The effects of density contrast surfaces on Airborne Gravity Gradiometry (AGG) data interpretation

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SUMMARY

The accessibility of high-powered computers, plus readily available and detailed topography, allows the explorer to account for the effect of terrain in gravity and gravity gradiometry surveys applied to highlight subterranean density variations.

Similarly, accounting for other known density contrasts can further enhance the geological understanding of a survey area. The bedrock/overburden interface, lake depth and snow thickness can be mapped to provide 3D geometric surface models. The gravity gradient responses of these surfaces are presented.

Overburden and lakes are shown to have significant influence on the survey data. The effect of snow cover on survey data was found to be negligible. However, it may be important for the next generation of airborne gravity gradiometer instruments.

Key words: Gravity, gravity gradient, modelling, density, snow, lakes, overburden

INTRODUCTION

Airborne gravity gradiometry (AGG) surveys are influenced by density contrasts. To date, the only systematic process to account for any density contrast is based on the air/ground interface applied using topography and some assumption about the terrain density, i.e. terrain correction. With no ancillary information, this density contrast is usually assigned a value of the average earth density (2.67 g/cm^3), and typically little consideration is given to other possible density inputs.

Nettleton (1939) provides a solution for optimising the density to use in terrain corrections. Following on from Nettleton's work, a multi-surface density decorrelation program was developed to determine the most appropriate terrain correction density. The default terrain correction will be compared with this improved method using real-world datasets.

Other density contrast surfaces can have an appreciable effect on the interpretable data. Some of these density contrasts can be mapped and defined and include overburden, water bodies and snow accumulations.

Fugro Airborne Surveys HeliFALCON^{TM} system measures the gravity gradient from a helicopter platform. The deliverable survey product includes the vertical gravity gradient (G_{DD}) before and after terrain corrections. The terrain model used in data processing is based on aircraft-mounted laser scanner data (LiDAR). A homogeneous terrain density to be used in data processing can be nominated, however there is no assertion that this density represents the true bulk density.

Michigan

A helicopter-borne AGG survey was flown over the Rio Tinto Eagle Project ground in the Upper Peninsula of Michigan during the winter of 2012. The known ore body is a high grade magmatic nickel-copper massive sulphide deposit hosted by a Mesoproterozoic peridotite and pyroxenite intrusion. A second intrusion of similar composition occurs some 800 m to the east and forms a ~15 m topographic high above the surrounding plains. The plains are the result of the last glacial period with variable till cover having an average depth to bedrock of 40 m.

A total of approximately 1600 line kilometres were flown along a north/south heading with a traverse line spacing of 100 m and a minimum drape height of 35 m. At the time of data acquisition, accumulations of snow were present with unknown thickness. A second LiDAR survey was flown once the snow had melted, and this was used in terrain corrections allowing for comparisons of AGG data with and without the effects of snow. Depth to the bedrock/overburden interface was determined using known drill hole intersects and an independent method not described in this paper.

Labrador Trough

A helicopter-borne AGG survey was flown over the Rio Tinto Exploration iron prospect in the southern Labrador Trough of Canada during the spring of 2012. Iron mineralisation is hosted by an extensively deformed and metamorphosed oxide facies of the Paleoproterozoic Sokoman Iron Formation. The Formation is dominated by the iron oxides hematite and magnetite and quartz (chert) with accessory carbonates, silicates and occasionally manganese oxides or carbonates. Within the survey area is an extensive network of waterways and lakes with unknown water depth.

A total of approximately 1200 line kilometres were flown along a north-west/south-east heading with a traverse line spacing of 150 m and a minimum drape height of 50 m.

METHOD

A component of the observed gravity gradient is correlated to the response of the topography and must be removed from the observed signal, by way of terrain correction, to allow for meaningful interpretation. Typically, a standard bulk density of 2.67 g/cm^3 is used in this process. The terrain density that gives a minimum correlation between the terrain effect and the residual signal can be derived. A script was developed to determine the Pearson correlation coefficient (r) between the residual and terrain effect for a range of terrain densities. The density leading to zero correlation is deemed the most suitable for data processing purposes.

Given overburden depth information, it was possible to extend the optimisation routine to systematically determine the ideal pair of bedrock/overburden densities. As there are multiple pairs of densities that lead to a zero-value (r), the variation of signal in the residual (standard deviation) was also minimised. The intersection of zero correlation and minimum residual signal was considered to be the optimum density pair (Figure 1a).

Where snow is present in a survey area, the LiDAR scans the top surface of the snow and not the true ground. In standard terrain corrections, all material below the LiDAR surface is assigned a uniform density. Not accounting for variable low density (<1 g/cm^3) snow accumulations can therefore lead to an overestimation of the terrain, resulting in erroneous negative anomalies where snow has gathered. By approximating the accumulated snow depth, it was possible to model the gravity gradient of the volume between the true ground and the surface of the snow and reduce the error in the processed data.

Just as the observed gravity gradient is correlated to the response of the topography, it will also be correlated to lakes and other water bodies with depth extent. Since LiDAR scans the water surface, any water body will be modelled with flat topography. A terrain correction, performed without considering the effect of low density lake water with variable depth extent, results in an overestimation of the mass that is corrected. This overestimation leads to an artificial gravity low in the residual. In the absence of accurate bathymetry data, the depth of a lake was simulated and its effects removed from the terrain corrected data.

RESULTS AND DISCUSSION

Michigan

Topography

Using the decorrelation algorithm, an optimum terrain density of 1.83 g/cm^3 was calculated. Figure 2 (a-f) shows the LiDAR DTM model and the terrain correction using the default (2.67 g/cm^3) homogeneous terrain density. Figure 2 (g-i) shows the G_{DD} residual using the optimum terrain density. The difference between the residual signals using the default and optimised densities has a range of 145 Eö and a standard deviation of 15 Eö.

The colloquially known "Bermuda Triangle" forms a triangular shaped topographic high. In the default terrain corrected G_{DD} results, it formed a gravity low suggesting an over-correction for topography (Figure 2d). The difference in the G_{DD} effect between default and optimum terrain density corrections has a range of approximately 50 Eö.

The Salmon Trout River incises the plains forming a topographic low. In the default terrain corrected G_{DD} results, it formed a gravity high suggesting an under-correction for topography (Figure 2e). The difference in the G_{DD} effect between default and optimum terrain density has a range of approximately 50 Eö.

The ~15 m high topographic feature sitting above the plain is expected to remain anomalous in both the default and optimised G_{DD} residuals. The difference in the G_{DD} effect between default and optimum terrain density corrections has a range of approximately 5 Eö. This suggests that the optimisation routine appropriately removes topographic effects and retains uncorrelated responses.

Bedrock

While 1.83 g/cm^3 was determined as the optimum terrain density, the use of a single earth density in terrain corrections is generally an oversimplification of the density character of a survey area.

Using the available depth to bedrock data, two distinct density contrast surfaces were recognised; air/overburden and bedrock/overburden. The gravity gradients for each of these were determined. The same decorrelation algorithm was run and optimal densities of 1.8 g/cm^3 for overburden and 2.3 g/cm^3 for bedrock were calculated. The difference in the G_{DD} effect between default and optimised bedrock/overburden density corrections has a range of 150 Eö.

Note the similarities between the G_{DD} effect of optimised terrain corrected result in Figure 2 (g-i) and the bedrock/ overburden corrected result in Figure 2 (j-l). This can be partially explained by the fact that the majority of the corrected effects with wavelengths shorter than about 400 m are due to the overburden, as seen in the power spectra in Figure 1b.

Snow

Winter and summer DTMs were compared and the differences primarily attributed to snow thickness (up to 2 m). The gravity gradient of the volume between each DTM surface was determined along the survey flight lines. The overall snow effect is less than several Eötvös across the survey area (Figure 3). In this instance, these results suggest that the uncertainty in the signal due to snow can be appropriately ignored (standard deviation = 1.1 Eö) for current gravity gradiometry instruments. However, this might not always be the case for future technologies.

Labrador Trough

Lakes

In the default gravity gradient data, there was an apparent gravity low coincident with a lake. To simulate the erroneous lake effect, a virtual lake floor with a maximum depth of approximately 30 m was created assuming continuous terrain based on the slope of the ground at the lake edges. Accounting for the simulated lake depth in processing shows significant changes (range = 50 Eö) to the interpretable results (Figure 4). Modelling has shown that water bodies can have an appreciable effect on data and must be accounted for to maximise the accuracy of results.

CONCLUSIONS

The most significant density contrast surface, the air/topography interface, is accounted for in terrain correction processing. While a single density in terrain correction is likely an oversimplification of the density character of a survey area, the decorrelation algorithm developed here provides an optimum density for use. In the Michigan example, the calculated optimum density is close to that calculated for overburden, implying that the effect of the bedrock/overburden density contrast is significant. The 150 Eö range of the effect of the optimised bedrock/ overburden contact has been shown to significantly alter the interpretable result when compared with the default terrain corrected residual.

The effect of snow accumulations less than 2 m thick are shown to be insignificant to the current generation of airborne gravity gradiometry systems. However, greater snow thicknesses may be significant, particularly for the next generation of gravity gradiometry systems measuring to greater sensitivity.

Erroneous gravity lows can exist over lakes in the default terrain corrected gravity gradient data and corrections for the lake depth should be considered for accurate results. In some cases, it may be necessary to collect bathymetry data to produce an accurate geometric model for input in to the optimisation routine.

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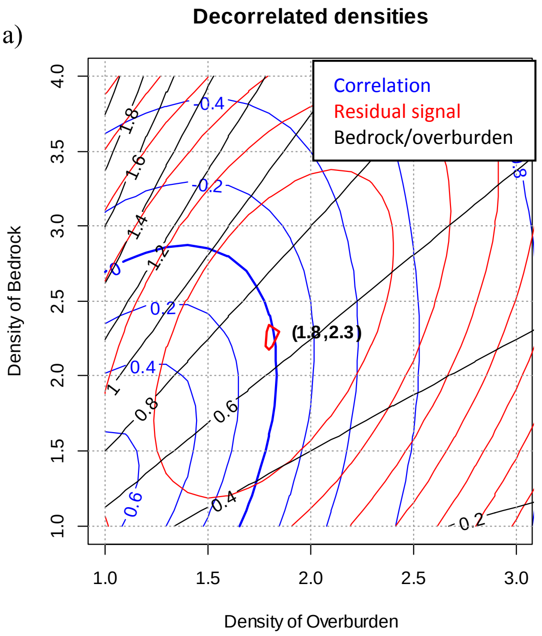
a)



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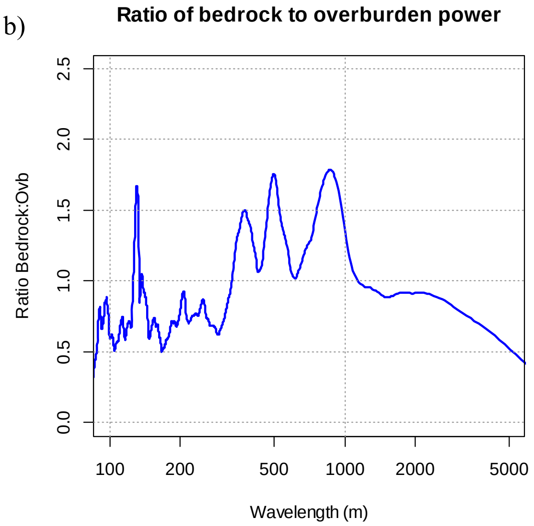

Figure 1. a) The correlation relationship between the total corrected effect of the bedrock/overburden and the residual signal. The blue lines represent the Pearson correlation coefficient (r) between the residual and terrain effect for a range of bedrock/overburden densities. The line of zero correlation is highlighted in bold blue and is deemed the most suitable for data processing purposes. As there are multiple pairs of densities that lead to a zero-value (r), the variation of signal in the residual (standard deviation) was also minimised, shown in the red lines. The intersection of zero correlation and minimum residual signal was considered to be the optimum density pair (2.3 and 1.8 g/cm^3 for bedrock and overburden respectively). The ratio of the standard deviation of the bedrock response to that of the overburden response is plotted in black. Where the ratio is <1, as is the case here, the contribution of the overburden to the total corrected effect is larger than that of bedrock. b) The ratio of the bedrock to the overburden, showing that the bedrock becomes dominant at wavelengths greater than about 400 m.

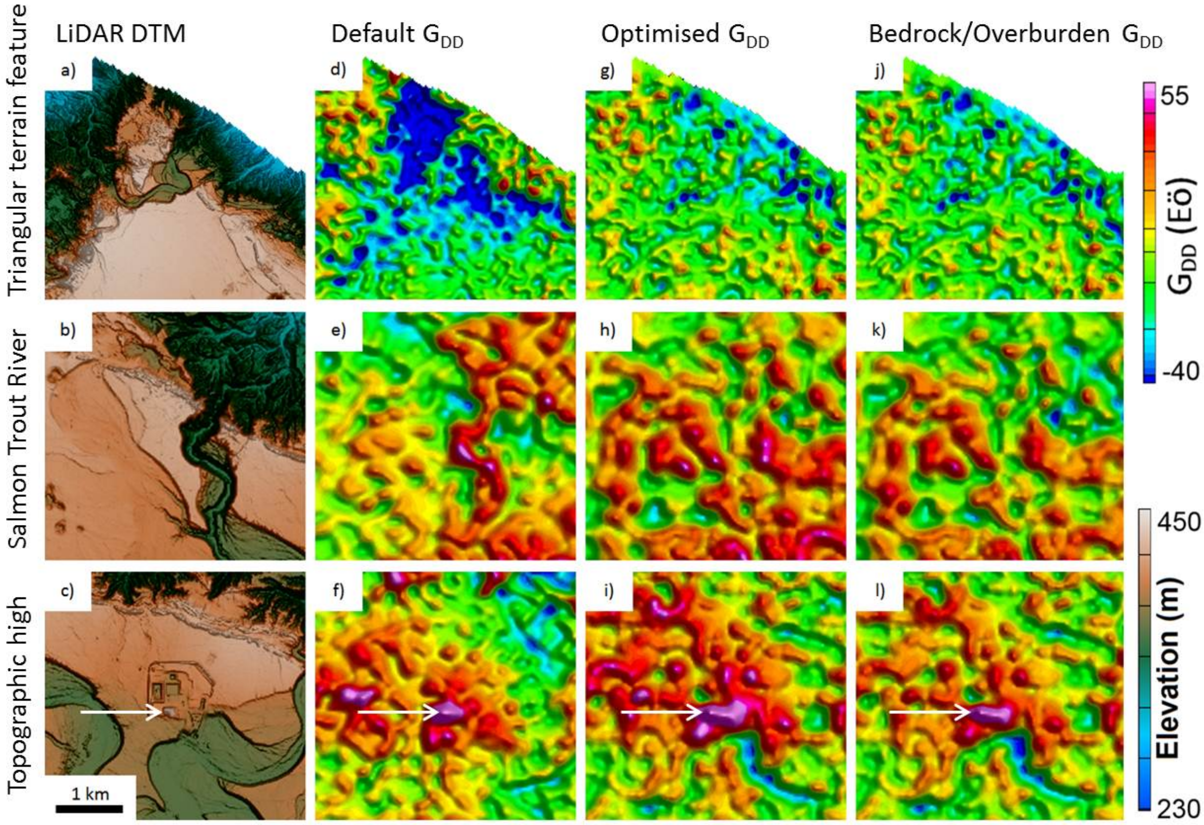

Figure 2. First row: Triangular terrain feature. Second row: Salmon Trout River. Third row: Topographic high sitting ~15 m above the plain (arrow). a-c) Digital Terrain Model (DTM) acquired by LiDAR. d-f) Default G_{DD} terrain corrected data (2.67 g/cm^3). g-i) Optimised G_{DD} terrain corrected data (1.83 g/cm^3). j-l) Optimised G_{DD} bedrock/overburden corrected data (2.3 and 1.8 g/cm^3 respectively).

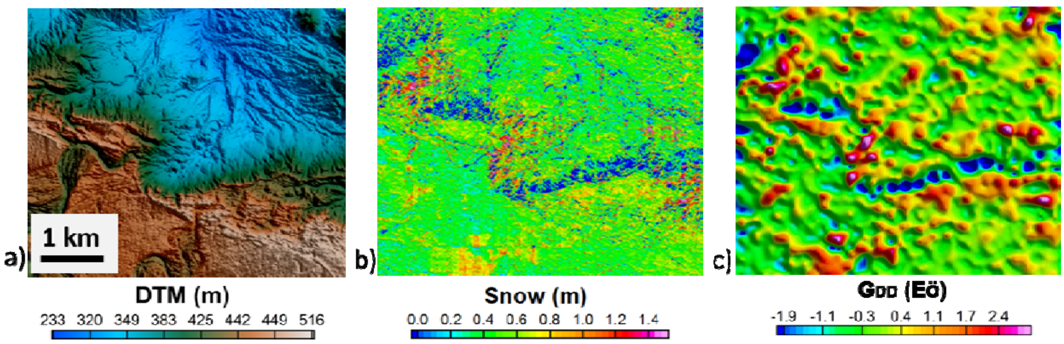

Figure 3. a) DTM acquired by LiDAR during summer. b) The depth of snow accumulations, based on the difference between winter and summer acquired LiDAR terrain models. c) The overcorrection in G_{DD} due to not accounting for snow accumulation.

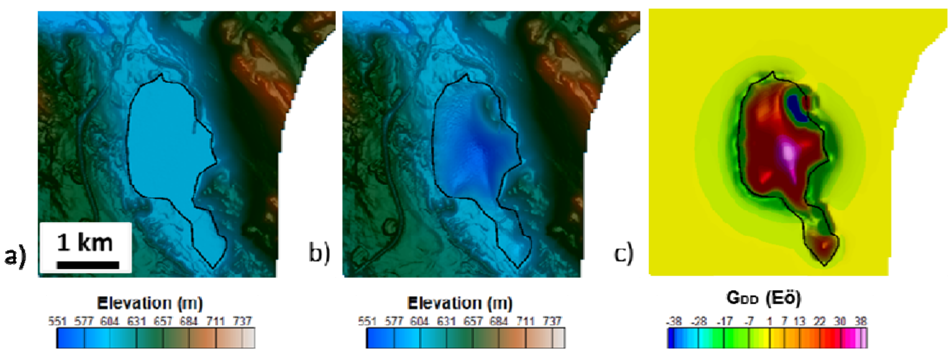

Figure 4. a) DTM acquired by LiDAR showing the lake (outline). b) DTM with simulated lake floor. c) G_{DD} effect of the lake.