Comments on “Magnetic Field Gradients and Their Uses in the Study of the Earth’s Magnetic Field” by Harrison and Southam

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HARRISON and SOUTHAM (1991) point out the many benefits of magnetic gradiometry including the enhancement of short-wavelength (nearby) anomalies relative to long-wavelength (far away) anomalies, and the heavy attenuation of diurnal or magnetic storm variations usually present in total-field measurements. In addition, they point out that gradient profiles, like field component profiles, can be used to test for anomaly linearity and strike angle. HARRISON and SOUTHAM (1991) propose using a SQUID gradiometer to measure the gradient tensor components due to crustal sources and suggest that SQUID gradiometers can be made sensitive enough to measure sea-floor spreading anomalies from orbiting satellites.

We believe that all of the benefits attributed to tensor gradiometry can be obtained with total-field gradiometry as well. First we will describe the capabilities of existing gradiometer systems, then we will describe how they can be used to obtain the same information as SQUID gradiometers.

1. Existing Airborne Total-Field Gradiometers

Airborne systems using several optically pumped magnetometers to measure the along-track (G_x), across-track (G_y), and/or vertical (G_z) total-field gradients have been in existence for several years (HARDWICK, 1984; HOGG, 1987; HOOD and TESKEY, 1989). The sensor-noise level of cesium-vapor magnetometers is typically 0.015 nT (HARDWICK and ONNO, 1991). The baselines of the gradiometers vary with aircraft type but the Convair 580 aeromagnetic survey aircraft operated by the National Research Council of Canada has a vertical baseline of 5.67 metres and an across-track baseline of 31.27 metres. The along-track gradient is calculated from the time rate of change of the total-field and the groundspeed (approximately 220 knots). This leads to the following sensitivities for the Convair system:

$$G_x \text{ sensitivity} = 0.0012 \text{ nT/m,}$$

$$G_y \text{ sensitivity} = 0.0006 \text{ nT/m,}$$

$$G_z \text{ sensitivity} = 0.0027 \text{ nT/m.}$$

However, sensitivity is only a measure of the smallest possible quantity that can be measured if there are no sources of noise in the system.

For inboard gradiometer systems, the largest source of noise is manoeuvre noise generated from magnetized materials in the aircraft. After modelling and removing most of this noise, the following noise levels are routinely achieved on the Convair 580 gradient channels (during approximately “straight and level” survey flights, in the frequency band 0–1.0 Hz):

$$G_x \text{ noise level} = 0.004 \text{ nT/m,}$$

$$G_y \text{ noise level} = 0.004 \text{ nT/m,}$$

$$G_z \text{ noise level} = 0.010 \text{ nT/m.}$$

The residual noise on all three gradient channels is predominantly at frequencies above 0.1 Hz and it is thought to be due to air turbulence. This is because the aircraft’s magnetic sources cannot be modelled exactly and as the aircraft responds to air turbulence some residual noise is generated.

Because aeromagnetic surveys are performed near sea-level, crustal sources are usually only hundreds of metres to a few kilometres beneath the sensors. Marine gradient anomalies typically have amplitudes of 0.05 nT/m at sea-level. Consequently the signal-to-noise ratios for unfiltered marine anomalies measured by the Convair aeromagnetic gradiometer is typically 10:1 (for G_x and G_y) and 5:1 (for G_z). Of course many marine anomalies have wavelengths of several kilometres and so the measured profiles can be filtered to improve the signal-to-noise ratio. (For an aircraft speed of 220 knots, a 1-km wavelength anomaly corresponds to a frequency of 0.11 Hz.) Consequently the signal-to-noise ratios given above considerably underestimate the true signal-to-noise ratios in most instances.

SQUID gradiometers are presently very expensive and, because of their cryogenic requirements, inconvenient to use compared to total-field magnetometers. An inboard SQUID gradiometer system would suffer from the same limitations as an inboard total-field gradiometer system, namely uncompensated noise at frequencies above 0.1 Hz. A towed SQUID gradiometer would not have this noise source (assuming the tow-body is constructed from non-magnetic materials), but WILSON (1988) has reported that moving SQUID gradiometer systems exhibit enhanced noise levels compared to stationary SQUID gradiometers. Thus, neither inboard nor towed SQUID gradiometer systems will be capable of reaching the noise floor achievable with stationary SQUID gradiometers. However, the signals from marine anomalies are typically much larger than the noise levels expected on the SQUID gradient channels, and the resulting signal-to-noise ratios will be very similar to those on the Convair total-field gradiometer.

Spaceborne total-field gradiometer systems are not practical because of the large baselines which would be required to obtain the sensitivity of 5×10^{-6} nT/m (HASTINGS *et al.*, 1985). We agree that SQUID gradiometers would be more practical for spaceborne applications, if indeed it can be demonstrated that a spaceborne gradiometer will provide more information on crustal or upper mantle sources than airborne total-field gradiometers. (For example, spaceborne gradiometers may be superior to airborne gradiometers when mapping anomalies with wavelengths of several hundred kilometres.)

2. Capabilities of Airborne Total-Field Gradiometers

Recently MARCOTTE *et al.* (1991) have demonstrated that for survey lines crossing anomalies due to two-dimensional sources at an angle θ ,

$$\frac{-G_y}{G_x} = \tan \theta. \quad (1)$$

Thus, if $\tan^{-1}(-G_y/G_x)$ is constant then the source is two-dimensional and the crossing angle is given by Eq. (1). Once the source has been established as two-dimensional, any one of a number of inversion methods can be applied to the profiles to obtain the source parameters. The resulting depth, width, and magnetization estimates should be multiplied by $\cos(\theta)$ to correct for the strike angle.

MARCOTTE *et al.* (1991) also pointed out that the vertical gradient (G_z) can be calculated from measured G_x and G_y profiles if the source has been determined to be two-dimensional. In some total-field gradiometers, the noise levels on G_x and G_y are much lower than on G_z because of their longer baselines. Consequently, this technique may yield lower-noise estimates of G_z than direct measurement for two-dimensional sources. For a more detailed description of the work, please refer to MARCOTTE *et al.* (1992).

NELSON (1986) has used vertical gradient (G_z) measurements to analyze sea-floor spreading anomalies. It was concluded that inversion using G_z is preferable to inversion using total-field data because the transition zones (from positive-to-reverse magnetization or vice versa) are better defined and there is less overlap of anomalies in the G_z data. This is consistent with the predictions of HARRISON and SOUTHAM (1991) for gradient tensor measurements.

NELSON (1988) has shown that the gradient tensor components can be derived from gridded measurements of either the vertical gradient or both horizontal gradients of the total-field. The resulting estimates of the gradient tensor components will have the same signal-to-noise ratio as the original horizontal or vertical gradient measurements. PEDERSEN and RASMUSSEN (1990) have used a similar technique to generate maps of the gradient tensor components and rotational invariants over the Siljan impact region.

3. Conclusions

We agree with HARRISON and SOUTHAM (1991) regarding the benefits of magnetic gradiometry vs total-field or component magnetometry. However, we believe that airborne total-field gradiometry performed with multiple optically-pumped magnetometers is more practical than airborne or spaceborne SQUID gradiometry. This belief is based on previous work with total-field gradient measurements which either demonstrates the same benefits of SQUID gradient tensor measurements described by HARRISON and SOUTHAM (1991), or allows one to calculate gradient tensor components from total-field gradient measurements. In addition, SQUID gradiometers have not been commercially produced for airborne survey work because they are expensive, inconvenient to work with, and exhibit enhanced noise levels when they are moved. We nevertheless agree that if it can be demonstrated that spaceborne gradiometers provide more information on crustal or upper mantle sources than airborne gradiometer systems, then SQUID gradiometers must be used, since the baselines required of total-field gradiometers to achieve noise levels of 5×10^{-6} nT/m are not practical.

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