NGU REPORT 2015.015

Helicopter-borne magnetic and radiometric geophysical survey in Romsdalsfjorden, Møre og Romsdal

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REPORT

Geological Survey of Norway
P.O.Box 6315 Sluppen
NO-7491 TRONDHEIM
Tel.: 47 73 90 40 00

Report no.: 2015.015	**ISSN: 0800-3416 (print)** **ISSN: 2387-3515 (online)**	**Grading:** Open

Title:
Helicopter-borne magnetic and radiometric geophysical survey in Romsdalsfjorden, Møre og Romsdal.

Authors: Frode Ofstad		**Client:** Statens Vegvesen / NGU	
County: Møre og Romsdal		**Municipalities:** Molde, Vestnes, Midsund, Skodje, Ørskog	
Map-sheet name (M=1:250.000) Ålesund		**Map-sheet no. and -name (M=1:50.000)** 1220-2 Vestnes, 1320-3 Åndalsnes	
Deposit name and grid-reference: UTM sone 32 Molde 406000 - 6957000		**Number of pages:** 24 **Map enclosures:**	**Price (NOK):** 80,-
Fieldwork carried out: Dec 2014, Jan 2015	**Date of report:** 20.02.15	**Project no.:** 353201	**Person responsible:** Jan S. Rønning

Summary:

NGU conducted an airborne magnetic and radiometric survey in Romsdalsfjorden in December 2014 and January 2015 on behalf of Statens Vegvesen.

This report describes and documents the acquisition, processing and visualization of recorded datasets. The geophysical survey results reported herein are from 2750 line km, covering an area of 550 km^2.

A Scintrex CS-3 magnetometer in a towed bird and a 1024 channels RSX-5 spectrometer installed under the helicopter belly was used for data acquisition.

The survey was flown with 200 m line spacing, line direction 0^o (N to S) at an average speed of 88 km/h. The average terrain clearance was 52 m for the bird and 80 m for the spectrometer.

The collected data were processed at NGU using Geosoft Oasis Montaj software. Raw total magnetic field data were corrected for diurnal variation and 2eveled using standard micro-levelling algorithm.

Radiometric data were processed using standard procedures recommended by International Atomic Energy Association.

Data were gridded with the cell size of 50 x 50 m and presented as a shaded relief maps at the scale of 1:50.000.

Keywords:	Airborne	Geophysics
Magnetics	Radiometrics	Technical Report

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INTRODUCTION

NGU (Geological Survey of Norway) conducted in December 2014 and January 2015 on behalf of Statens Vegvesen, an airborne geophysical survey in Romsdalsfjorden area, as shown in Figure 1. The helicopter survey consists of 2750 line-km of data, and covers an area of 550 km^2.

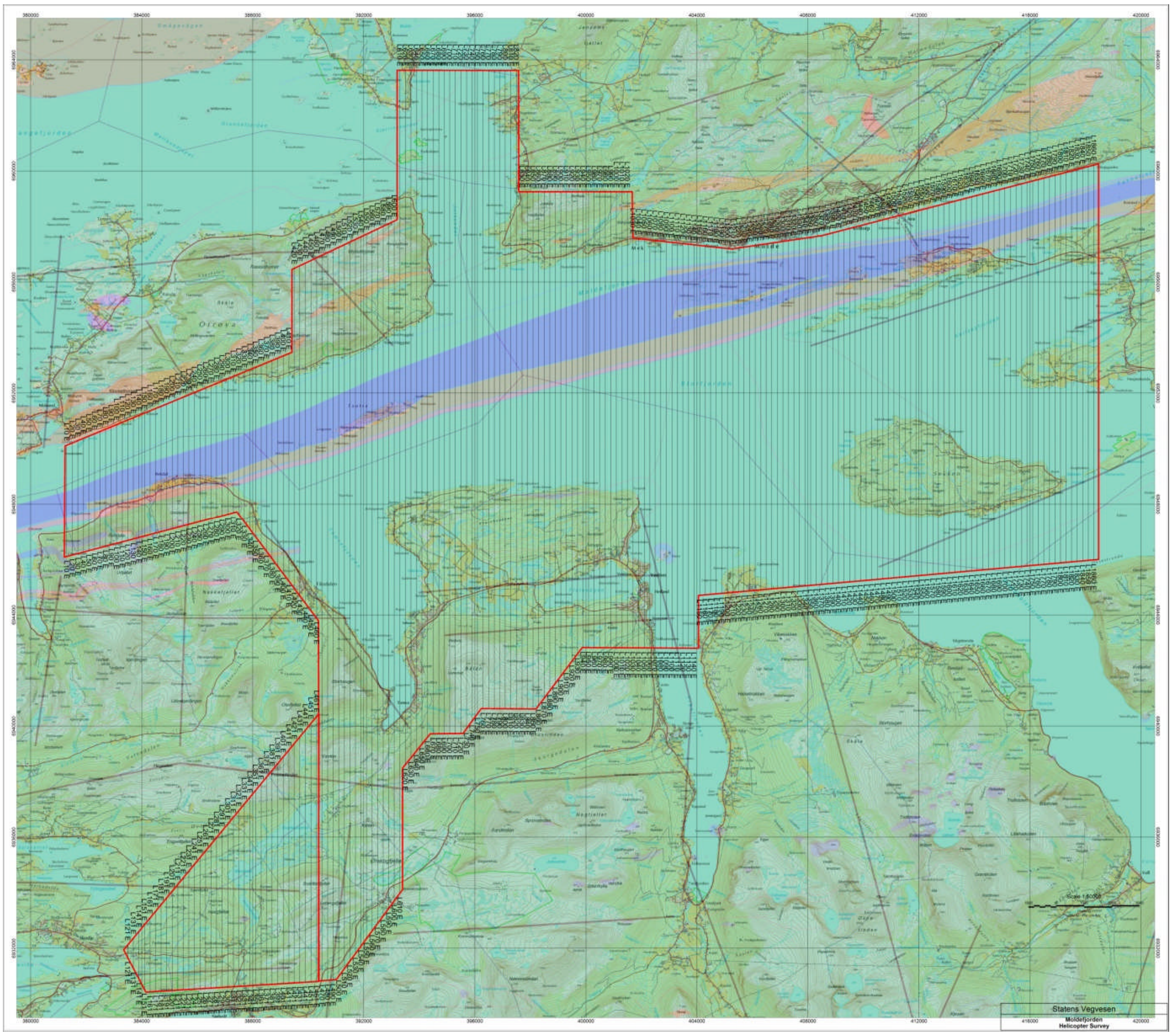

Figure 1: Romsdalsfjorden survey area in Møre og Romsdal.

The objective of the airborne geophysical survey was to obtain a dense high-resolution aero-magnetic and radiometric data set over the survey area. The magnetic data is required for the planning of future road projects in the area, and to improve the general understanding of the geology. The data can be used to map bedrock geology, contacts and structural features within the area, the potential of fracture zones, their geological settings, and identifying other areas of interest.

The survey incorporated the use of a high-sensitivity Cesium magnetometer, gamma-ray spectrometer and radar altimeter. A GPS navigation computer system with flight path indicators ensured accurate positioning of the geophysical data with respect to the World Geodetic System 1984 geodetic datum (WGS-84).

1. SURVEY SPECIFICATIONS

1.1 Airborne Survey Parameters

NGU used a helicopter survey system designed to obtain detailed airborne magnetic data. The system was supplemented by one 1024 channel gamma-ray spectrometer with 16 liters downward and 4 liters upward crystal volume, which was used to map ground concentrations of Uranium, Thorium and Potassium.

The survey started December 10th, and was aborted at December 17th 2014, d.t weather conditions. Five more flights were made from January 20th to January 22nd 2015 to complete the survey. A Eurocopter AS350-B2 from helicopter company HeliScan AS was used during the survey (Figure 2). The survey lines were spaced 200 m apart, and oriented at a 0° azimuth in UTM zone 32V. Instrument operation was performed by Heliscan AS employees.

The magnetic sensor was housed in a single 1.8 meters long bird (Figure 2) which was flown at a constant altitude above the topographic surface. The Radiation Solutions RSX-5 gamma-ray spectrometer was installed under the belly of the helicopter, registering natural gamma ray radiation simultaneously with the acquisition of magnetic data.

Figure 2: Pilots with Mag bird in front of the helicopter used in survey. (P1)

Rugged terrain and abrupt changes in topography affected the pilot's ability to 'drape' the terrain; therefore there are positive and negative variations in helicopter altitude with respect to the standard, which is defined as 60 m (200 ft), plus a height of obstacles (trees, power lines). The average altitude for the magnetometer in this survey was 52 m, and 80 m for the spectrometer.

The ground speed of the aircraft varied from 60 – 120 km/h depending on topography, wind direction and its magnitude. On average the ground speed during the whole survey was calculated to 88 km/h. Magnetic data were recorded at 0.2 second intervals resulting in approximately 5 meters point spacing. Spectrometry data was recorded every 1 second giving an average point spacing of approximately 25 meters.

A base magnetometer to monitor diurnal variations in the magnetic field was located 2 km west of the landing site at Haukabøen, at UTM 32V 6956980 N, 397858 E. The GEM GSM-19 station magnetometer data were recorded once every 3 seconds. The CPU clock of the magnetometer was synchronized through the built-in GPS receiver to permit synchronization with the recorded airborne magnetic data and subsequent removal of diurnal drift.

Navigation system uses GPS/GLONASS satellite tracking systems to provide real-time WGS-84 coordinate locations for every second. The accuracy achieved with no differential corrections is reported to be less than ± 5 m in the horizontal directions. The GPS receiver antenna was mounted externally to the cabin roof of the helicopter.

For quality control, the magnetic, radiometric, altitude and navigation data were monitored on two separate windows in the operator's display during flight while they were recorded in ASCII data streams to the acquisition PC hard disk drive.

2. AIRBORNE SURVEY INSTRUMENTATION

Table 1: Instrument Specifications

Instrument	Producer / Model	Accuracy / Sensitivity	Sampling freq interval
Magnetometer	Scintrex Cs-3	2.5 nT / 0.002 nT	5 Hz
Base magnetometer	GEM GSM-19	0.1 nT	3 s
Gamma spectrometer	Radiation Solutions RSX-5	1024 ch's, 16 liters down, 4 liters up	1 Hz
Radar altimeter	Bendix/King KRA 405B	± 3 % 0 – 500 ft ± 5 % 500-2500 ft	1 Hz
Pressure/temperature	Honeywell PPT	± 0,03 % FS	1 Hz
Navigation	Topcon GPS-receiver	± 5 meter	1 Hz
Acquisition system	NGU custom software		

The magnetic and radiometric, altitude and navigation data were monitored on the operator's displays during flight while they were recorded to the PC hard disk drive. Spectrometry data were also recorded to internal hard drive of the spectrometer. The raw data files were backed up onto USB flash drive in the field.

2.1 Airborne Survey Logistics Summary

Traverse (survey) line spacing:	200 meters
Traverse line direction:	0° N-S
Nominal aircraft ground speed:	60 – 120 km/h
Average sensor terrain clearance Mag:	52 meters
Average sensor terrain clearance Rad:	80 meters

3. DATA PROCESSING AND PRESENTATION

All data were processed by Frode Ofstad at NGU. The ASCII raw data files were loaded into separate Oasis Montaj databases and processed according to the descriptions in Appendix A1 and A2.

3.1 Total Field Magnetic Data

At the first stage the magnetic data were visually inspected and spikes were removed manually. A two-fiducial lag filter and a non-linear filter were applied to eliminate short-period spikes. Then the data from basemag station were imported into the magnetic database. Diurnal variation channel was also inspected for spikes and spikes were removed manually. Typically, several corrections have to be applied to magnetic data before gridding.

Diurnal Corrections

The temporal fluctuations in the magnetic field of the earth affect the total magnetic field readings recorded during the airborne survey. This is commonly referred to as the magnetic diurnal variation. These fluctuations can be effectively removed from the airborne magnetic dataset by using a stationary reference magnetometer that records the magnetic field of the earth simultaneously with the airborne sensor. Magnetic diurnals were within the standard NGU specifications during the entire survey (Rønning 2013).

Diurnal variations were measured with a GEM GSM-19 base magnetometer. The base station computer clock was continuously synchronized with GPS time. The recorded data are merged with the airborne data and the diurnal correction is applied according to equation (1).

$$\mathbf{B}_{Tc} = \mathbf{B}_T + \left(\overline{B}_B - \mathbf{B}_B\right), \qquad (1)$$

where:

$\mathbf{B}_{Tc}$ = Corrected airborne total field readings

$\mathbf{B}_T$ = Airborne total field readings

$\overline{B}_B$ = Average datum base level

$\mathbf{B}_B$ = Base station readings

The average datum base level ($\overline{B}_B$) was set to 51630 nT for this survey. This should bring all recorded magnetic data to a common level, but some flights had to be adjusted slightly to fix a mismatch which was visible in the final processed data. The mismatch is located as small level changes in the basemag data, most likely caused by a high magnetic gradient at the base station and variation in basemag position.

Corrections for Lag and heading

Neither a lag nor cloverleaf tests were performed before the survey. According to previous reports the lag between logged magnetic data and the corresponding navigational data was 1-2 fids. Translated to a distance it would be less than 10 m – the value comparable with the precision of GPS.

Magnetic data processing, gridding and presentation

The total field magnetic anomaly data ($\mathbf{B}_{TA}$) were calculated from the diurnal corrected data ($\mathbf{B}_{Tc}$) after subtracting the IGRF for the surveyed area calculated for the data period (eq.2)

$$\mathbf{B}_{TA} = \mathbf{B}_{Tc} - IGRF \tag{2}$$

The total field anomaly data were split in lines and then were gridded using a minimum curvature method with a grid cell size of 50 meters. This cell size is equal to one quarter of the 200m average line spacing. In order to remove small line-to-line levelling errors that were detected on the gridded magnetic anomaly data, the Geosoft Microlevelling technique was applied on the flight line based magnetic database. Then, the microlevelled channel was gridded using again a minimum curvature method with 50 m grid cell size.

The processing steps of magnetic data presented so far were performed on point basis. The following steps are performed on grid basis. The Horizontal and Vertical Gradient along with the Tilt Derivative of the total magnetic anomaly were calculated from the microlevelled total magnetic anomaly grid. The magnitude of the horizontal gradient was calculated according to equation (3)

$$HG = \sqrt{\left(\frac{\partial B_{TA}}{\partial x}\right)^2 + \left(\frac{\partial B_{TA}}{\partial y}\right)^2} \tag{3}$$

where $\mathbf{B}_{TA}$ is the microlevelled field. The vertical gradient (VG) was calculated by applying a vertical derivative convolution filter to the microlevelled $\mathbf{B}_{TA}$ field. The Tilt Derivative (TD) was calculated according to the equation (4)

$$\text{TD} = \text{atan}(\text{VG}/\text{HG}) \tag{4}$$

Magnetic data gridding and presentation

After the micro levelling technique was applied to the magnetic data to remove small line-to-line levelling errors, a 3x3 grid cells convolution filter was passed over the final grid to smooth the grid image.

The Vertical Gradient, Horizontal Gradient and the Tilt Derivative of the total magnetic field were calculated from the resulting total magnetic field map. These signals transform the shape of the magnetic anomaly from any magnetic inclination to positive body-centered anomaly and it’s widely utilized for mapping of structures. A list of the produced maps is shown in Table 3.

3.2 Radiometric data

Airborne gamma-ray spectrometry measures the abundance of Potassium (K), Thorium (eTh), and Uranium (eU) in rocks and weathered materials by detecting gamma-rays emitted due to the natural radioelement decay of these elements. The data analysis method is based on the IAEA recommended method for U, Th and K (International Atomic Energy Agency, 1991). A short description of the individual processing steps of that methodology as adopted by NGU is given bellow.

Energy windows

The Gamma-ray spectra were initially reduced into standard energy windows corresponding to the individual radio-nuclides K, U and Th. Figure 3 shows an example of a Gamma-ray spectrum and the corresponding energy windows.

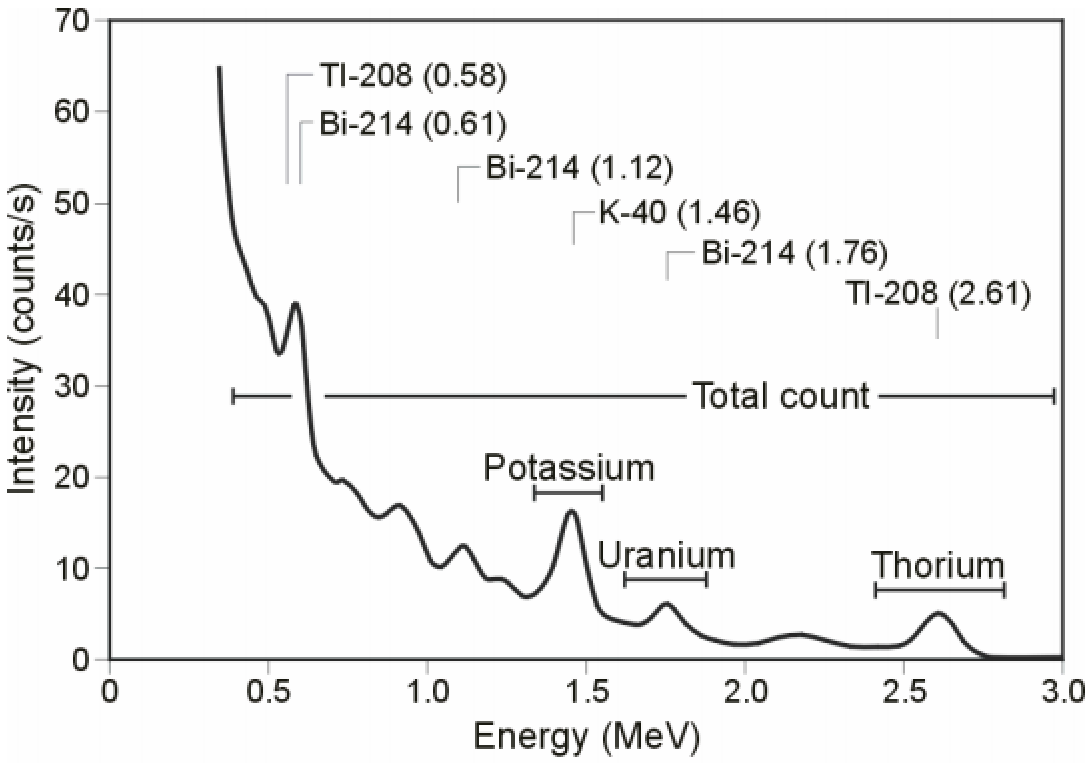

Figure 3: Gamma-ray spectrum with K, Th, U and Total count windows.

The RSX-5 is a 1024 channel system with a four downward looking and one upward looking detector, with a total crystal volume of 16 liters downward and 4 liters upward for cosmic corrections. The Gamma-ray spectrum of 0 to above 3000 keV is divided into 1024 channels, where each channel has a 3.0 keV range. Table 2 shows the channels and energies that were used for the reduction of the spectrum.

Table 2: Channel windows for the 1024 RSX-5 systems used in this survey

Spectrum	Cosmic	Total count	K	U	Th
Down	1022	134-934	454-521	551-617	801-934
Up	1022			551-617	
Energy, keV	>3000	407-2807	1367-1568	1658-1856	2408-2807
Peak, keV			1460	1765	2614
Peak channel			486	586	872

Live Time correction

The data were corrected for live time. “Live time” is an expression of the relative period of time the instrument was able to register new pulses per sample interval. On the other hand “dead time” is an expression of the relative period of time the system was unable to register new pulses per sample interval. The relation between “dead” and “live time” is given by the equation (5)

$$\text{“Live time”} = \text{“Real time”} - \text{“Dead time”} \quad (5)$$

where the “real time” or “acquisition time” is the elapsed time over which the spectrum is accumulated.

The live time correction is applied to the total count, Potassium, Uranium, Thorium, upward Uranium and cosmic channels. The formula used to apply the correction is as follows:

$$C_{LT} = C_{RAW} \cdot \frac{1000000}{Live\ Time} \quad (6)$$

where C_{LT} is the live time corrected channel in counts per second, C_{RAW} is the raw channel data in counts per second and Live Time is in microseconds.

Cosmic and aircraft correction

Background radiation resulting from cosmic rays and aircraft contamination was removed from the Total Count, Potassium, Uranium, Thorium and Upward Uranium channels using the following formula:

$$C_{CA} = C_{LT} - (a_c + b_c \cdot C_{Cos}) \quad (7)$$

where C_{CA} is the cosmic and aircraft corrected channel, C_{LT} is the live time corrected channel a_c is the aircraft background for this channel, b_c is the cosmic stripping coefficient for this channel and C_{Cos} is the low pass filtered cosmic channel.

Radon correction

The upward detector method, as discussed in IAEA (1991), was applied to remove the effects of the atmospheric radon in the air below and around the helicopter. Usages of over-water measurements where there is no contribution from the ground, enabled the calculation of the coefficients a_c and b_c of the linear equations that relate the cosmic corrected counts per second of Uranium channel with total count, Potassium, Thorium and Uranium upward channels over water. Data over-land was used in conjunction with data over-water to calculate the a_1 and a_2 coefficients used in equation (8) for the determination of the Radon component in the downward uranium window:

$$Radon_U = \frac{Uup_{CA} - a_1 \cdot U_{CA} - a_2 \cdot Th_{CA} + a_2 \cdot b_{Th} - b_U}{a_U - a_1 - a_2 \cdot a_{Th}} \quad (8)$$

where $Radon_U$ is the radon component in the downward uranium window, Uup_{CA} is the filtered upward uranium, U_{CA} is the filtered Uranium, Th_{CA} is the filtered Thorium, a_1, a_2, a_U and a_{Th} are proportional factors and b_U an b_{Th} are constants determined experimentally.

The effects of Radon in the downward Uranium are removed by simply subtracting $Radon_U$ from U_{CA}. The effects of radon in the other channels are removed using the following formula:

$$C_{RC} = C_{CA} - (a_C \cdot Radon_U + b_C) \tag{9}$$

where C_{RC} is the Radon corrected channel, C_{CA} is the cosmic and aircraft corrected channel, $Radon_U$ is the Radon component in the downward uranium window, a_c is the proportionality factor and b_c is the constant determined experimentally for this channel from over-water data.

Compton Stripping

Potassium-, Uranium- and Thorium- Radon corrected channels are subjected to spectral overlap correction. Compton scattered gamma rays in the radio-nuclides energy windows were corrected by window stripping using Compton stripping coefficients determined from measurements on calibrations pads at the Geological Survey of Norway in Trondheim (for values see Appendix A2).

The stripping corrections are given by the following formulas:

$$A_1 = 1 - (g \cdot \gamma) - (\mathrm{a} \cdot \alpha) + (\mathrm{a} \cdot g \cdot \beta) - (b \cdot \beta) + (b \cdot \alpha \cdot \gamma) \tag{10}$$

$$U_{ST} = \frac{Th_{RC} \cdot ((g \cdot \beta) - \alpha) + U_{RC} \cdot (1 - b \cdot \beta) + K_{RC} \cdot ((b \cdot \alpha) - g)}{A_1} \tag{11}$$

$$Th_{ST} = \frac{Th_{RC} \cdot (1 - (g \cdot \gamma)) + U_{RC} \cdot (b \cdot \gamma - \mathrm{a}) + K_{RC} \cdot ((\mathrm{a} \cdot g) - b)}{A_1} \tag{12}$$

$$K_{ST} = \frac{Th_{RC} \cdot ((\alpha \cdot \gamma) - \beta) + U_{RC} \cdot ((\mathrm{a} \cdot \beta) - \gamma) + K_{RC} \cdot (1 - (\mathrm{a} \cdot \alpha))}{A_1} \tag{13}$$

where U_{RC}, Th_{RC}, K_{RC} are the radon corrected Uranium, Thorium and Potassium, a, b, g, α, β, γ are Compton stripping coefficients.

Reduction to Standard Temperature and Pressure

The radar altimeter data were converted to effective height (H_{STP}) using the acquired temperature and pressure data, according to the expression:

$$H_{STP} = H \cdot \frac{273.15}{T + 273.15} \cdot \frac{P}{1013.25} \tag{14}$$

where H is the smoothed observed radar altitude in meters, T is the measured air temperature in degrees Celsius and P is the measured barometric pressure in millibars.

Height correction

Variations caused by changes in the aircraft altitude relative to the ground corrected to a nominal height of 60 m. Data recorded at the height above 150 m were considered as non-reliable and removed from processing. Total count, Uranium, Thorium and Potassium stripped channels were subjected to height correction according to the equation:

$$C_{60m} = C_{ST} \cdot e^{C_{ht} \cdot (60 - H_{STP})} \qquad (15)$$

where C_{ST} is the stripped corrected channel, C_{ht} is the height attenuation factor for that channel and H_{STP} is the effective height.

Conversion to ground concentrations

Corrected count rates were converted to effective ground element concentrations using calibration values derived from calibration pads at the Geological Survey of Norway (see Appendix A2). The corrected data provide an estimate of the apparent surface concentrations of Potassium, Uranium and Thorium (K, eU and eTh).

Potassium concentration is expressed as a percentage, equivalent Uranium and Thorium as parts per million (ppm). Uranium and Thorium are described as equivalent" since their presence is inferred from gamma-ray radiation from daughter elements (^{214}Bi for Uranium, ^{208}Tl for Thorium). The concentration of the elements is calculated according to the following expressions

$$C_{CONC} = C_{60m} / C_{SENS\_60m} \qquad (16)$$

where C_{60m} is the height corrected channel, C_{SENS_60m} is experimentally determined sensitivity reduced to the nominal height (60m).

Spectrometry data gridding and presentation

Gamma-rays from Potassium, Thorium and Uranium emanate from the uppermost 30 to 40 centimeters of soil and rock in the crust (Minty, 1997). Variations in the concentrations of these radio-elements largely related to changes in the mineralogy and geochemistry of the Earth's surface.

The calculated ground concentrations of the three main natural radio-elements Potassium, Thorium and Uranium, along with total gamma-ray flux (Total Count) were microlevelled to remove small line-to-line levelling errors, and then gridded using a minimum curvature method with a grid cell size of 50 meters, equal to one quarter of the 200m average line spacing.

During the radiometric data processing, it became obvious that there were large variations in weather conditions during the survey period. The air moisture and snow cover on the ground are not recorded by the temperature/pressure sensor, so it will not be taken into account during the processing steps.

The Thorium and Potassium ground concentration levels from flight 11 and 15 were clearly lower than the other flights. The micro-levelling and 3x3 convolution filtering did not completely remove this effect, so the final concentration levels of Th and K is not consistent for the whole survey.

A list of the maps is shown in Table 3. A list of the parameters used in the processing schemes is given in Appendix A2. For further reading regarding standard processing of airborne radiometric data, we recommend the publication from Minty et al. (1997).

4. PRODUCTS

Processed digital data from the survey are presented as:

1. Geosoft XYZ files: Romsdalsfjorden_Mag.xyz, Romsdalsfjorden_Rad.xyz.

2. Coloured maps (jpg) at the scale 1:50.000 available from NGU on request.

3. Geo-referenced tiff files (Geo-tiff).

Table 3: Maps in scale 1:50.000 available from NGU on request.

Map #	Name	Figure No
2015.015-01	Total Magnetic field Anomaly	5
2015.015-02	Magnetic Vertical Derivative	6
2015.015-03	Magnetic Horizontal Derivative	7
2015.015-04	Magnetic Tilt Derivative	8
2015.015-05	Uranium ground concentration	9
2015.015-06	Thorium ground concentration	10
2015.015-07	Potassium ground concentration	11
2015.015-08	Radiation Total Counts	12

Downscaled images of the maps are shown in figures 5 to 12.

5. REFERENCES

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P1: Photo by Mari Nymoen, Telen Newspaper, Notodden

Appendix A1: Description of magnetic processing

Meaning of parameters is described in the referenced literature.

Processing flow:

- Quality control.
- Visual inspection of airborne data and manual spike removal
- Import basemag data to Geosoft database
- Inspection of basemag data and removal of spikes
- Correction of data for diurnal variation
- Splitting flight data by lines
- Gridding
- Micro-levelling
- 3x3 Convolution filter

Appendix A2: Description of radiometry processing

Underlined processing stages are applied to the K, U, Th and TC windows.
Meaning of parameters is described in the referenced literature.

Processing flow:

- Quality control
- Airborne and cosmic correction (IAEA, 2003)

Used parameters: (From high altitude calibration flights at Frosta, May 2013)

Aircraft background counts:

K window	5.36
U window	1.43
Th window	0
Uup window	0.7
Total counts	42.73

Cosmic background counts (normalized to unit counts in the cosmic window):

K window	0.0570
U window	0.0467
Th window	0.0643
Uup window	0.0448
Total counts	1.0317

- Radon correction using upward detector method (IAEA, 2003)

Used parameters (determined from survey data over water and land):

a_u:	0.22771	b_u:	0
a_{Th}:	0.03547	b_{Th}:	0.32521
a_K:	1.08123	b_K:	2.84721
aTc:	18.0752	bTc:	5.19240
a_1:	0.061261	a_2:	0.029344

- Stripping correction (IAEA, 2003)
  Used parameters (from measurements on calibrations pads at the NGU in May 2013):

a	0.046856
b	0
g	0
alpha	0.30346
beta	0.47993
gamma	0.82316

- Height correction to a height of 60 m
  Used parameters (from high altitude calibration flights at Frosta in Jan 2014):
  Attenuation factors in 1/m:

K:	-0.009523
U:	-0.006687
Th:	-0.007394
TC:	-0.00773

- Converting counts at 60 m heights to element concentration on the ground
  Used parameters (determined from measurements on calibrations pads at the NGU in May 2013):
  Sensitivity (elements concentrations per count)::

K:	0.007458	%/counts
U:	0.08773	ppm/counts
Th:	0.15666	ppm/counts

- Microlevelling using Geosoft menu and smoothening by a convolution filtering
  Used parameters for microlevelling:

De-corrugation cutoff wavelength:	1200 m
Cell size for gridding:	50 m
Naudy (1968) Filter length:	800 m

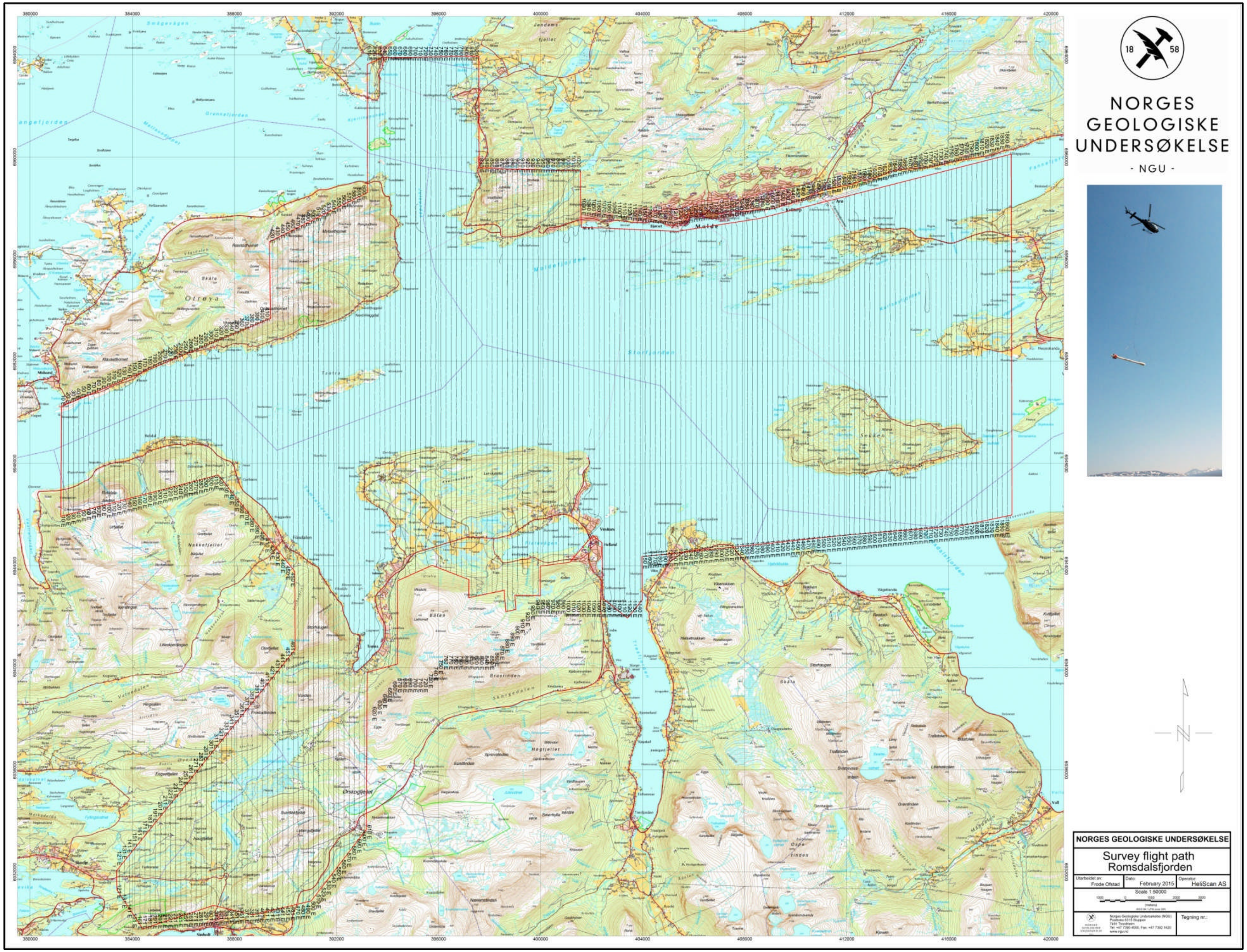

Figure 4: Romsdalsfjorden survey area with flight path

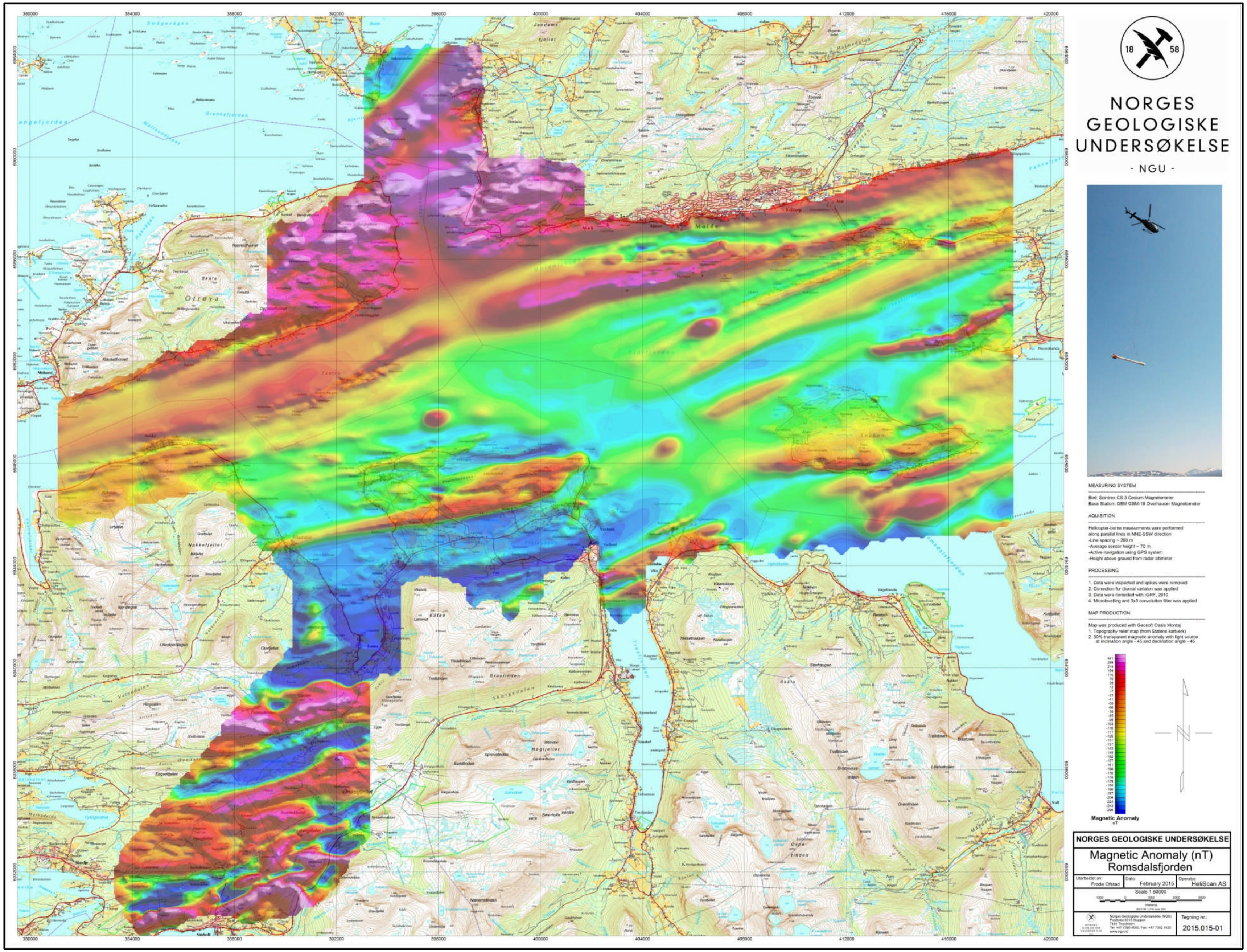

Figure 5: Total Magnetic Field Anomaly

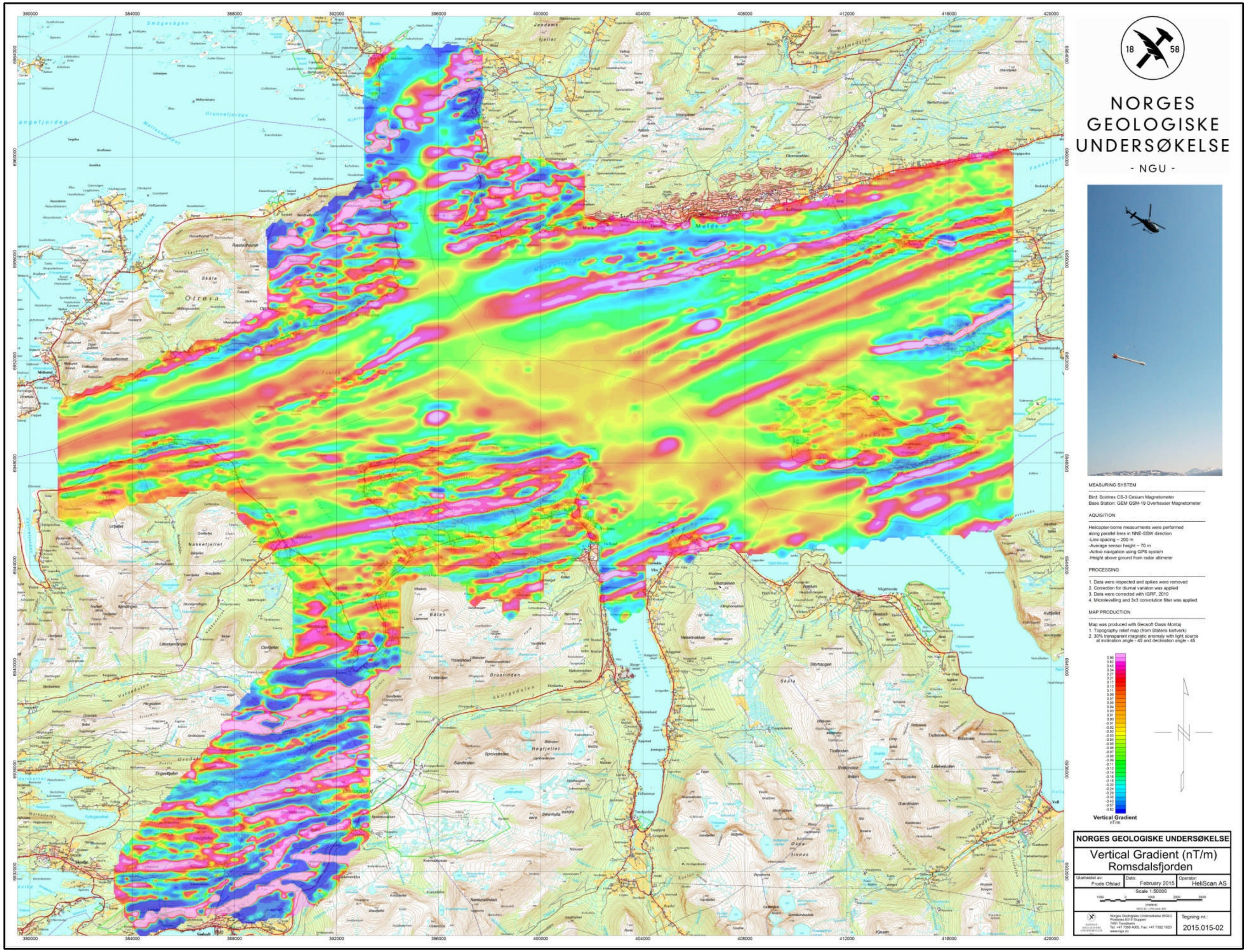

Figure 6: Magnetic Vertical Gradient

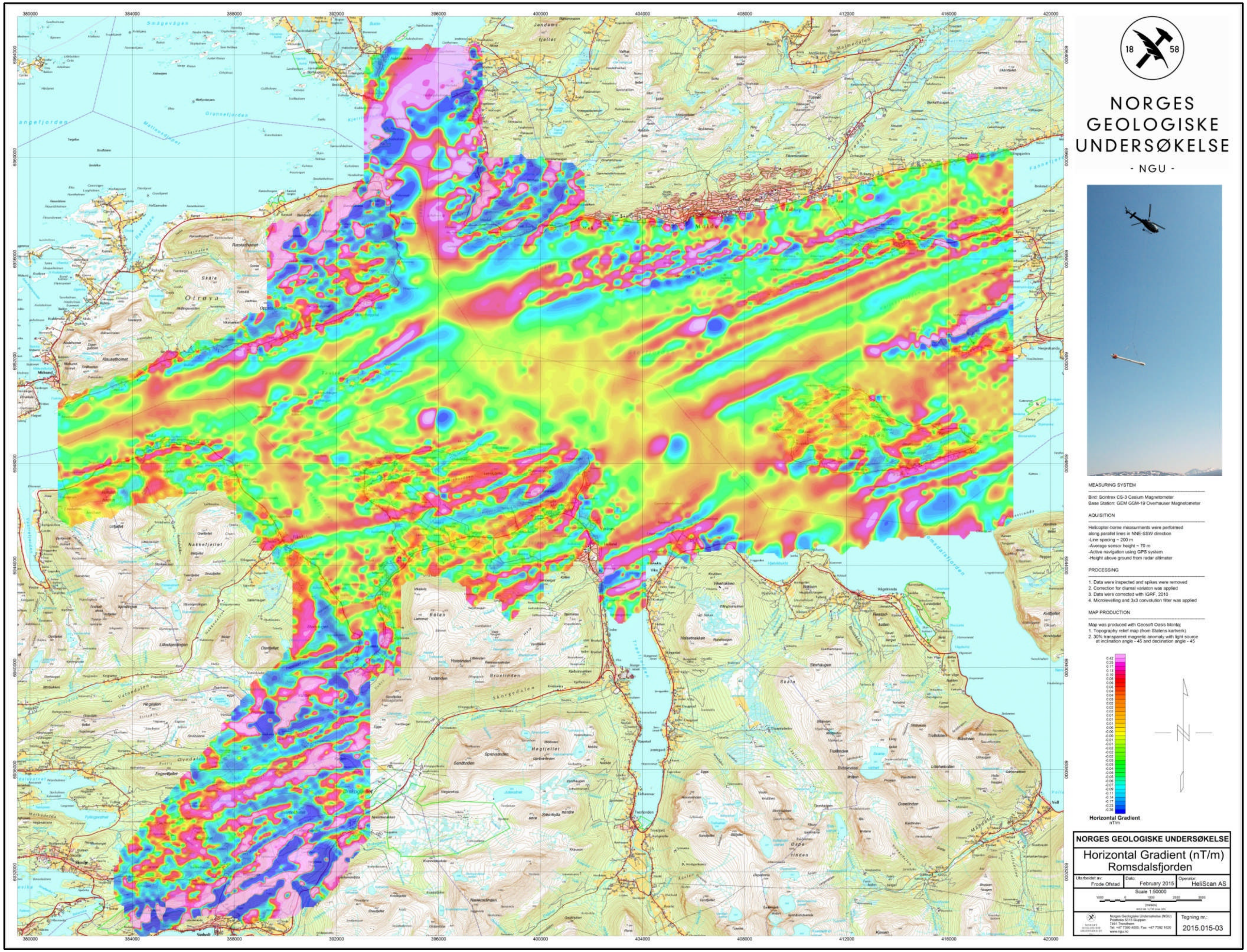

Figure 7: Magnetic Horizontal Gradient

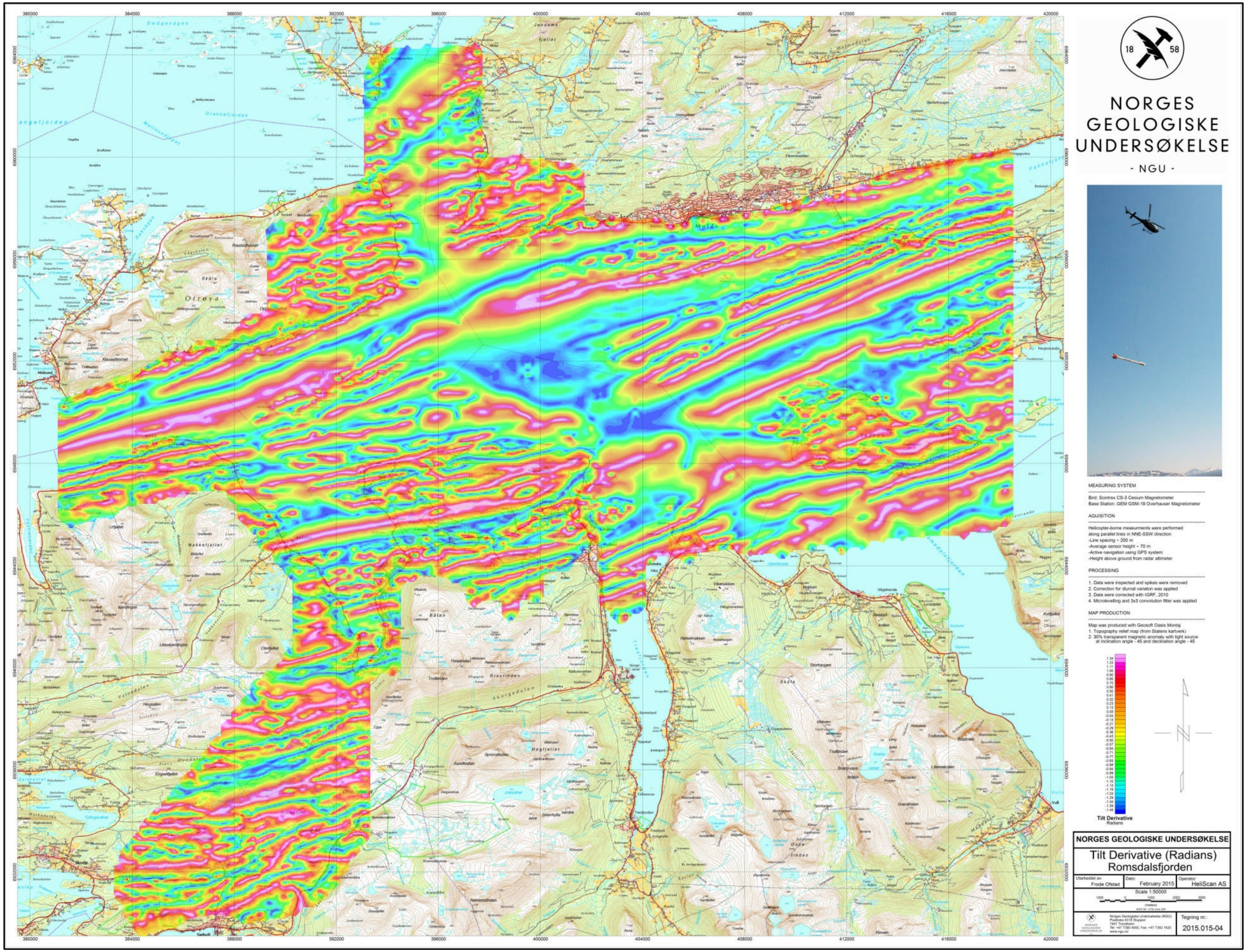

Figure 8: Magnetic Tilt Derivative

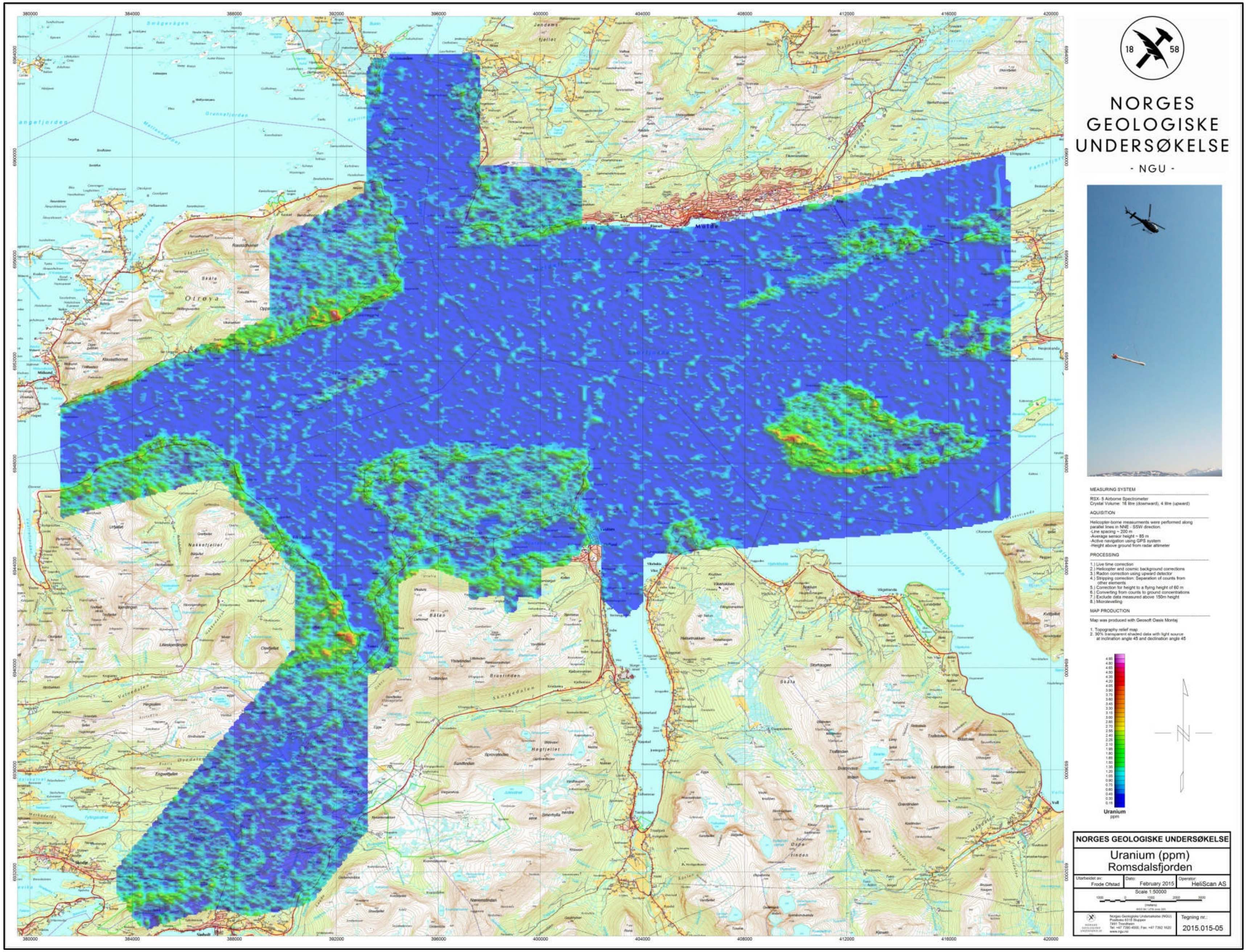

Figure 9: Uranium Ground Concentration

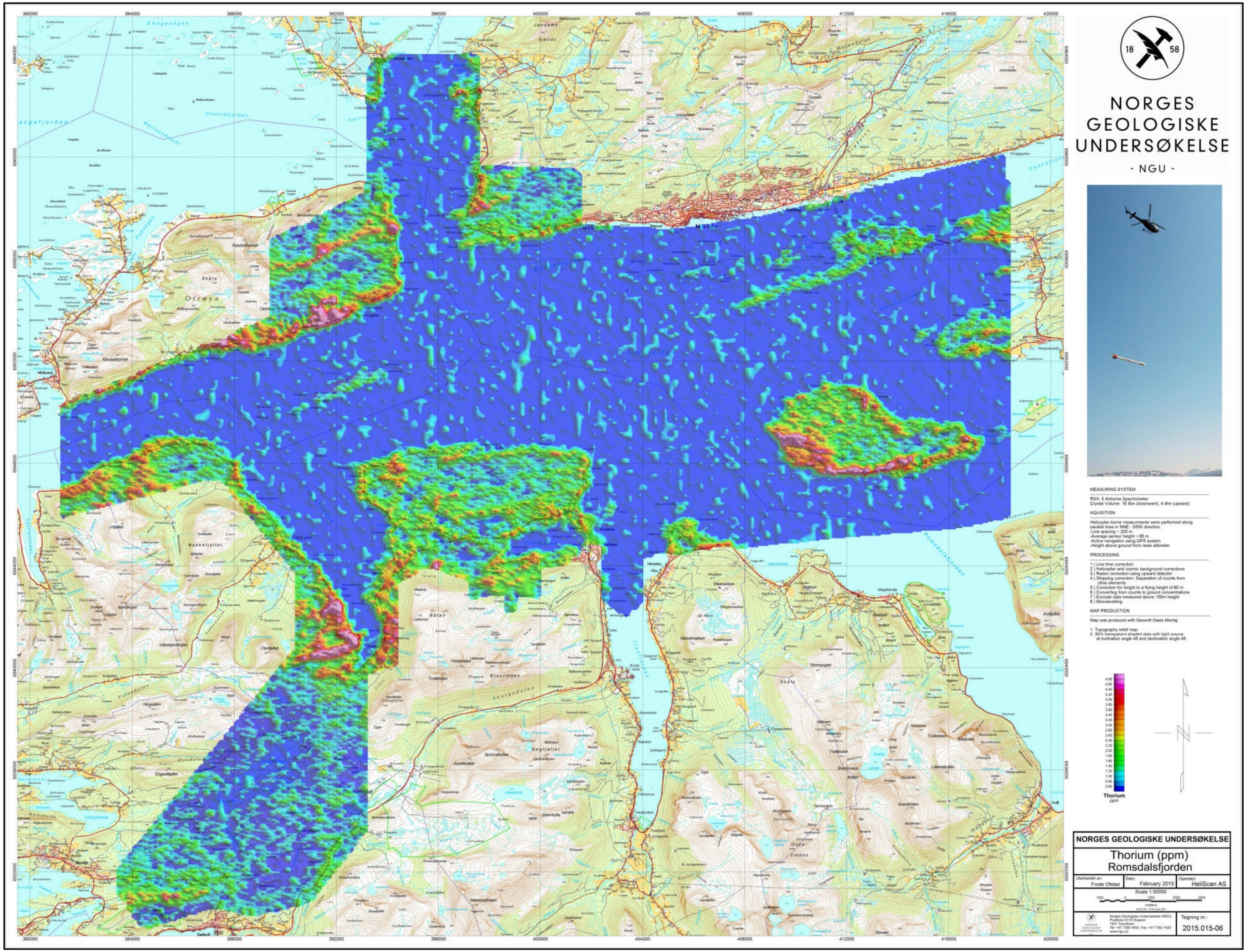

Figure 10: Thorium Ground Concentration

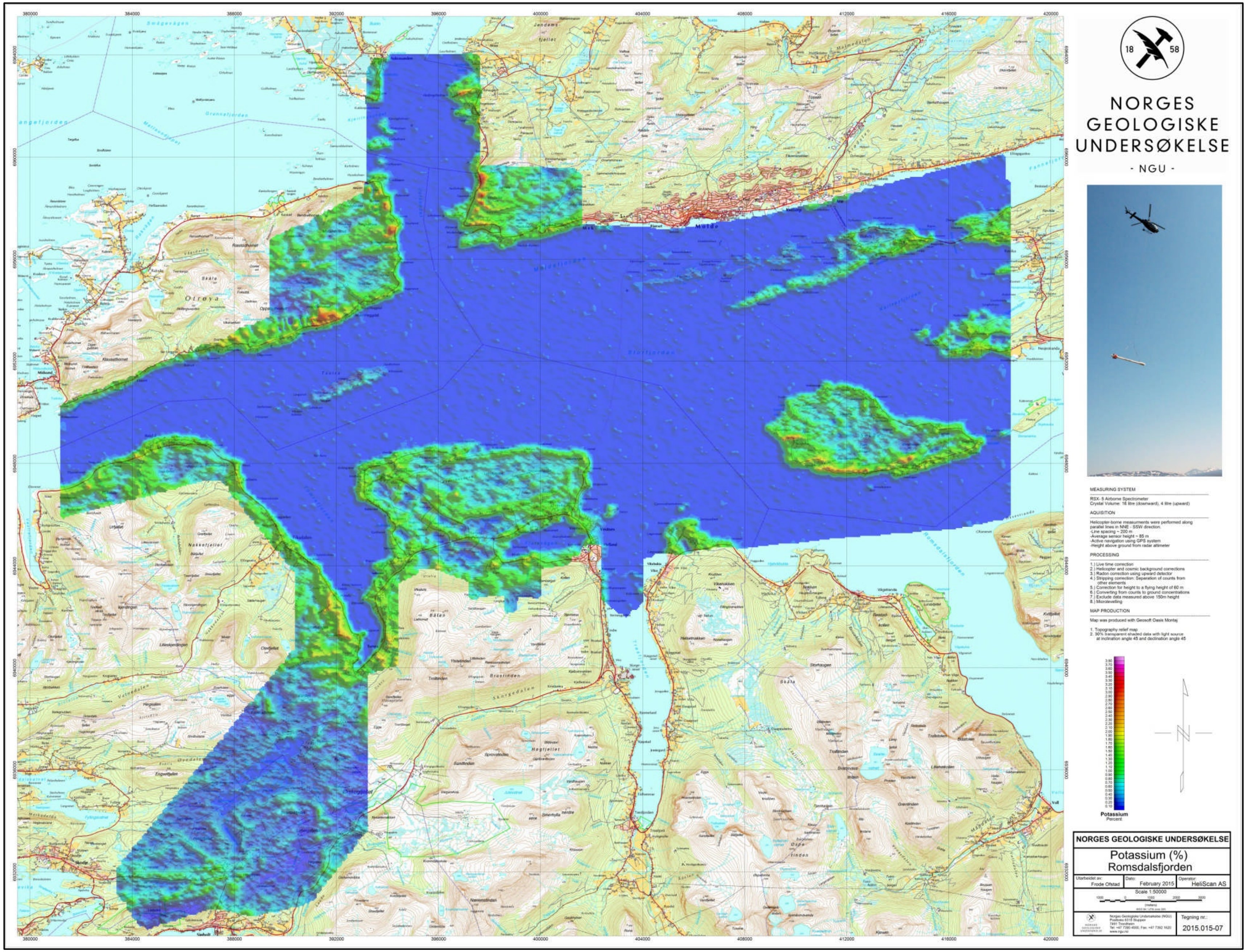

Figure 11: Potassium Ground Concentration

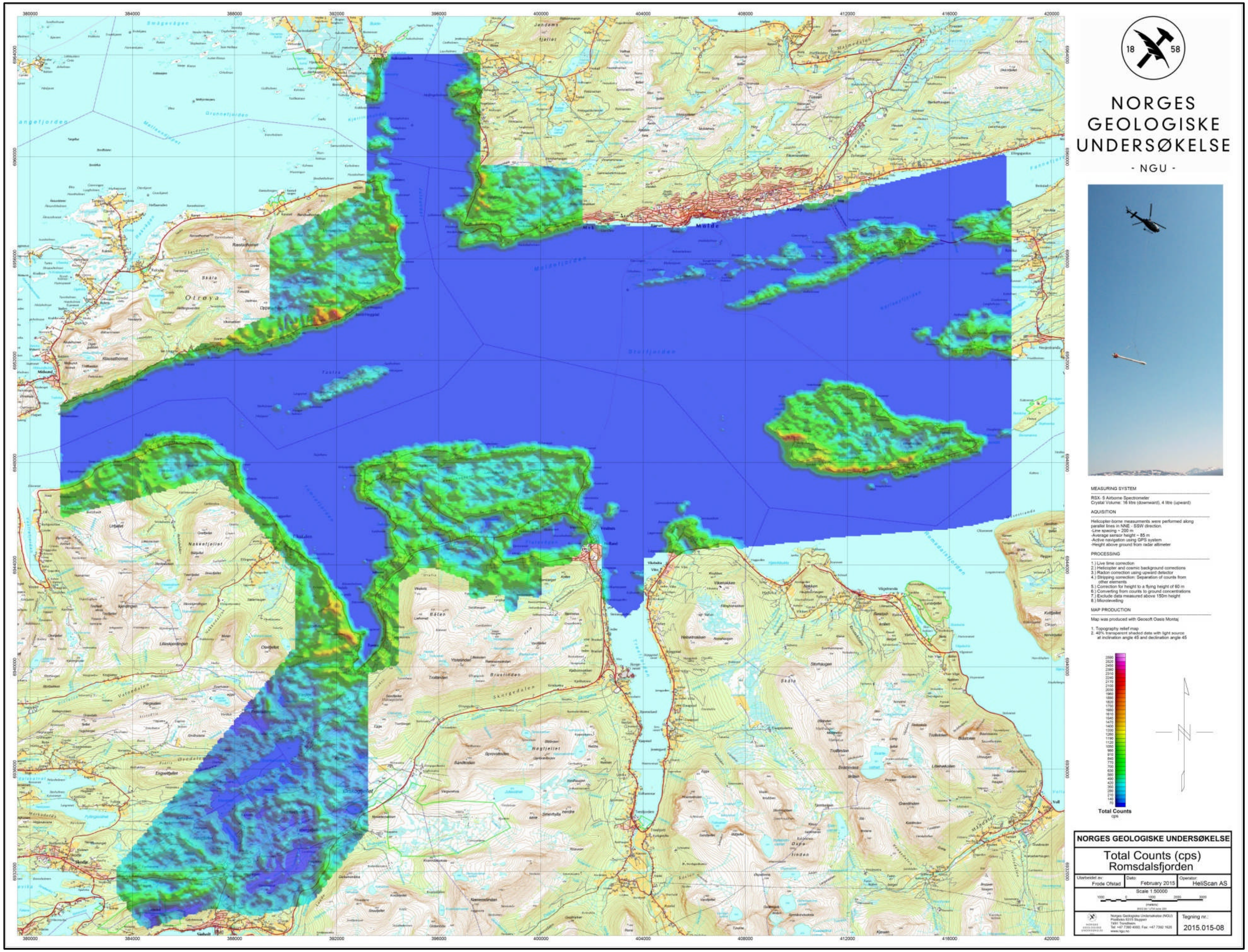

Figure 12: Radiometry Total Counts

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NORWAY
- NGU -

Geological Survey of Norway
PO Box 6315, Sluppen
N-7491 Trondheim, Norway

Visitor address
Leiv Eirikssons vei 39
7040 Trondheim

Tel (+ 47) 73 90 40 00
E-mail ngu@ngu.no
Web www.ngu.no/en-gb/