Preliminary Investigations Using a Helicopter Time-Domain System for Bathymetric Measurements and Depth-to-Bedrock Estimation in Shallow Coastal Waters – a Case Study in Broken Bay, Australia

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Abstract*-An airborne electromagnetic (AEM) survey over the shallow coastal waters of Broken Bay (Australia) provided data for bathymetric mapping and for mapping the coarse topographical features of underlying bedrock in areas of relatively shallow marine sediments. Inversion of AEM data assumed a crude one-dimensional layered-earth model consisting of a conductive seawater layer overlaying a less conductive sediment layer which in turn overlies an infinitely deep resistive basement. Known or assumed layer conductivities were used as fixed parameters in the inversion of data. The primary focus of this study is to test the accuracy of AEM for bathymetric mapping. A secondary objective is to determine the potential for mapping sediment thickness by sensing the depth to bedrock and to estimate sediment resistivity. The vertical accuracy of the AEM method was measured by comparing the depth profiles with those obtained from historical data - sonar soundings for water depths and marine seismic data for estimated depths to bedrock. Water depth accuracy of 1 – 2 m was achieved in water shallower than 25 – 30 m, and ~ 50 cm accuracy was obtained in water shallower than about 10 m. This study shows that the AEM method is suited as a reconnaissance technique for measuring seafloor gradients adjacent to beaches, and for rapid bathymetric mapping in turbid and surf-zone waters. The AEM data delineated a distinct paleovalley 60 to 70 m below sea level.

I. Introduction

A significant proportion of Australia's coastal waters within depths of about 50 m is affected by water turbidity as well as breaking waters in the surf zone adjacent to beaches. Traditional airborne bathymetric mapping techniques relying on LIDAR [1] cannot operate with full effectiveness in these waters. The airborne electromagnetic (AEM) method, developed for mineral exploration [2], [3] uses the bulk electrical conductivity as an important parameter for interpretting the elctromagnetic response from the ground, which in the 1D case, consists of a layered earth model overlaying a resistive basement. Each layer is defined by its thickness and electrical conductivity. For bathymetric applications, the simplest model consists of a two-layered earth, i.e., a seawater layer overlaying a sediment layer, overlaying a resistive basement (bedrock). If one assumes that the turbidity levels (caused by suspended particles) found in seawater do not affect the bulk seawater conductivity, then the interpreted layer thickness of the upper conductive layer of a layered-earth model derived from inversion of AEM data should not be influenced by water turbidity. Similarly, suspended air bubbles caused by breaking waters would not be expected to significantly affect the bulk electrical conductivity of seawater. Thus the AEM method could prove useful as a complimentary technique to LIDAR for mapping water depths in shallow coastal turbid waters and through the surf zone on approaches to beaches. In clear water, LIDAR is preferred because of the higher spatial resolution it offers compared to AEM systems [4], [5].

AEM methods have previously been used for bathymetric mapping in shallow water [3], [6], [7]. However, AEM bathymetry has not yet matured as a reliable bathymetric mapping technique. Several more recent studies in Australian waters based on commercial AEM systems have shown that the AEM bathymetry method can provide accurate water depths down to approximately 55 m using both fixed-wing [8], [9] and helicopter [10] time-domain AEM systems, and depths to about 30 m using helicopter frequency-domain systems [11], [12]. However, within these depth ranges there is generally a loss of accuracy as depth increases, and overall, these accuracies cannot be maintained throughout the survey region and are not routinely achieved.

A time-domain helicopter AEM system (referred to as "SeaTEM(1)") is currently being developed for the Defence Science and Technology Organisation for shallow water bathymetric mapping. This system consists of a transmitter and a concentric coplanar receiver loop assembly mounted on a rigid structure referred to as a "bird" that is towed as a sling load approximately 30 m below the helicopter. The AEM time-domain method [3], [13] uses the transmitter (Tx) loop to create a primary magnetic field which induces a time-varying current in the ground. These currents in turn induce a secondary magnetic field in the ground which is detected as a decaying voltage by the receiver (Rx) loop in the AEM system.

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Typical Tx-Rx survey altitudes are ~ 25 – 35 m above sea level.

An earlier investigation of the coastal waters in Broken Bay using a prototype SeaTEM system [14] showed that seawater depths could be accurately determined after an empirical correction to the data. This study [14] and a previous study in Sydney Harbour [10], [15] highlighted the importance of correctly calibrated AEM systems. Whilst these studies focused on bathymetry, an important outcome was the conclusion that carefully calibrated AEM systems had the potential for surveying sediment thickness and for delineating coarse scale features of the bedrock topography in areas of shallow (< ~ 25 m) seawater. Improvements in SeaTEM instrumentation since the prototype design have removed the necessity for empirical corrections to AEM data. This advancement significantly decreases the data processing time.

This paper is structured so that Section II provides a background to the choice of Broken Bay as a trial site for appraising the SeaTEM system. Section III describes the instrumentation and experimental procedure, including acquisition of seawater and estimated sediment electrical conductivities, and estimated depths to bedrock obtained from a recent marine seismic survey covering the AEM survey region. Section IV briefly describes the layered earth inversion methodology for interpreting AEM data to estimate water depth and depth to bedrock. Section V presents the water depths and depths to bedrock as line profiles and gridded maps, and compares the results with ground truths estimated independently from sonar surveys and marine seismic studies. Sections VI and VII present a discussion and conclusion.

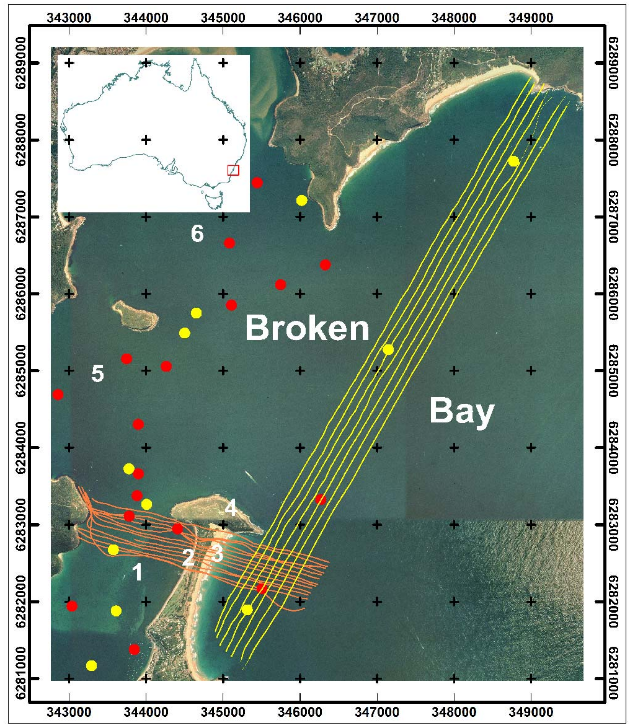

Fig. 1. Broken Bay trial site and flight lines for Area 8 (yellow) and Area 5 (orange). Locations: 1, Pittwater; 2, Barrenjoey Beach; 3, Palm Beach; 4, Barrenjoey Head; 5, Hawkesbury River outlet; 6, Brisbane Water outlet. The tombolo is the sand spit that links Barrenjoey Head to the mainland and is bounded by Palm Beach and Barrenjoey Beach. Area 5E is the eastern section of Area 5 extending seawards from Palm Beach. Area 5W extends from Barrenjoey Beach into Pittwater. Vibrocore sediment sample sites: red circles; seawater conductivity sounding sites: yellow circles. Inset shows location of Broken Bay (red box) relative to Australia's coastline. Grid spacing is 1000 m.

II. Broken Bay Trial Site

Broken Bay comprises varied bedrock topography with areas of relatively flat seafloor and regions of exposed bedrock (reef), and sediment layers that extend to estimated depths of about 100 m. The maximum depth of investigation obtained from the recent seismic survey is not known accurately. An earlier study [17] indicates deeper sediment depths of 150 to 200 m.

The bedrock topography and sedimentary environment in Broken Bay have been studied by Albani and co-workers [17]-[19]. Broken Bay constitutes a major estuary junction that drains the Hawkesbury River and its tributaries to the west, Brisbane Water to the north, and Pittwater to the south (Fig. 1). Broken Bay was formed by fluvial excavation of sandstone belonging to the Triassic age during periods of lower sea level. The Pleistocene lowering of the sea level enabled the existing valleys to be further eroded by coastal streams, which in the case of the Hawkesbury River, led to excavations exceeding depths of 125 m below present sea level. At the end of the Pleistocene, the eustatic rise of the sea level resulted in the drowning of the estuary, accompanied by the redistribution of unconsolidated sediment that was present offshore and which now presently fills the seaward portion of the drowned valleys [19].

Two bathymetric datasets obtained from single beam sonar soundings were used as ground truths. The 2 m bathymetric contours from a published chart (surveyed 1979 to 1985) were digitized and gridded. This chart excludes the Pittwater area (Fig. 1). A second bathymetry dataset for Broken Bay and Pittwater, referred to as B11709 (surveyed 1977 to 1978), included a relatively high density of depth soundings in the Pittwater region. The B11709 dataset was also digitized and gridded. Both bathymetry grids were sampled at the flight line fiducial point locations to provide water depth profiles for the AEM survey lines. These profiles are referred to as "bathy_2m" and "B11709".

Estimated depths to bedrock were obtained from 10 m bedrock contours [17] that were digitized, gridded and sampled at the flight line fiducial point locations to provide estimates of depth to bedrock profiles for the AEM survey lines. These profiles, referred to as "bedrock_10m", are inaccurate in some areas, especially adjacent to the coastline owing to sparse bedrock contour data and the 10 m contour spacing.

A marine seismic survey was undertaken in 2008 within the AEM survey region to estimate the sediment thickness and identify topographical features of the underlying bedrock [20]. Survey line spacing was ~ 100 m and provided a significantly greater density of data records than those obtained by sampling the 10 m bedrock contours [17] obtained from a relatively sparse survey track within Broken Bay. The bedrock depths were gridded and sampled at the flight line fiducial point locations to provide estimates of depth to bedrock profiles for the AEM survey lines. These profiles are referred to as “bedrock_2008”

III. Instrumentation And Method

The SeaTEM system is shown in Fig. 2. The framework consists of carbon composite material with aerodynamically shaped “wings” that support the outer single-turn Tx loop and the inner double-turn Rx loop. The Tx loop has an area of ~ 200 m^2 and a magnetic moment of ~ 58000 A m^2; the Rx loop has an area of ~ 80 m^2 per turn. The SeaTEM waveform is transmitted at a fundamental frequency of 25 Hz and comprises 5 ms bipolar pulses with 15 ms offtime between pulses. The current pulse is quasi-trapezoidal with a rise time of 1.5 ms, approximately 3.5 ms constant current (~ 300 A), and a 29 µs linear turn-off ramp. Decay voltages were measured over 112 channels binned into 21 windows with centre times ranging from 77.5 µs (early time) to 13.9 ms (late time) referenced to the start of the current turn-off ramp.

Fig. 2. SeaTEM system at take off. “Wing” span ~ 18 m.

The survey over Broken Bay (Fig. 1) took place in April 2009. Tide corrections ranging from 0.3 m to 1.2 m were added to the known bathymetry and depth to bedrock profiles for all survey lines. The tide-corrected depth profiles are used for comparison with depths obtained from layered-earth inversion of SeaTEM data.

Seawater electrical-conductivity soundings were recorded at eleven locations within the survey area and immediate surrounds (Fig. 1). Conductivities varied between 4.6 and 5.0 S/m. Conductivity measurements associated with a given survey area, and day of survey, were averaged for each area and used as a known fixed parameter for inversion of AEM data. In previous AEM bathymetry studies [10], [14], a seabed conductivity of 1.25 S/m was assumed, representative of unconsolidated marine sand sediment [21], [22]. For this study, sediment samples were obtained from 4.5 m length vibrocores extracted from 17 sites (Fig. 1) within the AEM survey region. Resistivity measurements on 64 sub-samples in four-electrode cells were deemed generally satisfactory for the purposes of the study and gave rise to a range of resistivities, which, when temperature corrected, plotted with some scatter about appropriate Archie Equation curves [20]. Resistivity (conductivity) values (20°C) ranged from 1.3 (0.8) to 0.6 (1.6) Ω m (S/m) for 64 samples. Conductivity values of 1.25, 1.0 and 0.8 S/m were used as a fixed parameter for inversion of AEM data to gauge the effect of variable sediment conductivity on inverted seawater and bedrock depths.

The primary focus of this study is the application of AEM for bathymetric mapping. The secondary focus is to detect the resistive basement (bedrock) in areas of shallow water using realistic sediment conductivities and to determine if these conductivities are consistent with resistivities obtained from a very limited number of samples of surficial (i.e. < 4.5 m) sediment. As the seawater layer increases in thickness, the EM response becomes increasingly less sensitive to the underlying less-conductive sediment layer. Any errors in the interpreted thickness of the upper conductive layer from AEM data, arising from choice of inversion parameters, noisy data and instrument calibration errors, are significantly magnified when determining the thickness of the underlying less conductive layer.

IV. Layered Earth Inversion

Water and sediment depths were interpreted via one-dimensional (1D) inversion of SeaTEM data using a time-domain extension [23] of a program initially developed in [24]. This time-domain program (*AMITY*) has been used effectively in previous AEM bathymetric studies on Australian coastal waters [10], [14]-16]. A two-layer model of seawater and sediment over resistive basement (10^{-4} S/m) was used for all inversions. The two interface depths (seawater/sediment, *d1* and sediment/basement, *d2*) are adjusted during inversion using the same starting model (*d1* = 10 m, *d2* = 20 m) for inversion at each fiducial point coordinate of the flight line. The AEM data at each fiducial point is an average of 5 readings spanning approximately 10 m in total. The inversion also used the height of the concentric transmitter-receiver loop whereby the elevation of the top of the first layer is allowed to change within user defined limits (e.g., ± 3 m) in order to compensate for possible altimetry errors and improve the fit to the AEM data. After inversion, all elevations are referenced to the upper surface of the first layer, i.e., sea level is restored to elevation zero. In all cases, upper and lower bounds for the first layer are 0.1 m and 40 m; and 0.1 and 150 m for the second layer. A moving average or median filter with a length of 20 samples (~ 200 m) is applied to the inverted interface depths to account for the expected AEM footprint [4], [5].

The degree of correspondence between observed and calculated data after inversion is gauged by the L1-norm misfit defined by [25],

$$L1 = \frac{1}{N}\sqrt{\frac{\pi}{2}}\sum_{n}\left|\frac{o_n - c_n}{\varepsilon_n}\right| \qquad (1)$$

where $\{o_n\}$ are the observed data, $\{c_n\}$ are the calculated responses, and N is the total number of data involved in the inversion. The residuals are normalised with respect to the corresponding standard deviations, $\{\varepsilon_n\}$. For convenience, the *nth* standard deviation, ε_n, is defined as some percentage (typically 1 to 2 %), of the *nth* measurement, o_n, with the proviso that ε_n must not be smaller than a specified noise threshold. If the errors in the data are realizations of independent normal random variables, with mean zero, the expected value of L1 is unity. The program is deemed to have converged if L1 is less than 1. Failure to achieve convergence may simply mean that the assumed level of error is too small. The quality of the data and the assumption of a layered sub-surface will govern the achievable degree of fit.

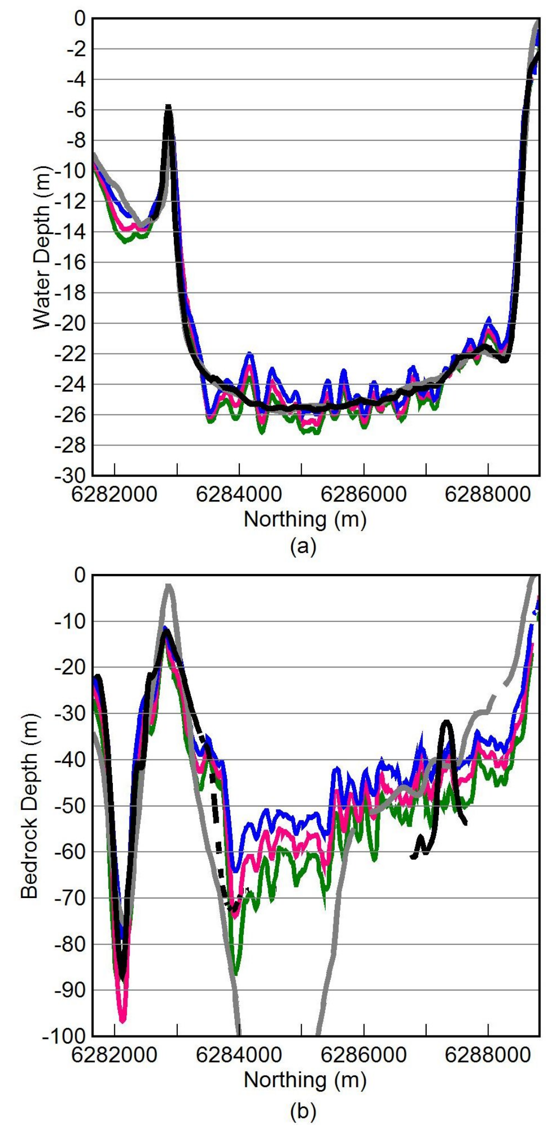

Fig. 3. Area 8 Line 8000. (a) Water depth profiles: *d1* (1.25 S/m sediment conductivity), blue; *d1* (1.0 S/m), red; *d1* (0.8 S/m), green; bathy_2m, grey; B11709, black. (b) Depth to bedrock profiles: *d2* (1.25 S/m sediment conductivity), blue; *d2* (1.0 S/m), red; *d2* (0.8 S/m), green; bedrock_10m, grey; bedrock_2008, black.

V. Results

Profiles of the seawater-sediment (*d1*) and sediment-bedrock (*d2*) interface depths from inversion of AEM data are presented for Areas 5E, 5W and 8 in Broken Bay for selected flight lines. The *d1* and *d2* depths for each survey area were subsequently gridded using the minimum curvature method. Only flight fiducial point coordinates for data where the L1-norm error did not exceeded 10 and where the laser altimetry did not exceed 45 m were included in the profiles and gridded bathymetry (*d1*) and depth-to-bedrock (*d2*) maps. This bathymetric mapping procedure, i.e., inversion of raw AEM data, smoothing, gridding and display of georeferenced maps, takes approximately one hour for each survey area. This processing time represents a significant improvement compared to previous investigations with the SeaTEM prototype AEM system [14], and earlier studies with a commercial helicopter time-domain AEM system [10], [15] that required an empirical correction to data. These corrections were based on cross-plots of modeled and observed AEM responses at representative sites (control points). Modelling at the control points was based on known seawater depth and conductivity, and estimated sediment depth and conductivity (required for shallow waters).

A. Area 8

Fig. 3(a) shows the profiles of *d1* and the ground truth (bathy_2m and B11709) for the most-western survey line of

Area 8, Fig. 1. The southern section (south of northing coordinate 6283000 mN) passes the seaward side of Barrenjoey Head skirting the protruding reef by ~ 35 m, and runs approximately parallel to Palm Beach (Fig. 1). The reef section is identified by the peak at ~ 6282800 mN. The *d1* bathymetry profile assuming a sediment conductivity of 1.25 S/m shows very good agreement with the bathy_2m and B11709 profiles. This sediment conductivity is slightly higher than the measured values that range between 0.8 and 1.1 S/m for the single vibrocore survey site opposite Palm Beach (Fig. 1). On the northern side of the protruding reef (north of 6283000 mN), the water depth drops rapidly to about 25 m and then rises rapidly as the flight line approaches the shore on the northern side of Broken Bay. Overall, the *d1* profiles show good agreement with the bathy_2m and B11709 profiles. In the deepest section of this survey area, the inverted depths oscillate about the known depth. Oscillations are also observed in shallow waters, but the amplitudes of the oscillations are significantly reduced. The cause of this phenomenon is under investigation and may be linked to sudden onset of vibrations within the SeaTEM frame which introduces noise in the recorded voltages induced in the receiver loop, as the helicopter approaches the survey speed of approximately 55 knots.

Fig. 3(b) shows the corresponding profiles of *d2* and the ground truth bedrock profiles (bedrock_10m and bedrock_2008) for the most-western survey line of Area 8. This AEM dataset clearly identifies (i) the paleovalley opposite Palm Beach which extends to 80 – 90 m below sea level and (ii) the protruding reef area immediately to the north of the paleovalley. This result is an interesting example of using AEM to remotely sense a paleovalley in shallow coastal waters. The *d2* profiles for all the survey lines in Area 8 generally show best agreement with estimated ground truth when assuming a sediment conductivity of 0.8 S/m, unlike the *d1* profiles. This suggests that a two-layer sediment with a more resistive bottom layer may be more appropriate for this area. The *d2* profiles accurately track the bedrock_2008 profile over the reef section centered at ~ 6282800 mN. In this region, there is either exposed rock or very shallow sediment and the *d2* profiles are insensitive to the three sediment conductivities, as expected. Further north, between 6283000 and 6284000 mN, the *d2* profile accurately tracks the deepening bedrock profile to depths of ~ 70 m below sea level. In the deepest section, between 6284000 and 6286000 mN, the bedrock_2008 profile is approximately level at 70 m below sea level (not shown in Fig. 3(b), but inferred from the next 6 adjacent survey lines, Fig. 1), and the bedrock_10m profile deepens to ~ 160 m below sea level. This noticeable discrepancy cannot be reliably resolved by comparison with the *d2* profiles for deep sediment layers beneath relatively deep seawater because of the limited depth of investigation using AEM.

Figs. 4 and 5 show a bathymetry map of the bathy_2m data adjacent to Palm Beach and zoomed-out for the whole region of Area 8. Similarly, Figs. 6 and 7 show equivalent bathymetry maps based on AEM (*d1*) data. Figs. 4 – 7 use the same color scale. These images show that AEM data can be used to map water depths with reasonable depth accuracy (1 to 2 m) in a relatively short time (2 to 3 hours flight time and preprocessing of data and ~ 1hour for inversion and georeferenced display of AEM data). Fig. 8 shows a map of

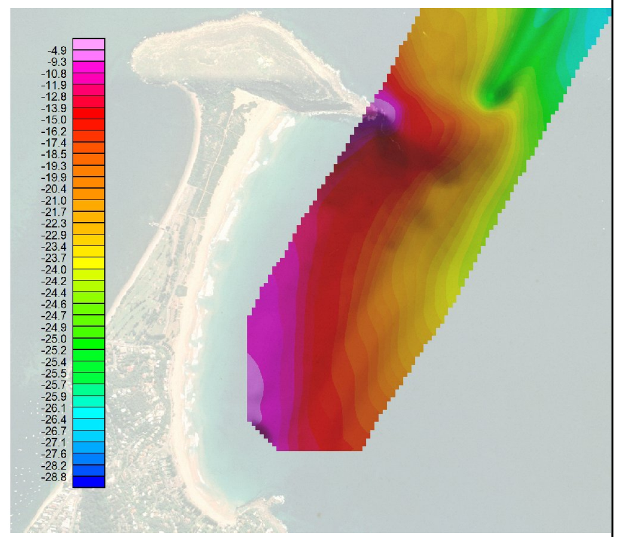

Fig. 4. Bathymetry map of Area 8 – adjacent to Palm Beach: bathy2m data. Georeferenced to Fig. 1. Color scale refers to depth below sea level.

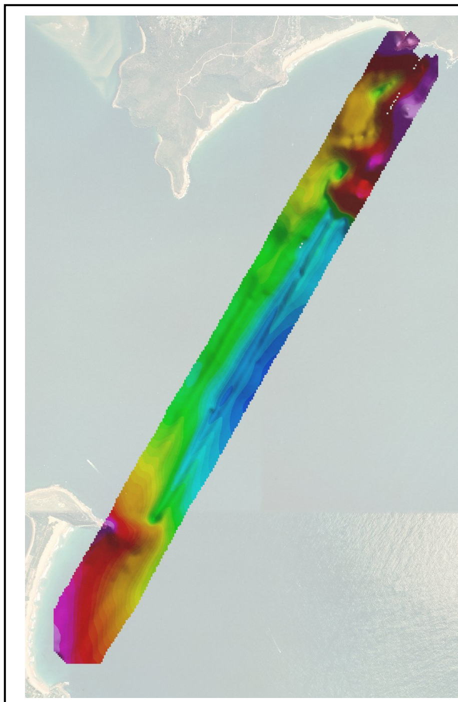

Fig. 5. Bathymetry map of Area 8: bathy2m data. Color scale: Fig. 4. Georeferenced to Fig. 1.

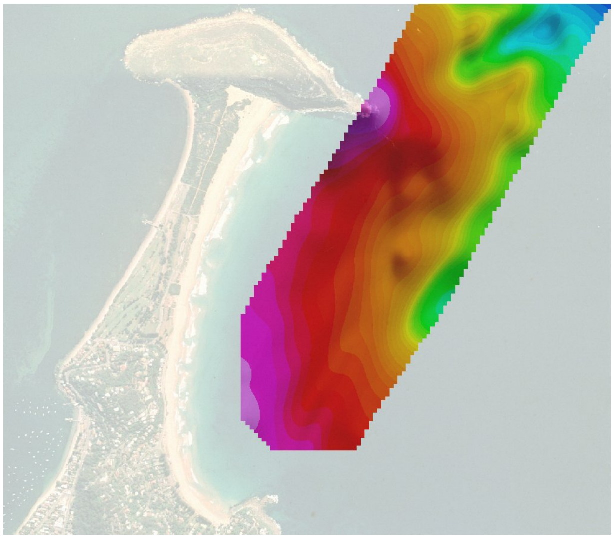

Fig. 6. Bathymetry map of Area 8 – adjacent to Palm Beach: AEM (*d1*) data. Color scale: Fig. 4. Georeferenced to Fig. 1.

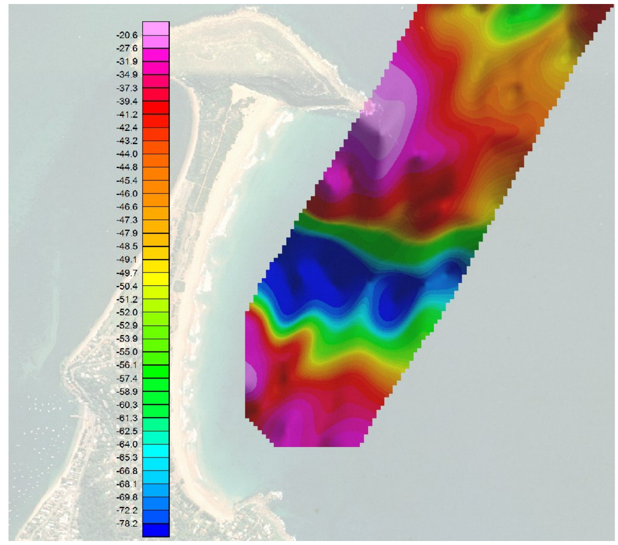

Fig. 8. Depth to bedrock map of Area 8 – adjacent to Palm Beach: AEM (*d2*) data. Georeferenced to Fig. 1. Color scale refers to depth below sea level (m).

the depth to bedrock obtained from the *d2* profiles, clearly exposing the paleovalley that runs east-west underneath the tombolo (sand spit) connecting Barrenjoey Head to the mainland.

B. Area 5E

Area 5 is split into two sections, east of the tombolo (Area 5E) and west of the tombolo (Area 5W). The eastern side includes the deeper waters on the seaward side of Palm Beach and the shallower waters in the surf zone approaching this beach. The western side includes and the relatively shallow waters in Pittwater and very shallow waters adjacent to Barrenjoey Beach. The maximum altitude constraint was relaxed from 45 to 60 m to enable the profiles to be imaged closer to Palm Beach and Barrenjoey Beach. This was necessary because the pilot deliberately flew at higher altitudes when approaching either side of the tombolo.

Figs. 9 and 10 show a bathymetry map of the bathy_2m data and *d1* data respectively, for the whole region of Area 5E. The maps use the same color scale, and show the good agreement overall between the two bathymetric datasets, especially on the approaches to the beach, through the surf zone to the beach shoreline, thereby reliably identifying the seafloor gradient adjacent to the beach. There are however some noticeable differences between the *d1* and bathy_2m

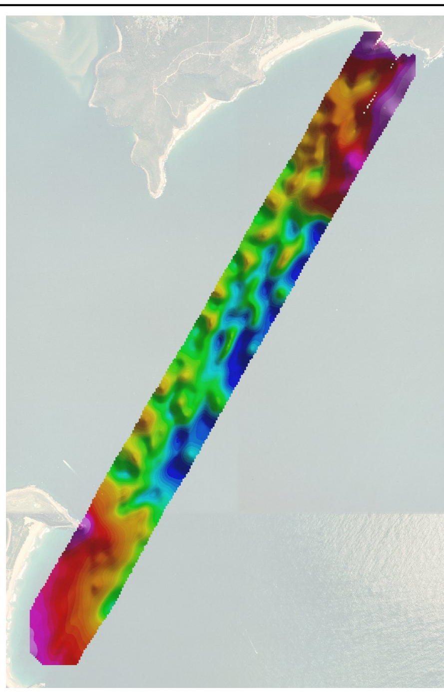

Fig. 7. Bathymetry map of Area 8: AEM data. Color scale: Fig. 4. Georeferenced to Fig. 1.

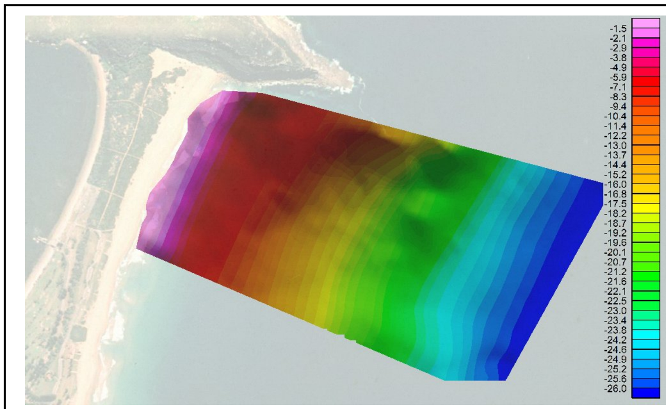

Fig. 9. Bathymetry map of Area 5E adjacent to Palm Beach: bathy2m data. Georeferenced to Fig. 1. Color scale refers to depth below sea level.

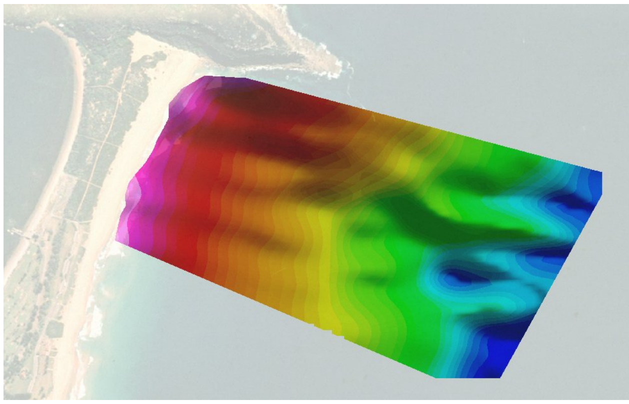

Fig. 10. Bathymetry map of Area 5E adjacent to Palm Beach: AEM (*d1*) data. Color scale: Fig. 9. Georeferenced to Fig. 1.

profiles for some of the survey lines in close proximity to the beach which may be due to beach erosion, and also arising from errors associated with a smaller signal to noise ratio in the AEM data at higher survey altitudes (50 to 60 m). Fig. 9 is derived from data acquired at least 23 years prior to the AEM survey, during 1979 to 1985, and the published 2 m contour chart includes a cautionary note stating that "where the seabed is sandy, the seabed contours may vary due to the action of waves and currents …. this is more marked in shallow areas, particularly within the surf zone".

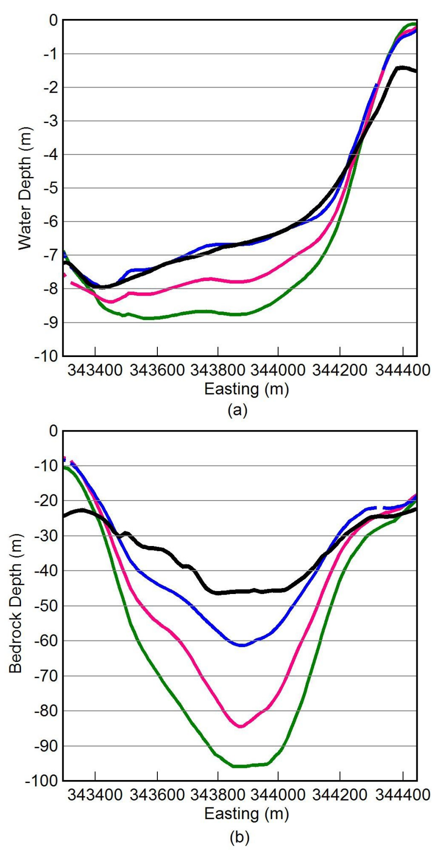

Fig. 11. Area 5W Line 5000. (a) Water depth profiles: *d1* (1.25 S/m sediment conductivity), blue; *d1* (1.0 S/m), red; *d1* (0.8 S/m), green; B11709, black. (b) Depth to bedrock profiles: *d2* (1.25 S/m sediment conductivity), blue; *d2* (1.0 S/m), red; *d2* (0.8 S/m), green; bedrock_2008, black.

There is generally a reasonable agreement between bedrock_2008 and d2 profiles, typically within ~ 10 m. A map of the depth to bedrock obtained from the *d2* profiles (not shown), identifies the most northern section of the paleovalley (Fig. 8).

C. Area 5W

This area consists of water shallower than 10 m in depth. Fig. 11(a) shows the profiles of *d1* and the ground truth (B11709) for the most-northern survey line of Area 5W. All five vibrocores sites in Pittwater (2 of which lie in Area 5W) yielded surficial sediment samples with sediment conductivities ranging between 1.1 to 1.6 S/m. The profiles of *d1* in Fig. 11(a) clearly show the deterioration in agreement with the B11709 profile when the sediment becomes more resistive (progressing from 1.25 S/m to 1.0 and 0.8 S/m). This is also clearly shown in the *d2* profiles in Fig. 11(b). Fig. 11(a) also shows that the *d1* profile, assuming a sediment conductivity of 1.25 S/m which is consistent with measured conductivity values, gives very good agreement with known bathymetry (B11709), typically to within ~ 30 cm. Figs. 12 and 13 show a bathymetry map of the B11709 data and *d1* data respectively, for the whole region of Area 5W using the same color scale. These maps show the very good agreement between the two bathymetric datasets, including the approach to the Barrenjoey Beach shoreline. The map of the depth to bedrock obtained from the *d2* profiles (Fig. 14) shows the northern edge of the deeper paleovalley clearly identified in Fig. 8 that passes beneath the tombolo, and a shallower paleovalley leading from Pittwater into Broken Bay.

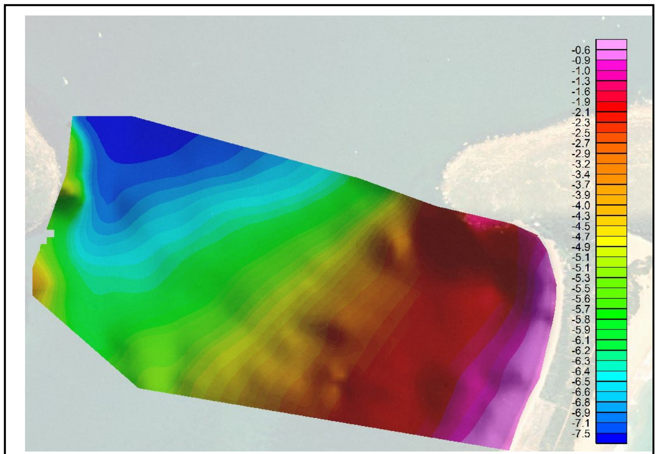

Fig. 12. Bathymetry map of Area 5W adjacent to Barrenjoey Beach: B11709 data. Georeferenced to Fig. 1. Color scale refers to depth below sea level.

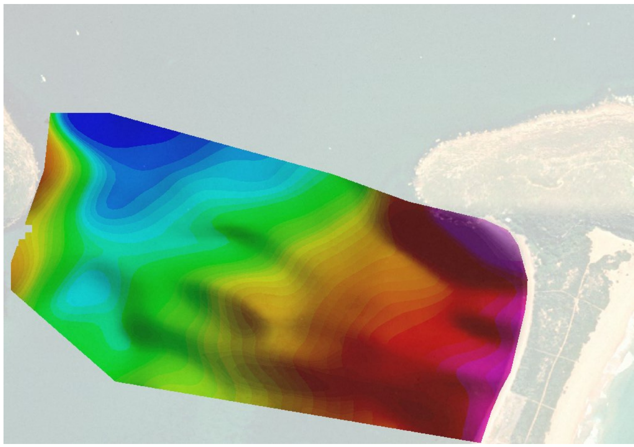

Fig. 13. Bathymetry map of Area 5W adjacent to Barrenjoey Beach: AEM (*d1*) data. Georeferenced to Fig. 1. Color scale: Fig. 12.

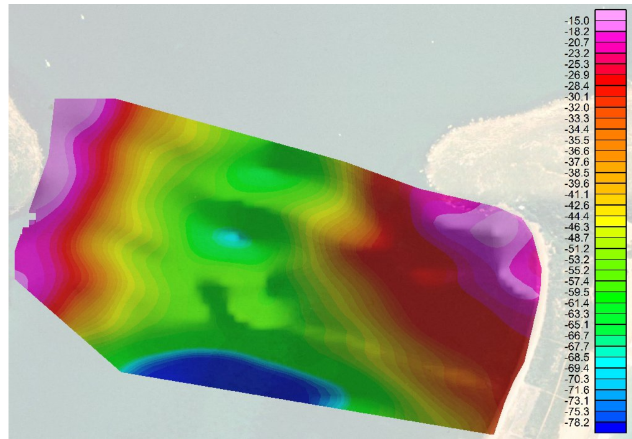

Fig. 14. Depth to bedrock map of Area 5W: AEM (*d2*) data. Georeferenced to Fig. 1. Color scale refers to depth below sea level (m).

VI. Discussion

The AEM bathymetry maps show a good agreement with sonar soundings for waters shallower than about 30 m, and very good agreement in waters shallower than 10 m where sub-metre accuracy can be achieved. (The AEM survey did not include areas with water deeper than 30 m.) The AEM data also provide information on the coarse features of bedrock topography and have identified a distinct paleochannel that passes beneath a tombolo. These findings are consistent with bedrock topography identified by marine seismic. The inversion of AEM data using selected sediment conductivities gives better agreement with ground truths for more conductive surficial sediments with conductivities of about 1.25 S/m, as opposed to more resistive sediment (0.8 S/m), especially in the Pittwater region. These findings are consistent with the limited resistivity measurements of vibrocore samples, however, the sampling density is sparse and this agreement needs to be treated with caution.

In Area 8, which contains the deepest waters in this study, the inverted seawater depths (*d1*) show an oscillatory pattern which is currently under investigation and may be linked to the structure of the bird (airframe) which has been observed to give rise to a sudden onset of noise in the voltages recorded by the receiver loop as the survey speed is approached.

At present, there are no attitude sensors attached to the bird to track pitch and roll. Inclusion of attitude is expected to improve the efficacy of AEM for bathymetric mapping by incorporating attitude as known parameters for inversion.

The accuracy of AEM for bathymetric sounding was investigated in a recent study [26] that floated a time-domain AEM system close to the water surface (5 – 12 m). The floating-AEM system was towed over shallow water at a speed of ~ 2 knots (1 m/s), compared to a typical SeaTEM survey speed of 55 knots, and in calm waters, provided data that was not degraded by uncertainties in altimetry, bird position, orientation and possible helicopter interference, and also, importantly, enabled longer averaging (stacking) times of data. The resulting water depths (*d1*) obtained after empirical correction to the data agreed within ~ ± 0.5 m of known depths up to 20 m. These results were expected to provide an upper limit to the accuracy which can be expected from airborne EM systems using current technology. These accuracies are not significantly different from the bathymetric accuracies found in this survey in water shallower than about 10 m. No oscillations were observed in the inverted depths obtained from the AEM data for this floating system.

VII. Conclusion

An airborne electromagnetic survey over Broken Bay provided data that was inverted, assuming a crude one-dimensional layered earth model, to provide water depths and depths to bedrock. This model consists of an upper seawater layer overlying a sediment layer which in turn overlies a resistive bedrock basement. The inverted depths were compared with two dated bathymetry datasets obtained from sonar soundings, and two datasets of estimated depths to bedrock from marine seismic studies. The water depths obtained from the airborne data showed good agreement with known depths and were used to produce bathymetric maps to enable a visual comparison with similar maps covering the same area obtained from sonar data. In areas less than about 10 m deep, sub-metre accuracy was achieved. The airborne data showed that it was possible to measure water depth up to the very shallow water adjacent to beaches, and through the surf zone. Further experiments are required with various surf and swell conditions to determine the limitations with this methodology. The depths to bedrock determined from the airborne data were of notable interest because they reveal the coarse features of the bedrock topography in areas where the overlying water depth is less than about 20 m, and the sediment thickness, depending on its resistivity, is less than about 60 m or so. These depths are very sensitive to the data quality and calibration errors associated with the airborne instrumentation. An interesting outcome of this airborne study was the remote sensing of a distinct paleochannel that passes underneath a tombolo and extends down to a depth of about 60 to 80 metres below sea level. This study also showed that airborne electromagnetic bathymetry is a useful and rapid reconnaissance technique for obtaining water depths in turbid and surf-zone waters.

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