The coming of age of gravity gradiometry

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SUMMARY

Eureka: (def.) "An interjection used to celebrate discovery." Literally: "I have found it!" Reaching a 'eureka moment' is the result of much thought, effort, success, failure, perseverance, patience, and fortune. It usually occurs as the result of a team effort – although one person may lead the way. With regard to gravity gradiometry – and its 'coming of age' – the "eureka moment" comes when an explorationist realizes that something that couldn't be done before can now be accomplished.

Gravity gradiometry surveys have been commercially available since 1999. Over the past 14 years, the capability has grown to a point of what could be called "adolescence." Adolescence (from Latin: *adolescere* meaning "to grow up") is a transitional stage of physical and capability development occurring during the period from youth to adulthood The period of adolescence is most closely associated with the teenage years. While gravity gradiometry doesn't retain human qualities and characteristics, the analogy is used here to review and discuss the advances and maturity of the capability. Improvements and growth in system performance, operational readiness, survey volume, and value of information will be addressed in this review.

Key words: gravity, gradiometry, airborne.

INTRODUCTION

Explorers have continually sought new and improved means to find resources. Gravity gradiometry has long been identified as a methodology providing an important measurement that reveals density characteristics of geologic structures. In the 19th century, Baron Roland von Eotvos developed a torsion balance used to map prospective regions for oil and gas. While the torsion balance produced an excellent measurement, the time required to collect data and the operational challenges associated with setup and transport proved unworkable. A practical, deployable gravity gradiometry capability was sought by many and became a reality in the 1990's.

GRADIOMETRY GROWTH

Bell Geospace conducted the first marine gravity gradiometry survey for commercial uses in 1994 in the Gulf of Mexico. In October 1999, at the Bathurst Camp, New Brunswick, Sander Geophysics flew the world's first airborne gravity gradiometer survey for BHP Billiton using a Lockheed Martin-developed system. Since that time, more systems have been deployed – today totaling 11 commercial partial-tensor and full-tensor gradiometers dedicated to resource exploration (see Figure 1.) Today, CGG (formerly Fugro Airborne Surveys) deploys five partial tensor systems in fixed-wing and helicopter installations under the Falcon™ trade name, ARKeX deploys three full-tensor gradiometer systems in Cessna Grand Caravan and DeHavilland Twin Otter aircraft, and Bell Geospace deploys 3 full-tensor systems in Basler BT-67 and Cessna Grand Caravan aircraft. Both ARKeX and Bell have also deployed systems on surface marine vessels over the years.

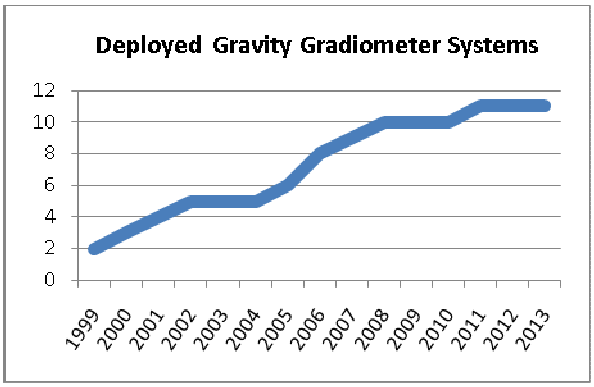

Figure 1. Increasing number of gravity gradiometer systems deployed for commercial natural resource exploration (1999-2013).

There was a steady growth in the amount of survey line-kms through the mid-2000's – followed by a down-turn due to the global economic crisis and falling commodity prices. In the past three years, survey activity has increased significantly (see Figure 2). To date, nearly 4 million line-kms of survey data have been collected by airborne and marine methods.

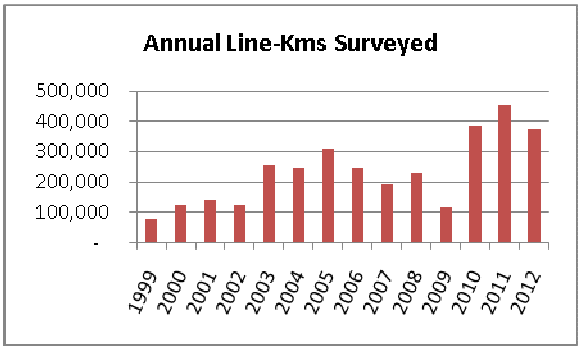

Figure 2. Annual line-kms surveyed using gravity gradiometry – including both airborne and marine activity.

Numerous applications have been cited for the use of gravity gradiometry in exploration including direct detection and geological mapping for a large variety of mineral commodities and deposit types. Diamonds have been the biggest single target with numerous kimberlites directly detected at Ekati, Canada. The diamondiferous Abner pipe in Australia and the Daniel diamond-bearing palaeochannel are also airborne gravity gradiometer discoveries. Airborne gravity gradiometry has proved useful in the search for coal, base metals in iron-oxide-copper-gold (IOCG) deposits, porphyries, volcanogenic massive sulphides, iron in massive haematite, nickel sulphides and gold. The Santo Domingo Sur copper deposit in Chile is the most advanced project that is a gravity gradiometer discovery (Dransfield, 2007). Recent reports from Providence Resources describe the success from acquired Full Tensor Gradiometry (FTG) and magnetic airborne surveys over its "Polaris Prospect", which lies in the Rathlin Sound just off the Northern Irish coast. All of the elements of a working petroleum system in this frontier basin, such as source, reservoir and seal have been proven in adjacent nearby onshore wells (O'Sullivan, 2013). Tullow Oil PLC has identified three good quality reservoir sand zones in the Auwerwer formation at the Twiga South-1 oil discovery on Block 13T in northwestern Kenya. This is being called South Kenya's first potentially commercial oil discovery (Editors O&G Journal, 2013).

OPERATIONAL ADVANCES

The measurement of gravity gradients from a moving vehicle is a daunting task. The dynamic environment of the vehicle is typically 8 orders of magnitude larger than the target signal of interest. This is overcome in large part by system design and post-mission data processing, yet the introduction of unique aircraft is also producing a significant benefit. Bell Geospace began using a Basler BT-67 aircraft for surveys in 2008 with exceptional results. This converted DC-3 aircraft provides longer range, better resistance to turbulence, and additional space for incorporating other sensors (see Figure 3). A U.S. DoE-funded project to integrate a Geotech ZTEM system with the Basler gradiometer installation is under test at this time. Unmanned systems are being considered the wave of the future for exploration. While permitting and safety issues are still being worked out, there are a number of unmanned systems – both airborne and submarine – that have been considered for geophysical survey deployment. Some of these include the Lockheed Martin K-MAX rotorcraft, the Global Aerial Imaging Solutions (GAIS) Star Shadow hybrid airship, the MQ-8B Fire Scout rotorcraft, the Shadowhawk™ Unmanned Aerial Vehicle (UAV), and the Lockheed Martin Marlin™ Autonomous Underwater Vehicle (AUV) – See Figure 4. Each of these potential survey vehicles represents a family of systems that are emerging as viable and game-changing for the exploration community. The cost of operation, safety (without manned operators) in rugged terrain, viability for long-duration surveys, and system reliability make these systems worthy of consideration for future geophysical survey operations.

Improvements in signal processing, data interpretation, and integration have also yielded a better overall gravity gradient data product. Some examples of these superior methods include the Full Tensor Noise Reduction (FTNR) methodology employed by Bell Geospace (see Figure 5); integrated seismic, borehole, gravity, gravity gradient, and magnetics by ARKeX (see Figure 6); and residual gravity (Falcon™), TMI, and EM (Tempest) data produced by Fugro Airborne Surveys over the Kauring Test Range (see Figure 7).

Figure 3. Bell Geospace Basler BT-67 aircraft – producing operational, range, and mobility benefits.

Figure 4. Potential survey vehicles (CW from upper left): K-MAX rotorcraft, Star-Shadow hybrid airship, Fire Scout rotorcraft, Shadowcraft UAV, and Marin AUV.

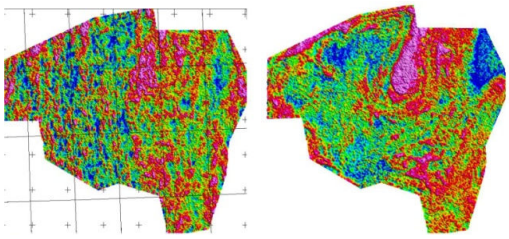

Figure 5. Bell Geospace's Full Tensor Noise Reduction – with improved terrain correction showing same data from 2004 (left) reprocessed in 2010 (right).

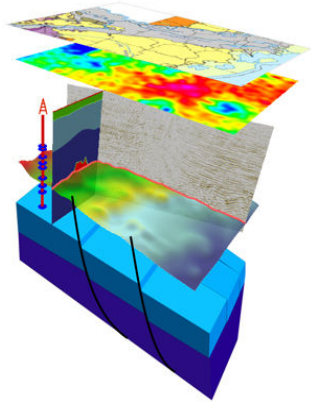

Figure 6. Image of ARKeX integrated processing workflow incorporating seismic, borehole, gravity (scalar and gradient), and magnetic data.

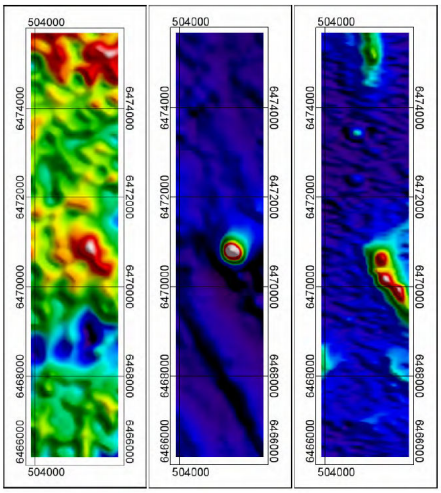

Figure 7. Fugro Airborne Surveys data collected over Kauring Test Range in Western Australia. L-R: Falcon™ gravity gradients, TMI, and EM (Tempest).

VALUE OF INFORMATION

The concept of Value of Information (VOI) is often used in assessing the overall benefit of a decision. VOI can be defined as the amount a decision maker would be willing to pay for information prior to making a decision. Value is often thought to be subjective: one person or company values an item differently than another. An attempt is made here to provide a more quantitative measurement of value for typical exploration activity using traditional methods.

In relation to gravity gradiometer survey capabilities, some questions to ask related to VOI include:

- What is the value of the find?
- How much will it cost to find it?
- How does the total cost of gravity gradiometry compare with other methods?
- Are there discriminators (technical or performance) that gravity possesses for this activity?
- Can I find the target with gravity gradiometry – where I couldn't find it by other means?

In considering these questions, it is illustrative to look at a theoretical example (continuum) of exploration targets. In Figure 8, signal detectability is plotted against wavelength for scalar gravity (blue curve), current gravity gradiometer systems (red curve), and proposed enhanced systems of the future (black curve). Each of these capabilities has a relative cost associated with their usage – represented notionally as one dollar sign for scalar gravity, two dollar signs for present-day gradiometry, and three dollar signs for future gradiometer systems. While one could argue whether these performance curves are correctly located or the relative cost indices are accurate, the reality is that gradiometry is more expensive than scalar gravity and future systems are expected to be more expensive than today's gradiometers. The figure also places notional bands around regions incorporating typical targets of interest. From the chart, it is clear than any of the three approaches (scalar gravity, current, or future gradiometers) can detect most basins, rifts, and bedrock targets. It also is seen that certain targets become harder as their spatial wavelength (i.e. diamonds) or depth (i.e. deeply buried targets) approach detectability limits.

Typical survey costs for airborne scalar gravity are on the order of $40-70 per line-km. Gravity gradiometry survey costs are more in the $120-175 per line-km range. Future systems – due to their improved performance or additional operational support requirements – might command prices in the $200+ per line-km range. Is this cost supported by the benefit produced from this data? Is true value being extracted from advanced gravity capabilities on the market today? The answer to both of these questions would seem to be yes. The fact that many users are returning as repeat customers of these advanced services would seem to indicate that value is present. The current survey contractors are keeping their fleets of gradiometer systems well committed – as evidenced by increasing line-km usage on a year-to-year basis. It is apparent that groups like Pinnacle Resources and Tullow Oil are extracting value (as previously described in this paper) resulting in key discoveries.

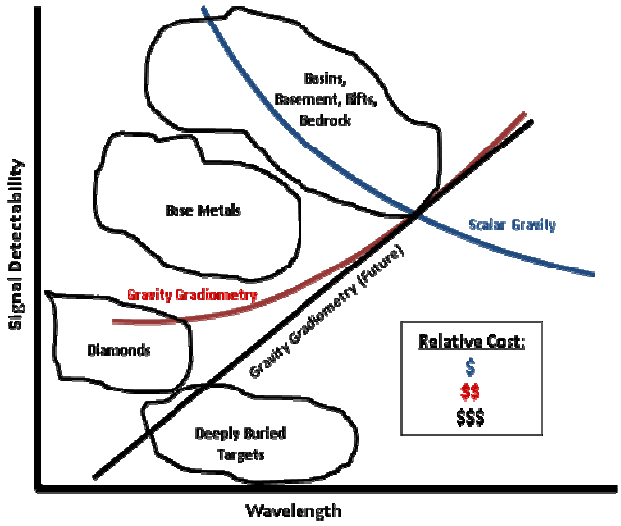

Figure 8. Notional representation of scalar gravity (blue), present-day gravity gradiometry (red), and projected enhanced gradiometer systems (black) performance capability.

CONCLUSIONS

Gravity gradiometry is progressing through adolescence and into adulthood as survey activity is on the increase, value is extracted from collected data, and general acceptance of the technique matures. The future holds great potential for this method as improved capabilities are brought on line.

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