Paper 10

Airborne Gamma-Ray Spectrometry in 2017: Solid Ground for New Development

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ABSTRACT

Decades of development and operational usage have brought airborne gamma-ray spectrometry (AGRS) to maturity. This has been recognized by the publication in the 1990s of standard guidelines that have been accepted by industry and governments and that are in worldwide use today. Over the last decade, while still based on the same proven system configuration favoring high volume detector arrays, commercial systems have been upgraded with digital electronics and are reaching an unprecedented degree of robustness and consistency. This renewed data quality offers the possibility to re-visit data processing and interpretation ideas that appeared previously interesting, in theory, but challenging to implement in practice. It also allows investigating new approaches in data collection that are now technologically available to practitioners.

Three of these ideas are reviewed here. They were selected because elements of solution, in the form of models and processes, have been presented before and are available. Combined with the renewed consistency of AGRS detection systems and the processing power now available to end-users, further development and standardization of these processes could lead to tangible benefits and improved end-products. 1) In the standard data processing methods, the ground is considered infinitely flat. This is obviously never the case in nature, and, on the contrary, the terrain may be quite significant. Approaches have been suggested to include terrain in data processing. 2) By considering the differential signal between each individual detector of the system's array, directional information on the origin of the signal can be extracted and included in the mapping process to potentially enhance spatial resolution. 3) Typically, only information from single photopeaks relating to Potassium, Uranium and Thorium are used for data processing. Modern AGRS systems, however, record full spectra containing many distinct photopeaks of Uranium and Thorium. Data processing schemes to make use of all this information should be reviewed and standardized. This will increase counting statistics and improve data accuracy.

Improvements to end-product quality should offer better contrast when targeting mineral deposits with AGRS, either directly or through alterations or geochemical dispersal. But, the increased readability and significance of end-products will also convey the value of AGRS for framework mapping of surficial geochemical variations and allow an insightful integration within bedrock and surficial mapping projects, providing more layers of information that will be useful at the planning, field work and compilation phases.

INTRODUCTION

Airborne geophysics is an essential component of geological mapping and exploration programs as it provides a continuous coverage of the structure and composition of the subsurface over large areas in a relatively short time. For reconnaissance and framework mapping, aeromagnetic surveying is of primary interest, providing a straightforward image of subsurface structures. But it is worthwhile to maximize return on airborne survey investment and with a small incremental cost, airborne gamma-ray spectrometry (AGRS) can be profitably included.

Among geophysical methods, AGRS provides distinct information on the nature of the geological materials at the surface of the earth. While most other geophysical techniques are used to resolve the structural setting of geological units, AGRS provides compositional information about these same materials in the form of a surface mapping of naturally occurring radio-elements ^{40}K, ^{238}U and ^{232}Th. As such, it traces the link between surface expression of geological features, their geochemical composition and their subsurface structural setting.

As part of a regional geophysical characterization effort, AGRS appears as a natural complement to aeromagnetic surveying.

However, AGRS end-products do not seem to be utilized to their full potential during the data integration and interpretation phases of mapping and exploration programs. While there is a need for successful applications, new or old, to be documented and published, there is also a need to enhance AGRS end-products readability. Many factors influence the significance of data. The intrinsic statistical fluctuations of radioactive processes can be a limiting factor for straightforward visual inspection and interpretation, especially for the occasionally weak signature of Thorium and Uranium. It is present as a component of statistical noise that is diluting the signal, and strategies to overcome this effect have to be investigated. Also, to simplify the data processing steps, a very simple geometry of a flat source half-space and a point detector above it is implied in typical data processing schemes, while the actual acquisition geometry and physical context are more complex. Gamma-rays are collected from all directions indiscriminately by a detector of finite extent and originate from a source volume varying in

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extent, shape and strength. Computing power and gamma-ray transport software packages are available now to approach this 3D problem.

Tracing the early development of AGRS to at least 70 years ago (Pringle et al., 1950; Pringle et al., 1954; Brownell, et al., 1959) the formalization of the methodology started in the 1970s culminating in the release of standard technical specifications in 1991 (IAEA, 1991). AGRS has now come to maturity with proven instrumentation, standardized methodology and demonstrated applications. A recent review was provided by Killeen et al., (2015) and an example of application is given in Figure 1. Over the last decade, while still based on the same proven system configuration, AGRS systems have been upgraded with digital electronics and are reaching an unprecedented degree of robustness and consistency. This renewed data quality offers the possibility to re-visit data analysis ideas that were suggested previously but deemed challenging to implement in practice.

Based on our experience as developers, practitioners and end-users, we will review and suggest here three of these ideas where development and application efforts could lead to substantial benefits in end results significance. This selection is somewhat subjective but we do believe it is at the reach of most practitioners. The overall gain will be to increase effectiveness and successes in using AGRS data set as part of exploration programs.

Status of AGRS

Airborne gamma-ray spectrometry has been used for many years for effective mapping of Potassium (K), Uranium (U) and Thorium (Th) over large areas, for direct detection of ore bodies and in support of lithological mapping. In AGRS, the object of data acquisition is to obtain a gamma-ray spectrum covering the energy range from 0 to 3000 keV, where gamma-ray photopeaks resulting from the radioactive decay of ^{40}K, ^{238}U and ^{232}Th can be identified and measured. The intensity of these photopeaks can be linked in turn to the concentrations of K, U and Th in the ground. Scintillation crystals, especially Thallium-doped Sodium Iodide (NaI(Tl)), are the preferred radiation detectors in AGRS applications due to their high efficiency. A typical detector array consists of an arrangement of individual NaI(Tl) 10.16 cm x 10.16 cm x 40.64 cm prismatic crystals. The scintillator produces a light output for each intercepted gamma photon of intensity proportional to the energy of the incident gamma photon. The light output is then collected by a photomultiplier tube (PMT), part of the detector assembly, which produces a voltage pulse of height proportional to the light intensity, and therefore proportional to the gamma photon energy. The voltage pulses are sorted by a multi-channel analyzer to create an energy spectrum of 256, 512 or 1024 channels, covering the energy range from zero to 3000 keV.

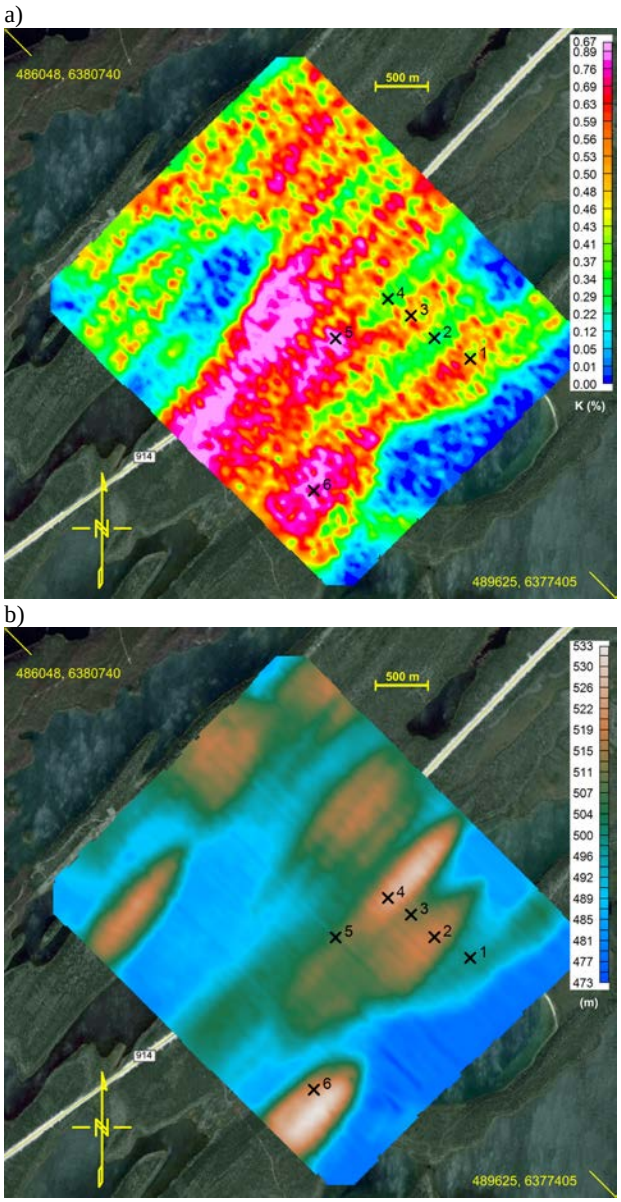

Figure 1: Results from a high resolution helicopter-borne AGRS survey conducted north of Key Lake, Saskatchewan (Fortin et al., 2015). AGRS has often been used for targeting anomalies related to mineral deposits, but this survey offers an example of the application of AGRS in support of surficial mapping. Smaller drumlinoids (locations 2 and 4), consequent from the re-advance and shift in flow direction of the ice margin, exhibit a lower K signature. The smaller drumlinoids are discriminated in surface till K concentrations from larger drumlins resulting from the main ice advance (location 6), and from glacio-fluvial deposits contained in low elevation areas (locations 1, 3, and 5). a) Map of K concentrations (%) obtained from the high resolution airborne survey. b) Digital terrain model (height above the GRS80 Ellipsoid) created with the laser altimetry data obtained from the high resolution survey. More details are provided in Fortin et al. (2015).

Over the last 10 years, the most significant advancement in AGRS probably consists of the modernization of the equipment to digital electronics. The new generation of spectrometers that were made available around 2007, are built around fully digital electronics utilizing field-programmable gate arrays (FPGAs) and digital signal processors (DSP) technologies. The digital electronics is inherently more stable since all filtering is performed in the digital domain with filtered data resolution of more than 20 bits. The digital filtering is independent of temperature, component tolerances and analog potentiometer adjustment making the output more accurate and more precise. With the high bit resolution, it is possible to make corrections for non-linear energy conversion effect in the NaI(Tl) crystals and produce linear spectra. Older systems have a non-linear spectral output with a first order off-set and slope correction but do not correct to higher order non-linearity.

Digital electronics and linearization of the output spectra have brought consistency to the response function of the standard prismatic detectors, minimizing the blurring of summed spectrum. It has also made the standard three windows (see section Spectral Analysis of Gamma-Ray Spectra) more uniform across different detectors and detector packs.

Also, the pulse conversion time has been greatly reduced from 50–100 µs down to about 1 µs (Figure 2). This is the effective digital filtering integration time and is distinct from the actual much faster analog to digital converter (ADC) sample rate, typically between 40 MHz and 120 MHz. The reduced conversion time results in a significant improvement in throughput of the spectrometer which in turn contributes to improving the count rate performance. Analog instruments with a single detector pack of four standard prismatic detectors saturate at around 50,000 cps. Digital gamma ray spectrometers will perform much better and easily work up to 1,000,000 cps per four detector pack (16 litre) with less pulse pile-up and distortion (a >20 times performance improvement). This is important for radiological emergency response operations but also where high count rates can be encountered while flying over exposed uranium mineralization and mine tailing.

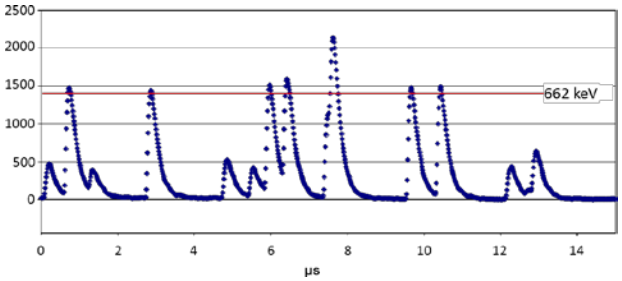

Figure 2: Gamma-ray pulse sequence over 15 µs showing the pulse conversion rate of approximately 1 µs. Red line indicates the 662 keV photopeak level of ^{137}Cs. The vertical voltage scale is arbitrary.

In addition, improvements have also been made on gain stabilization, changed from using single peaks from either K, U or Th to utilizing spectral K, U and Th templates and stabilizing on natural background, making calibration check sources not necessary in most locations. It results in greatly improved survey data, a consequence of the much improved spectral stability.

Overall, the new generation of spectrometers has provided a significantly higher degree of consistency in the data, opening up the possibility to extract more information from the data and to re-explore old ideas that were not possible before.

Height and Terrain Corrections

Processing of airborne gamma-ray data requires the removal of background radiation which is not associated with the radioelements of interest. Contributions to the background radiation include cosmic rays, radiation associated with the aircraft itself and atmospheric radon, and methods to remove all these background elements are well established (IAEA, 2003). Having corrected for background contributions, the impact of the distance from the source to the detector needs to be accounted for.

Radiation from the surface of the earth is attenuated as it passes through the air, the rate of attenuation of the count rate being dependent on the energy of the gamma-ray and the distance between the source and the detector adjusted for pressure and temperature. Variations in the survey height above ground occur naturally as a consequence of flying surveys over rugged terrain. In some circumstances additional inconsistencies in survey altitude may occur from one survey line to the next as for example when flying a survey in "contour mode" designed to optimize for low altitude at all times as opposed to following a more smoothly varying survey altitude obtained by following a pre-designed smooth "drape" surface. The attenuation with height above ground can be approximated by an exponential (IAEA 2003) and is therefore a very significant effect. Up to altitudes of 250 m above ground the attenuation is reasonably well described by the following equation (IAEA 2003):

$$n = n_0 \, e^{-\mu (H - h)}$$

where μ is the height attenuation coefficient, n_0 is the observed count rate, h is the height of the aircraft above the ground adjusted for pressure and temperature and H is the nominal survey height above the ground. Contour flying will provide the strongest signal data with highest signal-to-noise ratio by staying as close to the ground as possible, whilst drape flying will provide a more consistent signal from adjacent survey lines. Airborne surveys are often multi-parameters and the mode of flying may be a compromise between the different methodologies, to ensure an overall acceptable data quality. The value H may be the intended survey height as might be achieved when flying over flat ground, or might be the average achieved survey height so as to minimize the required corrections. Either way, the data must be corrected for the height of the aircraft above the ground to a constant height.

Radiation from a point source to a point detector attenuates at a constant linear rate if the medium through which the radiation moves is homogenous. The linear attenuation coefficients per metre for the gamma-rays of interest in air of a specific composition at standard temperature and pressure (temperature

of 0ºC and atmospheric pressure of 76 cm Hg) are as follows (Grasty 1979a):

K	-0.00680
U	-0.00619
Th	-0.00506

So it may appear that the correction for altitude is easy to apply. However, the signal recorded by the detector is complicated by the fact that radiation is detected not from a single point source but from a broad effectively infinite source from the surface of the earth beneath the aircraft and by geometrical factors associated with the detector itself. So the actual radiation detected is a function of the detector geometry and the height above the broad source. The contribution from an infinite broad source for a detector at different altitudes has been calculated based on the linear attenuation rates (Clark et al. 1972) and shows that, for example at 100 m above the ground, 80% of the detected radiation comes from within a radius of 300 m below the detector, and becomes wider as survey altitude increases (Figure 3). The rate at which the count rate decreases from the broad source depends on the geometry of the specific detector. It is not uncommon for multiple detector packs to be installed in an aircraft in order to maximize the number of counts measured and hence improve the signal to count ratio, especially if high survey altitudes are expected. Volumes of up to 67 litres of downward facing sodium iodide crystals have been employed, although about half that amount is more typical. Each installation will have its own geometry that impact how it "sees" the ground. Thus it is necessary to determine the actual attenuation coefficient for any particular survey aircraft's spectrometer installation experimentally. This is achieved by flying over a calibration range at different altitudes. A suitable calibration range is selected based on flat topography and consistent radiation levels (Grasty and Minty, 1995) so as to provide consistent data along the length of the line. In 2003 the IAEA updated values from 1991 and gave typical height attenuation coefficients per metre:

K	-0.0082 (1991)	-0.0088 (2003)
U	-0.0084 (1991)	-0.0082 (2003)
Th	-0.0066 (1991)	-0.0066 (2003)

Attenuation of the total count is expected to be within 5% of the value for Th. The question as to how high above the ground useful data may be acquired is partly dependent on the strength of the signal from the ground. It is not uncommon to limit data to that collected at or below 250 m or 300 m effective height. Methods to counter the problems of decreased signal at altitude include:

1) Employment of large crystal detector volume: The signal detected is directly related to the volume of the crystal packs employed. Up to 67.2 litres of downward facing NaI prismatic crystals have been employed to obtain a strong gamma-ray signal.
2) Noise reduction through spectral analysis: methods such as NASVD (Noise Adjusted Singular Value Decomposition, Minty and Hovgaard, 2002, see section Spectral Analysis of Gamma-Ray Spectra) can reduce the noise as if the effective crystal detector volume is increased by a factor of between 3 and 4 (Hovgaard and Grasty, 1997).
3) Height adaptive filters: adaptive filters can be applied to gamma ray data recorded between 300 m and 500 m effective height to improve the signal to noise ratio. For example, no filtering is applied up to 300 m effective height, a 3 second moving average filter is applied to data flown at 350 m, a 9 second moving average filter is applied to data flown at 400 m effective height, and there is a gradual transition in the degree of filtering applied at intermediate heights between these levels. Data above 400 m effective height is all filtered with a 9 second filter.

Through a combination of the methods described above, it may be possible to obtain coherent data at effective heights above 300 m. The coherency of the data acquired at heights above 300 m can be inspected and compared to adjacent lower flown data or coincident data to verify the validity of the data processing. The signal-to-noise ratio is higher and the resolution is better for data acquired at the lower altitudes, and the data acquired at higher altitudes can be interpreted accordingly.

Data is typically recorded at a rate of 1 s^{-1} so that each data point represents one second of counts. At a nominal survey speed of 70 m/s this would represent a data value every 70 m along a survey line. However, due to the way the detector records radiation from a large field of view (each measurement recorded is the sum of the radiation over a significant radius that is generally much larger than this amount) the signal will be smoothed out and sharp boundaries in the gamma-ray signal will be blurred along the line. In addition, there is the question of how you move from survey lines to data interpolated onto a regular grid. Data from adjacent lines will frequently detect some signal from the same sources of radiation that fall between the lines. The field of view of one line may even include an adjacent line.

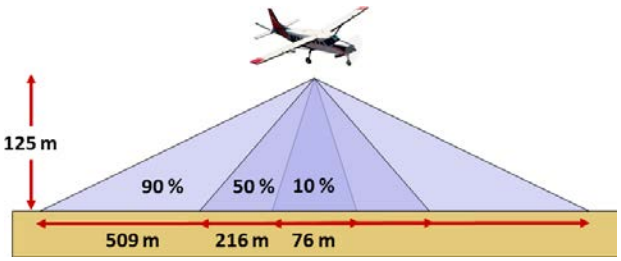

Figure 3: Field of view of an airborne gamma-ray spectrometer. This figure shows for a uniform half-space, the size of the area on the ground where the gamma photons recorded by the detector are coming from. For example, 90% of the counts recorded by the detector are coming from a circle on the ground of a diameter of 509 m, when the aircraft is at 125 m above the ground. Data is from Grasty et al. (1979b).

A gridding method based on a cosine weighted average of data within a particular radius accounts to some extent for the statistical noise within the data (Killeen et al, 2015) and to a degree matches the broad source nature of the signal. The cosine weighted gridding method matches the nature of the data, but does nothing to correct the source and detector geometry issues. Another commonly used gridding method is minimum curvature

(Briggs, 1974) which tends to represent boundaries in the data more sharply, but it too applies an artificial degree of smoothing to the data through its requirement to minimize the second derivative in two dimensions, a constraint that is more suitable for potential field data.

In addition to the lack of definition that results from the geometrical impact of the detectors, the signal when corrected for attenuation used in the classic method can be very misleading where the topography is significant as opposed to the flat calibration range used to determine the coefficients. As stated in (IAEA, 2003), "Topographic effects can be severe for both airborne and ground surveying. Both airborne and portable gamma ray spectrometers are calibrated for a 2π surface geometry." As a result data collected over valleys are likely to be over-corrected and appear stronger than it should be, and data from hill tops and ridges will be under corrected, complicating interpretation. In addition the simple exponential attenuation equation is only an approximation of the real transport behavior gamma rays.

Attempts have been made to account for the effects of the broad source and geometry of the detectors by deconvolution. The signal received is due to a combination or convolution of the signal function from the source and a function of the source to detector geometry. Deconvolution can separate the two, and is achieved in the frequency domain including an allowance for the impact of random noise superimposed on the signal (Gunn, 1978; Craig et al. 1999; Billings and Hovgaard, 1999; Billings et al. 2003). However, the method can only be applied at a given altitude above the ground so it would need to be repeated for several altitudes and results interpolated for altitudes in between, and does not account for terrain ruggedness.

Schwarz et al. (1992) presented a method to account for the impact of terrain in two or three dimensions along a profile. For the 2D approach the radiation in the field of view of the detectors at any given point is modelled by integration of strips of terrain perpendicular to the survey line within the field of view to determine the equivalent distance to a flat surface. In the 3D approach, each cell of gridded data within the footprint is considered individually. The data can then be scaled accordingly. The method assumes consistent count rates within the footprint, and does not account for directional effects related to detector geometry.

Druker (2012) demonstrated a 2D method that derives the relationship between the observed data and signal modelled for strips of ground along a survey line which allows for variation in the along line topography. As opposed to the approach of Schwarz et al. (1992), this method does not assume a homogenous level of radiation within the field of view, and recovers the ground concentrations by inversion of the observed data to best fit the model strips.

Wendorff (pers. comm., 2017) has developed a topographic correction method that divides the ground into polygons following the same mathematical foundation as Schwarz et al. (1992) but focusing more on the detector system allowing for improved computational efficiency when accounting for three dimensional terrain effects and a detailed definition of the sensor sensitivity making this approach, at least potentially, suitable from extremely low to extremely high altitudes.

The 2D terrain correction methods mentioned above require that the data be gridded using some suitable algorithm. The method described by Minty and Brodie (2016) uses an inversion of the observations to determine the 3D distribution of gamma-ray signal on a rugged terrain directly, accounting for detector geometry and allowing for the impact of random noise and how it compounds during the process of background removal of various gamma-ray sources. The result is a surface distribution that does not require gridding of the profile data, and sharpens the boundaries between areas of different gamma-ray signature on the ground. The method is not dependent on broad source attenuation coefficients as determined from calibration over a test range, although they would still prove useful for comparison of results and the fact that some background may need to be identified and removed using conventional processing methods. Overall the approach described by Minty and Brodie (2016) represents a significant advancement in achieving a more rigorous and accurate representation of the surface gamma-ray sources that could be adopted as a standard approach even where topographic effects are not a major concern.

Detector Directionality

In the standard data processing approach, each data value is referenced by the GPS coordinates obtained at the mid-time of the measurements. The measurements can be presented as a grid of points over the survey area. Along lines, considering a sampling time of 1 s, the measurements are separated by the distance covered by the airplane over 1 s, so numerically equivalent to the aircraft survey speed. Across lines, the measurements are separated by the distance corresponding to the line spacing. Usually, the data is interpolated on a grid, as mentioned, to create a continuous image of the distribution of K, U and Th.

Airborne gamma-ray spectrometry systems detect gamma photons from all directions indiscriminately. Any sources that is strong enough to compensate for the attenuation along the distance travelled by the photons from the source to the detector will contribute to the measurements. Strong sources can be detected from larger distance while small and weak anomalies may be diluted in the large field of view of the detector.

The broad and non-uniform field of view of AGRS system has the effect of blurring contrast between distinct radiometric domains on the ground. Provided that significant overlap actually exists for neighbouring measurements, image reconstruction or data inversion techniques could be applied to create maps with sharper details. But it may also be possible to benefit from the differential response from the individual detectors used in typical AGRS detector arrays to obtain information on the direction from which gamma photons interact with the detection system. A typical high-volume detector package consists of four individual NaI(Tl) 10.16 cm x 10.16 cm x 40.64 cm crystals placed side-by-side. In this configuration, the left-hand side crystal is effectively shielded from its right-side and will differentially receive more photons from the left. Similarly, the two middle crystals are shielded from both their

left and right sides and are receiving mostly photons from below. It should be investigated how this directional information can be used in the data processing to sharpen boundaries and enhance data presentation.

While other approaches exist to obtain directional information and can lead to fully developed gamma imaging system appropriate for mobile applications (Vetter, et al., 2006; Sinclair, et al., 2014; Jiang, et al., 2016), the self-shielding array approach has the advantage of being a very simple setup that can use similar detectors and electronics as those used in geophysical systems. Detector arrays that optimize the discrimination of directional information have been suggested (Khan, 2012; Burgada et al., 2014; Sinclair et al., 2016) and their usage in geophysical applications should be investigated.

Spectral Analysis of Gamma-Ray Spectra

The process of measuring gamma radiation involves collecting and counting individually each gamma photons that interact with the detector. A measurement is represented by *n* counts being registered during a sampling time *t* and its statistical error is approximated by the square root of *n*. AGRS measurements often result in low *n*, and as such, exhibit a low signal-to-noise ratio and therefore weak *counting statistics*. If the data is interpolated on a map, statistical fluctuations appear superposed as noise and can compromise visual interpretation. Spatial filtering may help presentation but may also dilute small anomalies beyond detectability. A straightforward approach to increase the significance of measurements is then to devise an approach to increase *n*.

In a typical airborne gamma-ray data collection context, and for any given source of radiation, the two parameters that determine the quality of the counting statistics are the detector volume and the sampling time. The larger the volume of the detector is, the higher will be the counting statistics since more gamma photons will be intercepted. Similarly, the longer the sampling time is, the counting statistics will be equally increased, as more time is allowed for gamma photon to be intercepted.

NaI(Tl) is a very dense material (3.67 g/cm^3), and a typical NaI(Tl) prismatic crystal weighs in excess of 15 kg, excluding any electronics. Detector arrays used in AGRS can include up to fifteen of these prismatic NaI(Tl) detectors resulting in a very significant total weight. Therefore, while counting statistics can be improved by increasing detector volume, the space required for system installation in survey aircrafts and the effects of AGRS system's weight on flight performance will be limiting factors on the maximum detector volume that can be used operationally.

In AGRS, sampling time determines the spatial resolution of the measurements. The extent of ground covered in one single measurement depends on the aircraft speed and on sampling time. With a survey speed of 70 m/s, typical of fixed-wing aircraft used for surveying (Cessna Caravan, Piper Navajo) and a sampling time of 1 s, there will be one measurement located roughly every 70 m along the flight lines. Small radiometric anomalies can be of a similar scale and this prescribes for the spatial resolution to be in that range as well. Increasing the sampling time to enhance counting statistics will be at the expense of spatial resolution. Typically, sampling time in AGRS is being set to 1 s, and that has appeared to be a good compromise between counting statistics and spatial resolution.

To analyse and process AGRS data, guidelines (IAEA, 1991; Grasty and Minty, 1995) recommend using the *window method*. The spectral data is reduced in four windows over which the counts are summed. These windows are centered on high energy photopeaks from the K, U and Th decay chains, namely the 1460 keV photopeak of ^{40}K, the 1765 keV photopeak of ^{214}Bi (Uranium) and the 2614 keV photopeak of ^{208}Tl (Thorium). The resulting three scalar values can be processed and calibrated to provide ground concentrations of the three radio-elements. A *total count* value is also computed, summing counts from low energies to 3000 keV, to obtain a total radioactivity indicator.

This approach has various advantages. It reduces the volume of data from 256 to 1024 channels spectra to four scalar values and simplifies the data processing steps in straightforward streams of arithmetic operations that require limited processing power. It is also very robust. If spectral stability is verified over the survey data and the quality of the pre-survey calibration parameters is checked, the data processing can be automated with confidence, and only a few limited issues, mainly related to correction for atmospheric radon, may require attention before final products. On 1 s sampling time, while the counting statistics is usually appropriate for processing data successfully, it can still be very weak, especially for the Th and U windows depending on the environment where the data is acquired.

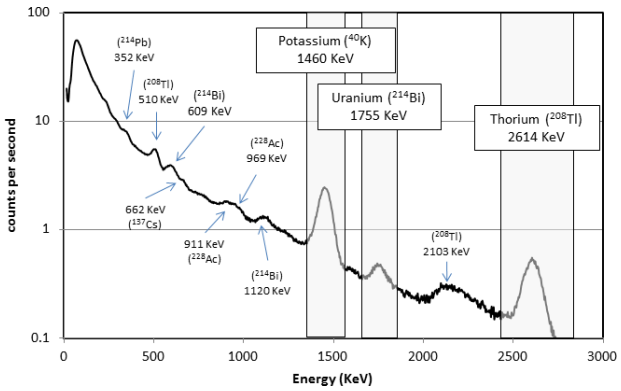

Figure 4: Gamma-ray spectrum obtained in Northern Canada from airborne data. To enhance features, it has been summed from 1800 individual 1 s spectra over an area exhibiting a distinctive radiometric signature. The three standard photopeaks and windows for K, U and Th are identified, but many other photopeaks from the decay chain of U and Th and a faint ^{137}Cs photopeak (662 keV) can also be seen.

Spectra collected during an airborne survey contain much more information than the summed counts in the three windows used in the window method. Except for ^{40}K which has only one photo peak, ^{238}U and ^{232}Th produce many gamma photons of distinct energies through their decay chains (see Figure 4), and each of these photo peaks contribute to the measured spectrum. These photons also interact with the ground constituents, with the air between the soil and the aircraft and with the aircraft itself and

are scattered in lower energy photons through Compton scattering (Tsoulfanidis and Landsberger, 2011). The resulting photons are then collected in the detector, creating a build-up of counts in the lower part of measured spectra. The shapes of the spectra are a signature of the source and of the scattering environment.

A fundamental concept in AGRS data acquisition is that each spectrum collected during a survey is the combination of the spectra originating from the various sources of radioactivity present in the environment of the measurement. These spectral components are associated respectively with the distribution of K, U and Th within the detector field of view, the presence of atmospheric Radon, the *cosmic* gamma photons (Grasty, 1979a) and the eventual presence of Cs-137 from nuclear testing and accident fallout.

As soon as development in electronics made it easy to implement in airborne systems, full spectra have been measured and recorded but mainly to monitor spectral drift of the system. If seldom, constant efforts were made over the years to make use of the entire spectral information (Dickson, et al., 1981; Grasty et al., 1985; Hovgaard and Grasty, 1997; Minty et al., 1998; Hendriks et al., 2001; Guillot, 2001; Caciollia et al., 2012). So far, however, it has not resulted in an accepted methodology despite the benefits that are anticipated. The reasons for this situation are unclear but could perhaps be explained partly by systems not being optimized for this approach. The optimized energy resolution and energy calibration obtained by the new generation of spectrometers and the processing power now achieved by standard computers are prompting a re-visit of this data processing approach and work toward development of a standardized approach.

In AGRS, the acquisition geometry is not constant and differs from measurement to measurement due to changes in pilot's control of the aircraft and varying terrain. In a controlled experiment, where the distance between ground-detector stays fixed, three 'unit' spectra, each representing respectively unit concentration in the ground of K, U and Th would be sufficient to fit background corrected measured spectra. But with actual survey data, the spectral decomposition must account for the changes in ground-detector distance, in fact, aircraft altitude above ground. Dickson, et al. (1981) showed by experiment that only two spectral components per radioelement are required to describe the changes with altitude of spectral shape of measured spectra. This simplifies the problem of spectral decomposition of AGRS spectra by limiting to six the number of spectral components needed to represent concentrations of K, U and Th in the ground.

The *spectral-fitting* procedure (Grasty, et al., 1985) can be seen as an extension of the three-window method to the whole spectrum. K, U and Th template or unit spectra are obtained from calibration experiment and must cover a range of survey altitudes. Airborne system calibration pads (Grasty et al., 1991) with varying thicknesses of plywood sheets to simulate the effect of altitude (Dickson et al., 1981; Minty et al., 1998) have been used for this purpose. The resulting spectra are resolved for K, U and Th, and for altitude variations (Dickson et al., 1981). They are analogs to the sensitivities of the window method. When fitted to a measure spectrum, the amplitudes of the fit yield the ground concentrations.

The workflow for the spectral fitting procedure is very similar to the required procedures of the window method. It involves a validation of the procedure through a calibration experiment, comparable to the pad tests and calibration flights of the standard approach (IAEA, 1991) and processing steps have analogs with steps of the window method. Implementation of this workflow should be straightforward as typical quality control procedures would be similar.

However, a limitation of the spectral fitting procedure is that spectral information contained in airborne spectra below 400–500 keV is not well reproduced in the unit spectra resulting from calibration pads experiment. The *skyshine* component, photons originating from the ground that are scattered back toward the detector by the atmosphere (Grasty, 1979a), isvery significant below these energies in AGRS data. The pads being of finite size do not produce a skyshine component of similar amplitude. The fit of the K, U and Th components to measured spectra is therefore very weak, and that portion of spectra is excluded from the fitting procedure. So, in effect, one sixth of the 0 to 3000 keV of the spectra, which corresponds to a much higher proportion of counts, is not used in the analysis.

Noise-adjusted singular value decomposition (NASVD) was introduced in AGRS (Hovgaard and Grasty, 1997) as a noise reduction procedure, and along with the Maximum Noise Fraction (MNF) method introduced in parallel (Dickson and Taylor, 1998), has proven to be very efficient in this capacity. NASVD is a purely statistical approach and its application to an AGRS data set results in a spectral decomposition from which measured spectra can be reconstructed. Low order components have more significance and as the order increases, the components start to represent only noise. By careful examination, the order above which remaining components represent only noise can be identified, and only the lower, significant components are included in the reconstruction, resulting in data in which noise is reduced. Usually, only the first six or seven spectral components contain significant information.

Noise-adjusted singular value decomposition offers more possibilities than just noise reduction as each significant spectral component represents a specific trend in the data set. The first component represents the average spectrum of the whole data set, but further component discriminate various effect that contribute to the shape of measured spectra. For example, a few components will describe variations in K, U and Th photopeaks in the data set. An appropriate mixture of these components will then allow reconstructing spectral shapes with varying proportions of K, U and Th that could be resulting from spatial variations in ground concentrations of K, U and Th or altitude variations during measurements. Similarly, the presence of atmospheric radon will results in spectral components describing its effect on the measurements (see Figure 5). Even any residual spectral drift of the spectrometer will be discriminated (Hovgaard and Grasty, 1997) in a component that can be used to include its effect on the measured data.

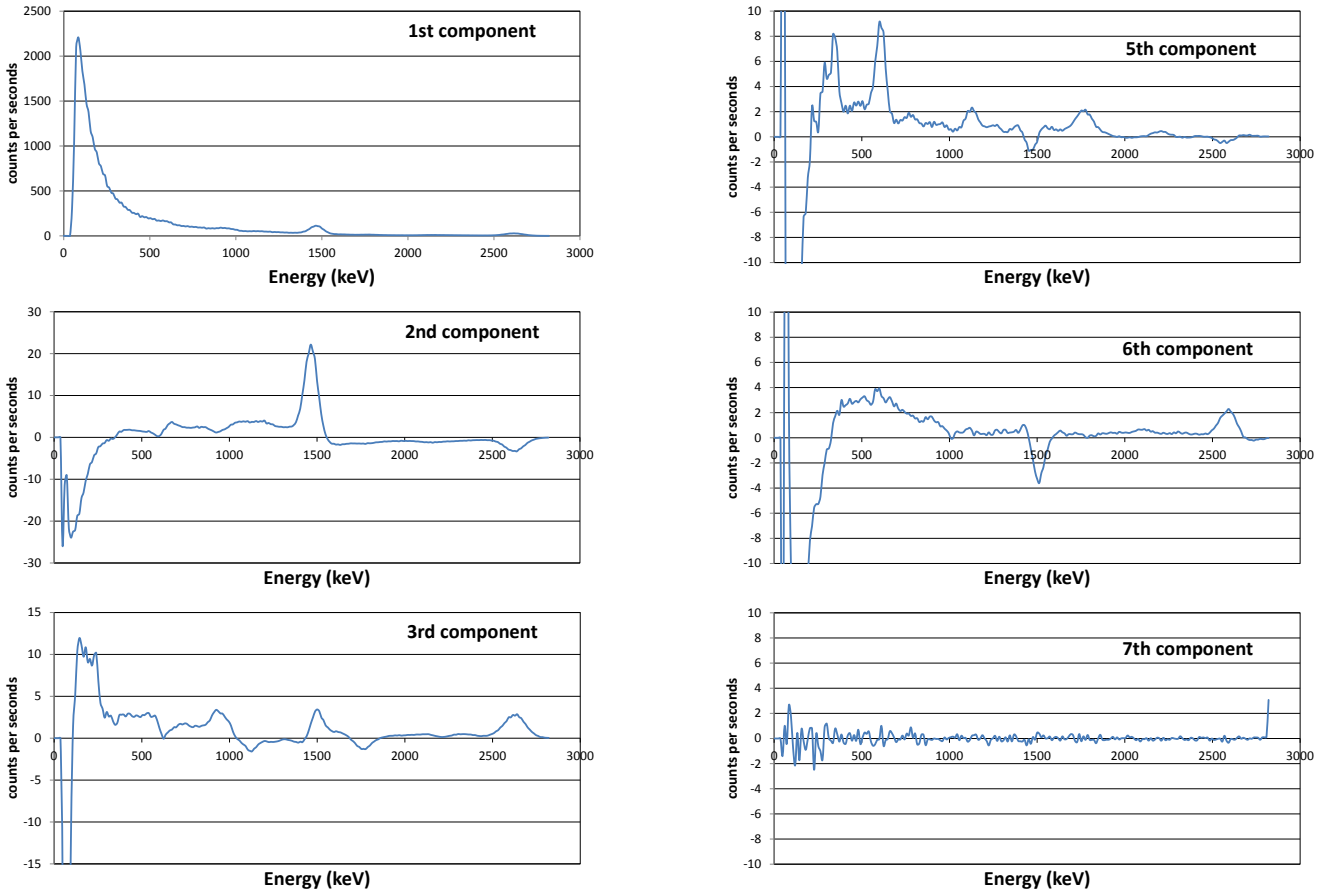

Figure 5: Example of an NASVD decomposition of airborne survey data. This figure presents the first seven components of the NASVD decomposition of the Miertsching Lake East AGRS survey data (Fortin et al., 2010). The 7th component appears to be mostly random noise and therefore components 1 to 6 were used for the reconstruction of the measured spectra. It can be easily seen that components 2, 3 and 6 are linked to K, U and Th concentrations in the ground and height attenuation effects, while components 4 and 5 represent the effect of atmospheric Radon; comparatively strong 352 keV, 609 keV and 1120 keV photopeaks, from ^{222}Rn decay chains imply proximity of the source to the detector.

An advantage of the NASVD method is that no a priori information is required on the data set for its analysis. Any effect creating changes in the spectral shape of the measured data will be identified in the component spectra. For example, if fallout material, like Cs-137, is present in the environment, it should be sorted in its own spectral component following application of NASVD. Moreover the whole energy range of the spectra can be included. As the skyshine component is represented in the AGRS survey data, it will be sorted as well in the resulting spectral components.

However, the spectral decomposition resulting from the application of NASVD has only a mathematical origin, and to be useful for further analysis of AGRS survey data, individual components have to be interpreted in terms of the physical context of the measurements. Processing and calibrating the NASVD components in a manner similar to the template spectra of the spectral fitting approach can prove interesting (Korsbech, et al., 1998) and bring the physical significance required to obtain K, U and Th concentrations information from the application of NASVD.

CONCLUSIONS

Airborne gamma-ray spectrometry is a mature geophysical technique that has seen many successful applications in mapping and resources exploration. The development and transfer to market of consistent and robust digital spectrometer systems over the last ten years has confirmed this statement even further. However, there is still a sense that the potential of AGRS data is

not being fully used and therefore enhancing AGRS end-products qualitative and quantitative readability should encourage its usage.

We suggested three themes in AGRS for which we believe efforts in development could be made. These choices are somewhat subjective but we are arguing that elements of solution, models and processes, are available. Combined with the renewed consistency of AGRS detection systems and the processing power now available to end-users, it could lead to tangible benefits. Other topics could have been reviewed and discussed, and Monte Carlo modelling, data inversion or imaging techniques and usage of Unmanned Aerial Vehicles (UAV) are all valid examples.

It can be noticed however that very similar issues were being discussed between these three topics and therefore, development on one side will very likely benefit the other sides, as well. In fact, a further objective should really be to combine these ideas in a single improved processing flow.

The success of AGRS is due in large part to well established, published and accepted guidelines that have been used worldwide, from regional mapping to property scale targeted surveys, with users ranging from government agencies to private industry. These de facto standards ensured a high level of consistency between surveys flown with different platforms for different goals. Any new development in AGRS should follow the same approach and lead to the establishment of guidelines that are both rational and practical. Pre-survey calibration or validation tests, regular and standard system's response check during survey operations and a robust and unequivocal data processing scheme that can be submitted to consistent quality control are all specific guideline elements that should be considered. This will ensure longevity of the data sets and optimize the extraction of useful information from AGRS survey in view of increasing exploration effectiveness and successes.

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