Towards lightweight airborne gamma spectrometry

A case study

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Introduction

The use of airborne gamma-ray measurements has a long-standing tradition in geophysical research. The airborne measurement of gamma radiation emitted by naturally occurring elements like potassium (^{40}K), thorium (^{232}Th) and uranium (^{238}U) finds applications in mineral exploration [de Meijer et al., 1997], environmental research [Medusa], and precision farming [SoilCompany].

Airborne gamma-ray measurements are rather costly, and involve non-portable equipment, large platforms (often helicopters are used) and specialized operators. Reduction of cost and simplification of operation has been an important force, driving innovations towards smaller systems and smarter data analysis. The promise of using a small aircraft flown by local pilots resulting in flexible surveys flown at low cost of operation appears to be very appealing to many stakeholders in the exploration industry.

To meet this promise, Medusa Systems have developed M.A.S.S[1]. MASS is a small, lightweight system that can simply be operated by a pilot. MASS results from about 10 years of R&D, which started in 1997 as a Dutch academic research project[2] [de Meijer et al., 2002]. After series of tests in the RSA and in The Netherlands, a first commercial system has been delivered in early 2007, to URAMAD, a Cline Mining subsidiary in Madagaskar. In this year, URAMAD have flown several tens of thousands line kilometers. This white paper compares their survey results to a commercially available reference data set obtained by an international survey company in the same area.

The paper shortly introduces the concepts of airborne gamma-ray systems; it describes the MASS system and assesses the data comparison.

Background

Records of gamma radiation are in general used to establish the concentration of radionuclides in a given sample or volume. This concentration, normally given in Becquerel[3] per kilogram (Bq/kg) or in ppm, is known to be specific for given mineral types. Each mineral can be characterized by a radiometric fingerprint, or a concentration vector $\{C^{40}K, C^{232}Th, C^{238}U\}$ [de Meijer, 1998].

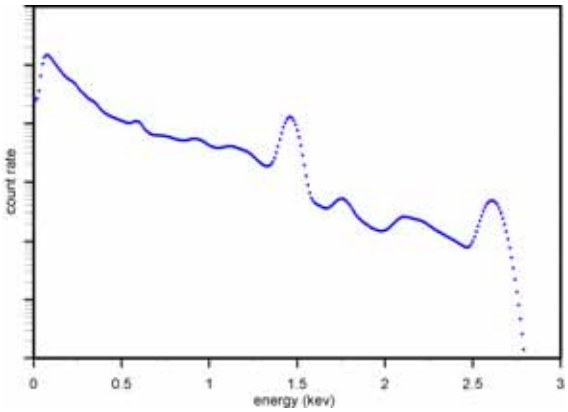

Figure 1. Sample spectrum of natural gamma radiation. The peak structure contains information on the contributing radionuclides.

Radionuclides emit photons with one or more unique energies that can be recorded using gammaspectrometer systems. Natural gamma spectra emitted by minerals and other soil components are a sum of contributions from different radionuclides. A gamma spectrum measured in nature therefore yields information on the actual concentration of nuclides in the material "seen" by the detector system, and – given known fingerprints – on the type of minerals present in the measured volume.

[1] Medusa Airborne Survey System.

[2] The project was initiated by the Nuclear Accelerator facility at the University of Groningen, The Netherlands in collaboration with the Council for Geosciences of South Africa.

[3] A Becquerel is the SI unit for radioactive decay. A source with activity of one Becquerel (Bq) equals one decay per second, on average.

Detector types

Most of the field systems used to record natural radiation consist of a scintillation crystal coupled to (a series of) multi-channel analysers (MCA's). Scintillation crystals 'translate" incoming radiation into flashes of light having an intensity proportional to the energy of the absorbed gamma photon [Debertin and Helmer, 1988]. The light output of a scintillator is translated into an electric signal that is stored using a MCA.

At present, there are many types of commercially available scintillator crystals, differing both in chemical composition and in shape. One can classify scintillator crystals on:

- ***Peak resolution.*** The resolution of a crystal is depending on its chemical composition and the quality of the making;
- ***Detection efficiency.*** The efficiency to detect gamma radiation depends on crystal density, and on the size of the crystal.
- ***Temperature stability.*** The light output of crystal systems varies with crystal temperature. This effect needs to be compensated for in field measurements.
- ***Robustness.*** For field applications, the robustness of a system is of course of utter importance.

Historically, the use of NaI crystal-based systems is widespread. NaI is relatively cheap, available and has excellent resolution. However, drawbacks are the low efficiency for gamma capture and the brittleness of the crystals. Nowadays, for specific applications, different materials are used more and more. For instance BGO, having a much better efficiency for radiation capture than NaI, is often applied in space-limited systems (slim borehole tools, but also in planetary exploration systems [Feldman et al., 1999]). The drawback of BGO is its lesser peak resolution and instability against temperature variation. Also, recently "exotic" crystal materials have become available that have very high resolution and a reasonably high Z value . These crystals are, however, still limited to relatively small sizes[4].

"Classic" hardware

Historically, most airborne gamma-ray systems are made up of a set of 4 to 8 NaI crystals looking "downwards". Depending on the system, all data from the detectors is fed via a multiplexing system into a MCA, or each detector has a dedicated MCA. In most systems, the concentrations of ^{40}K, ^{232}Th and ^{238}U are calculated on-line and stored on some media. Modern systems also log all spectral information to enable post-survey analyses. A differential GPS system used to store positions. Altimeter, air pressure and temperature loggers are added to correct the data for environmental variations. Some systems incorporate an extra crystal looking "upward" to measure cosmic background radiation and radiation from radon[5] surrounding the airplane.

"Classic" analysis

The reduction of the spectral information measured into concentrations of radionuclides, is mostly done using the Windows analysis method [Grasty et al., 1985]. In Windows, the activities of the nuclides are found by summing the intensity of the spectrum found in a certain interval surrounding a peak. In "classic" Windows, three peaks are used to establish the content of ^{232}Th, ^{238}U and ^{40}K.

A major drawback of the Windows method is the limited amount of spectral information that is incorporated into the analysis. Another weakness is the inherent use of *stripping factors* to account for contributions of radiation from nuclide A into the peak of nuclide B. Application of these stripping factors lead to propagation of uncertainties most prominently felt in the determination of the ^{238}U concentration.

[4] At the time of writing, the scintillation crystal Brilliance is available commercially at a maximum size of 3x3 inch.
[5] Radon is a gaseous daughter nuclide in the decay series of ^{238}U.

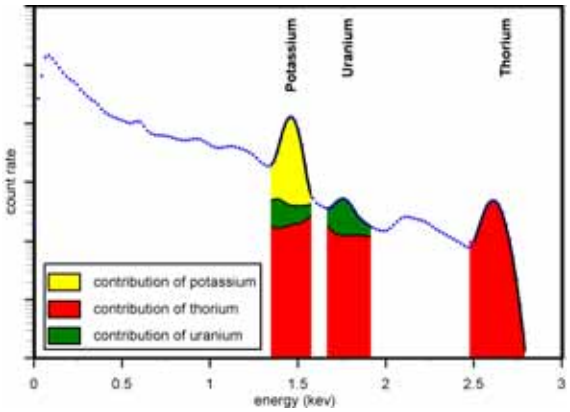

Figure 2. Windows analysis of a natural gamma spectrum (blue dots). Only a part of the measured spectrum is approximated by a fitted curve (black line), a large part of the measured spectrum is not used. In each peak the contribution of surrounding peaks is subtracted ("stripping factors"). Note the logarithmic Y-axis.

"Classic" calibration

One of the most important issues in airborne gammaray surveying is the calibration of the detector system. To derive "absolute" radionuclide concentrations from a field measurement, the field system must be calibrated such that its response to the field geometry is exactly known. In general for the calibrations of airborne systems, calibration pads are used. These pads are usually slabs of concrete having an enhanced concentration of one of the natural radionuclides. By mounting the detector system on top of each pad, the response of the system on a known source of radation is known.

The drawbacks of this method are several. For example, the pads can only mimic a very limited part of the volume that a system actually "sees" when airborne. Moreover, the surroundings (buildings, soil, etc) contribute to the measured signal and it also is quite a challenge to estimate the changing intensity of the radiation with varying elevation of the plane when using pads.

Stabilization issues

One of the main sources of errors in classic systems is the stabilisation of the measured spectrum. During a survey, the gain of detector systems tends to drift due to temperature variations. This means that the peaks shown in Figure 2 will be shifting out of the marked area, leading to miscalculations of activities. Multiple methods have been developed to compensate for such gain-drifts in hardware; amongst others using built-in radioactive sources, built-in LED's etc.

A novel approach

The major goal of the R&D traject set forward by Medusa Systems was to develop a single, light-weight detector; a tailored *sensor* instead of a complex measurement system. To get there, we have integrated a number of novelties and enhancements to the classic system design as described before. The MASS system is such a tailored sensor; it has a single 4 liter CsI crystal with a total system weight below 35 kgs. This is about a factor 3 lighter than traditional airborne survey systems.

To arrive at a small system, "full spectrum" analysis is combined with a high-Z crystal type (CsI instead of NaI). Fully automated software based stabilization and Monte Carlo simulation-based calibration complete the development.

Full spectrum analysis

In contrast to the "Windows" method described before, Full Spectrum Analysis (FSA) incorporates virtually all of the data present in the measured gamma spectrum. In FSA, a Chi-squared algorithm is used to fit a set of "Standard Spectra"[6] to the measured spectrum (see Figure 3). The fitting procedure yields the multiplication factors needed to reconstruct the measured spectrum from the standard spectra. The multipliers equal the actual concentrations of the radionuclides that led to the measured spectrum. The method is described in detail in Hendriks [2001].

Figure 4 shows an example of the advantage of using FSA versus Windows. The figure shows the uncertainty in the ^{232}Th concentration, calculated using "Windows" and FSA, as a function of spectral content (counts). The difference in uncertainty is about a factor of 1.7 regardless of the spectrum content (depicted as the difference between the red lines).

[6] A standard spectrum is the pure response of the detector system used on a 1 Bq/kg source of a given nuclide in a given geometrical setting.

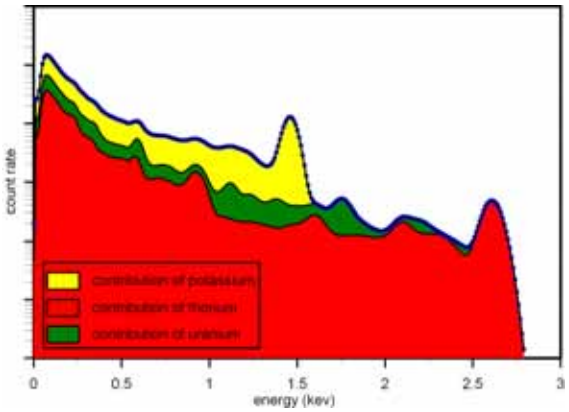

Figure 3. FSA analysis of a natural gamma spectrum. The measured spectrum (blue dots) is approximated by a fitted curve (black line). This curve is composed of the complete spectral contribution of ^{40}K (yellow), ^{232}Th (red) and ^{238}U (green).

The green lines in the figure denote the spectral content needed to get to an uncertainty of 5%, both for FSA and for windows. The difference in count rate (and thus crystal volume) for FSA and Windows in this case equals about a factor of 3. This reflects the statistical nature of the uncertainties in nuclide concentrations; the uncertainties scale with the square root of the spectral content.

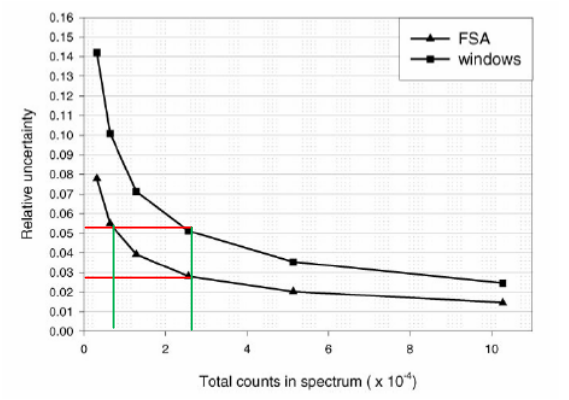

Figure 4. The relative uncertainty in the activity concentrations of ^{232}Th spectra analysed according to the full-spectrum analysis (triangles) and traditional windows analysis (squares) as a function of counts in the spectrum [taken from Hendriks, 2001].

Monte Carlo simulations

The Standard Spectra used in FSA are derived from *ab initio* Monte Carlo simulations of the radiation transport through a medium and capture inside a detector. The current version of the code (MCNP4), and additions written under contract of Medusa Systems, allow for a full calculation of spectral response for any given scintillator in any given measurement geometry [Hendriks et al., 2002]. This way, an almost perfect fit to the actual spectral shape can be obtained (as can be seen in Figure 3). The validity of this method has been tested for many different detector sizes and materials and for many different measurement geometries. One of its applications is in slim borehole logging systems [Antares].

CsI to replace NaI

The use of NaI detectors in airborne survey equipment is common practice. Many tens of detectors are manufactured each year for airborne purposes. However, NaI is not the most efficient capturer of high energy photons. Commercially available alternatives are BGO and CsI. BGO, as mentioned before has a quite low peak resolution, which prohibits use for cases where man-made nuclides (like the ^{137}Cs present in nuclear fallout) are subject of interest. Furthermore, the material is rather expensive and prone to temperature instability.

CsI is a very robust alternative to NaI and BGO. The material is readily available and only twice as expensive as NaI. The density of CsI is higher than NaI, yielding better efficiency, especially for smaller crystal sizes. Calculations and testing has shown that the difference in efficiency (count rate) between a 4x4x16 inch NaI and a same-sized CsI is about a factor 1.5. This advantage, taken with the fact that CsI is virtually unbreakable, made us use CsI instead of NaI. However, it must be noted that the FSA method is equally well applicable to NaI-based systems.

Gain stabilization

Since – in contrast to the "Windows" method – FSA is a mathematical strongly overdetermined solving method, the sensitivity of the nuclide concentrations to spectrum drift can be reduced. The quality of the fit (given by the Chi-squared resulting from the fitting procedure) is used to automatically find the gain of the detector system.

This procedure is described in some detail in Hendriks [2003].

A novel approach?

We expect that a combination of better detector material (improvement with a factor of 1.5) and improved data analysis (improvement with a factor of 3) should lead at least to a factor of 4 improvement of data quality. The use of smart automated gain stabilization and high quality standard spectra, will likely results in an even larger improvement.

In other words, we expect that data from a 4 liter CsI system using FSA would yield at least similar results as data from 4x4 liter NaI detectors using ordinary "Windows".

The proof of the pudding...

In the beginning of 2007, URAMAD Madagascar, a subsidiary of Cline Mining from Canada, acquired a single 4 liter CsI MASS system for mapping uranium outcrops in a large concession area in western Madagascar.

The system was mounted inside a small two-seater aircraft and was operated by the pilot of the plane. Power to the system was provided via small 12V car batteries that were charged overnight.

Figure 5. URAMAD airplane at the air strip of Tsiranomandidy, Madagaskar.

During 2007, URAMAD surveyed tens of thousands line kilometers in their concession area. Their average flying height was about 100m, average ground speed was about 150 km/h. Per day, about 4-6 hours of flying could be done.

A few of the areas that were covered in their survey were also covered by an international survey company some 5 years ago. In this "reference" survey a 32 liter traditional system (consisting of two 4x4 liter detector packs) was used.

For one of these areas we have done an extensive comparison of the results obtained with our MASS system with results of the traditional system.

Figure 6. Detector (lower box) and readout system (upper box) in the back of the plane.

The dataset covers an area of about 40x14 km^2. In the MASS survey, the area was covered using 200m linespacing at an elevation of about 100m. The reference survey was flown at similar height and line spacing. All data were taken at 2Hz. The area can be characterised as mountainous, with ground elevations ranging within 400m. A river stream crosses the location. This river stream is clearly reflected by low count rates (cf Figure 7).

The MASS dataset was corrected for radon and cosmic contributions and was consecutively corrected for elevation. All concentrations were normalised to 80m elevation. The reference dataset has been subject to a comparable, standard correction scheme.

To determine the quality of the MASS data compared to the reference dataset, we made a number of comparisons.

FSA vs Windows.

Unfortunately, the kind of analysis that was used to obtain the reference dataset, is unknown to us. However, knowing the system we assume some kind of "Windows" derivative was used, most likely in conjunction with spectral smoothing and interpolation techniques.

To mimic the improvement of FSA as compared to Windows, we analyzed the MASS dataset using both methods. We note that in both implementations, our software-based gain stabilization was used.

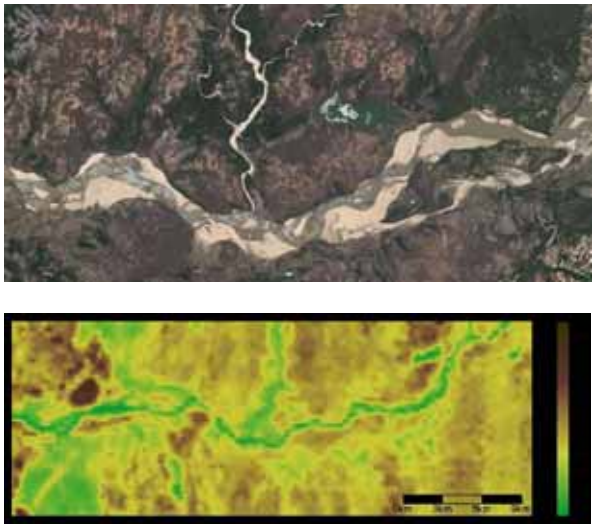

Figure 7. Top: aerial photograph. Bottom: count rate variation of the study area.

A method to estimate statistical uncertainties in spatial datasets is by geostatistics. Radiometric datasets always show a certain amount of statistical uncertainty. When many measurements are conducted at one spot, the measured concentrations will show a Poisson distribution [Debertin and Helmer, 1988]. The total uncertainty of the measured concentrations is a function of measurement time, method of data analysis and detector type used.

In an ideal situation we can determine the statistical uncertainty by conducting multiple measurements at one spot. In an airborne field survey, this is complicated since a plane moves at high speed over the area of interest. However, to estimate the uncertainty, we can compare adjacent datapoints by using geostatistical methods such as variogram analysis [Webster and Oliver, 2001].

Variograms provide a means of quantifying the commonly observed relationship that samples close together will tend to have more similar values than samples far apart. The *nugget* is defined as the variance at lag distance =0, it is the sum of variance due to statistical variation and variance due to variation on a scale smaller than the sample grid. The nugget is a direct measure of the uncertainty in the data. Comparing the nugget for FSA and Windows will thereby yield insight into the quality of the methods from a *geostatistical* point of view.

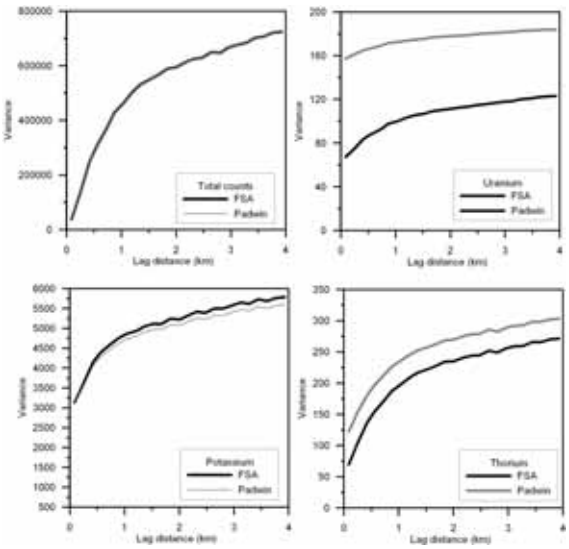

Figure 8. Variograms of total counts, uranium, potassium and thorium. All nuclide concentrations are in Bq/Kg, the data have been sampled 2 times per second.

The graphs in Figure 8 represent the variograms of the total counts and the three radionuclides analysed with full spectrum analysis (FSA) and windows analysis (PADWIN algorithm). The variogram of total counts is based on the total spectral content (corrected for gain drift). This variogram is for obvious reasons identical for both analysis methods. Also the variogram for potassium is similar for both methods. The area of study contains relatively low concentrations of potassium and we expect that for areas with higher concentrations, FSA will result in a different variogram.

The variograms of thorium and uranium clearly differ between PADWIN and FSA. Not only in absolute variance in the dataset, but also for the variance at lag distance 0 (the nugget). The nugget values for each dataset are estimated by extrapolation of the curves in Figure 8. As can be seen, the nugget values and thereby the uncertainties for the windows method are larger than for FSA. For the area under study, FSA improves the data quality (uncertainty per data point) for uranium by a factor of 1.6, and for thorium by a factor of 1.4. These data confirm the theory by Hendriks [2001] that using FSA instead of windows can reduce the size of a crystal by a factor of 3.

Please remember that the same input data for FSA and "Windows" was used to get to these values. We expect that smart automated gain stabilization, the use of one scintillation crystal (thereby reducing the complexity of data acquisition) and advanced interpolation techniques, will even result in a larger improvement compared to a traditional system.

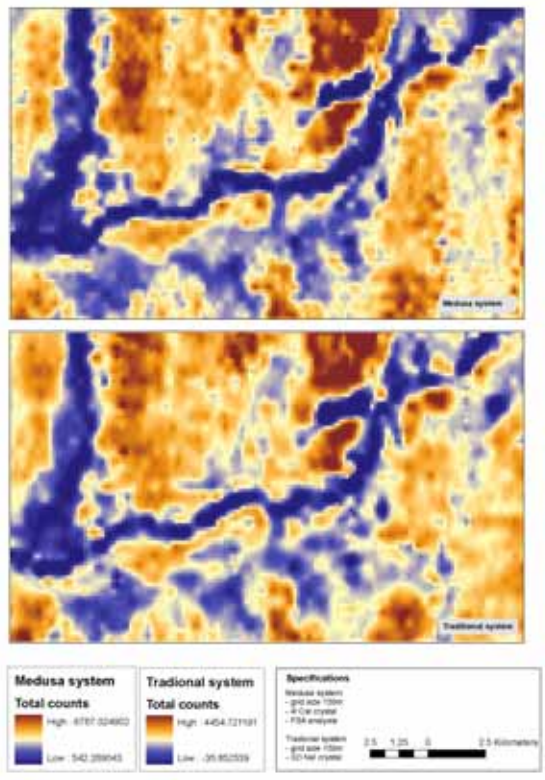

Figure 9. Total gamma activity. Top: MASS, bottom: Reference dataset.

MASS vs. Traditional system

Total count comparison

The images created from the total activities (Figure 9) from both systems are to a large extent comparable. They both show similar structures. The main difference is found in the count rate; the (FSA) MASS counts exceed the count rate of the traditional system by a factor of (about) 1.5. The reason for this difference is yet unknown; we would expect a much higher count for the traditional system, though.

^{40}K and ^{232}Th comparison

The following two images (Figure 10 & Figure 11) depict a comparison between the ^{40}K and ^{232}Th concentrations found with MASS and the traditional system. For these nuclides, the results of both systems are comparable. The MASS images show a bit more detail.

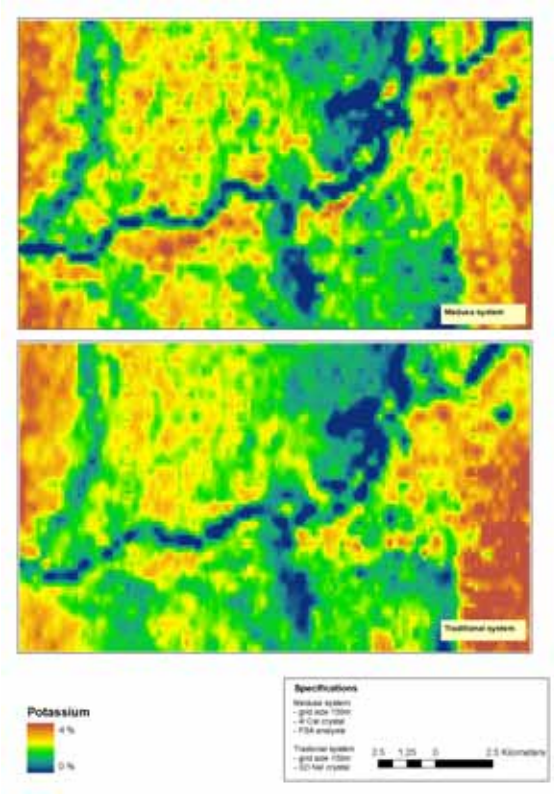

Figure 10. ^{40}K comparison. Top: MASS. Bottom: Reference dataset

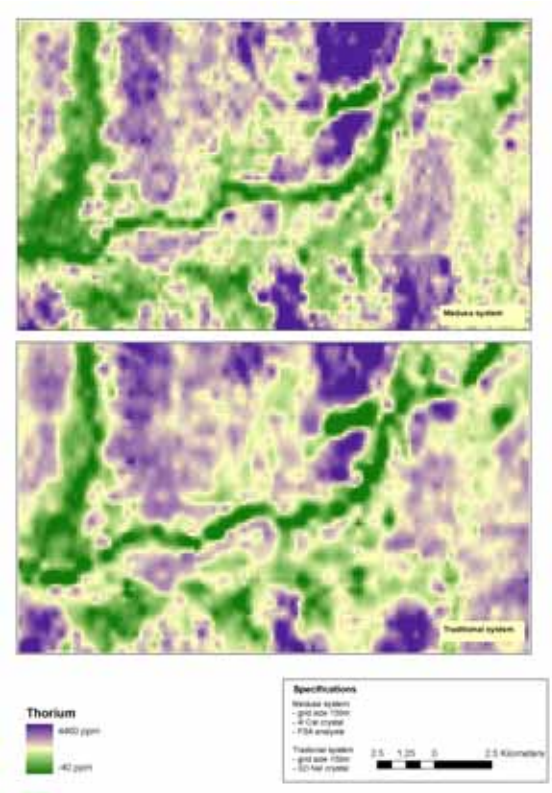

Figure 11. ^{232}Th comparison. Top: MASS. Bottom: Reference dataset.

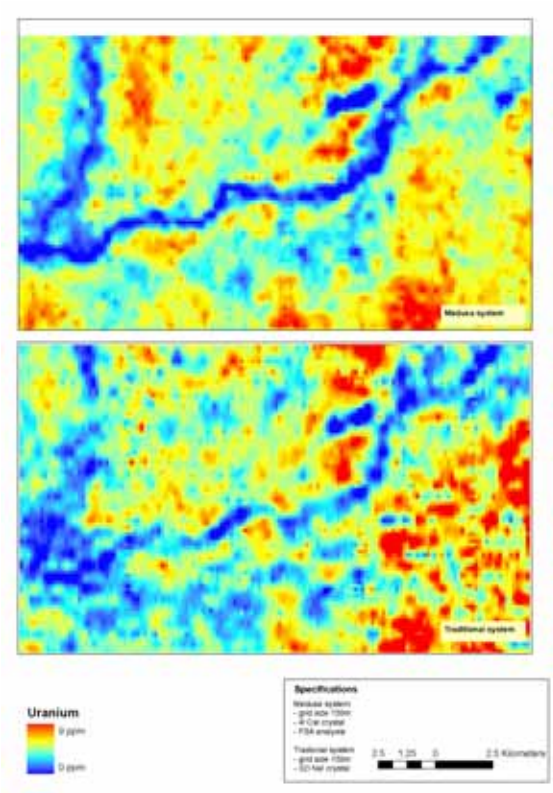

Figure 12. ^{238}U comparison. Top: MASS. Bottom: Reference dataset.

^{238}U comparison

The ^{238}U comparison (Figure 12) shows that the MASS data is clearly more coherent and shows finer structures. For instance, the river system is better defined in the MASS data.

In the Uranium prospecting area under study, the 4 liter MASS system performs at least equally well as an 8x4 liter traditional system.

Concluding remarks & outlook

Full spectrum analysis, combined with a single 4 liter CsI scintillator detector has proven to be a valid replacement, and possibly even an improvement of a classical 4x4 liter NaI-based system. Comparison of data obtained at a location measuring about 14x40 km^2 shows that – especially for ^{238}U– the MASS system merely outperforms a 8x4 liter NaI system.

This factor 8 volume reduction can be attributed to a difference in detector material, full spectrum data analysis and a sum of the improvements due to automated gain stabilization, the use of one scintillation crystal (thereby reducing the system complexity) and advanced interpolation techniques.

MASS, being much more costs-effective and less heavy, opens up new possibilities of prospecting at much lower cost per kilometer, using smaller aircraft, and local people to do the job.

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