Measuring gravity gradient in rugged terrain: HeliFalcon survey in Aso-Oguni, Japan

Tianyou Chen[1]* and Mark Dransfield[1] examine the technical challenges presented by the rugged terrains, describe aspects of the data acquisition and processing, and present the survey results.

Introduction

Since the first Falcon AGG survey in 1999 (van Leuwen et al., 2000), fixed-wing airborne gravity gradiometry (AGG) has proved to be a valuable tool for mining and oil and gas exploration (Dransfield, 2007). The more compact digital Falcon AGG allowed the system to be installed in a helicopter and helicopter AGG surveys began in 2006 (Boggs et al., 2007). Compared with fixed-wing aircraft, the helicopter platform can fly surveys low and slow, offering superior spatial resolution as well as an improved signal-to-noise ratio (Dransfield, 2007). The superior spatial resolution and improved signal-to-noise ratio provided by helicopter AGG enhances its capability to detect smaller targets and better delineate subtler features. Dransfield and Christensen (2013) reported a HeliFalcon performance of 6 Eö RMS at 45 m resolution in vertical gravity gradient, by far the finest spatial resolution of any airborne AGG system.

Another advantage afforded by helicopter AGG is its capability to follow terrains more closely especially in areas of high relief. Christensen and Hodges (2013) compared the vertical gravity gradient from HeliFalcon with the simulated fixed-wing result over the Iron Range survey in the Canadian Rocky Mountains where the terrain variation reaches 1900 m. They showed that in this terrain, a fixed-wing survey would have to fly at ground clearances of more than 1000 m for much of the survey area. This high ground clearance would have greatly suppressed the signal at short wavelengths and degraded the spatial resolution.

In this paper, we look at the HeliFalcon AGG survey conducted in the Aso-Oguni area exploring for geothermal fields,

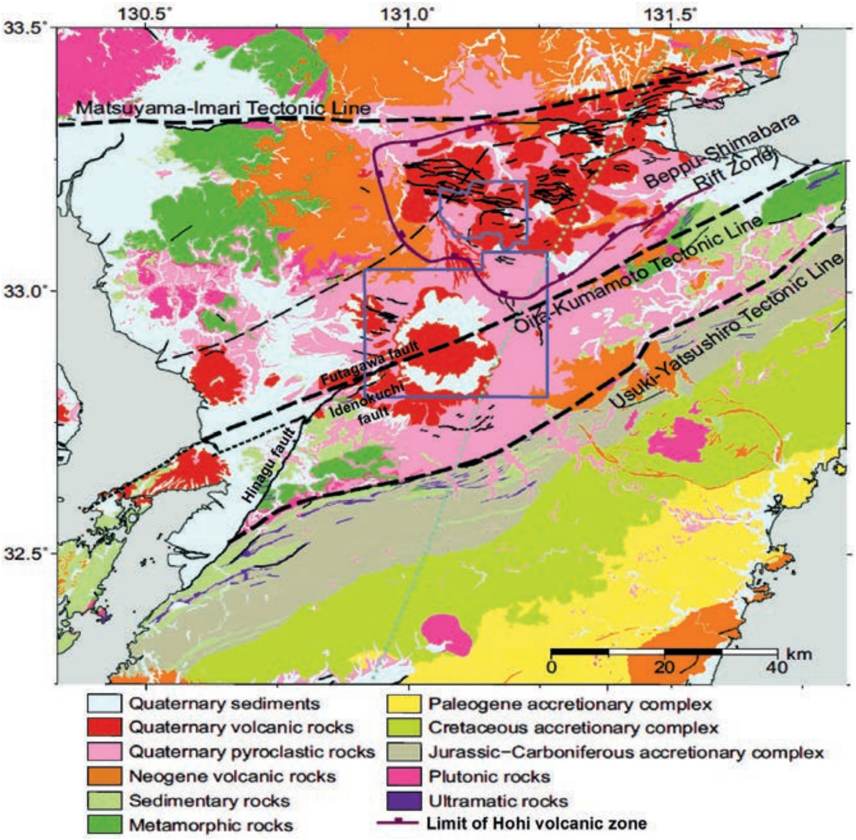

Figure 1 Geological map of the Beppu Shimabara Rift Zone and surroundings (Matsumoto et al., 2016). The survey outlines are indicated in blue and the volcanic front is shown as a cyan dotted line.

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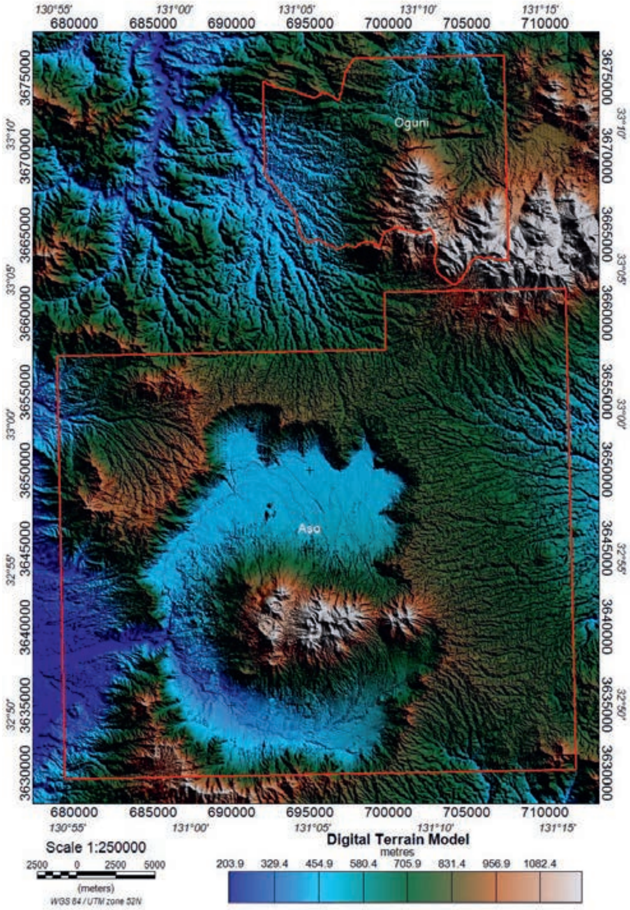

Figure 2 Aso-Oguni blocks (DTM referenced to EGM96 geoid).

examin the technical challenges presented by the rugged terrains, describe some aspects of the data acquisition and processing, and present the survey results.

Aso-Oguni HeliFalcon AGG survey overview

The Aso-Oguni HeliFalcon AGG survey was flown in late 2017 over the Mount Aso caldera on the island of Kyushu, Japan, as part of a comprehensive integrated study by Sumiko Resources Exploration and Development Co. Ltd. exploring for geothermal fields for JOGMEC. The study also includes helicopter time-domain EM, drilling, geological and other data.

The survey consists of the Aso block and Oguni block (Figures 1 and 2), together comprising about 4405 line-km. The survey was flown at nominal 250 m line spacing with tie-lines at 2500 m. The planned ground clearance was 120 m but the actual mean ground clearance is 155 m with a standard deviation of about 32 m. We shall see later the reason for this somewhat relaxed ground clearance and the effect this relaxation has on the result.

The Aso and Oguni survey blocks are located on Kyushu, the southernmost large island of Japan, partly in the Beppu Shimabara Rift Zone (Figure 1). This is a major tectonic zone between Beppu in the northeast to Shimabara in the southwest, connecting with the Okinawa trough. Large active volcanoes, such as Aso and Kuyju San, are located in this graben, and major active faults, such as the Beppu-Haneyama, Futagawa, and Hinagu faults, are located in or along the edges of this graben. The Oguni survey block is completely within the Hohi volcanic zone, a volcano-tectonic depression where Plio-Pleistocene volcanic rocks are widely distributed. The Aso survey covers the Aso caldera and the Oguni survey covers the western extension of the Shishimuta. Both calderas are located close to the current volcanic front. The Ōita Kumamoto tectonic line, the southern margin of the Beppu-Shimabara graben, crosscuts the Aso caldera. Numerous active faults have been identified in the survey blocks, in particular in the Aso block.

Rugged terrain challenges

Figure 2 shows the terrain in the Aso-Oguni survey area. The high terrain variation (more than 1000 m) poses a challenge for close terrain draping. The helicopter can fly low over the rugged terrain and maintain a more constant ground clearance. However, this would result in significant variation in helicopter speed and excessive changes in attitude (heading, pitch and roll), which deteriorate the gravity gradient quality. We relaxed the constraint on ground clearance but instead maintained better adherence to speed constraints and this resulted in much better data. Even with the relaxation, we still obtain much better terrain following and much closer ground clearance than would be possible with a fixed-wing aircraft (Christensen and Hodges, 2013). Figure 3 shows a sample profile of the terrain and the flight trajectory depicting the terrain draping capability of HeliFalcon in this survey.

Spatial resolution

The survey speed of a HeliFalcon survey is typically about 30 m/s. The standard low-pass filter applied to the HeliFalcon data is at 0.3 Hz with the equivalent cut-off wavelength of about 100 m, or a spatial resolution of 50 m. The final spatial resolution of the data also depends on the line spacing, the ground clearance and any other filters applied to the data. The ground clearance acts as an upward continuation filter on the data with an exponential fall-off in the wavenumber domain. The filter has a slow fall-off with wavelength and reaches 3 dB at 1.442 (1/log 0.5) times the upward continued distance.

We applied the 0.3 Hz along-the-line filter to the Aso-Oguni HeliFalcon data and transformed the measured curvature gradient to full tensor and vertical gravity using the equivalent source method (more detail on ES later) with the sources placed 300 m below the flight surface. This is equivalent to a 3 dB cut-off wavelength of 432 m. The line spacing of 250 m means that the shortest resolvable wavelength across the line is 500 m. The 155 m mean ground clearance gives the equivalent cut-off

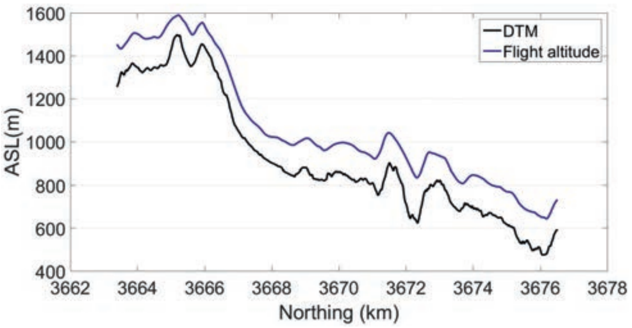

Figure 3 Flight trajectory over terrain.

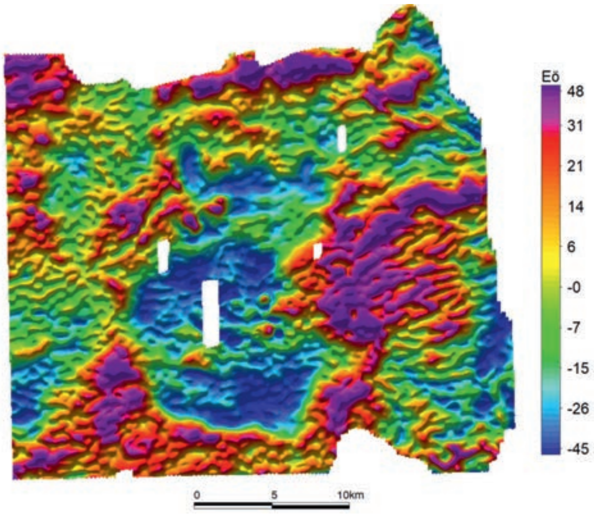

Figure 4 The Aso survey G_{DD}. Occasional data gaps are due to areas on the ground that could not be overflown.

wavelength of about 223 m. Therefore, the line spacing limits the spatial resolution to 250 m.

Terrain mapping

The accuracy of the delivered gravity gradient data depends very much on the accuracy of the terrain corrections. The accuracy of the terrain corrections in turn depends on the accuracy of both the position of the AGG sensor and the terrain. Dransfield and Zeng (2009) modelled the terrain accuracy for fixed-wing AGG at a nominal survey height of 80 m. Our internal model study indicates that, for helicopter AGG at 30 m ground clearance, the AGG sensor and the terrain height must be accurate to 0.5 m or better to achieve 1.0 Eö vertical gradient terrain correction accuracy. In addition, Dransfield (2010) has shown that the sampling of the terrain surface must be at a spacing of about one-third of the ground clearance.

To obtain a terrain model with the required accuracy, we use LIDAR (Light Detection and Ranging) systems mounted on the aircraft to acquire ranging data simultaneously during the AGG surveys. In order to achieve sufficient swathe width at the low altitude of a helicopter AGG survey, we have mounted two LIDAR sensors below the aircraft, each tilted away from the helicopter so that their scans just overlap on the ground directly below the aircraft path. This almost doubles the total swathe width. The LIDAR sensors scan 20 times per second at an accuracy of 5 cm, providing coverage over a swathe about 150 m wide and centered below the aircraft at a rate that provides DTM cells as small as 5m.

We converted the LIDAR range and scan angle data using the aircraft position and attitude (from the AGG) to ground surface elevation. Statistical processing selects the optimum elevations within areal bins and we manually edited the data to remove spikes before gridding them to establish a LIDAR DTM. We merged the SRTM (Shuttle Radar Topography Mission) data over the survey area and 60 km beyond the survey area with the LIDAR data by adjusting the SRTM to the level of the LIDAR. We used these adjusted data to fill any gaps between LIDAR swathes and to extend the DTM for terrain corrections. At Aso-Oguni, the DTM was gridded at 20 m, appropriate for the higher ground clearance. The terrain corrections were applied with a density of 2.30 g/cm^3, selected based on an analysis of the data. The terrain and positioning accuracy are more than sufficient to provide a better than 1.0 Eö level terrain correction accuracy.

Processing

Removing residual dynamic effects

We removed the residual dynamic effects from the measured differential curvature gradients via a model of the response of the gravity gradiometer to these dynamics. The model parameters are adjusted by regression against the acquired data and the modelled output subtracted from the measured to arrive at the low noise values of the compensated data (Lee, 2001).

Demodulation

The curvature gradient data are measured on a rotating disk and hence are referenced to rotating co-ordinates. Demodulation transforms the data to the standard north, east, down (NED) co-ordinates after which we apply an along-line filter (low-pass, 6-pole Butterworth). For standard fixed-wing surveys, the filter cut-off is set to 0.18 Hz and for helicopter AGG surveys it is set to 0.3 Hz. These settings are conservative, preserving some high frequencies. The subsequent transform to full tensor and vertical gravity using either Fourier transform or equivalent source method applies additional filtering to the final data. For the Aso-Oguni HeliFalcon AGG, the along-line filter was set to 0.3 Hz.

Measurement noise estimation

The Falcon AGG has two complements that provide two independent measurements of each of the curvature gradient components. Averaging these two complements provides a reduction in noise by a factor of $\sqrt{2}$. The standard deviation of half their difference provides a good measure of the survey noise (Dransfield and Lee, 2004). This difference noise is routinely used in all surveys to assess data quality. The mean turbulence of the Aso-Oguni survey was 26.5 milli-g and under this mild condition, HeliFalcon AGG measurement noise was 2.0 Eö RMS at 0.3 Hz.

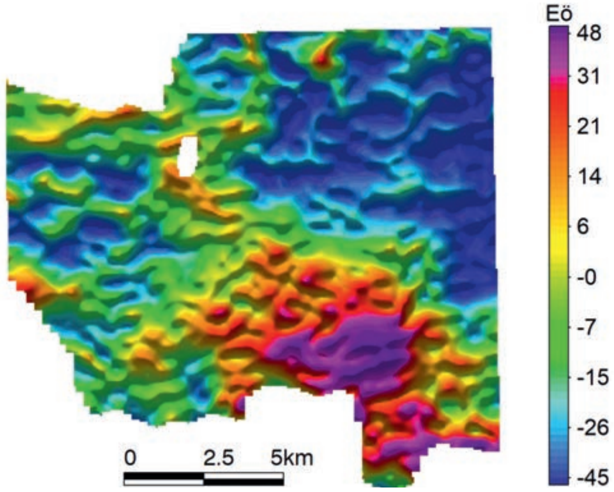

Figure 5 Oguni survey G_{DD}. Occasional data gaps are owing to areas on the ground that could not be overflown.

Self-gradient

Processing must also remove the true gradient signals owing to the mass distribution within the AGG and aircraft. These effects vary as the attitude of the aircraft changes during flight and are removed by the application of a model of these self-gradients as a function of aircraft attitude (Lee, 2001).

Equivalent source transform

We transform the processed curvature gravity gradients to provide all tensor components and the vertical gravity acceleration. The transform may be by either a Fourier method or an equivalent source method. The Fourier method is preferred for surveys over gentler terrains and the equivalent source method over very rugged terrain (Chen et al., 2016). The rugged terrain of the Aso-Oguni survey area naturally required us to use the equivalent source method.

Our transform process generally includes two basic steps: an inversion followed by a forward calculation (Blakely, 1995; Li and Oldenburg, 2010).

We usually construct the source layer using a smoothed version of the flight surface downshifted to a desired depth to maintain a constant observation – source distance. The observation – source distance should be chosen to provide an optimum solution.

For the Aso-Oguni survey, we constructed the source layer by downshifting the smoothed observation surface 300 m, which is consistent with the spatial resolution of the data. We calculated the full tensor gradient and the vertical gravity on the smoothed observation surface. The smoothing removes minor amplitude shifts in the data between adjacent lines owing to altitude variations but keeps the response surface very close to the observation surface in height.

Results

Figures 4 and 5 show the resulting terrain-corrected vertical gravity gradient data for the study area from the Aso and Oguni blocks, respectively. The estimated error of the vertical gradient data is 2.2 Eö RMS with a spatial resolution of 250 m. The 250 m resolution is consistent with the size of the smallest coherent features in the final data.

The low G_{DD} response of the Aso caldera in the middle of the block dominates the Aso survey. The caldera is centered at the intersection of the active Oita-Kumamoto tectonic line, with a north-east trend, and a major perpendicular fault zone. Within the caldera many volcanoes are located in the up to 5km-wide E-W zone with lineaments with a NE and E trend and variable G_{DD} amplitudes. There is a relatively high concentration of hot springs in the western part of this fault zone and at the caldera margin, most located at lineaments. This suggests conduits along faults. Potential geothermal reservoirs are located in a zone of active faulting in the north of the caldera, in areas with abundant hot springs in topographic lows.

The Oguni AGG data images a G_{DD} high with a NW trend. Pre-Tertiary metamorphic and granitic basement is shallow in the area of this anomaly. Prospective geothermal reservoirs are located along the flanks of this structural high, in areas with lower G_{DD} amplitudes and abundant hot springs.

Conclusions

The Aso-Oguni survey demonstrates the helicopter's ability to closely follow terrain and allow gravity gradiometer data to be collected at mean clearances of about 155 m even in the most extreme terrain where a fixed-wing aircraft would have to fly over a kilometre higher above the ground. Transforming the measured curvature gradients to gravity and the complete set of tensor components without loss of resolution requires the use of an equivalent source method.

The Aso-Oguni HeliFalcon survey achieved a vertical gradient error of about 2.2 Eö RMS at a spatial resolution of 250 m as determined by the line spacing.

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