domain derived values meant that additional processing of the EM data was required before all data could be merged into a single dataset.

7.2 EM data processing before merger

As discussed, slight variations exist between delivered EM data from the different survey phases. Reviewing the mean values of in-phase and quadrature values from the different survey blocks (Table 14) it can be seen that blocks A3 and A4 display lower mean quadrature values than that for other survey blocks due to a high percentage of the area flown over conductive sea water. The amplitudes are generally high indicating big negative values. These lower values affect the transformed resistivity values, which is indirectly proportional to the amplitudes of the signals. Values are taken from the delivered contractor data.

Table 14: Mean values and mean amplitudes of all FEM data

	MEAN (ppm)			MEAN (ppm)			RESISTIVITY (Mean –Ohm-m)	
BLOCK	P3	Q3	AMP3	P12	Q12	AMP	3KHz	12KHz
NI	978	831	1283	1947	1204	2289	246	512
TB	709	603	931	1332	989	1659	221	324
CAV	352	628	720	1014	1100	1496		
A1	245	378	450	620	709	942	368	755
A2	385	226	446	613	496	789	530	1577
TNM	NA	NA	NA	NA	NA	NA		
A3	386	227	1051	614	497	1488	826	607
A4	780	184	850	992	446	1273	759	600

To make all data compatible for merging and to apply consistent methodology it was decided to reprocess all original FEM data to produce new apparent resistivities for all survey blocks. This was done using the Helicopter Electromagnetic data processing and analysis (HEM) software extension in Geosoft. This allows the calculation of apparent resistivities based on in-phase and quadrature values by two methods, nomogram and inversion methods. The newly derived values could then be compared with the contractor supplied data, which used nomograms from their own in-house programme. The same filtering or levelling could then be applied to all data, rather than applying different filtering for different blocks.

Using the HEM extension of Geosoft new apparent resistivities were derived. The HEM software has two different schemes for calculating resistivity from real and imaginary components. These are:

- Nomogram (Grid look up) method
- Inversion method

The nomogram method calculates apparent resistivity, or apparent depth values, from HEM data using gridded look up nomograms. Both in-phase and quadrature components were used to calculate resistivity values. The gridded nomograms were produced using each frequency value.

The inversion method is used to invert resistivity values from airborne data using the uniform half space model. This is a single pass inversion to half-space model for airborne system, that does not rely on look up tables or nomogram files, but calculates forward models as required, sacrificing speed for flexibility and resolution (HEM V6.2 tutorial and user manual). The inversion works by finding the half space resistivity, which minimizes the error in least square sense between the input and calculated in-phase and quadrature values. Flight height, in-phase and quadrature components, frequency, coil separation and coil orientation are used as input for the inversion.

Resistivity values were produced using both methods from in-phase and quadrature components using a fractional error of 1%. These results were then compared with the resistivity values delivered by the contractors. It was also observed that when the error in the data is beyond the 1% range, or if both the in-phase and quadrature components are negative, the inversion does not return a value. This is in fact preferable to the nomogram method that always returns a value no matter how spurious the input values. Comparison of the different data sets shows that the resistivity values produced through the inversion method generally result in smoother and more consistent results and show good correlation with the mapped geology (Figures 23 & 24) for example.

As can be seen from comparison of Figure 23 (nomogram method by the contractor) and 24 (inversion method HEM), the inversion transformed resistivity shows clear geologic boundaries and structures compared to nomogram derived resistivity map, although strong edge effects are seen particularly at coastal margins and a greater degree of signal smoothing occurs.

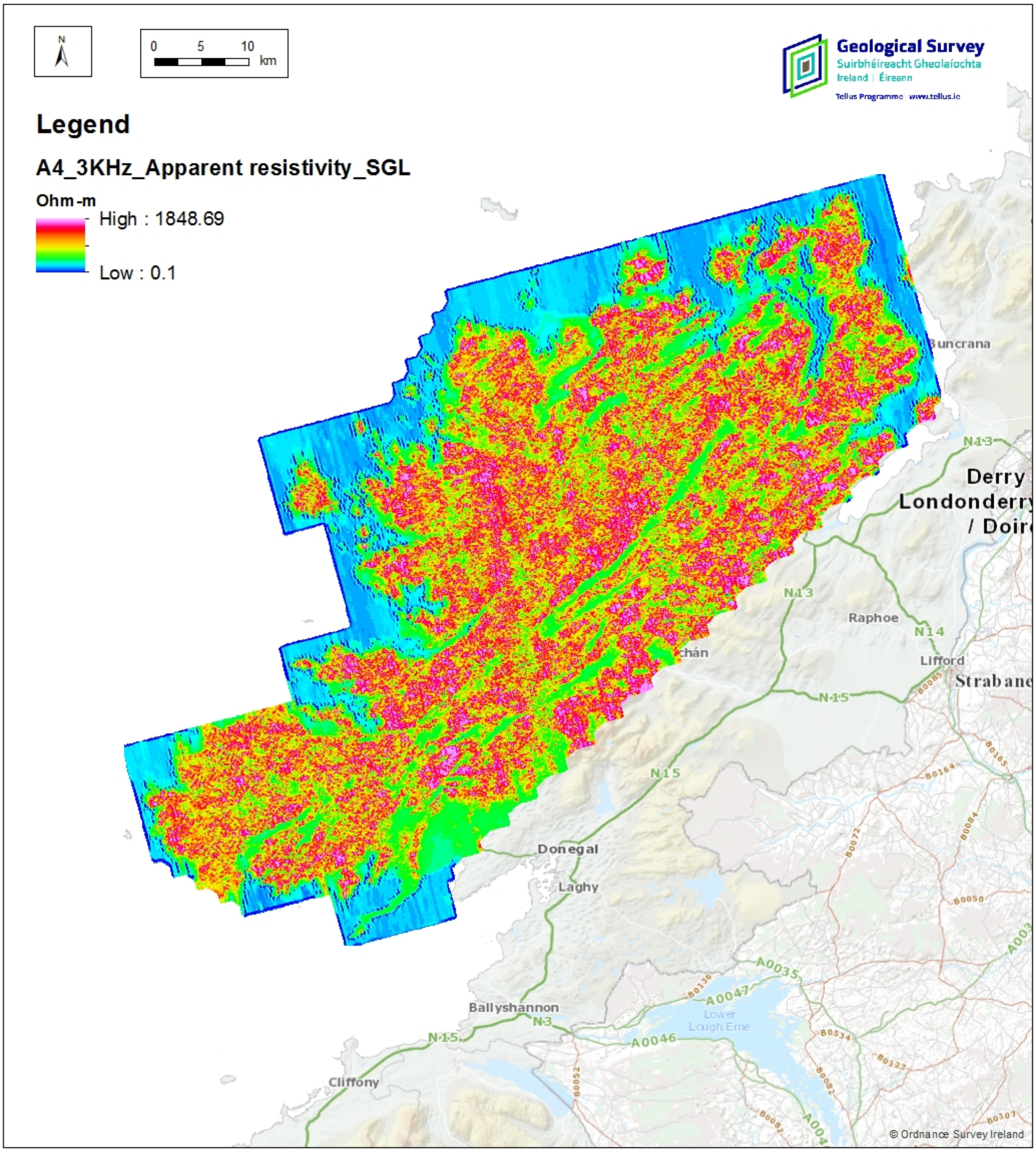

Figure 23: Apparent resistivity in Ohm-m of 3 KHz delivered by contractor

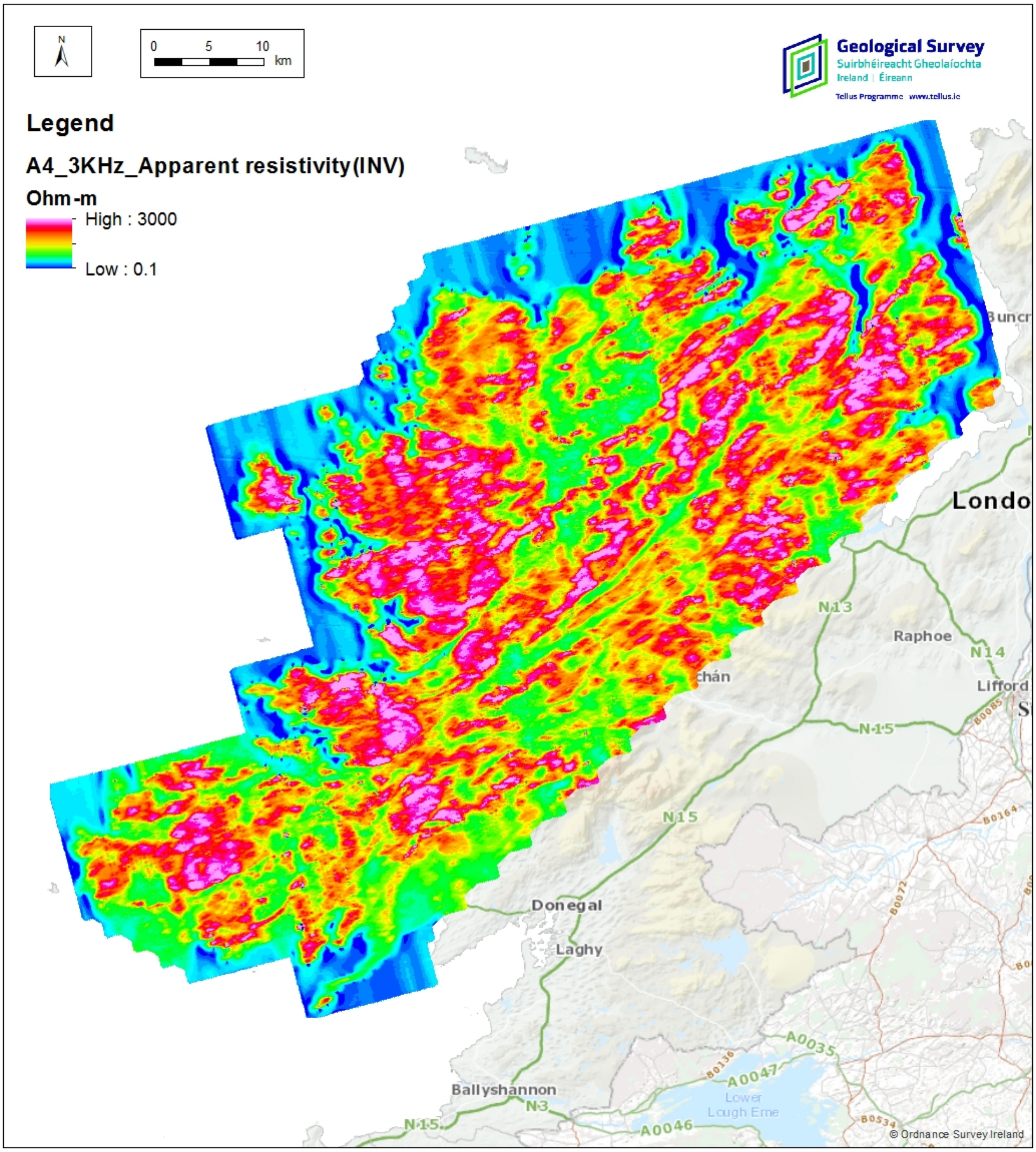

Figure 24: Apparent resistivity in Ohm-m of 3 KHz derived from HEM inversion method

7.3 Noise reduction of FEM data

Negative and very small positive amplitudes of both in-phase and quadrature values have been shown to produce erratic or no resistivity values. All data were clipped to 20ppm to reduce noise levels for both in-phase and quadrature components. The statistical distribution of the data shows that more than 95% of the data are within the range of 0 to 3000 ohm–m for both the 3KHz and

12KHz derived apparent resistivities. The negative values are generally related to very low resistivity over seawater or areas of high survey altitude. The data were then clipped to 0-3000 Ohm-m apparent resistivity range to remove any spurious values. Detailed investigations of the control test line flown at different survey altitudes during each survey phase has shown that data above an altitude of >150m is less reliable.

8. Data Merging Overview

8.1 Master Database

A master database was created from the previously merged data sets and from newly acquired A3 and A4 blocks. The previous merged data includes: Northern Ireland (NI), Tellus Border (TB) Cavan (CAV), Tellus North Midlands (TNM), A1 and A2 blocks. This previous merged data set is referred to as *merge2016* in this report. The newly acquired A3 and A4 blocks are situated to the south west and north east of *merge2016* (Figure 25).

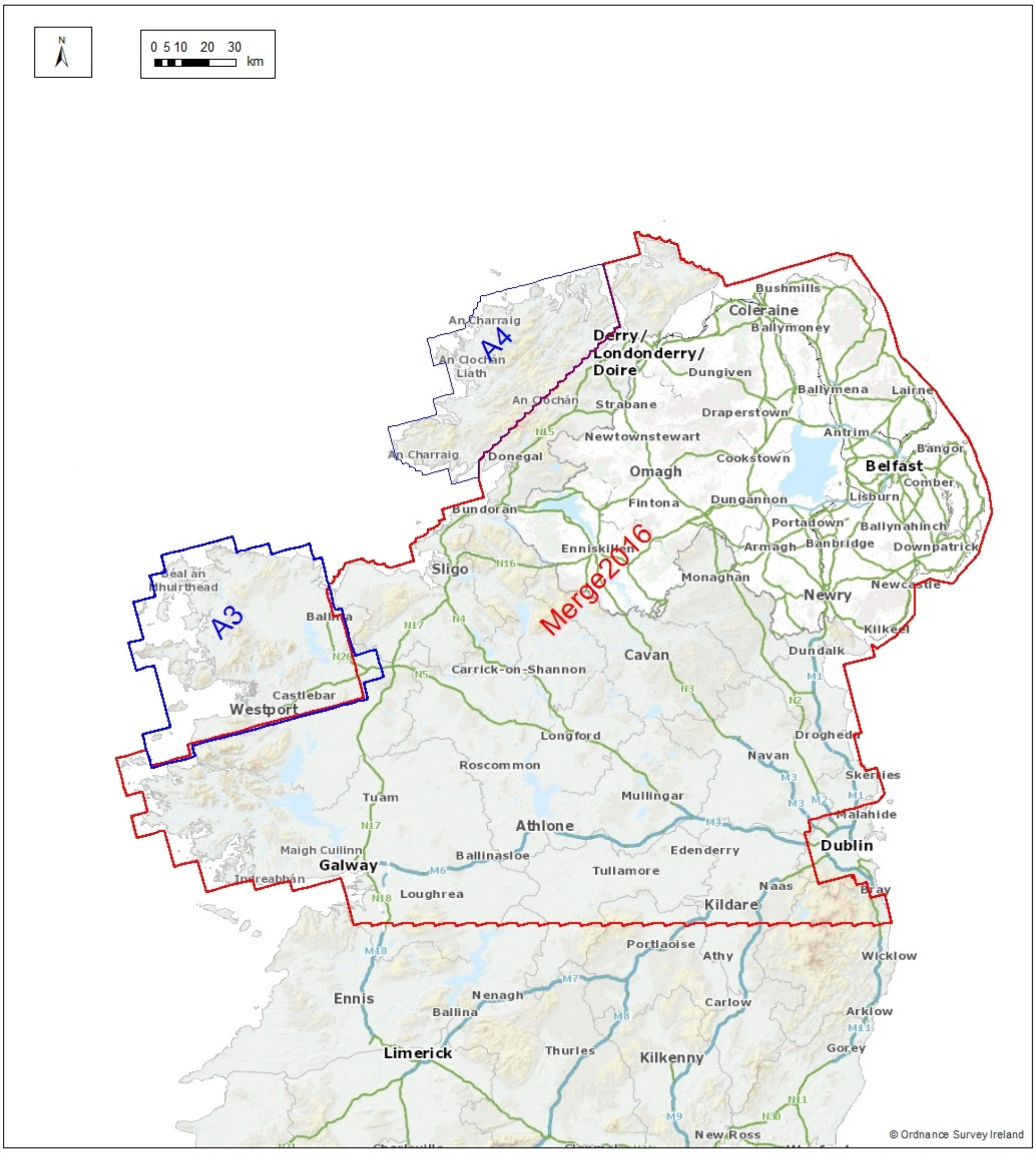

Figure 25: Data merge 2017. The red polygon is merge2016 and the blue polygons are the latest survey blocks (A3 and A4)

Due to the size of the merged data file a number of channels were clipped from the final master database and leaving only the most relevant channels for each database (1) magnetics, (2) radiometrics and (3) electromagnetics to conform to previous delivered datasets. A uniform name was applied to each of the relevant channels for each database.

A Survey ID (SID) channel has been produced to avoid any confusion in identifying the source of the data within the master database, where:

- **A4 indicates Tellus A4 data**
- **A3 indicates Tellus A3 data**
- **A2 indicates Tellus A2 data**
- **A1 indicates Tellus A1 data**
- **TB indicates Tellus Border data**
- **CAV indicates Cavan data**
- **TNM indicates Tellus North Midlands data**
- **NI indicates Tellus Northern Ireland data**

The A3 and A4 databases were merged with the *merge2016* to produce a single master database referred to as *merge2017* using the merge database tools in Geosoft. Data was corrected following assessment of gridded data from the overlap zones. Grids of the corrected data were then created and then sampled back to the new master database for each relevant channel.

8.2 Co-ordinates

Since 2014 it has been the policy of the Geological Survey Ireland (GSI) to use the Irish Transverse Mercator (ITM) co-ordinate system for all mapping. The previous surveys of Northern Ireland (NI), Tellus Border (TB) and Cavan Monaghan (CAV) were delivered using Irish National Grid co-ordinate system. Therefore, all previous datasets were changed into ITM co-ordinates to match with data from A4, A3, A2, A1 and Tellus North Midlands (TNM) and fit with the policy of the GSI.

Table 15: Summary of ITM co-ordinate system

IRISH TRANSVERSE MERCATOR	
Reference Ellipsoid:	GRS80
Central Meridian	08° 00’ 00” West
Vertical Datum:	Malin Head
Map Projection:	Transverse Mercator (Gauss Conformal)
True origin:	53° 30’ 00” North, 08° 00’ 00” West
False origin:	600km west, 750km south of true origin
Scale factor on Central Meridian:	0.999820

8.3 Magnetic Data Merging

Magnetic data from *merge2016* (NI, TB, CAV, TNM, A1 and A2) have been merged with A3 and A4 blocks to form a single dataset for the entire area surveyed to date as part of the Tellus Programme. The detail of *merge2016* is found in Hodgson and Ture 2017. As the airborne surveys continued over the years, each new survey was designed to include an area of overlap with previous survey blocks, therefore assisting in the merger of any new data. Datasets were compared in the regions of overlap, allowing direct comparison. A correction factor (difference) was then applied to the older dataset to bring it into line with the data which was most recently collected.

The final levelled residual magnetic data were used to achieve merge2017. This data had been corrected for compensation, diurnal variation and IGRF effects and is fully levelled. A grid of the magnetic anomaly was then created for merge2016, A3 and A4 blocks and the mean difference between the overlapping regions from the three grids was then calculated. This difference was then added to the older dataset (*merge2016*). Blocks A3 and A4 were surveyed at the same time but did not overlap themselves, therefore, A4 block was initially merged with merge2016 grid and then the grid of A3 was then merged with the resultant grid (merge2016+A4) to produce merge2017. A summary of the different survey blocks and the corrections applied is shown in Table 16.

The corrected data was then knitted together using the grid knitting program from Geosoft, using the suture stitching method and an output grid cell size of 50m. The de-trending method for both grids was set to none. The final fully merged grid was then re-sampled into the Master database using the sample-a-grid function in Geosoft. Figure 25 below shows the gridded result of the merged magnetic database.

Table 16: Summary of correction factors in nanoTesla applied to merge2016, A3 and A4.

A4 Overlap mean	Merge 2016 overlap@A4	Correction factor to Merge2016	Merge2016+A4 @A3 overlap	A3 overlap	Correction factor applied to merge2016+A4
14.04	-55.83nT	+69.87nT	47.44nT	39.00nT	-8.44nT

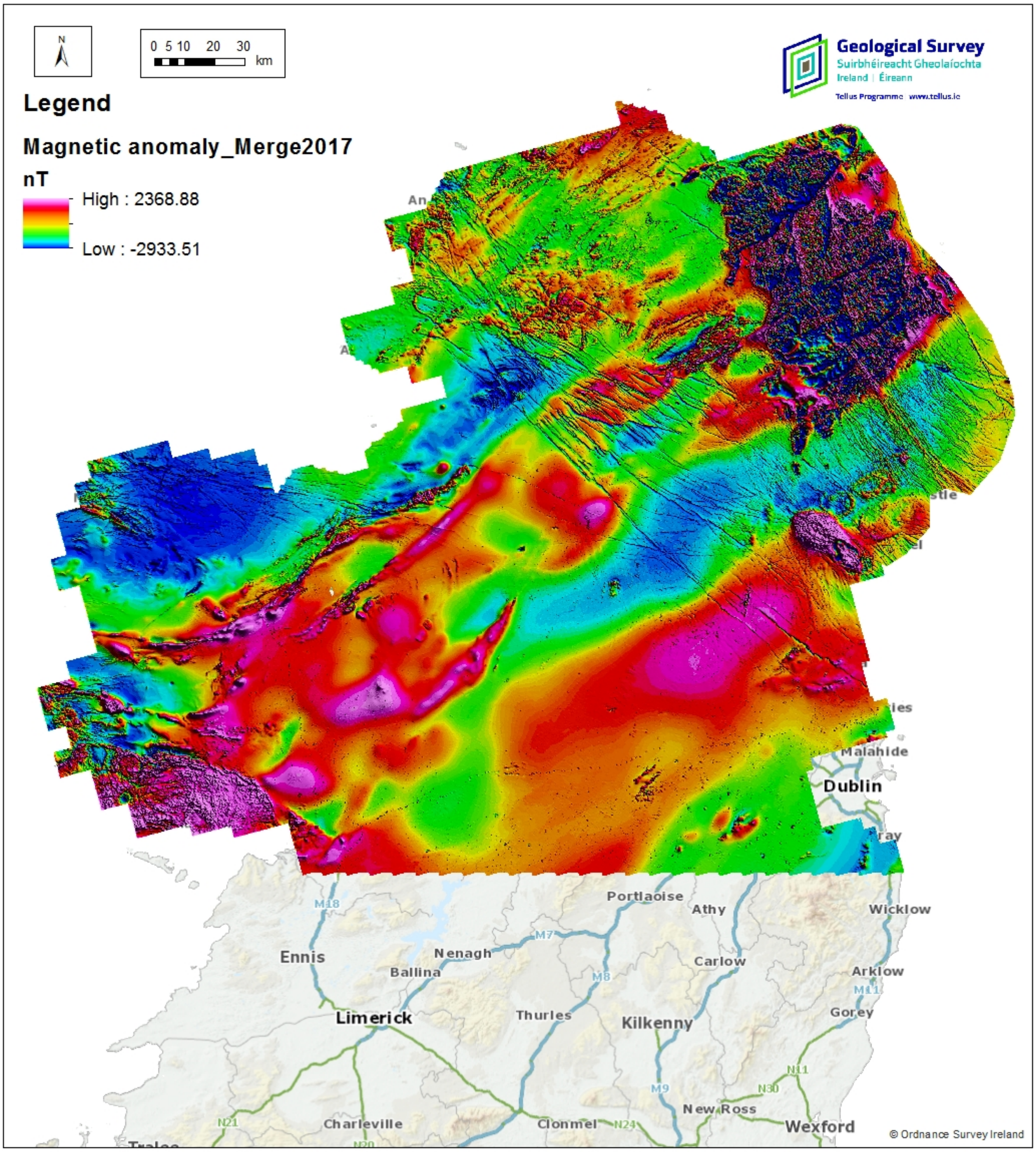

Figure 26: Merged residual magnetic anomaly (merge2017) from merge2016, A4 and A3 blocks data, illuminated from an angle of 45 degrees

8.4 Radiometric Data Merging

Radiometric data from *merge2016* (NI, TB, CAV, TNM, A1 and A2) have been merged with A3 and A4 blocks to form a single radiometric dataset (merge2017) for the entire area surveyed to date.. Datasets were compared in the regions of overlap and a correction factor for each dataset was established as outlined in the above section. These correction factors were then applied to the older datasets to bring it into line with the most recently collected data. Details of merge2016 are given in Hodgson and Ture (2017).

Standard processing and corrections to radiometric data were applied by the contractor as stated in IAEA (2003) and Grasty and Minty (1995). A1, A2, A3, A4 and Waterford data were collected using RS-501 spectrometer while the remaining data were collected by GR-820 Spectrometer.

Table 17: Standard Gamma Ray Energy windows for radiometric survey (IAEA2003)

Window name	**Energy Window**	**Major peak (KeV)**	**Radio nuclide**
Potassium (K)	1370 keV to 1570 keV	1460	K-40
Thorium (Th)	2410 keV to 2810 keV	2614	Tl-208
Uranium (U)	1660 keV to 1860 keV	1765	Bi-214
Total Counts	400 keV to 2810 keV		

Table 18: Energy ranges (channels) used by different Tellus surveys (From 2005-to-date) and ROI stands for Region of Interest.

SURVEY	ROI	LOW CHA.	HIGH CHA.	LOW ENERGY KeV	HIGH ENERGY KeV
NI	TC	34	240	396	2808
	POTASSIUM	117	134	1368	1572
	URANIUM	141	159	1656	1860
	THORIUM	206	240	2410	2808
CAV	TC	35	240	410	2810
	POTASSIUM	117	134	1370	1570
	URANIUM	142	159	1660	1860
	THORIUM	206	240	2410	2810
TB	TC	34	240	396	2808
	POTASSIUM	117	134	1368	1572
	URANIUM	134	159	1565	1860
	THORIUM	206	240	2410	2808
TNM	TC	34	240	396	2808
	POTASSIUM	117	134	1368	1572
	URANIUM	141	159	1656	1860
	THORIUM	206	240	2412	2808
A1	TC	136	936	408	2808
	POTASSIUM	460	524	1380	1572
	URANIUM	556	620	1668	1860
	THORIUM	804	936	2412	2808
WFD	TC	136	936	408	2808
	POTASSIUM	460	524	1380	1572
	URANIUM	556	620	1668	1860
	THORIUM	804	936	2412	2808

A2	TC	136	936	408	2808
	POTASSIUM	460	524	1380	1572
	URANIUM	556	620	1668	1860
	THORIUM	804	936	2412	2808
A3	TC	136	936	408	2808
	POTASSIUM	460	524	1380	1572
	URANIUM	556	620	1668	1860
	THORIUM	804	936	2412	2808
A4	TC	136	936	408	2808
	POTASSIUM	460	524	1380	1572
	URANIUM	556	620	1668	1860
	THORIUM	804	936	2412	2808

Details of all processing procedures and calibrations for the A3 and A4 data can be found in the technical report produced by the contractor (SGL, 2017a and SGL, 2017b) and are consistent with standard processing procedures as outlined by IAEA (2003) and Grasty and Minty (1995).

It was decided that all radio elements should be corrected to correspond with values measured for the most recent survey, i.e. A3 and A4. After comparing statistics on data in the overlap zones correction factors were determined on calculated means of gridded data. Correction factors were used rather than a simple shift (addition/subtraction) as this better reflects the radiometric data. Applying a simple subtraction, as applied to the magnetic data, could potentially result in negative concentrations in areas of low values, which would be meaningless. The following correction factors were applied to the merged2016 data (Table 19).

Table 19: Radiometric correction factors for A3, A4 and Merge2016

	A4 Overlap mean	**Merge 2016 overlap@A4**	**Correction factor to Merge2016**	**Merge2016+A4 @A3 overlap**	**A3 overlap**	**Correction factor applied to merge2016+A4**
Potassium (%k)	0.7045	0.7389	0.9534	0.6599	0.7506	1.1374
eThorium (ppm)	3.3790	3.7316	0.9055	2.049	2.0939	1.0219
eUranium (ppm)	0.5910	0.5653	1.045	0.6371	0.7163	1.124
Total Count	1513.01	1482.56	1.02	1385.21	1384.11	0.9992

Correction factors for total count, potassium, thorium and uranium are deemed acceptable, being close to one. Following the application of the correction factors, a new grid was created for each element using the new corrected values. These grids were then merged together using the suture stitching method of the grid knitting program from Geosoft. A cell size of 50m was used with the de-trending method for both grids set to 'none'. This merged grid was then resampled to the master database.

A final merged grid was created from the master database for each element using the inverse distance weighted method and a cell size of 50m. This gridding method was employed rather than the minimum curvature method (used for other datasets) as it helps to represent the large footprint from which the radiometric data is determined rather than from a single point. Figures 27-31 below shows resultant grids for merged, total counts, potassium, equivalent thorium, equivalent uranium and radiometric ternary image maps. The comparison of means of %K, eTH and eU for each block is given in Figure 27. It is seen that CAV data shows high means of three elements which may be due to no fly over water body which attenuates the signal. Means of eU are high in A1, A2 and TB data sets.

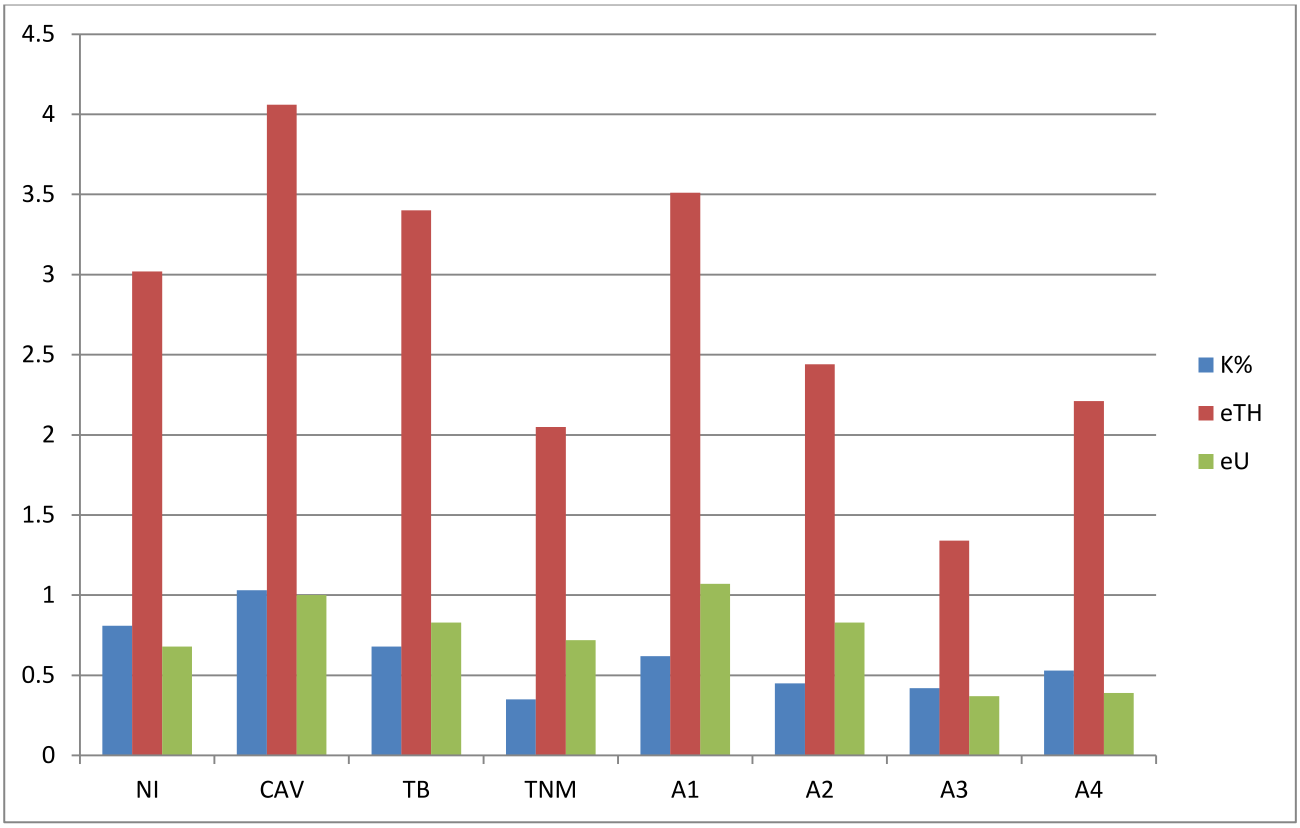

Figure 27: Means of K (%), eTh (ppm) and eU (ppm) for all blocks

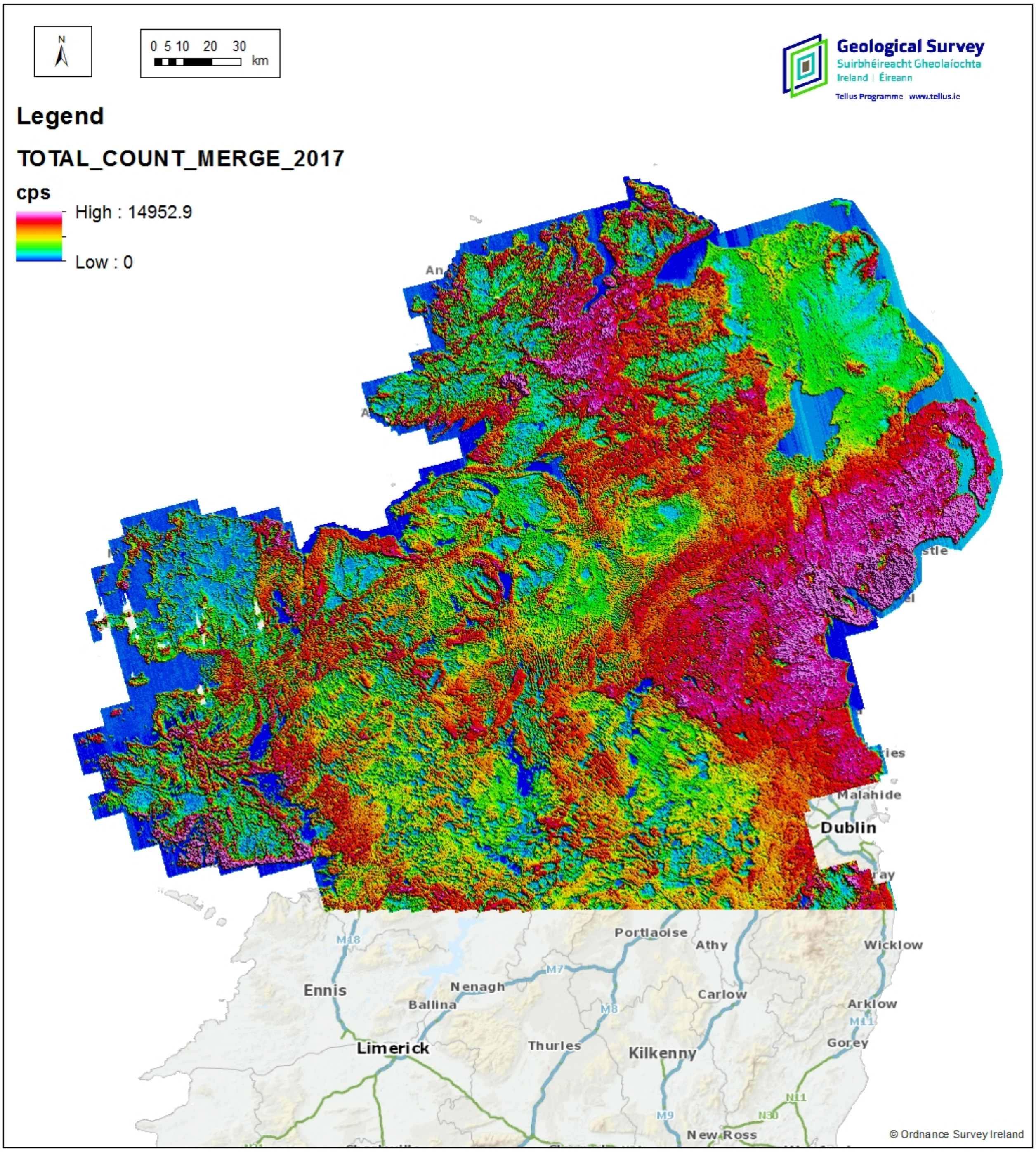

Figure 28: Merged total count radiometric data (cps) from merge2016, A4 and A3 blocks data, this merge is referred to as Merge2017.

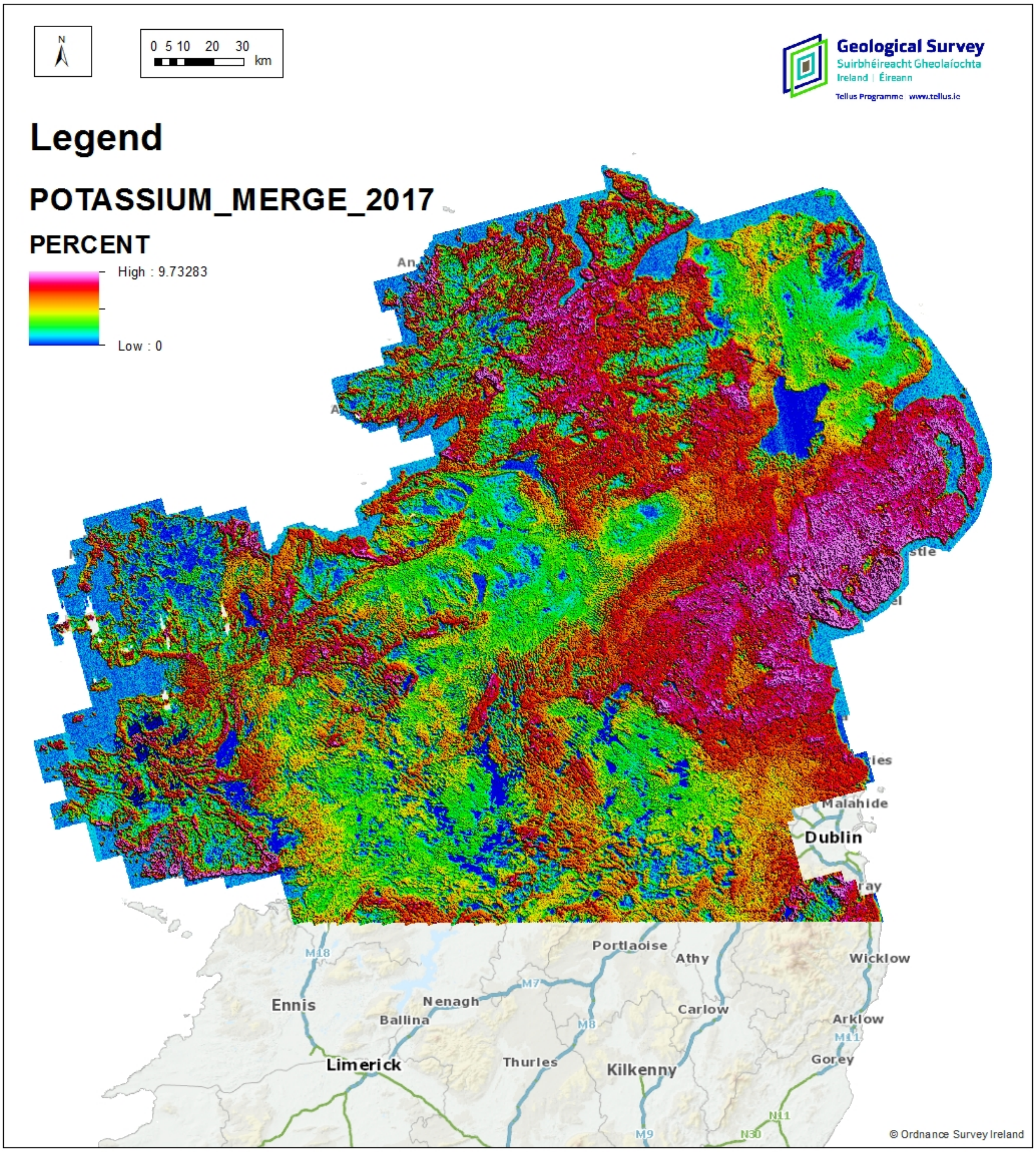

Figure 29: Merged potassium data (%) from merge2016, A4 and A3 blocks data, this merge is referred to as Merge2017

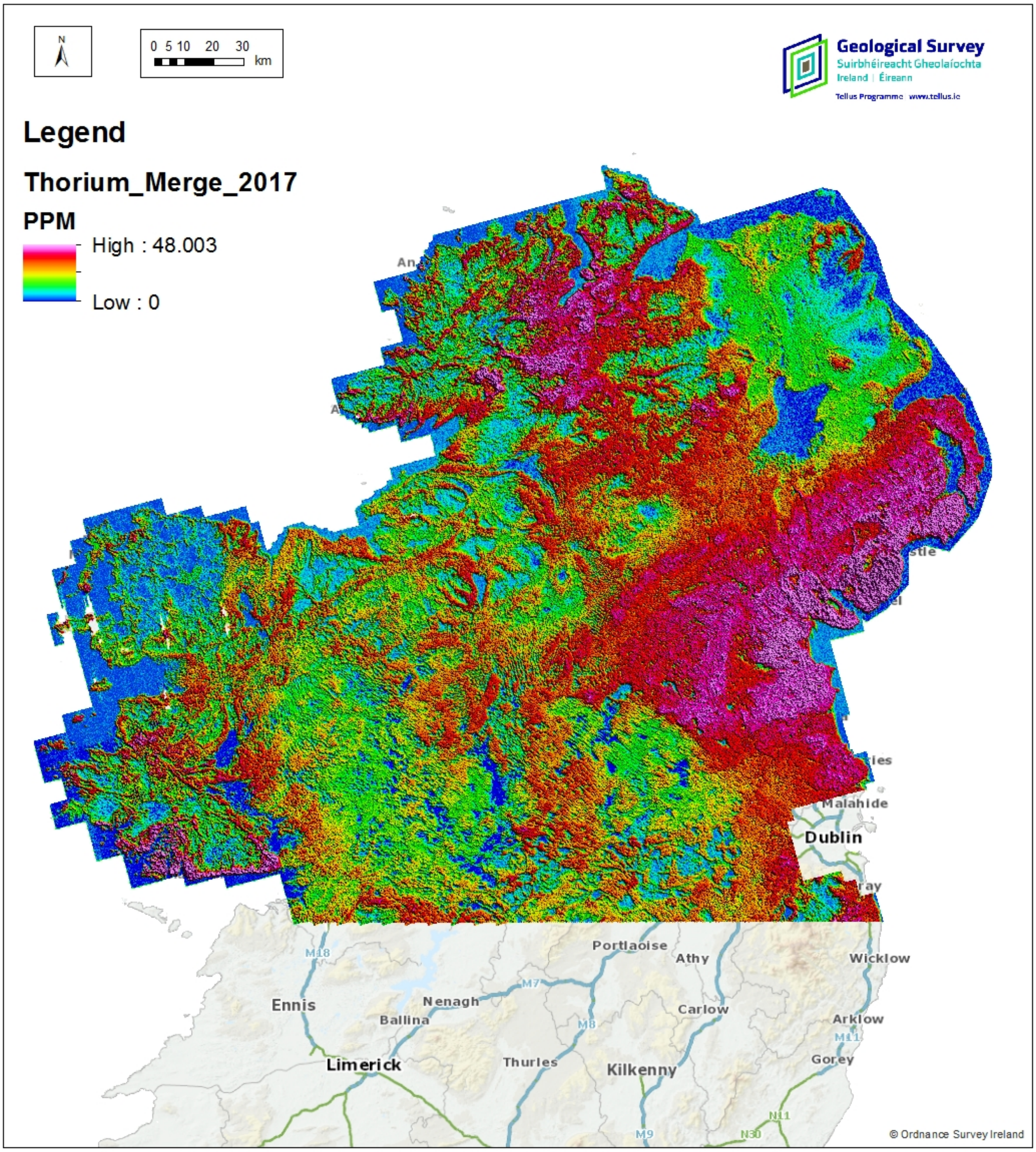

Figure 30: Merged equivalent thorium equivalent (eTh in ppm) from merge2016, A4 and A3 blocks data, this merge is referred to as Merge2017.

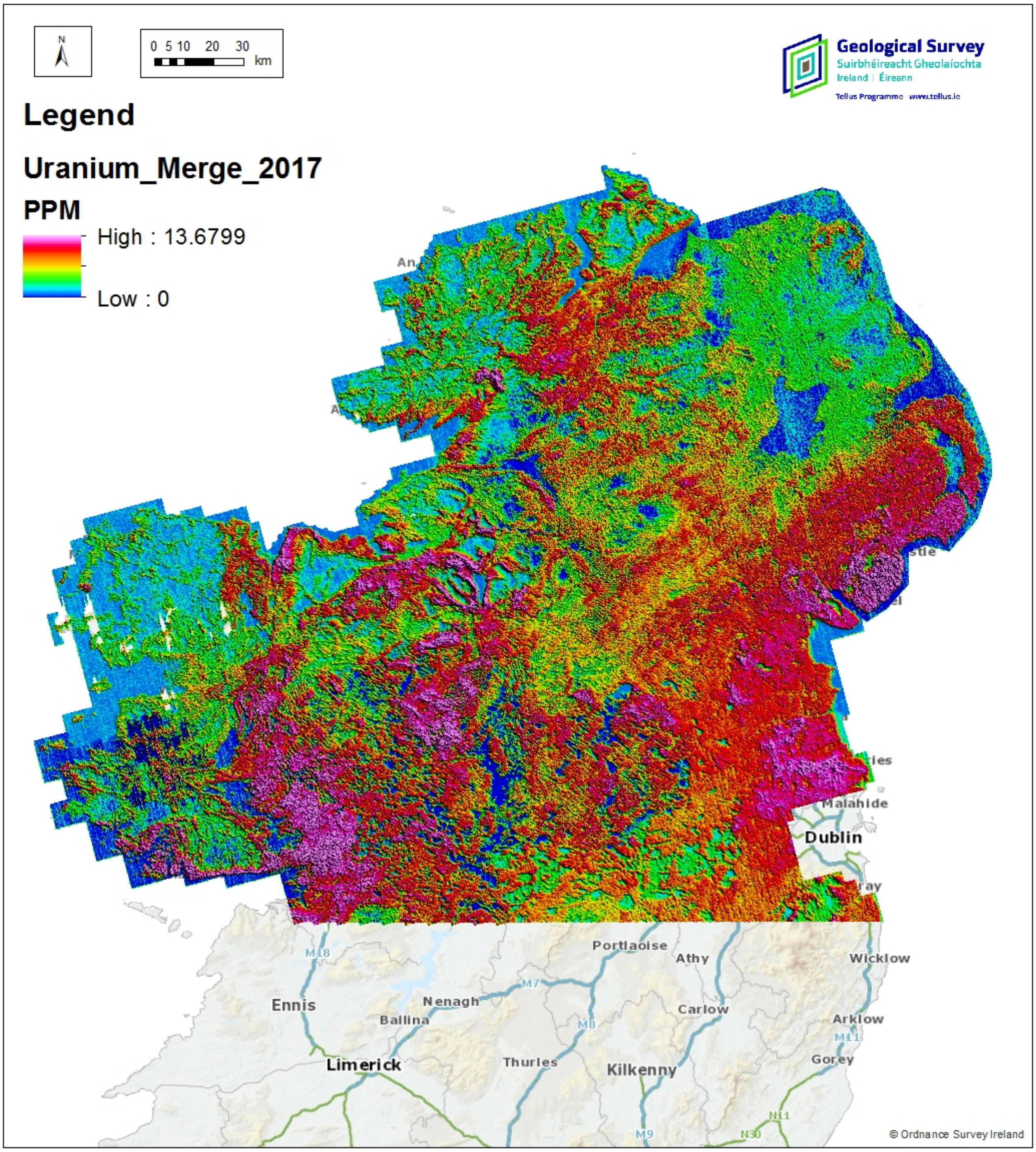

Figure 31: Merged equivalent uranium data (eU) from merge2016, A4 and A3 blocks data, this merge is referred to as Merge2017.

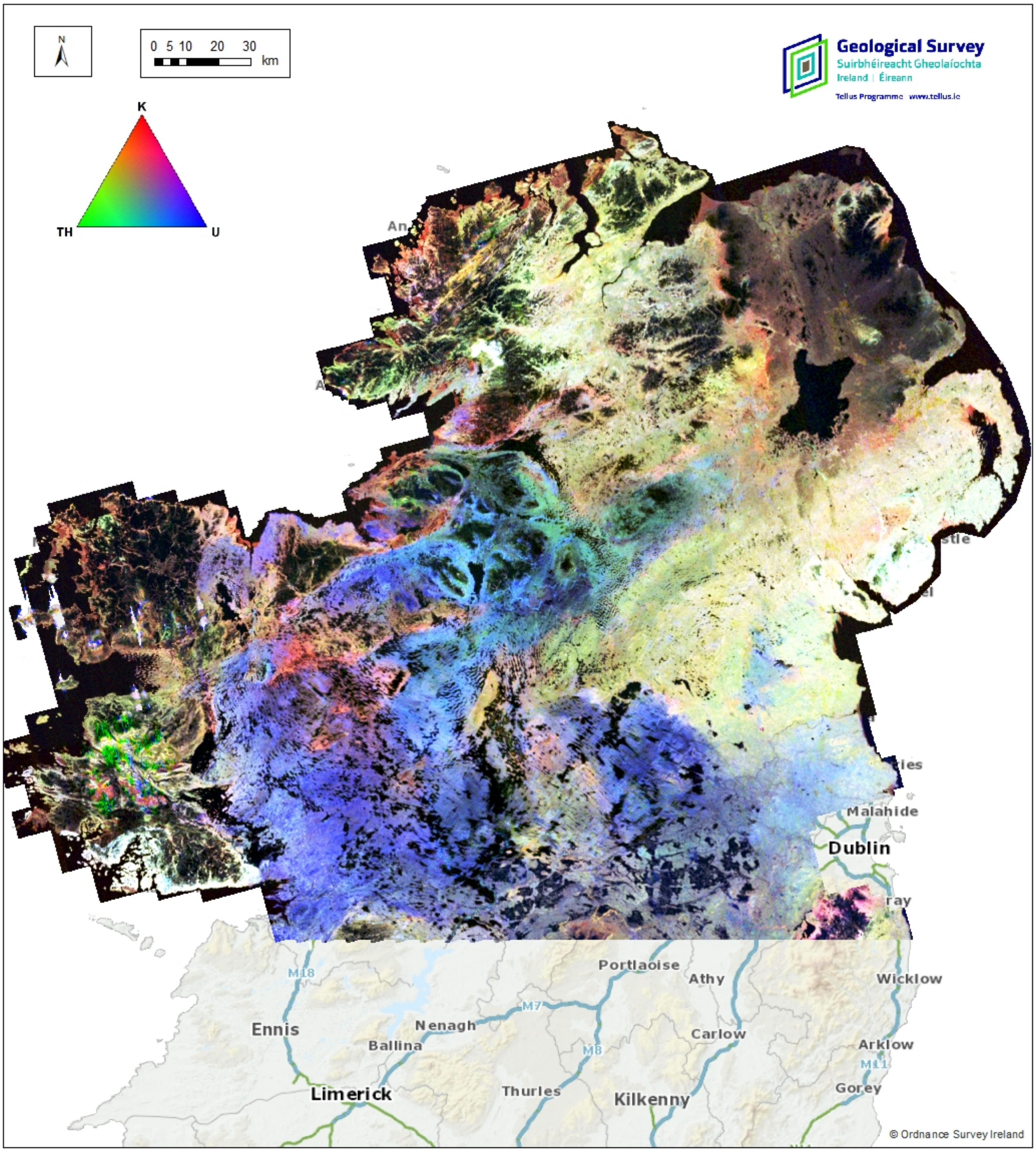

Figure 32: Merged radiometric ternary map from merge2016, A4 and A3 blocks data, this merge is referred to as Merge2017. Potassium - red, Uranium - blue and Thorium - green

8.5 Electromagnetic data merging

Overview of merge2016:

Merge2016 includes data from NI, CAV, TB, TNM, A1 and A2 blocks. One of the main complications in merging the electromagnetic data (*merge2016*) from the various different Tellus survey blocks is that both Time (TEM) and Frequency domain (FEM) data has been collected. Previously data has been merged for certain phases based on derived conductivities at specified depths for both FEM & TEM datasets. This requires inversion of all FEM data producing apparent conductivities at certain depths, which can then be merged with conductivity depth transforms of the Time domain data at the same specified depths. However, merging all data from all the phases included those from Northern Ireland (2005-2006) is an extremely time-consuming task. In addition, the inversion of the data results in significant smoothing of the data and a loss of resolution in parts. Therefore, a different approach using equivalent frequencies was used to obtain *merge2016*. This equivalent frequency approach is based on the delay and diffusion times of the FEM and TEM data. Frequencies were determined for corresponding time gates from the TEM data, which were equivalent to the 3KHz and 12KHz channels used for merging. Only these two frequencies (3kHz and 12Khz) were used because during the first Tellus survey in the western half of Northern Ireland only 2 frequencies were recorded.

These two frequencies correspond to time gate 1 and time gate 2 from the TNM dataset, which used the CGG GENESIS system (CGG 2015). Taking the derived apparent resistivity from the corresponding frequency, or time gate channel, the data was merged for each frequency (12KHz and 3KHz). The details of merging processes were given in Hodgson and Ture (2017).

Merge2017 (NI,TB,CAV,TNM,A1, A2, A3 and A4): EM data from merge2016 (NI,TB,CAV,TNM,A1 and A2) have been merged with A3 and A4 blocks to form a single EM dataset for the entire area surveyed to date as part of the Tellus Programme. The recently acquired datasets A3 and A4 blocks were designed to include an area of overlap with previous survey blocks so as to help the merger of new data. These new data blocks were compared in the regions of overlap with merge2016 and correction factors established. These correction factors were then applied to the older dataset. Details of merge2016 are given in Hodgson and Ture (2017). The merged data, merge2016, is in conductivity unit (mS/m) while the recently acquired A3 and A4 are delivered in resistivity unit and in ppm values.

The delivered resistivity values for A3 and A4 blocks were transformed using nomogram method by the contractor, while merge2016 were processed using HEM inversion method (except TNM) It was agreed that FEM data should be transformed to resistivities of all survey blocks using the same procedure. Hence, resistivities of blocks A3 and A4 were transformed using HEM inversion method (section 7.2 & Figures 24 & 25). The inversion transformed resistivity values were gridded and checked for leveling errors and noise. Combined Butterworth and directional cosine filters were applied to the grids so as to remove noise that related to survey direction and unwanted short wavelength noises. The filtered grid of A3 and A4 blocks were compared with merge2016 at overlap areas and correction factors were established.

The Butterworth filter is good for applying straightforward high-pass and low-pass filters. Since the cutoff rolls off over a range of wavenumbers, the outcome does not suffer from the Gibb's oscillation phenomena (Geosoft Technical notes www.geosoft.com) The degree of filter roll-off, centred on the cutoff wavenumber, controls the smoothness of the results along the inflection regions of the strong anomalies. If in these regions oscillation is observed the user reduces the degree of the filter by one unit and apply the filter again until satisfactory result is attained.

The directional cosine filter removes directional noise from a grid. The use of a cosine function instead of a straight pass/reject filter overcomes the ringing artefact associated with the discrete Fourier transform. The rejection (or pass) notch can be narrowed or widened by setting the degree of the cosine function so that highly directional features can be isolated. De-corrugation of poorly levelled data is a common application for this filter.

A summary of the different correction factors applied to the merge2016, A3 and A4 blocks are summarised in Table 20 below.

Table 20: Correction factors for block A3 and A4 EM data Table 21 based on overlap zones

	A3 Overlap mean	**Merge 2016 overlap@A3**	**Correction factor to Merge2016**	**Merge2016+A3@A4 overlap**	**A4 overlap**	**Correction factor applied to merge2016+A3**
3KHz	5.18	22.23	0.235	14.90	2.46	0.165
12KHz	5.74	18.43	0.31	13.09	3.22	0.24

8.5.1 Levelling of EM data using interactive spectral filter

A filtering procedure was applied to remove levelling affects from the merged EM data. Filters were applied to the gridded datasets to help reduce or remove non-geological effects caused by short-wavelength noise along survey lines (Geosoft Technical notes www.geosoft.com). This procedure was performed in Oasis Montaj MAGMAP 2D module using a Fast Fourier Transform (FFT). Combined Butterworth and Directional cosine filters were used. Filter parameters were modified interactively to obtain the best results for the data. Grid preparation consisted of the following steps:

1. Grid trend removal. The trend which is removed is stored in the user area of the grid header and is filtered together with the zero wave number. First order trend removal based on edge points was applied.
2. Expanding the dimensions of a grid by adding dummy areas to the grid edges to produce either a *square* (used for this process) or a rectangular grid. The system uses the Winograd FFT algorithm for dimensions up to 2520 X 2520 cells. Beyond this dimension it switches to a power of 2 FFT methods. 10% grid expansion was applied.
3. Replacing all dummies in a grid with interpolated values from the valid parts of the grid. The FFT routines require a completely filled grid resulting in some interpolation of data at the grid edges.

A grid expansion of approximately half the size of the features of interest within the gridded dataset was used. A multistep-expansion method was then used to fill the grid. The multistep expansion method extends the data inside a bounding rectangle within the same range of signal wavelength and amplitude as the real data. After the grid was prepared in the frequency domain, combined Butterworth and Directional cosine filters were applied.

Butterwort filter :applied with cut of wavelength 1600 (8 times line spacing) and filter order of 4 with high pass so as to create error grid to isolate short wavelength noise to be removed from the data.

Directional cosine filter: applied with cut of azimuth of 165 degrees and with degree of cosine function of 2, with pass direction to remove noise related to survey orientation from the data. This filter produces a levelling error grid which can then be removed from the data. This allows high frequency noise along the survey lines to be filtered without minimising the geological signal. An example of the error grid removed from the data is given in Figure 33 (grid comparisons before (Fig33) and after (Fig35) the noise is removed.

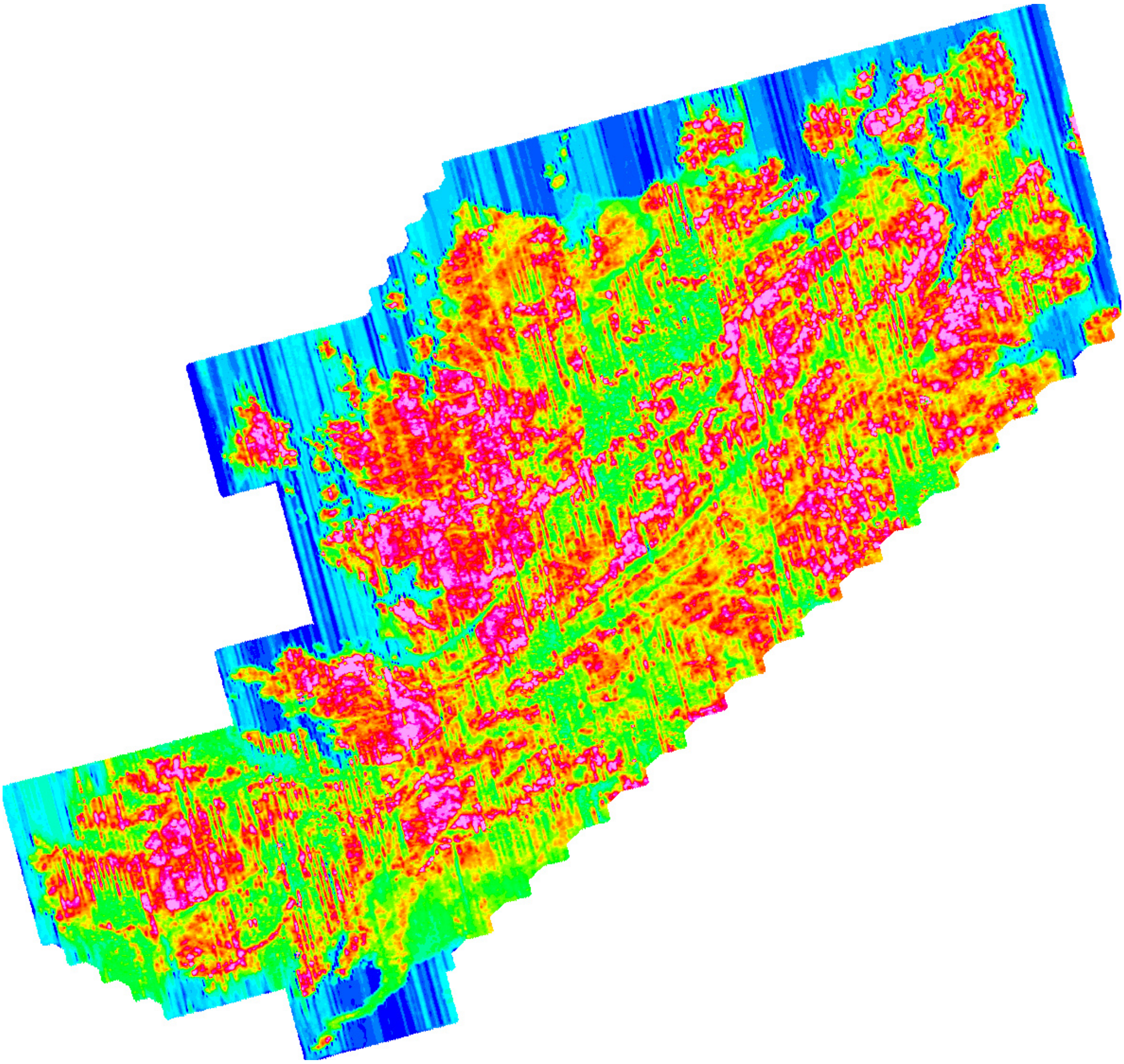

Figure 33: A raw resistivity grid obtained from HEM inversion method for A4 3KHz data. Noise related to survey direction is obvious in the grid.

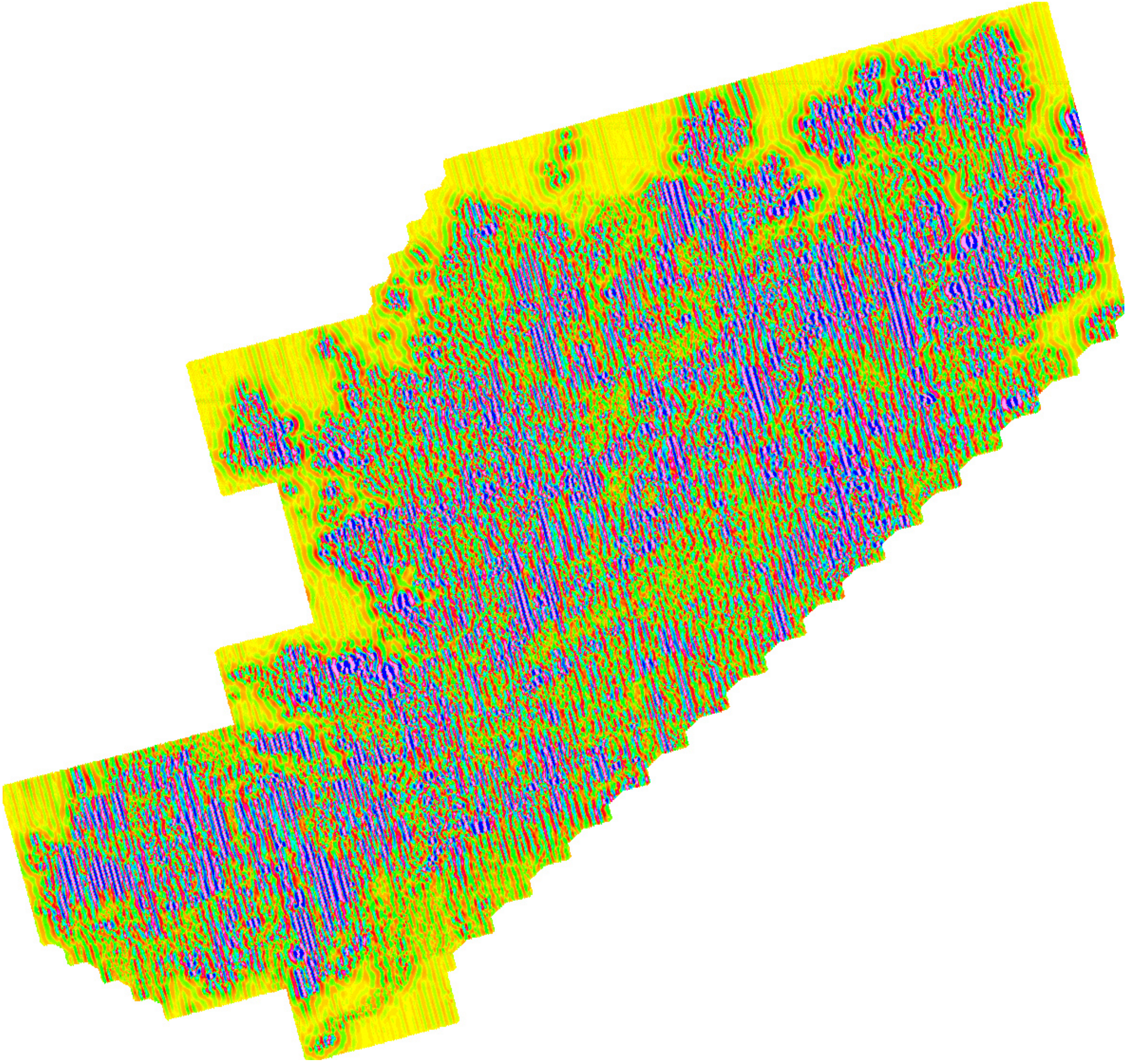

Figure 34: An error grid obtained by combined Butterworth and Directional cosine filters. This error grid was sampled in to the database and subtracted from the raw data (Fig 33 to obtain the levelled resistivity grid given in Figure 35).

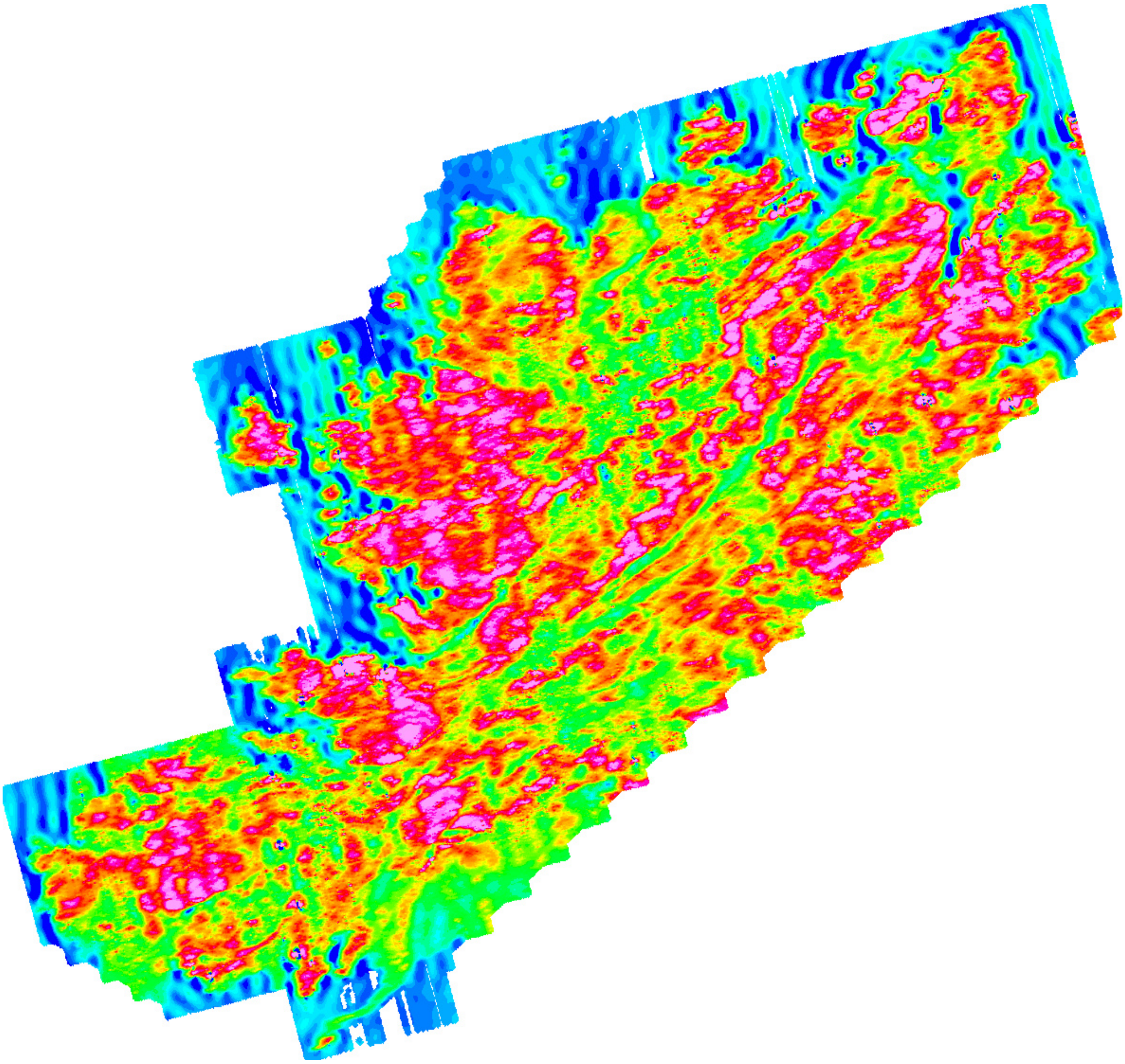

Figure 35: Levelled resistivity grid obtained by subtracting error grid (Figure 33) from original grid (Figure 32).

8.5.2 Final merged EM grids

The grid of apparent resistivity for the newly created merged2017 (NI, TBCAV, TNM, A1, A2, A3, A4) grids were sampled back to a master database. This data was then converted to apparent conductivity using simple transform Cond=1/ρ*1000 (mS/m). The recent surveys were flown over much of the sea and the conductivity over the sea water is very high and the data are dominated by these effects, which can mask detailed geological information. Because of this, the EM data has been trimmed to Irish coast to remove the effect of conductive seawater. The grids of conductivity were also clipped to values between -5 and 300mS/m so as to remove outliers.

Results of the merged apparent conductivities of the 3 KHz and 12 KHz frequencies are shown below in Figures 36 and 37 respectively.

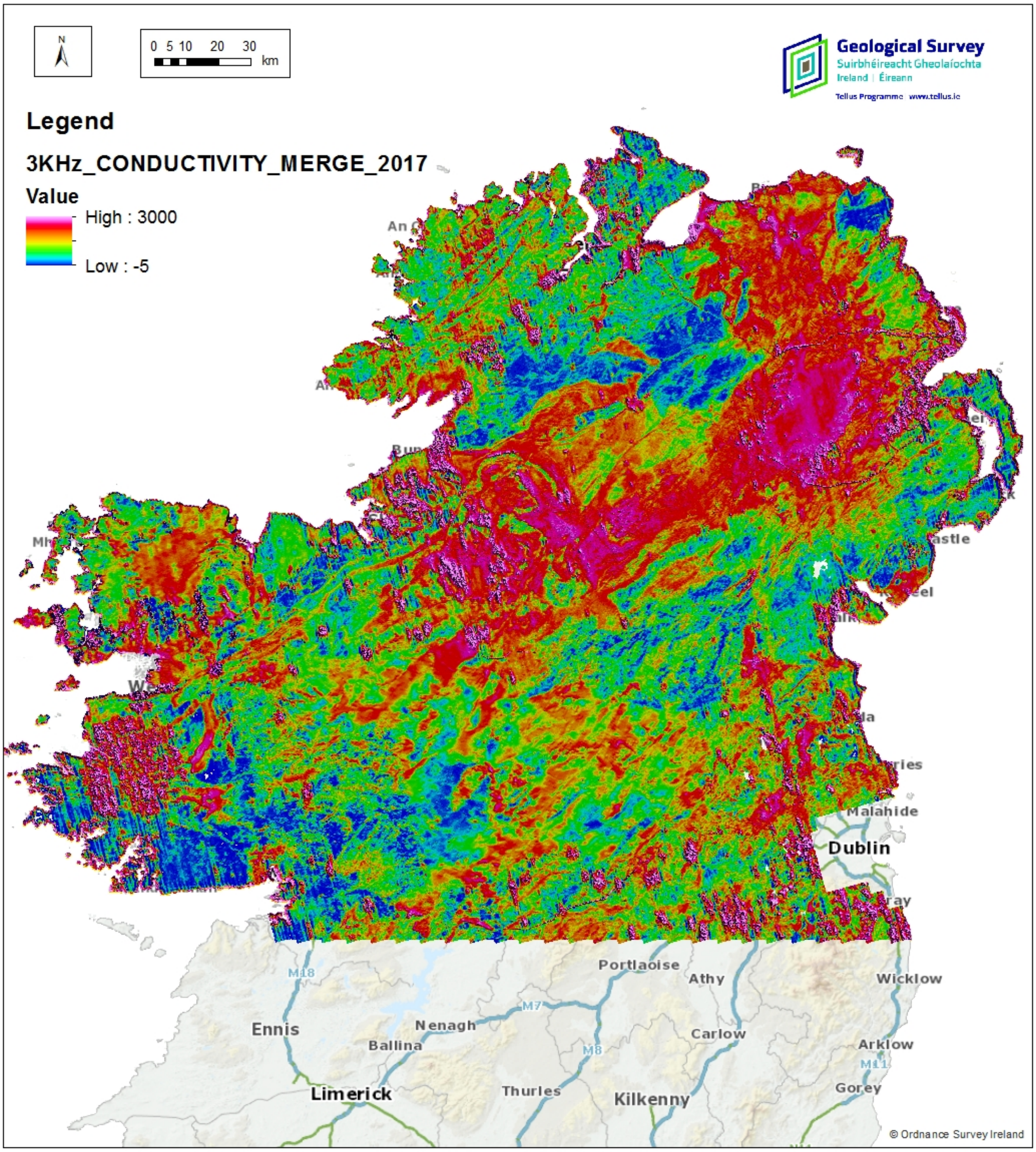

Figure 36: EM Merge2017 (NI, TBCAV, TNM, A1, A2, A3, and A4) merged apparent conductivity of 3 KHz.

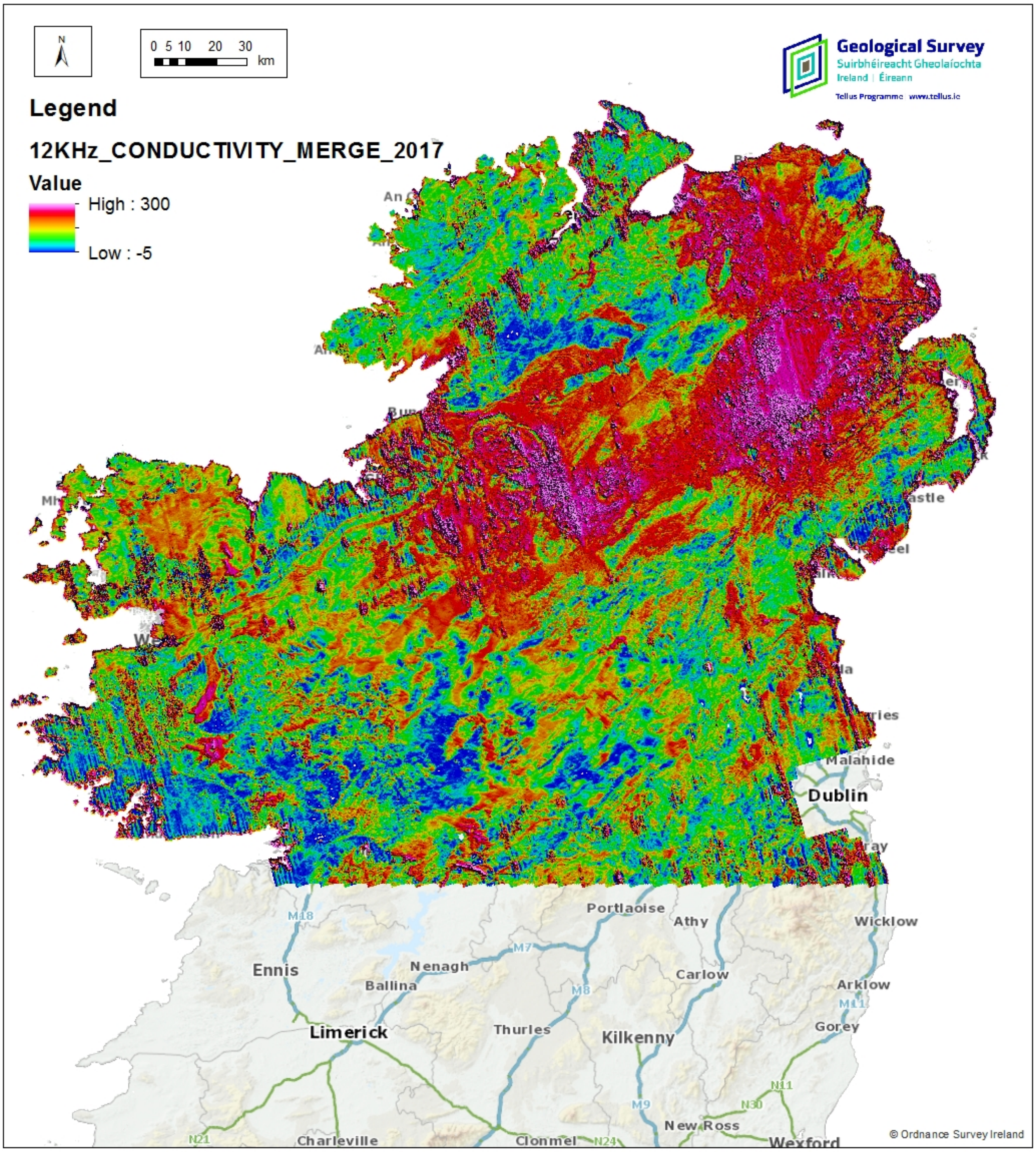

Figure 37: EM Merge2017 (NI, TBCAV, TNM, A1, A2, A3, and A4) merged apparent conductivity of 12 KHz

9. Data Assessment and Consideration

9.1 High Fly Zones

Survey altitude has a major impact on the electromagnetic signals with increasing altitude attenuating the signal. Increasing altitude also reduces the effective depth penetration of the system, particularly for FEM data. Since HEM inversion improves the result by nulling the data where high errors are intercepted, the data was not clipped for altitude above 150m. However, the user is advised caution when using FEM data over high altitudes (>150m), as investigation of data over the test-line at different survey altitudes has shown it deteriorating at altitudes greater than 150m.

The Tellus Border, TNM, A1, A2, A3 and A4 surveys were issued with a flying permit from the Irish Aviation Authority (IAA) for 60m altitude in non-congested (rural) areas. However, in upland areas which affected aircraft climb and descend rates, along with the presence of numerous wind farms some areas have been surveyed at higher altitudes. The Tellus North Midlands (TNM) survey was flown at a nominal survey altitude of 90m (with EM receiver 45m below) and with a drape system. Numerous enforced high flown zones were often clustered together and along with urban areas across the region resulted in large areas of high fly zones. Figure 38 shows altitude greater than 150m and data in these areas should be deemed to be less reliable (particularly FDEM).

Gamma-ray spectrometry data is also sensitive to survey altitude with a decrease in Gamma-rays sampled with increasing altitude. Although less sensitive than frequency-domain EM systems and with a larger crystal volume used in the A1, A2, A3, A4 and Waterford survey, data recorded at altitudes greater than 250m is considered less reliable even when allowing for altitude corrections to be made. Surveys using larger crystals (A1, A2, A3, A4 and Waterford) can have good data at altitudes greater than 250m but only if measured counts are reasonable high, and therefore should be reviewed on a line by line basis. Any data from altitudes greater than 450m should be removed as potentially erroneous.

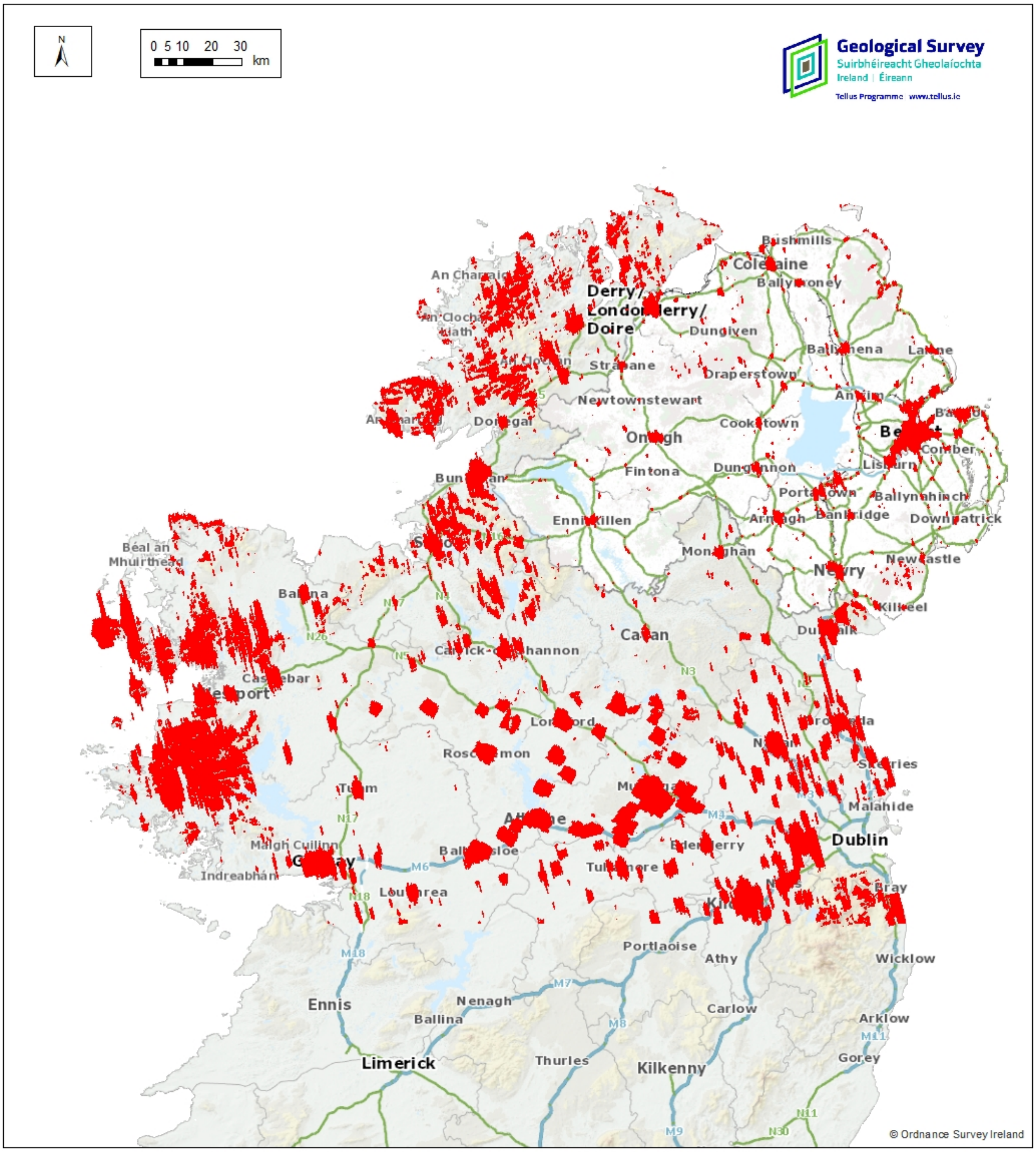

Figure 38: Survey altitude greater than 150m above ground level shown in red

As can be seen from Figure 38, significant high fly zones (> 150m) are present across the entire surveyed region. These include urban areas with populations greater than 2,500, along the M1, M6 and M7 motorway corridors in counties Dublin, Meath, Westmeath and Kildare, over areas of sensitive livestock and stud farms, and requests from the public and hilly terrain particularly in the northwest and west of the area.

9.2 Magnetic Noise

Magnetic data were measured using a Geomatrics G-822A caesium vapour magnetometers, which have a sensitivity of 0.005nT. Figures of Merit (FOM), derived from magnetic compensation tests during the A1, A2, A3, A4, TB and TNM surveys, showed values in the range of 0.4nT to 1.28nT. These values are corrected within the standard processing sequence but indicate possible background noise levels of approximately FOM/10, i.e., better than ~0.128nT within the measured data.

Cultural interference is the main source of noise affecting the data. Cultural interference from anthropogenic sources, such as, houses, farm buildings, roads, power lines, etc., creates spikes throughout the data. Both automatic and manual processes were used to help assess individual anomalies, using ortho-photographs and buildings databases to remove affected data points. Tellus Border, Cavan, Tellus North Midlands, A1, A2, A3, A4 and Waterford datasets were not subjected to de-culturing. However, a number of well-developed smoothing procedures are available. The upward continuation method is widely used and it does not produce mathematical artefacts. This method could be used to minimize high frequency cultural noise in the remaining magnetic data.

Diurnal and IGRF corrections have been made to all datasets. All data has been corrected to the most recent model of the IGRF. The largest corrections due to IGRF are found in the north of the survey areas because of increased latitudes.

9.3 Radiometric Noise

To assist in the assessment of the radiometric data, a 6km test line was flown throughout the duration of Tellus Border survey and at the beginning and end of all the Tellus survey blocks (NI, TBCAV, TNM, A1, A2, A3, A4 and Waterford) surveys. The test line was flown at different nominal altitudes and crossed from sea to land. The test line data, once re-sampled, allows direct comparisons at the same locations to be made over the duration of the survey, giving insight into the sensitivity of the system and any environmental impacts. Total count data along the test line during the A3 and A4 survey and also from previous phases show that readings vary by factors of +/-5% between individual flights. This would therefore indicate that measured values vary by up to 5% from the mean.

Rainfall data was taken from the Finner Meteorological Station in Co. Donegal, which lies approximately 7km to the NW of the test line to assist in the assessment of seasonal effects. As expected a negative relationship exists between total counts and increasing rainfall, whereby for every ~1mm increase in rainfall, total count values decrease by about 0.8%. Rainfall data was taken for each day of the flight as well as over a 3 day average and 14 day average. Taking rainfall only on the day of each flight may have incurred errors as the measurement was for the entire day and flights may have occurred before any measured rainfall for that day. The 3 and 14 day averages may indicate the degree of saturation of the ground. Recent studies have investigated how both soil and bedrock type, together with the degree of saturation of the ground, can influence the attenuation of gamma rays (Beamish, 2013 and Beckett, 2008).

9.4 Electromagnetic noise

Both frequency-domain and time-domain electromagnetic data are particularly prone to electromagnetic field interference from power lines, buildings and electric fences, which can create sources of noise that, cannot easily be resolved. The amplitudes of the measured coupling ratios, or corresponding time gate channels, decrease over areas of high resistivity/low conductivity. Because of this, the signal-to-noise ratio is reduced in highly resistive areas sometimes making it impossible to distinguish the true signal. In resistive zones levelling of the data also becomes more difficult and can result in small amplitude undulations. This is particularly the case for the low frequencies within FEM systems, as they are most susceptible to highly resistive zones (Hautaniemi *et al.,* 2005). Time domain data seems less affected by cultural noise affects and is generally able to penetrate deeper into the earth (depending on time / frequency windows used).

Survey altitude has a major impact on the electromagnetic signals with increasing altitude attenuating the signal. Increasing altitude also reduces the effective depth penetration of the system, particularly for FEM data. It is, therefore, recommended that FEM data collected at survey altitudes exceeding 150m should be considered with care. TEM data is less affected and should be reviewed on a case-by-case scenario. Typically, the measured FEM data can be inverted to consistent depth of 50m bgl, while the TEM data can extend to depths of 200m.

Therefore, the merging of conductivity data from the two systems can only be reasonably derived for the upper 50m depth.

Full details of the electromagnetic processing and a review of the inversion procedure can be found in Beamish (2013), Hodgson and Ture (2013), CGG (2015), SGL (2015, 2016), and Ture and Hodgson (2017).

9.5 Data filtering

There are many different approaches to data filtering; however, it has been decided that the Geological Survey, Ireland will provide data for public use with the minimum processing and filtering. This will allow the individual user to perform their own processing and filtering of the data to their own requirements and specifications. Therefore, no additional filtering of the magnetic and radiometric data has been carried out. The EM processing has been discussed in section 8.5.1 above and the applied filters are minimal and don't create artefacts. The delivered data consists of the contractor supplied final data and merged data, with corrections applied only to allow seamless merger of different datasets. Additional filtering may be required, i.e., upward continuation of magnetic data to remove cultural interference etc.

10. Data Delivery

10.1 Overview & Delivered Data

Standard processing was performed on all three datasets (1, Magnetics; 2, Radiometrics; and 3, EM) by the contractor and are discussed in detail in Beamish *et al.*, 2006 and reviewed by Hodgson and Ture (2013) for Tellus Border and Cavan-Monaghan data, and by CGG (2015) for the Tellus North Midlands data and by SGL (2015, 2016) for the A1 and A2 blocks and by SGL (2017a and 2017b) for A3 and A4 blocks. The contractors supplied data in ASCII.xyz and Geosoft grid format. Additional processing applied to the EM data was also undertaken and has been discussed in Sections 6, 7 and 8.

The merger of the new A3 and A4 data with the previous merge2016 datasets has been outlined in Section 8. Tables 22-24 outline all the delivered data for the newly merged data (merge2017) datasets. As the number of merged blocks became larger, the data file increases in size making data downloads difficult. Hence, only critical data channels as shown in tables 22-24 are included. Contractor supplied data for each survey phase is also available upon request from www.tellus.ie.

Table 22: Merged (2017) A1, A2, A3, A4, TNM,TBCAV, NI, magnetic merged data

No	***Name***	***Units***	***Description***
1	X_ITM	m	X coordinate, Irish Transverse Mercator
2	Y_ITM	m	y coordinate, Irish Transverse Mercator
3	DATE	YYYYMMDD	Date (year, month, day)
5	RALT	m	Altimeter height
4	SID	-	Survey ID (A1, A2, A3, A4, TB, CAV and NI)
6	IGRF	nT	Reference Field at December 1st 2017
7	MAG _RES_2017	nT	Magnetic Anomaly (IGRF & Diurnal corrected, Levelled)

Table 23: Merged (2017) A1, A2, A3, A4, TNM,TBCAV,NI radiometric merged data

No	*Name*	*Units*	*Description*
1	X_ITM	m	X coordinate, Irish Transverse Mercator
2	Y_ITM	m	y coordinate, Irish Transverse Mercator
3	DATE	YYYYMMDD	Date (year, month, day)
4	RALT	m	Altimeter height
5	SID	-	Survey ID (A1, A2, A3, A4, TB, CAV and NI
6	TC	cps	Merged Corrected Total Count
7	eTh	ppm	Merged Corrected Thorium Concentration
8	K	%	Merged Corrected Potassium Concentration
9	eU	ppm	Merged Corrected Uranium Concentration

Table 24: **Merged (2017) A1, A2, A3, A4, TNM,TBCAV and NI, EM Conductivity data**

Number	*Name*	*Units*	*Description*
1	X_ITM	m	X coordinate, Irish Transverse Mercator
2	Y_ITM	m	y coordinate, Irish Transverse Mercator
3	DATE	YYYYMMDD	Date (year, month, day)
5	RALT	m	Altimeter height, height above ground
4	SID	-	Survey ID (NI,TB,CAV,TNM,A1,A2, A3 A4)
6	Cond3_MERGE2017	mS/m	Apparent Conductivity derived from HEM inversion of 3KHz data & TEM equivalent data
7	COND12_MERGE2017	mS/m	Apparent Conductivity derived from HEM inversion of 12KHz data & TEM equivalent data

All data were processed and exported using the Oasis Montaj Geosoft programme and are available in .xyz format. Geosoft grids of different mapped elements are also available upon request.

It is the policy of the Geological Survey, Ireland that all data is free. Data can be downloaded from the project website www.gsi.ie/tellus.

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