Processing of Aero Gamma-Ray Spectrometry data as 2D inverse problem

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SUMMARY

Standard processing of AGRS data is based on the well defined one-dimensional theoretical and empirical facts from gamma-ray physics and experience. In many cases it is quite satisfactory approach giving good new information for geology. However there are situations when 1D conditions are violated at least in one of essential parameter – flight altitudes, rugged topography, abrupt changes in source contents, even aircraft speed (because processing is mostly in time). These deviations might lead to wrong results. Here different approach to processing is suggested, which has some attractive features: it explicitly uses 2D model of topography and ground sources and implements the processing of AGRS data as solution of 2D inverse problem which seems pretty natural for processing the data acquired along the flight lines; it does not uses powerful smoothing of data, it shows spatial resolution – and does not lose the details arbitrary. Eventually it clearly shows that inverse problem of AGRS has no unique solution, that is silently implied by standard processing.

Key words: airborne, gamma-ray, spectrometry, inversion, processing.

INTRODUCTION

Well known standard processing of Aero Gamma-Ray Spectrometry data, AGRS, is substantially based on one-dimensional (1D) model of geological and geometrical parameters in the problem of gamma radiation (Airborne Surveying, 1991; Grasty et al, 1995). Even so, the problem is too complicated to have simple solutions, mainly because the radiation process is totally random and transport equation is very difficult to solve. It results in situation when we use a very few exact physical relations and a number of statistically justified rules to substitute thereto statistically volatile data.

However, there exist a lot of situations where 1D approach gives unreliable and uncertain results. Some of them can be improved by relevant corrections (Schwartz et al, 1992), but others can be unnoticed.

A solution which can be useful in a number of situations where 1D conditions are hardly exist is suggested below. It is two-dimensional (2D) inversion of raw flight data, based on well known formula for source point of gamma field of monoenergetic volume element of radiation (Minty, 1997; Kogan et al, 1969):

$$dI = \frac{A\,\varepsilon}{4\pi R^2} e^{-\mu_e r_e} e^{-\mu_a r_a} N dV \qquad (1)$$

where A = effective cross-sectional area of the detector
ε = photopeak efficiency of the detector for gamma-rays of energy E_0
μ_e, μ_a = linear attenuation coefficients for the Earth and air
r_e, r_a = the distances through the Earth and air,
$R = r_a + r_e$
N = photopeak intensity

Integrating the radiation sources on the ground along the flight line in [a, b] and across the line in [-w, w] gives the field of plain horizontal rectangle:

$$\frac{\mu_2}{Q} J = \frac{h(b-a)}{2\pi\mu_2} \int_0^1 \frac{B(v)\cdot dv}{\rho^2(v)} \int_0^1 \frac{e^{-\mu_1 \rho(v) C(u)}}{C^2(u)} du \qquad (2)$$

where J_r = field of horizontal rectangle,
a, b = width of the rectangle, along x, $a<b$, where x is along the flight line
B(v) = arsh($w/\rho(v)$)
C(u) = ch(B(v)u)
w = length of the rectangle, across x, on each side
Q = Q(A,ε,q), where q = concentration of radiation sources in ground, constant in depth

This equation can be easily used for approximation of any 2D topography, by simple rotation the coordinate system.

The number of strips that should be taken into account for the field value in the point of measurement can be estimated, for example, as the strip giving 96% or more of direct radiation. The number of strips depends on some important parameters: radiation energy, the length of strips across the line, on the flight altitude.

The visibility issue can be solved as follows. If far end of the strip is visible from the detector point then the entire strip is considered as visible and it is included into computation, if far end is not visible then entire strip is invisible.

Case study

This example shows a strong dependence of radiation fields on altitude, and how it looks in processing. The example is taken from survey in Europe. The flights were in hilly topography conditions, almost in mountains.

Digital Elevation Model is shown on Figure 1. Flight lines are in West-East direction, with nominal altitude of 80m for helicopter. Actual flight altitudes, as measured by radar, were from 50m to 450m, and these values were used for processing. The map of radar altitudes is shown on Figure 2, which shows that in Northern part of survey the altitudes are significantly higher than nominal on the number of lines. Also, in the middle part of survey area, there are a number of lines with acceptable but obviously increased flight altitudes.

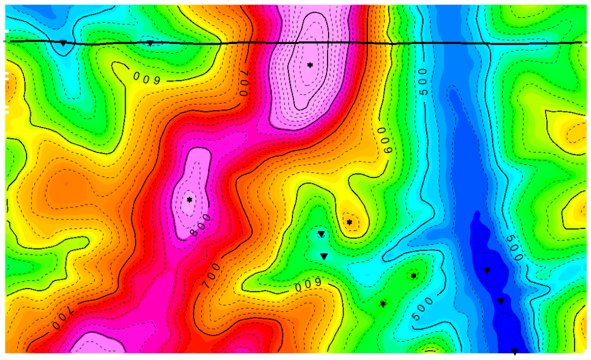

Figure 1. Digital Elevation Model. Topography changes from less than 400 m to more than 900 m. Lines were flown in West-East direction. One flight line is shown.

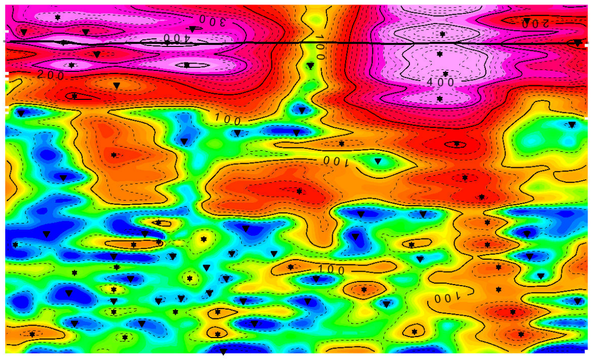

Figure 2. Radar altitudes of flight lines. The full range is from less than 50 m to more than 450 m.

The results of standard processing are shown on Figure 3 for K. It is very impressive that on the maps there is no visible relation between field and altitude of measurements; also there are visible great gradients of the fields in the direction of lines (maximal gradients on the area). Unfortunately, these details are wrong – no useful data could be measured on the altitude above 350m, especially above the river.

Now consider the solutions of inverse 2D problems shown on Figures 4 for K. The relation with flight altitudes is visible in several forms: (1) there is no great gradients along the flight lines - but there are gradients across the lines which is a consequence of independent solutions on the separate lines, and besides the solutions based on weak noisy data; (2) large values of solutions are related apparently with the lack of information from the ground, since even for very weak intensities on the highest altitudes very intensive radiation sources on the ground are needed; (3) even in the middle part of the area the line direction is visible – but the reason for this looks different: reduced spatial resolution in comparison with neighboring lines.

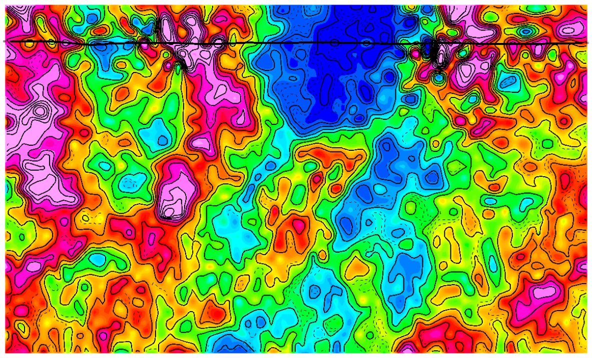

Figure 3. Potassium: standard processing. In the top part there are many details and strong gradients along the flight lines, which are not consistent with flight altitudes.

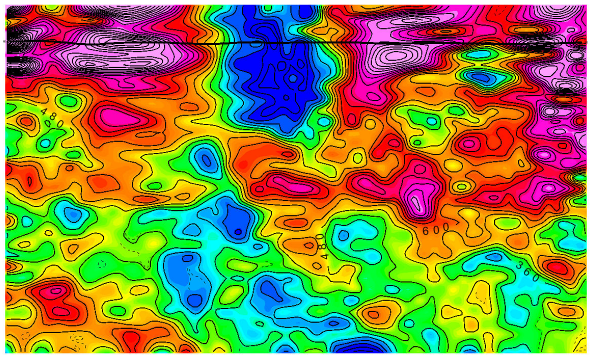

Figure 4. Potassium: inverse processing. In top part the largest gradients are across the lines because of uncorrelated solutions and interpolation. The increased values are the result of slightly positive input data.

One of the lines is shown on all the maps, and its fields are shown on the plots, Figure 5. The bottom plot shows the topography (brown) and GPS altitude (blue) in the same scale. Above this is the curve of flight altitude (cyan), which changes on this line from 26 to 436 m. The curve shows that reasonable data for ground radiation can be measured only in the middle and East parts of the line. Thin pink curve shows photopeaks of Thorium, while thick pink curve shows the 2D inverse solution for Thorium on the ground. Thin green curve shows energy window 'down' for Thorium, while thick green curve shows the standard solution for Thorium on the nominal altitude 80 m. It is seen that in the standard solution there is no relation with altitude, while inverse solution is closely related to the altitude. In this case, the spatial resolution can be estimated, e.g. via the number of extremums per unit length. Likely, in the areas of high flight altitudes, the inverse solutions not correlate to each other on the next lines because they depend not only on altitudes and topography but also on small changes of input data.

Calibration

With suggested 2D inversions the calibration over known areas can be done using simple operations. For the calibration were used the data measured at standard calibration Breckenridge test strip near Ottawa, Ontario, at June 2011.

The data were collected on lines flown over land and over water. Every set of lines was made on nominal altitudes from 200 to 900 feet, in every 100 feet. In terms of inverse problem, good calibration is possible if calculated ground concentrations are pretty similar for data from various altitudes.

Measured data are represented in the **Table 1** in form average/standard for the lines flown over land and water.

The water lines are over Ottawa River, and they are almost 1 km from the riversides. Therefore the water values in the table we consider as aircraft background, equal to 17.9 for Potassium, 1.7 for Thorium and 3.1 for Uranium.

Removing the aircraft background from all the measurement, we have the input data for inverse problems over the land, leaving over water only noise data. The inverse 2D solutions have statistics shown in the table in form average/standard:

Altitude feet	Potassium	Thorium	Uranium
200	1292/138	204/28	38/14
300	1277/141	208/22	39/11
400	1268/123	208/21	40/8
500	1245/141	213/27	47/16
600	1227/124	215/26	51/14
700	1232/168	198/42	55/19
800	1190/138	201/30	62/19
900	1202/175	191/39	61/17

Table 2. Statistics of 2D inversions for data described at Table 1. Left column: nominal altitude, feet. In columns there are averages/standard values for the lines. For Potassium and Thorium the results are reasonably good, i.e. almost constant as it should be. For Uranium, however, some additional correction (for Radon) is needed.

The table shows, calibrations for Potassium and Thorium can be made easily, however, for Uranium more thorough solution that includes Radon correction is needed.

DISCUSSION

I did not use measured values for attenuation factors - only approximate values computed via known air density with corrections for pressure and temperature. The precision of the air density is about 1% in energy range 0.1 to 3 MeV (Kogan et al, 1969). As input data I used simple photopeaks (Coetzee, 2009). Buildup factor is not taken into account because in AGS free path lengths in air are about 1 mean free path length, i.e. buildup process can be neglected.

Integration with Gaussian quadratures according to formula (2) needs a few nodes in each direction. For any reasonable sizes of strips and altitudes for relative error less than 1% it's enough to take 2-3 nodes along flight direction and 3-4 nodes across it. So Next Figures 6, 7 show a number of rectangles approximating the topography along the flight line:

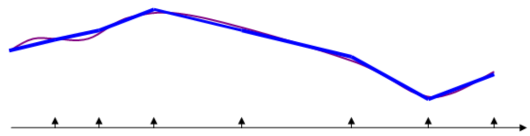

Figure 6. Continuous approximation of topography. Irregularity of strip widths is exaggerated in comparison with real. This model may be useful for wide strips or very irregular strips. In usual situations it results in more complicated computations without distinct advantage.

After all, it's time to call to mind that the inverse solution depends on a priori imposed suggestions about the solution. In this abstract so far was used only Tikhonov inversions with L-curve rule for regularization parameter (Press et al, 2007). Today it is the most famous and developed method to solve inverse problems.

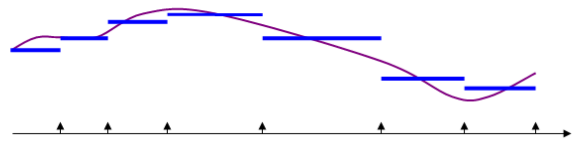

Figure 7. Approximation of topography, variant 2. Vertical surfaces are not shown because considered as not radiating. This model simplifies computations and even makes the inversions more stable.

There are also other interesting methods. E.g. using total variation stabilizers (instead of Tikhonov stabilizers) will result in step-wise solutions (like blue curve on Figure 7), where locations of jumps are not set a priori. As maps, such solutions are similar to standard or inverse solutions, while on the plots they might give unique geological information of another kind.

One more approach is to model ground sources of radiation by spikes on smooth background (e.g. Courbin et al, 2000). This solution is the result of iterations (instead of stabilizers) and is interesting in that it really needs using the resolution of spectrometer. One useful example of such solution was related with outliers in the moraine area.

CONCLUSIONS

Advantages of the above approach are in several aspects. First, input data don't need preliminary processing - equivalent actions are explicitly (e.g., air density) or implicitly (e.g. smoothness of solution) included in problem formulation. Many irregular situations are resolved automatically – topography influence, flight speed, flight altitude, uneven distribution of sources on the ground. Calibration can be done more or less accurately. The processing is quite the same for any energy, and can be largely automated.

The solutions can be smooth, step-wise, peak-wise, according to geological problem, survey parameters and interest of interpreter.

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Flight Altitude, ft(m)	Potassium		Thorium		Uranium		Data points	
	Land	Water	Land	Water	Land	Water	Land	Water
200(64)	219/30	17.3/7.2	40/9.4	1.6/2.0	8.4/7.2	2.9/3.1	147	111
300(92)	175/23	18.8/7.1	35/7.5	1.7/1.8	8.0/6.9	3.1/3.3	145	100
400(123)	141/21	17.2/6.5	29/7.0	1.6/1.8	6.8/6.2	3.0/3.6	151	115
500(156)	113/19	17.9/7.6	24/6.4	1.7/2.1	6.3/5.8	2.4/2.5	143	101
600(188)	91/17	17.9/7.2	21/6.8	2.0/1.9	5.4/5.2	3.5/3.2	151	113
700(214)	78/15	18.5/5.9	17/6.3	1.6/2.0	5.1/4.8	3.0/2.9	142	97
800(245)	65/14	17.3/7.7	15/5.5	2.1/1.9	5.0/4.8	3.3/3.4	152	115
900(276)	56/12	18.0/7.1	12/4.4	1.6/1.9	4.1/4.3	3.5/3.6	137	102

Table 1. Statistics of calibration flights. Left columns: nominal altitudes, feet, and actual, meters. In K, Th, U columns, every subcolumn (Land or Water) contains line's averages and standards separated by slash. The Water subcolumns actually show the almost constant values considered as aircraft background, equal to 17.9 for Potassium, 1.7 for Thorium and 3.1 for Uranium. Subtracting the background values from Land data and making 2D inversion gives the average data in Table 2.

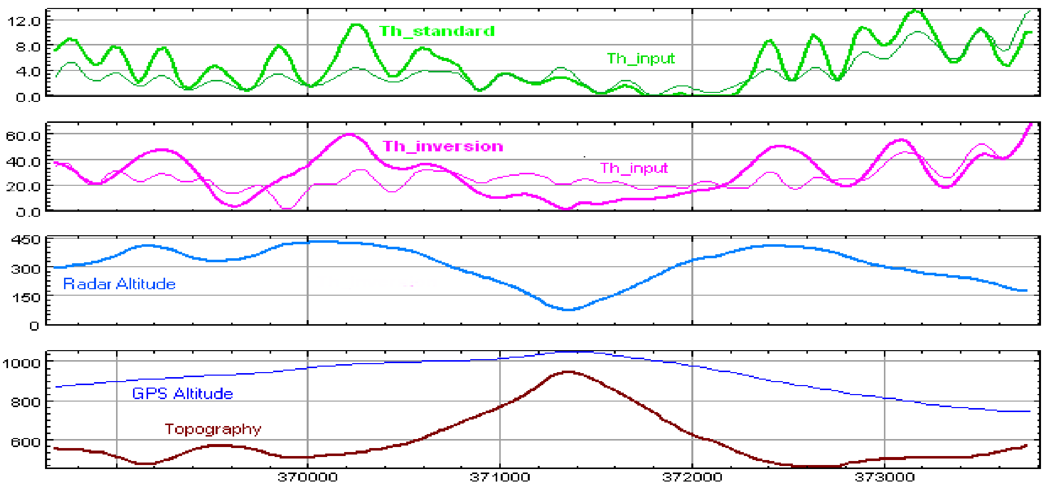

Figure 5. The line shown on the maps. Bottom: topography (brown) and GPS altitude (blue) in the same scale. Above, flight altitude (cyan), it changes from 26 to 436 m and shows that reasonable data can be measured only in the middle and East parts of the line. Thin pink - photopeaks of Thorium(a bit smoothed), thick pink - 2D inverse solution on the ground. Thin green - energy window 'down' for Thorium(a bit smoothed), thick green - standard processing to nominal altitude 80 m. It is seen that in the standard solution there is no relation with altitude, while inverse solution is closely related to the altitude. In this case, the spatial resolution can be estimated, e.g. via the number of extremums per unit length.