Fleas on a Camel: Advances, Challenges and Opportunities in Gravity Applications for Resource Discovery and Characterization

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ABSTRACT

Today's state-of-the-art gravity measuring devices are wonderfully engineered and extraordinarily precise instruments, capable of measuring and monitoring local changes (positional or temporal) at the parts per billion level – in effect, a flea on a Bactrian camel – with both relative and absolute measurement methodology. These minute variations in gravity have major implications and consequences in the exploration for natural resources, the study of crustal inhomogeneity, environmental monitoring and safety.

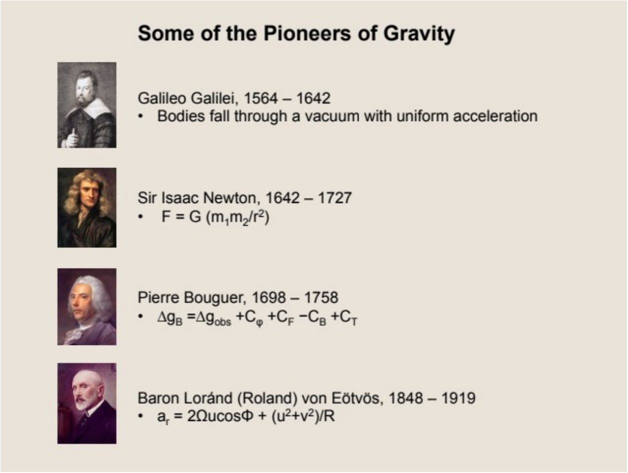
INTRODUCTION: A PART PER BILLION

A good commercial bathroom scale has increments of 100 grams and measure force at about one part per thousand. Although this may be sufficient to cause valid concern after a large meal, it is about six orders of magnitude too coarse for geoscience. Today's gravity meters measure acceleration in units of microgals. 1 microgal is 10^{-8} m/s^2, about one part per billion of earth's gravity. A scale this precise will sense a 1 mg flea landing on a 1,000 kg Bactrian camel (Figure 1).

Figure 1: 1 part per billion - Sensing a 1 mg flea landing on a 1000 kg Bactrian camel (picture is fortunately not to scale!)

Despite the huge difference in sensitivity requirements, the mass-on-a-spring method of measuring the force of gravity is used in both bathroom scales and today's highly precise gravity meters. On the bathroom scale, gravity is taken to be constant and changes in the measured force are caused by variation of mass. In a gravity meter, the mass is constant, and changes in the measured force are caused by variation of acceleration.

When subject of gravity comes up, many people immediately think of Sir Isaac Newton. Gravity was, however, identified much earlier as a force by scientists such as Aryabhata, who lived in India around 500 CE. Modern western thinking about gravity began with Galileo in the late 16th century. Figure 2 is a short list of some of the more prominent scientists who contributed significantly to the practical application of the gravity method for geoscientific exploration.



Some of the Pioneers of Gravity

Galileo Galilei, 1564 – 1642
- Bodies fall through a vacuum with uniform acceleration

Sir Isaac Newton, 1642 – 1727
- $F = G\,(m_1 m_2/r^2)$

Pierre Bouguer, 1698 – 1758
- $\Delta g_B = \Delta g_{obs} + C_\varphi + C_F - C_B + C_T$

Baron Loránd (Roland) von Eötvös, 1848 – 1919
- $a_r = 2\Omega u\cos\Phi + (u^2+v^2)/R$

Figure 2: Prominent Pioneers of Gravity

The earth's gravity is now measured above, on and below the earth's surface using a variety of relative and absolute "gravimeters". Over the past decade, measurement of gravity gradients for geoscientific exploration has gained traction. The following is a brief description of some commonly used gravimeters and gravity gradiometers with some examples of their applications in geoscience, from satellites down into boreholes.

GRAVITY FROM SATELLITES

The Gravity Recovery and Climate Experiment (GRACE) mission, a joint partnership between the National Aeronautics and

Space Administration (NASA) in the United States and Deutsche Forschungsanstalt für Luft und Raumfahrt (DLR) in Germany, launched two identical spacecraft in March, 2002, to measure variations in the earth's gravity from orbiting satellites. The two GRACE spacecraft fly about 220 kilometers apart in a polar orbit 500 kilometers above earth. Variations of the earth's gravity field are detected by making accurate measurements of the distance between the two satellites, using GPS and a microwave ranging system. The gravity variations studied by GRACE include large geophysical anomalies, Figure 3 (CSR, 2016), runoff and ground water storage on land masses, Figure 4 (NASA, 2014)

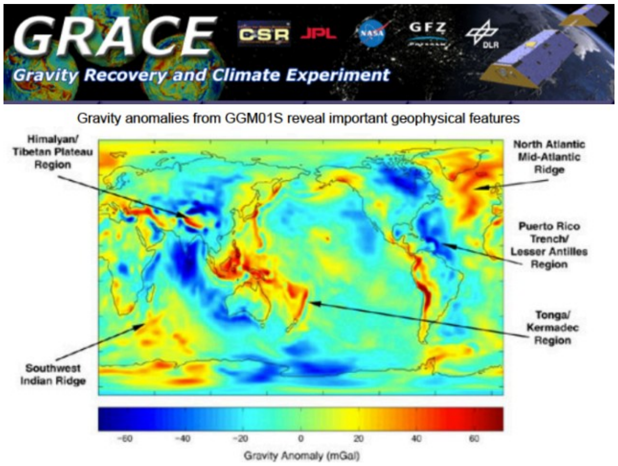


Figure 3: Gravity Anomalies from GRACE

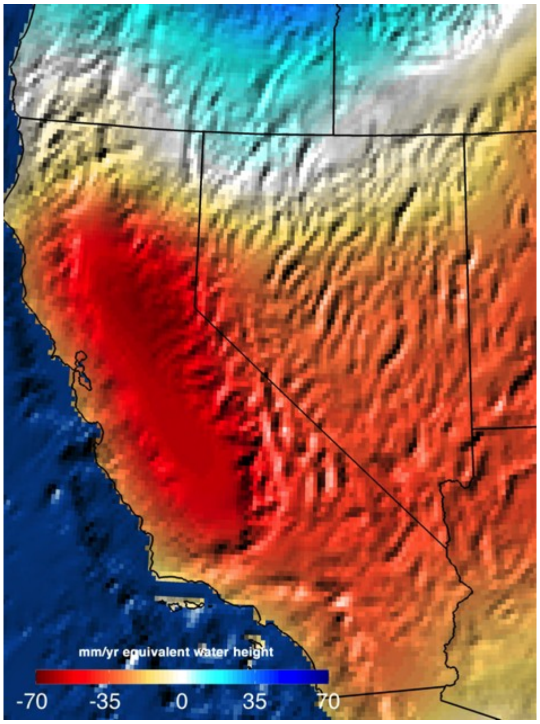


Figure 4: The severity of California's drought on water resources across the state, revealed by GRACE data. This map shows the trend in water storage between September 2011 and September 2014 (NASA, 2014)

The batteries in the original GRACE satellites have now weakened to the point that data is only being collected when the satellites are not in the shade. Two new GRACE Follow-On satellites are being built by Airbus in Germany, with launch scheduled for early 2018, Figure 5 (NASA JPL, 2016).

Figure 5: GRACE Follow-On Satellites under construction by Airbus Defense and Space at its manufacturing facility in Friedrichshafen, Germany, posted Nov 14, 2016 (NASA JPL, 2016).

In another mission, David Sandwell (SCRIPPS) and Walter Smith and Joshua Stevens (NASA) analyzed satellite altimetry data from the European Space Agency's CryoSat-2 and from the NASA-CNES Jason-1 satellites. Small variations in the height of the sea, caused by variations in the gravity field, reveal wonderful detail of the sea floor, Figure 6 (Steam Register, 2016).

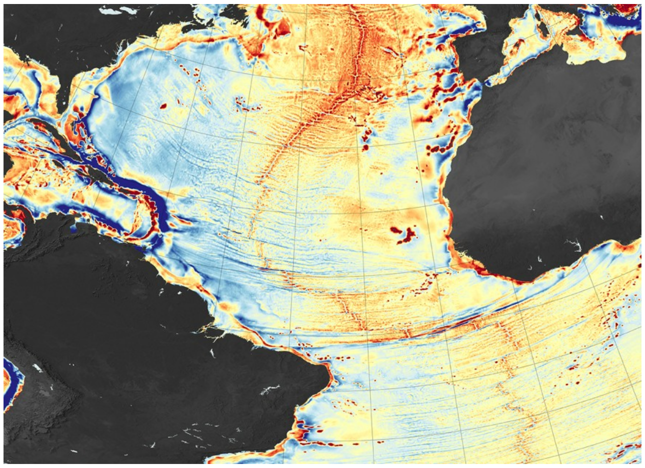


Figure 6: Seafloor gravity anomalies, Mid-Atlantic ridge, posted Jan 14, 2016 (Steam Register, 2016). Warm colours are highs

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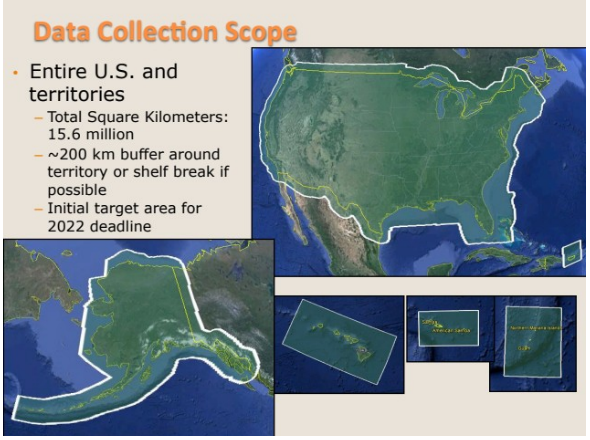
GRAVITY FROM AIRCRAFT

In October, 1981, Dr. Sigmund Hammer submitted a paper for publication in GEOPHYSICS titled "Airborne gravity is here!" The paper was reviewed, revised and published in GEOPHYSICS in February 1983 (Hammer, 1983). The paper generated significant discussion (e.g., Steenland, 1984), and was rather optimistic for its time. It was, however, prescient. With improved technology and, in particular, GPS, it is now possible to isolate gravity accelerations from aircraft motions at and below frequencies high enough to provide useful exploration data, even in a helicopter maintaining constant terrain clearance over moderate topography. This is a remarkable achievement – even a smooth flight on an aircraft has vertical accelerations in the targeted bandwidth many orders of magnitude higher than the variations in gravity. The gravity sensor must maintain the required precision over this huge dynamic range. Likewise, the motion of the aircraft must be independently recorded with similar precision by sensors that are not (or extremely minimally) coupled to gravity, and all the sensors must be well synchronized. The data are then processed to extract and interpret useful geophysical signal from the overwhelming noise. Several airborne gravity (AG) systems are now commercially available, Figure 7.

Figure 7: Commercial AG Systems developed by Canadian Micro Gravity (CMG), Micro-g Lacoste (MGL) and Sander Geophysics (SGL)

The National Geodetic Survey (NGS) of NOAA has a federal mandate "to re-define the vertical datum of the US by 2022". In 2007, NGS embarked on the GRAV-D Project to acquire airborne gravity data over the entire country, "one of the most ambitious projects in the history of the agency", Figure 8. "The gravity-based vertical datum resulting from this project will be accurate at the 2 cm level where possible for much of the country." (NGS, 2017).

GRAV-D airborne gravity data are being collected and processed in blocks, and almost 60% of the acquisition has been completed at the end of 2016, Figure 9. A suite of products for each block is made available on the GRAV-D website as processing is completed. Four examples of the Free Air Gravity Disturbance from around the USA are shown in Figure 10. Large topographic features, such as the mountains of Alaska, are clearly evident in the data.



Data Collection Scope

- Entire U.S. and territories
  - Total Square Kilometers: 15.6 million
  - ~200 km buffer around territory or shelf break if possible
  - Initial target area for 2022 deadline

Figure 8: The NGS GRAV-D Airborne Gravity Project

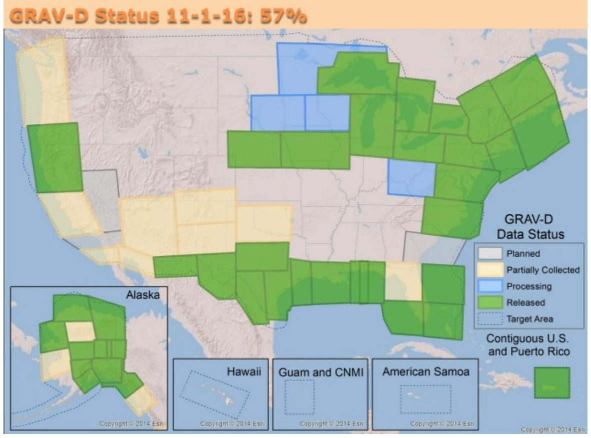


Figure 9: GRAV-D Status as of Nov. 1, 2016

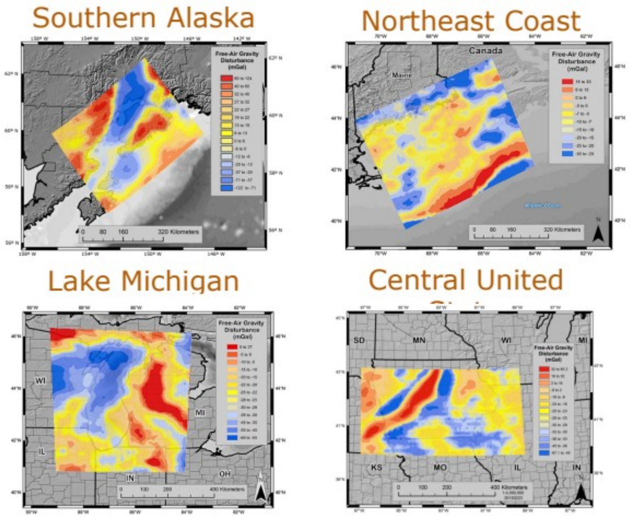


Figure 10: Four examples of Free Air Gravity Disturbance maps from the NGS GRAV-D project

NGS releases annual, downloadable, gravimetric geoid models that incorporate all available gravity sources, including new satellite gravity models and the GRAV-D airborne gravity data (NGS xGEOID, 2016). The 2016 geoid model is shown in Figure 11. The release of the final geoid, which will incorporate the completed GRAV-D project data, is targeted for 2022.

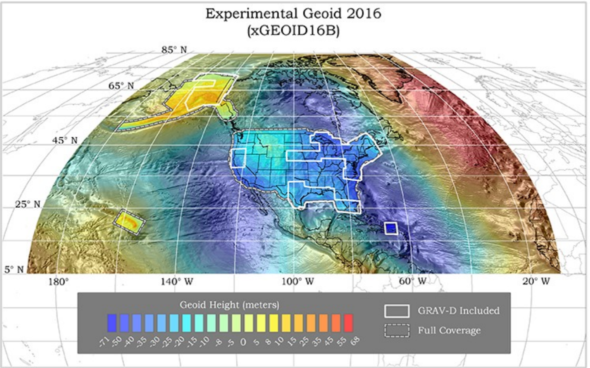
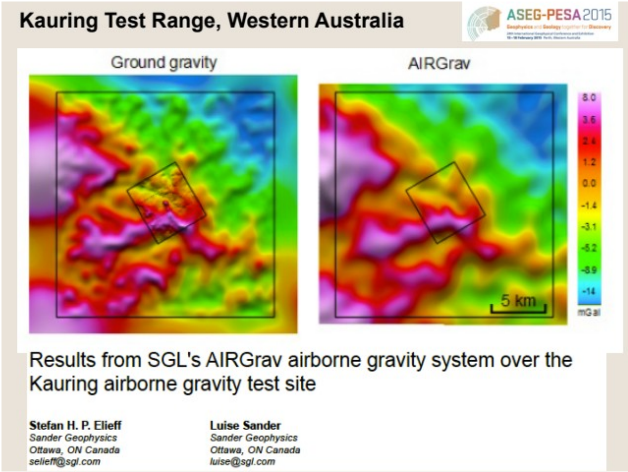


Figure 11: NGS Experimental Gravimetric Geoid 2016

In order to benchmark airborne gravity (AG) and airborne gravity gradiometer (AGG) systems, Geoscience Australia set up the Kauring Airborne Gravity Test Range in Western Australia, about 100 km east of Perth, during 2010. "The test site data will allow interested individuals and organizations to compare AG and AGG data to the detailed ground gravity data (or products derived from these data). It will also allow direct comparison of different AG and AGG systems over the same gravity features where all other variables, besides the measuring system, are defined and constant." (GA Kauring, 2010). Sander Geophysics (SGL) flew the test range with their AIRGrav system in a fixed wing aircraft (see Figure 7 above). in early 2012, Figure 12.


Kauring Test Range, Western Australia

Results from SGL's AIRGrav airborne gravity system over the Kauring airborne gravity test site

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Figure 12: SGL's AIRGrav data compared to ground gravity data over Geoscience Australia's Kauring Test Range

Common mode accelerations caused by aircraft motion are greatly reduced by subtracting the data recorded by two closely spaced, similarly affected, sensors. A much improved signal to noise ratio is evident in the higher frequencies, at the expense of low frequency attenuation, Figure 13.

Development of a gravity gradiometer commenced at Lockheed Martin (LM) for the US Department of Defense during the 1970's. BHP recognized the potential of airborne gravity gradiometry for mineral exploration and worked with LM in the late 1990's to install and test the "Falcon" gravity gradiometer in a geophysical survey aircraft (van Leeuwen, 2000). The first AGG survey was flown by SGL for BHP in late 1999 in New Brunswick. The Falcon AGG system is now flown by CGG Multi Physics, and a similar LM "Full Tensor Gradiometer" (FTG) system is flown by Bell Geospace.

Falcon AGG data were acquired by CGG over the Kauring Test Range, and the improvement in the signal to noise ratio of the high frequency signal compared to AG is evident, Figure 13.

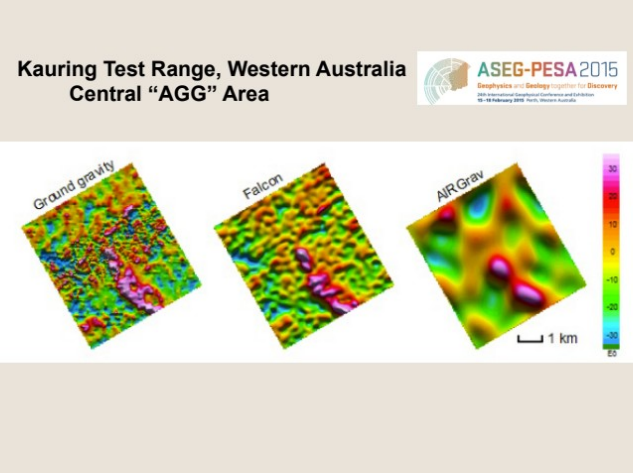
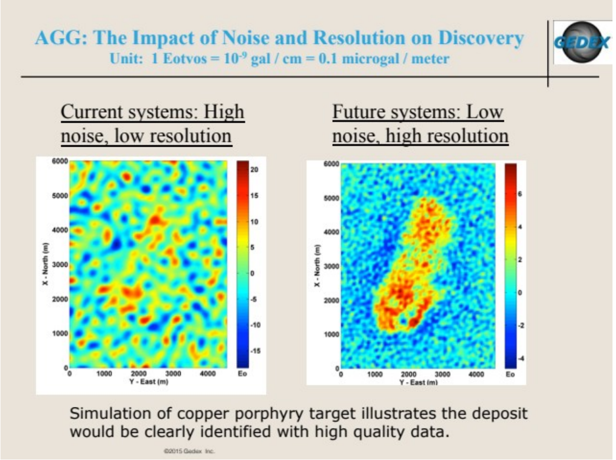

Kauring Test Range, Western Australia
Central "AGG" Area

Figure 13: Airborne Gravity Gradiometry, Kauring Test Range

The unit of measurement for AGG is the Eotvos, named after one of the pioneers of gravity, Baron Roland von Eötvös (see Figure 2). The measured quantities are the tensor gradients of acceleration over distance in three dimensions. 1 Eotvos is equal to a gradient of 0.1 microgal per metre. Geoscience Australia organized technical conferences on AGG in 2004, 2010 and 2016. The proceedings from 2004 and 2010 can be downloaded as pdf's (GA AGG 2004 and 2010), and the 2016 proceedings may be available by the time of the Exploration '17 conference. The "holy grail" for new AGG systems under development is performance levels at or better than 1 Eotvos/√Hz in the bandwidth from as low as .0001 Hz to as high as 5 Hz, particularly for the vertical tensor, Tzz, which is of most interest for mining exploration, Figure 14. This would be about an order of magnitude improvement over the current systems.



AGG: The Impact of Noise and Resolution on Discovery

Unit: 1 Eotvos = 10^{-9} gal / cm = 0.1 microgal / meter

Current systems: High noise, low resolution

Future systems: Low noise, high resolution

Simulation of copper porphyry target illustrates the deposit would be clearly identified with high quality data.

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Figure 14: The Impact of Noise and Resolution in AGG data, current systems (300 m resolution) and future systems under development (60 m resolution). Credit: Spence deposit studied by Mira Geoscience under CAMIRO Project 2001E01

Development of AGG technology is carrying on at several research facilities. LM is working on a new "Enhanced Full Tensor FTG System" will have several improvements, including three orthogonal rotating gradiometers, each roughly double the size (baseline) of the current system, a second complement of accelerometers for quality control and significantly lower noise, Figure 15.

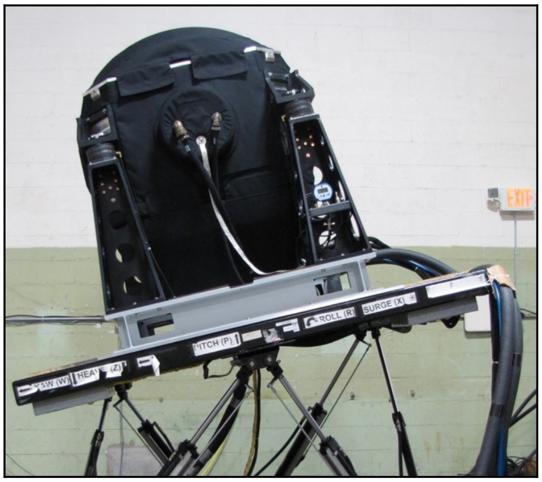
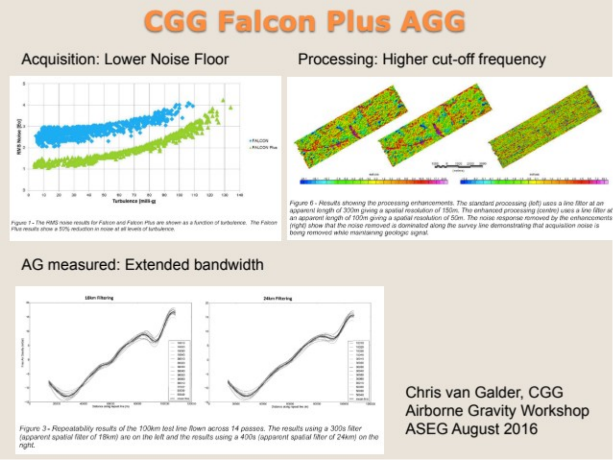


Figure 15: The Lockheed Martin EFT FTG System, under development (near completion)

CGG Multi Physics is working to lower the noise floor of the Falcon system and increasing the bandwidth with the addition of a strap down AG system for lower frequencies (.0001 Hz) and improved processing to extend the high frequency range (5 Hz), Figure 16. (van Galder, 2016)



CGG Falcon Plus AGG

Acquisition: Lower Noise Floor

Processing: Higher cut-off frequency

Figure 1 - The RMS noise results for Falcon and Falcon Plus are shown as a function of turbulence. The Falcon Plus results show a 50% reduction in noise at all levels of turbulence.

Figure 6 - Results showing the processing enhancements. The standard processing (left) uses a line filter at an apparent length of 300m giving a spatial resolution of 150m. The enhanced processing (centre) uses a line filter at an apparent length of 100m giving a spatial resolution of 50m. The noise response removed by the enhancements (right) show that the noise removed is dominated along the survey line demonstrating that acquisition noise is being removed while maintaining geologic signal.

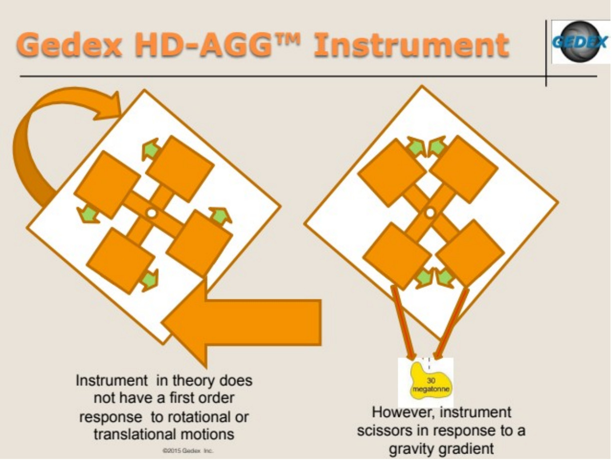
AG measured: Extended bandwidth

Figure 3 - Repeatability results of the 100km test line flown across 14 passes. The results using a 300s filter (apparent spatial filter of 18km) are on the left and the results using a 400s (apparent spatial filter of 24km) on the right.

Chris van Galder, CGG
Airborne Gravity Workshop
ASEG August 2016

Figure 16: CGG Falcon Plus AGG, under development

Gedex in Canada is developing a "high definition airborne gravity gradiometer". The Gedex HD-AGG™ system measures the gravity gradient by the scissoring action of a pair of balance beams, each of which is centered on a pivot spring, as the sensor is passing over a density target, Figure 17. The sensor is mounted on a flight cryostat and an isolation system. "The commercial target for the system is a post processed performance of 1 Eo/root-Hz in the bandwidth from 0.001 to 1 Hz." (Hatch, 2017).



Gedex HD-AGG™ Instrument

Instrument in theory does not have a first order response to rotational or translational motions

However, instrument scissors in response to a gravity gradient

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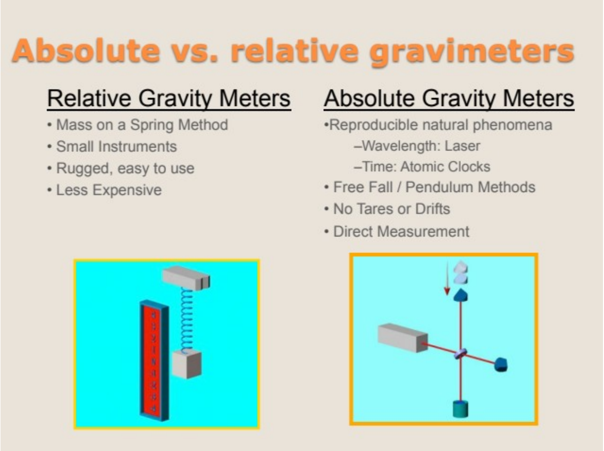
Figure 17: The Principal behind the GEDEX HD-AGG™ Sensor Technology

GRAVITY FROM GROUND MEASUREMENTS

Measurements of gravity at a point on land can be acquired with either a relative or an absolute gravity meter. The principal behind either type of sensor is simple – relative measurements are made with a mass on a spring, and absolute measurements are made by free fall and pendulum methods. The choice of sensor type depends on the application, Figure 18.



Absolute vs. relative gravimeters

Relative Gravity Meters

- Mass on a Spring Method
- Small Instruments
- Rugged, easy to use
- Less Expensive

Absolute Gravity Meters

- Reproducible natural phenomena
  - Wavelength: Laser
  - Time: Atomic Clocks
- Free Fall / Pendulum Methods
- No Tares or Drifts
- Direct Measurement

Figure 18: Absolute vs Relative Land Gravity Meters

Due to small size, ease of use and ruggedness, relative gravity meters are more commonly used for mining exploration than their absolute cousins. Scintrex's new CG-6 gravity meter has been commercially available since 2016, Figure 19.

Figure 19: The Scintrex CG-6 Gravimeter

Along with ruggedness, ease of operation, small size and various "bells & whistles", a critical competitive feature for all land gravity meters is to minimize the time required to acquire a gravity measurement that meets the required survey specification. This need is most obvious on large regional surveys that require a helicopter for transportation between stations. The Gawler Craton gravity survey in South Australia, 34,541 gravity stations, acquired on a 1 km and 2 km grid by Daishat (Daishat, 2017), is a good example. The data are available for download from the Geological Survey of South Australia "for explorers targeting Olympic Dam style Iron Oxide Copper Gold (IOCG) mineralization within the Gawler Graton", Figure 20 (Gawler Craton Gravity Survey, 2013).

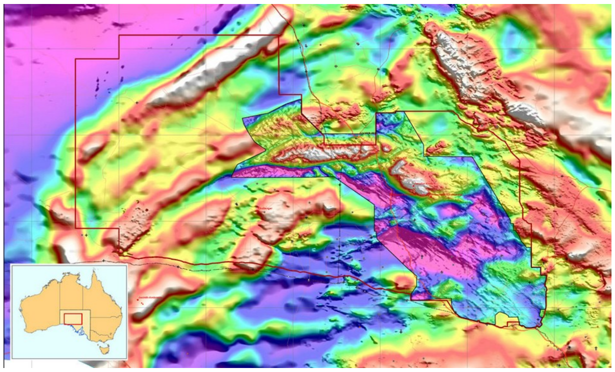


Figure 20: Gawler Craton gravity survey, Geological Survey of South Australia

Relative gravity meters measure the difference in gravity between two points, so the measurements must be tied back to a common "base station". Absolute gravity meters directly measure the earth's gravity at a point, eliminating the need for a base station. The principal is simple (free fall or pendulum sensors), however the precision required necessitates precision lasers, clocks and isolation systems. The Micro-g LaCoste (MGL) FG-5X Gravity Meter, Figure 21, is used for metrology and to establish countrywide networks of gravity base stations, but it is not a practical instrument for mining exploration. The MGL A10 Gravity Meter, Figure 21, is a field portable absolute gravity meter that is most practical when the requirement is to measure temporal change in gravity, since a relative survey base station must be located far enough away to be unaffected by the cause of the change. (MGL, 2017) Gravity measurements to monitor changing levels of an aquifer or reservoir flooding are examples where the A10 is effectively used, Figure 22 (Hare et al, 2008).

Figure 21: The Micro-g Lacoste Absolute Gravity Meters

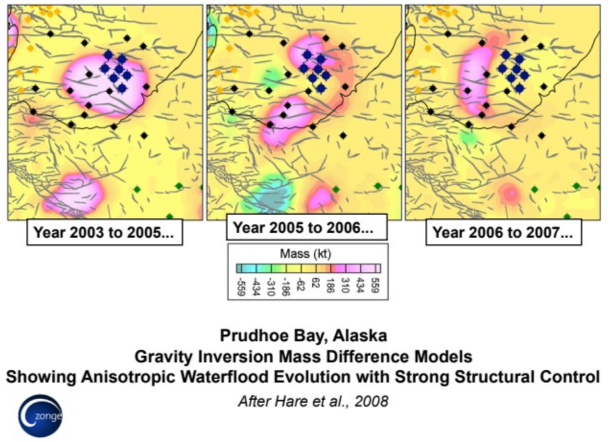


Figure 22: Inversion of A10 gravity data, Prudhoe Bay, Alaska, showing the progress of the water flood. Initially, the injected water collected around the injection wells (gravity change 2003 to 2005), then it spilled over and filled adjacent fault blocks (2005 to 2006, and 2006 to 2007)

BOREHOLE GRAVITY

Gravity instruments that can take measurement in boreholes have been available for petroleum exploration since the 1960's, Figure 23, (Chapin, 1999).

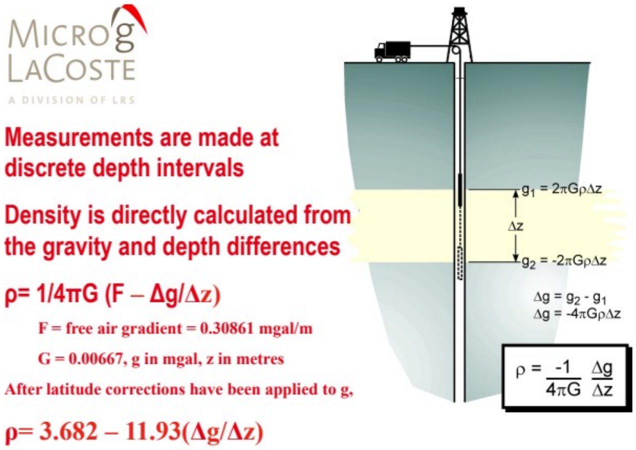


Figure 23: Bulk density from borehole gravity data

These first generation tools were impractical for mining exploration, due to their size. In 2007, Scintrex introduced a second generation borehole gravity meter, "Gravilog", that fit inside NQ drill rods (Nind et al, 2007). The prototype Gravilog tool was tested by Vale in a drill hole at Norman Township, Sudbury that intersected mineralization at 1400 m down hole. The results clearly show the crossover expected when the gravity sensor passes by a nearby dense body and allowed an approximation of excess mass to be calculated which, with reasonable density assumptions, gave an estimate of tonnage, Figure 24.

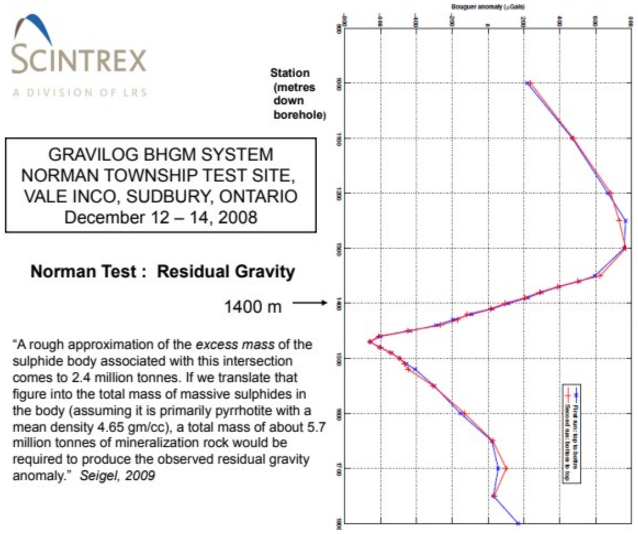
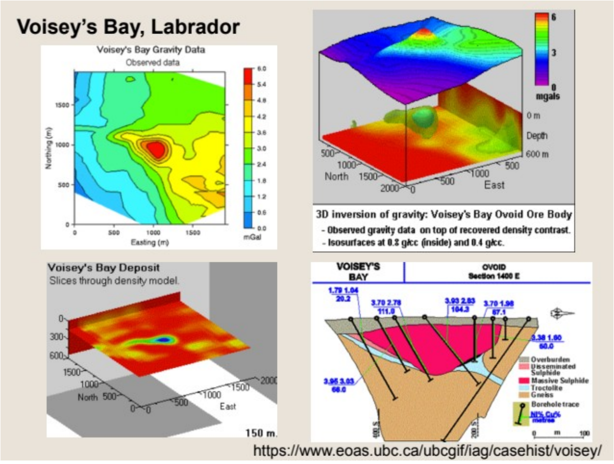


Figure 24: Gravilog borehole gravity test results, Vale's Norman Township Test Site, Sudbury, Ontario

Interpretation of borehole gravity measurements must take into account the geology that the borehole passes through. Density changes in the stratigraphy will cause crossovers similar to those caused by near-hole dense bodies. To date, the use of borehole gravity by the mining industry has been limited, both by the availability of Gravilog systems and by the logistics and cost. The results have been generally encouraging, however, and the author expects to see borehole gravity being more commonly used for mining exploration in the upcoming decade.

GRAVITY PROCESSING AND INTERPRETATION

There are several good modeling and interpretation software packages available for gravity data. One example is the package developed at the University of British Columbia, Figure 25 (UBC Voisey's Bay Gravity, 2007). The availability of high quality digital terrain maps and the development of new processing algorithms have allowed accurate terrain corrections to be efficiently applied to gravity data collected in rough terrain, including AGG systems (Chen, 2017).



https://www.eoas.ubc.ca/ubcgif/iag/casehist/voisey/

Figure 25: UBC Voisey's Bay gravity case history

CONCLUSIONS

There have been significant advances in gravity instruments for mining exploration since Exploration 2007. Gravity data is now being routinely acquired and used by mining companies from sensors orbiting satellites, aircraft, on land and inside boreholes. Airborne gravity and gravity gradiometry are now well accepted exploration methods, and R&D continues to expand the effective bandwidth and improve the signal to noise ratio of these systems.

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