Validating the Gedex HD-AGG™ Airborne Gravity Gradiometer

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SUMMARY

The Gedex High-Definition Airborne Gravity Gradiometer (HD-AGG™) was designed and developed to deliver measurements of the gravitational field with improved signal-to-noise and resolution. The system has been under development for more than 10 years and has reached the point of commercial deployment. Knowledge of the gradiometer components being measured, noise character and resolution of the system will allow end-users to select exploration targets and determine survey parameters appropriately.

The validation of the Gedex system has been progressive in nature consisting of laboratory tests and flight tests in a Cessna Caravan. The lab experiments consisted of static tests to establish the quiescent noise floor, signal confirmation tests and dynamic testing on a 6 degree-of-freedom shaker. The airborne testing included high altitude flights to confirm the noise level and character of the system over long periods. Low-level repeat surveys were carried out to establish the noise levels under survey conditions. High resolution terrain data were used to confirm the resolution of the system. Datasets from our validation program and the path forward are discussed.

INTRODUCTION

The commercial target for the Gedex system is a post-processed performance of 1 E/√Hz in the bandwidth from 0.001 to 1 Hz. Modeling and practical experience have demonstrated the value that this improved data quality will have on the discovery of resources and mapping of geologic features previously not detectable (van Kann, 2004).

System components were described and the performance of the prototype elements shown by Carroll, Hatch and Main (2010) and Baker et al (2016). The fundamental challenge in measuring accelerations due to changes in sub-surface geology is that the noise in the airborne environment is more than 7 orders of magnitude greater than signal. To enable weak gravity gradiometer signals to be detected in this noise background Gedex has followed a multi-faceted engineering approach with in-house development of a superconducting gravity gradiometer instrument, cryostat, motion isolation mount, and processing software.

To be successful with an AGG survey, petroleum and mineral explorers must know that the AGG system deployed has sufficient noise and resolution performance in order to map their target successfully. The system should also provide superior cost-benefit over competing solutions. For the first 14 years after the initial introduction of AGG systems the performance reported varied in metrics and magnitude. To help address this Dransfield and Christensen (2013) provided an extensive overview on the performance of AGG systems. The authors summarized how noise and resolution can be expressed and the performance levels of current AGG systems.

There are several iterative stages in evaluating a new gravity gradiometer system. Initially laboratory tests are conducted to establish the noise floor and calibration tests are used to confirm that the instrument is correctly measuring changes in the gravitational field. Dynamic tests on a flight simulator can also confirm repeatability and provide an initial idea of the noise performance in a controlled environment before moving to actual flight tests.

One approach to determining the flight performance of an AGG system is to fly over a test range where the signal is very well characterized utilizing both high resolution terrain and ground gravity data. However, only one such public domain dataset exists, namely the Bob Smith (formerly Kauring) test-range (Howard et al., 2010) in Western Australia. At this stage, testing the Gedex system in Australia is not practical and establishing a similar test range dataset proximal to Gedex facilities is unduly expensive.

An alternative method to characterize flight performance is to conduct a repeat survey and subtract the two datasets, eliminating consistent signal. Assuming the noise level of the two surveys is similar the system noise can be determined. If high quality terrain data are available over the survey area the resolution of the AGG system can also be investigated.

In order to understand the components that are being measured the basic configuration of the Gedex sensor is described. A brief description of the processing software is also provided. The results of the validation testing that has been conducted to date and the path forward are presented.

METHOD AND RESULTS

System Overview

Gedex Gravity Gradiometer Instrument

The Gedex HD-AGG™ system measures the gravity gradient utilizing a pair of beams each of which is centered on a pivot spring as described in Moody and Paik (2004 and 2007). When accurately balanced each of the beams has very little sensitivity to translational accelerations. Arranging a pair of these beams with one rotated 90° with respect to the other also allows the separation of rotational accelerations from rotations due to change in the gravitational field. Although designed to be a tri-axial instrument (Figure 1) the current implementation of the Gedex gravity gradiometer uses two sets of these cross-beam sensors (indicated as B and C in Figure 1) to measure the change in gravitational field in two orientations. The rotational axes of the beam-pairs are oriented horizontally , perpendicular to one another, and with each beam's long axis oriented 45° away from the vertical, such that they respond to the (Gzz-Gxx)/2 and (Gzz-Gyy)/2, components of the gravity gradient tensor, where z is the vertical direction. In combination, these two components measure all orientations of the geologic signal, and when transformed using Laplace's Equation, yield Gzz. The two-component system is preferable to a single-component system as it provides additional information for de-noising in post-processing and allows for a simple mathematical transformation of the measured components into Gzz.

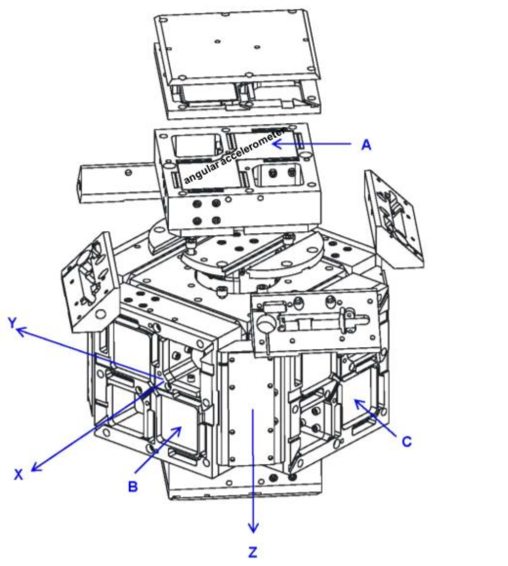

Figure 1: Originally designed as a three component gradiometer (A, B and C) the current implementation consists of two pairs (B and C) of angular accelerometers oriented vertically, perpendicular to one another. One balance beam-type accelerometer is labelled.

Post-Processing Software

The output of the gravity gradiometer instrument is essentially a pair of voltages which correspond to measurements of the differential test mass rotational displacements, which must be post-processed to obtain a calibrated gravity gradient.

After this initial processing to compensate for instrument kinematics, temperature, pressure and other effects, the data will contain residual noise. A significant proportion of this noise will have a character that is distinct from geologic signal. For example, content having wavelength shorter than any possible signal from geology, measured from an aircraft at an 80m flying height, is noise and can be filtered out. An equivalent source method is used to transform the measured gravity gradient components into a single density layer. This method provides a means to eliminate the non-geologic short-wavelength component of the gravity gradient measurements and to reject noise which does not satisfy Laplace's Equation (Barnes and Lumley, 2011).

System Validation

The performance of the Gedex system was conducted with a series of laboratory tests followed by flight tests. The initial lab tests consisted of static measurements to establish the quiescent noise floor of the instrument. This was followed by an experiment to confirm that the instrument is correctly measuring gravity gradient signals, and by dynamic testing using a 6 degree-of-freedom hexapod shaker that emulates motions that are experienced in flight.

After the required performance was achieved in the lab, the instrument was mounted in a Cessna C-208 Caravan aircraft for a series of test flights. The system was first flown at a high altitude over fairly flat ground which had the effect of minimizing signal and allowing residual noise to be characterized.

Laboratory Test Results

The first lab test was to determine the noise floor of the system. Figure 2 shows the Gzz measurement for a period of 500 s with the instrument sitting still and the isolation system turned off. The RMS noise level was 1.5 E using a low-pass cut-off frequency of 1 Hz. The power spectral density plot (Figure 2) for this data shows a nearly white-noise response down to 1 mHz. This test demonstrates good long-period performance of this instrument with low levels of drift evident in the time series data. The residual noise is thought to be related mainly to electronic noise. As no motion isolation was employed and the experiment was conducted during working hours, a significant component of the residual noise has likely originated from ambient building vibrations and vehicular traffic.

A signal validation test consisted of pushing a known mass past the instrument and comparing these measurements with the theoretical response. The predicted ((Gzz-Gyy))/2 response of moving a mass past the instrument is essentially identical in magnitude to the actual measured signal from this component. This experiment confirmed that the voltages measured by the instrument are being properly converted into gradiometer signals, verifying other calibration techniques that are also used.

Dynamic testing was conducted using a hexapod shaker which enables translational and rotational accelerations that have been recorded during an actual flight to be simulated in the lab. Although high and low frequencies cannot be reproduced the shaker permits the same flights to be repeated allowing the impact of specific changes to the system to be quantified. There was no correction applied to reduce the effect of the sensor moving relative to the isolation system (self-gravity) and relative to the local lab gravitational field.

Initial Flight Tests and Results

The test flights have been conducted in a progressive manner with high-altitude lines followed by low-level surveys flown at a constant altitude, and then finally in drape mode. This allowed the performance of the system to be characterized over a range of different turbulence levels, aircraft attitudes and signal levels. At higher altitudes turbulence levels are generally lower and relatively low resolution terrain data (SRTM) can be used to compute a terrain correction, allowing the noise level of the system to be assessed with relatively little geological signal present in the data. At lower altitudes translational and rotational accelerations induced by turbulence are found to be much higher. With closer proximity to the ground, signal levels are also greatly increased. Repeat surveys were conducted to determine the noise level of the system for the low level surveys.

The flight tests were conducted in the Muskoka area of Ontario approximately 150 km NNE of Toronto. Over the test area there is high resolution Lidar survey data available with 1 m sampling interval and 5 cm vertical accuracy. The geology is underlain by Precambrian granitic gneiss with shield derived sediments, lakes and swamps in the low lying areas. There are only a few regional gravity stations so there is little information on sub-surface density over the area.

Repeat surveys were conducted to determine the noise level of the system in both constant altitude and drape modes. In both constant altitude and drape mode the system experienced a range of turbulence levels which varied from line to line, with drape mode having higher accelerations induced by more numerous pilot corrections required to follow the terrain.

The results of the two constant altitude surveys are shown in Figure 3; note the high degree of similarity between the two images. The signal over the area arises mainly from topographic variations. Differences in the observed values are mainly due to system noise but also to differences in aircraft position between the two surveys. The RMS values of the two surveys vary by only a few percent indicating similar noise levels. The noise level of each constant altitude survey determined from the repeat survey analysis is 8.4 E RMS at 1 Hz bandwidth. Further improvements to the data processing are being investigated and this noise level may be further reduced.

A preliminary investigation of system resolution was also conducted by comparing the terrain response computed along the flight lines with the actual measured data. Detection of a single narrow feature and the ability to individually resolve two closely spaced features can illustrate the resolution of the system. The constant altitude survey was flown 100 m over the highest peak with average height above ground of 175 m. At this survey altitude the terrain over this area does not contain sharp peaks of sufficient elevation to investigate the limits of resolution. However, features with widths as small as 200m can clearly be resolved as shown in Figure 4. A drape survey is being flown over the area at a lower average terrain clearance and will provide a more robust determination of resolution.

CONCLUSIONS

A program of laboratory and flight tests is currently being conducted to validate the performance of the Gedex system. The lab tests confirmed the noise floor of the system and demonstrated white-noise character with low levels of long-wavelength drift being observed. In addition to other calibration procedures, moving a known mass past the instrument confirmed that the measurements from the sensors are correctly being converted into gravity gradient readings. Laboratory experiments on a six degree-of-freedom shaker confirmed white noise performance and demonstrated a noise level that justified progressing to flight tests.

Initial test flights were conducted at high altitude, followed by low-level surveys flown first at a constant altitude and in drape mode. A repeat survey analysis confirmed a noise level of 8.4 E RMS at 1 Hz bandwidth. Small scale features are visible but confirmation of the system resolution was limited by the greater distance from sources in the constant altitude survey. A repeat survey in drape mode will confirm the noise level under realistic survey conditions and will enable improved determination of resolution.

In the near future the system will be transferred to a larger aircraft suitable for commercial operations, where further improvement in performance is expected due to lower levels of turbulence induced noise. At that point, the system will be ready to commence commercial surveying. The ultimate performance goal is 1 E/√Hz and the Gedex system will undergo further upgrades. With each significant modification the validation process will be repeated.

ACKNOWLEDGMENTS

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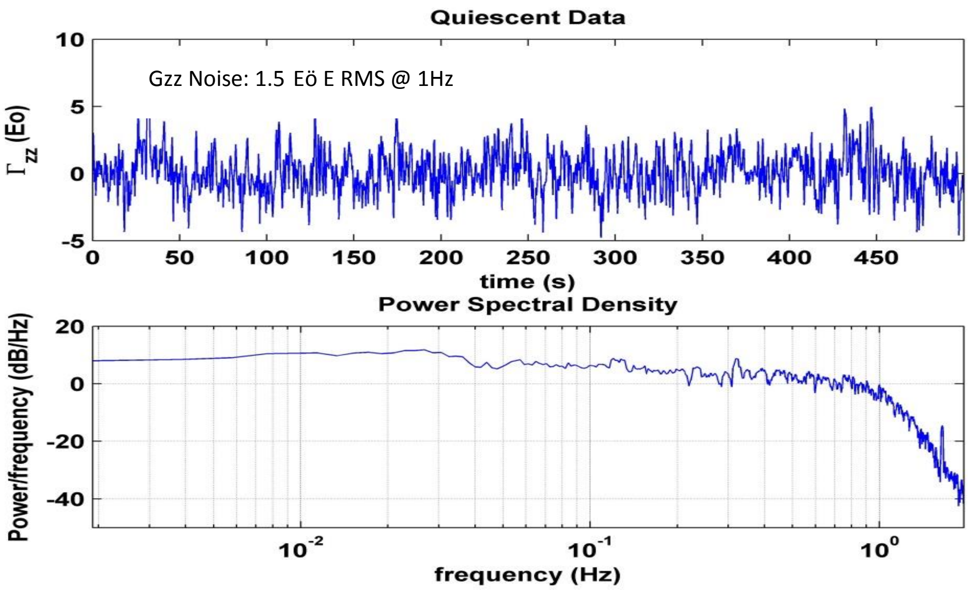

Figure 2: Quiescent lab test results showing time series data (top) with noise floor of 1.5 Eö RMS and PSD plot (bottom) illustrating white noise character.

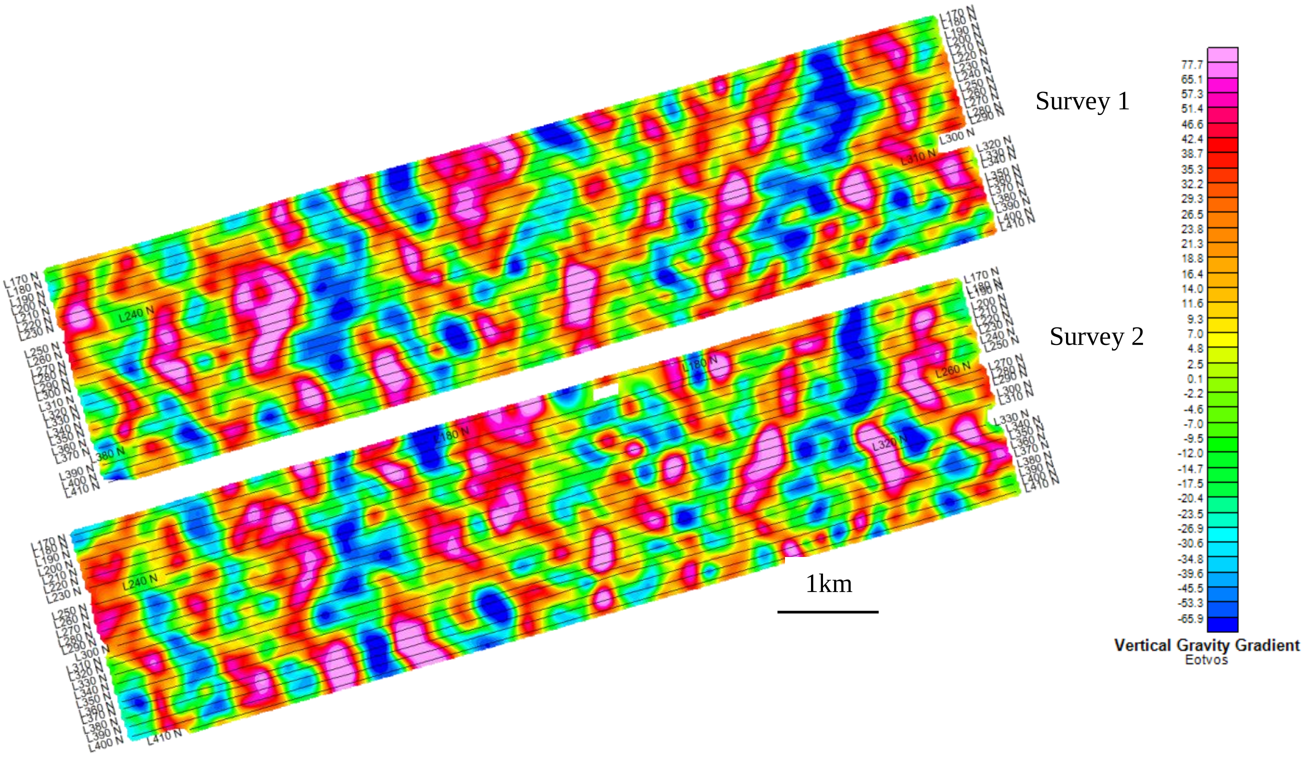

Figure 3: Repeat surveys both flown at constant altitude along the same flight path. Subtracting the two surveys eliminated consistent signal and yielded a survey noise level of 8.4 E @ 1 Hz.

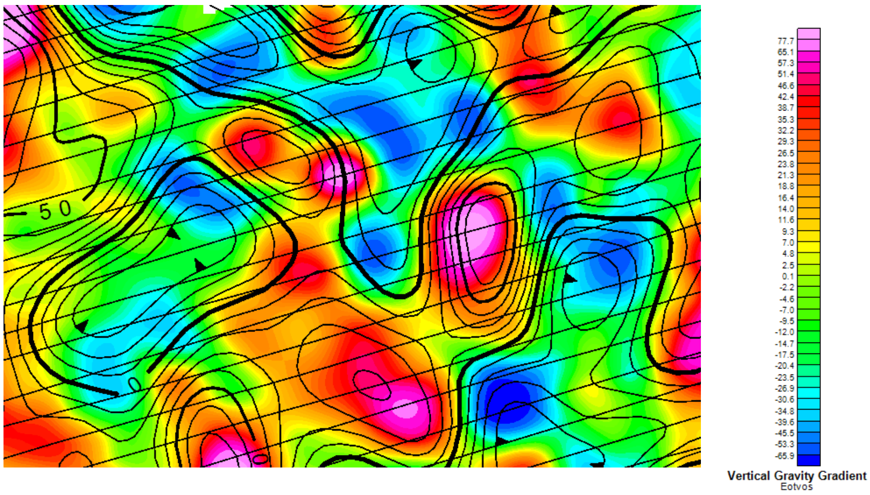

Figure 4: Measured data for survey 2 (colours) compared with computed terrain response (contours). Differences will be due to system noise and signal from sub-surface geology. Although the aircraft is on average 140m above the ground over this area several ground features that are approximately 200m wide are clearly visible.