

# **GRADIOMETRY: The New Standard**

The Evolution of Airborne Gravity Gradiometry (AGG) for Oil and Gas Exploration

**Christopher Van Galder and Alessandro Colla (Xcalibur Smart Mapping)**  
**Dan Difrancesco (Niagara Gravity Consulting)**

## OVERVIEW

The use of Airborne Gravity Gradiometry (AGG) for oil and gas exploration has expanded significantly since the year 2000, particularly in frontier areas. In some geological environments the use of this technology has become an essential tool and has been given the credit for some of the most important discoveries of the last decade. The ability of the AGG technology to cover very large areas in a short period of time has allowed explorers to optimise the amount of seismic acquired prior to drilling while significantly shortening the exploration cycle. In frontier evaluation the use of AGG remains an essential component of exploration programmes and has almost completely replaced conventional gravity acquisition.



Figure 1: Digital FALCON AGG ready for installation.  
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But what exactly is AGG, how does it work, and why has its application become an essential component of any exploration programme? We will try to explain it by sharing a bit of history of the development of this technology from its origins to the most recent advances.

## AGG – A LONG DEVELOPMENT HISTORY

Since the introduction of the torsion balance in the 1890s, it has been recognised that gravity gradient information is very valuable, yet difficult and time-consuming to obtain. Baron Loránd von Eötvös developed the first torsion balance instrument for field use with an accuracy of 10<sup>-9</sup> per sec<sup>2</sup> (this CGS unit ultimately received the name Eötvös or E). The only problem was that the measurements were very time consuming. Improvements in torsion balance design led to the introduction of the Oertling and Askania torsion balances in the 1920s, with similar accuracy as Eötvös's early instrument, only smaller in size.

Until its discontinuation in the late 1930s, the torsion balance contributed to the discovery of 79 oil fields in the Gulf coastal region of Texas and Louisiana. It is estimated that these fields contained petroleum reserves of approximately one billion barrels. Unfortunately, torsion balance field surveys were laborious and expensive. The instrument had to be housed in an insulated portable hut to reduce temperature variations while mounted on an aluminium baseplate for stability. Readings were required at three instrument orientations, at 120-degree intervals, with one orientation repeated. After each rotation, one hour was required for the beams to stabilise before readings could be made. A total of four hours were required at each measurement location or station. In 1930, about 125 of these instruments were in use in oil exploration worldwide. These became obsolete, not because they produced inferior results, but because the operational challenges were so great, and the use of spring gravity meters were easier and more efficient for the field operator. Fast forward to the 1970s when the need for gravity gradient measurements re-emerged – not for exploration purposes, but for



Figure 2: Improvement of noise levels with time obtained with equipment development and enhanced processing techniques. © Xcalibur Smart Mapping

assisting with missile launch and navigation functions. The US Air Force and US Navy and Ballistic Missile Defence Organisation (BMDO) all recognised the benefit of being able to make moving-base measurements of gravity gradients. The result of this interest was the deployment, in the 1980s, of the Gravity Sensors System (GSS) for the US Navy Fleet Ballistic Missile Submarine (Trident II) Navigation programme and the Gravity Gradiometer Survey System (GGSS) for the Air Force Geophysics Lab (AFGL). These systems incorporated the Bell Aerospace (now Lockheed Martin)-designed gravity gradiometer systems using full-tensor gradiometers (FTG) which measured all the independent gravity tensor components with accelerometers housed in three discrete instruments.

## BHP SEES POTENTIAL

At the same time, BHP engaged in an R&D effort with Bell/Lockheed Martin to develop a unique gravity gradiometer system for mineral exploration applications (e.g., diamonds). The intention was to build the next generation of equipment – one that would be a game-changer in resource exploration. The project began with a thorough investigation of existing exploration techniques and equipment. The one that showed the most promise was gravity gradiometry and the equipment was the FTG built by Lockheed Martin. BHP knew there were limitations for the technology when deployed on an aircraft. The dynamic airborne environment is orders of magnitude more turbulent than that of a submerged submarine. This vertical acceleration causes significant errors in the FTG

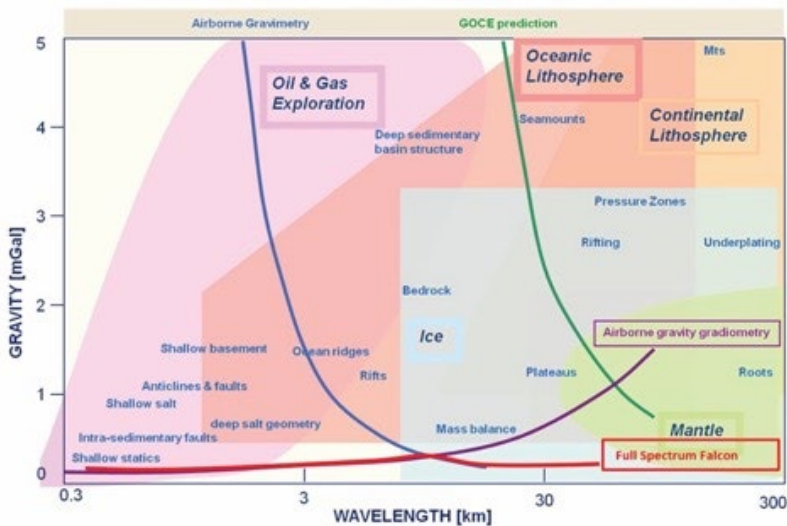


Figure 3: This plot illustrates the error profiles for airborne gravity, airborne gravity gradiometry and satellite gravity. The geologic features shown above the error curves are detectable at indicative wavelengths and anomaly amplitudes. The AG error curve decreases with increasing wavelength; the AGG error curve increases with increasing wavelength. Combining an AG and AGG system together provides the highest quality vertical gravity data. © Xcalibur Smart Mapping.

## FALCON® AGG TAKES FLIGHT

The results showed near-constant noise levels from the FALCON® AGG systems at all levels of turbulence. The next major modification was to build-in a second set of accelerometers, as well as increasing the sensor separation distance (baseline), to reduce noise further. This enabled the design to yield two near-independent gradiometers in one instrument. This allows for every data point to be a repeatability measurement. These changes allowed BHP to improve the gradiometer into a revolutionary exploration tool for mineral exploration. During their exclusive ownership of the equipment, they acquired nearly 2,000,000 line-km of exploration data.

They made countless discoveries until they exhausted all their mineral properties. BHP then divested the technology to Fugro Airborne Surveys, and subsequently to CGG. Xcalibur Multiphysics is now the proprietor of this technology. Numerous improvements to the FALCON® AGG systems over the past 25 years have yielded significantly better operating performance.

These include FALCON® Plus: a digital design which improves upon the original analogue functionality of FALCON® (this was first deployed in 2005); HeliFALCON® AGG: installation of the digital FALCON® AGG into a B3 helicopter for lower and slower data collection surveys yielding higher resolution data; and Full Spectrum FALCON®: an integrated system that melds the inputs from the gradiometer with an on-board gravimeter to assess all wavelengths of interest.

In addition to improvements noted for the FALCON® AGG systems, Lockheed Martin also embarked on an ambitious design called the Enhanced FTG (eFTG) that included the best features of FALCON® AGG integrated into a full-tensor configuration. This larger, more capable system is currently deployed by Austin Bridgeport for airborne surveys. Lockheed Martin remains the sole commercial supplier of gravity gradiometer systems (e.g. FALCON® AGG, FTG and eFTG) to the resource exploration industry. Both airborne gravity (AG) and AGG systems (Figure 1) measure derivatives of the gravity potential. While the noise in AG-acquired vertical gravity data decreases as wavelength increases, the noise in AGG-acquired vertical gravity increases as wavelength increases. Figure 3 illustrates the relationship between noise and wavelength for AG, AGG and satellite gravity. The optimal combination of both AG and AGG data can result in high quality gravity data with low noise across the entire acquisition spectrum.

The FALCON® AGG system, after its initial development by BHP, has been progressively improved over the last two decades with the many enhancements described above. Most recently the industry recognised the need to measure both short and long wavelength to improve the detection of the wide bandwidth gravity anomalies of geological interest. It is to fulfil this need that equipment like the Xcalibur's sGrav (gravimeter), measuring AG, has been developed and deployed simultaneously with the FALCON® AGG systems.

Each dataset is processed separately to obtain vertical gravity. For the AGG data, vertical gravity is derived from the measured gradients either via integration in the Fourier domain or an equivalent source process. For the AG data, standard gravity processing methods are used to obtain the vertical gravity. With the AG and AGG vertical gravity products, error curves for AG and AGG are derived as a function of wavelength as illustrated in Figure 4. These two error curves allow the determination of the ideal cross-over wavelength. Plotting these estimated errors together allows the visualisation of results to find the wavelength at which the two error curves intersect. The wavelength at this intersection is the ideal cross-over point for merging the AGG and AG gravity. Once the centre wavelength of cross-over filters is determined, the two datasets are merged to obtain the optimal dataset of low noise, wide bandwidth gravity.

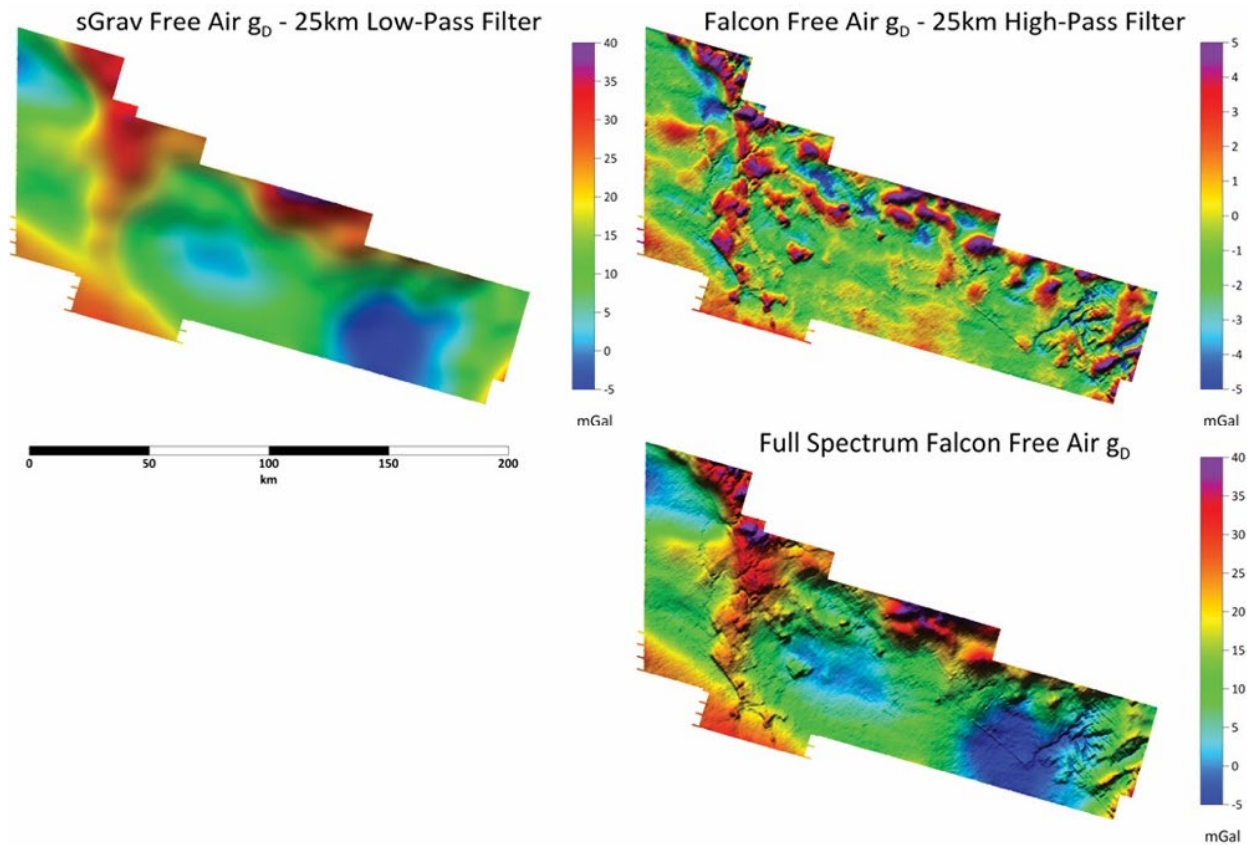


Figure 4: The Full Spectrum FALCON solution combines the medium to long wavelength data from the sGrav system (upper left) and the short to medium wavelength data from the FALCON® AGG system (upper right). These data are added together to give the Full Spectrum FALCON® product (lower right). © Xcalibur Multiphysics.

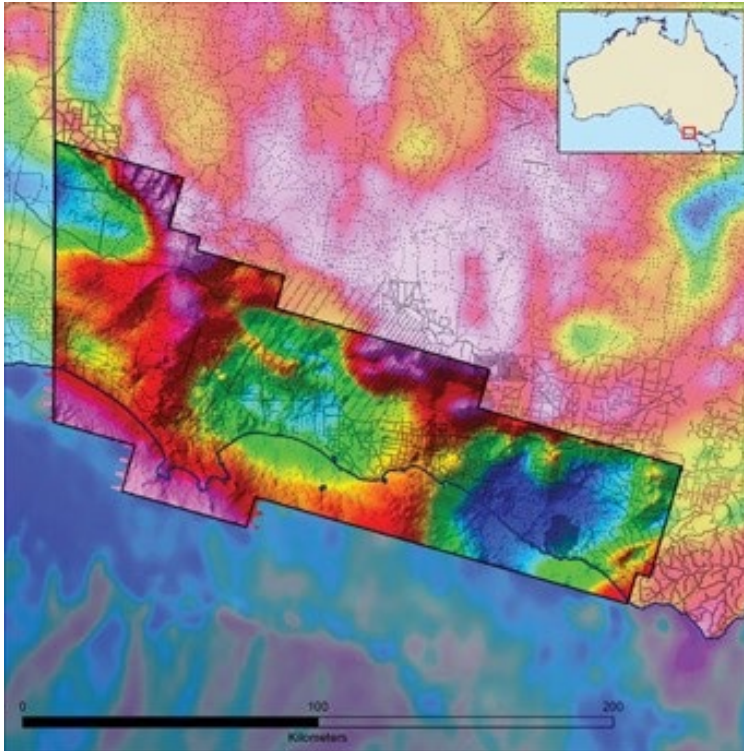
## VICTORIA (AUSTRALIA) CASE STUDY

To demonstrate the result of the combination of AG and AGG we show data examples from a recent survey flown for the Geologic Survey of Victoria in Australia. The survey covered an area of about 15,000 km<sup>2</sup> at a line spacing of 500m along the southern coast of Victoria. Both AGG and AG data were collected at the same time on the same aircraft. The AGG system was a FALCON® AGG and the AG system was an sGrav. From these two datasets, it is possible to estimate the AGG and AG gravity errors to determine the optimal cross-over wavelength to merge them.

Using a 25 km cross-over wavelength, the sGrav data (after application of a low-pass filter) and FALCON® AGG data (after application of the high-pass filter) were added together to create the Full Spectrum FALCON® product. These results are shown in Figure 4. The noise estimate for this survey was 0.3mGal.

The survey was acquired as part of the 'Victoria Gas Program' and covered both onshore and offshore regions, providing full coverage across the transition zone where little or no other data had been acquired. The resulting anomaly map (Figure 5) clearly shows both deep basement structures, where the sedimentary sequence is thicker, as well as more subtle intra-sedimentary or shallow geological structures. Since the initial deployment of AGG, there has been a continuous improvement of data quality as a result of both equipment development and processing techniques. The acquisition of data covering the full spectrum of geological responses of interest has been of increasing importance for oil and gas exploration. Collection of the highest quality vertical gravity data across a broad

bandwidth is best done by utilisation of both a conventional AG and an AGG system. Each of these system types has its advantages and weaknesses, but together they make a powerful exploration tool.



*Figure 5: Final image of Full Spectrum FALCON® AGG Data superimposed to public domain data and land gravity points onshore.  
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