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TECHNICAL REPORT

ERL-0186-TR

WATER TURBIDITY MEASUREMENTS IN GULF ST VINCENT

D.M. PHILLIPS, M.L. SCHOLZ and R.H. ABBOT

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WATER TURBIDITY MEASUREMENTS IN GULF ST VINCENT

D.M. Phillips, M.L. Scholz and R.H. Abbot

SUMMARY

Large scale surveys have been made of the horizontal and vertical distributions of turbidity in the waters of Gulf St Vincent in South Australia. The beam attenuation coefficient at a wavelength of 530 nm was determined from measurements made with a transmissometer operated from a boat. Both horizontal and vertical stratification of turbidity was observed and explanations for these two conditions are offered. Two methods for determining water turbidity from an aircraft were investigated. They involved measuring the amplitude and attenuation of the backscatter envelope from a laser pulse transmitted from the aircraft into the water. The relative merits of the two methods are evaluated.

POSTAL ADDRESS: Chief Superintendent, Electronics Research Laboratory, Box 2151, GPO, Adelaide, South Australia, 5001.

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1. INTRODUCTION

Water turbidity affects the performance of the laser airborne depth sounder (WRELADS) being developed at the Defence Research Centre Salisbury to assist the Royal Australian Navy in its task of charting Australian coastal waters. The operation of the system and some preliminary results obtained by it are described by Clegg and Penny(ref.1). The results of feasibility trials in 1975 are described by Abbot and Penny(ref.2) and a detailed report of the first stage of the development programme has been written by Abbot et al(ref.3).

The influence of water turbidity on the maximum depth that can be measured by the system has been studied experimentally by Phillips(ref.4). The water turbidity was characterised by the beam attenuation coefficient, which describes the rate of attenuation of a beam (per metre) due to both absorption and scattering. Measurements of this coefficient in both South Australian and Queensland coastal waters resulted in values ranging from 0.1 to 2 m^{-1}.

The maximum measurable depth in a given type of water, called the extinction depth, was estimated from return signals recorded by the WRELADS system. A limited amount of data obtained when the system was not optimised yielded extinction depths ranging from 33 to 13 m over the range of attenuation coefficients from 0.1 to 1 m^{-1}.

This memorandum extends the previous work in two ways. Firstly, the horizontal and vertical distribution of turbidity in Gulf St Vincent is surveyed more extensively, in order to gain a better understanding of the optical properties of the marine environment. Secondly, airborne techniques for describing water turbidity are explored, with a view to facilitating further studies of the relationship between turbidity and extinction depth.

2. MEASUREMENTS OF BEAM ATTENUATION COEFFICIENT FROM BOAT

The previous measurements(ref.4) suggested three important influences on the turbidity of shallow coastal waters. Firstly, rainfall on coastal land contributes to sediment in adjacent waters. Secondly, sediment becomes suspended in the water as a result of wave action on the sea bed. Thirdly, turbid water is transported to new locations by tides and currents.

2.1 Horizontal distribution of turbidity

The horizontal distribution of turbidity depends on the relative importance of generation and transport of suspended sediment. If particle settling times are short, turbidity will be closely related to the nature of the bottom and the water depth. On the other hand, if particle settling times are long, turbidity will be unrelated to bottom topography.

In order to resolve the relative importance of these processes, the horizontal distribution of turbidity in Gulf St Vincent was determined by taking measurements at the locations shown in figure 1. At each position the water transmittance was measured at a depth of 2 m with the transmissometer described by Woodcock(ref.5).

The two boat trips were made on consecutive days(29 and 30 April 1980) when the conditions were similar: gentle winds and slight seas.

The measured horizontal distribution of beams attenuation coefficient (c) at a depth of 2 m in Gulf St Vincent is presented in figure 2. It can be seen that the 0.4^{-1} contour of attenuation coefficient around the coastline is close to the 6 m depth contour. This suggests that the turbid water close to the shore is being generated by wave action on the bottom.

The turbid water in the central and deeper region of the gulf, however, could not have been generated by the slight seas experienced at the time. Significant wave action extends to a depth of only about half the wavelength (Phillips, reference 16). Therefore, on the days the measurements were made, significant wave action would have extended to a depth of only about 6 m compared with the water depth of over 20 m. The central turbid water could have been generated either by rough seas in that region a few days earlier or by horizontal transport of turbid water from shallow areas. The occurrence of the clearest patch of water ($c < 0.2\ m^{-1}$) in the northern part of the gulf suggests that clear ocean water has somehow been transported there.

2.2 Vertical distribution of turbidity

The previous measurements of the turbidity distribution over a vertical section of water along the Stansbury line of buoys(ref.4) hinted at complex circulation currents within the gulf. At the deep end of the line of buoys the clearest water was submerged deeply in summer but lay near the surface in winter. This suggested that, while the shallow water is well-mixed vertically, the deeper areas may be horizontally layered.

The vertical distribution of turbidity was investigated further on 13 May 1980 when measurements were made along the three lines labelled (a), (b), and (c) in figure 1. The measurements were made at 1 m increments in depth with a horizontal spacing of about 2 km.

The results are presented in figure 3. Section (a) reveals strong vertical mixing of the water on the eastern side of the gulf, but some horizontal layering on the western side. The latter agrees with the data obtained in 1977. The central turbid region, which was observed on the surface 14 days earlier (figure 2), can be seen to extend to the bottom of the trench along the western side of the gulf. Section (b) also shows the central turbid region extending to the bottom of the trench.

The general circulation pattern in Gulf St Vincent was studied by Bullock in April 1973(ref.7). Measurements of temperature and salinity were made throughout the gulf over a range of depths. Values of the water density ρ were calculated from these data and horizontal and vertical distributions of σ_t, the excess of the density over its pure water value,

where $$\sigma_T = \rho - 1000\ (kg\ m^{-3})$$

were derived and are reproduced in figure 4. It can be seen that the density does not vary greatly with depth. Consequently, the thermohaline circulation current depends primarily on the horizontal water density distribution, which shows a tongue of cool, low-salinity, low-density ocean water entering the gulf on the western side. This flow merges with the high-salinity, high-density water from the northern part of the gulf in the Port Adelaide region and drains out of the gulf along the eastern side.

The turbid water associated with the trench along the western side of the gulf may, therefore, result from the circulation current disturbing sediment on the bottom.

2.3 Small scale horizontal variation in turbidity

An important question for the operation of the laser airborne depth sounder is whether small-scale horizontal variations in turbidity commonly occur. One series of measurements was therefore specifically designed to look for such variations. Measurements were made at a constant depth of 2 m at 100 m intervals along an east-west line off Port Adelaide. This region was chosen because the water is relatively turbid and variations would be readily observed.

The results are shown in figure 5. It can be seen that significant variations occur over distances of several hundred metres. The largest variation over the 270 m swath width of the WRELADS system is about 20%.

2.4 Statistical variation of turbidity with water depth

The laser airborne depth sounder can detect the bottom in water of a given depth provided that the turbidity does not exceed what will be called the "limiting turbidity" for that depth. The proportion of coastal waters that can be sounded with the WRELADS system will therefore depend on the statistical distribution of turbidity as a function of water depth that occurs naturally.

Figure 6 is a scatter diagram of all values of the beam attenuation coefficient at a wavelength of 530 nm and a depth of 2 m measured in the waters of Gulf St Vincent. Different symbols are used to distinguish the dates of the boat trials. On all occasions (to facilitate work on the boat) the measurements were made in smooth to slight seas with winds below 15 kn. Thus none of these measurements correspond to the highly turbid water that can be generated by rough weather.

It can be seen that the vast majority of the water has a beam attenuation coefficient between 0.2 and 0.6 m^{-1}, independent of water depth. The limiting turbidity reported by Phillips(ref.4) varies from about 0.5 m^{-1} at 20 m depth to about 0.15 m^{-1} at 30 m. That would imply a practical limit of 20 to 25 m for depth soundings in the water sampled. However, the system was not optimised when the limiting turbidity measurements were made and there are reasons to believe that a depth sounding performance closer to 30 m will be achieved in these waters.

3. MEASUREMENTS OF WATER TURBIDITY FROM AIRCRAFT

The return signal recorded by the green receiver of the WRELADS system(ref.3) consists of four components: the surface, backscatter, and bottom reflections, together with reflected sunlight. Figure 7 shows a selection of typical green return signals recorded with the photomultiplier operating in the constant gain mode, with no block in the image plane, and with a polarizer oriented for maximum attenuation of the surface reflection. The signals recorded at the centre of the scan (transmitted beam vertical) all show a strong surface reflection. At the edge of the scan (nadir angle 15^{o}) commonly no surface relection is present.

The shape of the backscatter envelope depends on the water turbidity. In clear water, the amplitude of the backscatter is small and the decay time is long. The opposite is true in turbid water: the amplitude is initially large but falls rapidly. Consequently, the backscatter amplitude and the backscatter decay constant provide two independent measures of water turbidity that can be determined from an aircraft.

3.1 Theoretical shape of backscatter envelope

A simple theoretical model will be assumed for the purpose of analysing the shape of the backscatter signal. Let F be the radiant flux incident on the water surface. The amplitude of the backscatter component of the return signal from the water at depth is assumed to be given by

$$B_z = \beta F \exp(-2k_b z),$$

where

k_b is the attenuation coefficient that characterises the backscatter signal, B_z is a measure of the strength of backscattered light and β is a constant.

The factor of 2 in the exponent accounts for the passage of the laser radiation both down and up through the water.

The above equation can be reduced to a linear form, suitable for regression analysis, by taking logarithms:

$$\ln(B_z) = \ln(\beta F) - 2k_b z.$$

The backscatter signals are recorded by a Biomation 6500 digitising waveform recorder as a function of time. Before they are analysed they need to be transformed to a function of depth, using the speed of light in water of 224×10^6 ms^{-1}. Since the data can be clocked out of the waveform recorder at two different rates, the transform corresponding to the actual data rate must be used. The relevant data for the two modes of operation are summarised below:

	Direct output	Output via Signal Enhancer
Output clock rate	1MHz	25 kHz
Sweep speed	20 μs/div	1 ms/div
Display speed	40 ns/div	50 ns/div
Display scale (calc)	4.48 m/div	5.60 m/div
Display scale (meas)	4.55 m/div	5.56 m/div

If points on the backscatter signal are read from the oscillogram in x, y coordinates in divisions, the regression variables are:

$$2z = 8.96\ x\ (\text{or } 10.20x) \text{ and } \ln(B_z) = \ln y$$

The intercept and gradient will then be $\ln(\beta F)$ and $-k_b$ respectively.

3.2 Measurements of backscatter amplitude and attenuation

In a combined aircraft and boat trial on 20 June 1980, measurements of backscatter amplitude and attenuation coefficient made from a boat. The measurements were made along the line marked (a) in figure 1, that extends westward from Pt Adelaide. The results were obtained more than five weeks after the turbidity distribution in figure 3(a) was determined. In spite of the passage of time, however, the turbidity distribution (shown in figure 8) was similar: vertical stratification on the eastern side of the gulf and tending towards horizontal layers on the western side.

The results of the correlated measurements are given in figure 9. In both graphs, the abcissa is the beam attenuation coefficient, at a depth of 2 m, determined using the transmissometer in the boat. The upper graph shows the amplitude of the backscatter signal at a depth of 2 m. It can be seen that the amplitude of the backscatter tends to increase with increasing values of beam attenuation coefficient, although the scatter limits the usefulness of the correlation.

The backscatter attenuation coefficient shown in the lower graph was determined by regression analysis using the theoretical model described in the previous section. Because the expected positive correlation between the two attenuation coefficients was not observed, an analysis of possible sources of error is presented in the following sections.

3.3 Errors due to position and time differences

Each set of aircraft and boat measurements was made as close together in time and horizontal position as possible. Synchronisation in time was achieved by the boat proceeding between measurement locations as fast as possible while the aircraft manoeuvred to fly overhead when the boat was on station. Horizontal position fixing was achieved with a radio navigation system (ARGO DM54) which was fitted to both boat and aircraft. This system has an accuracy of a few metres in the region where the experiments were performed.

If the aircraft and boat measure water turbidity simultaneously at different locations, the magnitude of the resulting error depends on the horizontal turbidity gradient. If the results in figure 5 are taken as indicative of horizontal variations in turbidity, each 100 m of horizontal error can be expected to contribute about 3% error to turbidity.

If the aircraft and boat make measurements at the same location but at different times, currents and tides can move the water mass and errors can again result from horizontal turbidity gradients.

The aircraft and boat measurements, used to produce the results shown in figure 9, were made with a positional accuracy of about 100 m and a timing accuracy of about 3 min. The former could therefore contribute turbidity errors of about 3%. The turbidity error due to the latter depends on the strength of water currents in the area. If a current speed of 1 kn is assumed, the timing errors could also contribute turbidity errors of about 3%.

Consequently, positional and timing differences between the aircraft and boat measurements could account for a total of about 6% of the variation in turbidity. This is clearly insufficient to account for all the scatter in figure 9.

3.4 Errors due to vertical variation of turbidity

The theoretical model, described in Section 3.1 and used to determine the backscatter attenuation coefficients shown in figure 9, assumes the water turbidity to be independent of depth. That assumption can be seen from figure 8 to be satisfactory on the eastern side of the gulf where c is greater than about 0.5 m. However, on the western side, where the water tends to be horizontally stratified, the assumption fails. At one place, c increases by over 100%, from 0.35 m^{-1} on the surface to 0.72 m^{-1} on the bottom.

Six of the eight points plotted in the lower graph of figure 9 have values of c less than 0.5 m^{-1}. Those six points, therefore correspond to horizontally layered water exhibiting substantial variation of turbidity with depth. The six associated values of k_b must all be considered suspect.

The effect of turbidity increasing with depth is to produce a backscatter decay that is initially slower but later faster than that produced by water of uniform turbidity. The opposite is true in water of decreasing turbidity. This is illustrated in figure 10.

In analysing the data to produce the values of k_b shown in figure 9, the signal from the first few metres below the surface had to be ignored because of the presence of a large surface reflection. It is therefore likely that the portion of the backscatter signal used to determine k_b was like the right-hand part of figure 10(a). This would result in an overestimate of k_b and would account for the high values obtained for the six suspect points.

3.5 Errors due to shallow water

In shallow water, the backscatter signal is not long enough to determine the attenuation coefficient with precision, although the amplitude may still be measurable. This is illustrated in figure 7(a).

In figure 9 only one point has a value of c greater than 0.8^{-1}. While the backscatter amplitude is sensible, the backscatter attenuation coefficient appears to be too small probably for the above reason.

4. DISCUSSION

The results reported in this memorandum provide significant information about the physical processes that govern water turbidity. They also provide an indication of the potential and limitations of airborne techniques for determining water turbidity.

4.1 Horizontal and vertical layering of turbid water

The energy required to lift sediment from the sea bed is supplied by water motion, which can be caused by waves, tides and currents. Once generated, turbid water is transported to new locations by tides and currents. Waves do not produce a net transport of water except along the shore line where the waves break to form surf. Whether vertical or horizontal layering of turbidity occurs in a given region depends on the predominant generation and transport processes.

Because waves produce both vertical and horizontal motion of water particles, they provide strong vertical mixing of the water. When waves are responsible for the generation of turbid water, the strong vertical mixing tends to produce uniform turbidity at all depths. This is borne out by the near-vertical contours of equal turbidity observed in shallow regions where wave action is the predominant turbidity generation process (eg figures 3 and 6).

In deeper water there is more scope for thermohaline currents and tidal flows to drive water of one density into a water mass of a different density. This produces horizontal stratification of the water density, accompanied by similar horizontal stratification of the water turbidity. Such horizontal layering of turbidity is evident along the western side of Gulf St Vincent (in figures 3 and 8), where a tongue of low density water intrudes on the higher density water in the rest of the gulf (figure 4).

4.2 Measurements of turbidity from aircraft

Two measurements of water turbidity that can be determined from an aircraft have been investigated: the amplitude and attenuation of the backscatter envelope of the return signal from a laser pulse.

If the amplitude of the backscatter signal at the surface is proportional to the scattering coefficient, b, then it should be a linear function of $c = a + b$ (where a is the absorption coefficient). Four of the seven data points in figure 9(a) lie close to a straight line. The remaining three points could include extrapolation errors associated with turbidity variations discussed in Section 3.4. Thus the backscatter amplitude provides a promising measure of turbidity.

The main disadvantage of backscatter amplitude as a measure of turbidity is that it requires an absolute measure of signal strength. The gain of the receiving system depends on many factors including the transmission of the green filter, the photomultiplier supply voltage, the gain of the dynode gain controller. Consequently, whenever any component is replaced or is operated differently, the system must be recalibrated.

The backscatter attenuation coefficient has been determined using a theoretical model that assumes water turbidity to be independent of depth. Since this was not true (except in one case) in the calibration experiments reported in Section 3.2, it was not possible to establish a relationship between this parameter and the beam attenuation coefficient.

In principle, the backscatter attenuation coefficient has the advantage that it is independent of receiver gain. Against this, however, are two disadvantages. Firstly, the simple theoretical model described in Section 3.1 is applicable only in water of uniform turbidity. Secondly, the attenuation of the backscatter cannot be determined in shallow water.

The backscatter amplitude has the advantages that it can be determined in shallow water and it is less dependent on turbidity variations with depth. However this is only true when measuring turbidity close to the surface. Use of the backscatter amplitude to measure turbidity at greater depths renders this technique dependent on turbidity variations with depth.

5. CONCLUSION

Large scale surveys of the horizontal and vertical distributions of water turbidity in Gulf St Vincent have shown both vertical and horizontal layering of turbidity. Vertical layering is associated with wave induced turbidity in the shallow waters around the edge of the gulf. Horizontal layering is associated with the entry of low density ocean water into the deep western side of the gulf.

Backscatter amplitude and backscatter attenuation coefficient have both been studied as parameters that may be suitable for determining water turbidity from an aircraft. The present experiments suggest that backscatter amplitude is the more promising parameter because it is less dependent on uniform turbidity than the other. Both parameters deserve further study.

6. ACKNOWLEDGEMENTS

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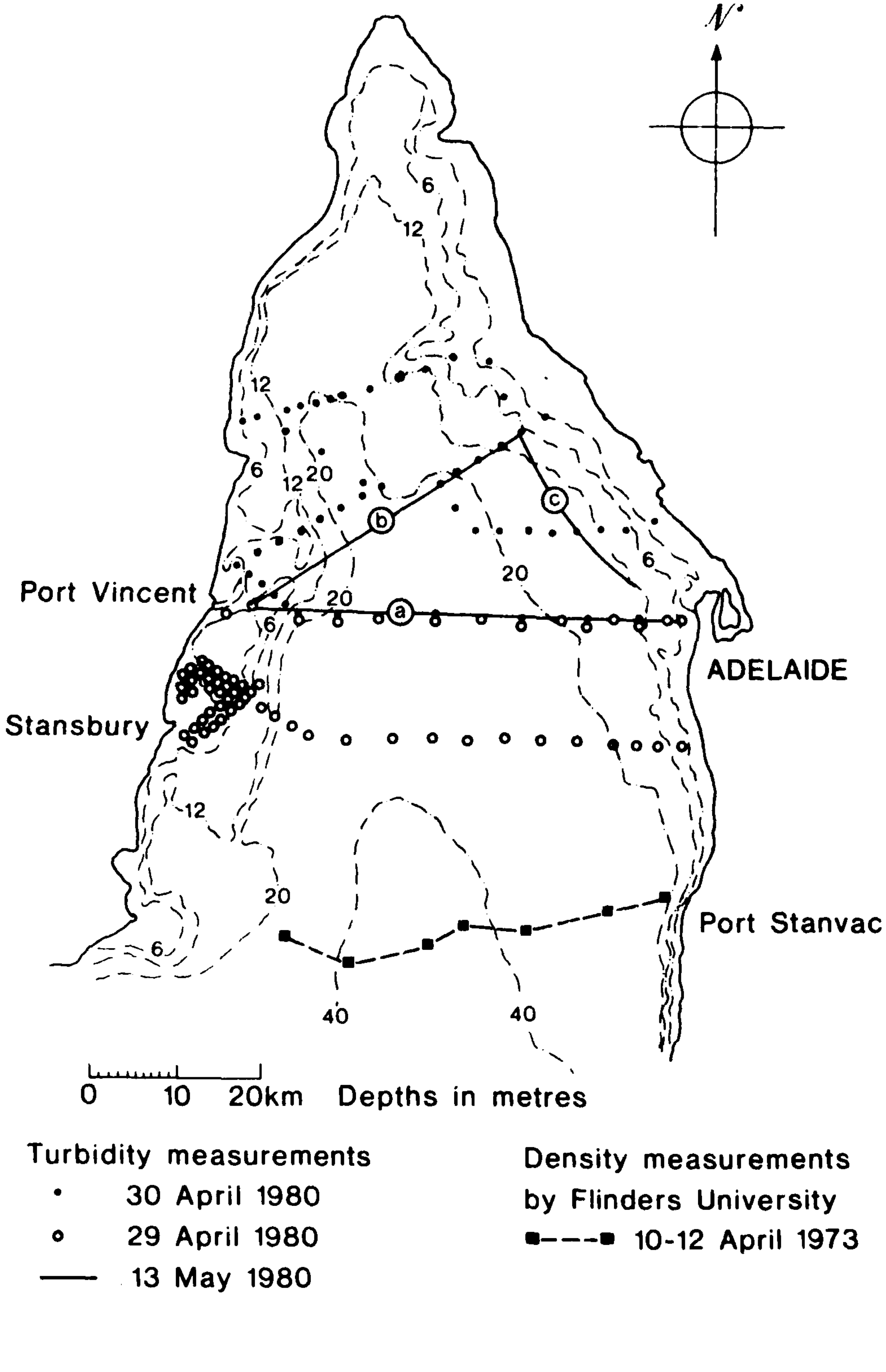


Figure 1. Chart of Gulf St Vincent showing locations of water turbidity and density measurements

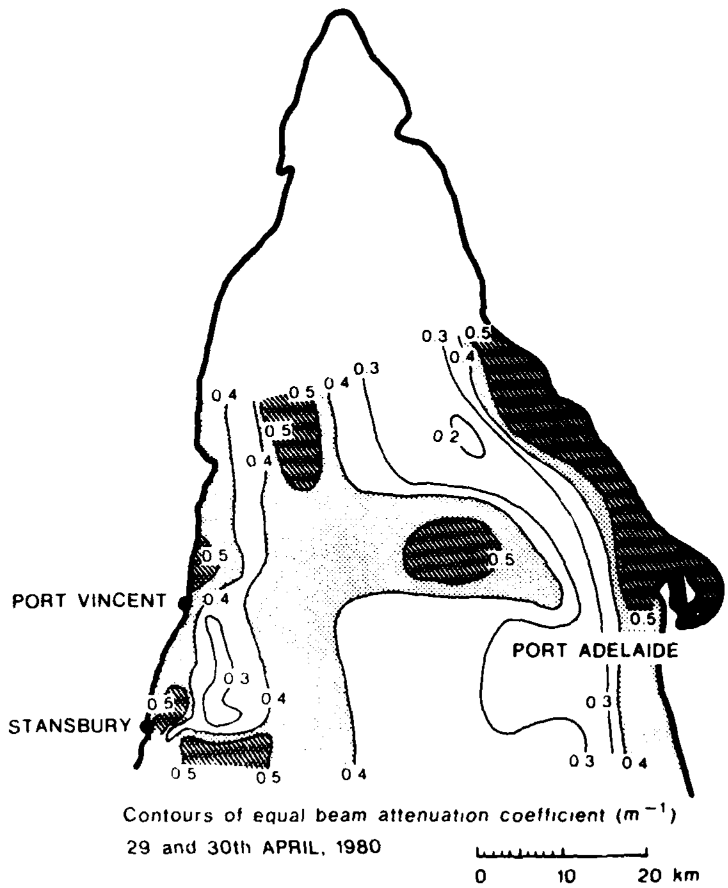


Figure 2. Measured horizontal distribution of beam attenuation coefficient of water at 2 m depth in Gulf St Vincent on 29 and 30 April 1980

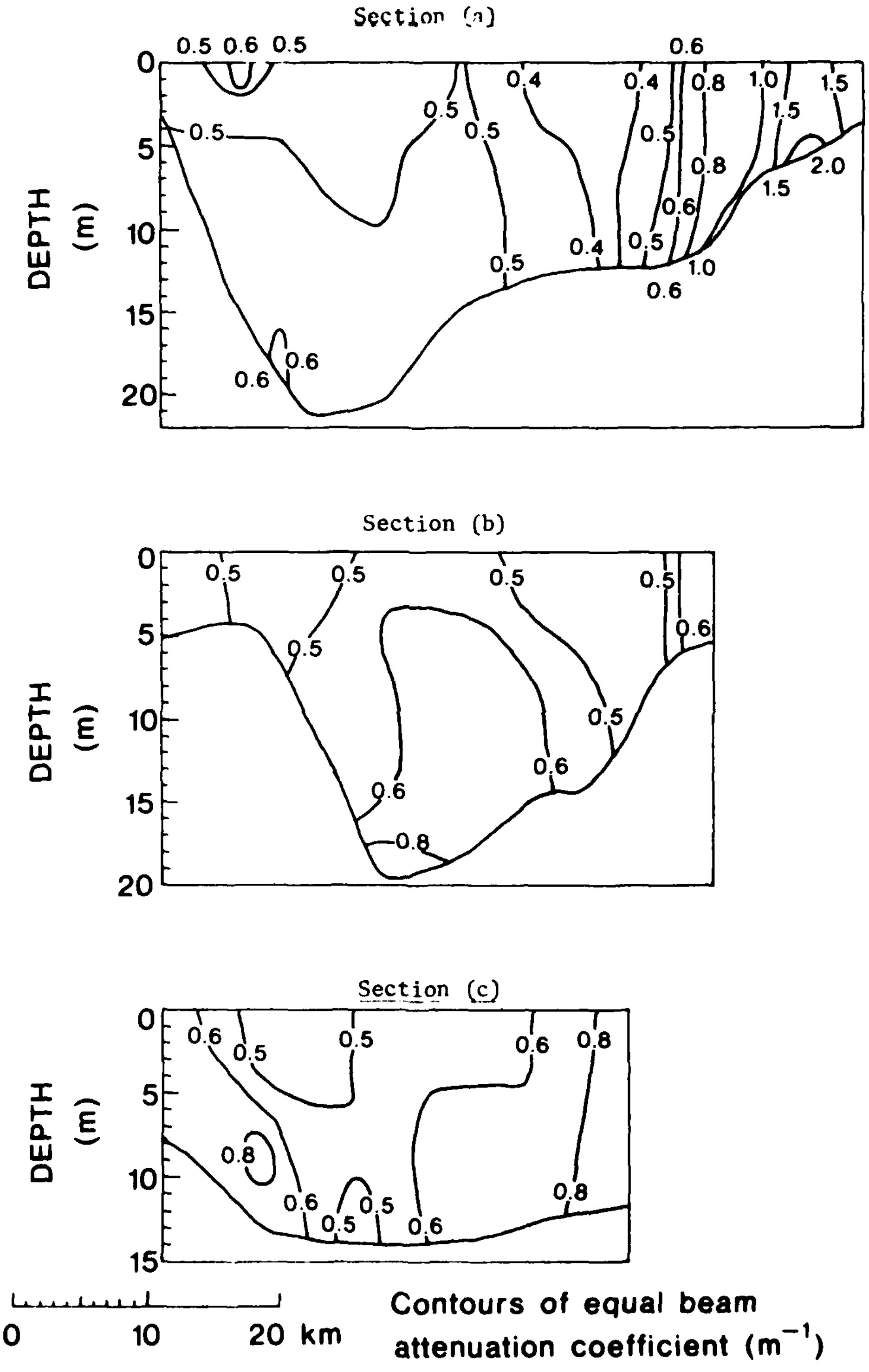
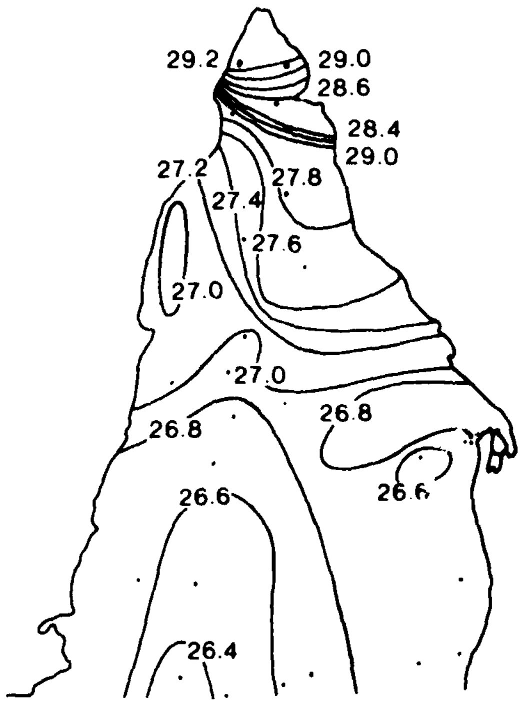
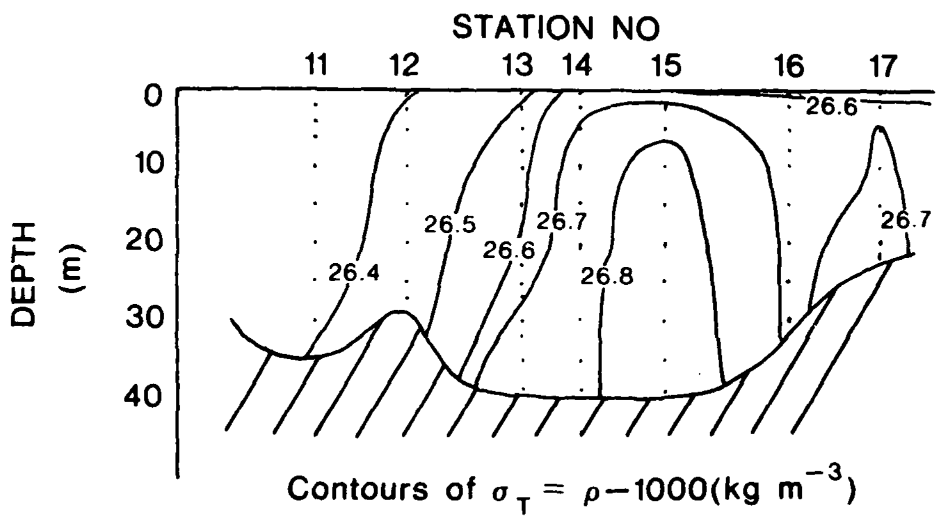


Figure 3. Measured distributions of beam attenuation coefficient of water in Gulf St Vincent on 13 May 1980



(a) Horizontal distribution of depth average



(b) Vertical section

Figure 4. Horizontal and vertical distributions of water density in Gulf St Vincent measured in April 1973(ref.7)

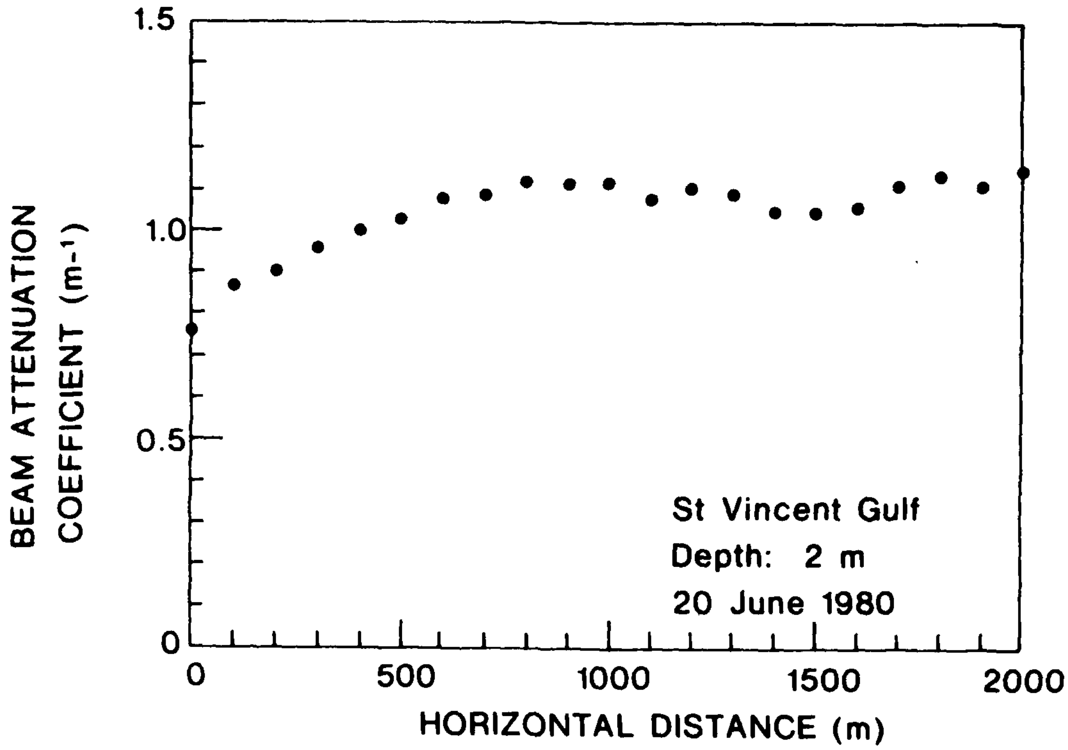


Figure 5. Measured small scale horizontal variation of beam attenuation coefficient of water in Gulf St Vincent on 20 June 1980

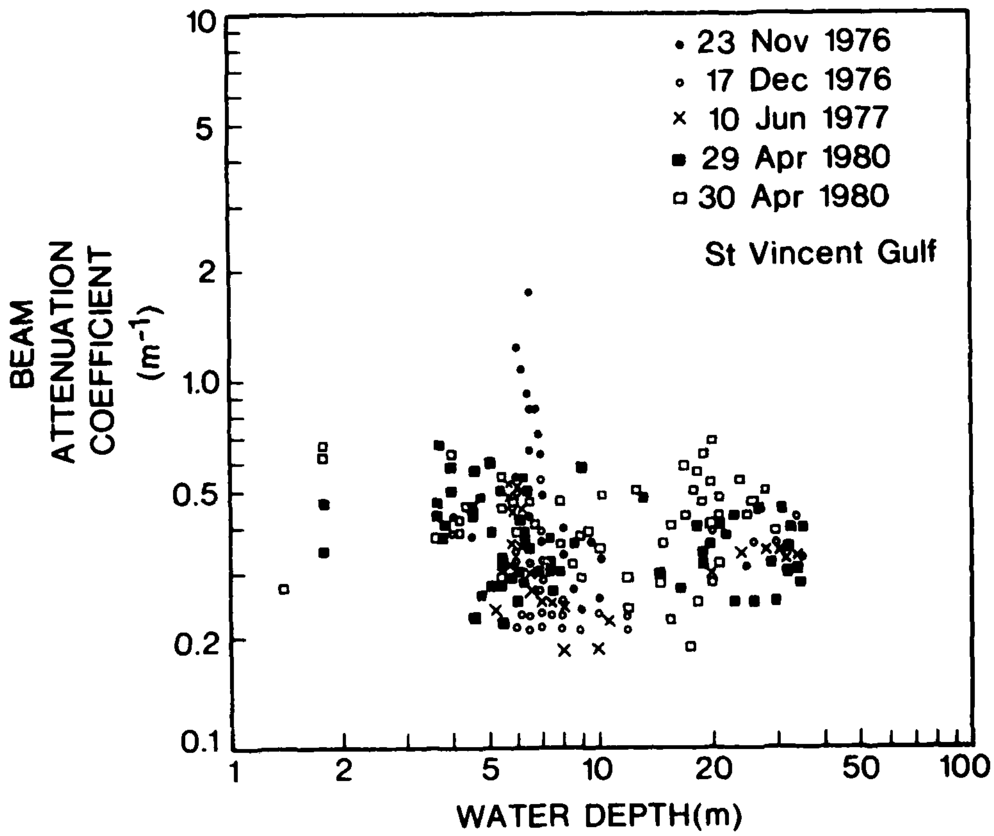
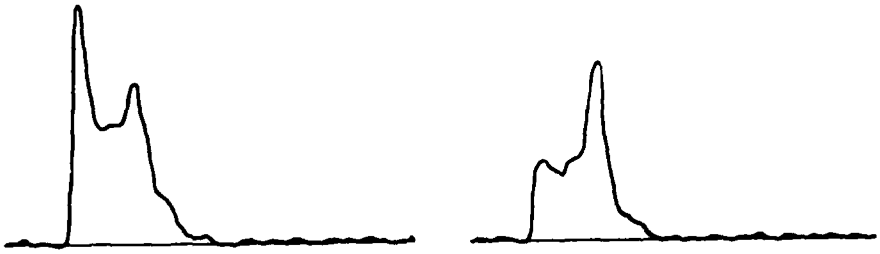
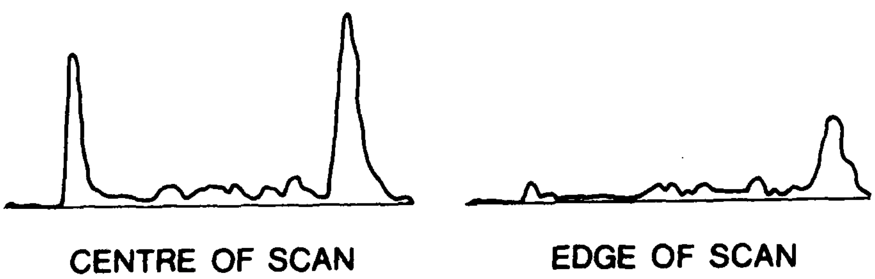


Figure 6. Statistical distribution of beam attenuation coefficient with water depth in Gulf St Vincent during calm weather conditions



(a) Shallow turbid water

(b) Deep turbid water



(c) Deep clear water

Figure 7. Typical green laser return signals from clean and turbid water at the centre and edge of scan

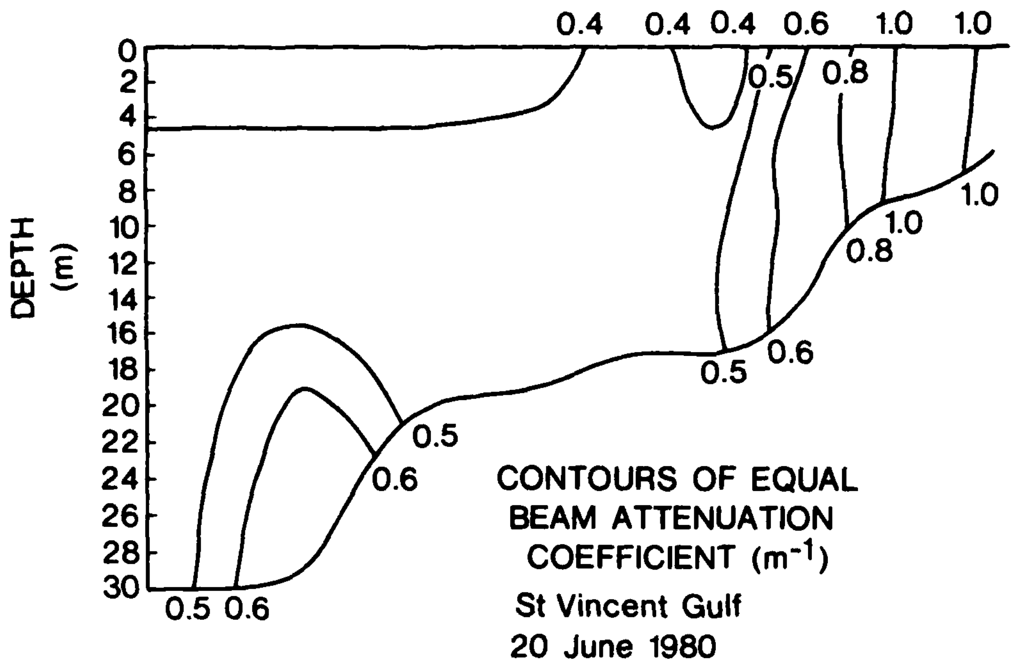
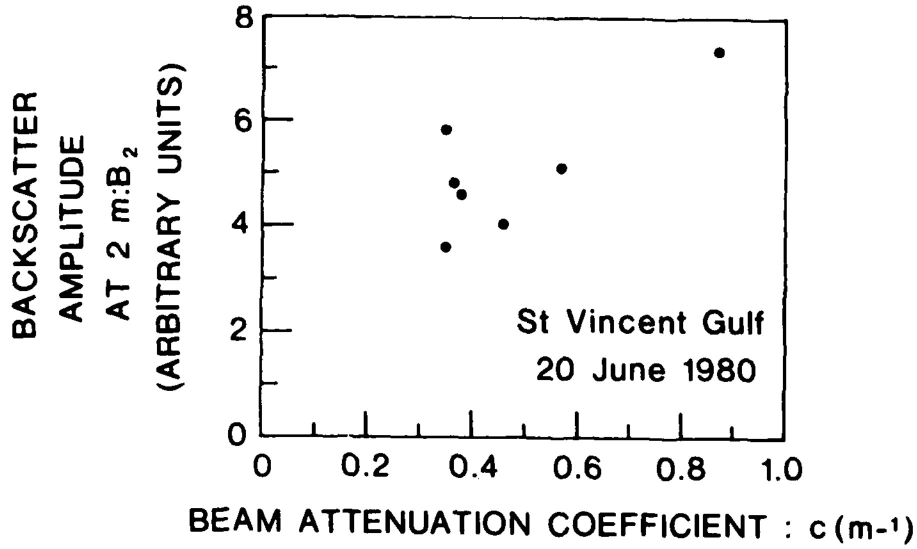


Figure 8. Measured distribution of beam attenuation coefficient of water in Gulf St Vincent on 20 June 1980



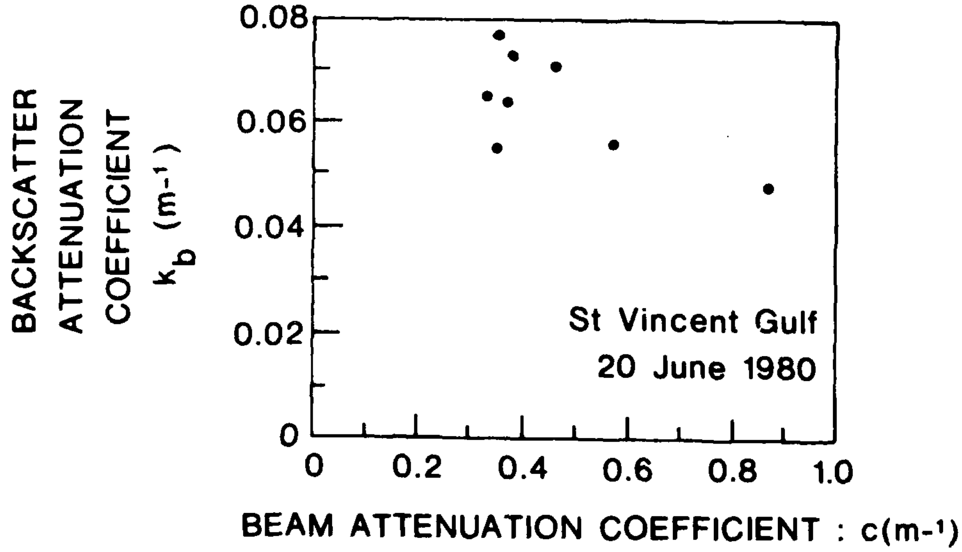
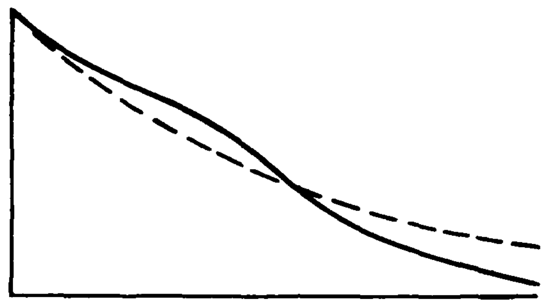
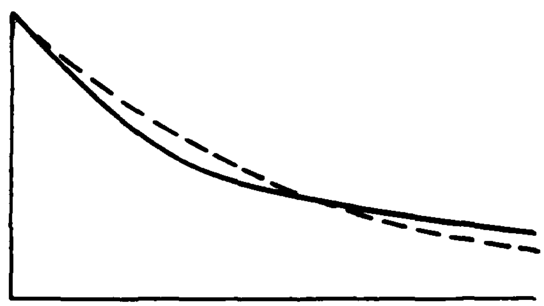


Figure 9. Measured dependence of backscatter amplitude and attenuation coefficient on beam attenuation coefficient in Gulf St Vincent on 20 June 1980



(a) Turbidity increasing with depth

(b) Turbidity uniform



(c) Turbidity decreasing with depth

Figure 10. Conjectured shapes of laser backscatter signals in water of varying vertical turbidity profiles

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b. Non-Thesaurus Terms	Gulf St Vincent WRELADS Beam attenuation	

16 LIBRARY LOCATION CODES (for libraries listed in the distribution):

17 SUMMARY OR ABSTRACT:
(if this is security classified, the announcement of this report will be similarly classified)

Large scale surveys have been made of the horizontal and vertical distributions of turbidity in the waters of Gulf St Vincent in South Australia. The beam attenuation coefficient at a wavelength of 530 nm was determined from measurements made with a transmissometer operated from a boat. Both horizontal and vertical stratification of turbidity was observed and explanations for these two conditions are offered. Two methods for determining water turbidity from an aircraft were investigated. They involved measuring the amplitude and attenuation of the backscatter envelope from a laser pulse transmitted from the aircraft into the water. The relative merits of the two methods are evaluated.

Security classification of this page: UNCLASSIFIED

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