

Gravity gradiometry – today and tomorrow

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ABSTRACT

Gravity gradiometry is coming of age as a standard exploration process. The acceptance and scope of airborne surveys is on the rise, with success stories published and documented. A renewed interest in marine surveys for hydrocarbons is also occurring. New sensor and system developments are nearing a point where they may be ready for field tests and commercial deployment. It is accurate to say that the state of gravity gradiometry is healthy in today's commercial marketplace. As good as this is, there remain a number of challenges and opportunities for full utilization of gravity gradiometry as a tool for the explorationist. A number of questions and concerns need to be addressed ranging from sensor performance to operational efficiency to data handling to educating users. While these challenges might seem daunting, the future looks bright for gradiometry as innovation and acceptance continue to grow. In fact, the time seems right to ask some thought-provoking "What if" questions: Is the era of gradiometry just beginning to dawn? How will the future unfold for this capability? What is the optimal exploration system? What if multiple gravity components could be measured at the same time (i.e. scalar gravity, 2nd order tensors, and 3rd order tensors)? Are the physical limits of measurement already being met? What if data were available without limits throughout the world?

Key words: gravity, gradiometry, airborne, survey

INTRODUCTION

Gravity gradiometry is becoming an accepted and important tool for the resource explorer. Only 10 years ago this capability was being introduced to the commercial marketplace – with both a sense of anticipation and skepticism. A decade later, it is evident by a steady increase in demand and usage that this capability has become mainstream. Successes have been proclaimed, and yet challenges remain. This paper will attempt to recap the present situation with gravity gradiometry, look at some of the challenges, and then take a futuristic view to what's ahead.

THE STATE OF GRAVITY GRADIOMETRY

During the past decade, gravity and gravity gradiometry has received a significant amount of attention. Focused workshops held during the 2001 SEG meeting in San Antonio ("Gravity Gradiometry Workshop"); 2002 SEG meeting in Salt Lake City ("Noise in Gravity Data"); 2003 EGS-AGU-EUG Joint Assembly in Nice, France ("Gravity Gradiometry: Measurements, Sensors and Applications"); 2004 ASEG Annual meeting in Sydney, Australia ("Airborne Gravity 2004"); numerous KEGS special workshops held in conjunction with PDAC meetings; 2007 EAGE "EGM 2007" International Workshop in Capri, Italy; 2008 EAGE Workshop in

Bahrain ("The Future of Non-Seismic Methods"); and the 2008 SEG Workshop in Las Vegas ("Gravity in Motion") all highlight a rise in interest and understanding. The fact that this SAGA meeting has a dedicated track on gravity gradiometry supports this growth in interest. A planned workshop on gravity gradiometry in conjunction with the 2010 ASEG meeting in Sydney also highlights ongoing interest. As a testimonial, the decennial *Exploration 07* meeting in Toronto, Canada included a talk by Steve Thomson from Fugro suggesting that airborne gravity gradiometry is one of the top five developments in the past decade (Thomson, 2007).

Another mark of industry acceptance is the number of actual gravity gradiometer survey systems deployed. As of 2008, a total of 10 systems have been commercially deployed. These have been used in land, marine and airborne applications (DiFrancesco, 2007) with good success. This might not seem like a large number, but consider that the first commercial system was fielded in 1998; the rate of acceptance appears to be growing. Companies like ARKeX and their BlueQube™ gravity gradient offering, Bell Geospace with the Air-FTG® Full Tensor Gradiometer, and Fugro Airborne Surveys (using the heritage BHPBilliton *FALCON*™ system) have all found success and niches in the exploration marketplace. Figure 1 shows the cumulative line-

kilometers of gravity gradient surveys conducted over the past 10 years, with an upward trend as market acceptance grows.

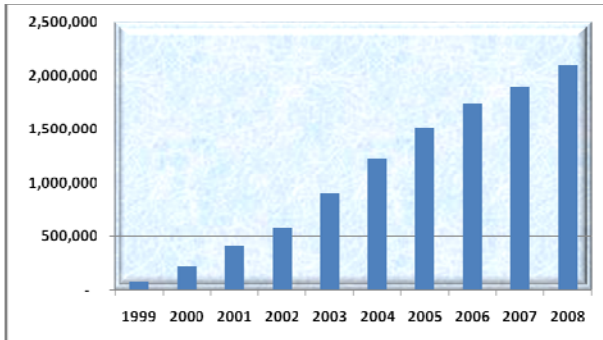


Figure 1. Cumulative line-kilometers of gravity gradiometer surveys (airborne and marine) conducted from 1999 through 2008.

Another measure of the acceptance of gravity gradiometry is the number of repeat users of this data. All three commercial survey companies (ARKeX, Bell Geospace, and Fugro Airborne Surveys) have reported that repeat business is a significant component of their portfolio.

Deployment scenarios have also broadened over the past decade, and include a wide range of survey vehicles (Lee, 2001). Some of these include: single engine fixed wing aircraft such as the Cessna Grand Caravan; multi-engine fixed wing aircraft like the DeHavilland Twin Otter and Basler BT-67; rotary wing helicopters such as the Eurocopter AS350; a Zeppelin airship; and marine vessels of various shapes and sizes. This reflects the fact that multiple paths are being pursued to provide better data and more efficient survey operations.

Finally, from a state-of-the-community perspective, it is important to note that many development projects are underway around the world seeking to provide alternative capabilities to the presently-deployed Lockheed Martin gravity gradiometer sensors. These projects include:

- AOSense Atomic Interferometer (AI) gravity gradiometer
- ARKeX Exploration Gravity Gradiometer (EGG)
- GEDEX High Definition Airborne Gravity Gradiometer (HD-AGG™)
- Gravitec Ribbon Sensor Gravity Gradiometer
- University of Twente MEMS gravity gradiometer
- University of Western Australia VK-1 gradiometer

CHALLENGES

While the advances in gravity gradiometry are becoming well documented, there remain a number of challenges to reaching the full potential of this capability. Let's take a brief look at some of the major challenges impacting the full use of gravity gradiometry:

1. Dynamic conditions:

Aircraft turbulence and acceleration result in a less-than-optimal operating environment in which very sensitive gravity gradient measurements are made. These factors are addressed via stabilized platform systems that house the gravity gradiometers, but even with this, dynamic noise is a significant impediment to conducting optimal surveys. The application of post-mission compensation techniques greatly attenuates this noise, and makes meaningful data collection possible. Even with these provisions, airborne operations are often limited due to the dynamic conditions (including weather) and result in reduced productivity.

2. Survey operations:

Gravity gradiometer surveys operate as low and slow as possible to take advantage of signal strength and data density. Aircraft on survey typically fly in the 50 meter/second range at 80 to 100 meters altitude. The relatively slow speed provides a limit for aerial coverage rate, which if increased could yield higher production. This limitation is in part a function of the gradiometer sensor measurement bandwidth which is currently limited by the accelerometer disk rotation rate of deployed systems.

3. Geophysical variations:

Another challenge to the efficient collection of gravity gradient data is the influence of terrain, vehicle elevation, and naturally-occurring geologic density variations. While the intrinsic noise of gradient sensors steadily improves, the sensitivity to other noise factors also increases. Many of the gravity gradient sensors under development promise lower intrinsic noise. Performance claims of better than $1E/\sqrt{Hz}$ 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 2 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.

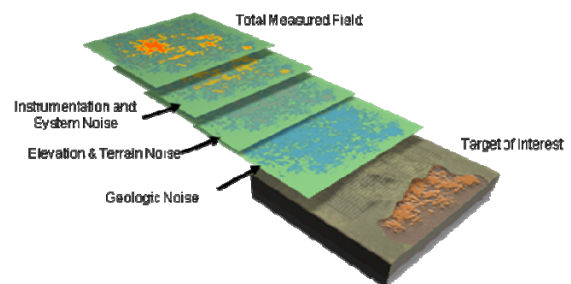


Figure 2. Notional depiction of layered noise sources masking target of interest in a geologic survey. Noise includes contributions from sensors and systems, topography, and underlying geology variability.

4. Industry understanding and acceptance:

While there has been a progression of education about gravity in the market place, there remains a significant need for communicating the benefits of gravity gradiometry to the user community. Progress is slow – but steady. Figure 3 shows a metric of submissions to the SEG over the past 22 years covering seismic and gravity topics. It is apparent that seismic papers are plentiful, while gravity shows a relatively flat rate of entries. Obviously, a challenge remains to raise this capability to a higher level of understanding.

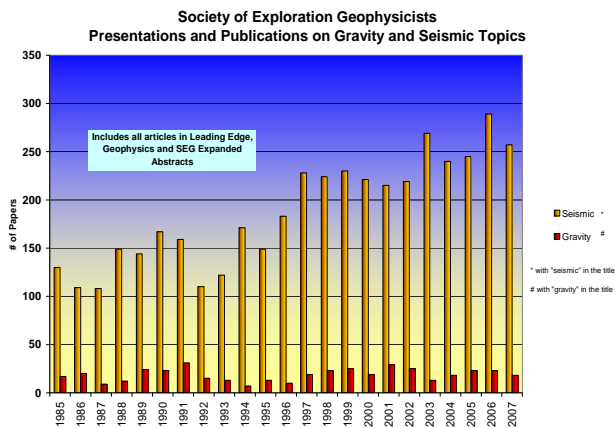


Figure 3. Society of Exploration Geophysicists (SEG) record of publications on seismic and gravity topics (1985-2007). Seismic growth is evident while gravity is languishing.

5. Use restrictions:

Hardware and data export controls pose another challenge for the growth of gradiometry. Today's deployed systems have restrictions due to their military heritage and require an export license from the U.S. State Department. While this is usually not a show-stopper for most users, the process does require a planning lead time that often is in conflict with commercial business cycles.

THE FUTURE OF GRAVITY GRADIOMETRY

It's time for a little speculation and looking into the crystal ball to see where gravity gradiometry is headed in the future. Improved sensor performance appears to be a reasonable expectation – both from advances with the current accelerometer-based systems to the many active development programs underway. Enhanced performance (defined here to mean lower intrinsic sensor and system noise) is anticipated and should open up greater utility and missions for surveys. In addition to lower sensor/system noise, improvements in dynamic noise rejection through superior isolation and compensation techniques are anticipated as operational experience is gained. Supplemental capabilities are also realizable from the integration of multiple measurements. For example, scalar gravity combined with both second and third order tensor measurements would seem to be a very attractive offering. In addition, combining gravity, gradient measurements, magnetics,

and electro-magnetics would address the full breadth of potential fields in a survey system. A brief look at just one of these possibilities is provided here.

Third-order gravity tensor data:

The addition of more fidelity in tensor measurement has the benefit of improved lateral resolution. A limitation in current second-order gravity tensor systems (FTG/Falcon) is the lower limit on the spatial resolution. Lower vessel speed solutions (helicopter & airship) have mitigated this to some point, but these approaches come at a disproportional higher acquisition cost. A third order gravity tensor system would probably have little interest for applications requiring deep penetration (i.e. hydrocarbon plays); but the increased sensitivity to shallow sources and the aforementioned improved lateral resolution would have benefit to certain mineral exploration scenarios: kimberlite detection, covered placer gold deposits, channel iron deposits, and channel uranium deposits. Hydrological surveys mapping aquifers in paleochannels would be another area for usage.

Assuming the introduction of a third order gravity tensor system, perhaps it is worth considering the deployment of a stacked system which simultaneously acquires gravity (deep), gravity gradient (shallower) and second gravity gradient (third-order tensor; near surface), combining the best of all worlds with respect to bandwidth. In this scenario, two of the acquisition streams are used to enhance the third. For example, an enhanced gravity gradient measurement where the long wavelength component is enhanced by the gravity data, and the short wavelength component is enhanced by the third order tensor data has strong appeal.

The increased sensitivity to nearby sources is of course a double-edged sword requiring greater attention to near-field variable masses (i.e. self-gradient) and positioning. The third order gravity tensor signal will fall off with r^4 . Hence effects from the survey vessel itself will now be even more significant than what has been the case for current second-order gravity tensor systems. Terrain effects will dominate over any near-surface geological signal; and errors in the digital terrain model used for terrain corrections may now introduce noise with an amplitude and wavelength content similar to the near-surface geology signal. This will place even greater demands on the accuracy of the positional data from the aircraft and the digital elevation model used for terrain corrections.

WHAT IF...

It might be interesting to identify some of the 'wish list' items associated with gravity gradiometry. Many of these are not so far-fetched and are actively being pursued. So, here is a "Top 10" list for consideration as gradiometry moves from childhood into adolescence:

1. **What if...**airborne surveys could be flown at faster speeds and coverage rates and in higher dynamic conditions?
2. **What if...**gravity gradients could be measured with greater precision than available today?
3. **What if...**survey costs for airborne and marine gravity gradiometry were significantly lower?
4. **What if...**scalar gravity plus second and third order tensor gradient data were available in a single service offering?
5. **What if...**gravity (scalar and tensor), along with both magnetics and EM, were configured on the same survey aircraft and an economy of scale were realized?
6. **What if...**terrain measurement/compensation and geologic noise were addressed to higher fidelity?
7. **What if...**there were no restrictions on usage and dissemination of gravity gradient data?
8. **What if...**answer products incorporating gravity gradient data became the standard for making exploration decisions?
9. **What if...**a series of significant exploration successes were attributed to gravity gradiometry?
10. **What if...**people really understood what gravity gradients can do for them?

CONCLUSIONS

The past decade has shown what is possible with gravity gradiometry in resource exploration surveys. There have been growing pains as this new capability has been introduced, yet now that it has become a more mainstream practice, the future looks very bright. The foundation has been laid with commercial survey activity, and many new offerings and improvements are on the horizon. Growth will come from addressing the technical, cultural, and practical challenges. The value proposition for gradiometry looks strong – and it is expected that the days ahead will yield full potential.

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