Aerogeophysics in Finland 1972–2004:
Methods, System Characteristics and Applications,
edited by Meri-Liisa Airo.
Geological Survey of Finland, Special Paper 39, 21–74, 2005.

THE "THREE IN ONE" AEROGEOPHYSICAL CONCEPT OF GTK IN 2004

by
H. Hautaniemi, M. Kurimo, J. Multala, H. Leväniemi and J. Vironmäki

Hautaniemi, H., Kurimo, M., Multala, J., Leväniemi. H. & Vironmäki, J. 2005. The "Three In One" aerogeophysical concept of GTK in 2004. *Geological Survey of Finland, Special Paper* 39, 21–74, 39 figures, 6 tables and 7 appendices.

The airborne geophysical system of the Geological Survey of Finland (GTK) has been in operation and active development for the last half century. GTK's expertise and ingenuity is demonstrated by its "three-in-one" concept, which showcases many of GTK's own areas of expertise. This paper describes the whole airborne system, from equipment to processing, from measurements to the nationwide mapping project. Special attention is paid to GTK's own innovations, such as the frequency domain electromagnetic system (hardware and software), very low altitude flying and high-precision positioning in survey operation, and the almost completed in-house designed processing software. The unique high-resolution Second Finnish National Mapping Project is also described.

Key words (GeoRef Thesaurus, AGI): geophysical methods, airborne methods, electromagnetic methods, magnetic methods, gamma-ray methods, instruments, measurement, Global Positioning System, data processing, Geological Survey of Finland, Finland

Authors' address: Geological Survey of Finland, P.O. Box 96, FI-02151 Espoo, Finland

E-mail: heikki.hautaniemi@gtk.fi, maija.kurimo@gtk.fi, jukka.multala@gtk.fi, hanna.levaniemi@gtk.fi and jouko.vironmaki@gtk.fi

INTRODUCTION

This paper highlights the Geological Survey of Finland's (GTK) leading edge survey and processing concept – the "three-in-one" airborne geophysical system. The essence of this system lies in the simultaneous measurement of magnetometer, frequency domain electromagnetic system and gamma-ray spectrometer in one survey. All three measuring systems are installed in a fixed wing aircraft. At present, this is still the only known operational system of this nature in the industry.

Another important aspect of GTK's airborne survey activities is the high-resolution national coverage; so far in 2004 over 95 % of the country has been covered with our standard, three-in-one survey. Originally, the requirement for lowest possible flight altitude originated with the EM-system, but over the years the 30 metres nominal altitude has also proven to be very advantageous in magnetic measurements. In addition, during the past few years decreasing the line spacing has shown promising results.

The pioneering work to develop a frequency domain system for a fixed-wing aircraft was made during the early 1950s. The optimum between the required powerful primary electromagnetic field and reasonable coil size and weight was achieved. The method proved to be very successful in exploration in the Precambrian Shied area, and it was adopted as a permanent survey method in Finland (Peltoniemi 1982)

Although the development of geophysical instruments has improved the quality and usefulness of airborne geophysical data, one of the major leaps has been improved accuracy in the positioning and navigation due to the satellite navigation systems. Unlike many other survey operators, GTK has adopted the combination of GPS and GLONASS for real-time navigation. This system utilises simultaneously both the American (GPS) and the Russian systems (GLONASS), thereby providing more satellites for accurate position calculations.

The safety aspects of the survey have always been paramount and are discussed regularly between GTK's geophysicists and the aircraft captains. GTK has joined IAGSA (International Airborne Geophysics Safety Association) as an active member, and has adopted its safety manual for regular use.

This paper outlines the present airborne system. Markku Peltoniemi has described the history and development phases (Peltoniemi 2005, *this volume*). This paper is divided into four main sections: the Finnish National Mapping Project, hardware, measurement methodologies and data processing. The technical features of installing the equipment in the aircraft are included in the hardware section, and the methodology sections concentrate more on measurement principles and geophysical corrections. In the data processing section the main processing flow is explained.

The authors wish to dedicate this paper to all the devoted experts who have put their efforts into building and carrying out GTK's airborne system during the last 50 years or so, since 1951.

THE SECOND FINNISH NATIONAL MAPPING PROJECT

GTK has carried out two huge airborne mapping projects in Finland. The First National Mapping Project that began in 1951 was designed to provide geophysical information for exploration and geological mapping with the best accuracy of the time, as technology evolved. This meant that a myriad of instruments and flight platforms were used until the end of the project in 1971. For example, in 1951 the surveys were undertaken with Airspeed Oxford twin-engine aeroplane. Subsequent platforms such as the Lockheed Lodestar and the AeroCommander were used to complete the project. Even at that early stage, the concept of simultaneously measuring the earth's magnetism in conjunction with electromagnetism and radiometrics were practised whenever possible. The high altitude survey covered the whole country including the coastal areas and the sea using 150-m flight altitude, 400-m line spacing and analogue recording with questionable accuracy in positioning control. The hand-drawn magnetic contour maps and electromagnetic profile maps were found to be very useful for exploration and bedrock mapping.

The Second Finnish National Mapping Project was started in 1972 when the high altitude survey (1951–1971) was completed. The New Project was begun with a DC-3 aeroplane platform with a subsequent change to the present DHC-6/300 Twin Otter and the Cessna Caravan. New techniques allowed digital recording and more precise positioning with the benefit of Doppler data combined with photographic flight path registration, which was later replaced by a satellite positioning system.

The GTK airborne geophysical system was designed to measure effectively the typical geological features found in Finland, the glacial Quaternary overburden and the Precambrian bedrock with narrow and vertical geological units. The experience of the high altitude surveys from the First National Mapping Project confirmed the effectiveness of the combined magnetic, electromagnetic and gamma ray spectrometry measurements in subsequent surveys. The EM system was found to be especially useful. The EM frequency and the flight specifications were adjusted to meet the exploration purposes in Finland, in particular exploration for massive sulphide deposits.

EM systems require low and stable terrain clearance and in that vein 30 m was found to be the lowest safe flying altitude. The line separation had to be tight, but also reasonable time schedules for surveying the whole country affected the choice. Horizontal transverse gradiometer was chosen for the magnetic survey to improve the data quality, especially after disturbance from the EM transmitter on the magnetometer sensor was completely compensated for. The survey areas followed the Finnish map sheet system. The choice of standard flight direction (North-South and East-West) was made to suit the general sheet line system of Finland. Throughout the whole period the basic geophysical and operational standard features have been in use (Table 1).

Table 1. Systematic of Second National Mapping Project.

Line spacing	200 m
Terrain clearance	30 m
Line direction	N-S or E-W
Typical single survey area	1:100 000 map sheet
Geophysics	Mag + Freq.EM + Gamma Ray

The improvement of the data resolution over the most potential exploration areas covering about one-third of the country was the primary aim of this project. The initial results of digital data, high quality grey tone magnetic maps and precise EM profile maps were so impressive and profitable that it was very soon obvious that the project would have to be continued to cover the whole country. The three-in-one concept has proven, in addition to exploration, to be beneficial in bedrock and Quaternary mapping, and in specific geological studies.

The basis of the system has remained standard over the years. The annual survey capacity (Fig. 1) depends mainly on the length of the Finnish summer, particularly the time without snow cover, but also on the available resources and commercial assignments. For example, there were two large airborne mapping projects being carried out in Africa during the years 1997 and 2003, and the Cessna Caravan joined the mapping project in 2001, and these are all easily reflected in the capacity changes. Equipment, processing methods and software have been improved along with the evolution of new techniques. The main modifications are listed below and also annually in Tables 2a and 2b. More information and an index map connecting each survey area to the survey year are available on GTK’s web site: http://www.gtk.fi/aerogeo.

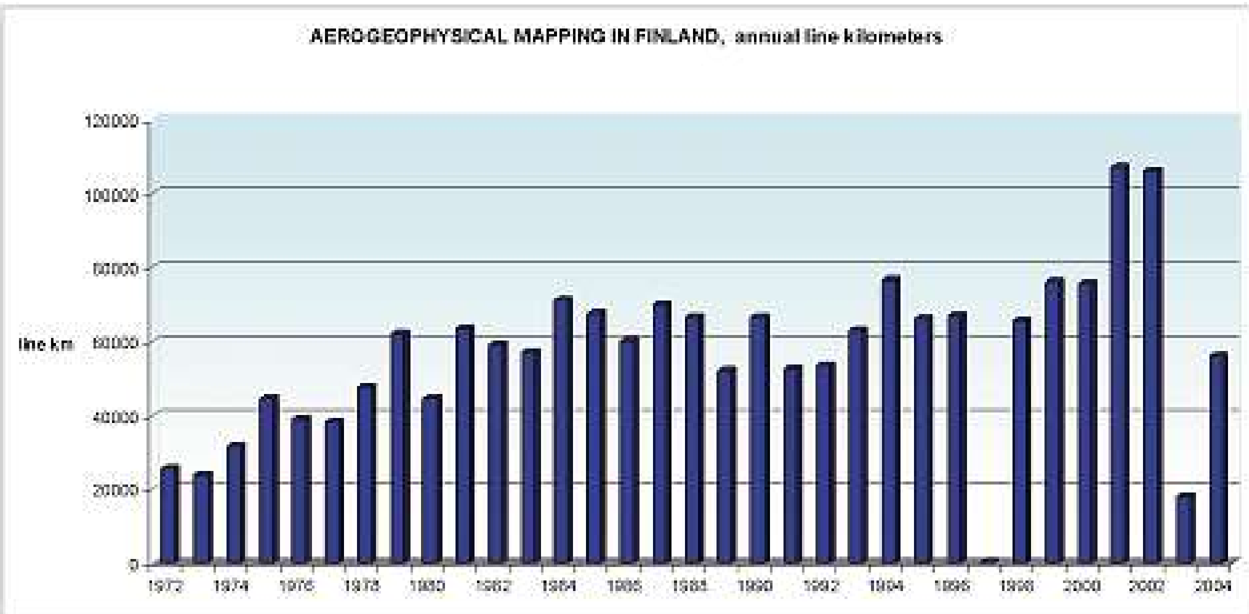


Fig. 1. Annual survey kilometres flown during the Second National Mapping Project up to the present. During the 1970s the annual survey took about 300–350 flight hours. Since 1979 it has risen to 500–550 hours/year. Since 2001 the surveys have been done with two aircrafts.

Table 2a. The annual geophysical instrumentation in Twin Otter and DC-3 aircraft during The Second National Mapping Project.

Year	Magnetometers Sensors P=Proton/C=Cesium		Magnetometers Registration	Electromagnetics Coil distance	Electromagnetics Frequency	Electromagnetics Moment	Electromagnetics Registration	Radiometrics Crystal volume	Radiometrics Channels
	N:o	C/P	(1/s)	(m)	(Hz)	(Am*2)	(1/s)	(l)	N:o
1973	1	P	2	26,5	3220	127	2	27,3	36
1974	1	P	2	26,5	3220	127	2	27,3	36
1975	2	P	2	25,8	3220	127	2	27,3	36
1976	2	P	2	25,8	3220	127	2	27,3	36
1977	2	P	2	25,8	3220	127	2	27,3	36
1978	2	P	2	25,0	3220	127	2	27,3	54
1979	2	P	2	25,0	3220	127	2	27,3	54
1980	2	P	2	21,44	3222	105	4	25,0	120
1981	2	P	2	21,36	3113	105	4	25,0	120
1982	2	P	2	21,36	3113	105	4	25,0	120
1983	2	P	2	21,36	3113	105	4	25,0	120
1984	3	P	4	21,36	3113	105	4	25,0	120
1985	3	P	4	21,36	3113	105	4	25,0	120
1986	3	P	4	21,36	3113	105	4	25,0	120
1987	3	P	4	21,36	3113	105	4	25,0	120
1988	3	P	4	21,36	3113	105	4	25,0	120
1989	2	P	4	21,36	3113	105	4	25,0	120
1990	2	P	4	21,36	3113	105	4	25,0	120
1991	2	P	4	21,36	3113	105	4	25,0	120
1992	2	C	4	21,36	3113	105	4	25,0	120
1993	2	C	4	21,36	3113	105	4	25,0	120
1994	2	C	4	21,36	3113	105	4	25,0	120
1995	2	C	4	21,36	3113	105	4	25,0	120
1996	2	C	4	21,36	3125/14368	115/55	4/4	25,0	120
1997	2	C	8	21,36	3125/14368	115/55	4/4	42 (34+8)	256
1998	2	C	8	21,36	3125/14368	115/55	4/4	42 (34+8)	256
1999	2	C	8/10	21,36	3125/14368	115/55	4/4	42 (34+8)	256
2000	2	C	8/10	21,36	3125/14368	115/55	4/4	42 (34+8)	256
2001	2	C	10	21,36	3125/14368	115/55	4/4	42 (34+8)	256
2002	2	C	10	21,36	3125/14368	115/55	4/4	42 (34+8)	256
2003	2	C	10	21,36	3125/14368	115/55	4/4	42 (34+8)	256
2004	2	C	10	21,36	3125/14368	115/55	4/4	42 (34+8)	256

Table 2b. The annual geophysical instrumentation in Cessna Caravan aircraft during The Second National Mapping Project.

Year	Magnetometers Sensors P=Proton/C=Cesium		Magnetometers Registration	Electromagnetics Coil distance	Electromagnetics Frequency	Electromagnetics Moment	Electromagnetics Registration	Radiometrics Crystal volume	Radiometrics Channels
	N:o	C/P	(1/s)	(m)	(Hz)	(Am*2)	(1/s)	(l)	N:o
2000	1	C	10	16,96	3005/14368	50/18	4/4	21 (17+4)	256
2001	1	C	10	16,96	3005/14368	50/18	4/4	21 (17+4)	256
2002	1	C	10	16,96	3005/14368	50/18	4/4	21 (17+4)	256
2003	1	C	10	16,96	3005/14368	50/18	4/4	21 (17+4)	256
2004	1	C	10	16,96	3005/14368	50/18	4/4	42 (34+8)	256

Main modifications:

EM coil configuration was vertical coaxial in the DC-3 during 1973–1979. For the Twin Otter it was modified to vertical coplanar (in 1980) and a second frequency was installed in 1996. The EM configuration of the Cessna (installed in 1999) has been maintained in a similar fashion to that of the Twin Otter. The coverage of different EM systems is shown in Figure 2.

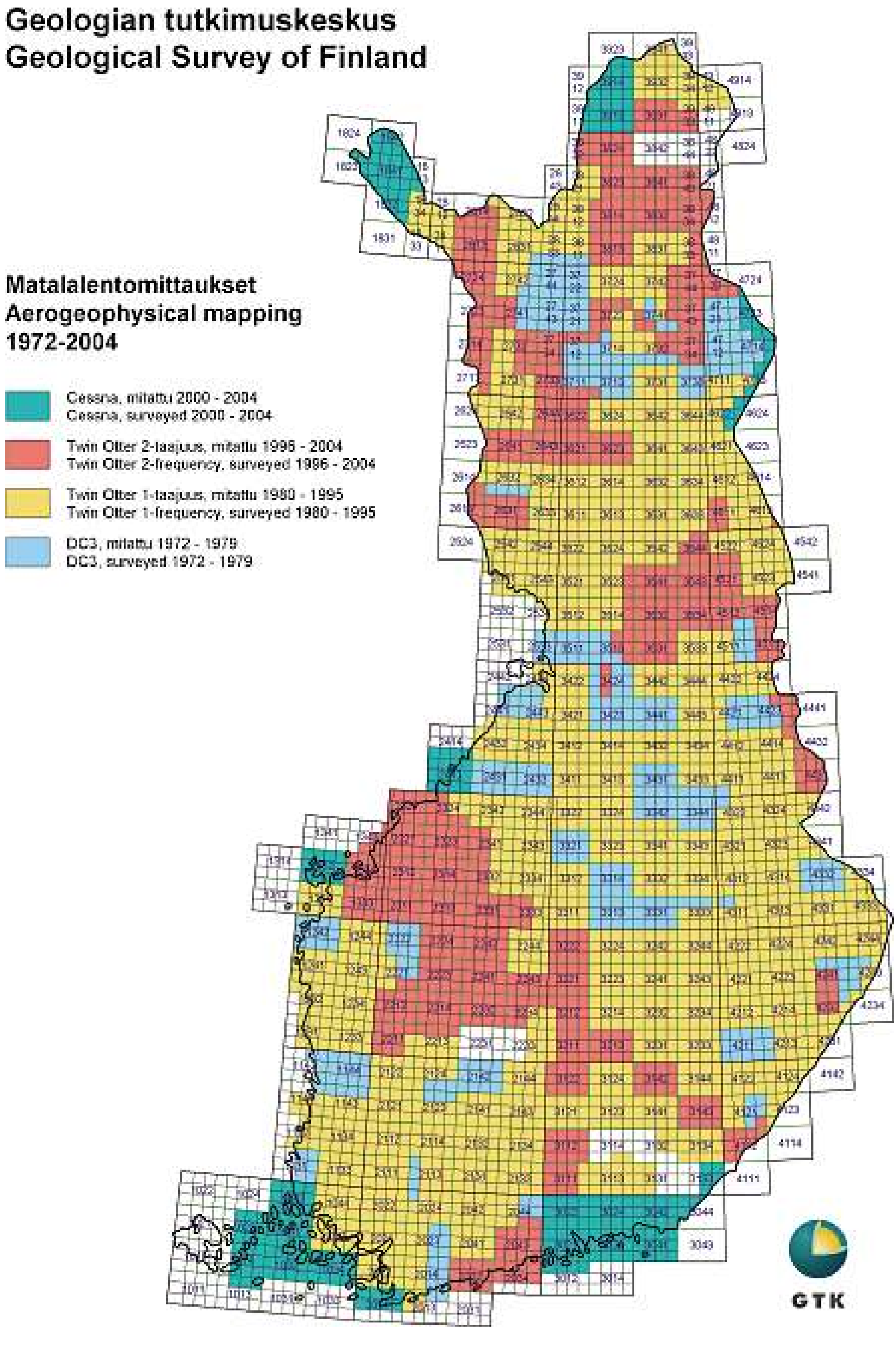


Fig. 2. The index map showing the EM system during the National Mapping Project:
1972–1979 (DC3, vertical coaxial)
1980–1995 (1-frequency vertical coplanar)
1996–2003 (2-frequency vertical coplanar)

Spectrometer crystal volume was increased at the time of the installation of the second frequency for the EM system. The number of spectral channels was also increased at the same time to 256.

Magnetometer sensor was only in the left wingtip at the beginning (1973–1974) and the right wingtip magnetometer has been in use since 1977. A third magnetometer in the tail boom was used 1984–1988. The experimental installation of VLF in the tail boom since 1988 disturbed the magnetic recordings and the magnetic sensor was removed. The benefit of a third magnetometer was found to be inconsequential in defining the local magnetic anomaly field. The Cessna Caravan with one magnetometer has been used in coastal areas since 2001.

Since 1972 the magnetic base station at the airport and since 1978 inside the area has been utilised.

Positioning was made using aerial photomosaic maps and fix points were located using the flight path photographs or video and Doppler data between fix points up to 1992. Since then the DGPS (Differential GPS) has been in use. The coverage is shown in Figure 3.

Recording intervals have been increased by technical developments; for example, magnetometer sensor readings were increased up to 10 per second in the late 1990s.

The countrywide geophysical maps are combined from annual survey data, and are shown in Appendices 1–7. The magnetic field map is a combination of the First and Second National Mapping Projects. The older data is digitised to 1-km grid from manually drawn contour maps. The apparent resistivity with a half-space model is calculated from the In-Phase and Quadrature components of the measured electromagnetic field. The radiometric ternary image is a composition of uranium, potassium and thorium radioelements.

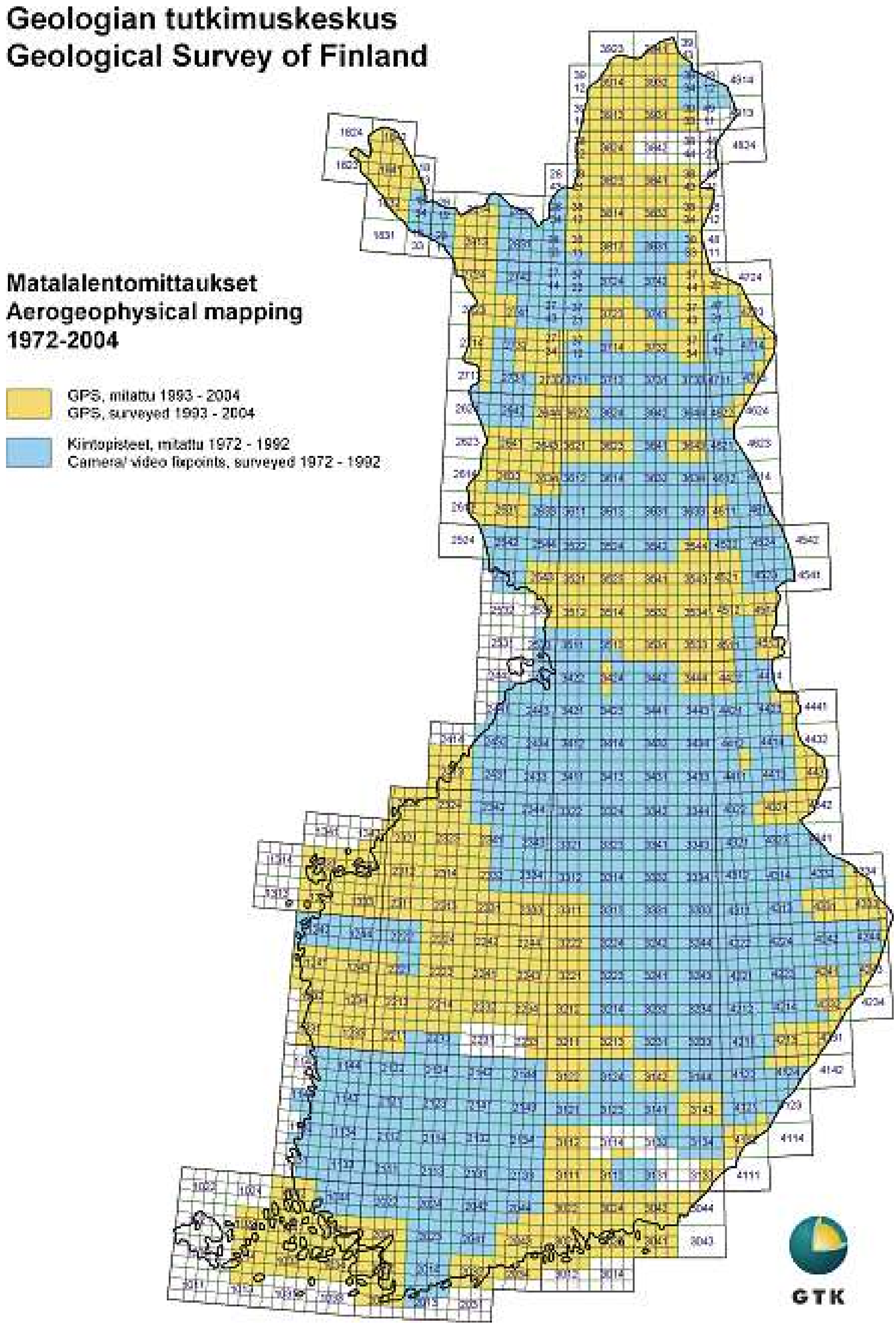


Fig. 3. The index map showing the navigation system during the National Mapping Project:
1972–1975 Camera fixpoints
1976–1992 Camera/video fixpoints and Doppler
1993–2003 DGPS

HARDWARE AND INSTALLATIONS

Aircraft

Currently (2004), GTK employs two aircraft: a DeHavilland Canadian Twin Otter (DHC-6) and a Cessna Caravan I (C-208I). The Twin Otter (Fig. 4) was chosen to replace the old, but reliable DC-3 in 1980. The Twin Otter was selected for its characteristic slow speed performance and for its sufficient cabin dimensions. The total weight of the geophysical instruments at the time was about 700 kg and the instruments hardly left any room for the instrument operator in the DC-3. In its passenger version the Twin Otter is designed to have 19–20 seats. Malmilento, a part of Finnair Cargo Oy, is the flight operator of the Twin Otter. Co-operation between GTK and a private aviation company Kar-Air started in 1951. In 1988 Kar-Air became wholly owned by Finnair and since 1996 the geophysical survey flights have been carried out under the name Malmilento. During the manufacture of this Twin Otter aircraft, special attention was paid to reduce its electromagnetic noise. All the aviation instruments were cabled with double (+ and – cables) twisted pair cables and generators were metal shielded. The grounding of the aviation instruments was wired so as to minimise the eddy currents on the fuselage.

Fig. 4. The survey aircraft Twin Otter DHC-6 (OH-KOG) in 2004. Photo: Kai Nyman

In 1998 GTK expanded the survey capacity with the introduction of a Cessna Caravan aircraft (Fig. 5). The planned capacity of the Cessna Caravan is 10 passengers. Due to developments in instrumentation (weight reduction, and durability especially for vibrations etc.), a faster and smaller aircraft could be employed. A turboprop engine is still one of the requirements as it is considered to be more reliable than a piston engine. Also the Jet A1 fuel required by the Cessna is less flammable and thus safer, and is more readily available in certain regions. Utin Lento Oy owns and operates the aircraft.

Fig. 5. The survey aircraft Cessna Caravan I, C-208 (OH-USI) in 2002. Photo: Kai Nyman

Instruments in the aircraft

Although the equipment in the Twin Otter and the Cessna Caravan aircraft is basically identical, there are some minor differences. The following sections describe how the instruments are installed and the differences in instrumentation and installation between the two aircraft. The data sheets of the instruments and the main characteristics are shown in Table 3.

Table 3. The specifications of GTK's airborne geophysical instrumentation.

THE PRESENT MEASURING EQUIPMENT (2004):

The measurement units installed in the aircraft are connected to each other by local area network (LAN). This makes it easy to install just the right measurement units for each running project. The Geological Survey of Finland owns all equipment mentioned below.

Magnetics:

- Twin Otter: Two Cesium magnetometers at wing tips, sensor distance 21.36 m
- Cessna Caravan: Cesium magnetometer at tail boom
- Scintrex CS-2 sensors
- Automatic RMS AADCII compensating unit
- Registration rate 10 samples/sec

Electromagnetic dual frequency unit:

- Model GSF-95, vertical coplanar coil configuration,
- Twin Otter: coil distance 21.36 m
- Cessna Caravan: coil distance 16.96 m
- Registration 4 times/sec

Gamma-ray spectrometer Exploranium GR-820/3:

- 2 sets of NaI crystals, each containing 4 downward and 1 upward looking crystals (totally 42 litres)
- Registration once/sec

Navigation system

- Ashtech GG-24, 24 channel GPS+GLONASS receiver. Accuracy 7 m/16 m (50%/95%). Real time DGPS if differential signal is available,
- Visual navigation with maps, left-right navigation indicator (GPS)
- Radar altimeter (Collins), resolution 0.1 m, accuracy 0.5 m, max. 10 samples/sec

Others

- Barometer, thermometer, accelerometer

Recording

- The measurement data is recorded during the flight to PC hard disk and then copied to PC compatible Iomega Zip disk,
- analogue display for monitoring the geophysical instruments operation during the flights.

Electromagnetic system (EM)

GTK has been one of the few advocates of frequency domain airborne electromagnetic systems since the early 1950s, although time domain EM seems to be dominating the industry currently. With decades of experience coupled with theoretical studies, GTK upgraded from the single-frequency EM system to two-frequency system by 1996 to meet the new challenges in environmental studies.

The transmitter and the receiver coils are located either in both wingtips of the aircraft (Twin Otter and Cessna) or, in the case of DC-3 during 1970s, in the nose and tail. The electronics associated with the coils are located close to them and the power unit for the frequency domain EM system is positioned inside the cabin. The choice of location of the transmitter and the receiver coils is based on the following factors: the rigidity of the fuselage compared to the wings, the distance between the coils and the distance of the coils to the moving parts and also to the engines of the aircraft. The reasons to choose the coil configuration (vertical-coplanar, axis of the magnetic dipole moments are horizontal and parallel with the fuselage) were technical and geophysical. The construction has to be as rigid as possible to minimise motion noise so that disturbance from the aircraft is kept to a minimum. The spatial resolution with vertical coils is good, which is important when localising narrow vertical geological units.

In the case of Twin Otter, the transmitter coils are located on the right wingtip and the receiver coils on the left wingtip, and the distance between the coils is 21.36 m. Figure 6 shows how the two coils are mounted on the wingtip. The weight of the total wingtip installation (including the Cs magnetometer sensor) is about 2 x 44 kg. The distance between the coils is kept as constant as possible, because the thermal expansion has an effect to anomaly level. Besides the variations in coil separation, the vertical movement of the coils in respect to the aircraft fuselage during the survey flight can cause some noise in the in-phase and quadrature components. With careful design and testing of the construction and the electronics of the EM systems, GTK has been able to reduce the systemic noise to a minimum. For example, the angle between the wing and the EM coil holder (see Fig. 6a) is very important, as well as the type of the rigid fixing.

A similar dual frequency EM system installed in the Twin Otter has been designed for the Cessna Caravan. The system in the Cessna Caravan was first test flown in April 1999 and made ready for production surveys in June of the same year. The coil configuration of the EM system is the same in both aircraft, but due to shorter wingspan the distance between the transmitter and receiver coils in the Cessna Caravan is only 16.96 m. The coil dimensions and weight of the wingtip installations were also modified for the Cessna. Figure 7 shows the new technique for fitting the EM pod to the wingtip. Instead of mounting the wingtip system to the supporting structure inside the wing, as in the case of Twin Otter, the EM pod was affixed to the aluminium plate

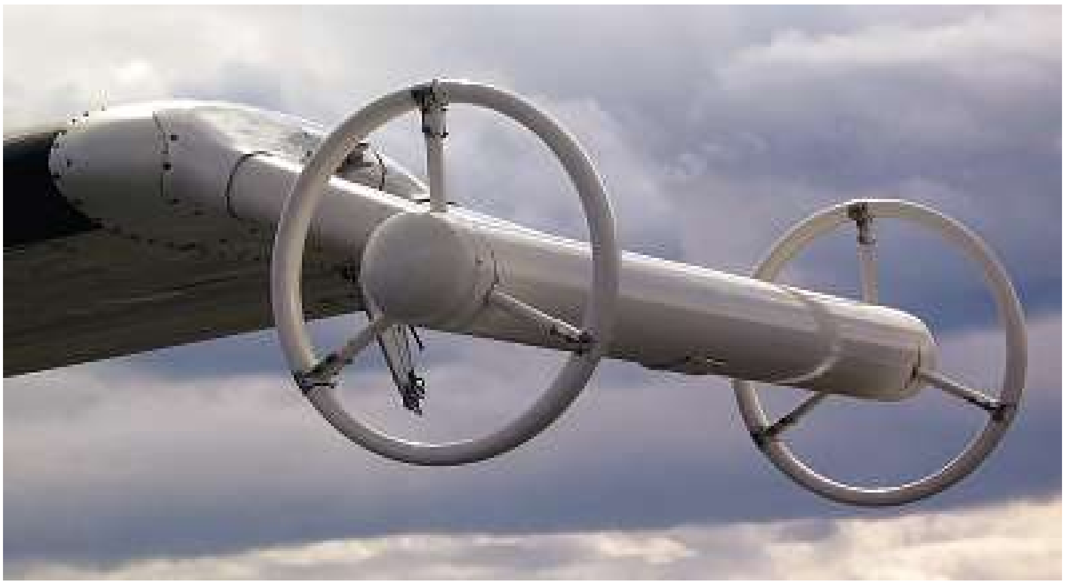


Fig. 6a. The EM wingtip installation in the Twin Otter. Photo: Kai Nyman

Fig. 6b. The EM pod fitting to the Twin Otter wing. Photo: Kai Nyman

a)

b)

Fig. 7. (a–b). The technique for fitting the EM pod to the wing tip. a) installation and b) the pod. Photo: Kai Nyman

of the wing in the Cessna Caravan. This technique was possible mainly due to the lightweight structure of the wingtip system, which has a total weight of only 15 kg for each wingtip.

Some technical specifications are listed in Tables 4 and 5. More detailed description of the EM system is given by Poikonen et al. (1998).

Table 4. Parameters of the EM equipments in Twin Otter and Cessna Caravan

	Frequencies (Hz)	Coil spacing (m)	Sensitivity	Range	Registration rate (samples/sec)
Twin Otter	3 125 and 14 368	21.36	1 ppm	1-50 000 ppm	4
Cessna	3 005 and 14 368	16.96	1 ppm	1-50 000 ppm	4

Table 5. Properties of the EM system in Twin Otter and Cessna Caravan. Noise is determined in real flight situation and it includes the movement noise from the wings.

	Twin Otter		Cessna Caravan	
Frequencies (Hz)	3 125	14 368	3 005	14 368
Magnetic moment (A/m^2)	115	55	50	18
Noise STD/In-phase (ppm)	55	63	13	69
Noise STD/Quadrature (ppm)	24	58	9	60

Magnetometers

The Earth's magnetic field is measured with cesium magnetometers. The sensitivity of the cesium magnetometer is 0.001 nT. This is a great improvement in accuracy in comparison to that of the proton magnetometers (0.5nT), which were in use until 1992. Another improvement has been in the gradient tolerance of the cesium magnetometers. Proton magnetometers have poor operational characteristics when measuring in a high magnetic gradient environment. This is critical, especially when flying at very low altitudes and close to strong magnetic anomaly sources. The Finnish experience was that surveys using proton magnetometers recorded data gaps in areas of high magnetic gradients.

The influence and the disturbance of the aircraft on the magnetometer recordings were minimised in two main ways: adjusting the location and the manner of installation of the sensor and applying software corrections. The first step was to mount the magnetometer sensor as far as possible from the aircraft itself. The mounting has to be as rigid as possible. In the case of the Cessna Caravan, that was done with the aid of a tail stinger. The stinger (Fig. 8) is 1.8 m long and the Cs magnetometer sensor is located in the far end of the stinger. The Twin Otter installation includes two Cs-2 magnetometers and the sensors are located in the wingtip pods between the EM coils (see Fig. 6). The vibration of the sensor in respect to the aircraft fuselage and wing – even a small vibration – can increase noise that is recorded by the magnetometer. Of course, the vibration produces this response from the magnetic material close to the sensor. Therefore to minimise excessive noise, all screws, bolts and other materials used in the installation were of an absolutely nonmagnetic nature. Sometimes even the pop rivets used in the aircraft were replaced with less magnetic ones. The Cs sensors are far more resistant to the quite strong electromagnetic fields caused by the EM transmitter in the left wingtip of the Twin Otter compared to the proton magnetometer sensors. However, in order to reduce the small interference from the EM transmitters, the Cs sensors were installed inside modified Helmholtz coils.

The second step in minimising the influence and disturbance of the aircraft was to apply software corrections to reduce the offsets in the magnetic measurement values caused by the aircraft. Presently, an integral part of the GTK magnetometer system is an active automatic digital compensator (AADCII) made by RMS Instruments. The compensator includes a three-axis fluxgate magnetometer to observe and register the various aircraft orientations. With this compensator the typical improvement ratio is 10–20 for magnetic total field measurements.

Fig. 8. Tail boom installation of the Cs magnetometer sensor in the Cessna Caravan. Photo: Kai Nyman

Gamma-ray measurements

The radiometric measurement unit consists of a set of NaI detectors and a gamma-ray spectrometer (Exploranium 1996). Nowadays the most common dimension of detectors used are 10.16 x 10.16 x 40.64 cm (4 x 4 x 16 ins) size prismatic NaI crystals (volume 4.195 litres) that are packed four side by side and a fifth one on the top of the four in a thermally insulated box. So the total crystal volume of one such package is then 21 litres. The four detectors shield the fifth from gamma radiation originating from the ground. The fifth crystal is for measuring atmospheric gamma radiation and is commonly referred to as "upward looking" crystal. In order to increase the detector volume and thus the measurement accuracy, several crystal boxes can be connected to the spectrometer. Today both aircraft are equipped with two crystal boxes.

There are several aspects to be considered when choosing the location for the crystal boxes in the aircraft. The mass between the detector and the outside air should be kept to a minimum, and furthermore, it should be constant during the survey flight. In some aircraft, such as the Twin Otter, the fuel tanks are located below the cabin floor. Thus the crystal boxes are installed as far as possible from the tanks. Gamma radiation attenuates when travelling through the full fuel tanks; the attenuating effect is not constant during the flight. As the weight of the crystal boxes is considerable (each crystal box weighs about 104 kg.), their location has some influence on the aircraft's centre of mass. Placing these boxes too far from the aircraft's centre of gravity can compromise the safety of the plane in some extreme situations. In the Cessna Caravan aircraft the fuel tanks are located inside the wing and sufficiently distant from the crystal box, so that their effect is minimal.

In order to minimise the background radiation caused by the aircraft itself, all the self-luminous signs and aviation instruments were checked for gamma radiation and changed to less radiating types. Certain types of aviation batteries have been found to have high potassium content, and those have been replaced by less radioactive models.

One problem with the airborne spectrometers used to be the drift of the energy stabilisation. The spectrometer (Exploranium GR-820), which is the mainstay of GTK's operations, monitors continuously every individual crystal and in turn adjusts the spectrum automatically. Besides automatic gain control, modern spectrometers have several software functions to aid in the quality control activities like daily source checks and follow-up of crystal resolutions. Spectrometer data are recorded, summed once every second, which ensures enough pulses for each measurement to avoid noisy data. Still this represents the smallest reasonable sampling area (footprint), because radiation from the ground is scattered over quite a large area when measuring at the altitude of 30 metres.

Positioning instruments

The positioning system based on satellites (GPS+GLONASS) is used for flight time navigation and flight path recovery. Besides the X and Y (or originally, latitude and longitude) coordinates, the Z coordinate can also be calculated with reasonable accuracy.

Single frequency, 24 channel GPS+GLONASS receivers in differential mode are adequate for today's airborne survey projects. The present accuracy of about 1 metre in the X-Y plane is sufficient, because airborne geophysical footprints generally are wide.

GTK uses Ashtech GG24 satellite receivers, which have 12 channels for GPS and 12 channels for GLONASS satellites on both planes and also at the GPS base station. Differential correction for the GLONASS satellites can also be utilised. The positioning accuracy is better than 1 m (95%). The antenna of the satellite receiver was fixed in a location where the obstructions and reflections from the aircraft parts, such as the rudder, were least, so that the antenna would receive signals from all directions and elevation angles without problems.

Variation in the distance from the aircraft to the ground has a major influence on the accuracy of all three measuring systems (EM, magnetic, radiometric). A radar altimeter (Collins) is used in the aircraft to maintain and measure accurately the flight altitude during a survey.

During the 1970s and early 1980s, flight path recovery was based on so called fixed points on continuous black and white film and photo mosaic maps. Later the continuous-strip camera was replaced by a video camera. Although the video is not needed anymore for constructing the flight path, a digital video or still camera provides additional information, for instance, in verifying man-made anomalies in the data in environmental surveys.

Other instruments

There are additional instruments besides the basic geophysical and positioning instruments that are required in the aircraft. Most of these instruments collect information that helps in the correction of the geophysical data at a later date.

A barometric altimeter, whose output is in metres above sea level, is used to measure the air pressure. The information is utilised in gamma-ray data corrections. Air temperature inside and outside the aircraft is monitored with thermometers. The outside temperature is primarily used for gamma-ray data correction but is also useful in the quality control and removing drift from EM data.

Data flow and recording

GTK has developed an in-house system for handling frequency of measurement, data flow and registration procedure. Most of the instruments mentioned above, even the majority of the EM system components, are industrially made and publicly available. However, many of the instruments are meant to run individually or to run when connected to data recording systems manufactured by the same company. On the other hand, none of the commercially available data recording systems are designed to handle a variety of instruments manufactured by different companies, as is the case with GTK airborne installations.

Every instrument is connected to a microprocessor. The microprocessor controls the measurement frequency of the instrument and data transfer to the Local Area Network (LAN). A GPS based synchronisation pulse is provided through the LAN at a frequency of 40 Hz. One specific microprocessor takes care of the data recording in the hard drive during the flight. This kind of configuration allows flexibility and use of commercial software. Besides the data from the instruments mentioned above, additional information is also recorded during the flight. Information about the use of the aviation VHF radio, the aircraft beacon lights, the operation of the hydraulic pump, and the use of wipers are recorded as they may introduce noise in the data. Figure 11 is a schematic presentation of the data flow.

During the survey flights it is very important to keep track of the running of the various instruments. There is always one operator on board to monitor the instruments (Figs. 9 and 10) with a special graphical output on a computer screen, and also to record the flight log and details.

Fig. 9. Inside view of the Twin Otter with the instruments installed. Photo: Kai Nyman

Fig. 10. Inside view of the Cessna Caravan with the instruments installed. Photo: Kai Nyman

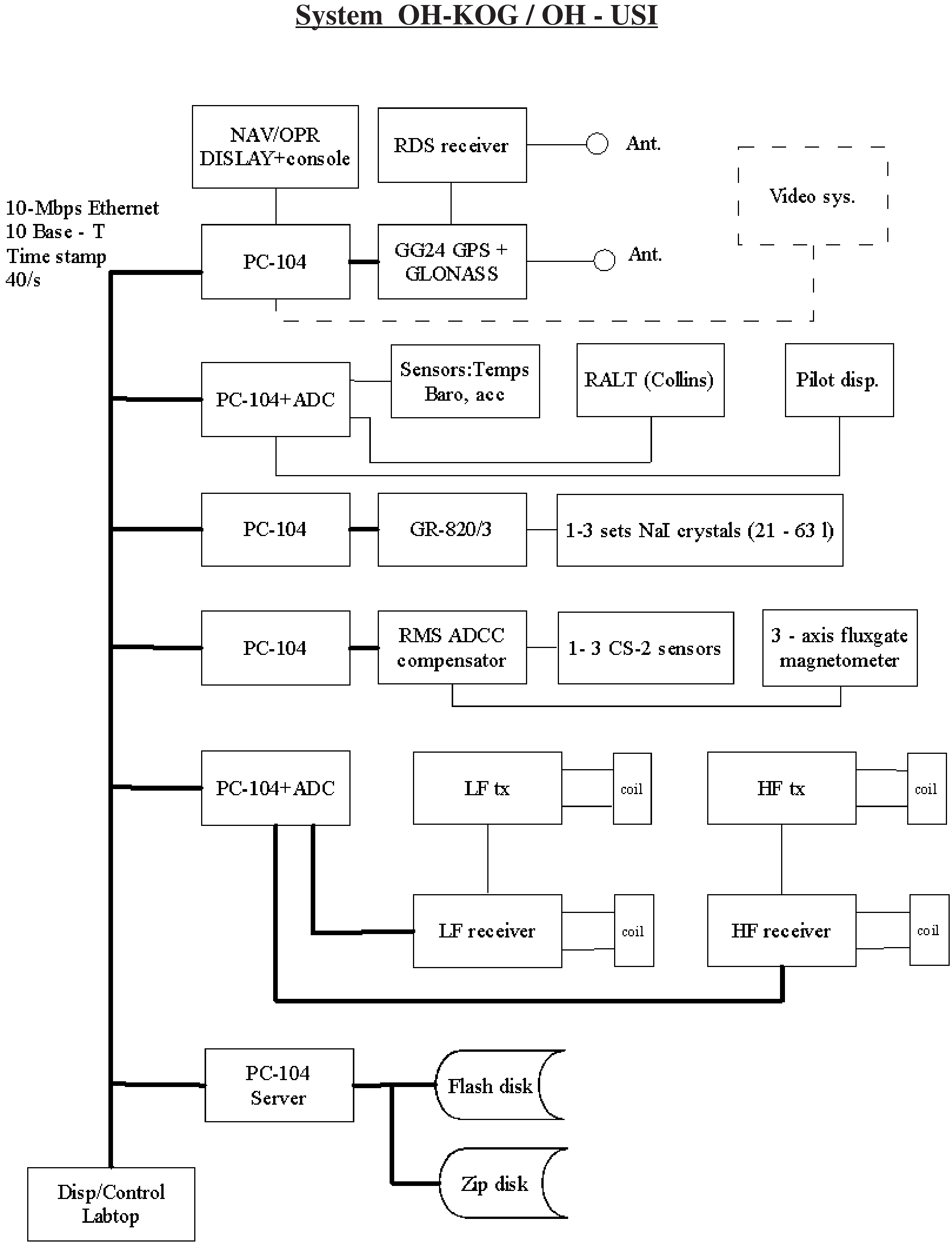


Fig. 11. Schematic view of the dataflow between the instruments in the aircraft.

Base stations

There is always one or two base stations inside or near the survey area to monitor time dependent variables. The base station data are then used to remove the temporal variation from the data recorded in the aircraft during the survey flight. The instruments used at base stations (Fig. 12) are normally a magnetometer and a GPS+GLONASS receiver as well as monitor and data storage facilities. Both the GPS data and the magnetometer readings are recorded every second. Special attention has been focused on minimising the size and maximising the transportability of the whole base station unit. The base station can be housed in a caravan, in a cottage or in a tent depending on the circumstances. In Finland electricity to the base station is easy to obtain, otherwise a solar cell system is prepared to provide power.

The diurnal variation of the earth's magnetic field is measured at a reference base station using a cesium magnetometer. There are three main requirements that influenced this choice: i) accuracy, ii) sample interval requirements of the magnetic survey, and iii) the possibility of a spare part for the aircraft magnetometer. The base station magnetic readings are synchronised with the base station GPS for exact time.

Fig. 12. Base station "housings". Magnetometer, GPS unit and control pc inside the tent, magnetometer sensor and GPS antenna in the field. Photo: Kai Nyman

FREQUENCY DOMAIN ELECTROMAGNETIC MEASUREMENTS

The frequency domain electromagnetic (EM) system

The EM system is an independent unit, in which a transmitter produces the primary signal and the receiver unit measures its response. The EM transmitter signal is a continuous sinusoidal wave, which induces a primary field. The primary field induces a secondary field in a conductor like conductors in the ground and also in the aircraft fuselage (aircraft field). The secondary field is obtained by cancelling the primary field from the received signal with a compensation unit (see Fig. 13). The measured secondary field is scaled to the primary field.

The measured EM field is divided in two perpendicular components, the in-phase (real) component, which is in the same phase as the primary signal and quadrature (imaginary) component, which has 90 degrees phase shift compared to the primary signal. The components have different characteristics, as described by Suppala et al. (2005, *this volume*).

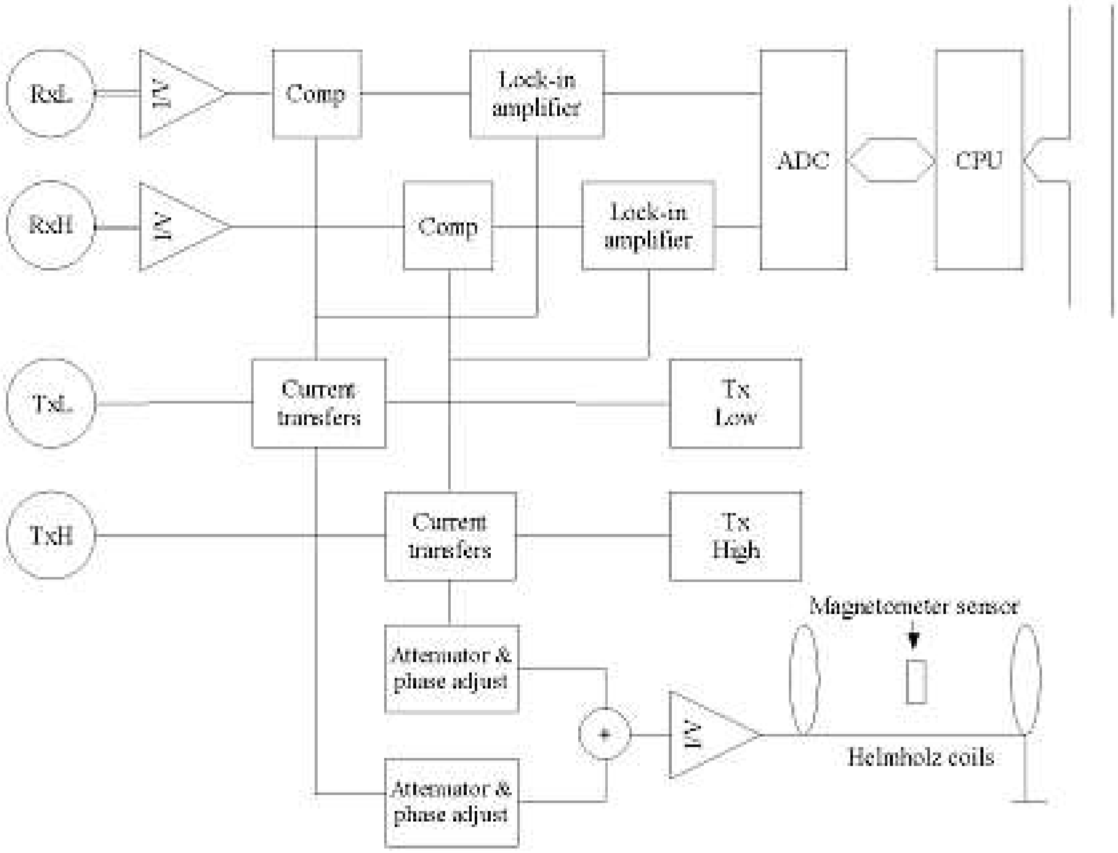


Fig. 13. Block diagram of the dual frequency EM instrumentation (Poikonen et al. 1998).

Frequency design

The EM system design is a compromise of the following factors: the weight of the wingtip installation with the number of coils, coil dimensions, coil configurations, the number of frequencies and the intensity of the primary field. Technical solutions depending on the aircraft were discussed in a previous chapter. In the search of the lowest functional frequency, the coil size and high current are considered. Large coils together with high current are needed to transmit a powerful primary field, where as high voltage is needed with higher frequencies. In order to optimise the design parameters GTK has used the so called tuned coils, where for each frequency there is one transmitter coil, which is tuned to that specific frequency in order to produce maximal magnetic moment and thus maximal magnetic flux. The chosen low frequency (about 3 kHz) was optimal, as the necessary current is not yet too high and the coil dimensions are not too big and wiring construction not too heavy. In the case of higher frequencies, the capasitivity problems increase causing more noise, and the noise with the 14.4 kHz was not yet too high. The influence of power lines, cables and others were minimised by selecting the EM frequencies so that the commonly used 50/60 Hz current systems would not interfere.

Noise in the EM measurements

There are several ways to reduce the electromagnetic noise in the aircraft as described in the hardware section. However, there are some phenomena that cannot be eliminated by hardware desing but fortunately some of them can be minimised afterward. Thunderbolts and lightning create electromagnetic pulses that can be measured with the EM system from long distances. As these pulses usually have a characteristic shape they can be filtered out in the data processing phase.

The motion noise due to the thermal expansion of the wing is more problematic. If the distance between the transmitter and receiver coils decreases by about 2 mm that will cause an in-phase component anomaly of 280 ppm. An aluminium rod of 20 metres will shorten by 2 mm if the temperature drops about 4°C. During the summertime in Finland the air temperature can sometimes drop 4°C when flying under a very large cloud or in the rain. These kinds of long wavelength anomalies are very difficult to distinguish automatically from actual anomalies, but can be reduced in interactive post-processing with the help of outside temperature data.

The influence of the variations in the flight altitude and the variations in the aircraft orientation (pitch, roll and yaw) to the in-phase and quadrature components depends on the conductivity of the ground. For instance, when flying above well conducting objects that can be considered as infinite half space (like seawater) the EM data can be used to calculate the flight altitude. The magnitudes of the effects from variations in pitch, roll and yaw are smaller but should be taken account in certain extreme cases.

One way of reducing the effects caused by flight altitude variations is to convert the measured in-phase and out of phase values to apparent conductivity or apparent resistivity values using one or two layer models. With this approach it is possible to compare data originating from different EM systems and frequencies and carry out visual interpretations more easily. Transformations to apparent resistivity as well as numerous calibration phases and procedures are described in details in the following sections.

Calibration of EM system

Perpendicularity of the components

At the beginning and at the end of each survey flight the phase shift between in-phase and quadrature components is checked, and adjusted at the beginning if necessary. In Figure 14 there is an example of an output of this perpendicularity calibration check. As the phase shift is 90 degrees, there should not be any trace in the quadrature component as an artificial signal (1960 ppm) is applied to in-phase component and vice versa. This procedure is done separately on each frequency to the in-phase and quadrature components. At the end of a survey flight this procedure is repeated to check the possible phase drift during the flight. Normally, there is no noticeable phase drift. The test procedure at the end of each flight guarantees the high quality of the EM

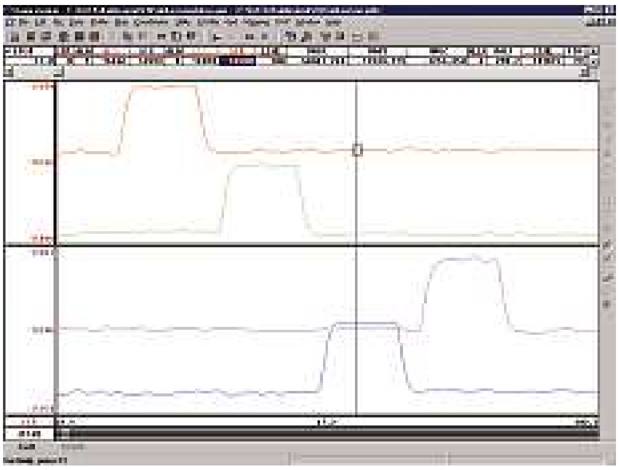


Fig. 14. A perpendicularity test for real and quadrature components, at 3125 and 14368 Hz in Twin Otter EM configuration at the beginning of a survey flight. Perpendicularity is good, as there is no effect from other components seen.

system. In addition a signal check is performed after the perpendicularity test to ensure that the transmitter is working properly.

From registration units to ppm

The output of the EM system is in relative units (mV), which must be calibrated to ppm (parts per million of the transmitted primary signal) in order to make quantitative interpretation possible. The calibration is also needed to minimize the effect of the conductive body of the aircraft.

The calibration of the EM system is carried out by flying at different altitudes over the sea, which can be regarded as a homogenous and conductive half space. These requirements are fulfilled by Baltic Sea: it is more than 50 metres deep and the conductivity of the seawater is 0.3–1.0 S/m. Fresh water lakes as a more resistive calibration environment are not usually deep enough in Finland for reliable calibration because electrically conductive lake bottom clays may disturb the measurements.

The calibration flight is usually flown over the Gulf of Finland, near Helsinki, along a calibration line. This N-S profile is 4 km long. At the same time the conductivity of the seawater is measured from a boat on five locations along the calibration line. The vertical distribution of seawater conductivity and temperature is measured from surface to seafloor. An example of one conductivity profile is presented in Figure 15. The effect of slight changes in conductivity below 30 metres is negligible to the EM response so the average of S/m was chosen to be the calibration conductivity of the half space model.

The measured conductivity is used to calculate theoretical responses for in-phase and quadrature components at both frequencies. The theoretical response of the airborne EM is calculated using Leroi-air program developed by AMIRA (Suppala et al. 2005, *this volume*), and these responses are presented by solid curves in the Figure 16. Using non-linear optimisation, a best fit for a scalar coefficient is obtained. Using this coefficient the measured units can be converted to ppm. The fit between measured and theoretical responses is good at normal measuring altitudes, at 30–50 metres.

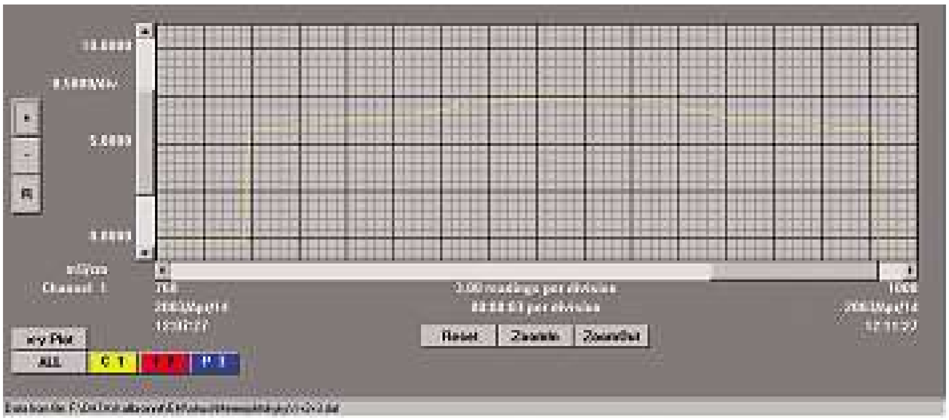


Fig. 15. An example of one conductivity profile on EM calibration flight above the sea.

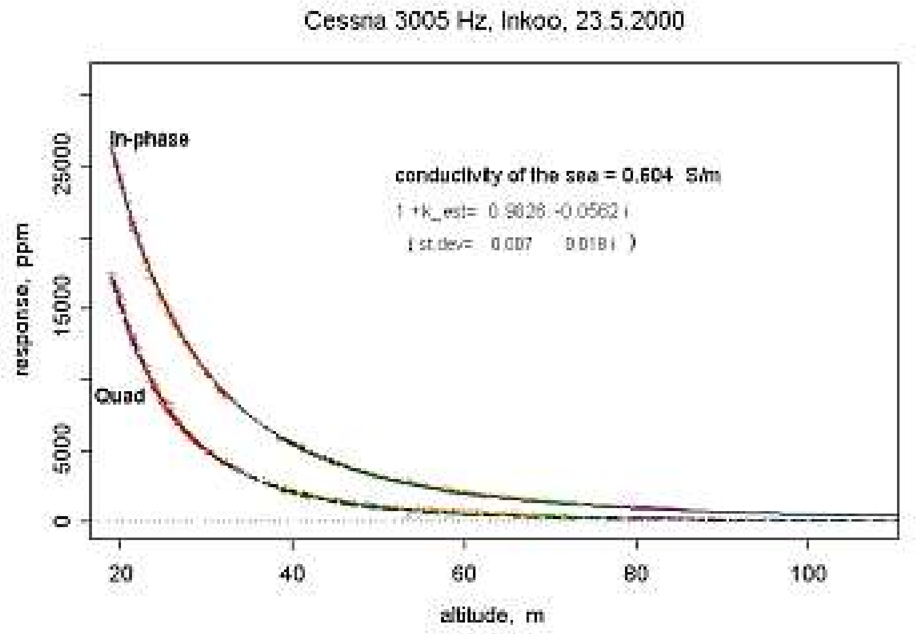


Fig. 16. An example of results of a EM calibration flight over sea at various altitudes. Theoretical curve is plotted with a solid black line and measurements after calibration with coloured dots. Residual error between theoretical and measured curves is negligible.

Methodological corrections applied to the EM system

Zero-level correction

A zero-level is adjusted to an artificial level at the beginning of each survey flight to ensure a large enough scale to register both positive and negative anomalies. The registered values then are independent of the real zero-level. This calibration is performed at a high altitude (commonly 300 metres above ground) to attenuate ground EM response. The zero-level calibration procedure is repeated at the end of each flight. The level of the EM data can be corrected linearly using these calibration results. This preliminary automatic correction gives good results if the drift is linear and low in magnitude. The linear part of the drift is usually less than 100 ppm in an hour if there is no temperature gradient.

If the flight lines are long, the air temperature can sometimes vary significantly during a flight line, and this causes non-linear drift to the zero-level. A temperature variation of one degree centigrade changes the coil separation so that the zero-level changes about 70 ppm. It would be possible in theory to correct this effect, but unfortunately wings of an airplane cannot be regarded as one rigid piece. Wings are made of complicated materials, which may have a non-linear relationship of the length of the wing with temperature change, and hence the coil separation. There are also other reasons for this drift, like temperature flows in coils and in other analogue components, which are never ideal.

The non-linear drift can be estimated for each flight and for each EM component. An interactive in-house-made Windows program, Emprelev, does this job. The user can provide a set of points, which estimates the drift during that flight for each component. The outside temperature is usually plotted above the EM profile to help to determine whether a high temperature gradient exists and the online/offline parameter profile on the bottom is there for observation of the flight lines and turns. In Figure 17a there is a 3.1 kHz in-phase component profile of one complete flight (37 flight lines) presented together with the drift estimation points (small red circles) and linear drift estimation line (blue), which connects the calibration points and the first and last red circle. It can be seen that the non-linear drift estimation gives far better results than the automatic linear estimation and helps the latter line by line processing.

The zero-level of every flight line has still to be checked, and if necessary, corrected interactively. An in-house graphical Windows program, Level32 has been produced in GTK for this purpose. An example of this program is presented in Figure 17b. Vari-

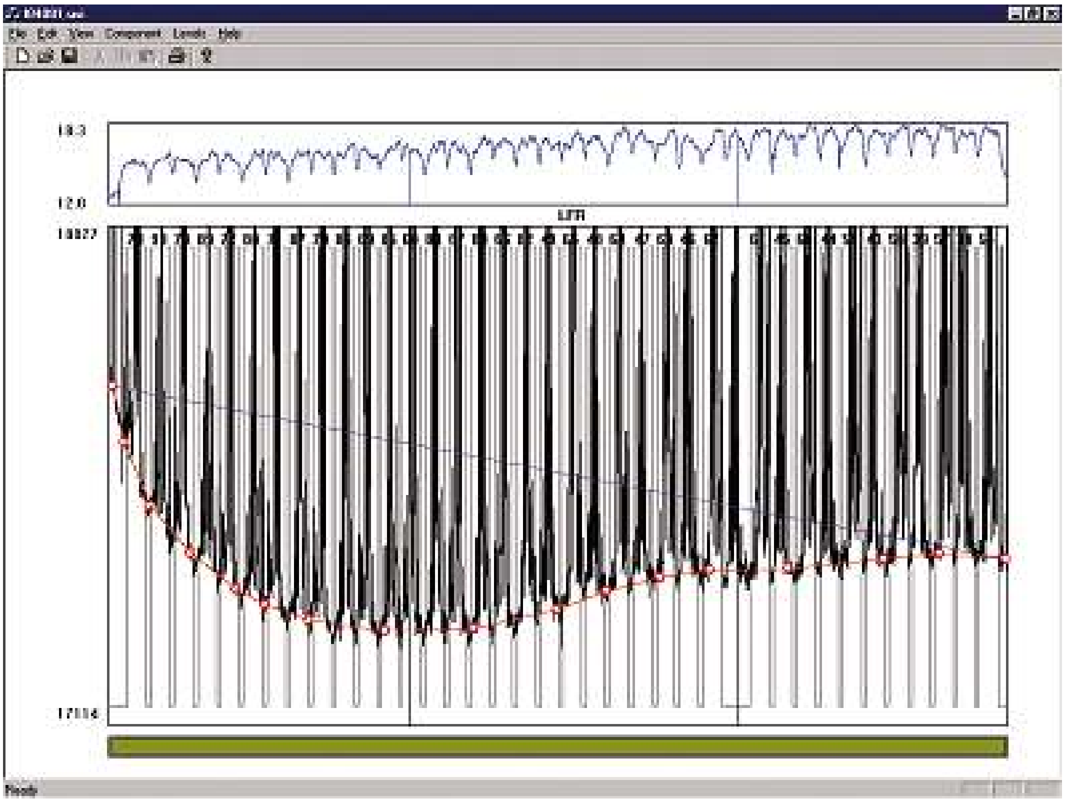


Fig. 17a. EMPRELEV, an interactive program for prelevelling slow drift from EM components on the whole flight. Lower panel: in-phase profile (black) with estimated drift curve (red) and linear drift estimation line (blue). Upper panel: temperature profile.

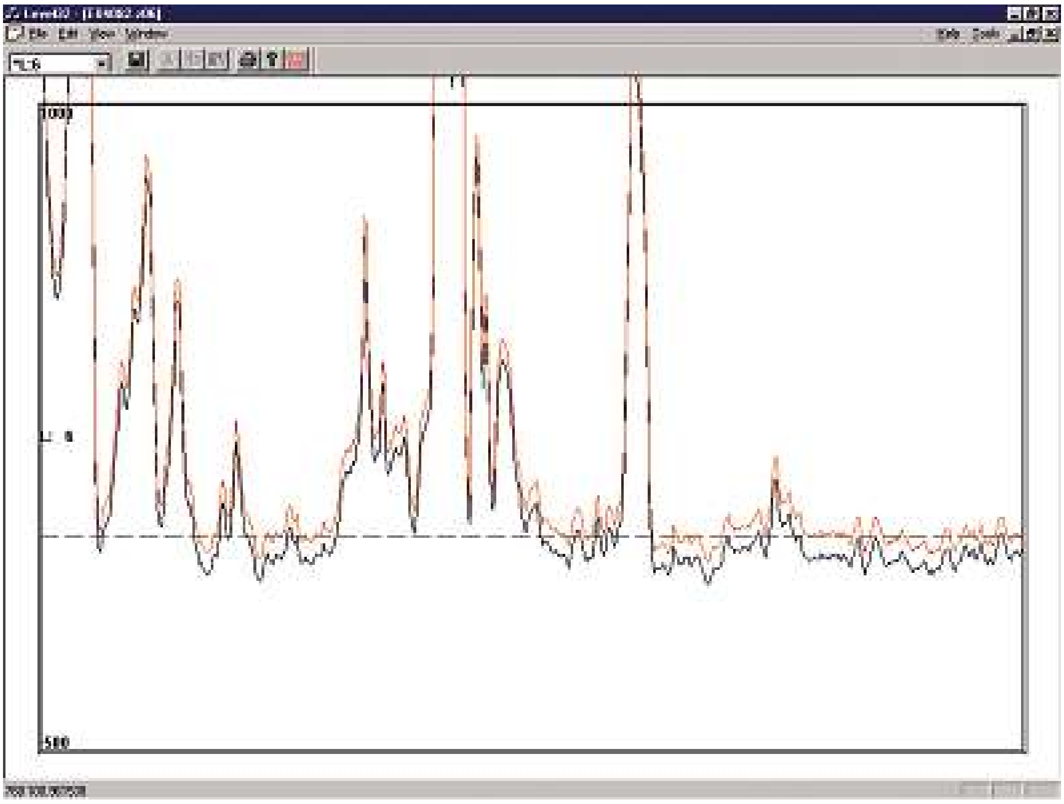


Fig. 17b. Level32, an interactive program for levelling slow drift from EM components. The black curve is original EM LFR data from one flight line and the red curve interactively levelled data.

able numbers of profiles of an EM component can be presented simultaneously in a window. Lines are sorted in the data file, and adjacent profiles can be compared to provide information for easy decision-making in the levelling of a profile. In this program we can provide a set of points, which determine the estimated zero-level. Usually two points are enough to determine the drift curve for correction. However, in case of a fast drift three or more points must be used. To provide a better resolution in the levelling process, it has been observed that three survey lines in a window is the maximum. When Emprelev program is processed properly there is less to do with Level32 software.

Additional microlevelling is needed to remove small levelling errors, which were left behind by the above processes before high quality grids and maps can be produced. Both automatic and interactive levelling phases are absolutely necessary before micro-levelling. Otherwise, the final levels would not be correct, and false interpretation would result. At GTK "Floating median difference method" was developed for this final levelling problem. By proper choice of parameters, like filtering radius, one can ensure that filtering is affected to the zero-level background and has only minimal effect to the anomalies.

Time constant correction

The time constant is the small delay in the measurements caused by the detector circuit. A short median filter is used when gathering measurements to avoid single error peaks. The time constant depends on the sampling frequency and causes a shift of anomalies and a small skewness to narrow, sharp anomalies. This is corrected by shifting the anomalies backwards correspondingly. This correction coefficient is verified from the sea-test flight which is flown at different altitudes.

The effect of time constant for anomalies caused by objects like thin plates must be made in the interpretation process. This processes is not performed systematically for all the EM data because it would raise the noise level and require additional noise filtering which in turn may produce unwanted secondary effects.

Sferics filtering

Sferics are caused by electrical discharges, like thunderstorms. Usually measurements are not carried out if there is a thunderstorm near the survey area. The peaks of the sferics can be monitored from the EM profile and then be removed. The anomaly is recognised by its shape: it rises very fast and falls slowly, exponentially. It makes for a good processing philosophy to filter out only those peaks that originate from electrical discharges, and to leave uncertain cases untouched. Wholesale filtering of all data would certainly result in unwanted filtering of real anomalies. The less averaging and smoothing of the data, the more reliable it is.

Lag correction

A lag correction corrects data for the registration delay from EM unit to CPU of the aircraft LAN-system. The lag difference is determined by flying several times over a sharp anomaly source in opposite directions. This is usually made over a small electrical line.

Apparent resistivity and depth by a half-space model

Primary EM components, in-phase and quadrature, can be quickly transformed to apparent resistivity and depth using a half-space model (Suppala et al. 2005, *this volume*) to give a first, rough interpretation of the data. Altitude changes have no more effects on the results, and apparent resistivity and depth results are also independent of the measuring system. When these results are used properly they give valuable information on different kind of conductors. Shallow and deep conductors can also be classified with apparent resistivity and depth maps.

In-phase and quadrature values, which correspond to a set of conductivity and height values, are first calculated. Then the calculated values of in-phase and quadrature with correspondent conductivity and height are interpolated to a constant logarithmic set to aid later interpolation. These steps are done only once for each coil configuration and frequency. In the actual transformation process, for each pair of measured in-phase and quadrature values, the nearest values of conductivity and height are searched from the table. Exact values are interpolated and converted to apparent resistivity and apparent depth. In the calculation process, limits must be used to prevent one calculating from too small and uncertain input values of in-phase and quadrature. The limit values depend on the noise and error level of the components. The lower they are, the smaller the values of in-phase and quadrature that can be utilised. The transformation programs used are based on a version of TRANSAEM (Markku Pirttijärvi 1995). In Figures 18 and 19, diagrams of the GTK Cessna Caravan coil system are presented for both frequencies, 3005 Hz and 14368 Hz. Values of in-phase and quadrature are presented as a function of apparent resistivity and flight altitude.

Under certain conditions, apparent resistivity and depth data requires microlevelling as in the normal in-phase and quadrature components. A special version of the ”Floating median difference method” (FMD) for apparent resistivity has been developed for that purpose. Low values of apparent resistivity can be calculated with better relative accuracy than high values, because they are calculated from high values of in-phase and quadrature, and thus the relative error caused by noise, zero-level error and other factors is smaller. If apparent resistivity is zero, then no correction is done at all, and the higher the value of apparent resistivity, the greater the possibility of correction. This method also prevents appearance of negative values in apparent resistivity, although in the interpolation process some negative values may appear. Values of apparent resistivity up to 1500 ohm-metres can be expected for low frequency (3 kHz) and around 3000 ohm-metres for higher frequency (14 kHz).

One ought to be aware that the apparent resistivity and depth data and maps are an application of a half-space model. The appropriateness of this model must be ascertained before detailed interpretation is made. It is a first step to presenting EM results in derivative units, which gives a closer meaning to physical properties of the object source. Final detailed interpretation with the proper model should be carried out only using original in-phase and quadrature data. A more detailed interpretation can be made using e.g. AMIRA software (Suppala et al. 2005, *this volume*). The first interpretation presentation with half space model is still a useful way to show overall apparent conductivity and depth of large areas.

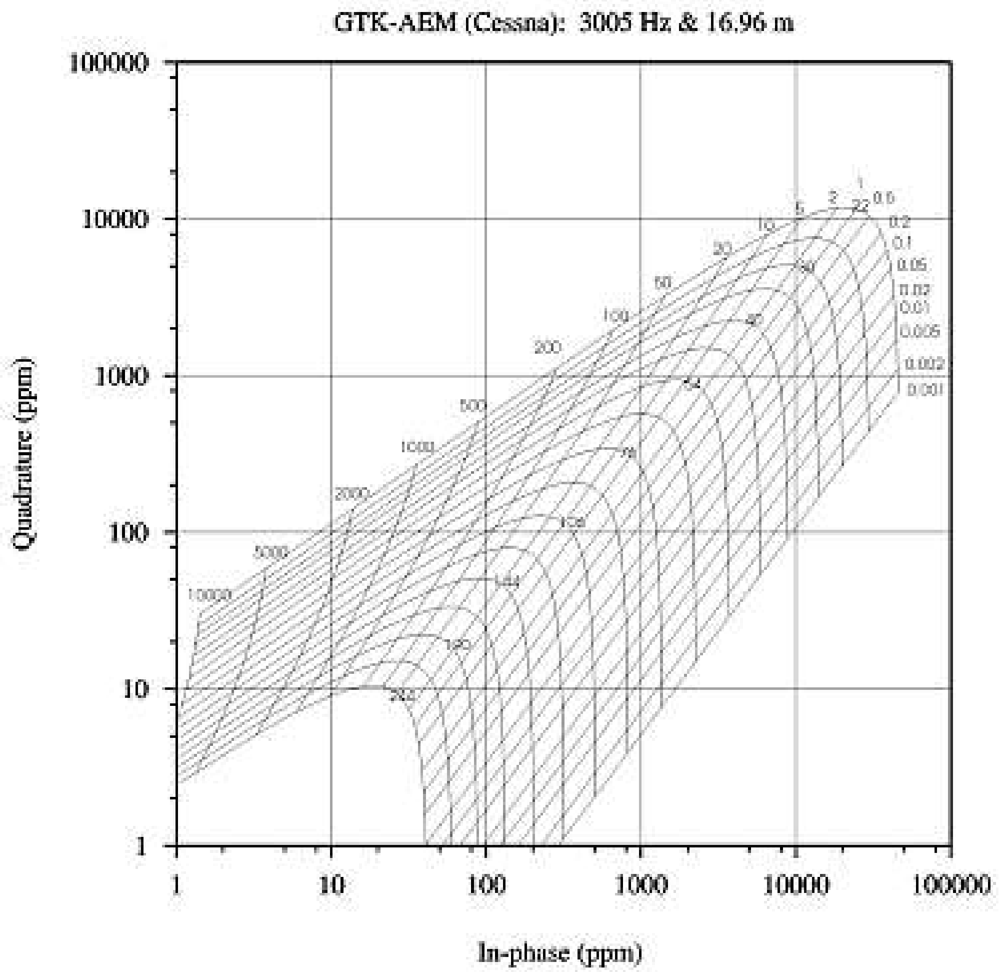


Fig. 18. A half-space diagram for our Cessna EM low frequency (LF 3005 Hz), on which apparent resistivity and depth transformations are based.

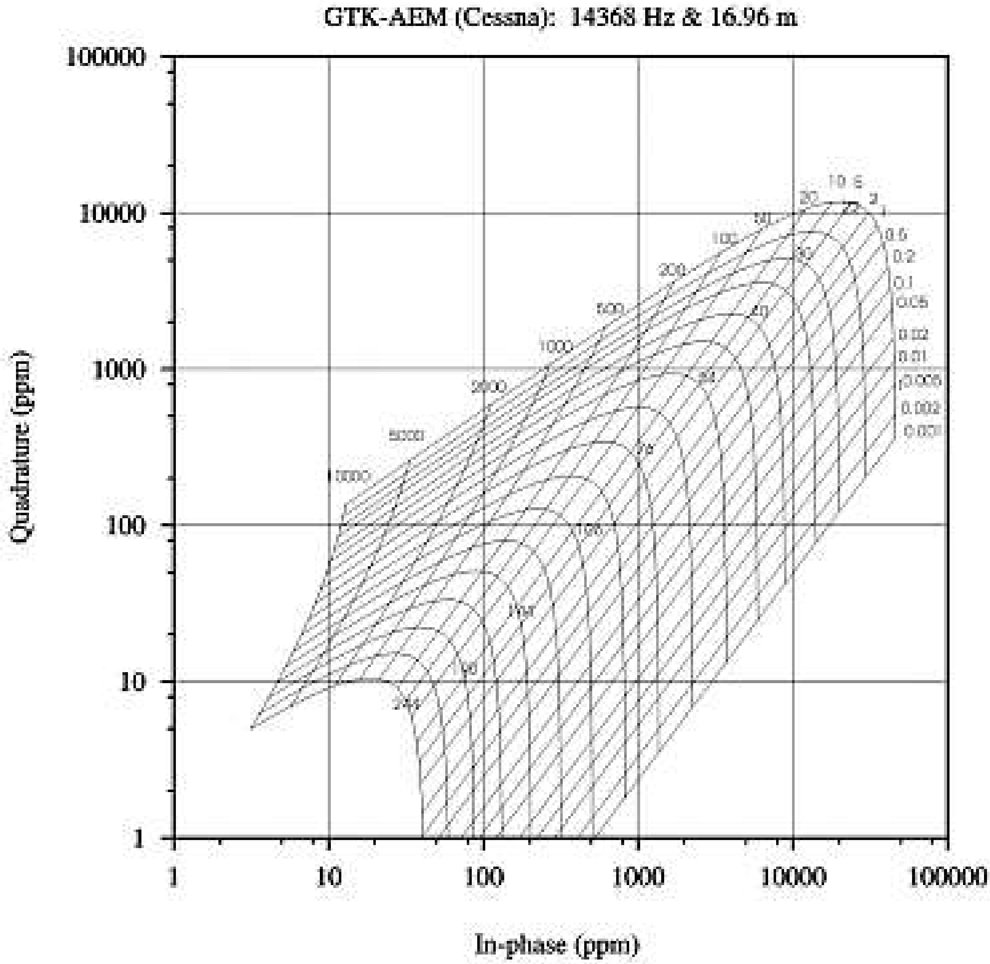


Fig. 19. A half-space diagram for GTK's Cessna EM high frequency (HF 14368 Hz), on which the apparent resistivity and depth transformations are based.

MEASURING THE MAGNETIC FIELD

Measuring the magnetic field from the aircraft requires high resolution equipment installed properly in the aircraft, high measuring capacity, careful correction procedures, continuous observation of Earth's magnetic field variations and several data processing phases. At GTK the transverse horizontal gradiometer was adopted at an early stage during 1970s and it has been in use since to improve the magnetic field estimation between flight lines. Special attention has been paid to the diurnal variation correction because of the location of Finland – the country is located in the northern latitudes, between latitudes 60 and 70 degrees, where the auroral zone reaches to the northern part of the country. The data processing has to be specially developed to meet the requirements of Finnish geology, which causes sharp and strong anomalies, and to benefit the measurements at very low flight altitude.

The cesium magnetometers have some clear advantages compared to the classical proton precession (including Overhauser) magnetometers. These features are: high sensitivity, continuous signal, high gradient tolerance, low radiated electromagnetic interference and worldwide orienting capabilities. The sampling is made 10 times per second allowing 6–7 metres sample interval, The output of the cesium magnetometer is the total intensity of the Earth's magnetic field expressed in nanoTeslas.

Special features of the transverse horizontal gradiometer

GTK's horizontal gradiometer system consists of two independent total field magnetometers with sensors at the wingtip of the aircraft at a distance of 21.36 metres. After compensation, applying the results of the Clover Leaf flight and microlevelling, they are in the same magnetic field level.

On normal surveys with 200 m line spacing the transverse gradiometer improves the data quality remarkably. On very high-resolution surveys line spacing of 50 metres can be replaced by 75 metres spacing, and the same 50 m actual spacing information is achieved due to wide wingspan. The same effect can also be achieved with broader line spacing surveys. Moreover, transverse gradient gives information on magnetic field behaviour between the lines, and at 30 metres flight altitude the whole anomaly field is fully covered.

Dense measurements along the line (6–7 metres spacing) with two magnetometers provide good data for calculating the horizontal differences. Using the transverse and longitudinal differences, the horizontal direction of the total field gradient can be calculated. This can be utilised both in improving the interpolation and in interpretation of small targets, an example of which is visualised in Figure 20. Also, calculated vertical gradients are reliable for this kind of high-resolution data.

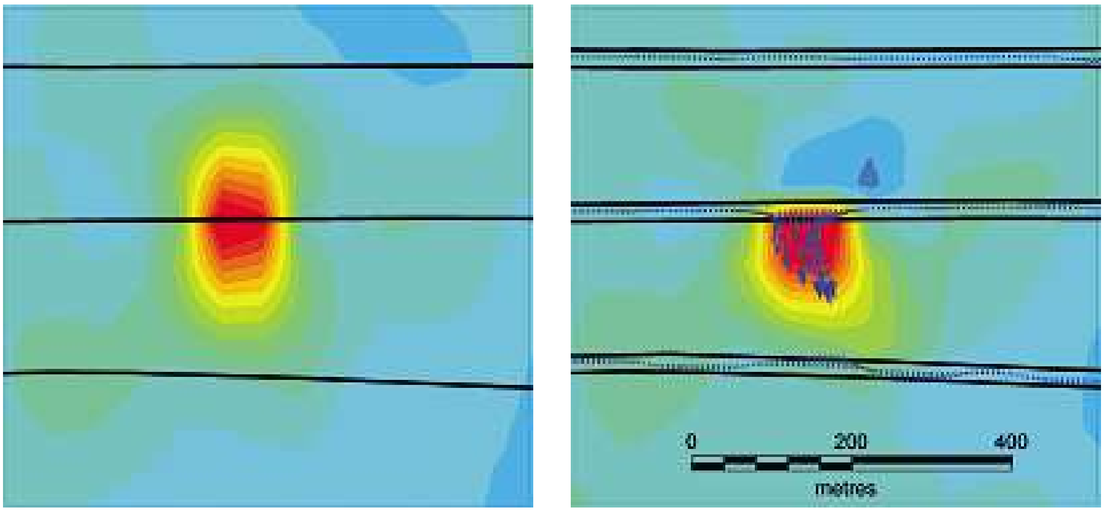


Fig. 20. On the left the magnetic grid is interpolated using one magnetometer data. On the right a magnetic map showing an area of three flight lines (line separation 200 metres) and arrows showing the gradient of magnetic field calculated from wingtip magnetometer measurements. The grid is interpolated using GTK's program using horizontal gradients.

Magnetic calibrations and methodological corrections

The measured magnetic total field values include the magnetic field of the Earth, its time varying components, man-made anomalies and many aircraft-based errors. The principle of the corrections is to remove all unrepeatable components, whereas the anomalies due to bedrock, overburden and man-made constructions are not removed. The corrections are done to remove the aircraft's own influence in the measurements, to eliminate the time dependent changes of the Earth's magnetic field and to correct the errors originating from the measurement process.

Aircraft's influence

The aircraft is a magnetised obstacle moving in the Earth's magnetic field. The magnetic impact depends on flight direction (heading) and the movement of the aircraft (pitch, roll, yaw). The properties vary with time. The magnetic effects depend on time and place within Earth's magnetic field, so the calibrations have to be made separately for each survey area, and have to be repeated in cases of prolonged surveys.

The effect caused by the movement of the aircraft is removed or diminished automatically during the flight by use of the compensation data. The compensation flight is close to the survey area, where magnetic anomalies are rather small, and flown high enough to avoid short wavelength anomalies. The aircraft flies in directions equal to original survey lines and perpendicular lines and performs pitch (±5 deg), roll (±10 deg) and yaw (±5 deg) movements separately along each direction. The aircraft's total movement towards nominal direction is not important, but the heading has to be the same as the true flight line direction. After recording the magnetic effects of all twelve movements, the compensation coefficients are calculated, the file of which will be saved and used during the actual survey.

The effectiveness of the compensation is verified by a Figure-Of-Merit flight, where the same movements as described above are repeated and the new compensation parameter file is utilised (Fig. 21). All three compensated movement effects are summarised in all four directions, and the FOM parameter is thus the sum of these 12 peak-to-peak anomaly values of the compensated magnetic field.

After the compensation the heading correction is calculated following a Clover Leaf test flight. Above a magnetically smooth area, all line and perpendicular line directions are flown, and preferably back and forth numerous times along the precisely same line. The result is more accurate if the flight can be done when the wind is quiet, in order to maintain the true heading.

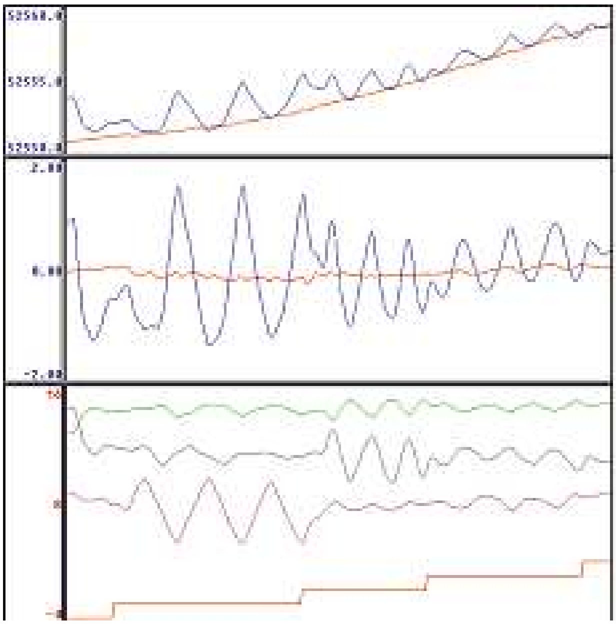


Fig. 21. Aircraft's movements FOM of the magnetic measurements in one direction
Upper: Uncompensated (blue) and compensated (red) total field. Scale nT
Middle: High-pass filtered total field data, where the trend is removed; same colours. Scale nT
Below: Flux-gate magnetometers recordings of the RMS compensator showing the aircraft's movements, and fix point steps showing pitch, roll and yaw movement areas

Diurnal correction

Short time variations of the Earth's magnetic field are removed by using a magnetic base station. The magnetic base station is established near the survey area, preferably in the middle of the area. This condition is important especially in North Finland, inside the auroral belt area. The location is chosen in a non-anomalous area. There is normally another base at the operation airport, which gives reference data to verify the time dependence of magnetic variations.

The magnetic variation during the survey flight has to be small enough so that it can be considered that the magnetic variation has minimum time difference between survey aircraft and the base station. The suitable allowed limits of variation are defined according to local magnetic anomaly level, required accuracy and quality and possible cost and time limits of the survey. Both short and long time variation limits are defined. In Finland short time limits are 5–10 nT/3 min, long time limits 20–50 nT/10 min, but also the value of the magnetic field should be near the quiet time average. As an example a set of diurnal recordings from northern Finland is seen in Figure 22.

Secular variation and IGRF

To eliminate the drift of the secular variation, all total field magnetic measurements in Finland are transferred to the year 1965.0 with the help of Finnish Geomagnetic Observatory data provided by Department of Geomagnetism in Finnish Meteorological Institute. The year was chosen because DGRF1965.0 was properly defined at the time when the Second National Project started in 1972. The transform depends on place and date of the surveys. Figure 23 shows the secular variation in Finland during the Second National Mapping Project measured

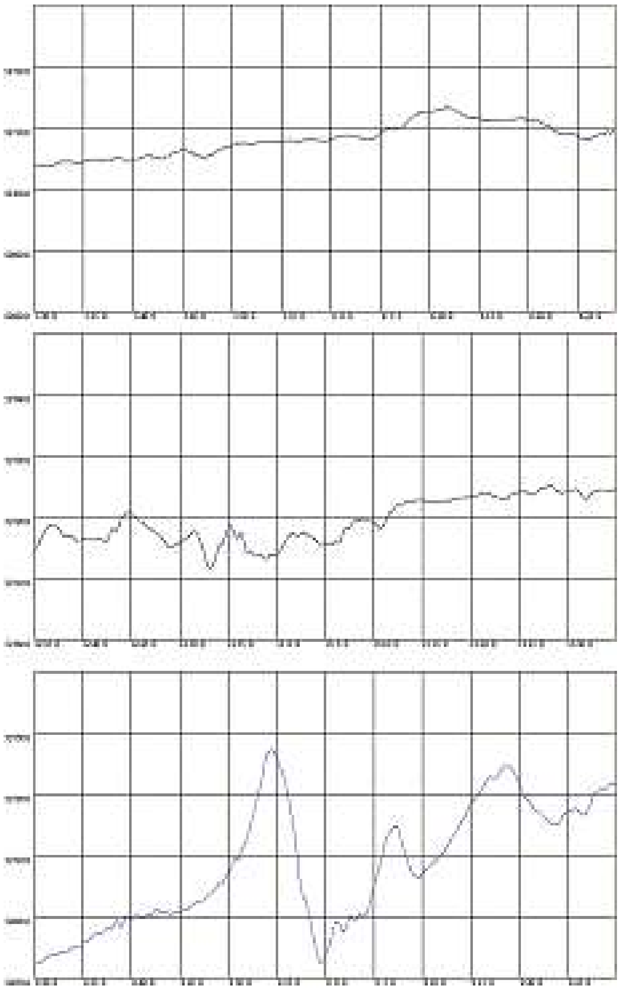


Fig. 22. A set of diurnal variation recordings in Finland: quiet day, moderate variation, strong variation.

at the Geophysical Observatories in Nurmijärvi, South Finland, and Sodankylä, North Finland.

In the second phase, the data is gridded and the DGRF1965.0 reference field (Fig. 24) is removed. After removal of DGRF1965.0, the standard deviation of the Finnish magnetic anomaly field is about 300 nT and thus the anomaly maps can be combined using the same colour table for the whole country.

Other corrections

A lag test is performed to verify the recording delay. Due to the real time RMS compensation, its prefiltering, and delays in network data transmission, a small lag exists in the recording of the data. This is verified by repeating a flight line in opposite directions above a sharp but sideways wide magnetic

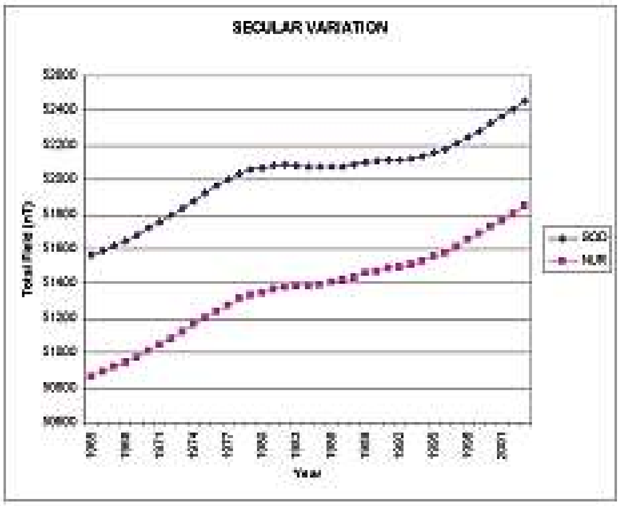


Fig. 23. The secular variation in Finland during the Second National Mapping Project. Measured at the Nurmijärvi Geophysical Observatory by Finnish Meteorological Institute, Southern Finland and in Sodankylä Geophysical Observatory by University of Oulu, Northern Finland.

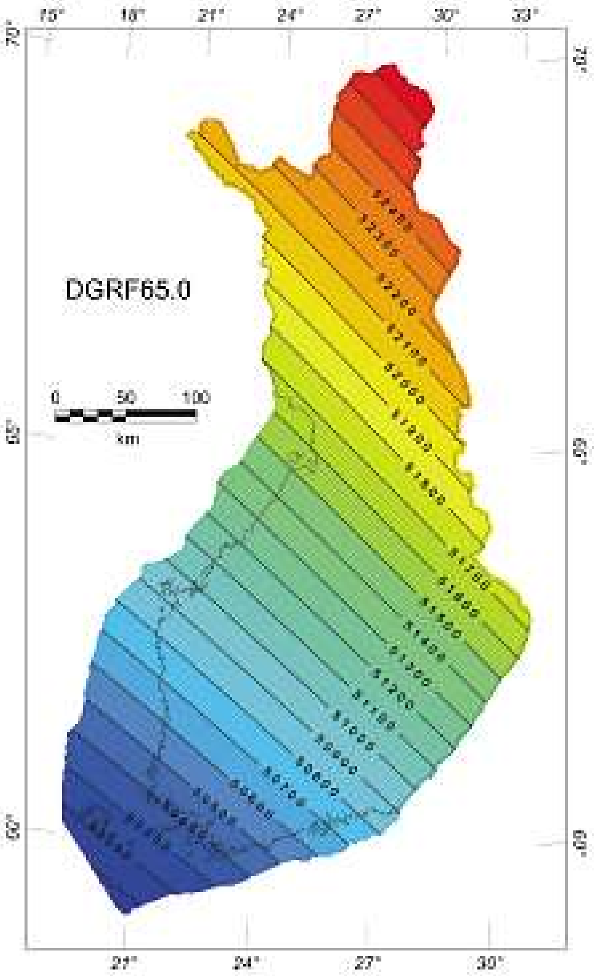


Fig. 24. DGRF65.0 reference field in Finland, which is removed from the final TMI data.

anomaly source like a railway or thin magnetic dyke. Comparing these repeated measurements, the exact lag is then determined.

The aircraft's own instrumentation can cause small errors in the magnetic data. A typical disturbance with the Twin Otter aircraft is the effect of the hydraulic pump. The hydraulic pump causes a 1–2 nT anomaly which lasts 1–2 seconds during its operation. When the pump works, the duration is recorded and the magnetic data is then removed automatically.

Levelling magnetic data

Some levelling of magnetic data is still needed after all the corrections described above. One source of residual error is the incomplete diurnal correction. Magnetic base stations are almost always located some distance from the measuring aircraft; but the transient field varies in time and also space. The error is small, usually less than 1 nT, but it can be very clearly seen in today's high resolution measurements over magnetically flat areas. In Finland where the auroral zone and magnetic north pole are very close, fast and high drift in the earth's magnetic field often occurs and makes accurate transient correction difficult. There are also other possible error sources, for example incomplete compensation and heading correction. The aim in applying any correction is to eliminate errors in the data that have an effect on the true magnetic intensity of the earth; to be avoided is the application of corrections, which have the sole objective of producing smooth and beautiful maps. If the original measured data is poor in quality, acceptable corrections may not be able to bring it to high quality level.

The correct levelling has to be based on original line data. Adjacent magnetic profiles can be compared to find out the difference, which may be used to correct that difference. If the trend of the magnetic field is not very strong, the magnetic data median in one flight line can be used to compare it to those of the other adjacent flight lines. As the correction term is a constant for each line, no distortion is made to the data in this process. With this method, residual errors can be reduced nominally to less than 1 nT. Interactive feedback is essential in this process, because the median is not always a good figure to represent the height of magnetic base level.

Micro-levelling is a term used generally for all those final processing steps in which minor residual errors are removed from the data (Fig. 25), if standard processing has not produced a data set of acceptable quality. Micro-levelling should be applied to the profile data to keep all data sets comparable and based on same origin. In the process employed at GTK the poorly levelled magnetic profiles or part of them are localized from grids and then by a combination of automatic and interactive work the profile data are levelled. As this levelling is made to the profile data, all magnetic data, profiles and gridded data, are comparable, which is always our goal.

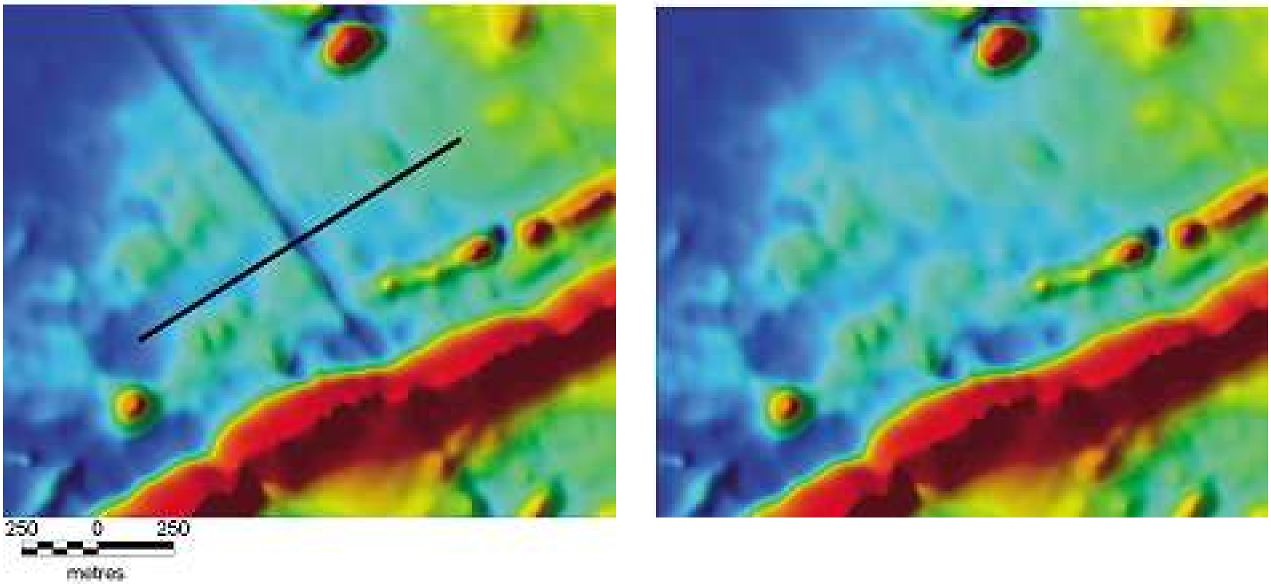


Fig. 25. Magnetic data before (left) and after (right) microlevelling.

When tie line correction is reasonable?

GTK do not normally fly tie lines in Finland. The tie line correction is ineffective due to low survey altitude and typically strong gradients of anomaly field. The error on intersection points between normal lines and tie lines is very often bigger than expected accuracy for present high-resolution magnetic surveys.

Tie lines are commonly flown at right angles to the normal flight lines and the line spacing is normally ten times wider. The wide tie line spacing prevents the removal of high frequency diurnal variations. Tie lines should be measured under magnetically very quiet periods. In tie line corrections the essential question is how we process the intersection errors, the errors at the crossover points, which are measured at the traverse and control lines. If we assume that the intersection error is due to navigational positioning error, we can move the coordinates a little bit to reduce the error. But if the positioning accuracy is less than one metre and magnetic measurements are made after each 6 metres, there is not too much to be expected. Before the GPS era, when positioning accuracy was much poorer than these days there were more arguments on behalf of this method as coordinates could be shifted even 100 metres with good conscience. Loop closure method is another method used in tie line correction, but it works well only if variations of the intersection errors are small, which means that there cannot be high gradients in the area. This prevents using this method as a general solution. Polynomial levelling is still another tie line correction method, in which a polynomial is fitted to the intersection errors as a function of flight time by a method of least squares. All these methods still require further levelling.

Magnetic interpolation

In magnetic measurements the data from the two aircraft used by GTK are different because the Twin Otter has two wingtip sensors but Cessna has only one sensor in the back boom. In the Twin Otter the two sensors are used as separate total field measurement units, which mean that the real line spacing of the measurements is even tighter than the nominal line spacing and thus the resolution of the measurements is improved.

At the moment there are two commercial interpolation algorithms in use with aeromagnetic total field data: minimum curvature algorithm by Geosoft Oasis Montaj and a distance weighting interpolation algorithm by Uniras A/S. The former is mostly used in our special surveys and the latter in the national mapping program. Of these two, the minimum curvature algorithm produces slightly better map images (Leväniemi 2002) but the Uniras algorithm is adequate and is preferred as it integrates better in the interpolation process.

Interpolation with horizontal gradients

A large ratio of line spacing to flight altitude leads to aliasing of anomalies on map images interpolated from the total field measurement data. This phenomenon is especially profound along the long linear anomalies such as magnetic dykes that intersect the flight lines at an acute angle; this may lead to wrong conclusions when interpreting the structures. This problem is acknowledged and GTK has researched and developed interpolation methods that make use of the measured horizontal gradient since the 1970s (Korhonen 1984). In this method a plane is fitted to three pairs of wingtip measurements (sample interval 12 or 25 metres), and the lateral and longitudinal gradients of this plane is then calculated. This trend information weighted by the inverse of the square of the distance was the source to calculate a 50 m by 50 m grid. The data from two adjacent flight lines were processed at the same time. The method was simple and fast which was necessary during the 70s, but caused occasionally clear overestimations. The problem was that measured horizontal distance was 21 metres, and this data was used to estimate values even further than 100 metres.

Recently a new method has been implemented at GTK for interpolating aeromagnetic gradiometer data with horizontal gradients (Leväniemi 2002). This method uses the idea of pseudolines introduced also by Hardwick (1999): pseudolines are comprised of artificial data points calculated off the line with the measured total field and horizontal gradient values, in other words the point density of the interpolation data is increased which leads to a better interpolation result. The new GTK method utilize the pseudolines but the gradients are calculated following loosely the idea of the older method, that is, with a fitted plane. Additional points located off the flight line are used with conventional line-based, scalar datasets in interpolating aeromagnetic data in order to reduce the aliasing effects on the maps.

In Figure 26a is presented the interpolation result of total field data measured by Twin Otter in 2001 in central Finland. The line spacing is 200 metres, nominal altitude 30 metres and flight direction N-S. There is a strong aliasing effect in linear anomalies that intersect the flight lines at an acute angle. In Figure 26b the new method has been applied to the total field measurement data and the interpolation result has improved significantly. Linear anomalies appear more continuous and the structures are clearer and better distinguished from each other.

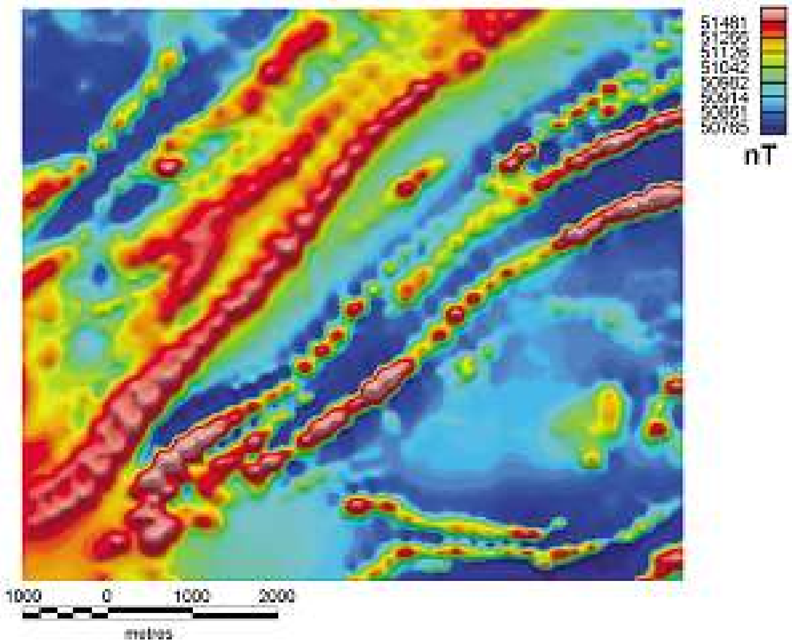


Fig. 26a. A standard interpolation result of magnetic total field data measured by the Twin Otter. The line spacing is 200 metres, nominal altitude 30 metres and flight direction N-S.

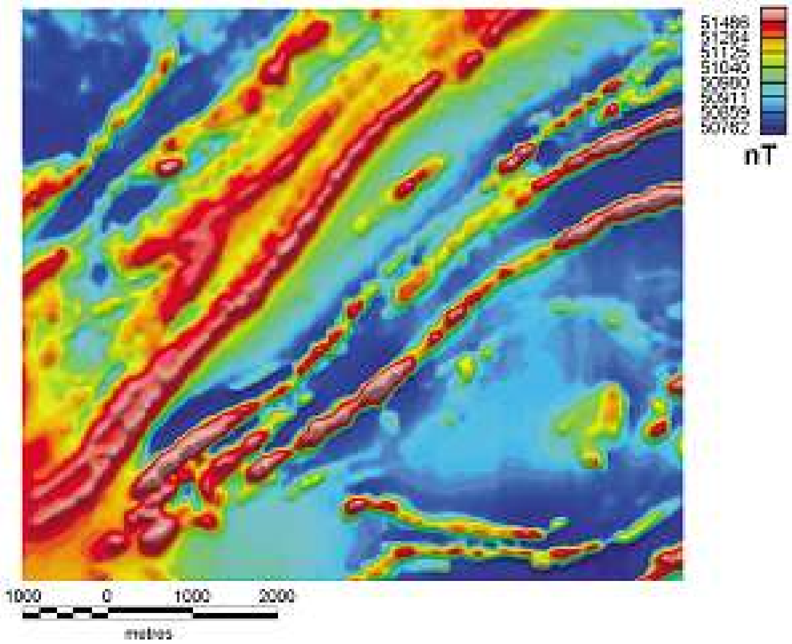


Fig. 26b. The result from GTK's interpolation method, which utilizes measured horizontal gradient information.

GAMMA-RAY MEASUREMENTS

Spectrometer and the NaI detectors

When a gamma quantum hits the NaI crystal a light scintillation is produced. The brightness of the scintillation is proportional to the energy of the gamma quantum. The scintillation in the NaI crystal is amplified with photo multiplier tube that is attached to the crystal. The pulses from the photo multiplier tubes are summed up and forwarded to the spectrometer. The height of a pulse is proportional to the original energy of the gamma quantum. In the spectrometer each pulse is analysed and sorted to one of the 256 channels (Fig. 27) according to its height, and the width of each channel being 12 keV. The output of the spectrometer is the counts in 256 channels summed up over a period of one second.

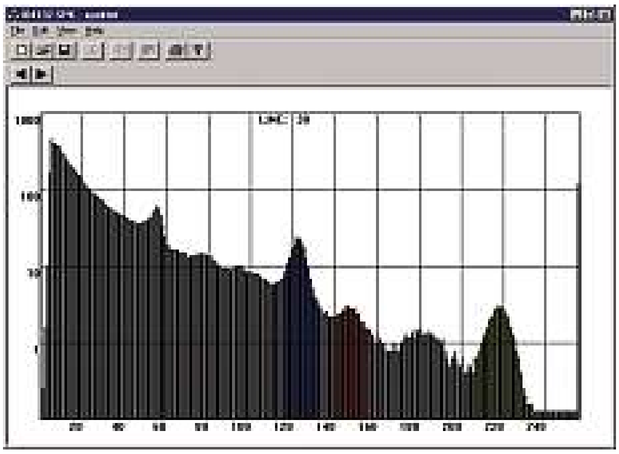


Fig. 27. A typical 256 channel average spectrum of one flight line, representing 255 channels, a cosmic channel and windowed channels (blue=potassium, red=uranium, yellow=thorium)

Dead time is one of those effects that recent developments in electronics and processing procedures have managed to almost eliminate. The spectrometer can analyse only one pulse at a time. In the case that the next pulse arrives to the spectrometer while the previous one is still being analysed the arriving pulse is rejected. Modern spectrometers, like Exploranium GR-820, provide automatically information for the dead time correction.

The majority of the natural gamma radiation originates from potassium (^{40}K) and the decay series of uranium (^{238}U) and thorium (^{232}Th). The potassium is measured at 1.46 MeV energy peak of ^{40}K, ^{238}U is monitored at 1.76 MeV peak of ^{214}Bi nuclide that belongs to the disintegration series of ^{238}U and thorium is measured using the gamma-rays at 2.62 MeV of ^{208}Tl that pertains to the decay series of ^{232}Th. Due to the characteristic behaviour of NaI crystals certain spectrometer channels below and above 1.46 MeV, 1.76 MeV and 2. 62 MeV are summed up to potassium, uranium and thorium windows. The recommended (IAEA) energy rates of the windows are listed in Table 6.

Besides the natural gamma radiation, the measured spectrum contains also some counts originating from man-made radiation, which can be separated from the natural to some extent in certain cases.

Table 6. The recommended (IAEA) energy rates of the spectral windows

WINDOW	ENERGY RANGE MeV
Thorium	2.41 – 2.81
Uranium	1.66 – 1.86
Potassium	1.37 – 1.57
Total	0.41 – 2.81

There are two major concerns related to the airborne gamma-ray surveys and how they are carried out. Both of them are related to rains. Water attenuates gamma-radiation quite effectively and thus the day-to-day variations in soil moisture can cause severe levelling problems in the airborne gamma-ray data. It has been monitored in practice that shortly after rain the radon count increases. The ^{214}Bi is a decay product of ^{222}Rn and thus the increase of the radon content of the air will produce false anomalies in the uranium window.

The variations of flight altitude can be normally corrected effectively with the aid of the radar altimeter measurements.

The commonly adopted standard in carrying out an airborne gamma-ray measurements is to process and to calibrate them in the manner presented in AGSO and IAEA reference manuals (Grasty & Minty 1995, IAEA 1991). Besides calibration, the AGSO manual also contains a full description of actions that should be carried out in order to avoid the difficulties described above.

Calibrations and corrections in gamma-ray spectrometry

The main purpose of the calibration is to produce data that is independent of the measurement instruments and to convert the original data (counts/sec/channel) into more useful units. Recommendations of calibrations in modern airborne gamma-ray spectrometry methods are presented in IAEA Technical Reports Series 323 (IAEA 1991), and our calibrations are made according to these instructions.

Energy Calibration

Nowadays the self-stabilising spectrometers eliminate the drift of photopeaks from their proper positions and the drift is not a problem anymore. Normally in real-time the spectra is stabilised by potassium (1.46 MeV). In the case of very high concentrations of uranium it can be unstable to use potassium for this purpose as pulses from uranium window can overcome pulses from potassium and hence the automatic stabilisation may drift or fail. It is wiser then to use thorium (2.62 MeV) to stabilise the spectra. The average spectra from each flight line is checked after each flight for suspicious data; a closer look at all data is then made and in case of a spectral shift a correction will be made to shift the channels to their proper locations.

Noise filtering

Noise in gamma-ray spectrometry is, in terms of radioactive decay, mainly statistical in nature. Even with large crystal volumes and at low survey altitudes there is clearly noticeable noise especially in the U channel, because some background errors may still persist in practice. The two main methods developed to remove noise from the gamma-ray results are NASVD (Noise Adjusted Singular Value Decomposition) and MNF (Maximum Noise Fraction) (Minty 2000). Noise is reduced by a principal component analysis procedure whereby higher order components represent noise. A new, lower noise, spectra can then be reconstructed by omitting the high order components.

Although a major reduction of noise is the effect of noise filtering, it tends to eliminate some real uranium anomalies. This method is therefore implemented with care to minimise the elimination of the uranium anomalies. Improved noise filtering methods are in development to ameliorate this situation.

Dead time Correction

The spectrometer needs a short time to process each pulse and so might have some difficulty observing any subsequent pulse arriving while the first one is being processed. This time is the dead time. Dead time correction is carried out using electronically measured dead time data for each window.

Filtering before corrections

Digital filters are applied to the radar altimeter data to smooth sudden jumps that can arise when flying over steep terrain. These sudden spikes in the data, if uncorrected, can cause problems when height correcting the data later. The spectrometer's cosmic channel is also filtered to reduce statistical noise. To calculate radon background from the upward-looking detector data, heavily filtered uranium upward, uranium downward and thorium downward data are needed.

Aircraft and cosmic background

The aircraft has a background radiation component for each of its radiation windows. The background radiation of the aircraft is constant for each window as long as there are no changes made to the aircraft and its contents. Cosmic background radiation increases with height and it is proportional to the number of radiation pulses in the high-energy cosmic window (3–6 MeV). The determination of the aircraft and cosmic background count rates for each spectral window has been described in chapter 4.4 of IAEA Technical Report 323 (IAEA 1991).

Radon background

Radon gas makes it difficult to measure uranium concentrations accurately. It is not always evenly distributed in the air and thus eliminating it from background radiation is not simple. Determination of the constants necessary for the correction of the background due to radon using upward detectors requires several steps. The procedure outlined in IAEA 1991 is generally correct, but more recent studies have refined the process. The first step, determining the contribution of atmospheric radon to the various spectrometry windows, is best achieved through a series of test flights over water. The method of least squares allows the constants in equations 4.9 to 4.12 (IAEA 1991) to be determined. The next step is to determine the response of the upward looking detector to radiation from the ground (equation 4.13 IAEA 1991). The procedure recommended by Grasty and Hovgaard (1996) is more reliable than that in IAEA1991 for the second step.

Effective height

The count rates depend on the density of air and thus on the temperature and pressure of the air. The filtered radar altimeter data is used in adjusting the stripping ratios, for altitude corrections and also to correct for the attenuation of the radioactivity at nominal height. The filtered radar altimeter data is converted to effective height at standard temperature and pressure (STP).

Height correction

The radiometric results must be corrected to a nominal height to remove the effect of varying survey altitude and thus make them comparable. The background corrected total count and stripped count rates vary exponentially with aircraft altitude.

Stripping correction

The spectra of K, U and Th overlap and so one radioelement will also contain some effect from the other two radioelements. This channel interaction must be corrected to produce pure concentration. The stripping ratios α, ß, γ, a, b and g are determined over calibration pads as described in Chapter 4 of IAEA 1991. The dimensions of our transportable calibration pads are 1m x 1m x 30cm and the weight of each one of them is approximately 660 kg. The principal ratios α, ß and γ vary with standard temperature and pressure (STP) altitude above the ground and is usually adjusted before stripping is carried out. Using the six stripping ratios, the background corrected count rates in the three windows can be stripped to give the counts in the potassium, uranium and thorium windows that originate solely from potassium, uranium and thorium. These stripped count rates are given by equations 4.44 to 4.47 in the IAEA 1991.

Man-made spectra

Man-made spectra can be distinguished from natural gamma-ray spectra in many ways. Our method is based on an assumption that natural gamma-ray spectra originate from the decay series of uranium, thorium and from ^{40}K. The coefficients needed in this case were determined from the background corrected overland data, which had almost no man-made nuclides. Coefficients were solved by regression analysis. Pulses in one channel i (0.1–1.31 MeV) can be calculated accurately enough, when we have the corresponding pulse counts of potassium, uranium and thorium. Nowadays NASVD technique can also be used to distinguish man-made nuclides from radiometric spectra.

Conversion to Apparent Radioelement Concentrations

The fully corrected count rate data is used to estimate the concentrations in the ground of each of the three radioelements, potassium, uranium and thorium.

The procedure determines the concentrations that would give the observed count rates, if uniformly distributed in an infinite horizontal slab source. Because the U and Th windows actually measure ^{214}Bi and ^{208}Tl respectively, the calculation implicitly assumes radioactive equilibrium in the U and Th decay series. The U and Th concentrations are therefore expressed as equivalent concentrations, eU and eTh. Total counts will usually be converted into Ur (Units of Radiation) units but other units can also be used. A dose rate can also be estimated, using full spectra technique or by calculating from concentrations of K%, eU ppm and eTh ppm.

Microlevelling – Floating median difference method (FMD)

In radiometric surveys external conditions, which affect the measurements, can vary daily. Moisture of soil and Radon can cause residual errors between adjacent lines and also along a line. Additional microlevelling is needed before high quality grids and maps can be produced. At GTK, we use an application of median filtering (“Floating median difference method”) to remove long wavelength level errors from the radiometric data. Sometimes short wavelength Radon residual errors caused by a short rain shower must also be removed. By the proper choice of parameters we can ensure that the anomalies are not filtered, but the background levels are.

Gridding

Many of the standard gridding algorithms are not well suited to radiometric data, because of the inherent statistical variations. A suitable gridding algorithm is one, which takes into account the average of all data points lying within a circular or elliptical area, inversely weighted for distance from the grid point. Akima Spline method is good for radiometrics. A minimum curvature method is unsuitable in some cases, especially in coastal areas, where the count rate varies sharply between islands and water areas.

NAVIGATION AND POSITIONING

General

Positioning and navigation have been under great development in the last 15 years. The influence of the developments has been remarkable both in accuracy and speed in data processing and in the total effect on the final quality of the airborne data. The theoretical positioning accuracy has improved from 50–100 metres to less than 1 metre and in navigation the flight lines can nowadays be flown at the accuracy of less than 15 metres (95%) without any differential real time correction, and with 2–10 metre with differential correction signal.

GPS is today the standard in airborne geophysical navigation. 24 satellites at an altitude of just above 20,000 km give reasonable coverage to nearly all locations on the globe. NAVSTAR GPS is under the control of the US Department of Defence, which degraded the accuracy in the beginning of 1990s by selective availability (SA) from 15 metres to 100 metres for civil users of GPS. Fortunately this degradation of accuracy was withdrawn in 2001 and the technical accuracy has been available for all users since then. GLONASS is an equivalent Russian system, which also has 24 satellites, when fully completed, in orbits, which are better for exact positioning. A European GALILEO system will probably be available in the near future and in Japan there are similar plans. So in the near future there will be numerous possibilities, more combinations, hopefully, and GPS will no longer be such a critical infrastructure as it was in 1990s.

Today one can presumably obtain an accurate position of oneself by GPS with just 4 satellites, under ideal satellite geometry. Mountains, other obstructions, multipath and environmental effects may affect the ideal satellite geometry that one may require for accurate positioning. To achieve consistently the 1 metre accuracy level one may need a lot of satellites. A combined GPS+GLONASS system may be necessary to provide this advantage.

Before GPS era

In the 50s and 60s visual navigation with aerial mosaic maps was the best navigation method available. Decca radio navigation system was the first to bring some help to navigation and positioning in the 60s. The accuracy was only 100–300 m, but it was still serviceable over the sea, where there was no chance for visual navigation.

Doppler (1976–1992) was the first real navigation aid, although in the beginning it was used only for positioning, because the drift of the system was too large if no other method was used with it. An application in which the navigator gave feedback to the Doppler navigation system was built in 80s at GTK. The Doppler navigation system had good short-term accuracy but lost it quite quickly subsequently. To forestall that phenomenon, a navigator regularly input a feedback to the navigation calculator when the aircraft was thought to be on the actual flight line.

Positioning was done by using fixpoints and a 35 mm B/W (monochrome) continuous strip camera.

Later in the 80s the B/W film was replaced by standard VHS video. The Doppler navigation system was also a step forward in positioning. With it the path between fix points could be tracked instead of just a straight line. Since the Doppler system is a summing system, the relative position error grew rapidly in time. The actual average accuracy at that time was only around 50–100 metres; there were many sources of errors, which made the final positioning inaccurate.

Current navigation

The navigation system must provide exact real-time information to the pilot or navigator so that they can steer the aircraft along the predetermined flight line precisely. The practical aid for the navigator is a left-right LED indicator. In front of the navigator or pilot there is a box displaying a row of different colour LEDs. The across-track indicator has a numeric display, which shows the cross-track error, line number and the remaining distance to the end of line, or to the beginning of a new line, depending on whether we are in on-line or off-line state. Figure 28 shows this left-right indicator in action.

A Combined GPS+GLONASS system combines both GPS and GLONASS satellites. Today the GLONASS constellation is not fully operational, but it provides in any case 2 to 3 additional satellites for calculations. The real-time navigation accuracy is also improved with GPS+GLONASS – 15 metres (95%) without any differential correction. For high performance surveys a differential correction signal is needed. The difference between GPS and combined GPS+GLONASS system can clearly be seen in Figure 29. It depicts the number of satellites and PDOP (Position dilution of precision) for a day for both GPS and combined GPS+GLONASS systems. The number of satellites with GPS+GLONASS is much higher and the PDOP is lower than with the GPS system, which implies that the satellite geometry is very stable and provides good, smooth accuracy all the time.

There are many real time correction signals available nowadays for differential correction in many parts of the world. RDS (Radio Data System) is a real-time correction system, which uses local FM radio stations to broadcast the correction information in their sub-carrier. The Finnish Geodetic Institute operates GPS base stations for this system, and the Finnish Broadcasting Company operates the FM radio network. This system is in use in Finland and in many other European countries, the USA and some Asian countries. The accuracy levels provided are between 2m and 10m, which is enough for most applications in navigation. There are also some coastal stations, which broadcast differential correction signals on LF mainly for marine purposes, and some commercial services which offer correction signals via satellite links.

Current positioning and processing

Positioning is done after a survey flight, which allows for more time and even more effort to achieve the ultimate, accurate results. The purpose is to find the exact coordinates for each of the measuring sensors in the actual, local coordinate system for each measurement.

The accuracy of the basic GPS system or better, the combined GPS+GLONASS system is not good enough for positioning in airborne geophysical surveys. Even real-time differentially corrected coordinates are not as good as the post-flight differentially corrected ones. In real time processing there are limited possibilities to correct the coordinates. The post-processing differential correction program, for example, processes the data forwards and backwards in its algorithms, which is not possible in real time.

Fig. 28. The LED left-right indicator with green/red colours and numeric display are easily seen when flying along the flight line. Photo: Kai Nyman

If a radio link transmits differential corrections in real time, some correction messages may be lost because of poor receiving conditions. In post-processing this does not happen. The base GPS station is usually closer to the survey area than the station that broadcasts those real-time correction messages. The closer the base station is to the survey area the better it corresponds to the same ionospheric and tropospheric conditions that the receiver experiences in the aeroplane.

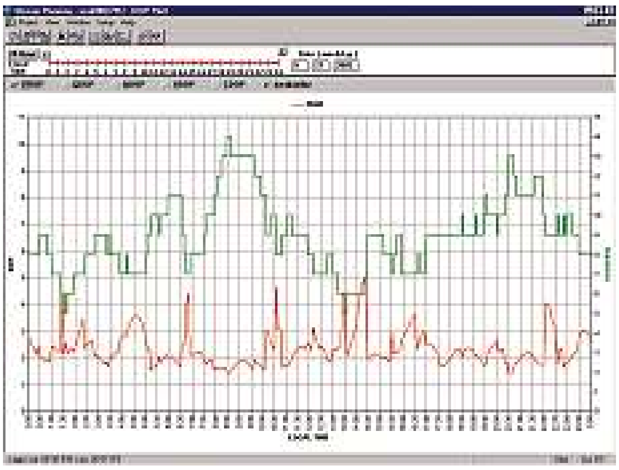


Fig. 29a. In a standard GPS system number of satellites (green) varies from 5 to 14 and several peaks in PDOP (red).

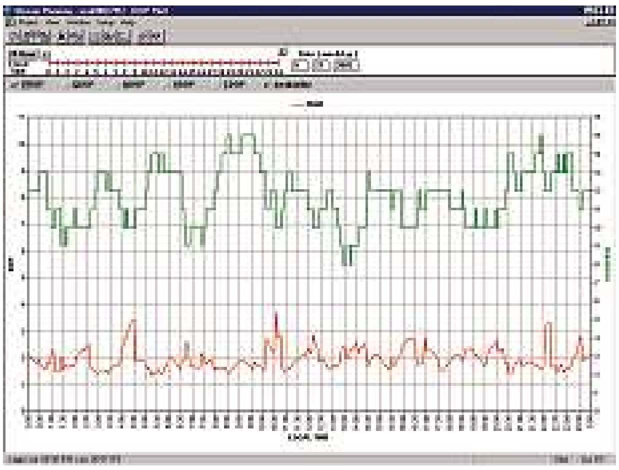


Fig. 29b. In a combined GPS+GLONASS system the number of satellites varies from 8 to 15 and PDOP curve is smoother. Overall accuracy expected is better and gaps are more unlikely than with the GPS system alone.

A base GPS+GLONASS station is usually located in the survey area. The location should be open to the sky in all directions, preferably down to 10 degrees from the horizon so that all usable satellites can be received and there will not be any reflections from nearby objects, which may cause multipath effects. The accurate coordinates of this base station are calculated with help of another GPS+GLONASS station at a known location, if there are not commercially available GPS reference data for this purpose.

To improve the observed GPS+GLONASS data a differential correction is calculated and applied to the observed coordinate data. In differential correction, errors caused by ionospheric and tropospheric refraction, ephemeric and lock errors are decreased significantly. Coordinate transformation from WGS84 to local planar coordinate system can be made today by many commercial programs. A test location should always be used to ensure that the transformation is done correctly.

How to assure that the coordinates are correct

For high quality airborne surveys every effort must be made at every step of the process to ensure that the final coordinates are correct for all geophysical components. The mere fact of using GPS does not necessarily mean that the coordinates are correct and accurate. The possible error sources could be incorrect differential GPS base station coordinates, timing error in data acquisition, incorrect time difference between GPS and UTC time, incorrect locations of geophysical sensors during processing and wrong coordinate transformations.

The Ashtech GG24 GPS+GLONASS receiver as well as many other similar receivers provides NMEA coded messages for navigational purposes from its serial port. The time component of that data is in UTC. This coordinate data, which is transformed to UTM, Finnish Uniform Coordinate System (KKJ) or some other coordinate system, is recorded together with the three-in-one measurement and any auxiliary data to the main measurement file. After differential correction the differentially corrected and the NMEA coded coordinates are compared every second and a difference is calculated. A histogram of these differences is a very revealing way to find out if there are problems either in the time difference between GPS and UTC times, in the timing of the data acquisition or in the GPS base station coordinates. The difference between GPS and UTC time is a multiple of 0.5 seconds. If there is an incorrect time difference in the processing procedure, of say 0.5 seconds, a shift of around 25 metres can be experienced, and this can be clearly seen from a histogram. A shift in a histogram will also indicate incorrect coordinates of the GPS base station. Figure 30 shows an example of this.

The best way to find out that the final coordinate transformation is done correctly is to use a test site. A test site can be any local site whose coordinates we know both in WGS84 and the local planar coordinate system. A local test site will be transformed using the same processing algorithm from WGS84 to the local planar coordinate system. If the results are the same, we can then be sure that the coordinates are correct. Local topographic maps in the same coordinate system can be compared to radiometric maps if there are islands, lakes or sea, but the accuracy encountered may not be good.

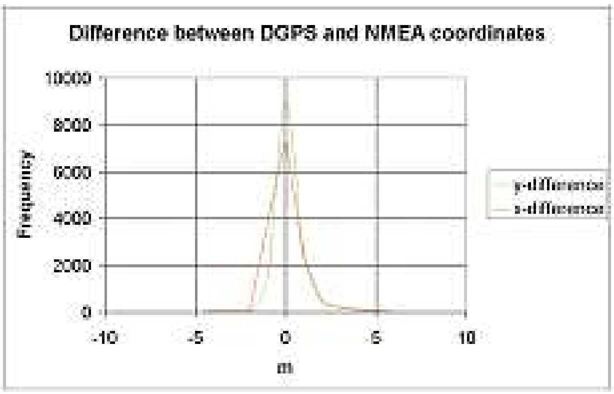


Fig. 30. Differences of x and y coordinates between DGPS and NMEA in a normal flight.

Digital elevation model from GPS-data

Digital elevation model can be calculated from the survey data as the height from the reference ellipsoid is measured by GPS and the height from the ground by radar altimeter. With single frequency GPS+GLONASS receivers in differential mode we can measure the reference height at an accuracy of less than 1.5 metres. The accuracy of a radar altimeter is better than 0.5 metres normally. It does not all the time measure the height from the ground, but sometimes from the nearest object, which can be a building, tree tops or other civil object. We can anticipate accuracies in the order of 2 metres with this kind of system – the radar altimeter and the GPS+GLONASS system. Ground control sites are needed to convert these geocentric heights to heights above sea level.

As a result, an elevation map can be made to show the topography of the survey area. This can be very useful especially in areas where good topographic maps are unavailable. Figure 31 shows a digital elevation model calculated by using GPS+GLONASS and a radio altimeter. It is compared to a digitised map of heights made by National Land Survey of Finland. The reference data is of high quality and is digitised from height contours at 5 metres interval.

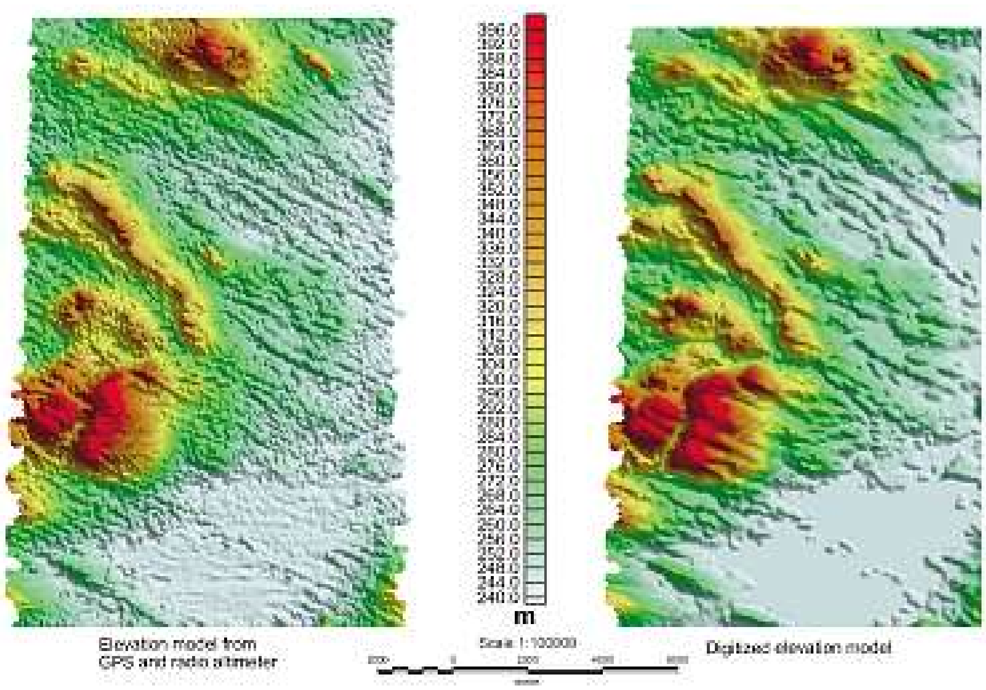


Fig. 31. Comparison of digitized and airborne measured (DGPS/radio altimeter) elevation models in Riisivaara area, Finland. Base map © National Land Survey 466/MYY/05.

DATA PROCESSING AND QUALITY CONTROL

Ten years ago airborne survey projects could be divided into two major phases, the field measurement period and the data processing period. They took approximately equal amounts of time. All the survey data was transported to the office for quality checking, which often meant a delay of up to one week before feedback was provided to the field crew. Positioning of the survey data before maps could be produced took a lot of labour and time. Usually the maps from last year's season were just ready when the new season started. New technology makes the fast processing possible. Powerful laptop computers have made it possible to carry out quality control and preliminary processing in the field. A revolution in positioning in 90s was another very big step, which enabled preliminary maps of the survey data to be produced within a couple of hours after the survey flight. Nowadays processing can be done almost in real time, which allows new applications of airborne surveys to be envisioned.

Today's processing software must be easy to run, reliable and fast so that most of the data processing can be run in the field. The programs have been designed to cater for the processes that are common to all the components while ensuring that there are specialised programs for dealing with specific airborne geophysical components of the three-in-one system. So methodological processing has been divided into three different program flows, which can be run separately and sometimes simultaneously, independent of each other. This guarantees maximum speed for processing.

The main ideas in the processing are that all calibration, correction and definition parameters are ready for use in separate files, and that the original survey data is not altered at any phase of the processing. All the programs create new files for errors, flight line time extensions and other corrections. All the files are kept in ASCII format for easy editing and checking. All in-house programs are made compatible with Oasis Montaj™ and thus the data outputs in all processing stages can be viewed easily.

Software and computer environment

Most of the processing software is written inhouse, although some commercial software for airborne survey processing is available (Oasis Montaj, Intrepid, Pinnacle etc.) on the market. The reason for writing one's own software packages stems from the fact the commercial software packages invariably miss an important aspect that is needed in our processes. Since the GTK processing package is constantly under review and new ideas are being implemented continuously, it would be very difficult for a commercial software house to follow our development cycle. There is no software available for processing our EM data.

The EM processing, gridding of transverse magnetometer data and microlevelling are the most important in-house developments of our own software. We use graphical AVS/UNIRAS libraries for map production and interpolation and IMSL for some mathematical processes. C++ is the most important programming language for our software, but also C, Fortran and Pascal are used.

In fieldwork powerful, lightweight laptop PCs are used for quality control and preliminary processing. In the office more powerful desktop PCs are employed, and only some microlevelling is processed in UNIX.

Processing flow

A processing flow diagram for field processing is presented in Figure 32 and the names of the flow chart are used in the following chapters. Afterwards only levelling and microlevelling are needed. Only the first processing steps and quality control is essential in the field, and the rest of the work can be done either in the field or in the office. If speed is essential, everything can be done in the field. Normally the work is divided so that all flight by flight based processing is done in the field and the whole survey area data set is processed in the main office. Before the main processing can be started, a lot of pre-defined information has to be available. The nominal flight line file (*Line.dat*), all methodological calibration and correction files have to be ready (*Magkalib.dat, Elkalib.kog/usi, Radkalib.kog/usi*), and the survey data format (*KOG/USI*) has to be defined. The names are based on the aircraft registration figures (Twin Otter OH-KOG and Cessna OH-USI). A survey data format is specified in an ASCII description file, which makes it simple to make small changes in the format without making any changes to the software.

Basic processing

The processing flow in Figure 32 has three input channels: processing the geophysical flight data, processing the GPS data and processing magnetic base station data.

The basic processing of the data is done immediately after the flight and before the next flight. The first step of processing is to run the ALKU2000 program (Fig. 33), which reads the flight data (*LENTO.TXT, renamed to L*.KOG/USI*), makes the basic check for the relevant values, writes down the found alarms, data and file errors, flight lines and statistics of the survey parameter. An in-house program, WLINJA, is used to plot the flight path over the nominal flight lines. This same program is also used to crop the continuous data into flight line data. An example screen copy of this program is shown in Figure 34. Every flight line is checked separately, suitable acceptable extensions beyond the survey area are determined and the flight path deviation compared to nominal lines is verified.

After every flight differential correction is made to the satellite data using Javad's post-processing software PINNACLE. It uses both GPS and GLONASS satellites. The inputs are the flight and base station satellite recordings. With in-house program GPS2KOG the differentially corrected WGS84-coordinates are transformed to required local planar coordinates. With exact time information these coordinates are used in adjusting right coordinates to final XYZ data.

The in-house produced computer program MAG32 (Fig. 35) is used to process the magnetic data from base station; the program reads the data in e.g. binary Picodas format, compares the variation against the allowed limits (e.g. 50 nT per hour and 5–15 nT per 3 minutes for magnetic diurnal limit) and if necessary abrupt error peaks are eliminated interactively. Noise or those features, which can be regarded as local, are filtered out by a combined median and average filter. First a median filter of 24 points is applied and after that a moving average filter of 16 points is applied. The filter parameters depend on how far the magnetic base station is from the flight lines. The closer the base station is to the flight lines the smaller the values that can be used in the filters, because small variations in the magnetic field can be regarded as true indications of real magnetic field variations simultaneously at the base station and in the aircraft. Single peaks can also be removed separately.

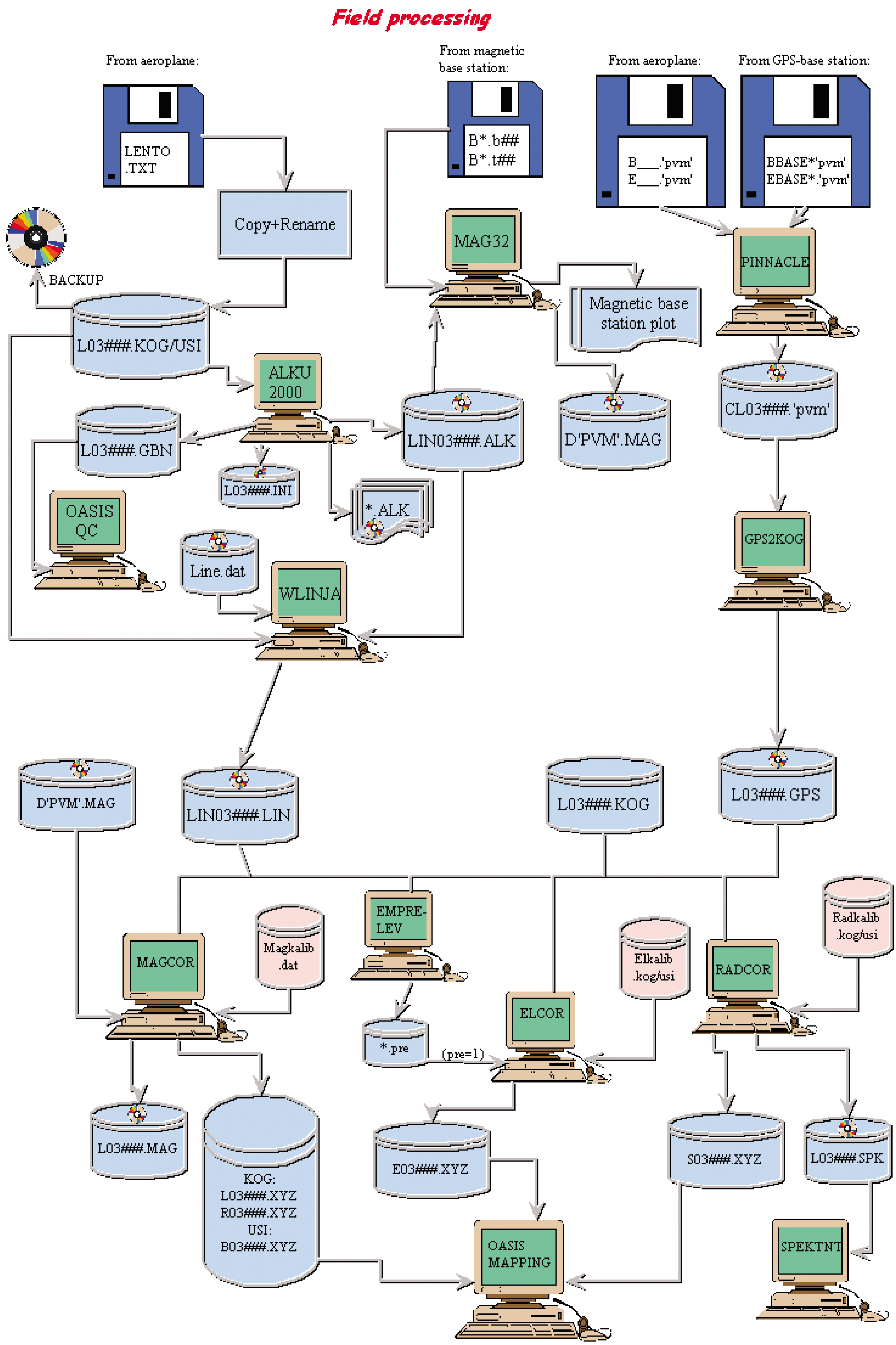


Fig. 32. A processing flow for field processing. All of the 3-in-one main components have a methodological correction program of their own.

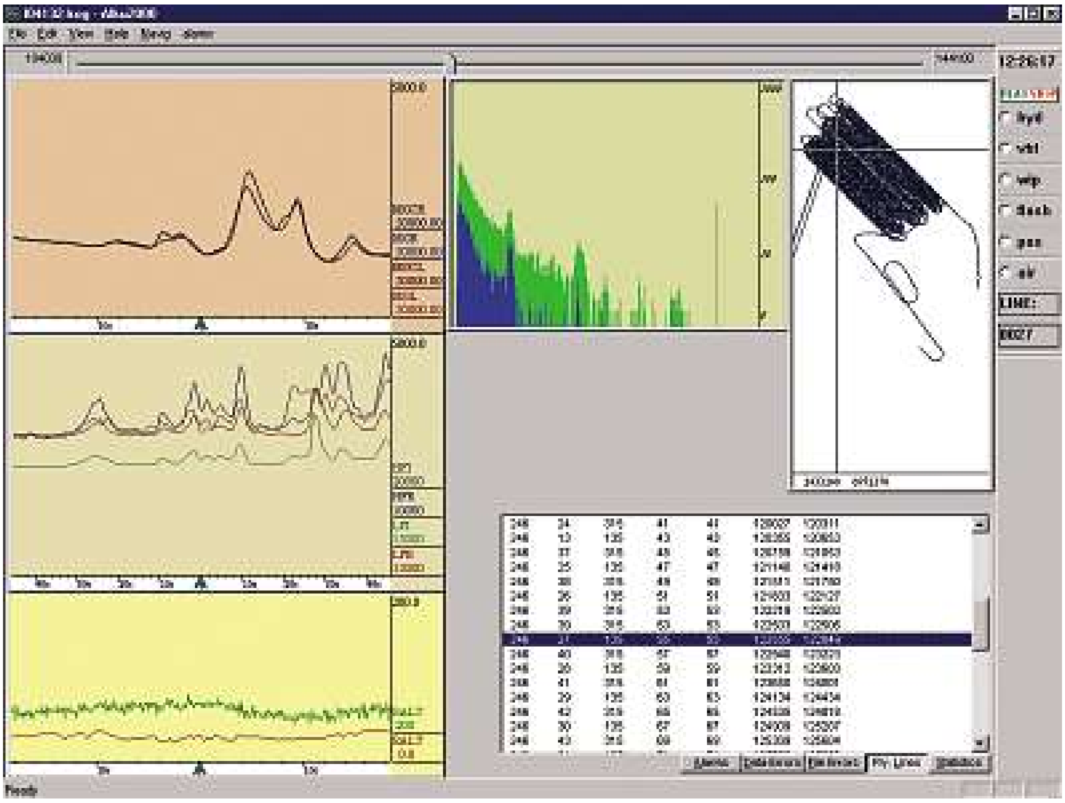


Fig. 33. Outlook of ALKU2000 program. Magnetic, EM and altitude recordings in the left windows, radiometric spectrum in the middle, whole flight path and message window on the right.

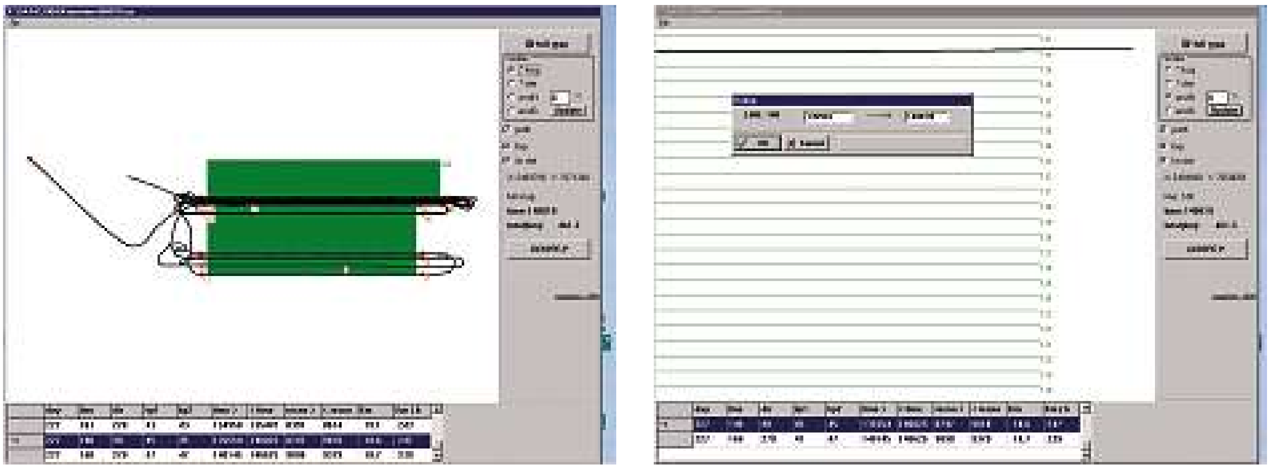


Fig. 34**.** An example of WLINJA program, which is used to crop continuous data into line data. The whole flight path is seen in the left figure. Each flight line is zoomed in for better precision (right figure). Nominal flight lines are shown on the background.

Methodological processing

Separate programs for magnetics (*MAGCOR*), electromagnetics (*ELCOR*) and radiometrics (*RADCOR*) are used for the methodological corrections. The inputs are the original flight data (*L*.KOG/USI*), information of flight line lengths (*LIN*.LIN*), coordinate data (*L*.GPS*) and as a very important part, all methodological correction files (*Magkalib.dat, Elkalib.kog/usi, Radkalib.kog/usi*). The methodological corrections are described in methodology sections earlier in this paper. The outputs are separate Geosoft XYZ files for each component. The left and right wing-tip magnetometer measurements are also in separate files due to different coordinates for both sensors.

Final processing

When the whole survey area is completed, the levelling and microlevelling are carried out with the whole data sets. These procedures are described in previous separate geophysical methodology sections. All unsolved problems and errors during the flight-by-flight processing are verified and corrected, and coordinate transformation is certified. When the whole data set is ready, and all magnetic base station data and magnetic observatory data for secular correction are available, the geomagnetic reference field corrections are carried out.

Quality Control

Before and during the flight

At the base station, the permanent GPS recording at the measured site and the Earth's magnetic field variation are monitored during the survey. In case of a sudden magnetic storm, the survey operator in the aircraft is notified and the survey flight is interrupted. Time synchronisation between the base and the aircraft is achieved using the GPS.

In the aircraft the pilot or the navigator follows the defined flight path and altitude with the help of visual displays based on real time GPS coordinates and the radar altimeter. The GPS receiver in the aircraft is verified in real time as it is used together with our in-house program for navigating.

There is always one operator onboard to monitor the instruments on a computer screen. The operator also records the flight log and details during the flight.

Fig. 35. Program MAG32: Magnetic base station recording during a stormy day. The green horizontal line at the bottom shows the result of the utilised criteria shown in the dialog window

After each flight

Immediately after each flight the basic quality control is carried out. With ALKU2000-program (Fig. 33) it is verified that all survey data exists and corresponds to flight log information. In the graphic display the geophysical measurement values, radiometric spectra and flight altitude and path are monitored, choosing a suitable view to display all data sets. The second vital check is to verify that the base station data are correct and the magnetic variation is below defined limits (see Fig. 35). A copy of the data is made for security reasons. After that the next flight is allowed to commence.

The second step is to verify the geophysical measurements quality in detail. ALKU2000 creates a Geosoft binary file (GBN) easily transferable to Oasis Montaj™ for a more comprehensive data analysis (Fig. 36). The appearance, quality and noise levels of all components, EM calibrations, drift, levels and noise peaks are studied along the survey data.

During the differential GPS processing, the quality of the satellite coordinates is verified by controlling the number of satellites and PDOP parameter value, as shown in Figure 29b.

After the methodological programs we get the line-by-line XYZ-files of each geophysical parameter. For quality control the corrected data sets are transferred to Geosoft databases. Altitude deviation is checked statistically and also by plotting colour profiles. Comparing the lines to the nominal lines, calculating the distance to the nominal line and analysing the path deviation statistically verify the true flight path. Flight line separation is verified visually and by the Oasis Montaj™ Airborne QC module. Sample separation and survey speed are checked.

Processed data from each flight are appended to the survey area databases. Geophysical parameters, errors and noise level of all measurements are studied line by line. Geophysical parameters are also interpolated to grids and suitable calculations like derivatives and high-pass filters are done and displayed. A map of each component is produced daily from all the data gathered so far to verify their conformity and quality. Although the final EM levelling is performed after the whole area has been surveyed, a rough preliminary levelling may be needed for quality control.

Average radiometric spectra and the main energy windows are plotted (see Fig. 27) from each flight line in order to check for spectral drift during the course of a flight. Spectral stability and overall functioning of the spectrometer is controlled during surveying in real-time, and by ALKU2000 and SPEKT-NT afterwards. Daily source, resolution, test line and high altitude checks are performed according to Grasty et Minty (1995) to ensure that the equipment is working properly and the conditions are acceptable.

After lines below quality standard are discarded and required re-flights are specified, the pre-processed data in XYZ-files are saved for final processing, which is done after the survey area has been surveyed completely.

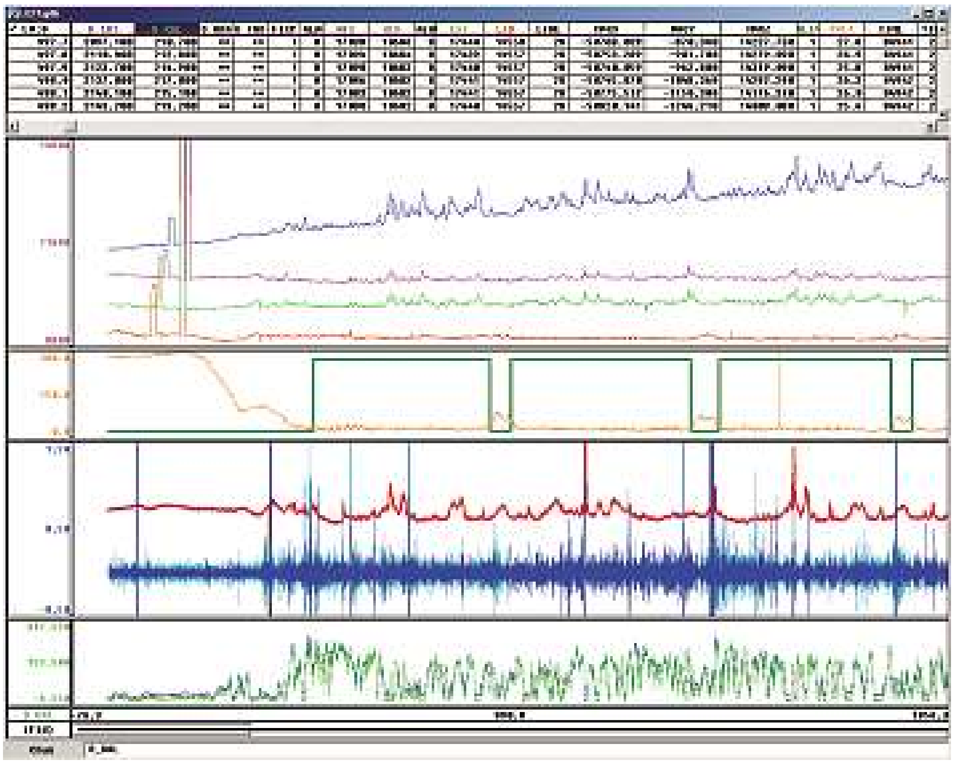


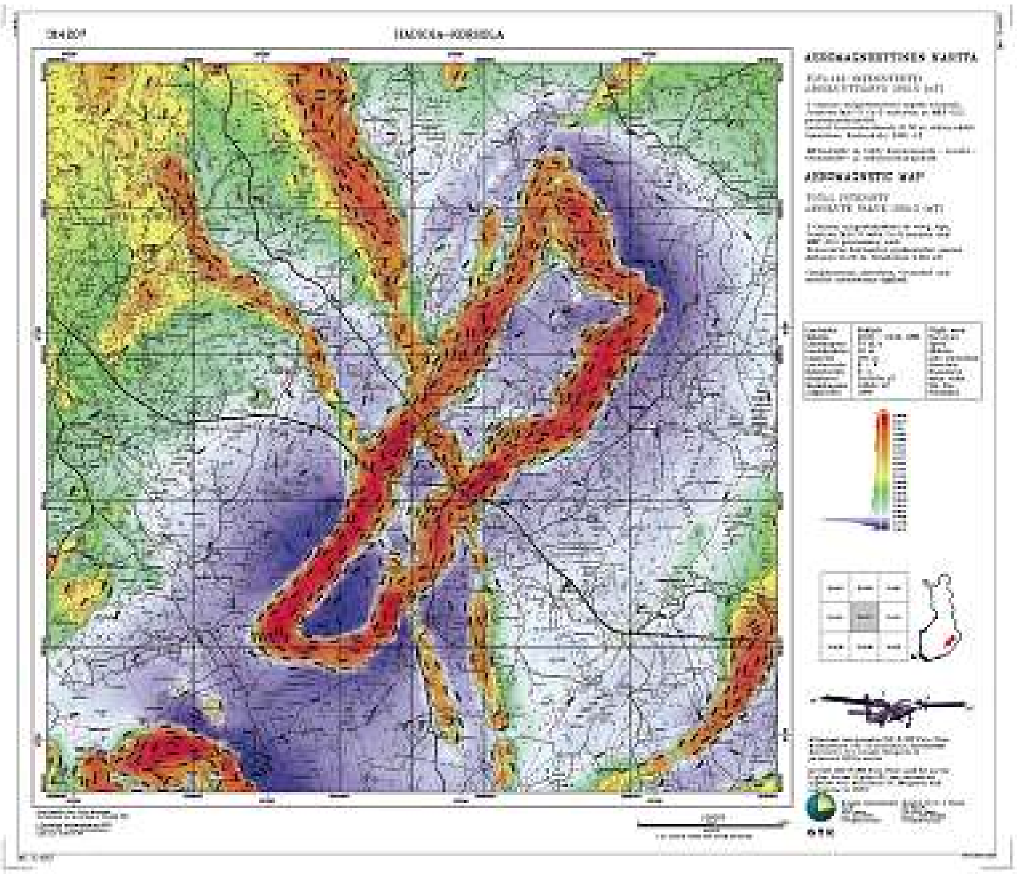
Fig. 36. Quality control of one survey flight with Oasis Montaj^{TM}. On this view there are the starting calibrations and three first survey lines.
Uppermost panel: EM components with perpendicular test at the beginning
Second panel: yellow: flight altitude, green: on/off step showing online/offline flag
Third panel: red: magnetic measurement, blue: noise check by 4th difference of mag
Lowermost panel: two radiometric components.

Map Production

Maps are still needed, although data sets are becoming more and more important as most clients have computers and suitable software. For map production we utilise the AVS/UNIRAS Toolmaster graphical library. It has the basic routines to produce colour and contour maps.

In the Finnish National Mapping Project, we use topographic base map information in the background for all maps. Location of anomalies is made easy with the aid of topographic features. A set of maps from our national mapping project is presented in Figure 37 a–d.

a)



b)

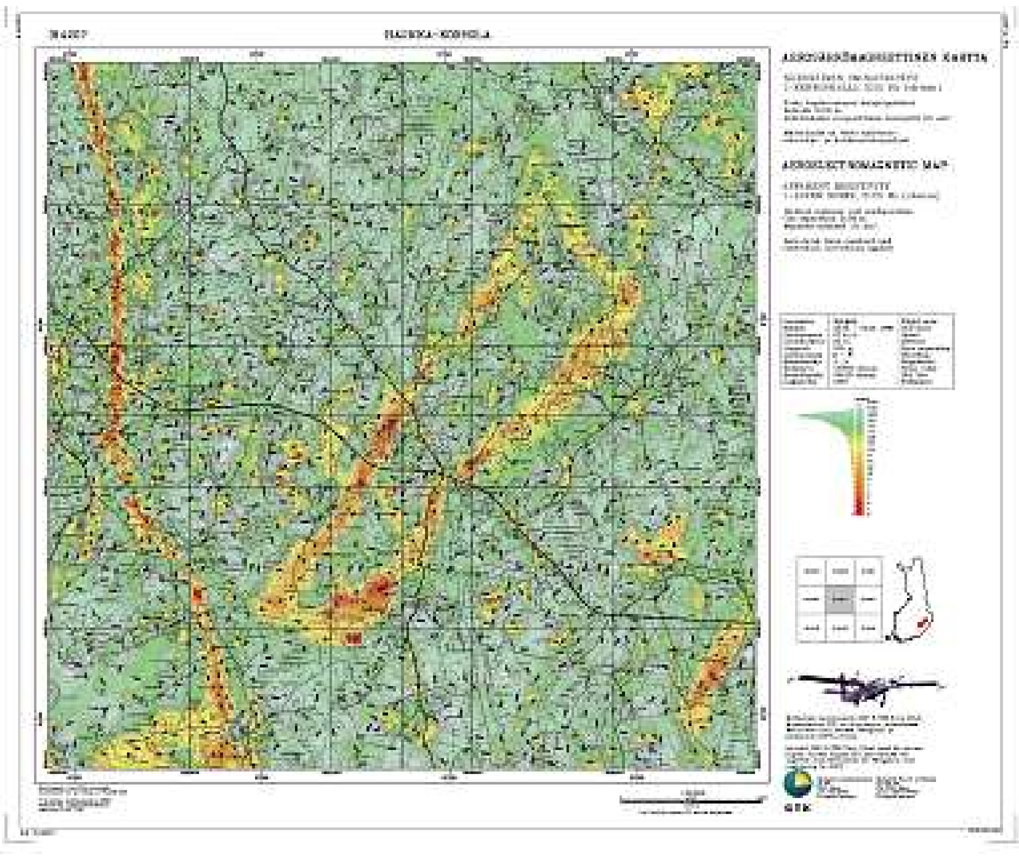
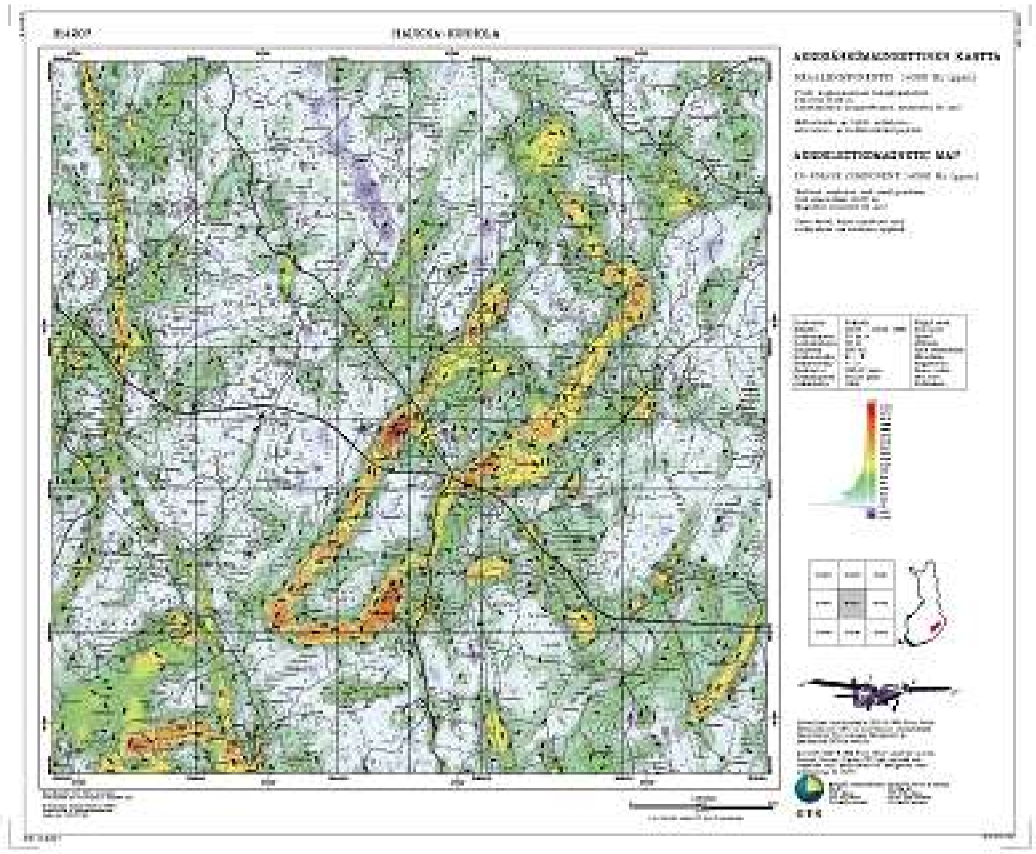


Fig. 37a and b. Examples of National Mapping Project maps. Originally plotted in scale 1:20 000. Base map © National Land Survey 466/MYY/05.
a. total magnetic field
b. EM : Apparent resistivity.

c)



d)

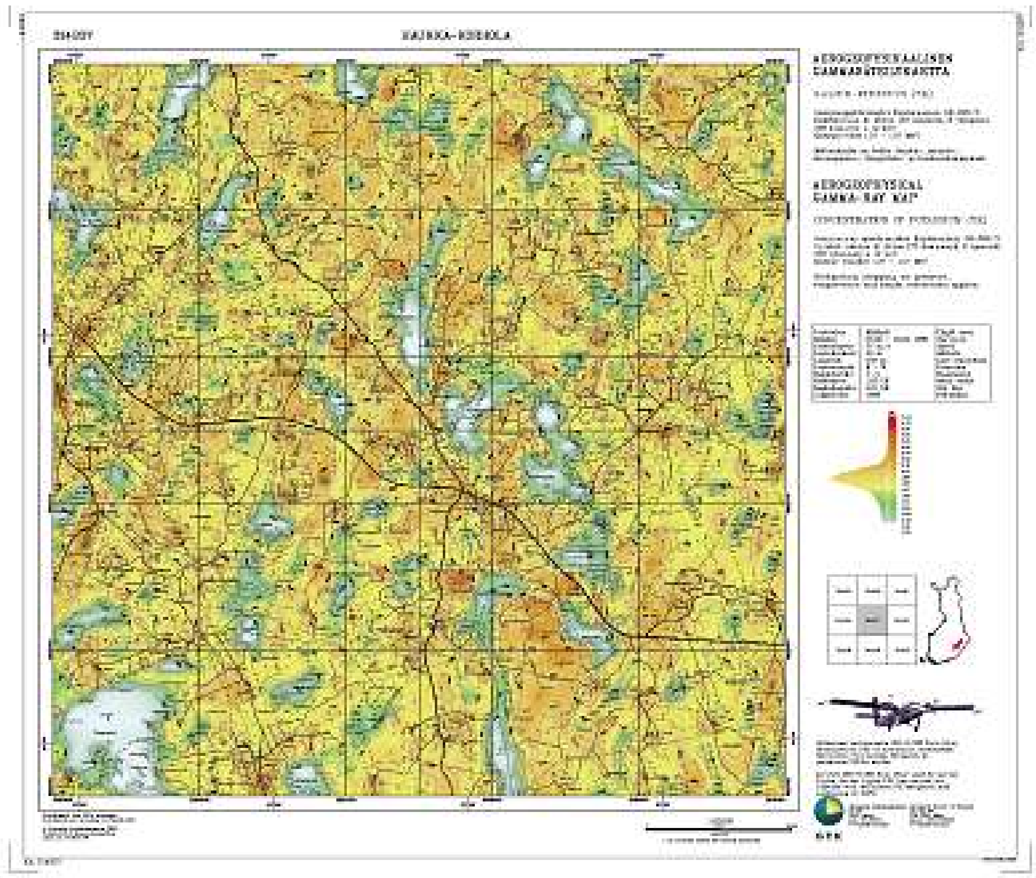


Fig. 37c and d. Examples of National Mapping Project maps. Originally plotted in scale 1:20 000. Base map © National Land Survey 466/MYY/05.
c. EM in-phase
d. RAD potassium (K)

Archives

Today data are stored on CD-ROMs. They are reliable and inexpensive. Their capacity is not large enough for today's needs but their reliability and worldwide use make them still unbeatable. DVDs, with larger storage capacity, are coming on the market, but their lack of adequate standardisation prevents their use as a primary archive media. Special attention is focused on backup copies. These multiple copies are stored in separate places to avoid any data loss of the huge national airborne database. Also all data are rewritten at least every third year.

In addition to the original data and the final, corrected data, all files and log files that describe the processing steps of each data set are archived. With the aid of those files it is possible to run the procedures again if needed.

SPECIAL SURVEYS

Introduction

During the early 1990s GTK and Ministry of Trade and Industry adopted a new concept. State organisations were encouraged to expand their expertise to commissioned surveys and to follow closely the demands of the industry and public organisations. New applications were developed for ice thickness measurements, water content of snow measurements, peat thickness surveys and environmental studies (Lahti et al. 2005, *this volume*). The most important trend was to offer services to exploration companies and to international development projects in developing countries, mainly in Africa. There were technical improvements aimed at environmental studies that meant the addition of a higher frequency to the EM system to detect weaker shallow conductors.

The operational procedures ranging from large area mapping to small-scale targets and long-range profile flights were implemented, as well as flying above very rough terrains. The needs of the clientele provided both impetus and speed in the adoption of high tech instrumentation, the improvement of quality control procedures and the acceleration of the data processing. The step to move most of the data processing to the field sped up the processing and quality control significantly. The accelerated processing of the data permitted immediate re-flights of invalid measurements (which may be due to out of specification nominal flight path or altitude and other factors). Preliminary data for interpretation can therefore be available few hours after each flight.

Ice thickness

Sea ice thickness has been measured with the airborne EM system (Multala et al. in Cold Regions Science and Technology 1996). The application is based on the fact that seawater as a saline solution is a good electrical conductor whereas sea ice is poor one. The AEM system determines the altitude of the aircraft above the seawater surface, ice bottom, while the altitude above the ice is measured with a radar altimeter, or laser profilometer. For good accuracy, information of the conductivities of seawater and ice is needed. Our EM system has been used in the Baltic Sea and Bay of river Ob successfully. In good mapping conditions the thickness accuracy ± 0.2 m was achieved for undeformed ice but worse for deformed ice with variable geometry. The raw horizontal resolution was found to be 100 m.

Water content of snow

For the viewpoint of optimal use of watercourses, it is vital to forecast the amount of water forming from the snow for power production companies. Nearly half of the annual water resources in northern Finland originate from snow and that is why it is important to be able to forecast the amount of water in snow (Tervonen 1997). The method is based on the damping of natural gamma radiation in medium.

The survey profiles are measured two times, once in the summer season without snow, and second time in the winter when the water content of snow is maximum. From these two survey data sets the amount of water, the damping medium, can be calculated. This fast method has been used successfully many years in northern Finland. The results usually give a little too high water contents as this method takes into account the water also in the soil.

Peat thickness

Peat thickness has been classified successfully in Finland by using gamma ray absorption method (Virtanen & Vironmäki 1985). The gamma ray absorption depends on the properties of the medium and the energy of the gamma nuclides. Normal corrections, background, stripping and height corrections are made to the airborne gamma ray data and the data are classified and presented as a map. Potassium was found to be the best component for this application. It was modelled, using experimental coefficients that gamma ray radiation would not penetrate through 0.6 meters thick layer of peat. The same could be confirmed by comparing gamma ray maps and observations made in the mire area. Although this application does not give accurate thickness of the peat layer, it can be utilised to classify mires to thin, less than 0.6 metres deep and to thick, more than 0.6 metres deep. It saves a lot of costs when many thin swamps can be rejected from further exploration. It was also found that some deep swamps, which cannot be seen on the topographic maps at all, could be localised by this method.

Local, very high-resolution surveys

The improvement in the accuracy of real time positioning with the use of GPS together with RDS signal provided the opportunity to effectively employ low altitude flights with very narrow line spacing. When the pilots are able to follow in real time the exact position and nominal flight path, the flight path deviation decreases significantly. The standard deviation of cross track error is even less than 10 metres. Thus up to 50–75 metre line separations are successfully utilised for very high-resolution surveys. Together with 30 m flight altitude all detectable anomalies are shown in the data, and according to our experience, the flight line direction is no more so significant.

Rough terrain with fixed-wing aircraft

Flights in rough terrain have to be planned carefully. A normal gradient for a survey aircraft climb may be about 100 m vertically for every 1 km horizontal distance. Before a steep hill the aircraft has to start climbing well ahead (see Fig. 38) of it. The pitch angle of the descent of the survey aircraft has to be kept reasonable for adequate magnetic compensation to take place. The speed of the aircraft also needs to be within specifications when descending in a rough terrain. The altitude variations significantly affect the measurements, especially the electromagnetics. The quality of the systematic coverage can be improved by double flying, i.e. flying all lines in both directions and using only the data where the flight altitudes meet most of the specifications.

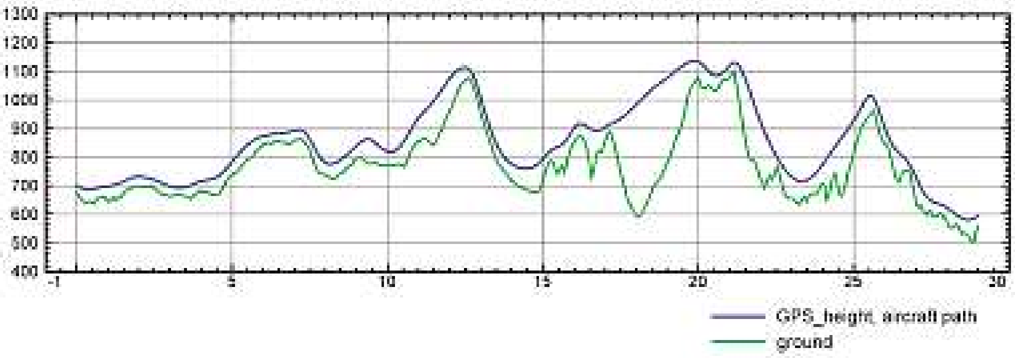


Fig. 38. Flight altitude above rough terrain. Green: ground topography, blue: flight altitude path. Vertical scale: metres above the GPS-ellipsoid. Horizontal scale: kilometres.

Line separation, survey altitude and survey efficiency in different cases

The Second National Mapping Project, which has been continuous since the early 1970s and several commissioned surveys during the 1990s have brought many insights for efficient survey planning. Line spacing depends on the purpose of the survey and the level of detail required. At a height of 30 m, the width of the smallest detectable magnetic anomaly is about 80–100 metres. An EM anomaly may have a footprint of about 20–30 metres and the radiometrics, recorded over one second may be sufficient to achieve the appropriate count rates. In this case, 50, 75 or 100 metres line spacing is favourable for detailed exploration work, while 150–250 metres line spacing is suitable for geological mapping. Larger spacing can be applied for general overviews or regional mapping, even when flown at higher altitudes. When flying a survey at 100 m nominal flight altitude, the width of the magnetic anomaly of the smallest magnetic source is expected to be at least 200 metres; therefore a line spacing of over 200 m may be adequate.

The EM system prefers low and steady flight altitude. The suitable altitudes are between 30 to 60 metres. A flight altitude of 30 metres is appropriate in Fennoscandinavia, where the anomalies are sharp, magnetic and EM anomaly sources are narrow and are located near the surface. Flight altitudes between 45 and 70 metres may be suitable in the areas where the anomaly sources are deeper, such as in sedimentary areas. In planning a survey, terrain clearance has to be selected with close regard for local conditions (e.g. vegetation, trees, houses, antennas, timid animals, etc.) so that a fixed altitude can be maintained steadily throughout the project.

In exploration, the lengths of the flight lines are chosen according to the target size, bearing in mind that sufficient length of the survey line must lie outside the conductive areas to aid in the levelling of the EM data and outside the magnetised area to allow proper interpretation. In a systematic mapping program, technically optimum length can be chosen for the survey. The optimum length is selected based on many factors. For example, it is naturally profitable to spend the majority of flight time on a flight line, not on turns or ferry flights. Very long lines make the processing a bit more complicated; they also makes re-flights more expensive, especially in a high-quality survey that needs unbroken lines. Longer flight lines increase the distance to the magnetic base station, thus may require several base stations. The weather can also change during a long flight line and may cause line breaks or disturbances in the data.

Figure 39 can be utilised to optimise the most profitable flight line lengths; the values here were calculated using the normal survey speed of 50–70 m/s (180–250 km/h) and one minute turn (during 1 minute the aircraft flies 3–4 km).

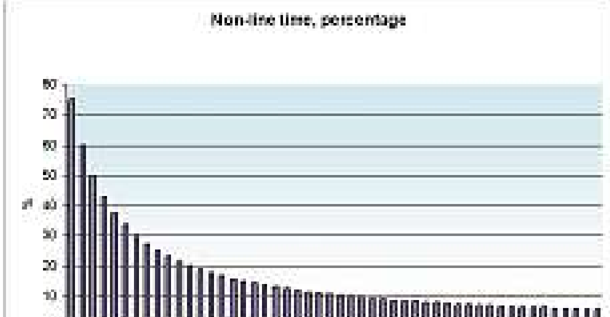


Fig. 39. The percentage of flight time wasted for turns at the end of the lines with varying line lengths (at speed 60m/sec and with 1 min turns)

The effective outcome of each survey is assessed by its efficiency, calculated from the total survey time and the approved survey lines inside the survey area. The total survey time includes ferrying to the survey area, flying along the lines, turning at the end of a flight line and re-flights and interrupted flights due to weather, equipment problems or magnetic storms. It can be calculated for each survey flight or for the whole survey area. In general, the efficiency, the percentage of time when flying along the survey line, is expected to be between 50–75%.

DISCUSSION

In the above chapters the reader can find detailed information on GTK’s airborne geophysical instrumentation. The basic knowledge of geophysical measurement methodology has also been described in addition to the functioning of the equipment. Some of the major ideas in data processing have also been explored. This knowledge base has improved over the decades. The computer technology for processing the airborne geophysical data has also been greatly enhanced during the period of our surveys.

In the 1970s, the first digital era instrumentation was based on a tailored unique central processor, which was the prototype of Nokia’s first computer, Mikko 1. This was a splendid processor with discrete components and with computer oriented assembler programming. By the end of the 1980s this approach had proven to be old-fashioned.

In the1980s, the debate over the superiority of the Unix and PC systems was very lively. After some time working with both systems, the PC was chosen as the new processor for the airborne geophysical data processing computer solutions. The most important advantage was the ready availability of spare parts and programs. This choice has proven to be wise in hindsight.

Before the PC era measurements were stored on 1/4-inch magnetic tapes. The only way to check these records was to read the tapes at the headquarters of GTK in Espoo. All the tapes had to be couriered by various Finnish courier companies or by Finnair freight to the GTK headquarters in Espoo for processing. The response from the headquarters with regard to whether the data was registered correctly was phoned or radioed back to the field, normally some days after the measurement flights. Probably the single greatest technological advance to improve aerogeophysical processing was the use of laptop computers for data checking in the field. Currently, the response for registration failures is instant.

Another important step was in the implementation of GPS positioning systems. Before the GPS era three months between measurement flights and the production of the first maps was acceptable. These days three hours to produce preliminary maps in some cases may be too long.

One big issue is the rapid development of the instrumentation of the measuring systems. Although the old systems were good and very reliable, the new instrumentation is more accurate, light weighted and robust. It is difficult to see further need for better instruments, although in the fields of positioning, measuring aircraft altitude and orientation some advances may be needed. There could be some further improvements made in some of the advanced geophysical instruments.

Besides better instruments, we can still dream about some real advances in the field work. In the future, one may anticipate unmanned ultralights with remote control or with programmable self-control systems to collect the data and send it by telemetry to the office. This is not a far off concept, because all the technology is available. In Finland, as elsewhere, the number of telecommunication masts poses a constraint. More realistic in the short term may be the addition of an accurate aerogravimeter and development of multi-frequency electromagnetic measurement unit.

A good launch for the next technical generation of the three-in-one airborne system is the renewal of the EM system and improvements in positioning and anomaly verification, which process has started during 2004 in co-operation with British Geological Survey (BGS). GTK and BGS are establishing a Joint Airborne-geoscience Capability (JAC) for carrying out high-resolution airborne geophysical surveys as part of their respective national strategic science programmes. The Twin Otter, with its modernised instrumentation, will be then ready to meet tomorrow’s new challenges with its Finnish-British scientists and engineers.

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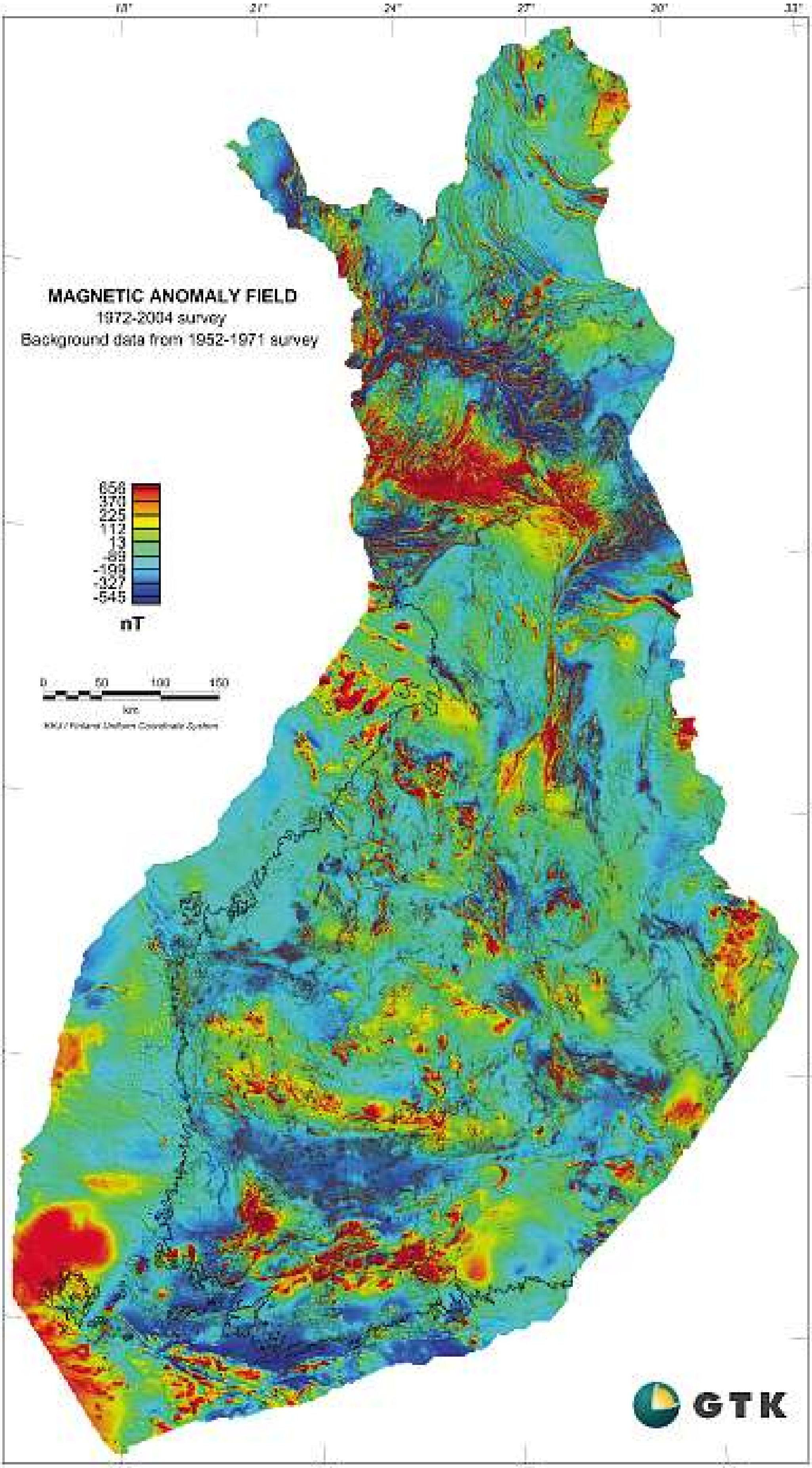

Appendix 1. Magnetic field map of Finland. Old 1 km grid plus Second National Mapping project data.

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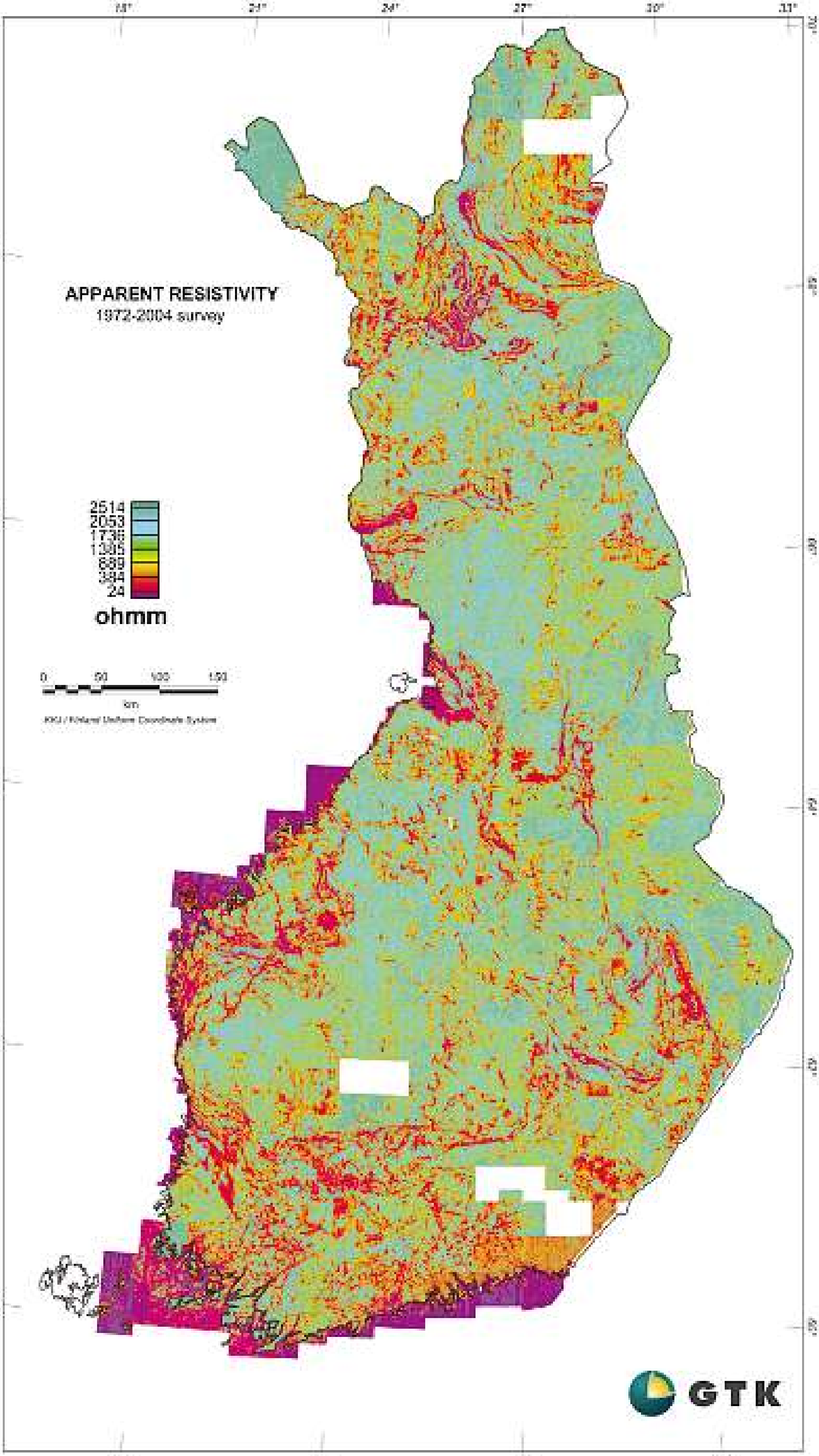

Appendix 2. Apparent resistivity map of Finland. Calculated from EM in-phase and quadrature components using horizontal half space model.

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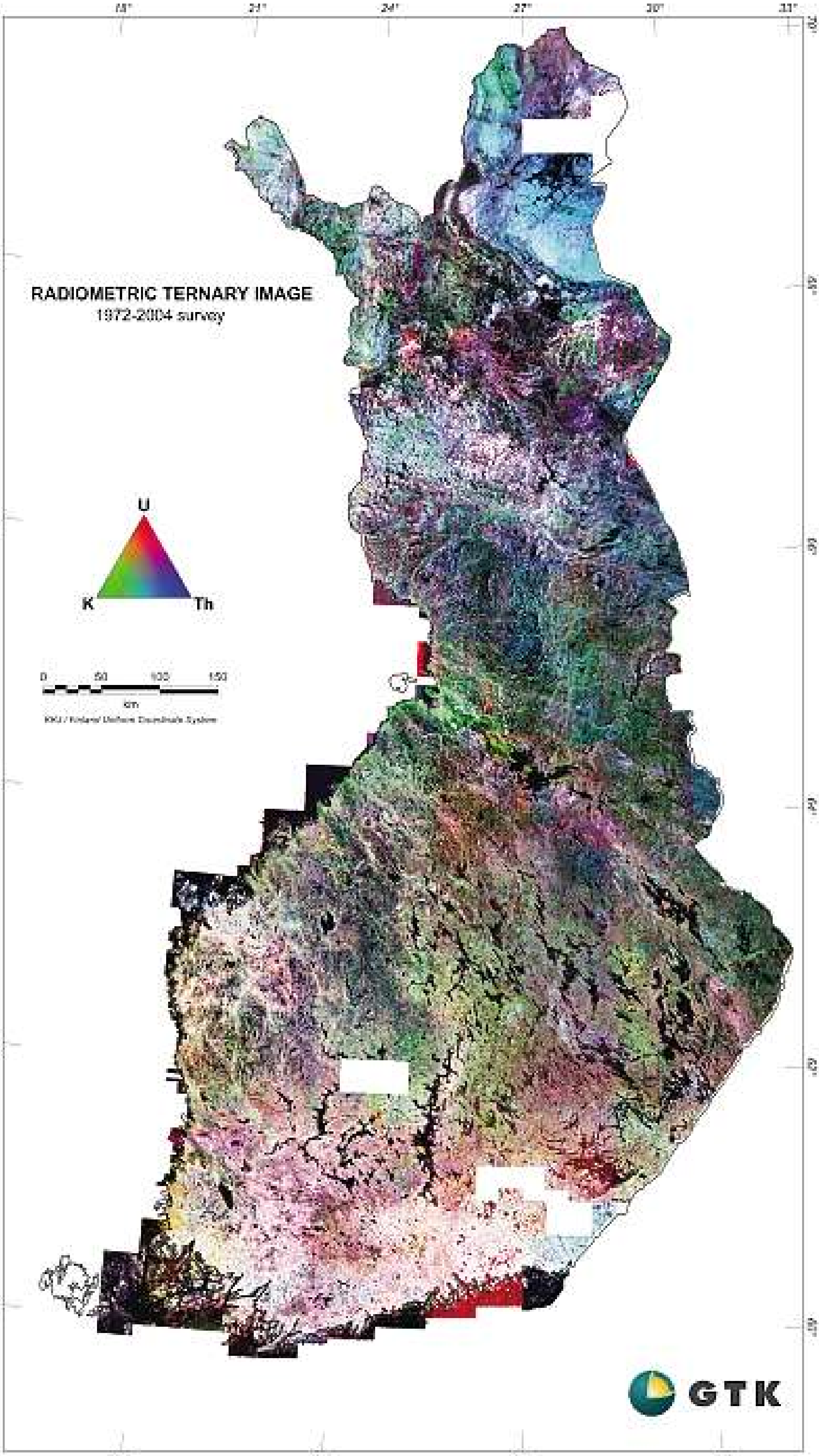
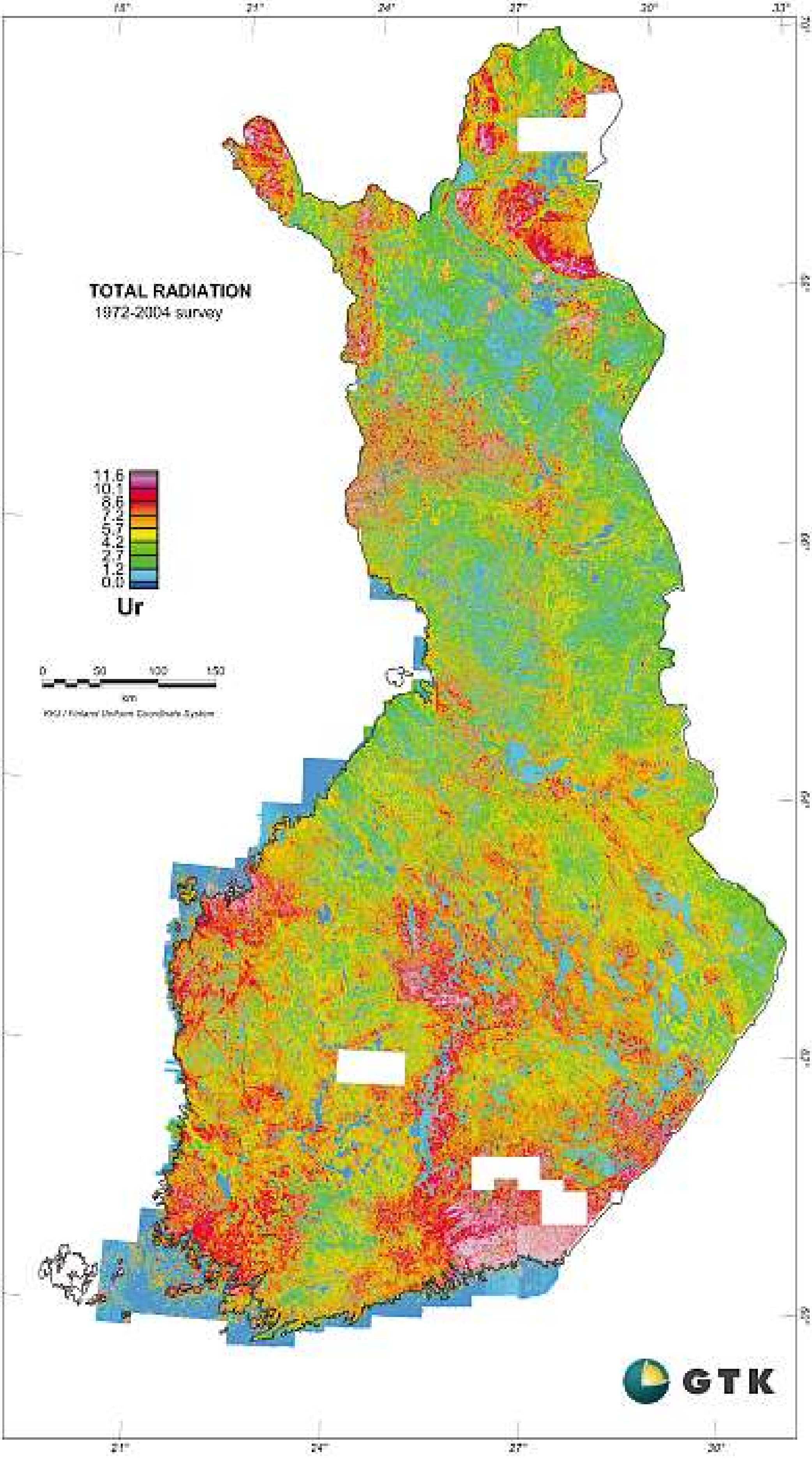
edited by Meri-Liisa Airo.
Geological Survey of Finland, Special Paper 39, 21–74, 2005.



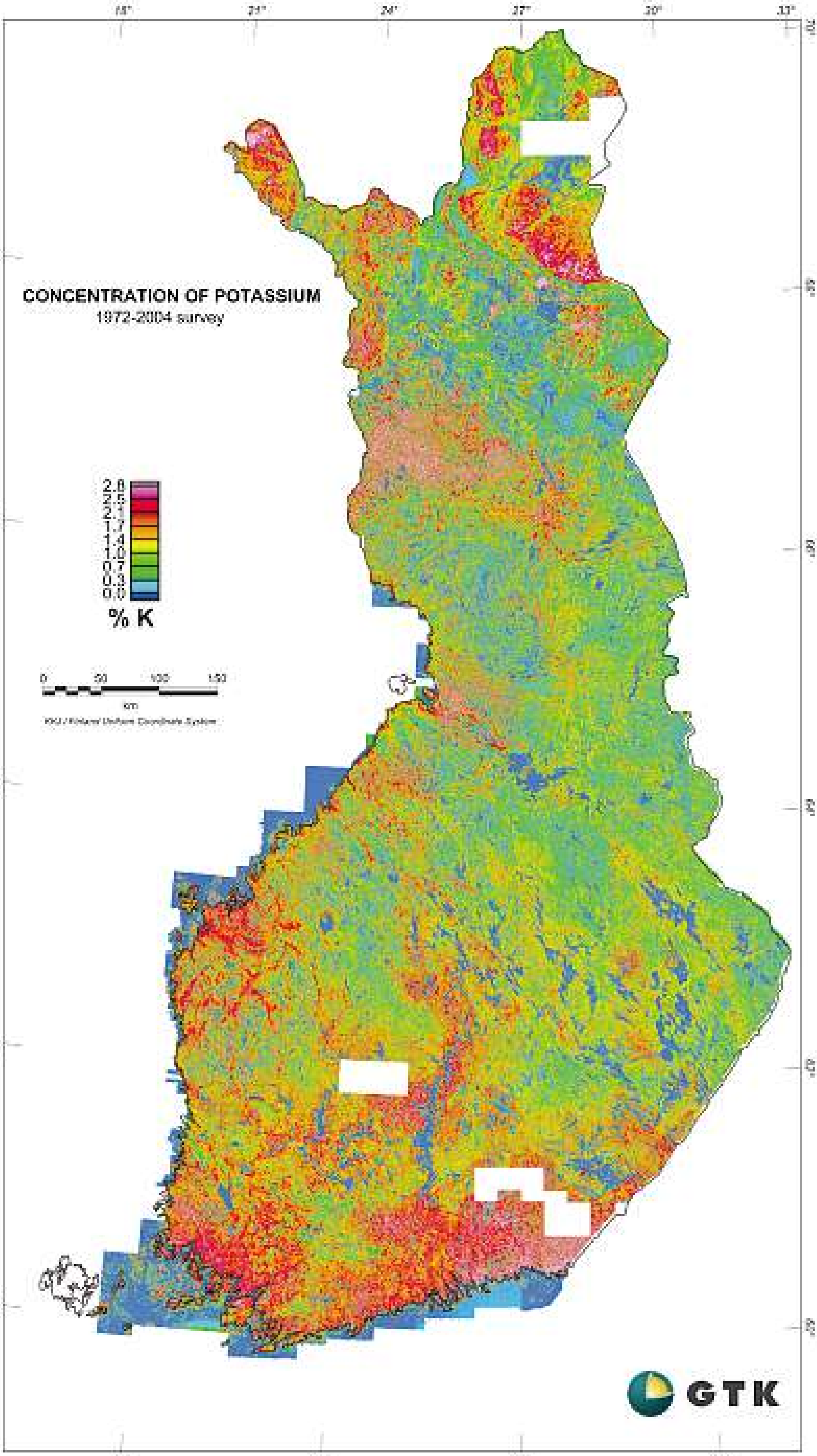
Appendix 3. Radiometric ternary image of Finland.

Aerogeophysics in Finland 1972–2004:
Methods, System Characteristics and Applications,
edited by Meri-Liisa Airo.
Geological Survey of Finland, Special Paper 39, 21–74, 2005.



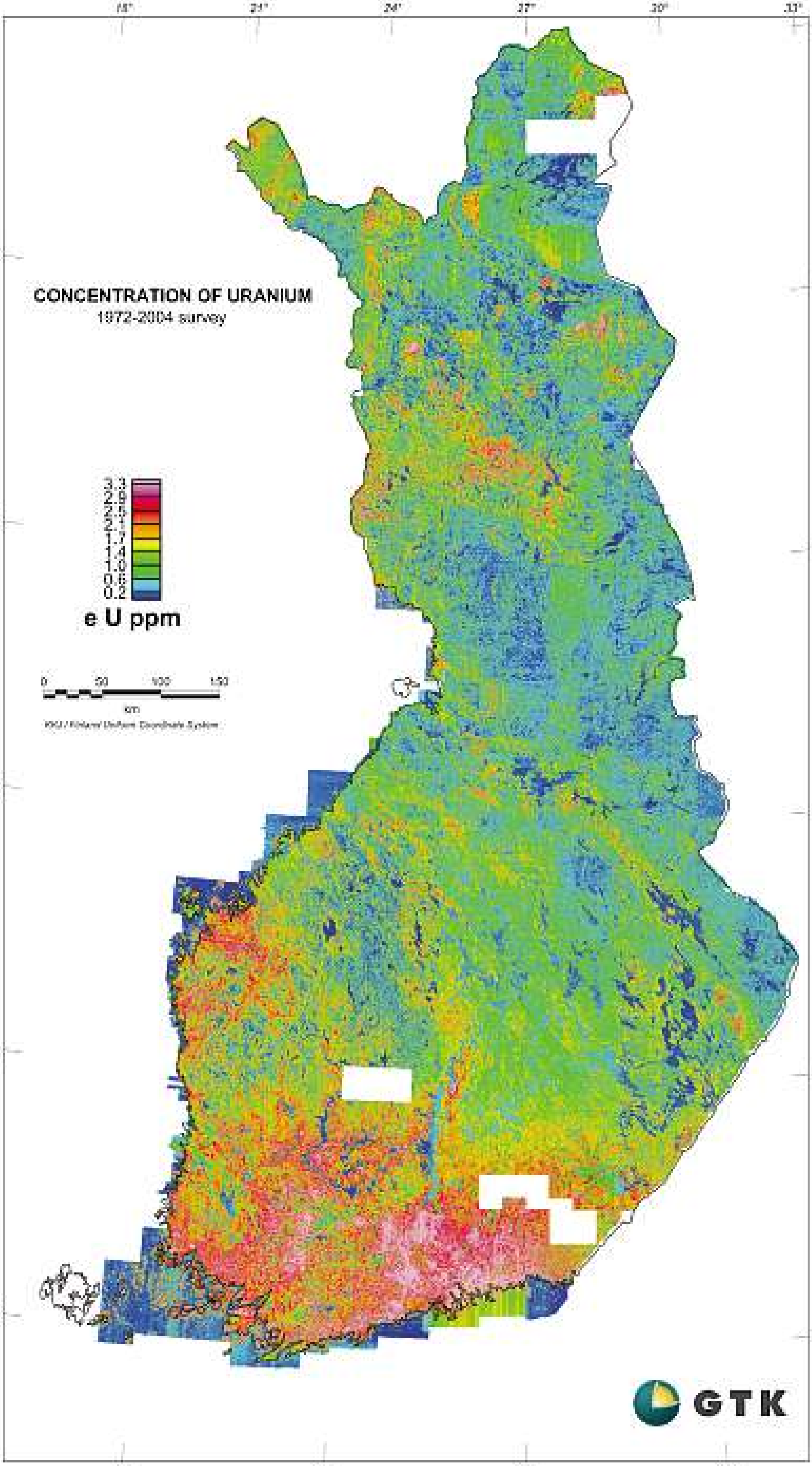
Appendix 4. Total radiation (Ur) in Finland.

Aerogeophysics in Finland 1972–2004:
Methods, System Characteristics and Applications,
edited by Meri-Liisa Airo.
Geological Survey of Finland, Special Paper 39, 21–74, 2005.



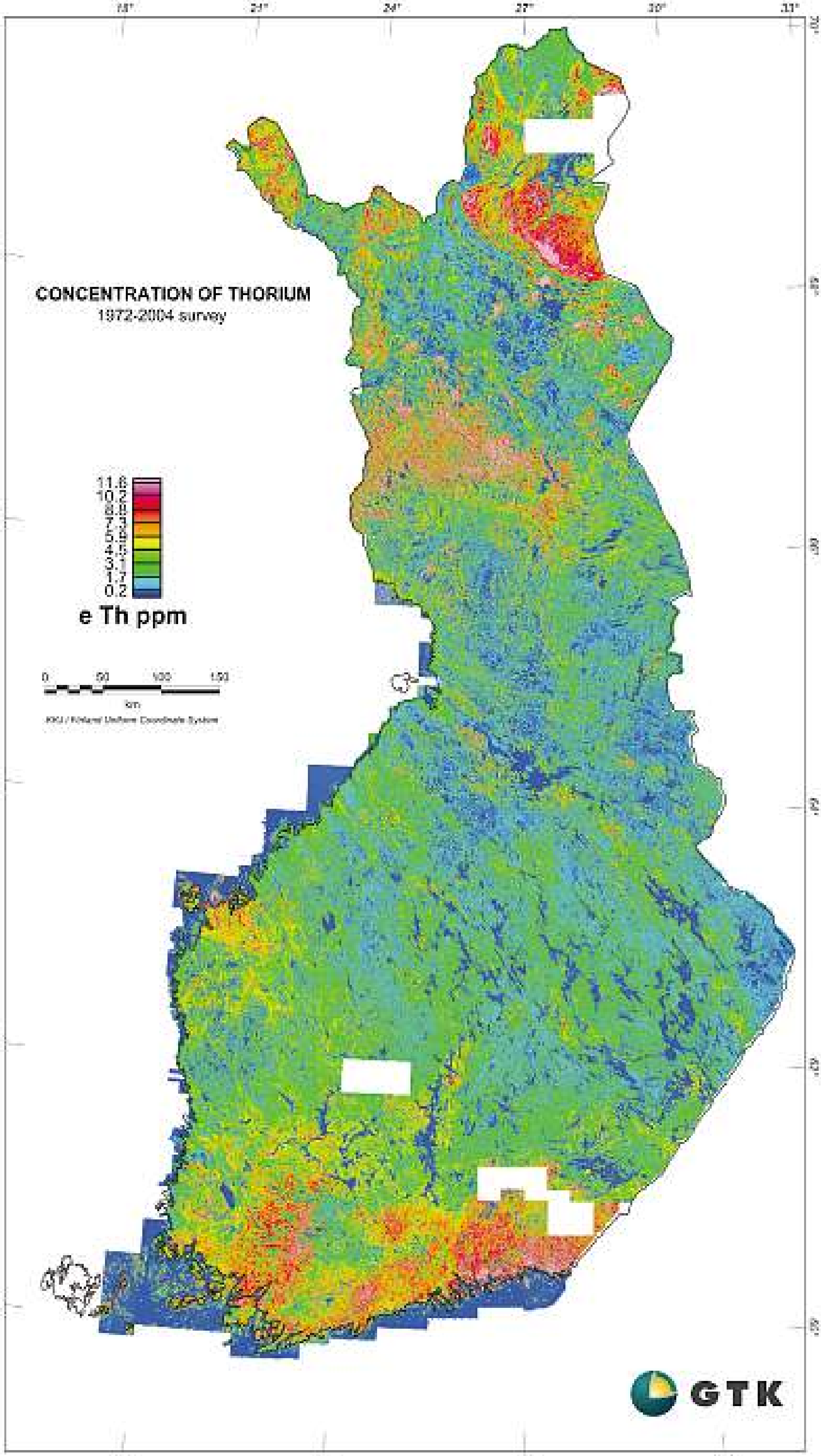
Appendix 5. Potassium (K %) concentration in Finland.

Aerogeophysics in Finland 1972–2004:
Methods, System Characteristics and Applications,
edited by Meri-Liisa Airo.
Geological Survey of Finland, Special Paper 39, 21–74, 2005.



Appendix 6. Uranium (eU ppm) concentration in Finland.

Aerogeophysics in Finland 1972–2004:
Methods, System Characteristics and Applications,
edited by Meri-Liisa Airo.
Geological Survey of Finland, Special Paper 39, 21–74, 2005.



Appendix 7. Thorium (eTh ppm) concentration in Finland.