Constructing high resolution DEMs from airborne laser scanner data

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SUMMARY

In processing and interpreting the data collected during FALCON airborne gravity gradiometry surveys it is necessary to carefully compensate for topographic features. So that surveys may be performed even in areas where accurate DEMs (Digital Elevation Maps) are unavailable, the FALCON aircraft have been fitted with laser scanners, providing ground return data across a sufficiently wide swathe so that very adequate DEMs over the whole survey area can be produced. Additionally, in one aircraft, a laser profilometer has been fitted adjacent to the scanner, providing independent data to monitor the scanner integrity throughout a survey.

This paper briefly describes the scanner features and details the post processing of the scanner ground returns through to gridded DEM format.

The intrinsic accuracy of the scanner at low scan angles is demonstrated to be very good, accounting for a ground height error of less than 0.1m standard deviation. Taking into account that DGPS height errors are about 0.15m, the resulting ground height error is estimated as 0.2m standard deviation, which is confirmed by the analysis of height differences in the overlapping areas between adjacent lines. This estimate is characteristic of a lightly vegetated terrain. This level of topographic error will have a negligible impact on our ability to identify target anomalies arising from geological variations.

Key words: DEM, GPS, laser scanner, airborne gravity gradiometry.

INTRODUCTION

In FALCON airborne gravity gradiometry (Lee, 2001; van Leeuwen, 2000) surveys, the major contributor to measured signal is often the topography. In such situations, very careful modelling of the topographic gradient signal is required in order to correctly identify that residual part of the signal which constitutes—exclusive of other generally smaller deterministic disturbances such as self-gradient—the effect of target anomalies. Vital to this correction is access to a suitably accurate DEM which is properly registered to the aircraft position. Such a DEM must cover both the survey area and a sufficient boundary beyond the survey extent. However, it is the topography closest to the aircraft, which will have the most profound effect on the gravity gradient signal. For this reason, the FALCON aircraft are fitted with laser scanner instruments so that accurate and up to date DEMs can be constructed from data collected during the survey flights. These DEMs are then stitched as postage stamps within coarser and less accurate photo DEMs (alternatively SRTM—Shuttle Radar Terrain Mapping—or numerous other sources) outside the survey area.

In order to maximise the gradiometer's sensitivity to target signals, the FALCON survey flight plans usually specify nominal ground clearances of between 80 and 120 metres, dependent upon topographic relief. These low clearances enable the laser scanner instruments fitted to the aircraft to provide good quality and dense ground return data suitable for the generation of useful DEMs.

In summary, the advantages of having the scanner fitted are:

- the scanner DEM will be correctly registered relative to the aircraft, especially in the region close to the aircraft where topographic gravity gradient effects are not inconsiderable—this is the overriding advantage,
- scanner DEM's can be composed in remote regions where existing DEMs are inaccurate, out of date or unavailable—this enables the FALCON aircraft to collect valid data over almost any ground,
- scanner DEMs will generally be more accurate than other commercially available DEMs.

In this paper we deal with the three central tasks in producing high quality DEMs from scanner data:

- calculating aircraft position,
- transforming laser ranges into *nominal* ground return positions, and
- removing ground return data which are not *true* ground postions.

Fortunately, the integrity of this processing stream can in large part be confirmed by observing the statistics of so-called *cross point height errors*—the error between ground heights reported in two different survey lines in a common grid area (10 by 10 metres is used here). These cross points exist in surveys where close line spacing (100m) and higher ground clearances are found, so that there is comfortably full coverage of the whole survey area by the laser scanner swathes. Additionally, one aircraft is fitted with a laser profilometer—which points in a constant direction with respect to the aircraft fuselage at all times—and this instrument can provide an additional check on scanner ground return accuracy.

Data from surveys performed in North-West Australia and the Canadian Northwest Territories in late 2000 are used in this paper to illustrate the performance of the data processing stream in producing good DEMs. Combined with analysis of data collected during earlier testing of the scanner and profilometer, we can construct an approximate error budget for the resulting DEMs and identify strategies to further improve their accuracy.

Modelling conducted at BHP Minerals Technology has concluded that, over a broad wavelength of topographic features, ground position accuracies better than 1.0m standard deviation will result in topographic gravity gradient correction errors of insignificant levels. This sets the standard by which the suitability of the scanner DEM accuracy needs be assessed.

AIRCRAFT CONFIGURATION

The two FALCON aircraft (CESSNA Grand Caravans) are nearly identically configured, each having the same model laser scanner but one having an additional laser profilometer.

Scanner specifications

The Riegl laser scanner (model LMSQ 140-80i) runs at a 12kHz pulse rate with a 33% duty cycle and returns 276 readings per scan line at a line rate of 20Hz. Table 1 gives the scanner's nominal specifications. Practically, the scanner performance can vary from this ideal, with valid scan return density depending upon the following:

- Aircraft ground clearance: above 200m clearance return density can be negligible.
- Ground coverage: return density over smooth or icy bodies of water is usually low and can vary widely according to foliage distribution and characteristics.
- Scanner window condition: regular cleaning of the scanner window is required.

Parameter	Nominal Value
Scan rate (per sec)	20
Returns per scan	276
Aircraft ground speed (m/s)	50
Scan angle limits (deg)	[-40,40]
Ground clearance (m)	100
Scan separation along aircraft track (m)	2.5
Average scan separation across aircraft track (m)	0.60
Cross track scan swathe length (m)	167
Mounting point aft of aircraft centre of lift (m)	4.8

Table 1. Riegl laser scanner nominal specification and operational configuration.

The laser profilometer is mounted adjacent to the laser scanner and points in a constant—roughly downwards—direction relative to the fuselage.

Both the scanner and profilometer are carefully adjusted when installed so that they point in the correct direction. In particular, the scanner should point in the local inertial DOWN direction when the aircraft attitude is zero pitch and zero roll. Additionally, the scan rotation direction must be colinear with the aircraft's principal axis. In practice, this perfect alignment is impossible and it is necessary to perform calibration flights to determine the actual pointing offset of each instrument.

Aircraft Attitude

In order to transform scanner range data into ground return positions, it is necessary to both calculate the aircraft position (described later in this paper) and measure the aircraft attitude (roll, pitch and heading). Fortunately, the inertial platform, inside which the FALCON gradiometer sits, provides very accurate measurements of the attitude.

SCANNER CALIBRATION

Scanner range and aircraft attitude data are collected whilst a set of rolling and pitching manoeuvres is performed over a flat lake surface. Using the ground return model—described in the next section—a least squares optimization engine is used to ascertain the best set of scanner pointing offsets such that the deviation from flatness of the estimated lake surface is minimised. The same approach is used to calibrate the profilometer. Pointing offsets for the FALCON aircraft fitted with both scanner and profilometer are given in Table 2.

Instrument	[roll,pitch, heading] Pointing Offset (deg)	Calibration standard deviation from flatness of estimated lake surface (m)
Scanner	[-0.2,-2.8,-2.0]	0.2
Profilometer	[0.6,-0.27,NA*]	0.2

Table 2. Scanner and profilometer calibration results. * Heading pointing offset is not relevant for the profilometer.

The 0.2m standard deviation from flatness of estimated lake surface reported in Table 2 for both scanner and profilometer should be taken as the best possible accuracy achievable with these instruments, accounting for all possible error sources from raw measurement through the geometric transformation to final ground position but exclusive of errors otherwise due to inadequate foliage penetration, built environment and horizontal position errors.

CALCULATION OF AIRCRAFT POSITION

The FALCON aircraft are fitted with dual frequency Dorne-Margolin GPS antennae and NovAtel Millenium receivers. The raw GPS data is recorded at 2 Hz at the aircraft and at a reference station, and post-processed by Sander Geophysics Ltd (SGL) using GPSoft version 1.31, SGL's in-house DGPS data processing software.

Gpsoft has been customized to the requirements of the FALCON project. A robust algorithm with a few layers of integrity monitoring has been implemented to guarantee sub-meter accuracy in a real-world survey environment with baselines up to 300km, possibility of rough flying, poor GPS coverage, strong ionospheric effects, and multiple cycle slips. A floating ambiguity ionosphere-free phase solution combined with C/A code is used.

GPSoft in FALCON mode includes automated multi-step processing, which is adjusted for the actual project environment and minimizes human involvement both in terms of labour time and possibilities of human errors. The algorithm starts with C/A code processing to check for the availability of the initial static period. If initial static is detected, its position is computed with phase and used to initialize the final processing with ionosphere-free phase and C/A code. If initial static is not available, phase-smoothed code processing is used for OTF initialization. The program outputs a comprehensive QA section, which includes average and maximal residuals, number of cycle slips and epochs with incomplete data, and a few parameters that quantify averaged effect of ionospheric activity on DGPS measurements. When initial static is available, and if the aircraft comes back to the initial static location at the end of the flight, the height closure error is also reported, which makes an important internal measure of accuracy.

Though there is no direct way to verify DGPS-derived positions for flight data, a number of indirect methods can be used. Firstly, the noise of DGPS positions may be estimated when data collected at another reference station is processed instead of the flight data; such estimates usually amount to a standard deviation of 6-8cm for baselines up to 200 km. Secondly, different DGPS programs may be compared to one another. In (Bruton, Kern, Schwarz, et al., 2001), DGPS heights for two sets of flight data are computed with the help of 8 software packages used in the airborne surveying industry. This comparison shows that 4 programs, which use the ionosphere-free phase solution, agree to each other within standard deviations of about or less than 0.1m. Thirdly, assuming that the errors of the initial static position are negligible, height closure errors make a good measure of height accuracy. The root mean square value of the height closure error for FALCON flights is 0.15m

The conclusion is that the standard deviations of height errors are below 0.1m for an idealized environment (no cycle slips, good GPS coverage), and are about 0.15m in actual conditions of FALCON surveys.

CALCULATION OF GROUND POSITION

Figure 1 illustrates the processing steps required to construct a DEM from the scanner laser range data, fully accounting for aircraft attitude and scan angle. The major steps in the laser scanner data processing stream are described below.

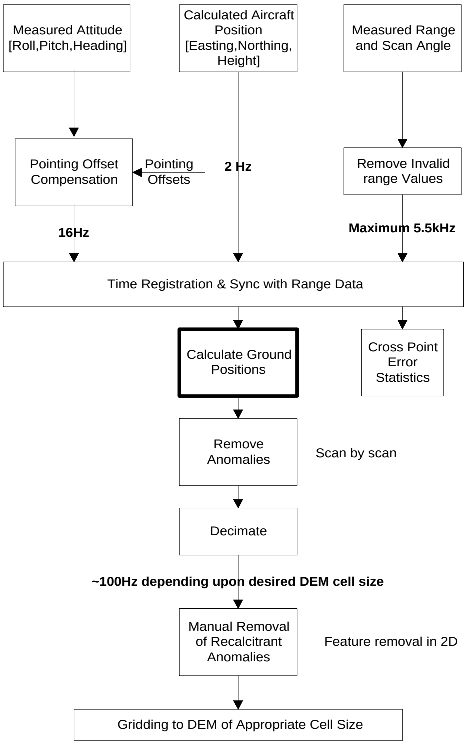

Figure 1. Flowchart for production of scanner DEM.

Remove Invalid Range Values

The raw range data usually contains a number of invalid range returns, which are recorded as values less than 20 metres. These are removed from the data stream early on, creating an asynchronous data stream.

Time Registration and Synchronising with Range Data

The lower rate attitude and aircraft position data are linearly interpolated onto the range data time instances. Processing of scanner calibration data has demonstrated that the interpolation of the low rate 2 Hz position data can result in ground position estimation errors of up to 0.2m standard deviation during periods of extreme aircraft attitude change. However, in normal survey conditions, these extremes of attitude change are rarely encountered.

Calculate Ground Positions

The transformation of range data into ground position is achieved by performing a set of vector rotations of the range vector about the GPS antenna. These rotations account for heading, pitch and roll—compensated for their respective pointing offsets—yaw pointing offset and scan angle as well as the lever arm effect associated with the rear mounting of the scanner on the aircraft underbelly. The transformed range vector is then added to the aircraft position, giving the ground return position.

Range Anomalies and Decimation

We then analyse the ground return data on a scan by scan basis. Firstly, only every Nth scan is processed. For the selected scans, single point abnormally high ground returns are discarded, being indicative of foliage or built environment features. Further in-scan decimation is achieved by allowing only a specified number of returns per scan (M) to be used in the DEM formation.

For example, allowing only one in eight scans to be processed (N=8) and a maximum of nine (M=9) evenly spaced ground returns per scan will provide an average ground return coverage suitable for the creation of a DEM with a 20m cell size. The choice of M valid returns per scan is achieved by selecting the points with the *lowest* ground position in M evenly spaced bins across the scan swathe—this procedure not only decimates but also filters out high points which are possibly anomalous returns. Other filtering strategies are also applied—these strategies aim to retain the lowest height returns and make accurate judgements as to the validity as ground returns of all other returns. Axelsson (1999) and others in the same volume of the ISPRS journal describe various approaches to achieve this goal.

Manual Review of Preliminary DEM

The decimated ground return data is then mapped in a preliminary gridding step. A software tool (illustrated in Figure 2) has been designed to enable users to manually view and, if necessary delete, scan returns.

ACCURACY

The actual accuracy of the ground heights calculated from the scanner range returns can be verified through the analysis of two sets of so called *cross point* data in addition to the over-lake calibration data set. Those are:

- near-coincident scanner and profilometer returns (viz: when scan angle is close to zero and the range measurements are coincident in time also),
- near-coincident scanner returns from adjacent lines where swathes intersect.

The good agreement between scanner and profilometer returns (Table 3) shows that the instrumental noises of both instruments at low scan angles are very low, standard deviation of about 0.07m each. The scanner error for the whole range of scan angles can be estimated from the over-lake calibration and amounts to a standard deviation of 0.13m $= \sqrt{0.2^2 - 0.15^2}$.

Data Set	Cross-Point Height Error Std. Dev. (m)
Scanner and profilometer returns	0.10
Scanner returns on adjacent lines	0.28

Table 3. Scanner accuracy verification—all measurements are spatially coincident in easting and northing to ±5m. The Cross-Point Error is defined as the difference between calculated ground heights of coincident points.

Error Type	Height Error (m)
Aircraft height DGPS error	0.15
Scanner instrument error	0.13
TOTAL (Root Sum of Squares)	0.20

Table 4. Best case scanner ground position error budget, including all processing transformations.

The overall terrain height error may be estimated on the basis of the assumption that both DGPS height and scanner errors are random and independent (Table 4). This estimate is in an excellent agreement with the standard deviation of the cross-point height errors on adjacent lines ($0.2\text{m} = \sqrt{0.5 * 0.28^2}$ —the squared error must be halved because errors on both lines will contribute). Thus a value of 0.2m may be accepted as a measure of the DEM height accuracy for lightly vegetated terrain.

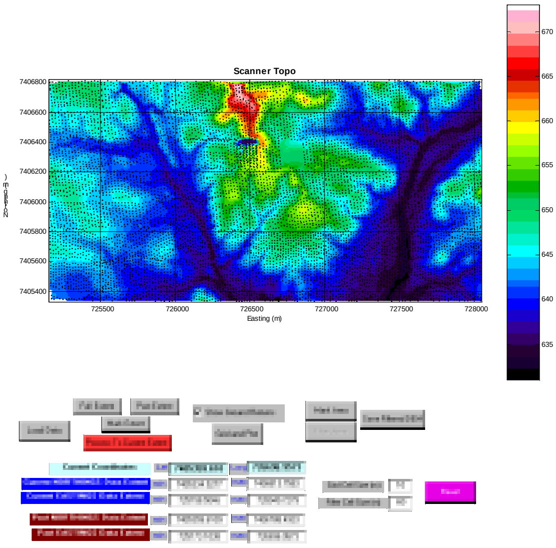

Figure 2. Example of GUI for manual review of preliminary DEM.

DIGITAL ELEVATION MAPS

For the purposes of fully correcting the FALCON gradient measurements for topographic effects, it is necessary to first manufacture a gridded version of the scanner ground position data set (the scanner DEM), then merge that DEM with a less accurate but larger regional DEM. This merging process consists of the following steps:

- postage stamp insertion of the scanner DEM inside the regional, allowing the regional "frame" to be at least 5000m,
- tilting and shifting of the regional DEM to match the scanner DEM boundary conditions,
- allowing the regional DEM to in-fill any internal gaps in the scanner DEM.

CONCLUSIONS

We have outlined the processing steps involved in the creation of a DEM from data supplied by a laser scanner mounted underneath the FALCON gravity gradiometry survey aircraft. It is shown that the intrinsic accuracy of the scanner at low scan angles is better than a standard deviation of 0.1m, while the standard deviation of DGPS height errors can be estimated as 0.15m. The final accuracy of terrain heights is estimated as 0.20m. This is confirmed by the analysis of scanner returns from overlapping swathe areas, which also shows a standard deviation of 0.20m. This accuracy is more than adequate for the purpose of correcting the gravity gradient measurements.

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