Falcon vs FTG - Estimating Precision and Accuracy of Airborne Gravity Gradiometers

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SUMMARY

As more commercial airborne gravity gradiometer systems enter the market for exploration, a common method needs to be found to compare the results from each of the systems. While each of the systems has a different design, they all produce the same output tensor data. Two methods will be evaluated as means to estimate precision and accuracy. The odd-even difference technique will be used for the precision analysis and the ground truth technique will be used for the accuracy analysis. The precision of the FTG system using an open-source dataset will be shown to be 9.2E using the odd-even difference technique and the precision of the Falcon system using a comparable open-source dataset will be shown to be 1.9E. The accuracy of the Falcon system will be shown to be 1.39 mGal using the ground truth technique; there was no comparable ground data for the FTG area, so it could not be used.

Key words: Falcon, FTG, precision, accuracy, AGG.

INTRODUCTION

Airborne gravity gradiometry continues to be one of the most important tools in geophysical exploration. The high-resolution gravity and gravity gradient data produced by an airborne gravity gradiometer (AGG) can be used to identify anomalies from across the exploration wavelength spectrum. Each system employs different techniques to estimate the inherent noise of the acquired data, but none of these measurements can be used commonly across all the different systems. For anyone using the gravity gradient data for exploration purposes, these noise measurements can be confusing and do not relate directly to the final data products they will be using in further interpretations. In this paper, we will explore common methods to estimate both precision and accuracy of any type of AGG system that relates to the final tensor data.

AIRBORNE GRAVITY GRADIOMETERS

There are currently three types of commercial AGG systems used in airborne exploration: the FTG design, the Falcon design and the e-FTG design. All systems were developed by Lockheed Martin and are rotating disc gradiometer systems employing pairs of accelerometers equally spaced around rotating discs.

FTG

This is the historical starting point for all the Lockheed Martin gravity gradiometers that was used in US Navy submarines for navigation and with the US Airforce for the first set of airborne testing (Lee 2001). The design incorporates 3 rotating discs aligned orthogonal to each other and inclined from the horizontal axis at an angle of about 35^{o} (Veryaskin 2018). There are two pairs of accelerometers on each disc that deliver in-line gradient and cross-gradient measurements. Each disc is called a Gravity Gradiometer Instrument (GGI). These in-line gradients and cross-gradients from each GGI are transformed into the gradient tensor data via a series of linear transformations (Brewster 2016). The linear series of equations used to generate the gravity gradient tensor data is shown in Equation 1, where i_n and c_n are the in-line and cross measurements from each of the 3 GGIs, $\alpha_2 = 1/\sqrt{2}$ and $\alpha_3 = 1/\sqrt{3}$.

$$\begin{pmatrix} i_1 \\ i_2 \\ i_3 \\ c_1 \\ c_2 \\ c_3 \end{pmatrix} = \begin{pmatrix} 0 & -\alpha_2\alpha_3 & -\alpha_2 & -{}^1\!/_2\,\alpha_3 & {}^1\!/_2 \\ 0 & -\alpha_2\alpha_3 & -\alpha_2 & -{}^1\!/_2\,\alpha_3 & -{}^1\!/_2 \\ 0 & {}^{\alpha_3}\!/_{\alpha_2} & 0 & \alpha_3 & 0 \\ {}^1\!/_2 & \alpha_2\alpha_3 & -{}^1\!/_3\,\alpha_2 & -\alpha_3 & -{}^1\!/_3 \\ {}^1\!/_2 & -\alpha_2\alpha_3 & -{}^1\!/_3\,\alpha_2 & \alpha_3 & -{}^1\!/_3 \\ {}^1\!/_2 & 0 & {}^{\sqrt{2}}\!/_3 & 0 & {}^2\!/_3 \end{pmatrix} * \begin{pmatrix} G_{zz} \\ G_{xz} \\ G_{yz} \\ G_{xy} \\ G_{uv} \end{pmatrix}$$

Equation 1 - FTG Transformation matrix from measurements to gravity gradient tensor data.

FALCON

In the early 90's, BHP undertook an extensive feasibility study to optimise the performance of the FTG systems for airborne exploration (Dransfield 2004). The operational environment inside a submarine is vastly different to that of an aircraft. An aircraft will undergo significantly more vertical acceleration due to the turbulent conditions of low-level survey operations. This increased vertical acceleration translates as noise that requires rejection from the FTG data measurements. BHP's design improvements were to focus on one GGI that is larger and nearly horizontal. The larger disc allows for both increased separation between the accelerometer pairs decreasing the noise in the gradient measurement and the addition of another set of accelerometer pairs onto the same disc creating two near-independent gravity gradiometers measuring the same signal. The second set of data allows for both noise reduction from averaging the result and a noise estimation at each data point. In this orientation, the measurements are the G_{xy} and G_{uv} tensor components. These are transformed into the gradient tensor via a series of Fourier transformations. The series of Fourier transformations used to generate the gravity gradient tensor data is shown in Equation 2, where AB_{xy} and AB_{uv} are the averaged measurements of the measured G_{xy} and G_{uv} components from each GGI accelerometer pair and k_x and k_y are the wave numbers in the Fourier domain.

$$\begin{bmatrix} G_{xx} & G_{xy} & G_{xz} \\ & G_{yy} & G_{yz} \\ & & G_{zz} \end{bmatrix} = F^{-1}\left(\frac{-2i}{(k_x - ik_y)^2} \begin{vmatrix} -k_x{}^2 & -k_xk_y & -k_xk_z \\ & -k_x{}^2 & -k_yk_z \\ & & -k_x{}^2 \end{vmatrix} * F\left[AB_{xy} + iAB_{uv}\right] \right)$$

Equation 2 - Falcon transformation matrix from measurements to gravity gradient tensor data.

eFTG

In the 2010's, Lockheed Martin developed a new FTG design that incorporates 3 of the Falcon style GGIs into the FTG design. The same set of linear equations as the FTG (Equation 1) are used to generate the gravity gradient tensor data. This design allows for the in-line and cross gradient measurements from the FTG design and the dual set of nearly independent GGI measurements from the Falcon design. These improvements result in a processing noise floor that is 1/3 that of the FTG design (Richards 2017).

PRECISION AND ACCURACY

Precision and accuracy are terms that are often used interchangeably in exploration; however, they are different qualities as shown in Figure 1. The precision of the gradiometer data will be a measure of the repeatability of the measurements. The precision of the data will increase as the standard deviation of a repeatability analysis decreases. The accuracy of the gradiometer data will be a measure of the closeness to the true value of the measurements. The accuracy will increase as the standard deviation of a trueness analysis decreases. To fairly compare these systems, we require similar examples of their data and common precision and accuracy estimation methods.

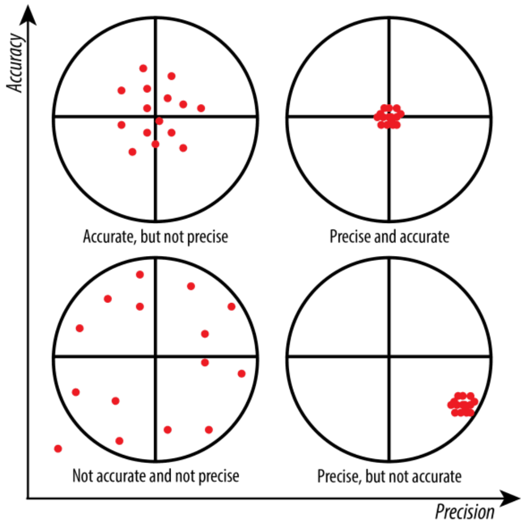

Figure 1 – Visual representation of the differences between precision and accuracy

ANALYSIS DATA

At publication of this article, there are no open-source examples of eFTG data, so it will not be considered in the comparison. As the output data will be the same as the FTG data, the common precision and accuracy estimation methods detailed here will apply to the e-FTG. Using these, once there is open-source data available from an e-FTG survey its results can be incorporated into these results. For the FTG dataset, a 500m line spaced survey flown in 2012 for Natural Resources Canada over the Bay St. Georges in Newfoundland and Labrador, Canada was chosen (Bell 2013). The final vertical gravity gradient results for that survey can be seen in Figure 2. For the Falcon dataset, a 500m line spaced survey flown in 2018 for the Geologic Survey of Victoria over the Otway Basin in Victoria, Australia (Xcalibur 2019) was chosen. The final vertical gravity gradient results for that survey can be seen in Figure 3. The dimensions of the survey are quite dissimilar, thus a subset of the survey for the Falcon dataset will be used for the images. The area chosen for the subset is shown in Figure 4. For this analysis, the terrain corrected vertical gravity gradient data of each area will be used.

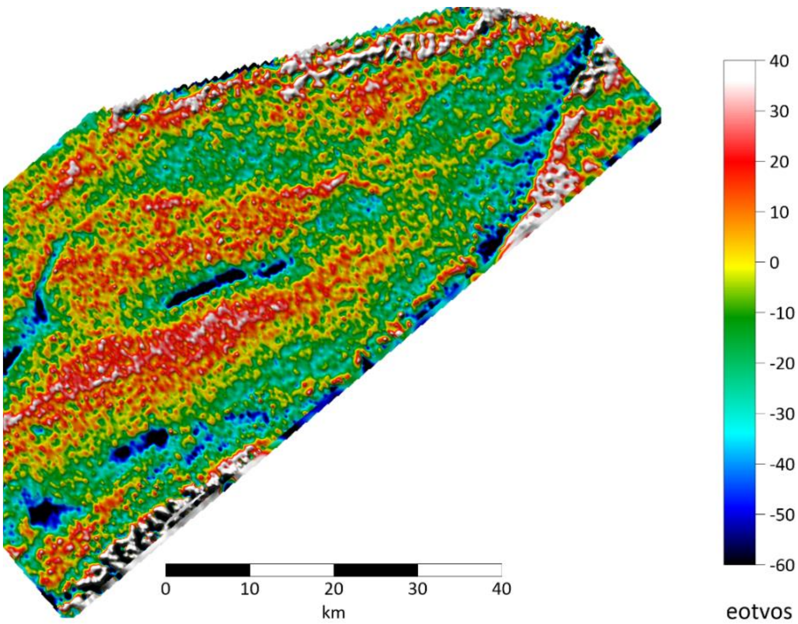

Figure 2 – Terrain corrected, vertical gravity gradient data from an FTG survey over the Bay St Georges survey area (Bell 2013).

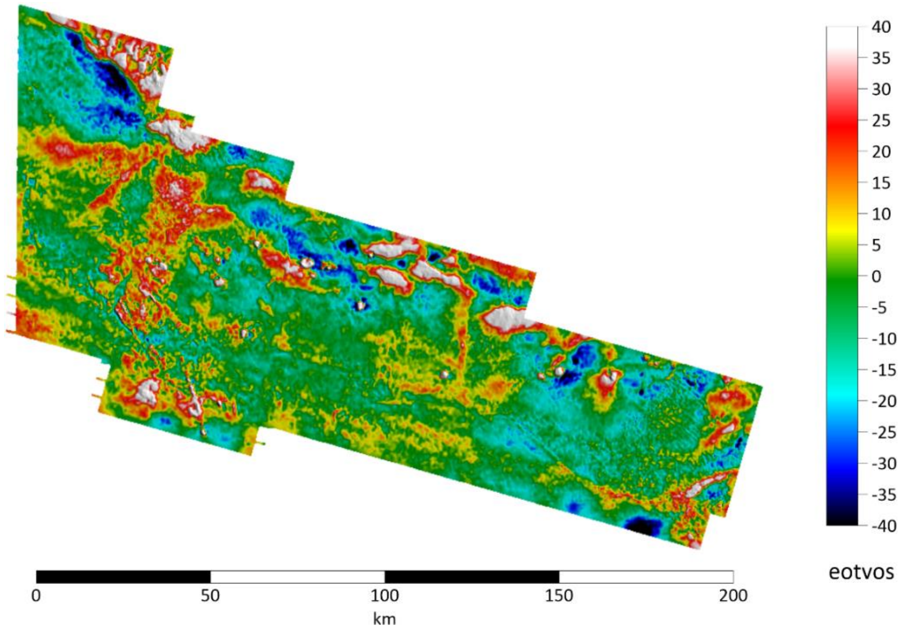

Figure 3 – Terrain corrected, vertical gravity gradient data from a Falcon survey over the Otway Basin survey area (Xcalibur 2019).

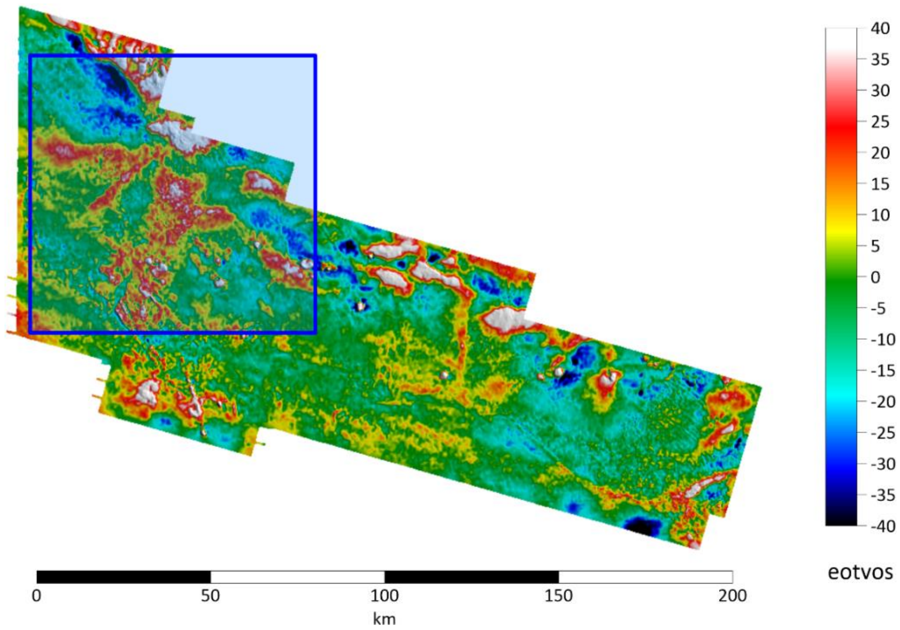

Figure 4 - Subset of the Falcon survey area that will be used to create a similar sized dataset to use for demonstration images.

PRECISION ANALYSIS

As precision is an estimate of the repeatability of a measurement, the best precision test would be to have two full passes of the same survey area; however, this would not be very economical in execution. Instead, the precision can be estimated using an odd-even difference analysis (Sander 2002). Using each dataset, the data is split into one dataset using the even numbered lines and another using the odd numbered lines. This effectively simulates having flown the survey twice, but at double the original line spacing. The two grids are then differenced, and the odd-even difference repeatability value is taken as ½ of the standard deviation of this difference grid. In this case, each survey would now have two datasets at a 1000m line spacing over the same area. The results from the FTG area using the odd and even lines are shown in Figure 5. The results from the Falcon area using the odd and even lines are shown in Figure 6. The difference of each of these subsets was taken (Figure 7) and the odd-even difference results are 9.2E for the FTG area and 1.9E for the Falcon area.

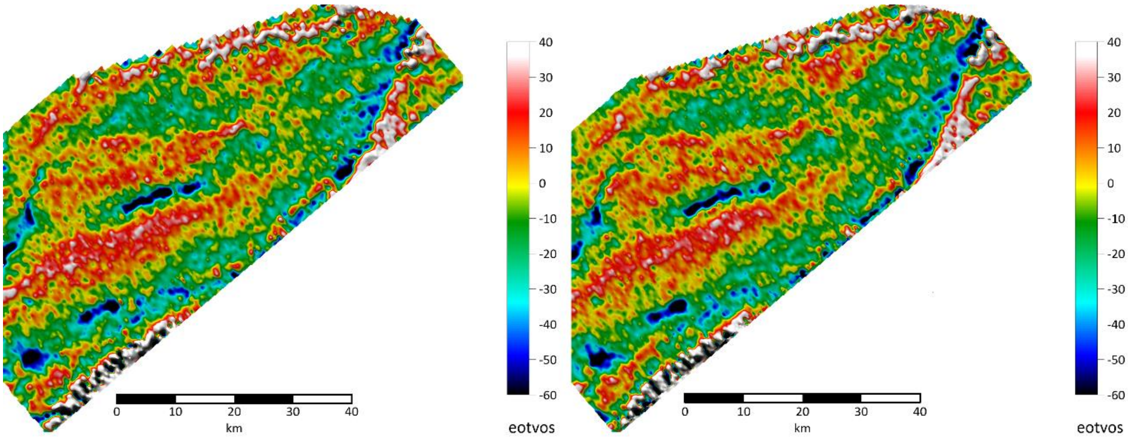

Figure 5 – The terrain corrected, vertical gravity gradient results from the FTG dataset using the odd lines (left) and using the even lines (right).

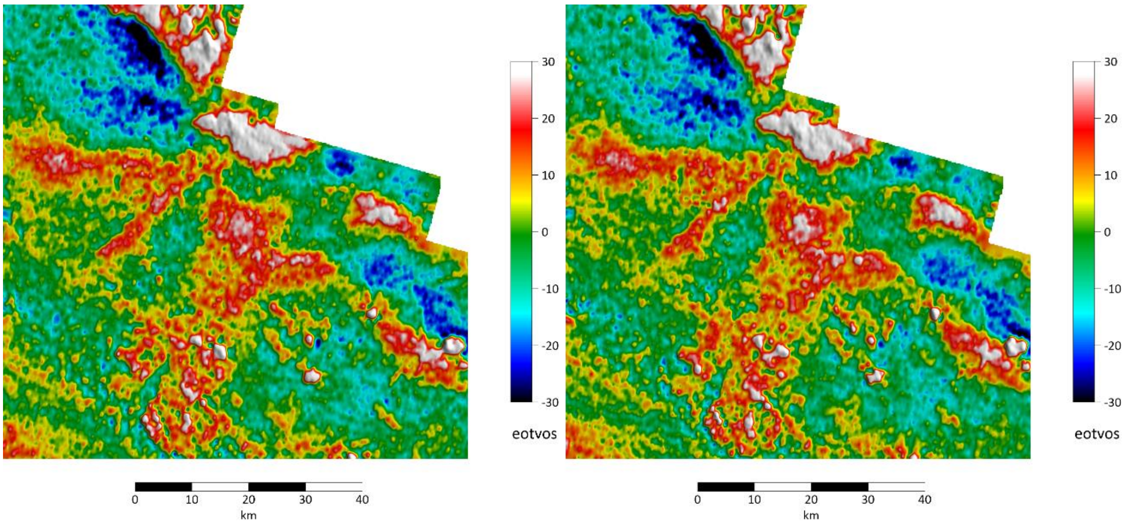

Figure 6 - The terrain corrected, vertical gravity gradient results from the subset Falcon dataset using the odd lines (left) and using the even lines (right).

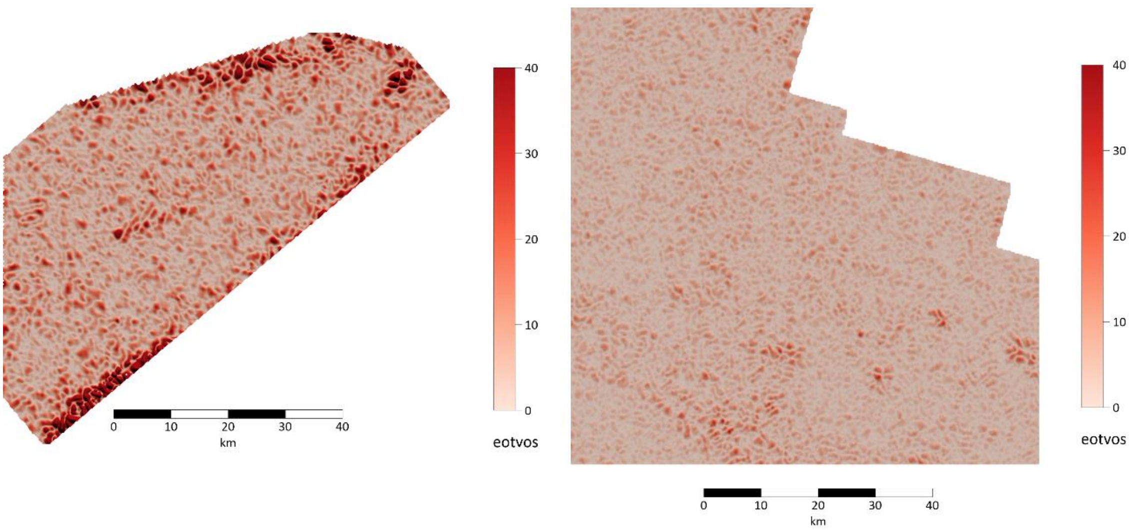

Figure 7 – The results of the odd-even difference analyses. The absolute value of the difference grids was used to simplify the visual representation. The FTG odd-even difference results were 9.2E (left). The Falcon odd-even difference results were 1.9E (right)

ACCURACY ANALYSIS

As accuracy is an estimate of the trueness of a measurement, the best accuracy test would be to have a survey flown over a known quantity; however, this would require having a geophysical tool that can provide an exact measurement of gravity or gravity gradient. Instead, the accuracy can be estimated using a ground truth analysis (Christensen 2014). Within the Falcon survey area, there are around 11,000 ground gravity readings (Figure 8). There are no other sources of gravity data within the FTG area, so this accuracy analysis will focus on the Falcon data. Calculating the vertical gradient of ground data can introduce noise because of the non-regular spacing of the data points. In order to avoid this noise from biasing the results, the vertical gravity data will be used to estimate accuracy. The ground data was gridded using a cell size of 250m and then nulling the data after 3 cell sizes (Figure 9). The ground data was then upward continued by 150m to simulate the height of the aircraft. The Falcon data was nulled out to match the ground data points (Figure 10). The two grids are differenced, and the ground truth value is taken as the standard deviation of this difference grid. In this case, the ground truth was 1.41 mGal.

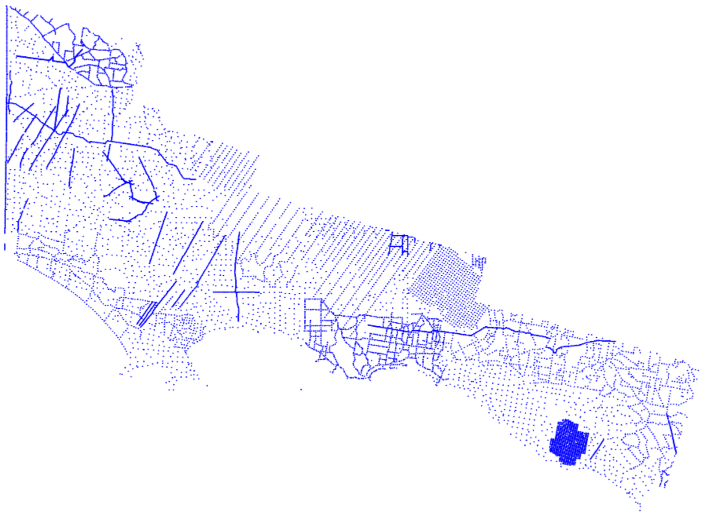

Figure 8 – The location of over 11,000 ground gravity data readings within the Otway Basin Falcon survey area.

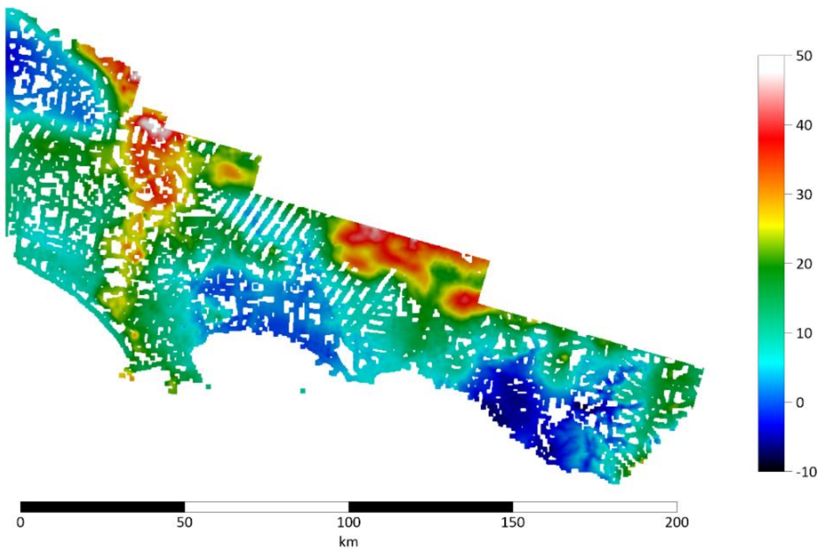

Figure 9 – The terrain corrected, vertical gravity data results using the ground gravity data. Each ground reading was gridded using a cell size of 250m and nulled after 3 cell sizes. The data was then upward continued by 150m to simulate the height of the aircraft.

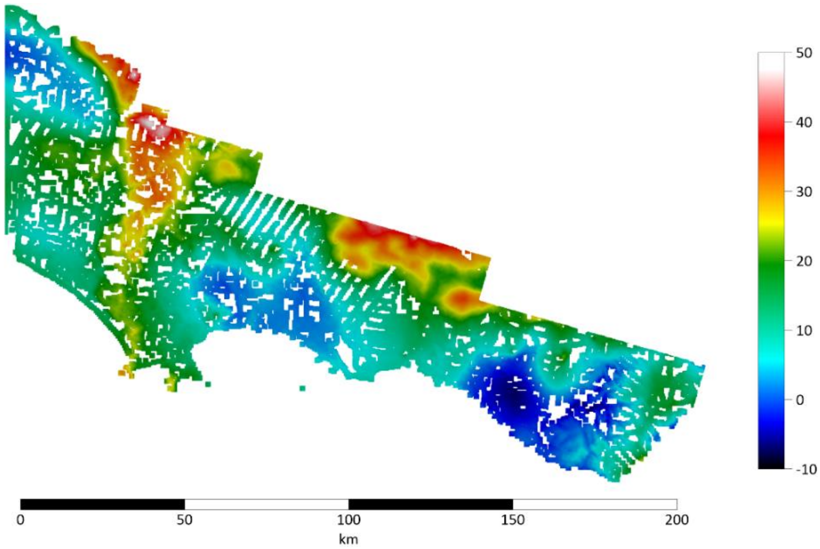

Figure 10 – The terrain corrected, vertical gravity data nulled out to only show results where there is a corresponding cell in the grid of the ground data.

This estimate will include errors from both the Falcon data and the ground data. Repeating the precision process with the Falcon data using the odd-even difference technique results in a repeatability value of 0.33 mGal. The ground data can be split into two datasets in a similar fashion using a spatial method to split the database into odd and even portions (Figure 11). This analysis results in a repeatability value of 0.65 mGal. The ground data also includes a height error channel (Figure 12). This height error will affect the ground data reading via the free air correction. The average height error for the area is 1.32m; this correlates to a free air correction error of 0.41 mGal using Equation 3. The combined error from the Falcon data and the ground data is the sum of all the error sources. In this example, the combined error is 1.39 mGal which compares well with the ground truth analysis value of 1.41 mGal.

Figure 11 – The ground data locations split into an effective odd and even dataset. The data points are arranged sequentially by X and Y coordinate respectively and every alternating point is used for each of the subsets.

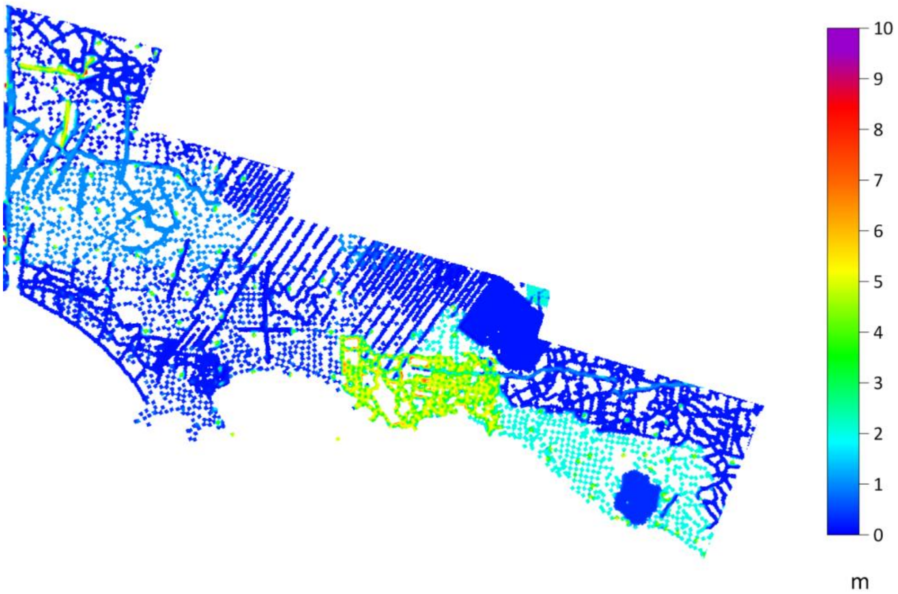

Figure 12 – The height error channel in the ground dataset. This height error will be used to estimate the free air correction error in the ground data.

CONCLUSION

With the growing number of different commercial AGG systems, there is a need for common methods to compare the quality of the different data outputs. The two areas to review for quality are precision and accuracy. For precision, the odd-even difference technique works as a repeatability analysis tool. For accuracy, a ground truth analysis works as a means to test against another comparable technology. Using two open-source datasets (Bay St Georges for the FTG system and Otway Basin for the Falcon system), the precision was estimated using an odd-even difference analysis. Using this technique, the precision was shown to be 9.2E and 1.9E for the FTG data and the Falcon data respectively. There was no ground truth data available for the FTG area, but the Falcon area ground truth was shown to be 1.41 mGal. The total combined error for the Falcon data and the ground data was 1.39 mGal, which agrees with the ground truth result.

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