Advances and Challenges in the Development and Deployment of Gravity Gradiometer Systems

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Summary
The past few years have witnessed significant advances and unparalleled interest in gravity gradiometer instrument technology as well as new deployment scenarios for various applications. Gravity gradiometry is now routinely considered as a viable component for resource exploration activities as well as being deployed for global information gathering. Since the introduction of the torsion balance in the 1890's, it has been recognized that gravity gradient information is valuable – yet difficult and time-consuming to obtain. This paper will summarize advances in gradient sensor development, and will also look at deployment scenarios and gradiometer systems that have been successfully fielded. Finally, we will briefly address the most significant challenges associated with improved gravity gradiometer operational capability including instrument and system intrinsic noise, vehicle dynamic noise, terrain noise, geologic noise and other noise sources.

Gravity Gradient Sensors
A boon in the development of new technologies for measuring gravity gradients has occurred over the past few years – spurred in part by rising oil, gas and commodity prices as well as a renewed commitment to basic research. A brief overview of these technologies is provided below:

Lockheed Martin Rotating Accelerometer Gravity Gradiometer
The Lockheed Martin gravity gradiometer, which incorporates high-precision, room-temperature accelerometers, has been operationally deployed for more than 25 years (Metzger, 1982; Hofmeyer, 1994). Recent improvements to this instrument concept include the digitization of critical signals to provide for lower noise and higher reliability. An additional benefit of this digital design is the reduction in size and weight for the installed system, making helicopter surveys possible (Lee, 2006). Gradiometers developed by Lockheed Martin have been deployed in commercial systems used by BHP Billiton (FALCON^{TM}; a partial tensor system with 8 accelerometers); Bell Geospace Inc. (Full Tensor Gradiometer – FTG) and by ARKeX Ltd. (also using an FTG system). Figures 1 and 2 depict Lockheed Martin gravity gradiometers and systems.

Gravitec Ribbon Sensor
Gravitec Instruments Ltd., a UK company with research operations based in Perth, Australia, has developed a novel concept for measuring gravity gradients. The Gravitec gravity gradiometer sensor is comprised of a single sensing element (a ribbon) that responds to gravity gradient forces (see Figure 3). External electronics provide control, measurement and modulation functions (Veryaskin, 2000). The sensor is versatile in that the sensing element can be configured for airborne, ground, static, or borehole deployment. Specifications for the sensor are detailed below:

- Dimensions: 400 x 30 x 30 mm
- Weight: 500 gms. Bandwidth: DC - 1 Hz
- Target Sensitivity: 5 E/√Hz flat response

- Gradients: Txy, Tyx, Txz, Tzx, Tyz, Tzy
- Modulation frequency: 5 - 10 Hz
  (information from www.gravitec.co.nz)

Figure 1. Lockheed Martin Gradiometers.

Figure 2. Gradiometer system: platform & electronics.

Figure 3. Gravitec ribbon sensor.

ARKeX Exploration Gravity Gradiometer (EGG)
ARKeX, a UK company, is in the advanced stages of testing a superconducting gravity gradiometer (Lumley, 2001). The EGG uses two key principles of superconductivity to deliver impressive performance: the "Meissner effect", which provides levitation of the EGG proof masses and "flux quantization", which gives the EGG its inherent stability. The EGG has been specifically designed for high dynamic survey environments. The EGG operates at four degrees above absolute zero (–269 °C) and is maintained vertical by a state-of-the-art stabilized platform. Figure 4 shows components of the EGG.
EGG performance is specified to be:

- Resolution: 1E/√Hz (target sensitivity)
- Bandwidth: 200 m – 60 km

- Measurements: Vertical gravity gradient (Tzz)
  (information from www.arkex.co.uk)

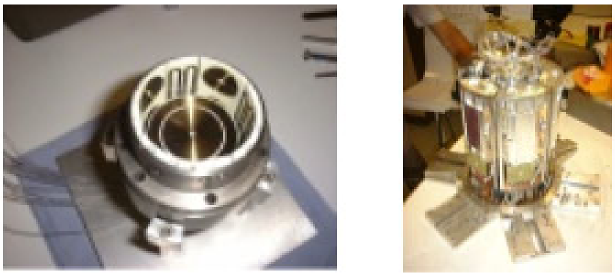

Figure 4. ARKeX EGG components.

Stanford University Atomic Interferometer (AI) Gravity Gradiometer

The atomic interferometer gravity gradiometer uses the fundamental principle of position measurement of free-falling objects – with the unique aspect of having atomic particles serving as the test masses. Atom trajectories are interrogated by coherent laser pulses to derive the necessary inertial information. Combining two sensors provides the basis for a gravity gradient measurement. This concept is enabled by laser cooling techniques to achieve the required velocity (wavelength) control for the atom source (ref. 1997 Nobel Prize in Physics) and by the production of bright, coherent atomic sources (ref. 2001 Nobel Prize in Physics). Figures 5 and 6 depict the AI gradiometer concept and prototype.

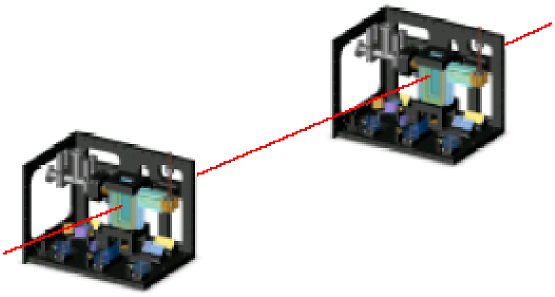

Figure 5. Dual AI accelerometer gradiometer concept.

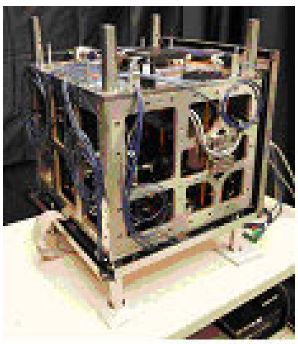

Figure 6. AI gradiometer prototype.

Gedex High-Definition Airborne Gravity Gradiometer (HD-AGG™)

Gedex is integrating a high-performance gravity gradiometer with an active six-degree-of-freedom isolation system to minimize vehicle dynamic inputs resulting in a robust system for exploration. The gradiometer design also uses superconducting components to achieve low instrument quiescent noise. Laboratory tests indicate that noise levels of 0.3 Eotvos at 3 Hz have been achieved (Main, 2006). Figure 7 shows a schematic of the gradiometer (without the stabilization system).

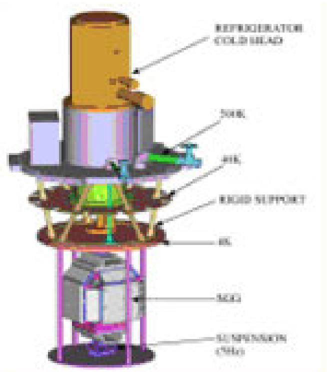

Figure 7. Layout of the Gedex HD-AGG™.

University of Western Australia (UWA) Gravity Gradiometer

The UWA Gravity Gradiometer uses an orthogonal quadrupole responder (OQR) design based on pairs of micro-flexure supported balance beams (Tryggvason, 2003). Performance from this gradiometer is anticipated to be better than 1 E/√Hz. Figures 8 and 9 show the gradiometer and system concept.

Figure 8. UWA Gradiometer.

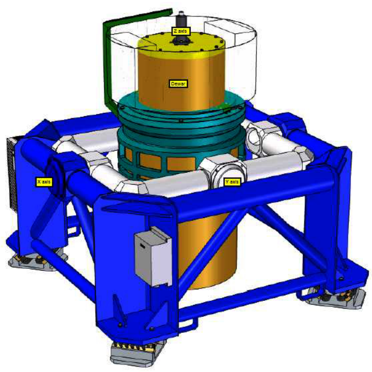

Figure 9. UWA system concept.

Gradiometer System Deployments

Gravity gradient measurements have been conducted using a wide variety of survey scenarios, from very simple static collection to the use of satellites. Figure 10 depicts a collage of survey mechanisms used to date including:

- US Navy Trident Submarine Gravity Sensors System (GSS)
- Lockheed Martin Land Gradiometer System (LGS) – for static measurements
- Cessna Grand Caravan (Model 208B) aircraft used by the BHP Billiton FALCON™ system, the Bell Geospace Full Tensor Gradiometer (Air-FTG®) system, and the ARKeX FTGeX.
- Surface ships (e.g. Seacor Surf) used by Bell Geospace for marine FTG surveys in the Gulf of Mexico and North and Barents Seas.
- Eurocopter AS350-B3 used by BHP Billiton for FALCON™ surveys.
- Zeppelin airship used by Bell Geospace and DeBeers for FTG surveys in Africa.
- CHAMP, GRACE and GOCE satellite systems to measure the earth's gravity field

Each of the examples identified has a common element of being viable for measurements in 'real world' applications. This is the rsult of significant effort focused on the development of stabilized platform systems to isolate the gradiometers from vehicle dynamics, as well as intricate system engineering activity to integrate the gradiometer with the host vehicle. In some cases (such as the Zeppelin airship and satellite systems) the focus on reducing high dynamic inputs has been extensive.

Figure 10. Gravity gradiometer deployment regimes.

Challenges for Today – and the Future

Gravity gradiometers don't discriminate – they 'see' everything and 'measure' everything. This fact has both positive and negative ramifications. While the intrinsic noise of gradient sensors steadily improves, the sensitivity to other noise factors also increases. For example, as the resolution of a gradient measurement improves by a factor of ten (say from 1 E to 0.1E), the influence of disturbing sources (e.g. terrain and subsurface geology) also increases by the same amount. Liken it to now seeing the trees instead of the forest – yet trying to identify individual timbers in the group. Many of the gravity gradient sensors under development promise lower intrinsic noise. Performance claims of better than $1E/\sqrt{Hz}$ for the ARKeX EGG, Stanford AI, Gedex HD-AGG™ and UWA OQR sensors point to the need for better measurement of terrain as well as a way of dealing with the subsurface variations that will now be observable. Figure 11 illustrates the concept of "stripping away" layers of noise combined with signal measured by the gradiometer – with the top layer indicating the total measured gradient, and subsequent lower layers indicative of the instrument/system, terrain, subsurface and other noise sources. Ultimately, the signal of interest lies beneath all of the disruptive noise sources – and the challenge in processing is to get past the noise to the geology that is the source of the signal.

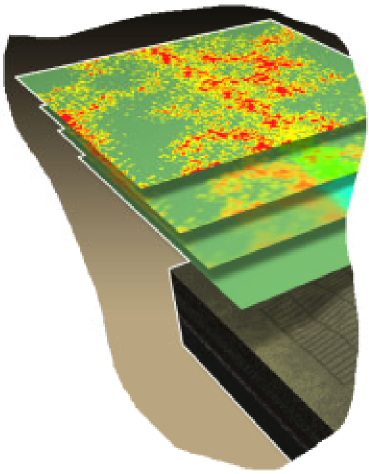

Figure 11. Multiple signal sources.

Conclusions

Significant advancements in gravity gradiometer instrumentation and deployment have been realized in recent years and the gradiometer is fast becoming a widely accepted tool for the geophysicist. The gravity gradiometer is opening new doors of opportunity in the resource exploration, hydrocarbon production monitoring, and emerging geophysical markets. The challenges for today – and the future – will be to continue to get the most signal information from such surveys through improvements in both instrumentation and processing.

References

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