NGU REPORT
2016.037

Helicopter-borne magnetic,
electomagnetic and radiometric
geophysical survey in Raudsand area,
Nesset municipality,
Møre og Romsdal county

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REPORT

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Title: Helicopter-borne magnetic, electromagnetic and radiometric geophysical survey in Raudsand area, Nesset municipality, Møre og Romsdal county.

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Deposit name and grid-reference: Raudsand UTM 32 V 455000 – 6967000	**Number of pages:** 31 **Price (NOK):** 120,- **Map enclosures:**

Fieldwork carried out: October 2016	**Date of report:** 25.10.16	**Project no.:** 353204	**Person responsible:** Jan S. Rønning

Summary:

NGU conducted an airborne geophysical survey in the Raudsand area in October 2016 on request from the company Bergmesteren Raudsand AS. This report describes and documents the acquisition, processing and visualization of recorded datasets.

The geophysical survey results reported herein are from approximately 700 line km, covering an area of 70 km^2.

The NGU modified Geotech Ltd. Hummingbird frequency domain EM system supplemented by optically pumped Cesium magnetometer and a 1024 channels RSX-5 spectrometer was used for data acquisition.

The survey was flown with 100 m line spacing, line direction 160^o (NNW to SSE) at an average speed 80 km/h. The average terrain clearance of the EM bird was 47 m, and 75 meters for the spectrometer.

Collected data were processed at NGU using Geosoft Oasis Montaj software. Raw total magnetic field data were corrected for diurnal variation and leveled using standard micro levelling algorithm. Radiometric data were processed using standard procedures recommended by International Atomic Energy Association (IAEA).

EM data were filtered and leveled using both automated and manual levelling procedure. Apparent resistivity was calculated from in-phase and quadrature data for two coplanar frequencies (880 Hz and 6600 Hz), and for two coaxial frequencies (980 Hz and 7000 Hz) separately using a homogeneous half space model.

Magnetic and electromagnetic data were gridded using cell size of 25x25 m, while radiometric data was gridded with cell size of 50 x 50 m. All data were presented as 40% transparent shaded relief grids on top of topographic maps, at the scale of 1:100.000.

Keywords: Geophysics	Airborne	Magnetic
Electromagnetic	Gamma spectrometry	Radiometric
		Technical report

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1. INTRODUCTION

The company Bergmesteren Raudsand AS contracted NGU to fly a geophysical survey over the old mining area of Raudsand in Nesset municipality, a possible site for a future underground storage facility. The helicopter survey described in this report amounts to 700 line km, or 70 km^2 over the area, as shown in Figure 1.

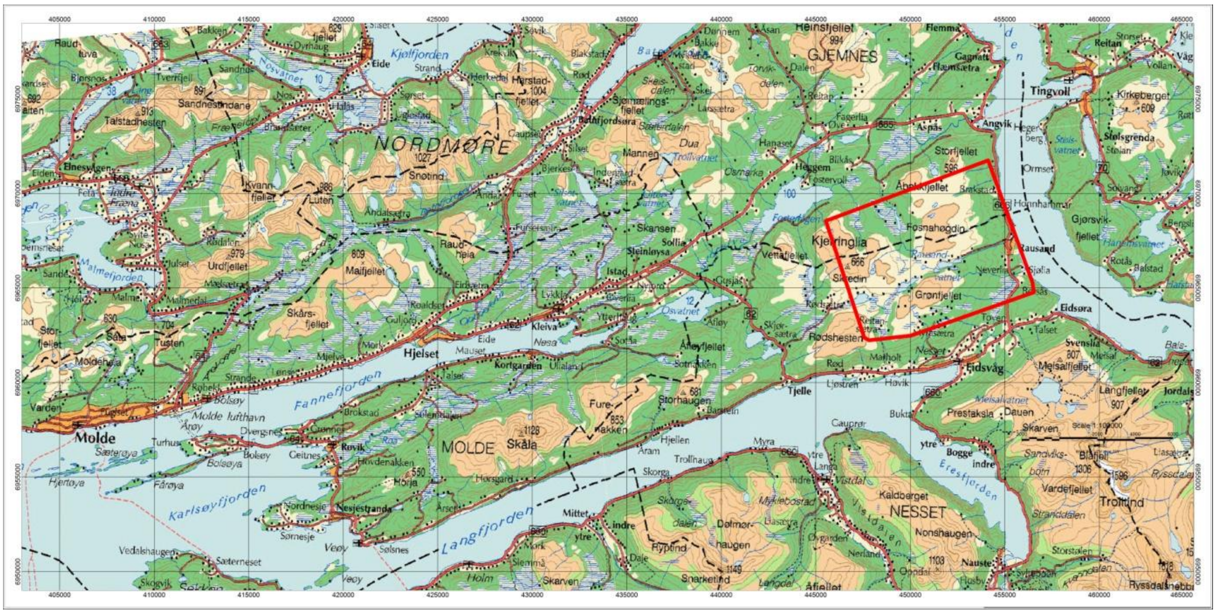

Figure 1: Raudsand survey area in Nesset municipality

Table 1. Flight specifications

Name	Surveyed lines (km)	Surveyed area (Km^2)	Flight direction	Average flight speed (km/h)
Raudsand	700	70	NNW-SSE	80

The objective of the airborne geophysical survey was to obtain a dense high-resolution magnetic, electromagnetic and radiometric dataset of the area of interest. The data is required to enhance the understanding of the geology and structures in the area, a possible future site for underground hazardous materials storage.

In this regard, the data can be used to map contacts and structural features within the area. It can help defining the boundaries of known zones of mineralization, their geological setting, and to locate possible fracture and weathered zones in the area of interest.

The survey incorporated the use of a Hummingbird™ 4-frequency electromagnetic system supplemented by 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).

2. SURVEY SPECIFICATIONS

2.1 Airborne Survey Parameters

NGU used a modified Hummingbird™ electromagnetic and magnetic helicopter survey system designed to obtain low level, slow speed, detailed airborne magnetic and electromagnetic data (Geotech 1997). The system was supplemented by 1024 channel gamma-ray spectrometer, installed under the belly of the helicopter, which was used to map total gamma counts and ground concentrations of U, Th and K.

The airborne survey was flown on October 11th and 12th 2016. A Eurocopter AS350-B3 helicopter from helicopter company HeliScan AS was used to tow the bird. The survey lines were spaced 100 m apart, with lines oriented at 160°. The magnetic and electromagnetic sensors are housed in a single 7.5 m long bird, flown at an average of about 47 m above the topographic surface.

Rugged terrain and abrupt changes in topography affected the aircraft pilot's ability to 'drape' the terrain; therefore the average instrumental height was higher than the standard survey instrumental height, which is defined as 30 m plus a height of obstacles (trees, power lines etc.) for EM and magnetic sensors.

The ground speed of the aircraft varied from 20 – 120 km/h depending on topography, wind direction and its magnitude. On average the ground speed during measurements is calculated to 80 km/h. Magnetic data was recorded at 0.2 second intervals resulting in approximately 4.4 m point spacing.

EM data were recorded at 0.1 second intervals resulting in data with a sample increment of 2.2 m along the ground in average. Spectrometry data was recorded every 1 second giving a point spacing of approximately 22 meters. The above parameters allow recognizing sufficient detail in the data to detect subtle anomalies that may represent mineralization and/or rocks of different lithological and petro-physical composition.

A base magnetometer to monitor diurnal variations in the magnetic field was located at Eidsvåg, UTM 32 6960400N, 452460 E, 1 km southwest of Eidsvåg. GEM GSM-19 base station magnetometer data were recorded once every 3 seconds. The CPU clock of the base magnetometer and the helicopter magnetometer were both synchronized to UTC (Universal Time Coordinates) through the built-in GPS receiver to allow correction of diurnals.

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 ± 5 m in the horizontal directions. The GPS receiver antenna was mounted internally in the cabin of the helicopter.

For quality control, the electromagnetic, magnetic and radiometric, altitude and navigation data were monitored on four separate windows in the operator's display during flight while they were recorded in three data ASCII streams to the PC hard disk drive. Spectrometry data were also recorded to an internal hard drive of the spectrometer. The data files were transferred to the field workstation via USB flash drive. The raw data files were backed up onto USB flash drive in the field.

2.2 Airborne Survey Instrumentation

Instrument specification is given in Table 2. Frequencies and coil configuration for the Hummingbird EM system is given in Table 3.

Table 2. Instrument Specifications

Instrument	Producer/Model	Accuracy / Sensitivity	Sampling frequency / interval
Magnetometer	Scintrex Cs-3	<2.5nT throughout range / 0.0006nT √Hz rms	5 Hz
Base magnetometer	GEM GSM-19	0.1 nT	3 s
Electromagnetic	Geotech Hummingbird	1 – 2 ppm	10 Hz
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 feet ± 5 % 500 – 2500 feet	1 Hz
Pressure/temperature	Honeywell PPT	± 0.03 % FS	1 Hz
Navigation	Topcon GPS-receiver	± 5 meter	1 Hz
Acquisition system	NGU custom software		

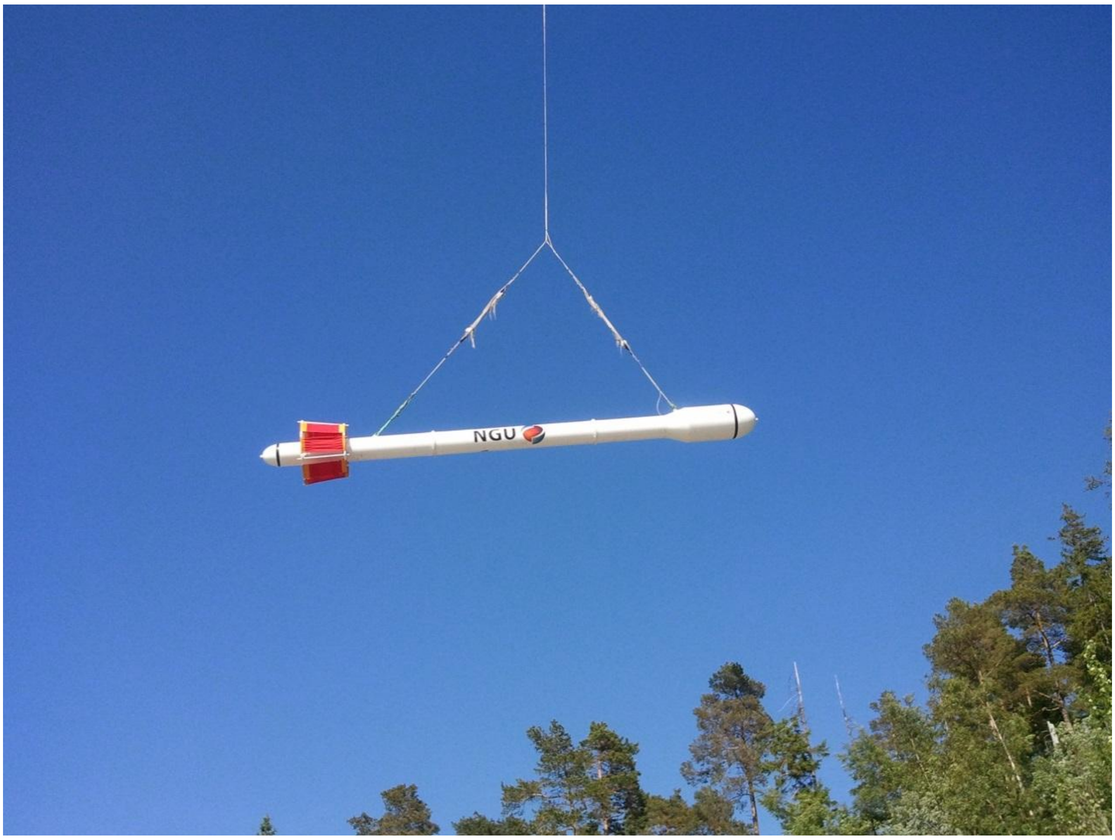

Figure 2: Hummingbird system in air

Table 3. Hummingbird EM system, frequency and coil configurations

Coils	Frequency	Orientation	Separation
A	7700 Hz	Coaxial	6.20 m
B	6600 Hz	Coplanar	6.20 m
C	980 Hz	Coaxial	6.025 m
D	880 Hz	Coplanar	6.025 m

2.3 Airborne Survey Logistics Summary

A summary of the survey specifications is shown in Table 4.

Table 4. Survey Specifications Summary

Parameter	Specifications
Traverse (survey) line spacing	100 meters
Traverse line direction	NNW-SSE (160°)
Nominal aircraft ground speed	20 - 120 km/h
Average aircraft ground speed	80 km/h
Average sensor terrain clearance Mag	47 m
Average sensor terrain clearance Rad	75 m
Sampling rates:	
Magnetometer	0.2 seconds
EM	0.1 seconds
Spectrometer, GPS, altimeter	1.0 second
Base Magnetometer	3.0 seconds

3. DATA PROCESSING AND PRESENTATION

All data were processed by Frode Ofstad at NGU. The ASCII data files were loaded into three separate Oasis Montaj databases. All three datasets were processed consequently according to processing flow charts shown in Appendix A1, A2 and A3.

3.1 Total Field Magnetic Data

At the first stage the raw magnetic data were visually inspected and spikes were removed manually. Non-linear filter was also applied to airborne raw data to eliminate short-period spikes. Typically, several corrections have to be applied to magnetic data before gridding - heading correction, lag correction and diurnal correction.

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 at given short time interval.

Diurnal variation channel was inspected for spikes, and spikes were removed manually if necessary. Magnetic diurnals that were recorded on the base station magnetometer were within the standard NGU specifications during the entire survey (Rønning 2013).

Diurnal variations were measured with GEM GSM-19 magnetometer. The base station computer clock was continuously synchronized with GPS clock. 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 ($\overline{B}_{\mathrm{B}}$ **)** was set equal to 51505 nT for this survey.

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 no more than 10 m **-** the value comparable with the precision of GPS. Flight 1 was lagged 0.2 sec, and flights 3 and 4 was lagged -0.2 sec to smooth he magnetic data grids.

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)

$$\mathbf{B}_{TA} = \mathbf{B}_{Tc} - IGRF \qquad (2)$$

IGRF 2015 model was employed in these calculations.

The total field anomaly data were split into lines and then were gridded using a minimum curvature method with a grid cell size of 25 meters. This cell size is close to one quarter of the 100m average line spacing. In order to remove small line-to-line levelling errors that were detected on the gridded magnetic anomaly data, the Geosoft Micro-levelling technique was applied on the flight line based magnetic database. Then, the micro-leveled channel was gridded using again a minimum curvature method with 25 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 stitched micro-leveled total magnetic anomaly grid. The magnitude of the horizontal gradient was calculated according to equation (3)

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

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

$$TD = \tan^{-1}\left(\frac{VG}{HG}\right) \qquad (4)$$

A 5x5 convolution filter was applied to smooth the resulted magnetic grids. The results are presented in a series of colored shaded relief maps (1:100.000). The maps are:

A. Total field magnetic anomaly
B. Horizontal gradient of total magnetic anomaly
C. Vertical gradient of total magnetic anomaly
D. Tilt Derivative (or Tilt angle) of the total magnetic anomaly

These maps are representative of the distribution of magnetization over the surveyed areas. The list of the produced maps is shown in Table 6.

3.2 Electromagnetic Data

The EM system transmits four fixed frequencies, and records an in-phase and a quadrature response for each of the four coil sets of the electromagnetic system. The received signals are processed and used for computation of an apparent resistivity.

In-phase and quadrature data was filtered with 10 fiducial non-linear filter to eliminate spherical spikes, which were represented as irregular noise of large amplitude in records and high frequency noise of bird electronics. Then, a 20 fiducial low-pass filter was applied to suppress instrumental and cultural noise. These filters were not able to suppress all the noise completely, due to irregular nature of noise. Also, shifts of 7000 IP and Q records, with amplitude of 5-10 ppm, was observed in most flights. Shifts were edited manually where possible.

In order to remove the effects of instrument drift caused by gradual temperature variations in the transmitting and receiving circuits, background responses are recorded during each flight. To obtain a background level, the bird is raised to an altitude of 1400 ft above the topographic surface so that no electromagnetic responses from the ground are present in the recorded traces.

The EM traces observed at this altitude correspond to a background (zero) level of the system. If these background levels are recorded at 20-30 minute intervals, then the drift of the system (assumed to be linear) can be removed from the data by resetting these points to the initial zero level of the system. The drift must be removed on a flight-by-flight basis, before any further processing is carried out. Geosoft HEM module was used for applying drift correction. Residual instrumental drift, usually small, but non-linear, was manually removed on line-to-line basis.

When levelling of the EM data was complete, apparent resistivity was calculated from in-phase and quadrature EM components using a homogeneous half space model of the earth (Geosoft HEM module) for frequencies 6600, 7000, 980 and 880 Hz. A threshold value of 3 ppm was set for inversion.

Secondary electromagnetic field decays rapidly with the distance (height of the sensors) – as z^{-2} – z^{-5} depending on the shape of the conductors and, at certain height, signals from the ground sources become comparable with instrumental noise. Levelling errors or precision of levelling can lead sometimes to appearance of artificial resistivity anomalies when data were collected at high instrumental altitude.

Application of threshold allows excluding such data from an apparent resistivity calculation, though not completely. It’s particularly noticeable in low frequencies datasets. Resistivity data were visually inspected; artificial anomalies associated with high altitude measurements were manually removed.

Data recorded at the height above 100 m were considered as non-reliable and removed from presentation. Remaining resistivity data were gridded with a cell size 25 m. Power lines strongly affected low frequency data – 880 and 980 Hz channels, and the most prominent noise from power lines were filtered manually.

3.3 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; 2003). 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 Potassium, Uranium and Thorium. Figure 3 shows an example of a Gamma-ray spectrum and the corresponding energy windows and radioisotopes (with peak energy in MeV) responsible for the radiation.

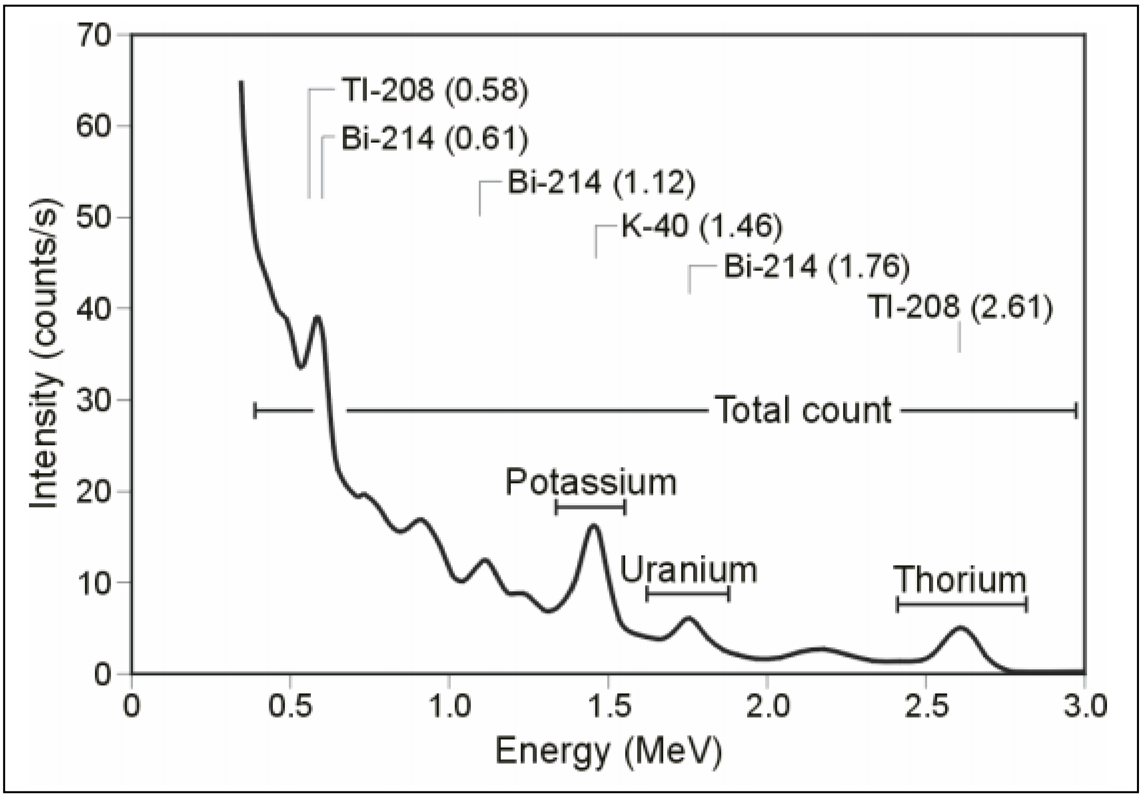

Figure 3: Gamma-ray spectrum with K, Th, U and Total Count windows.

Table 5. Specified channel windows for the 1024 RSX-5 system

Gamma-ray spectrum	Cosmic	Total count	K	U	Th
Down	1022	134-934	454-521	550-617	801-934
Up	1022			550-617	
Energy windows (MeV)	>3.07	0.41-2.81	1.37-1.57	1.66-1.86	2.41-2.81

The RSX-5 is a 1024 channel system with four downward and one upward looking detector, which means that the actual Gamma-ray spectrum is divided into 1024 channels. The first channel is reserved for the “Live Time” and the last for the Cosmic rays. Table 5 shows the channels that were used for the reduction of the spectrum.

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)

$$\text{“Live time”} = \text{“Real time”} - \text{“Dead time”} \tag{5}$$

where the “real time” or “acquisition time” is the elapsed time over which the spectrum is accumulated (about 1 second).

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:

$$C_{LT} = C_{RAW} \cdot \frac{Acquisition\ Time}{Live\ Time} \tag{6}$$

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

Cosmic and aircraft correction

Background radiation resulting from cosmic rays and aircraft contamination was removed from the total count, Potassium, Uranium, Thorium, upward Uranium channels using the following formula:

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

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. Using spectrometry data over-water, where there is no contribution from the ground sources, enables the calculation of the coefficients (a_C and b_C) for the linear equations that relate the cosmic corrected counts per second of Uranium channel with that of 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:

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

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 (Grasty et al, 1991) at the Geological Survey of Norway in Trondheim (see values in 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 and a, b, g, α, β, γ are Compton stripping coefficients. U_{ST}, Th_{ST} and K_{ST} are stripped values of U, Th and K.

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 was 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:

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

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

Finally, corrected count rates were converted to effective ground element concentrations using calibration values derived from calibration pads (Grasty et al, 1991) at the Geological Survey of Norway in Trondheim (see values in 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:

$$C_{CONC} = C_{60m} / C_{SENS\_60m} \tag{16}$$

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 spectrometry data were stored in a database and the ground concentrations were calculated following the processing steps. A list of the parameters used in these steps is given in Appendix A3.

Then the data were split in lines and ground concentrations of the three main natural radio-elements Potassium, Thorium and Uranium and total gamma-ray flux (total count) were gridded using a minimum curvature method with a grid cell size of 70 meters. In order to remove small line-to-line levelling errors appeared on those grids, the data were micro-leveled as in the case of the magnetic data, and re-gridded with the same grid cell size.

Quality of the radiometric data was within standard NGU specifications (Rønning 2013). For further reading regarding standard processing of airborne radiometric data, we recommend the publications from Minty et al. (1997).

A 3x3 convolution filter was applied to smooth the concentration grids. A list of the produced maps is shown in Table 6.

4. PRODUCTS

Processed digital data from the survey are presented as:

1. Three Geosoft XYZ (Confidential, property of Bergmesteren Raudsand as): Raudsand_Magnetics.XYZ, Raudsand_EM.xyz, Raudsand_Radiometrics.XYZ

2. Coloured maps at the scale 1:100.000 (see table 6) available from NGU on request.

3. Grid-files in Geotiff format (Confidential, property of Bergmesteren Raudsand as)

Table 6. Maps in scale 1:100.000, available from NGU on request.

Map #	Name
2016.037-01	Total magnetic field
2016.037-02	Magnetic Horizontal Gradient
2016.037-03	Magnetic Vertical Derivative
2016.037-04	Magnetic Tilt Derivative
2016.037-05	Apparent resistivity, Frequency 6600 Hz, coplanar coils
2016.037-06	Apparent resistivity, Frequency 880 Hz, coplanar coils
2014.060-07	Apparent resistivity, Frequency 7000 Hz, coaxial coils
2016.037-08	Apparent resistivity, Frequency 980 Hz, coaxial coils
2016.037-09	Radiometric Total counts
2016.037-10	Potassium ground concentration
2016.037-11	Uranium ground concentration
2016.037-12	Thorium ground concentration
2016.037-13	Radiometric Ternary Map

Downscaled images of the maps are shown on figures 4 to 17.

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Appendix A1: Flow chart 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
- Merge basemag data with EM database
- Import of diurnal data
- Correction of data for diurnal variation
- IGRF removed
- Splitting flight data by lines
- Gridding
- Microlevelling
- 5x5 convolution filter

Appendix A2: Flow chart of EM processing

Meaning of parameters is described in the referenced literature.

Processing flow:

- Filtering of in-phase and quadrature channels with non-linear and low pass filters
- Selective application of B-spline filter to 880 Hz 7 kHz and 980 Hz data
- Automated leveling
- Quality control
- Visual inspection of data.
- Splitting flight data by lines
- Manual removal of remaining part of instrumental drift
- Calculation of an apparent resistivity using both - in-phase and quadrature channels
- Gridding

Appendix A3: Flow chart of radiometry processing

Underlined processing stages are not only applied to the K, U and Th window, but also to the total count.
Meaning of parameters is described in the referenced literature.

- Airborne and cosmic correction (IAEA, 2003)
  Used parameters: determined by high altitude calibration flights (1500-9000 ft) at Frosta in 2013

Channel	Background	Cosmic
K	5.3584	0.057
U	1.428	0.0467
Th	0.0	0.0643
Uup	0.7051	0.0448
Total counts	42.726	1.0317

- Radon correction using upward detector method (IAEA, 2003)
  Used parameters determined from survey data over water and land at Raudsand on October 2015

Coefficient	Value	Coefficient	Value
a_u	0.11421	b_u	1.15911
a_K	3.79039	b_K	0
a_{Th}	0.39483	b_{Th}	0
a_{TC}	31.83204	b_{TC}	19.35168
a_1	0.003703	a_2	0.030736

- Stripping corrections (IAEA, 2003)
  Used parameters determined from measurements on calibrations pads at NGU on April 2015

Coefficient	Value
a	0.046856
b	0
c	0
α	0.30346
β	0.47993
γ	0.82316

- Height correction to a height of 60 m
  Parameters determined by high altitude calibration flights (100 – 700 ft). The average values from tests performed at Frosta (2014) were used. Attenuation factors in 1/m:

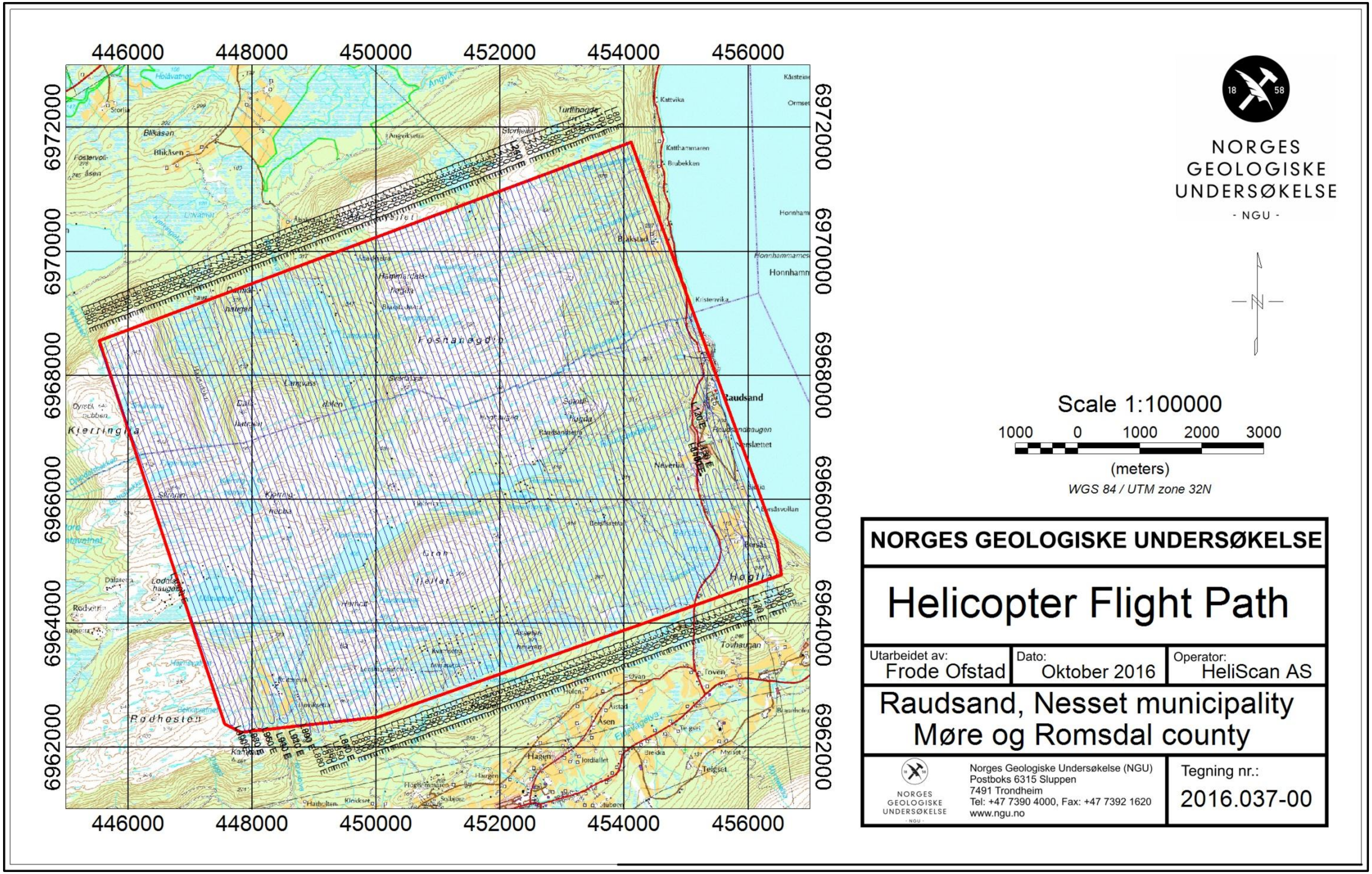
Channel	Attenuation factor
K	-0.009523
U	-0.006687
Th	-0.007394
TC	-0.00773

- Converting counts at 60 m heights to element concentration on the ground
  Used parameters determined from measurements on calibrations pads at NGU on April 2015

Channel	Sensitivity
K (%/count)	0.007458
U (ppm/count)	0.08773
Th (ppm/count)	0.15666

- Microlevelling using Geosoft menu and smoothening by a convolution filtering

Microlevelling parameters	Value
De-corrugation cutoff wavelength (m)	800
Cell size for gridding (m)	50
Naudy (1968) Filter length (m)	500



NORGES GEOLOGISKE UNDERSØKELSE

Helicopter Flight Path

Utarbeidet av: Frode Ofstad

Dato: Oktober 2016

Operator: HeliScan AS

Raudsand, Nesset municipality
Møre og Romsdal county

NORGES
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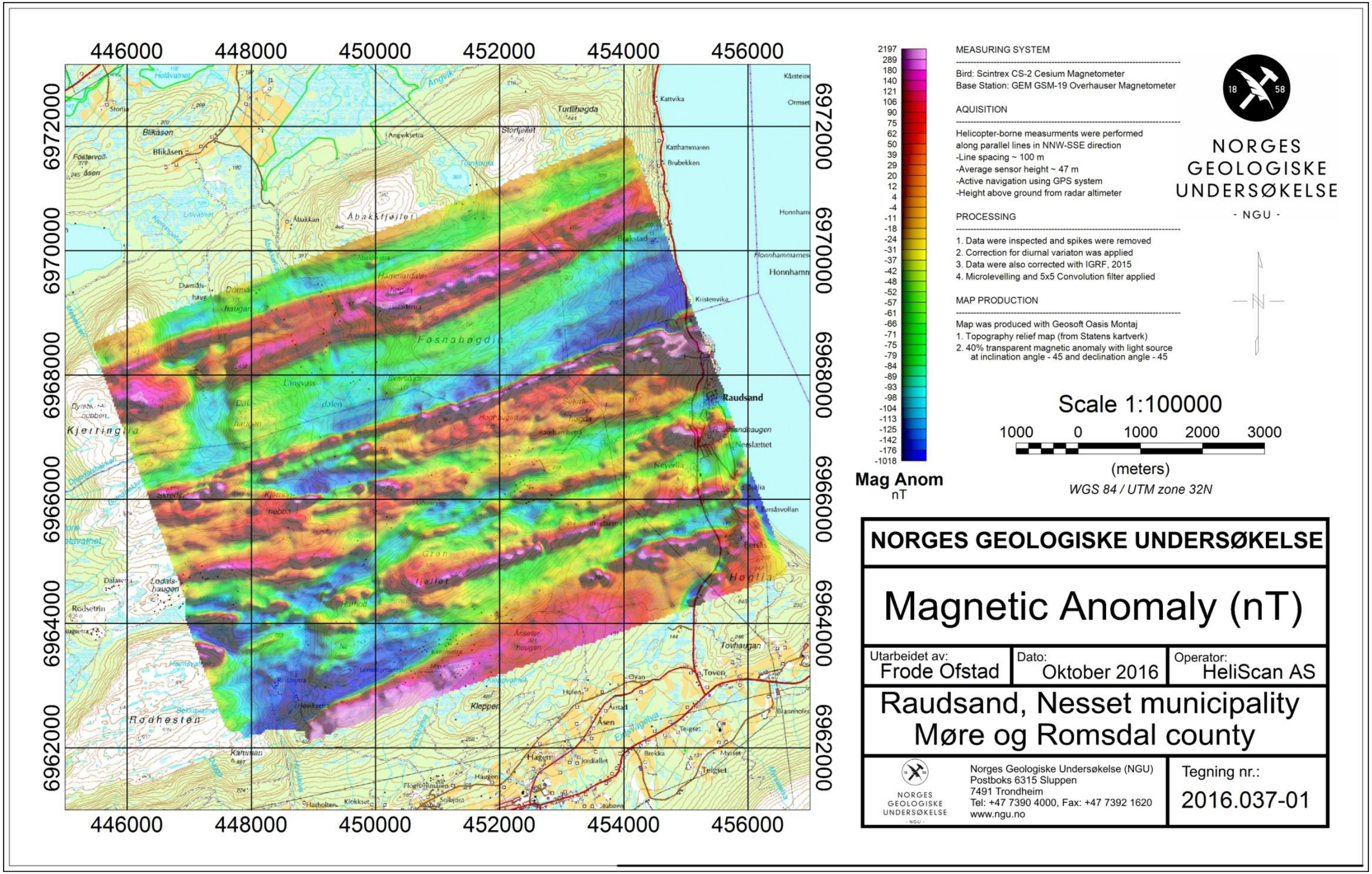
Norges Geologiske Undersøkelse (NGU)
Postboks 6315 Sluppen
7491 Trondheim
Tel: +47 7390 4000, Fax: +47 7392 1620
www.ngu.no

Tegning nr.: 2016.037-00

Figure 4: Raudsand survey area with flight path



MEASURING SYSTEM

Bird: Scintrex CS-2 Cesium Magnetometer
Base Station: GEM GSM-19 Overhauser Magnetometer

AQUISITION

Helicopter-borne measurments were performed along parallel lines in NNW-SSE direction
-Line spacing ~ 100 m
-Average sensor height ~ 47 m
-Active navigation using GPS system
-Height above ground from radar altimeter

PROCESSING

1. Data were inspected and spikes were removed
2. Correction for diurnal variaton was applied
3. Data were also corrected with IGRF, 2015
4. Microlevelling and 5x5 Convolution filter applied

MAP PRODUCTION

Map was produced with Geosoft Oasis Montaj
1. Topography relief map (from Statens kartverk)
2. 40% transparent magnetic anomaly with light source at inclination angle - 45 and declination angle - 45

NORGES GEOLOGISKE UNDERSØKELSE

Magnetic Anomaly (nT)

Utarbeidet av:	Dato:	Operator:
Frode Ofstad	Oktober 2016	HeliScan AS

Raudsand, Nesset municipality
Møre og Romsdal county

Norges Geologiske Undersøkelse (NGU)
Postboks 6315 Sluppen
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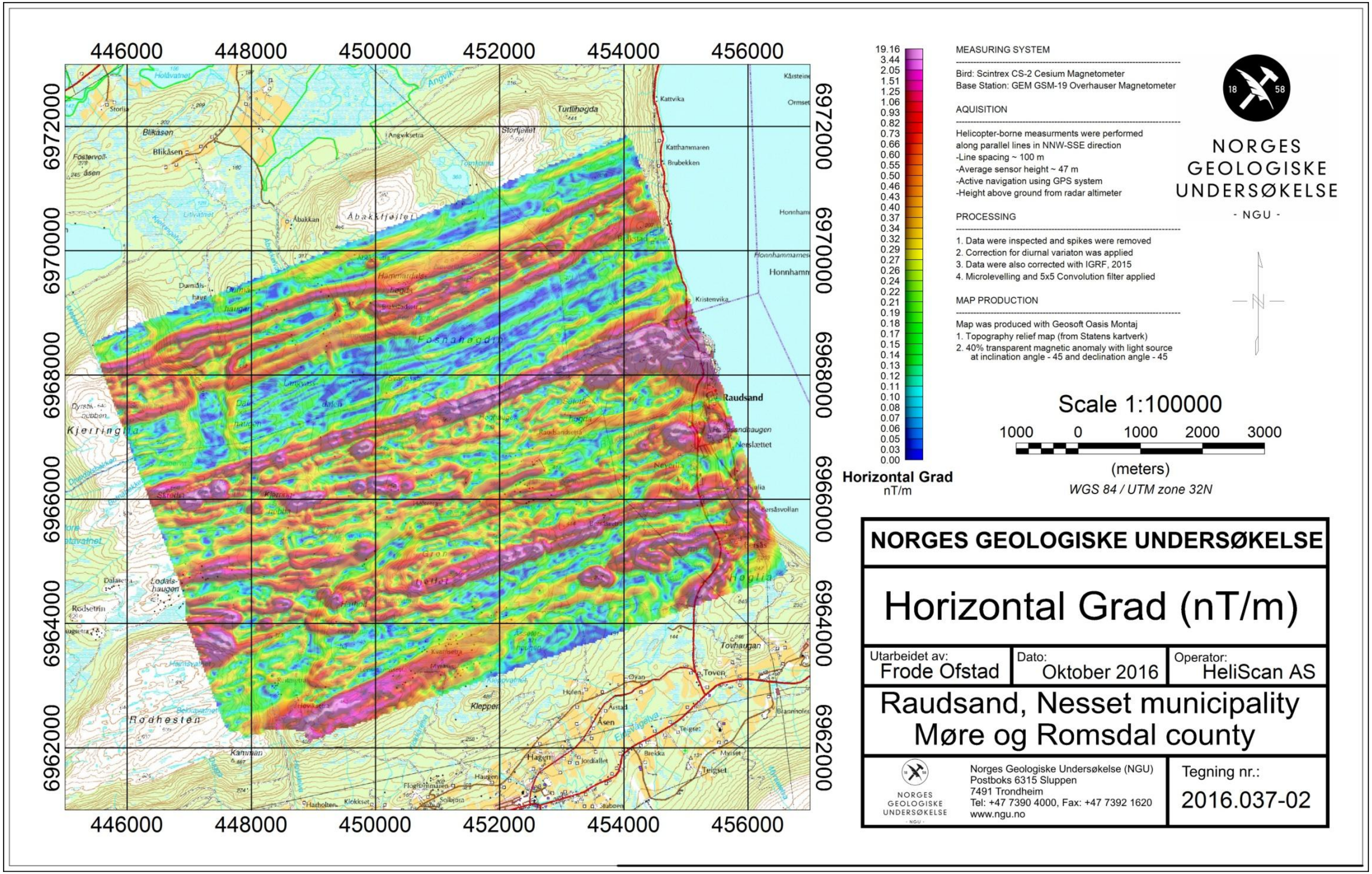
Tegning nr.:
2016.037-01

Figure 5: Total Magnetic Field



MEASURING SYSTEM

Bird: Scintrex CS-2 Cesium Magnetometer
Base Station: GEM GSM-19 Overhauser Magnetometer

AQUISITION

Helicopter-borne measurments were performed along parallel lines in NNW-SSE direction
-Line spacing ~ 100 m
-Average sensor height ~ 47 m
-Active navigation using GPS system
-Height above ground from radar altimeter

PROCESSING

1. Data were inspected and spikes were removed
2. Correction for diurnal variaton was applied
3. Data were also corrected with IGRF, 2015
4. Microlevelling and 5x5 Convolution filter applied

MAP PRODUCTION

Map was produced with Geosoft Oasis Montaj
1. Topography relief map (from Statens kartverk)
2. 40% transparent magnetic anomaly with light source at inclination angle - 45 and declination angle - 45

NORGES GEOLOGISKE UNDERSØKELSE
- NGU -

NORGES GEOLOGISKE UNDERSØKELSE

Horizontal Grad (nT/m)

Utarbeidet av: Frode Ofstad
Dato: Oktober 2016
Operator: HeliScan AS

Raudsand, Nesset municipality
Møre og Romsdal county

Norges Geologiske Undersøkelse (NGU)
Postboks 6315 Sluppen
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Tegning nr.: 2016.037-02

Figure 6: Magnetic Horizontal Gradient

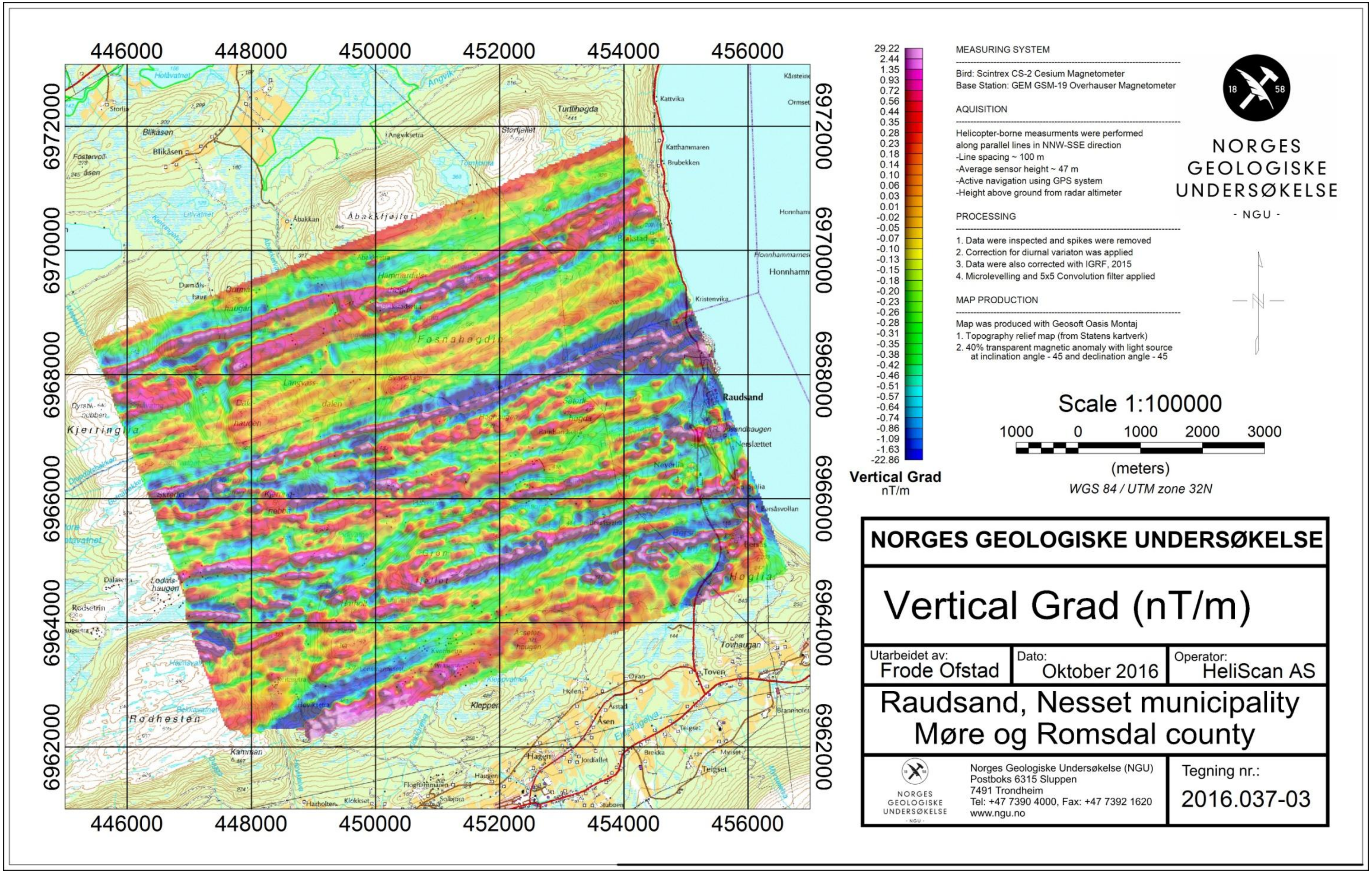
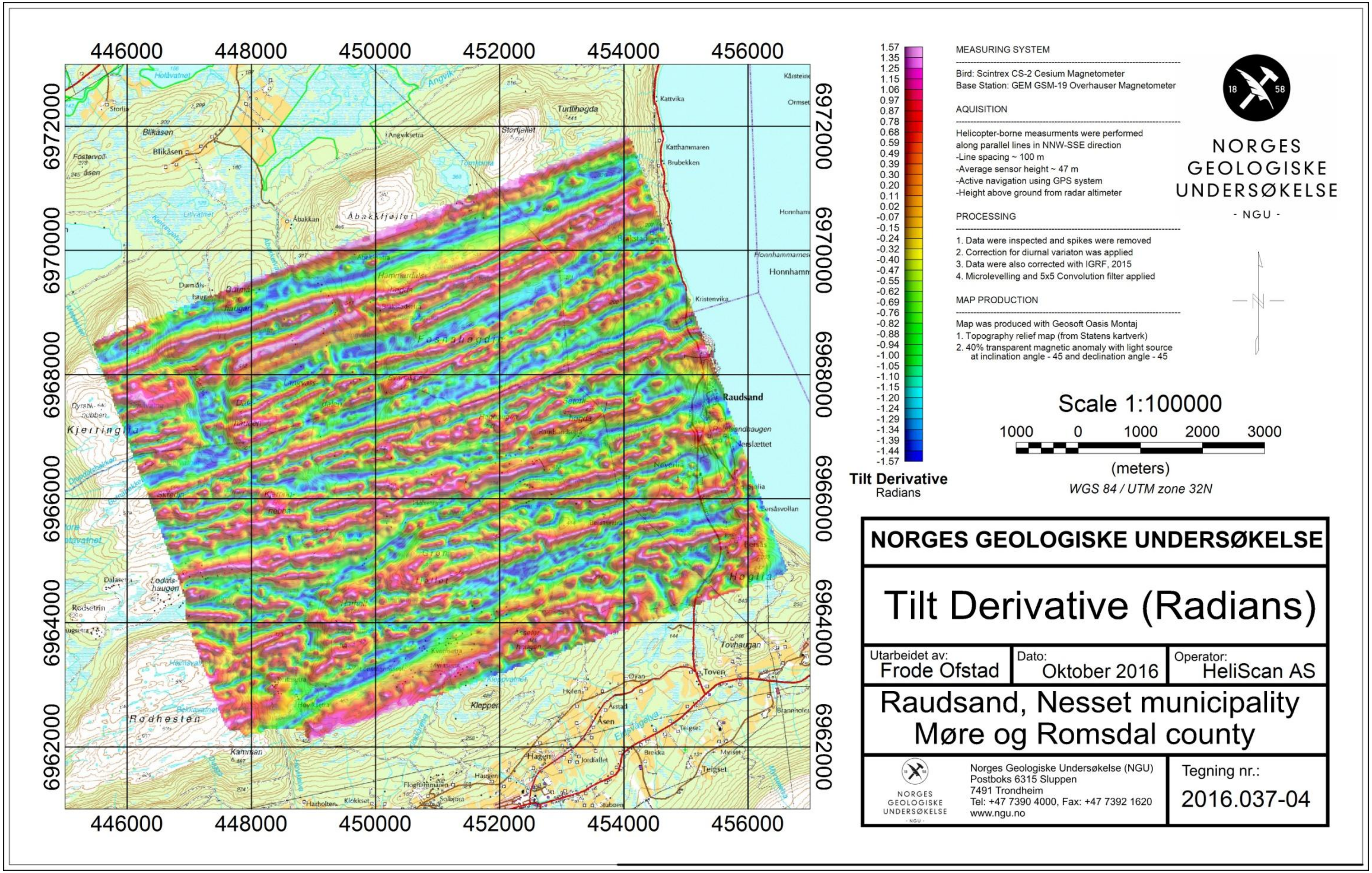


Figure 7: Magnetic Vertical Derivative



MEASURING SYSTEM

Bird: Scintrex CS-2 Cesium Magnetometer
Base Station: GEM GSM-19 Overhauser Magnetometer

AQUISITION

Helicopter-borne measurments were performed along parallel lines in NNW-SSE direction
-Line spacing ~ 100 m
-Average sensor height ~ 47 m
-Active navigation using GPS system
-Height above ground from radar altimeter

PROCESSING

1. Data were inspected and spikes were removed
2. Correction for diurnal variaton was applied
3. Data were also corrected with IGRF, 2015
4. Microlevelling and 5x5 Convolution filter applied

MAP PRODUCTION

Map was produced with Geosoft Oasis Montaj
1. Topography relief map (from Statens kartverk)
2. 40% transparent magnetic anomaly with light source at inclination angle - 45 and declination angle - 45

NORGES GEOLOGISKE UNDERSØKELSE
- NGU -

NORGES GEOLOGISKE UNDERSØKELSE

Tilt Derivative (Radians)

Utarbeidet av:	Dato:	Operator:
Frode Ofstad	Oktober 2016	HeliScan AS

Raudsand, Nesset municipality
Møre og Romsdal county

Norges Geologiske Undersøkelse (NGU)
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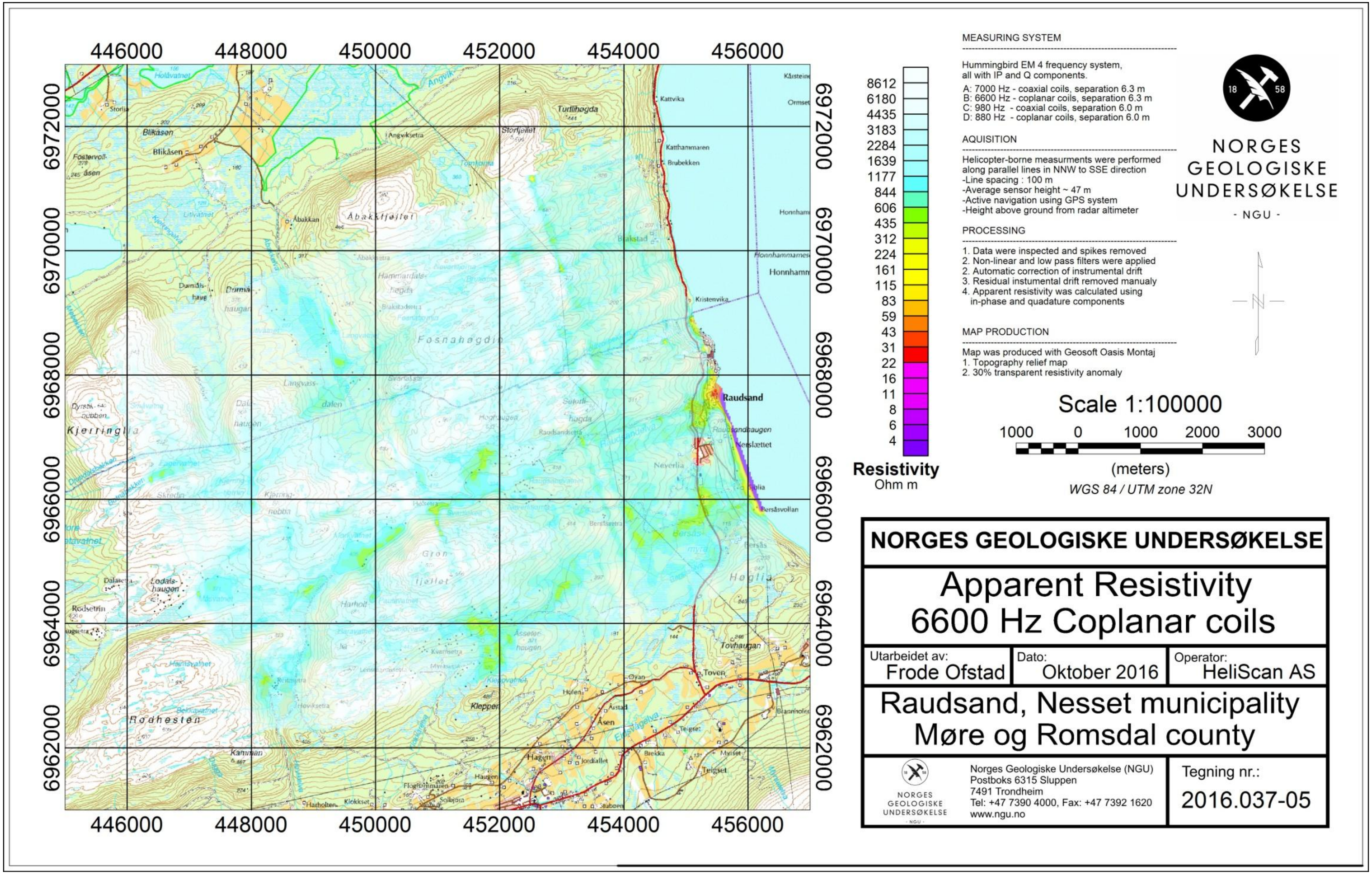
Tegning nr.:
2016.037-04

Figure 8: Magnetic Tilt Derivative



MEASURING SYSTEM

Hummingbird EM 4 frequency system,
all with IP and Q components.
A: 7000 Hz - coaxial coils, separation 6.3 m
B: 6600 Hz - coplanar coils, separation 6.3 m
C: 980 Hz - coaxial coils, separation 6.0 m
D: 880 Hz - coplanar coils, separation 6.0 m

AQUISITION

Helicopter-borne measurments were performed along parallel lines in NNW to SSE direction
-Line spacing : 100 m
-Average sensor height ~ 47 m
-Active navigation using GPS system
-Height above ground from radar altimeter

PROCESSING

1. Data were inspected and spikes removed
2. Non-linear and low pass filters were applied
3. Automatic correction of instrumental drift
4. Residual instumental drift removed manualy
5. Apparent resistivity was calculated using in-phase and quadature components

MAP PRODUCTION

Map was produced with Geosoft Oasis Montaj
1. Topography relief map
2. 30% transparent resistivity anomaly

NORGES GEOLOGISKE UNDERSØKELSE
- NGU -

NORGES GEOLOGISKE UNDERSØKELSE

Apparent Resistivity
6600 Hz Coplanar coils

Utarbeidet av:	Dato:	Operator:
Frode Ofstad	Oktober 2016	HeliScan AS

Raudsand, Nesset municipality
Møre og Romsdal county

Norges Geologiske Undersøkelse (NGU)
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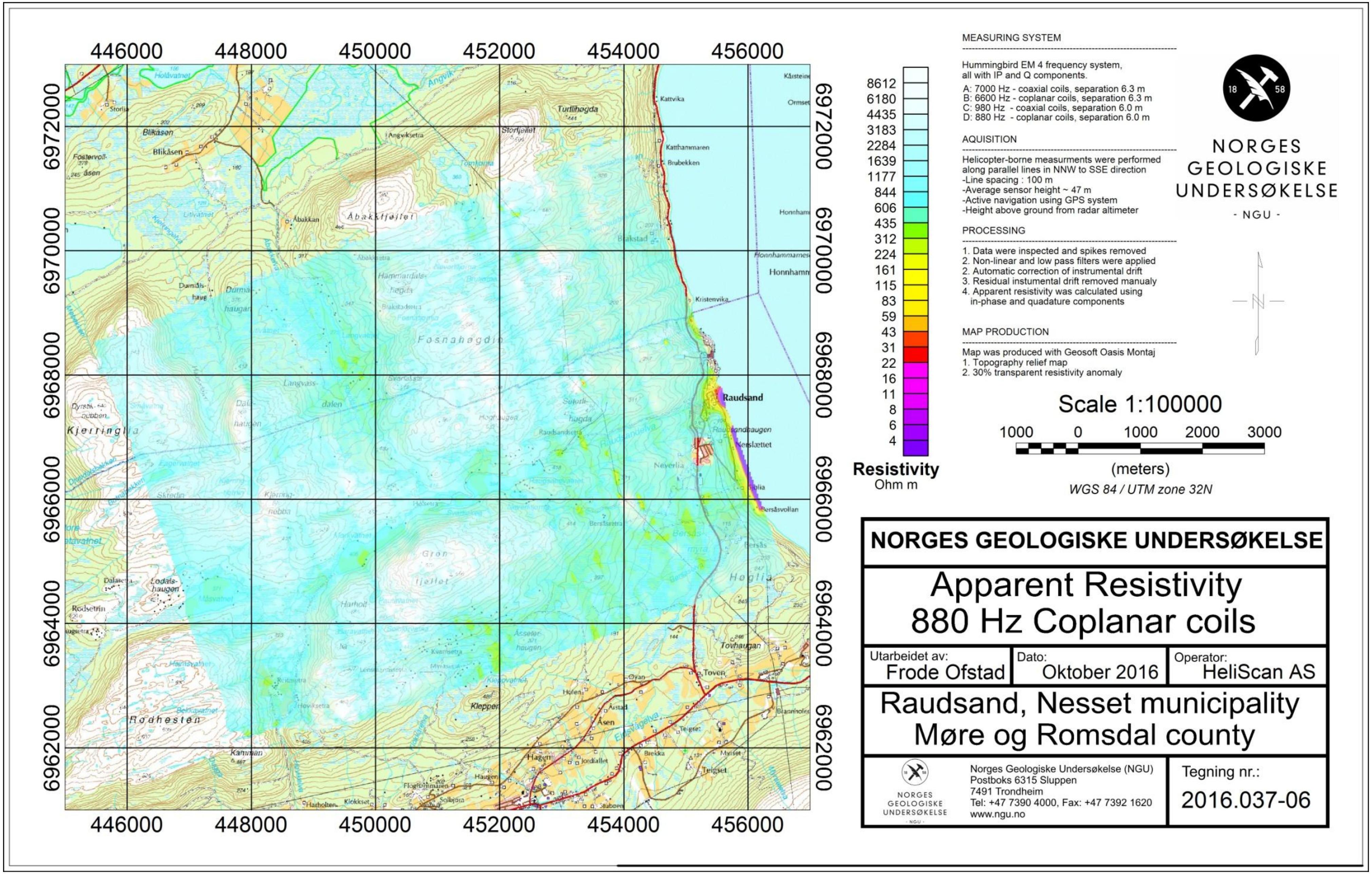
Tegning nr.:
2016.037-05

Figure 9: Apparent resistivity. Frequency 6600 Hz, Coplanar coils



MEASURING SYSTEM

Hummingbird EM 4 frequency system,
all with IP and Q components.

A: 7000 Hz - coaxial coils, separation 6.3 m
B: 6600 Hz - coplanar coils, separation 6.3 m
C: 980 Hz - coaxial coils, separation 6.0 m
D: 880 Hz - coplanar coils, separation 6.0 m

AQUISITION

Helicopter-borne measurments were performed along parallel lines in NNW to SSE direction
-Line spacing : 100 m
-Average sensor height ~ 47 m
-Active navigation using GPS system
-Height above ground from radar altimeter

PROCESSING

1. Data were inspected and spikes removed
2. Non-linear and low pass filters were applied
2. Automatic correction of instrumental drift
3. Residual instumental drift removed manualy
4. Apparent resistivity was calculated using in-phase and quadature components

MAP PRODUCTION

Map was produced with Geosoft Oasis Montaj
1. Topography relief map
2. 30% transparent resistivity anomaly

NORGES GEOLOGISKE UNDERSØKELSE

Apparent Resistivity
880 Hz Coplanar coils

Utarbeidet av:	Dato:	Operator:
Frode Ofstad	Oktober 2016	HeliScan AS

Raudsand, Nesset municipality
Møre og Romsdal county

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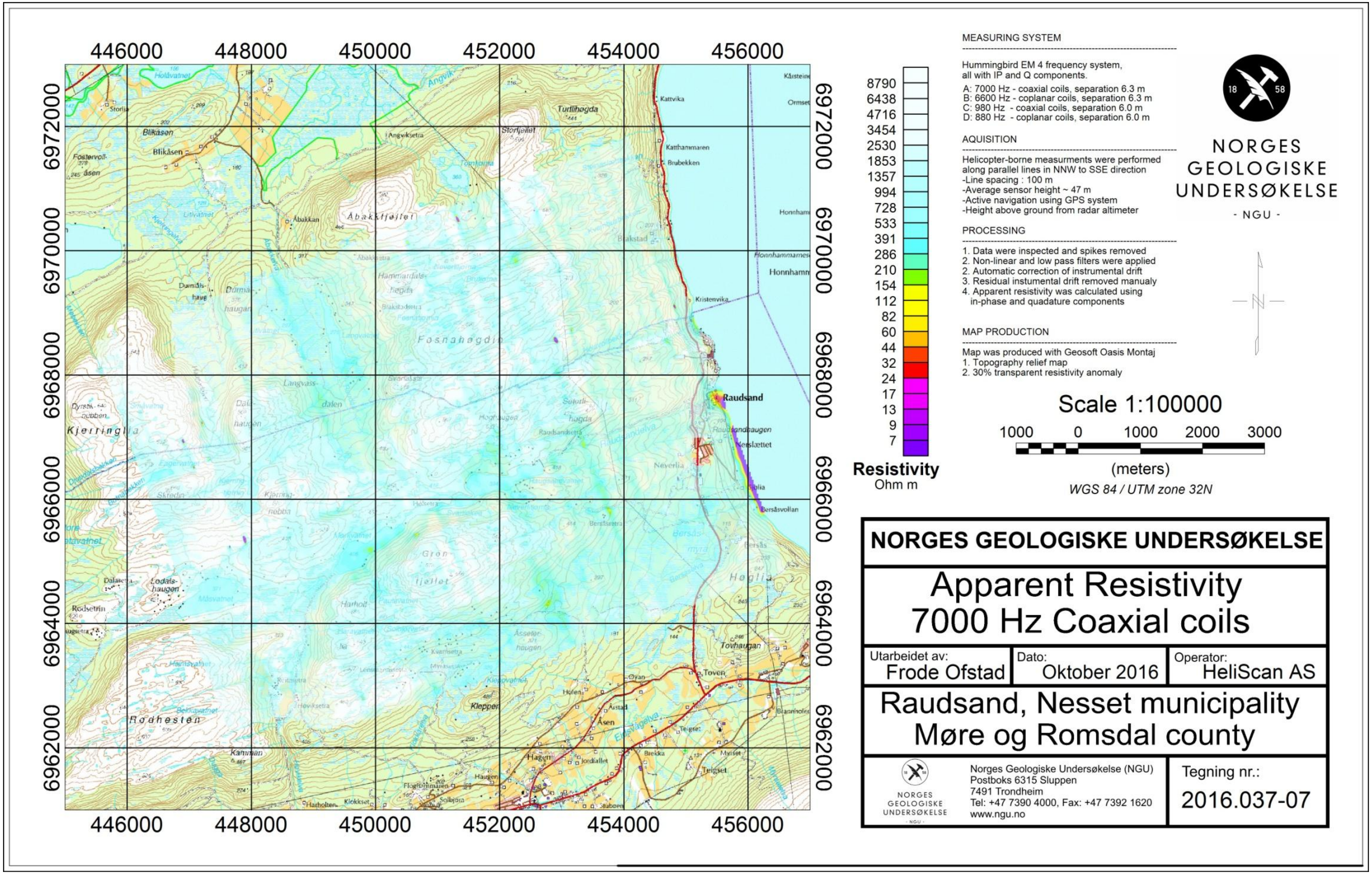
Tegning nr.:
2016.037-06

Figure 10: Apparent resistivity. Frequency 880 Hz, Coplanar coils



MEASURING SYSTEM

Hummingbird EM 4 frequency system, all with IP and Q components.

A: 7000 Hz - coaxial coils, separation 6.3 m
B: 6600 Hz - coplanar coils, separation 6.3 m
C: 980 Hz - coaxial coils, separation 6.0 m
D: 880 Hz - coplanar coils, separation 6.0 m

AQUISITION

Helicopter-borne measurments were performed along parallel lines in NNW to SSE direction
-Line spacing : 100 m
-Average sensor height ~ 47 m
-Active navigation using GPS system
-Height above ground from radar altimeter

PROCESSING

1. Data were inspected and spikes removed
2. Non-linear and low pass filters were applied
3. Automatic correction of instrumental drift
3. Residual instumental drift removed manualy
4. Apparent resistivity was calculated using in-phase and quadature components

MAP PRODUCTION

Map was produced with Geosoft Oasis Montaj
1. Topography relief map
2. 30% transparent resistivity anomaly

NORGES GEOLOGISKE UNDERSØKELSE

Apparent Resistivity
7000 Hz Coaxial coils

Utarbeidet av: Frode Ofstad
Dato: Oktober 2016
Operator: HeliScan AS

Raudsand, Nesset municipality
Møre og Romsdal county

Norges Geologiske Undersøkelse (NGU)
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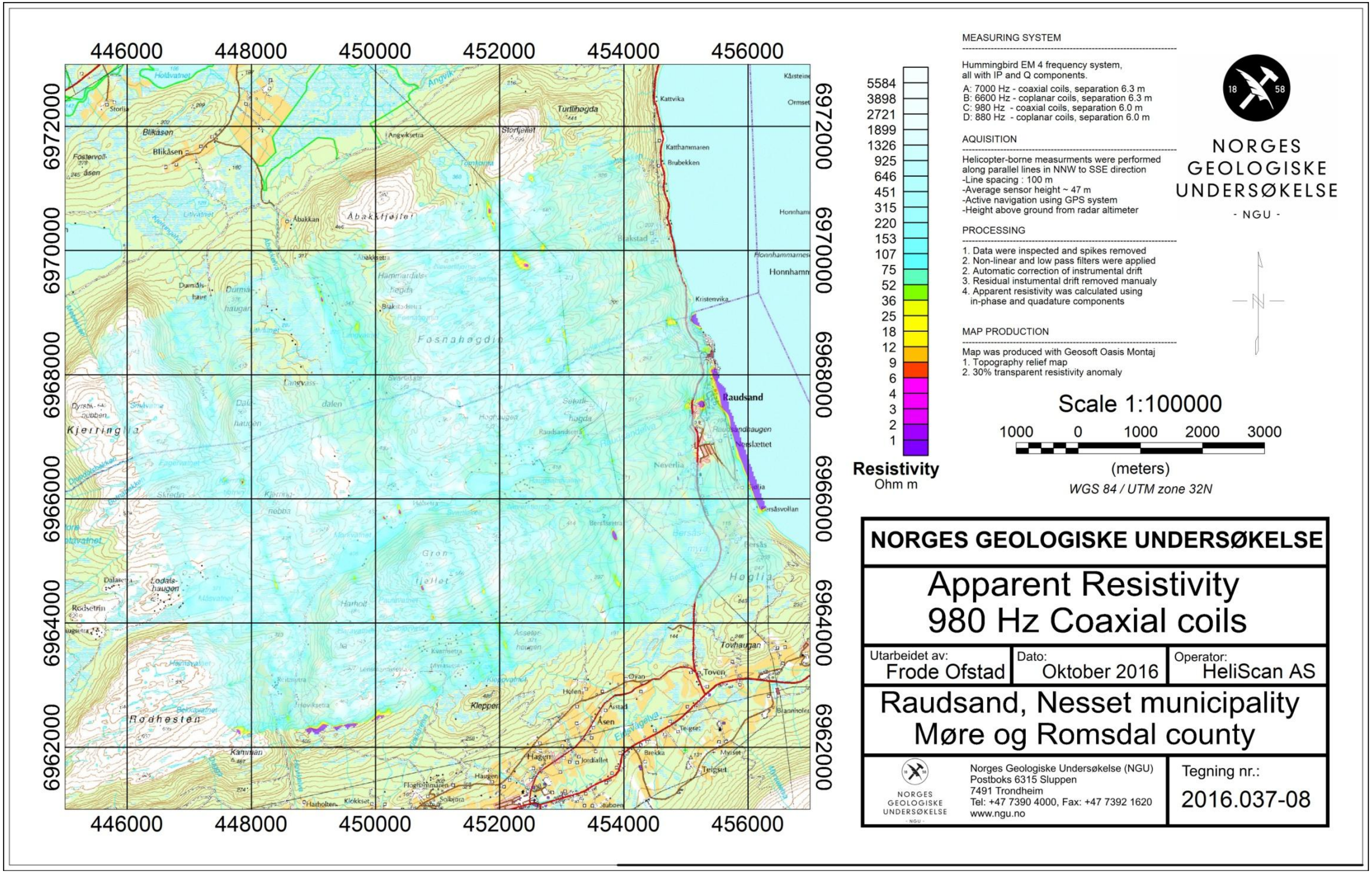
Tegning nr.: 2016.037-07

Figure 11: Apparent resistivity. Frequency 7000 Hz, Coaxial coils



MEASURING SYSTEM

Hummingbird EM 4 frequency system, all with IP and Q components.

A: 7000 Hz - coaxial coils, separation 6.3 m
B: 6600 Hz - coplanar coils, separation 6.3 m
C: 980 Hz - coaxial coils, separation 6.0 m
D: 880 Hz - coplanar coils, separation 6.0 m

AQUISITION

Helicopter-borne measurments were performed along parallel lines in NNW to SSE direction
-Line spacing : 100 m
-Average sensor height ~ 47 m
-Active navigation using GPS system
-Height above ground from radar altimeter

PROCESSING

1. Data were inspected and spikes removed
2. Non-linear and low pass filters were applied
3. Automatic correction of instrumental drift
3. Residual instumental drift removed manualy
4. Apparent resistivity was calculated using in-phase and quadature components

MAP PRODUCTION

Map was produced with Geosoft Oasis Montaj
1. Topography relief map
2. 30% transparent resistivity anomaly

NORGES GEOLOGISKE UNDERSØKELSE - NGU -

NORGES GEOLOGISKE UNDERSØKELSE

Apparent Resistivity
980 Hz Coaxial coils

Utarbeidet av:	Dato:	Operator:
Frode Ofstad	Oktober 2016	HeliScan AS

Raudsand, Nesset municipality
Møre og Romsdal county

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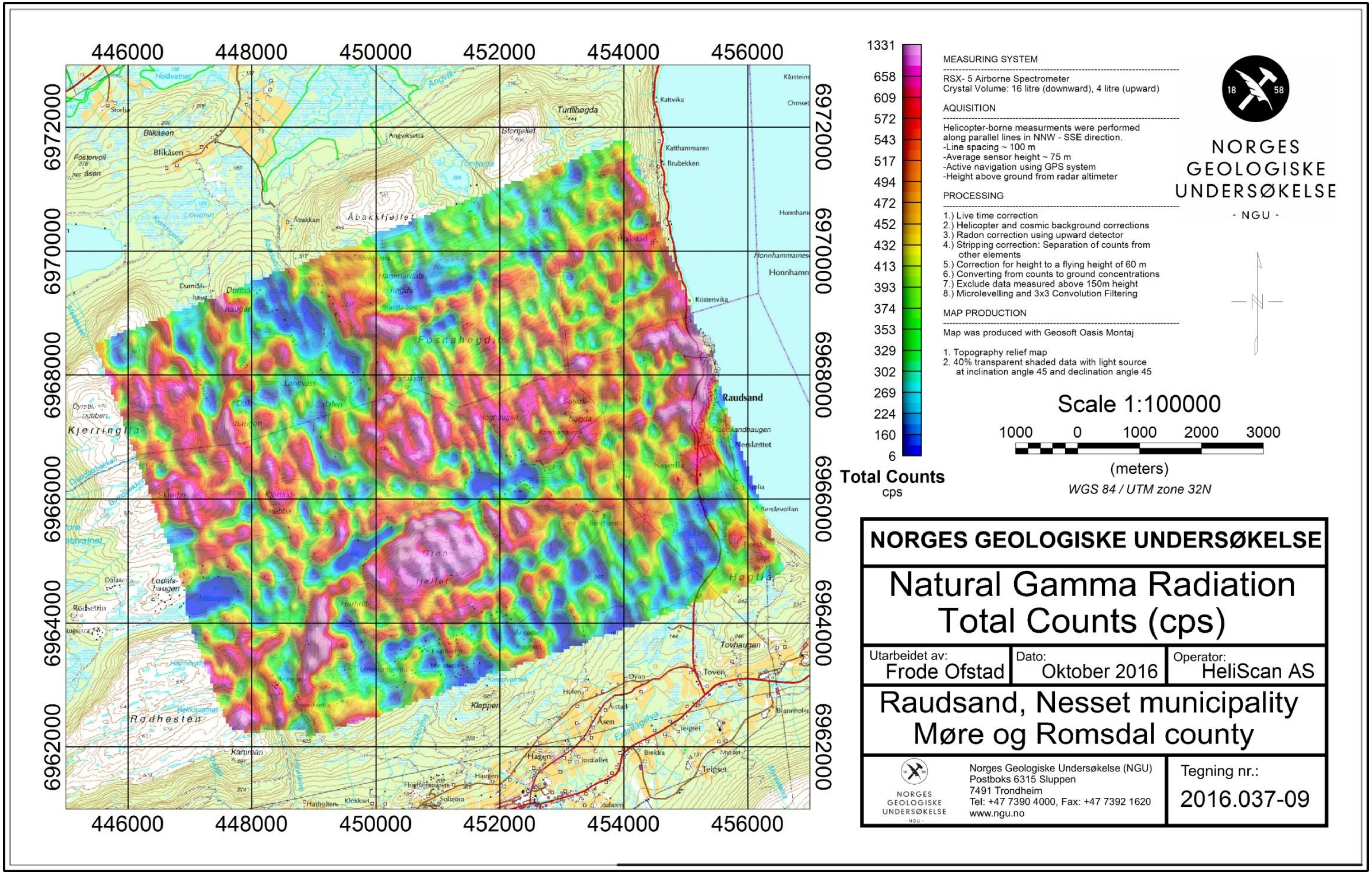
Tegning nr.:
2016.037-08

Figure 12: Apparent resistivity. Frequency 980 Hz, Coaxial coils



MEASURING SYSTEM

RSX- 5 Airborne Spectrometer
Crystal Volume: 16 litre (downward), 4 litre (upward)

AQUISITION

Helicopter-borne measurments were performed along parallel lines in NNW - SSE direction.
-Line spacing ~ 100 m
-Average sensor height ~ 75 m
-Active navigation using GPS system
-Height above ground from radar altimeter

PROCESSING

1.) Live time correction
2.) Helicopter and cosmic background corrections
3.) Radon correction using upward detector
4.) Stripping correction: Separation of counts from other elements
5.) Correction for height to a flying height of 60 m
6.) Converting from counts to ground concentrations
7.) Exclude data measured above 150m height
8.) Microlevelling and 3x3 Convolution Filtering

MAP PRODUCTION

Map was produced with Geosoft Oasis Montaj

1. Topography relief map
2. 40% transparent shaded data with light source at inclination angle 45 and declination angle 45

NORGES GEOLOGISKE UNDERSØKELSE

Natural Gamma Radiation
Total Counts (cps)

Utarbeidet av:	Dato:	Operator:
Frode Ofstad	Oktober 2016	HeliScan AS

Raudsand, Nesset municipality
Møre og Romsdal county

Norges Geologiske Undersøkelse (NGU)
Postboks 6315 Sluppen
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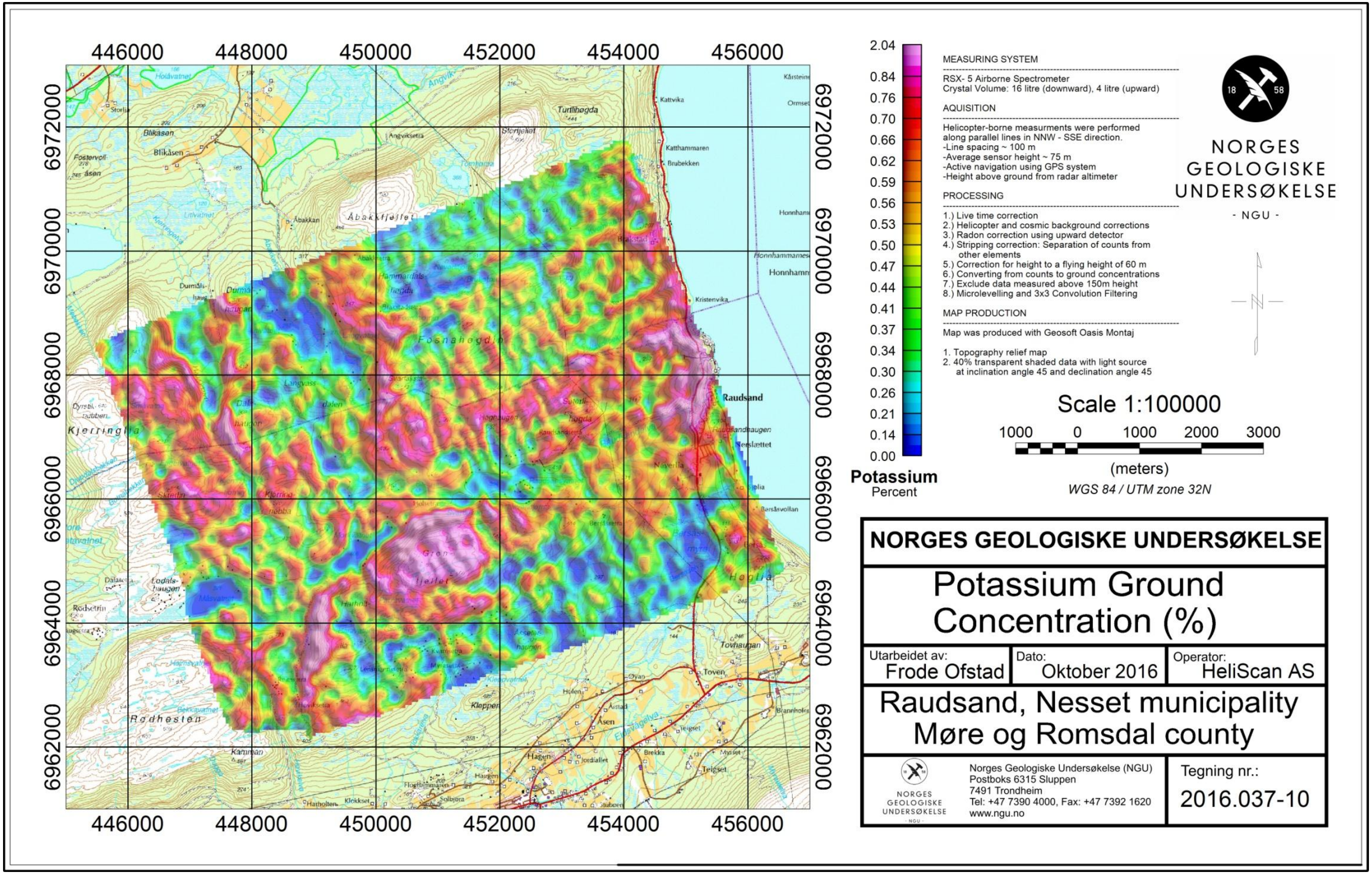
Tegning nr.:
2016.037-09

Figure 13: Radiometric Total Counts



MEASURING SYSTEM

RSX- 5 Airborne Spectrometer
Crystal Volume: 16 litre (downward), 4 litre (upward)

AQUISITION

Helicopter-borne measurments were performed along parallel lines in NNW - SSE direction.
-Line spacing ~ 100 m
-Average sensor height ~ 75 m
-Active navigation using GPS system
-Height above ground from radar altimeter

PROCESSING

1.) Live time correction
2.) Helicopter and cosmic background corrections
3.) Radon correction using upward detector
4.) Stripping correction: Separation of counts from other elements
5.) Correction for height to a flying height of 60 m
6.) Converting from counts to ground concentrations
7.) Exclude data measured above 150m height
8.) Microlevelling and 3x3 Convolution Filtering

MAP PRODUCTION

Map was produced with Geosoft Oasis Montaj

1. Topography relief map
2. 40% transparent shaded data with light source at inclination angle 45 and declination angle 45

NORGES GEOLOGISKE UNDERSØKELSE

Potassium Ground Concentration (%)

Utarbeidet av: Frode Ofstad
Dato: Oktober 2016
Operator: HeliScan AS

Raudsand, Nesset municipality
Møre og Romsdal county

Norges Geologiske Undersøkelse (NGU)
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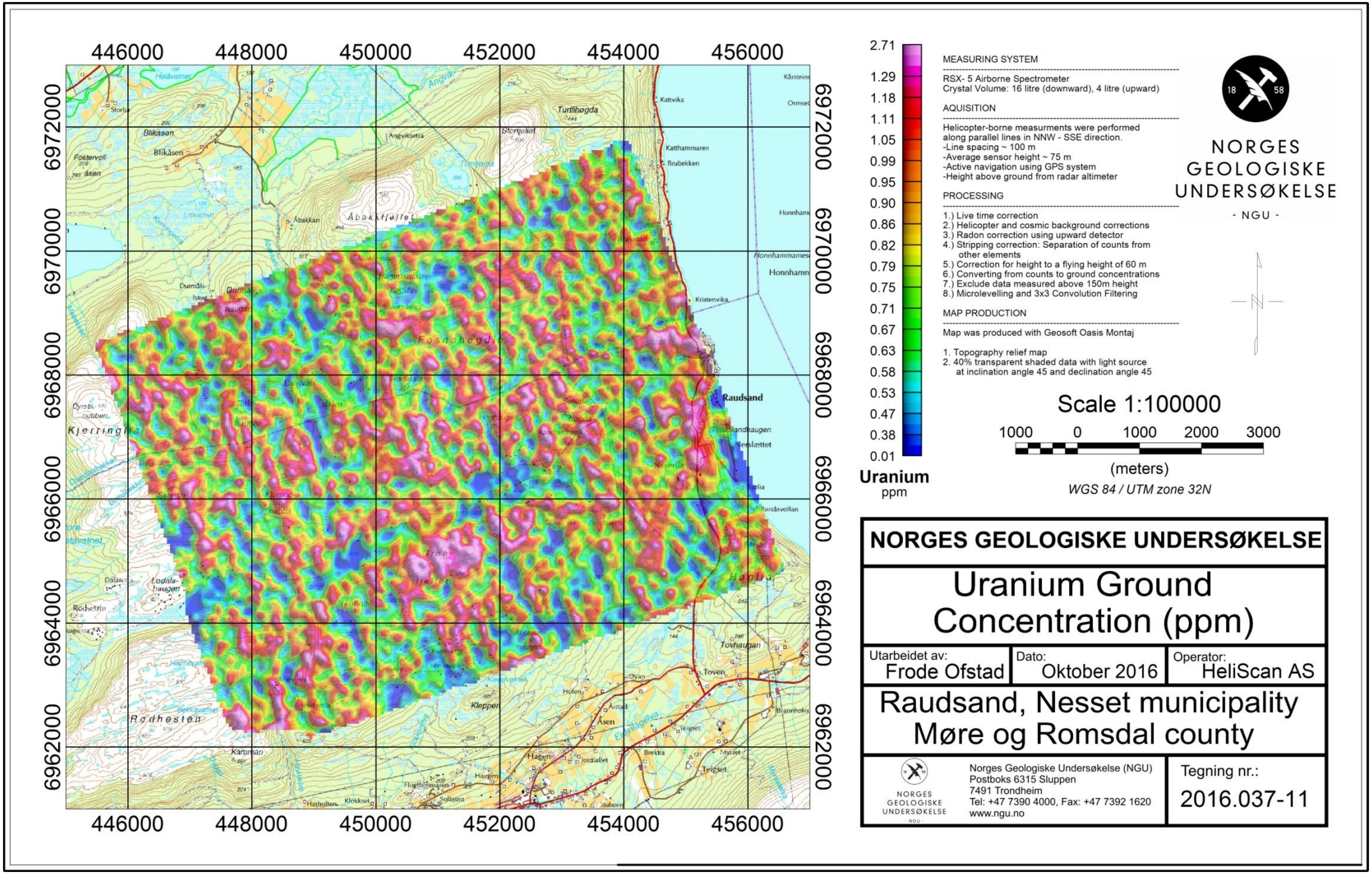
Tegning nr.: 2016.037-10

Figure 14: Potassium ground concentration



MEASURING SYSTEM

RSX- 5 Airborne Spectrometer
Crystal Volume: 16 litre (downward), 4 litre (upward)

AQUISITION

Helicopter-borne measurments were performed along parallel lines in NNW - SSE direction.
-Line spacing ~ 100 m
-Average sensor height ~ 75 m
-Active navigation using GPS system
-Height above ground from radar altimeter

PROCESSING

1.) Live time correction
2.) Helicopter and cosmic background corrections
3.) Radon correction using upward detector
4.) Stripping correction: Separation of counts from other elements
5.) Correction for height to a flying height of 60 m
6.) Converting from counts to ground concentrations
7.) Exclude data measured above 150m height
8.) Microlevelling and 3x3 Convolution Filtering

MAP PRODUCTION

Map was produced with Geosoft Oasis Montaj

1. Topography relief map
2. 40% transparent shaded data with light source at inclination angle 45 and declination angle 45

NORGES GEOLOGISKE UNDERSØKELSE

Uranium Ground Concentration (ppm)

Utarbeidet av:	Dato:	Operator:
Frode Ofstad	Oktober 2016	HeliScan AS

Raudsand, Nesset municipality
Møre og Romsdal county

Norges Geologiske Undersøkelse (NGU)
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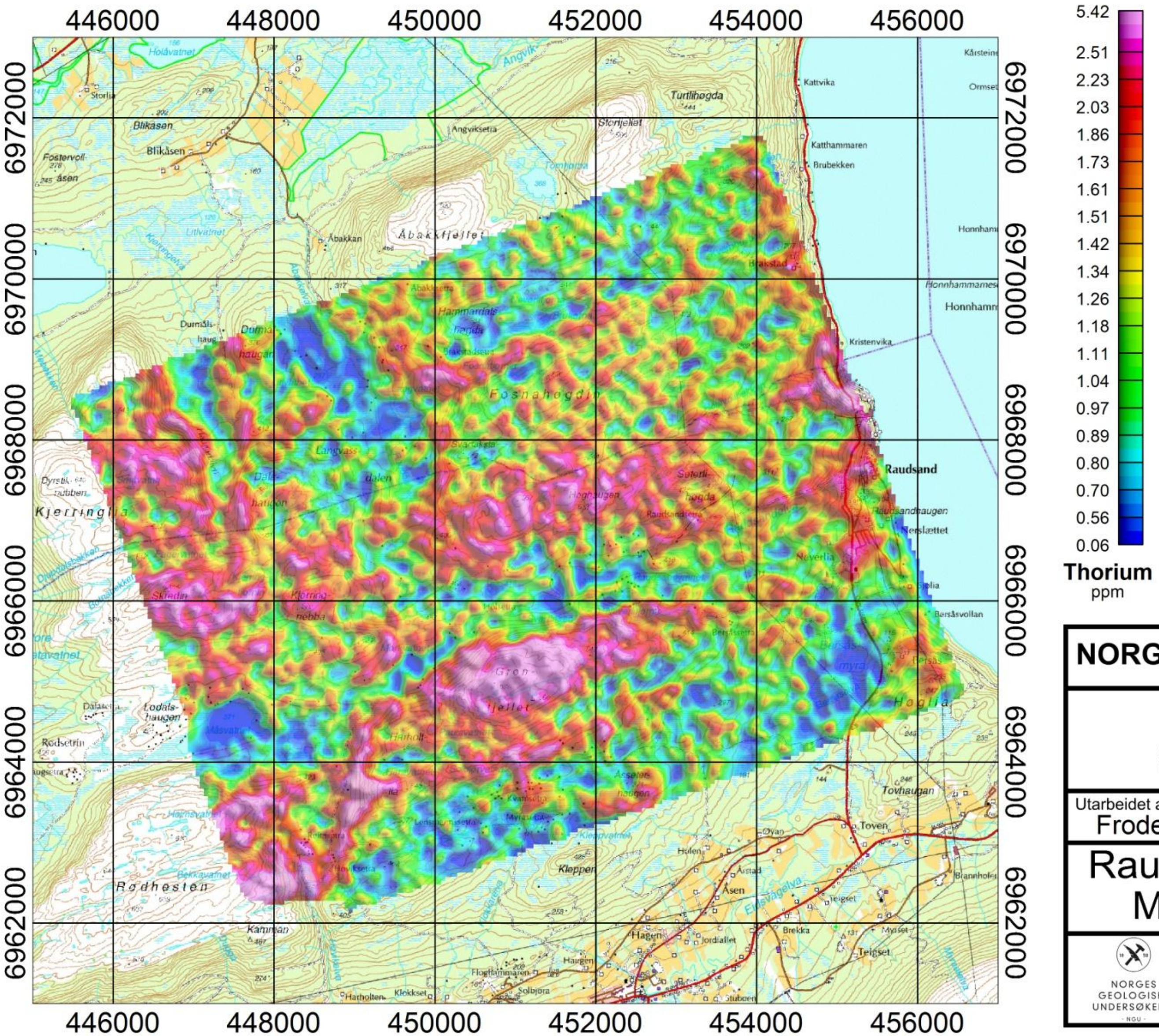
Tegning nr.:
2016.037-11

Figure 15: Uranium ground concentration



MEASURING SYSTEM

RSX- 5 Airborne Spectrometer
Crystal Volume: 16 litre (downward), 4 litre (upward)

AQUISITION

Helicopter-borne measurments were performed along parallel lines in NNW - SSE direction.
-Line spacing ~ 100 m
-Average sensor height ~ 75 m
-Active navigation using GPS system
-Height above ground from radar altimeter

PROCESSING

1.) Live time correction
2.) Helicopter and cosmic background corrections
3.) Radon correction using upward detector
4.) Stripping correction: Separation of counts from other elements
5.) Correction for height to a flying height of 60 m
6.) Converting from counts to ground concentrations
7.) Exclude data measured above 150m height
8.) Microlevelling and 3x3 Convolution Filtering

MAP PRODUCTION

Map was produced with Geosoft Oasis Montaj

1. Topography relief map
2. 40% transparent shaded data with light source at inclination angle 45 and declination angle 45

NORGES
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- NGU -

Scale 1:100000

1000 0 1000 2000 3000

(meters)

WGS 84 / UTM zone 32N

NORGES GEOLOGISKE UNDERSØKELSE

Thorium Ground
Concentration (ppm)

Utarbeidet av:	Dato:	Operator:
Frode Ofstad	Oktober 2016	HeliScan AS

Raudsand, Nesset municipality
Møre og Romsdal county

Norges Geologiske Undersøkelse (NGU)
Postboks 6315 Sluppen
7491 Trondheim
Tel: +47 7390 4000, Fax: +47 7392 1620
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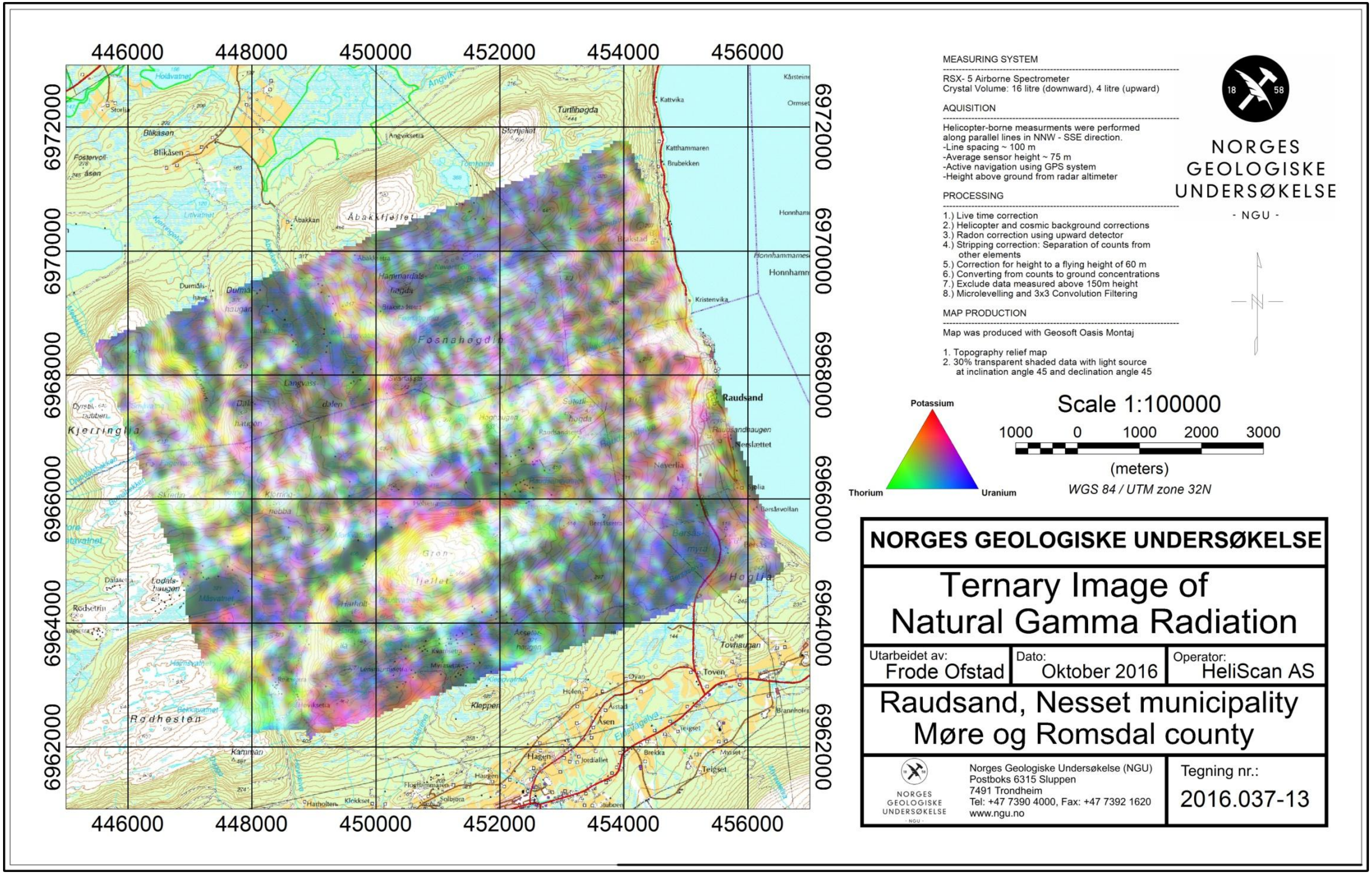
Tegning nr.:
2016.037-12

Figure 16: Thorium ground concentration



MEASURING SYSTEM

RSX- 5 Airborne Spectrometer
Crystal Volume: 16 litre (downward), 4 litre (upward)

AQUISITION

Helicopter-borne measurments were performed along parallel lines in NNW - SSE direction.
-Line spacing ~ 100 m
-Average sensor height ~ 75 m
-Active navigation using GPS system
-Height above ground from radar altimeter

PROCESSING

1.) Live time correction
2.) Helicopter and cosmic background corrections
3.) Radon correction using upward detector
4.) Stripping correction: Separation of counts from other elements
5.) Correction for height to a flying height of 60 m
6.) Converting from counts to ground concentrations
7.) Exclude data measured above 150m height
8.) Microlevelling and 3x3 Convolution Filtering

MAP PRODUCTION

Map was produced with Geosoft Oasis Montaj

1. Topography relief map
2. 30% transparent shaded data with light source
   at inclination angle 45 and declination angle 45

NORGES GEOLOGISKE UNDERSØKELSE

Ternary Image of Natural Gamma Radiation

Utarbeidet av:	Dato:	Operator:
Frode Ofstad	Oktober 2016	HeliScan AS

Raudsand, Nesset municipality
Møre og Romsdal county

Norges Geologiske Undersøkelse (NGU)
Postboks 6315 Sluppen
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Tel: +47 7390 4000, Fax: +47 7392 1620
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Tegning nr.: 2016.037-13

Figure 17: Radiometric Ternary map

GEOLOGICAL
SURVEY OF
NORWAY
- NGU -

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

Visitor address
Leiv Eirikssons vei 39
7040 Trondheim

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E-mail	ngu@ngu.no
Web	www.ngu.no/en-gb/