03-01 The canopy effect in AEM: investigations using radar and laser altimetry

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Introduction

This study addresses a specific issue, often termed the canopy effect, which relates to our ability to provide accurate conductivity models from AEM coupling ratios. At face value the issue is one of the correct determination of sensor height(s) above the ground surface (terrain clearance). Historically, AEM systems have used barometric, radar and laser altimetry for this purpose. The present study uses the radar and laser systems installed on the JAC fixed-wing AEM-05 system (Leväniemi et al., 2008) to further investigate the effect. The canopy effect can arise due to a variety of elevated features below, and in the vicinity of, the flight line. The most obvious features are well-defined forest and copse zones together with domestic, commercial and agricultural buildings. Such features may cause the terrain clearance to be underestimated and this has the potential to introduce resistive artifacts into conductivity models. Correct determination of terrain clearance is also important for the accurate processing of the other geophysical data sets acquired by our surveys.

Altitude estimation in AEM systems

Altitude estimation in airborne systems may utilise a variety of sensors and procedures. These include differential or multi-receiver GPS (required as part of survey navigation and accurate survey data location). Currently radar and laser altimeter systems are the primary sensors used to determine height above ground surface. The typical and stated accuracy of a modern laser system is a few centimeters while that of a typical radar may be ≥ 0.5 m. A significant difference in the two types of altitude measurement lies in their physical beam widths. A radar system, at a frequency of ~4.3 GHz, may have a beam width defined by an angle of up to 68°. The system will measure the distance to the nearest reflecting object within a spatial scale defined by a 3D cone of influence. The cone of influence typically may have a radius in excess of 50 m at the ground surface. Reflections from objects that are off-line are a distinct possibility, particularly as survey elevation increases. In direct contrast, a modern laser system data is capable of combining very rapid sampling with very low beam dispersion (e.g. 1 to 2 mrad). At normal AEM survey altitudes, a laser system should provide a zone of influence that is approximately a vertical tube <10 cm in diameter at the ground surface. A final difference that stems from their physical beam widths is their differing abilities to provide accurate measurements of height above ground surface in the presence of elevated features. Features such as forest and copse zones together with domestic, commercial and agricultural buildings may cause either of the two systems to record an underestimated ground clearance and this is generally called the canopy effect (e.g. Fraser, 1978; Beamish, 2002). Canopy effects, due to elevated features, may result in underestimated radar and laser altimeter readings of height above ground. A second class of effect, termed the paddock effect, has been noted by Richardson (2000) and by Brodie and Lane (2003). The paddock (meaning a ploughed portion of land) effect, as currently defined, results in overestimated *radar* altimeter readings only.

The sensitivity of coupling ratios to altitude is both system and survey specific. The highest frequency of each system determines the highest accuracy required. The altitude accuracy requirement is also more stringent for surveys performed in conductive environments. Simple sensitivity calculations for the AEM-05 system indicate that in a 100 mS/m environment, a 10 cm error in altitude is significant. This is clearly beyond the accuracy available from typical radar systems and can only be achieved with a laser ranging device.

Influence of altitude errors on 1D conductivity models

The standard single frequency Fraser half-space transformation (Fraser, 1978), when applied using both in phase and quadrature coupling ratios, is effective in returning conductivity estimates unbiased by errors in altitude. Many of the published multi-layer inversion strategies do not appear to require the use of an equivalent pseudo-layer (a fixed high resistivity at-surface layer of variable thickness) to accommodate errors in altitude. It is theoretically possible to include sensor altitude as an unknown parameter in an inversion strategy (e.g. Hodges, 2003). An alternative procedure in few layer inversion strategies was proposed by Beamish (2002) and reiterated by Tølbøll and Christensen (2006). The air-layer technique introduces a high resistivity (equivalent to air) upper layer to represent sensor altitude above ground surface. The layer thickness is free to vary but the resistivity is highly constrained or fixed. The air-layer technique is more difficult to implement within a many layer, regularised inversion procedure since it is the first or second vertical derivative of the conductivity profile that is constrained to be a smooth function. The influence of altitude error on conductivity models is illustrated later.

Laser altimetry

Modern laser altimeter systems of the type employed in AEM systems (e.g. manufactured by Optech and Riegl) have a typical pulse repetition rate of up 2 kHz. Laser systems deployed in bird systems appear to sample the laser data at the fastest geophysical channel rate e.g. 10 Hz. More recent laser systems deployed on some EM birds and in the AEM-05 system have used a dual-pulse (dual meaning first and last) laser altimeter (Levaneimi et al., 2008). The device is programmable so that for longer measurement times, single laser shots are averaged.

In practice, by operating the laser at 200 Hz, an oversampling of x50 is achieved in relation to the standard 4 Hz sampling of the EM components. The averaging is useful for accurate detection of badly reflecting targets or for targets with changing reflection characteristics during measurement (e.g. a water surface). At a typical flying speed of 60 m/s, the raw 2 kHz sampling equates to a shot every 3 cm. Averaging over 10 points to provide a 200 Hz estimate equates to a distance of 30 cm. In practice, one or more ‘null returns’ may be generated within the 10 point window. Ultimately all ten points may be null. In these circumstances it is possible to consider alternative strategies such as an expanding window technique.

The 50 point redundancy in the sampling then allows a post-processing algorithm, based on independent windows, to obtain an accurate (although necessarily spatially-averaged) estimate of height above ground surface for the EM data channels (i.e. resampled to 4 Hz). The simplest procedure is to determine the maximum value of the laser data across the 50-point data window. The procedure is referred to here as an Lmax estimate. As indicated above, several aspects of the basic Lmax algorithm can be developed to suite different circumstances and requirements. In most cases this provides an effective measure of true height above ground surface through vegetation, most types of canopy and structures of limited extent.

A case study

This example considers continuous data acquired across the edge of a lake, then across a dense canopy and then across a single isolated building. The features are included within a profile length of some 660 m. Selected flight video images (Fig. 1) show a lake in sunlight (A) a central deciduous wooded area (B) and an isolated building (C).

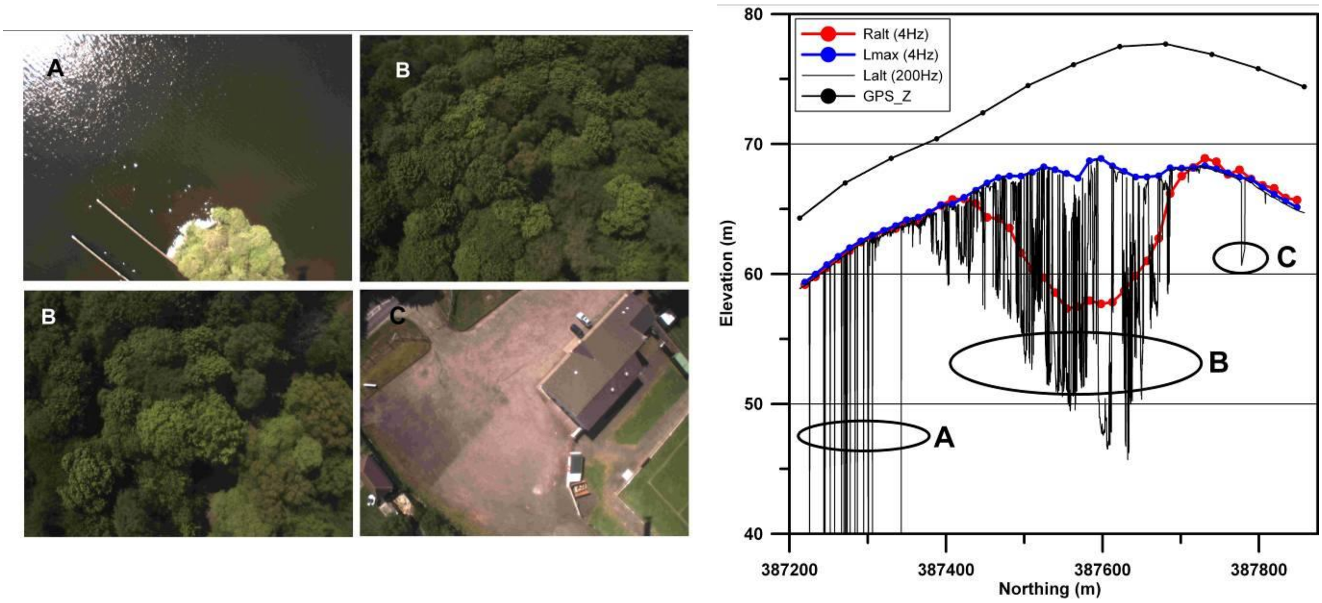

Figure *1. Video images at 4 locations across the study profile (the flight line crosses the centre of each image horizontally. Altimeter data recorded across the study profile (length 660 m). GPS_Z has had a constant removed to enable comparison.*

Figure 1 shows a comparison of radar altitude (Ralt, 4Hz), raw laser altitude (200 Hz) and Lmax laser data (4 Hz, resampled) across the profile. Over the lake (A), the raw laser data suffers a series of zero amplitude returns that are classed as null returns. The radar altitude returns are stable. Across the wooded area (B), the 200 Hz laser data show a complex sequence of returns (altitudes between 46 and 68 m). We assume the largest altitudes indicate full penetration of the canopy across this zone. The radar, with a much lower (averaging) spatial resolution, shows a characteristic smooth decrease from the woodland edges (less dense foliage) through to the centre of the woodland (foliage most dense, and taller trees). The raw laser data clearly identifies the isolated building (C), a sports pavilion, together with the slope of its pitched roof. The resampled Lmax 4 Hz data is shown by the blue trace. Over the body of water we obtain correspondence between the radar and Lmax laser estimates. Across the forested area, a realistic upper bound to the raw 200 Hz laser data is obtained. In the absence of the Lmax procedure, it is evident that Lalt sampled at 4 Hz would provide a highly variable and frequently underestimated altitude. The Lmax trace follows the same trend observed in the GPS height above geoid. The depression observed in the radar altitude across zone B is interpreted as reflecting the height of the canopy. The results indicate that errors in the radar estimate of height above ground extend to 11 m, in this example.

The effect of the underestimated radar altitude on conductivity models for these data has been investigated by comparing the results obtained using Ralt and Lmax as the known altitude parameter in an inversion procedure. A few layer inversion with lateral constraints is used to reduce the point-to-point variability in the conductivity models and to better demonstrate the canopy effect. The inversion method used is the constrained conjugate gradient inversion described by Tartaras and Beamish (2006). The 4 frequency AEM-05 data were used to obtain the 5-layer conductivity models shown in Figure 2. Two conductive layers are detected; an upper thin zone and a deeper, more conductive, 20m thick zone.

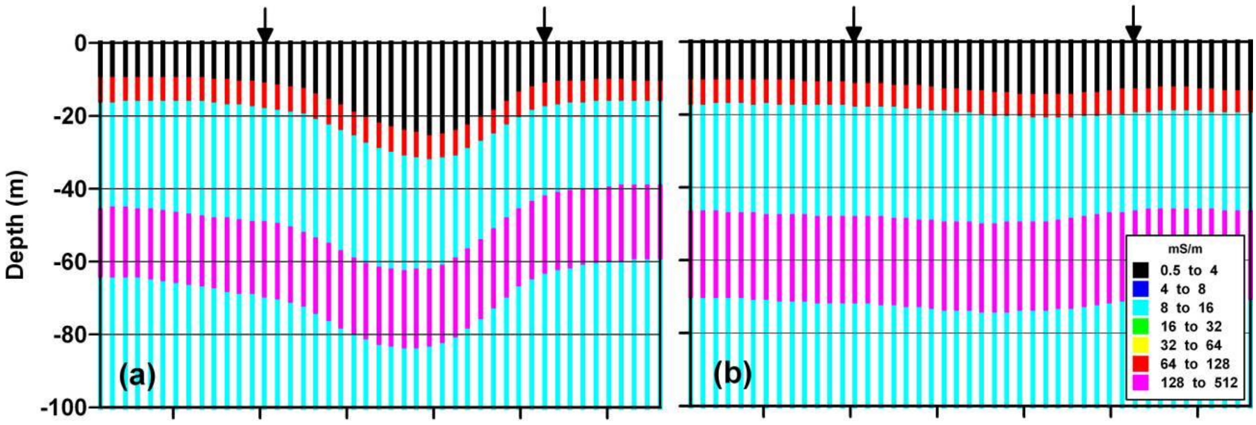

Figure 2. Conductivity cross-sections obtained across the study profile (660 m) by laterally-constrained inversion of 4 frequency data. Arrows denote width of canopy zone. (a) Using Ralt as altitude. (b) Using Lmax.

In the Ralt inversion (Figure 2a) the perturbation in the depth to the top of each conductor follows the general behaviour of Ralt observed previously. In this example, the thickness of each conductive layer remains uniform largely as a result of the simple nature of the canopy zone and the lateral constraints applied. Canopy and its influences can give rise to much more complex, high wavenumber effects on conductivity models and it is the combined accuracy and reliability of the Lmax procedure that is it’s most important feature.

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