DEVELOPMENT OF AN ACOUSTIC SYSTEM FOR REMOTE SENSING OF BENTHIC FISHERIES HABITAT FOR MAPPING, MONITORING AND IMPACT ASSESSMENT

C.R. Pitcher, S.R. Gordon, R.J. Kloser, P.N. Jones

CSIRO
MARINE RESEARCH

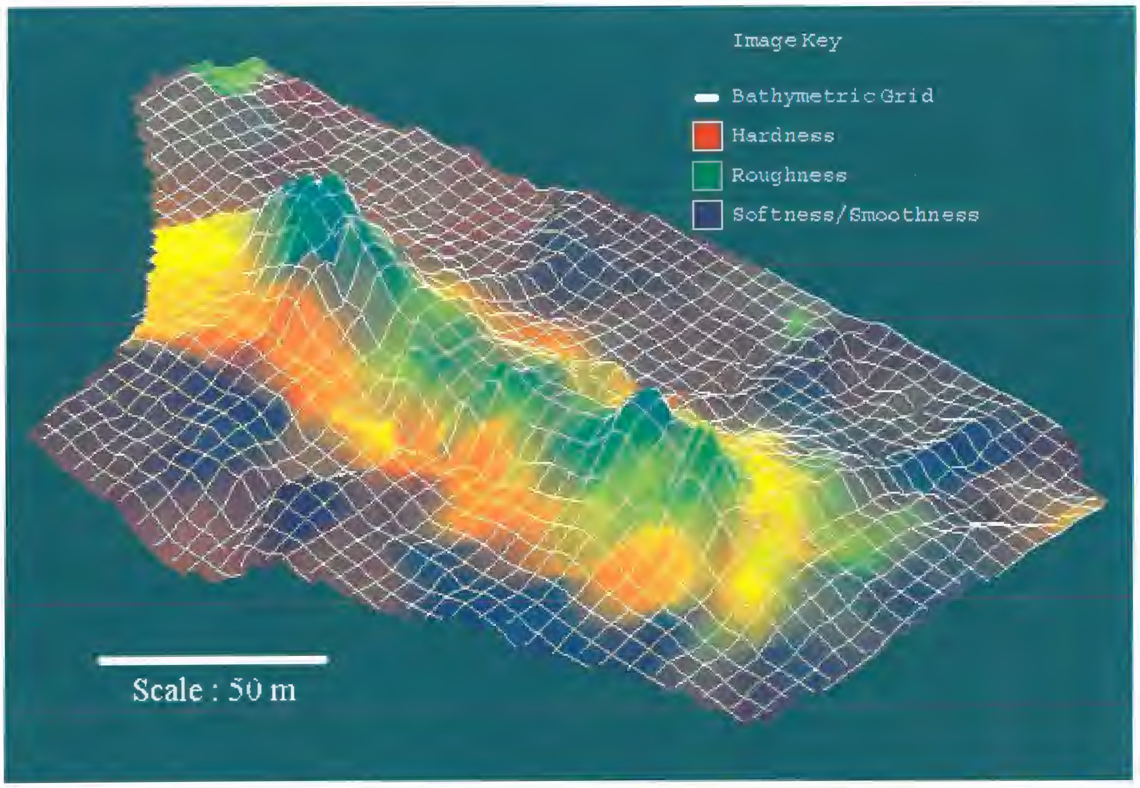
FISHERIES
RESEARCH &
DEVELOPMENT
CORPORATION

PROJECT NO. 93/058

Bibliography.
ISBN 0 643 06196 7.

1. Ocean bottom - Australia - Remote sensing. 2. Digital mapping. 3. Fishes - Habitat - Australia - Remote sensing. 4. Benthic animals - Australia - Remote sensing. 5. Underwater acoustics - Australia - Instruments. I. Pitcher, C. R. (Clifford Roland). II. CSIRO. Division of Marine Research. III. Fisheries Research and Development Corporation (Australia).

620.250994



Three dimensional acoustic habitat image of a small, low coral reef, approximately 200m by 150m in area, of about 20 m depth, consisting of a mixture of coral boulders, live hard & soft corals. The coral outcrop rises approximately 2 m from the surrounding seabed of sand and sparse benthic fauna.

NON TECHNICAL SUMMARY

Project: 93/058 : Development of an Acoustic System for Remote Sensing of Benthic Fisheries Habitat for Mapping, Monitoring and Impact Assessment.

Principal Investigator: Dr Roland Pitcher

Address: CSIRO Division of Marine Research
PO Box 120 CLEVELAND QLD 4163
Telephone: (07)3826 7250 Fax: (07)3826 7222
E-mail: roland.pitcher@marine.csiro.au

Objectives

The objective of the research was to develop a digital instrument that uses echo-sounder pulses reflected from the seabed to detect habitat types and communities of large attached fauna. The instrument would facilitate mapping of seabed habitats. The project had three sub-objectives:

1. Assemble electronics components for digital sampling of analogue acoustic signatures and subsequent data-storage and analysis.

2. Field test the system against the off-the-shelf RoxAnn™ system and against seabed ground-truth data collected concurrently.

3. Refine the system to achieve highly sensitive classification of seabed habitat types and some of the life they support, suitable for real-time implementation.

Non Technical Summary

Background & Need

Seabed habitats are important for many commercial fish species, which need them for shelter and food. Different seabed habitats vary in their fisheries productivity and their susceptibility to impact (from fishing or other causes). The ability to discriminate and map seabed habitats would allow fishers to target more efficiently areas of high productivity, and provide baseline data for management, environmental monitoring and impact assessment. However, mapping and assessment of these habitats has been limited to <2% of Australia's fishing grounds due to the time and costs of sampling.

Conventional mapping tools used on land, such as satellite imagery and aerial photography are unsuitable for mapping most seabed habitats. Instead, the analysis of underwater sound pulses emitted from echo-sounders and reflected by the seabed provides the potential to differentiate seabed habitats because different habitats produce different echoes.

This project aimed to develop an objective method of analysing echo sounder pulses to classify the seabed, allowing rapid and continuous mapping. An off-the-shelf processor (USP RoxAnn™) of echo-sounder pulses, which outputs two simple indices of seabed roughness and hardness, has been available since ca 1991. Based on these indices, and when "ground truthed" over known seabed types, RoxAnn can provide real-time classification of the seabed (e.g. mud, sand, rubble, and rock) — a powerful adjunct to conventional sampling. However, the RoxAnn processor integrates only two parts of the reflected pulses, limiting its ability to differentiate among seabed habitat types. Digital sampling and analysis of entire reflected pulses has much greater potential to discriminate different seabed types. Development of such a digital-sampling system and the analysis techniques was the objective of this proposal.

Methods

The project involved designing and constructing the electronics hardware of the acoustics receiver and writing software to acquire and record digital acoustic signals. Through collaboration with CSIRO mathematicians additional, more powerful methods of discrimination, using many features of the shape of reflected echoes, were developed.

Results

Electronics hardware and software: CSIRO designed and constructed several revisions of the acoustics receiver to achieve stable calibrated amplification, improved filtering to exclude noise, and high dynamic range. The echo-sounder pulse, conditioned by the receiver, was captured into digital form by a high performance analogue/digital (A/D) acquisition board. Software was written to control the A/D board, capture the digital data (at up to ~500MB of data per hour) and record it for subsequent analysis. A high-performance computer was assembled for the project. The refined software, re-written in the Windows™ environment, displayed the shape of the acoustic signal, a colour echogram, a plot of the vessel's track (provided by the vessel's GPS navigation system) and provided data play-back and data manipulation functions. The combined system of hardware, software and digital data format was called the Benthic Acoustic System (BAS).

Field testing: To test the ability of the BAS to discriminate seabed habitats, it was compared with other methods of sensing seabed habitat type. Various revisions of the BAS were operated on several research vessels and recorded digital acoustic signals while samples were being taken from the seabed, using other methods such as remote video (e.g. sled mounted), grab, and benthic dredge. The RoxAnn unit was run concurrently to record its "hardness" and "roughness" indices. On CSIROs FRV Southern Surveyor, the Simrad EK500 scientific echo sounder sampled the immediate near-bottom echoes. Field trials were conducted in the central and far northern Great Barrier Reef, the Torres Straits, the Gulf of Carpentaria, and parts of the South East Fishery region.

Data analysis: Different types of seabed reflect acoustic signals with different shapes. Analysis required mathematical descriptions of these shapes and the use of statistical methods for discriminating among them. Tests of the ability of the acoustic data and these statistical methods to discriminate seabed habitats showed that RoxAnn type indices could lead to incorrect classifications in 25%–50% of cases, whereas measures of shape from EK500/BAS digital signals had a 10%–25% error rate and a new type of analysis of full digital signals had an error rate of only 10%. The analysis of fully digitised signals was clearly the most powerful method, and though it was a computationally intensive analysis to perform, it has a further major benefit in that would be the easiest to implement in a real-time system and would perform the fastest classifications.

Conclusions

This Project has developed a functioning system of advanced prototype hardware, software and analysis procedures that provides powerful and highly sensitive classification of seabed type. The range of habitats that can be discriminated is not absolute, but depends on the complexity of the seabed and scale of mapping surveys. In the most difficult cases of complex seabed at large scales, the system can discriminate at least basic seabed types such as mud, sand, rubble, and rock more accurately than previous systems. In other circumstances, the system would be able to discriminate living seabed fauna and beds of algae and seagrass, though these can be difficult to separate from the underlying seabed type if complex. The accuracy and repeatability of these classifications is ensured by recording the whole of water column and seabed echoes and removing noise biases prior to analysis. Current commercial "black-box" systems can not perform this function and are unable to provide data quality control. Our approach has been to ensure repeatability of measurement, which is a fundamental requirement for long term monitoring and mapping applications. The spatial resolution of the system depends on the beam-width of the echo-sounder pulse and depth (footprint is about 50-150 m^2 area at 50 m depth) and these footprints overlap as the vessel moves. The coverage of mapping surveys can vary depending on the users requirements that determine the size of the mapping grid. Vessel mounted systems can (depending on acoustic frequency) operate to depths of about 200 m on relatively flat seabeds, and perform best in calm conditions, though technologies could be applied to stabilise the receiver. Deep towed systems can operate in rougher conditions, to deeper depths. A typical mapping survey would involve designing the sampling strategy based on known information, running the system continuously over the sampling grid, collecting regular ground-truth data for each habitat, quality control of data, classification analysis and map production.

As with any new technology, this new system is still complex to operate and, in its present form, is suitable for operation by skilled technicians and analysts, but there is significant potential for further development. Nevertheless, benefits are available immediately and include use by researchers to map the distribution of seabed habitats to provide information for spatial management of demersal fisheries and of other multiple uses of, or impacts on, the seabed.

Further work

The advanced prototype system has scope for further development, such as implementation of the mathematical discriminatory functions for real time processing. Collaboration with another FRDC project (T93/237), showed that the new mathematical functions were even more powerful with multifrequency data. Error rates better than 10% were achieved in preliminary tests, which is extremely encouraging for future applications. The prototype system developed by this Project has the potential to be commercialised and be widely available as an instrument for research and the fishing industry. Because the system can use a conventional echo-sounder for sending and receiving acoustic signals, it could be useable on any suitable vessel equipped with a suitable echo sounder and power supply for a computer. If commercialised, such a system would have potential as a cost-effective search instrument for use on commercial fishing vessels for identifying seabed habitat supporting the most productive stocks, thus improving the efficiency and reducing the costs of fishing.

Keywords

Ocean bottom, Seabed, Remote sensing, Digital mapping, Fishes habitat, Benthic animals, Underwater acoustics, Instruments.

CONTENTS, FIGURES & TABLES

Contents

Figures

Tables

1 INTRODUCTION

1.1 Background

Many fisheries depend on benthic environment (e.g. nursery, shelter, & breeding habitats) for their long term productivity, yet these fisheries and many other human activities or natural phenomena may impact the benthic environment on which they depend. Currently, sampling and assessment of these impacts is limited to relatively few sites due to the time and costs of deploying nets, dredges, cameras etc and, because only a minor fraction of a study area can be sampled, detailed maps of the benthic fisheries habitat are not possible. Above water remote sensing tools (LANDSAT, aerial photography etc) are severely limited for mapping seabed habitat. A system for analysing reflected hydro acoustic signals from echo sounders and using them to classify the benthic environment would permit rapid and continuous mapping of the seabed, even over terrain too rugged for conventional sampling techniques.

Professional fishers that use conventional colour echo-sounders can often make some interpretation of the seabed type; however, this interpretation is confounded by gain settings on the sounder and is limited because the information is subjective and can not be recorded automatically. In 1993, when this project started, there was very limited capacity for automated classification of seabed type. Of course, side-scan sonars that could form images of the seabed had been available for decades, but these also required human interpretation — they did not classify habitats automatically. To our knowledge there was only one instrument available at that time that used acoustic signals to automatically classify seabed type.

The instrument available (USP RoxAnn™, Marine Microsystems) was an analogue processor of echo sounder hydro acoustic signals that corrected for gain and records numerical seabed roughness and hardness indices derived from two specific portions of the reflected hydro acoustic pulses. Once calibrated over known seabed type and with appropriate "ground truthing" the unit provides continuous classification of the seabed in real-time. When integrated with navigation information (GPS), real-time surveying and mapping of seabed type is possible — a powerful adjunct to conventional sampling. RoxAnn can classify the seabed according to the type of sediment (e.g. mud, sand, rubble, rock) and texture (smooth, hard, rough). RoxAnn had been used by some hydrographic survey, offshore industry, and marine research organisations in Europe, the North Sea and the North Atlantic. The CSIRO Division of Fisheries purchased a RoxAnn in 1992 and was the first to attempt this type of application in Australia.

1.2 Need

Although RoxAnn's capabilities were a major advance, the unit integrated only two portions of the reflected acoustic signatures — whereas digital-sampling of entire reflected hydro acoustic signals from echo sounders has the potential to provide much more detailed information to remotely sense more subtle changes in the seabed and especially epifaunal communities that cause only slight changes to the acoustic signature. Development of such a digital-sampling system was the overall objective of this proposal. Ability to remotely sense the presence of epifaunal communities (e.g. sponges, gorgonians etc) is particularly important for studies of demersal stocks and the impact of fishing gears on the habitat. The process would involve recording digitally-sampled acoustic signatures and storing them on computer mass storage devices for subsequent analysis. Post-survey analysis of these acoustic signatures would build on the classification provided by the existing RoxAnn through additional, and powerful, discriminatory software. At completion of the project, there would also be scope for further development — such as implementation of discriminatory functions for real time processing. This proposed system would be a highly sensitive and innovative seabed classification system for research on the marine benthic environment. Because the system would use a conventional echo-sounder for sending and receiving ultrasonic signals, it would be useable on any size vessel equipped with a suitable echo sounder and power supply suitable for a computer. Once developed, such a system would have the potential as a cost-effective search instrument for use on commercial fishing vessels.

1.3 Objectives

1.3.1 Original objectives

The objective of the research was to develop a digital hydro-acoustic instrument that remotely-senses seabed type and epifaunal communities for mapping, monitoring and impact assessment. The project had three sub-objectives:

a) To assemble electronics components for digital sampling of analogue acoustic signatures and subsequent data-storage and analysis.

b) Field test the system against the existing RoxAnn unit and against seabed ground-truth data collected concurrently.

c) Refine the system to achieve a highly sensitive and powerful method suitable for real-time seabed-type and biotic-habitat classification.

1.3.2 Proposed scope of objectives

a) Construction of system electronics hardware and acquisition/storage software

Acoustic echoes reflected from the seabed would have to be conditioned before they could be acquired digitally. Appropriate conditioning of the signal would be achieved by building the following electronics circuitry: amplifiers to amplify the echo, band-pass filters to exclude high frequency signals, rectifiers to convert the AC voltage variation to DC, and low-pass anti-alias filters. A suitable analogue/digital (A/D) sampling board would be purchased to acquire the conditioned signal. These first prototype hardware costs were contributed by CSIRO.

Software would be written to capture the digital data and store for subsequent analysis. The amount of data to be captured will be large (up to 64KB per ping), i.e. an acoustic signature from one reflected echo pulse may be digitised into >32,000 samples. With a moderate pulse frequency of one pulse per second, the system may sample up to ~250MB of data per hour of surveying. However, because any data reduction at acquisition could lead to un-recoverable corrupted acoustic signatures, all raw data would be stored as sampled. This required very high-capacity high-speed hard disk drives for immediate storage and longer-term storage on large capacity devices. The custom software would also display the form of the acoustic signature as well as the survey track with latitude and longitude provided by GPS navigation systems.

b) Field test the hydro acoustic system against RoxAnn and seabed ground-truth data

To test the ability of the system to discriminate seabed habitats, it will be compared with other methods of sensing seabed habitat type. The system would be set up on a research vessel and while samples are being taken the system would be run to store digitised data on the acoustic signature of the seabed. The existing RoxAnn unit would be run concurrently to record its "hardness" and "roughness" indices. On the FRV Southern Surveyor, the Simrad EK500 would be set up to sample the immediate near-bottom echoes. Geo-referenced ground-truth information on the benthic habitat would be collected wherever possible, by such methods as remote video (e.g. sled mounted), grab, and benthic dredge. Over the duration of the study, the number of potential ground-truth observations would be very numerous, thus comparisons between the acoustic signature data and ground-truth data would likely be very powerful. The likely study areas for the field trials include the Gulf of Carpentaria, the Great Barrier Reef, and parts of the SE Fishery region.

Analysis of the data would be based around methods of discriminating different shapes of acoustic signature from different seabed types. The shape of an acoustic signature generally consists of three peaks of sound separated by two relatively quiet flat areas. The first peak is the transmit pulse which should remain constant given certain output power settings. The second peak is the sound returning from the sea-bed to the ships transducer (i.e. the first echo). This sound may reflect off the sea-surface to the seabed again and then return to the transducer as a third peak (i.e. the second echo). If, for example, the seabed is hard, the reflected peaks will be relatively larger. If the seabed is rough, the peaks would be more scattered, particularly the trailing tail of the peaks. The presence of epibenthos (sponges, gorgonians etc) on the seabed is expected to be detected primarily by changes/patterns in the leading edge of the first echo, a portion of the acoustic signature not measured by RoxAnn.

Data analysis, initially would involve standardisation of the signatures to a consistent transmit power and depth so that comparisons between signatures can be made. "Type-signatures" representative of major broad habitat types would be identified for visual inspection of the major ways that signatures differ between habitats. Derived measures will also be investigated; such as ratios of peaks or integrals, slopes or exponents of ascending or descending portions of signatures, the level of variation at each part of the signature from pulse to pulse within the same habitat. Multivariate techniques (such as discriminant function analysis) will be applied to the standardised signatures and derived measures by using "training data-subsets" of the benthic habitat information as "predictors" of the acoustic signatures to develop discriminating or predictor functions that will subsequently be used to test the ability of the acoustic data to discriminate/predict and classify independent "test data-subsets" of the benthic habitat information. The roles of the training and test data-subsets would then be reversed as a further test of the system. It is anticipated that there will be many independent sets of training and test data-subsets with which to test the hydro acoustic system.

c) Refine the system and re-test to achieve a highly sensitive and powerful classification

The final phase of the project would be to revise the electronics of the system as a result of the experience gained in the construction and testing stage. This will increase the reliability and flexibility of the system hardware, to achieve a more sensitive and robust system for seabed habitat classification. The software could eventually be enhanced to take advantage of the discriminator/ predictor functions arising from the analysis phase — this would provide the basis for real-time seabed habitat classification while the vessel is underway. The display software could be updated so that the plot of the survey track also provides coded habitat classification information. Re-testing would be undertaken as resources and ship-time permit.

Even prior to the refinement phase, it was anticipated that this project would provide valuable habitat mapping information of substantial benefit to other projects which would supply vessel time; e.g. effects of prawn trawling in the Great Barrier Reef, and effects of trawl design on bycatch and benthos.

Results of the research would be in several forms including: hardware prototypes of the system, plans of the electronic circuitry, and associated software; and reports to FRDC. Depending on commercial-confidence issues, the results may be published in fisheries magazines and scientific journals. It is conceivable that the prototype system could eventually be commercialised and be produced as an instrument for research and the fishing industry.

1.4 Structure of this report

This project has three logical and distinct components that match the objectives as specified originally. These three components are (1) the benthic acoustic system, including development of the hardware and software, their revisions and refinement; (2) the field testing including collection of ground truth data; and (3) the analysis of the acoustics data including development of discriminant functions. The methods, results and discussion sections of this report have been structured around these three major components of the project.

1.4.1 Benthic Acoustic System – Development & Refinement

In this section we have described the methods and results related to the development and refinement of the "Benthic Acoustic System". The requirement and components of the BAS will be described. The description of the hardware will include, acoustics design & system specifications, signal conditioning electronics, block and circuit diagrams, electronics specifications, receiver performance, digital data acquisition system, and data back-up system. The description of the software will include, acquisition & instrument control, data display, data management, and analysis software.

1.4.2 Field Testing & Ground Truth

In this section we have described the methods and results related to the field-testing and collection of ground truth data. This will include the voyages (dates, locations, related projects), the acoustic instruments and their methods of operation (RoxAnn, Simrad EK 500, CSIRO BAS), ground truth sampling using real-time video and habitat coding, sediment grab sampling, GPS positional data for cross-referencing, and the acoustics and ground-truth datasets.

1.4.3 Analysis of Acoustic Seabed Data

In this section we have described the methods and results related to the analysis of acoustic seabed data. This will include the various approaches to analysis, methods appropriate for analogue acoustics data (i.e. RoxAnn), for digital acoustics data (i.e. EK500, BAS), methods of extracting shape features from each ping, and statistical methods for analysing fully digital ping data, and comparison of the performance of different classification methodologies.

2 METHODS

This chapter describes the methods used for the three major components of the project. These components and their accompanying sub-sections are:

2.1 Benthic Acoustic System – Development & Refinement. In this section we describe the methods relating to the development and refinement of the CSIRO "Benthic Acoustic System", hardware and software.

2.2 Field Testing & Ground Truth. In this section we describe the methods relating to the field-testing of acoustic seabed classification systems and collection of both acoustic and ground truth data.

2.3 Analysis of Acoustic Seabed Data. In this section we describe the methods relating to the analysis of acoustic seabed data, including development of classification algorithms for digital acoustic data.

2.1 Benthic Acoustic System – Development & Refinement

The nature of the seabed has previously been described acoustically, at least in terms of some basic characteristics, by recording and analyzing parameters of seabed echoes from simple normally-incident sounders operating in the frequency range 20–200 kHz. Several relatively simple commercial systems are now available on the market, e.g. RoxAnn™ (Marine Microsystems) (Chivers, 1990) was available from about 1991, and the QTCView™ (Quester Tangent) (Prager, 1995) became available in about 1996. These commercial systems usually attach to an existing echo sounder and process the first and (sometimes) second seabed returns. They have proven useful for classifying the seabed to varying extents in terms of resolution and accuracy. Unfortunately, many problems in the underlying acoustic system, including acoustic and electrical noise and weather, can corrupt the data prior to it being recorded and analyzed by these systems. Other factors, such as the limited dynamic range and noise rejection, and physical changes in acoustic reflectance due to large depth changes (e.g. 5-200m), also change the predictions of bottom type. If these artefacts are not removed or left uncorrected, the data will be corrupted and the classifications of bottom types will be unusable and/or wrong. These artefacts could be removed in real time with appropriate algorithms but given the variety of possible signal corruption mechanisms, this may be difficult to achieve in practice. Our aim was to develop new methods of signature classification that were capable of finer habitat discrimination, so our approach was to digitally record the 'whole of the water column' and seabed-echo by developing an appropriate Benthic Acoustic System with a large dynamic range, acquiring high resolution data, and developing powerful methods of post-processing the data.

An appropriate 'Benthic Acoustic System' would need to comprise a number of components. The first is the echo-sounder — we proposed that our system would be able to acquire data from a typical fishing echo-sounder and we used this category of sounder in this project. The second component is the receiver — this is attached across the connection between the echo-sounder head and the transducer and without interfering with the operation of the sounder, intercepts the high frequency electrical signals and amplifies, filters and rectifies them into a form suitable for recording. The third component is the analogue-to-digital-converter (A/D) — this is an off-the-shelf component of suitable specifications that is mounted in a computer and acquires signals from the receiver by digitally sampling and converting them into a form that can be stored and analyzed on a computer. The fourth hardware component is the computer — this runs custom written software that controls the A/D, saves the acquired acoustic data, and allows this data to be managed and analysed.

In this section we describe the methods relating to the development of the CSIRO "Benthic Acoustic System". The detail of the requirements and components of the BAS are described, including both hardware and software. The description of the BAS hardware includes, system specifications, block diagrams, signal conditioning electronics specification and design, and benthic acoustic data acquisition and archiving systems. The description of the BAS software includes acquisition & instrument control, data display, management, and analysis software. During the course of the project, the BAS was refined substantially. The methods relating to this refinement are also described; including redesigning and rebuilding the electronics of the system as a result of the experience gained in the construction and testing stages, as well as continually improving the software.

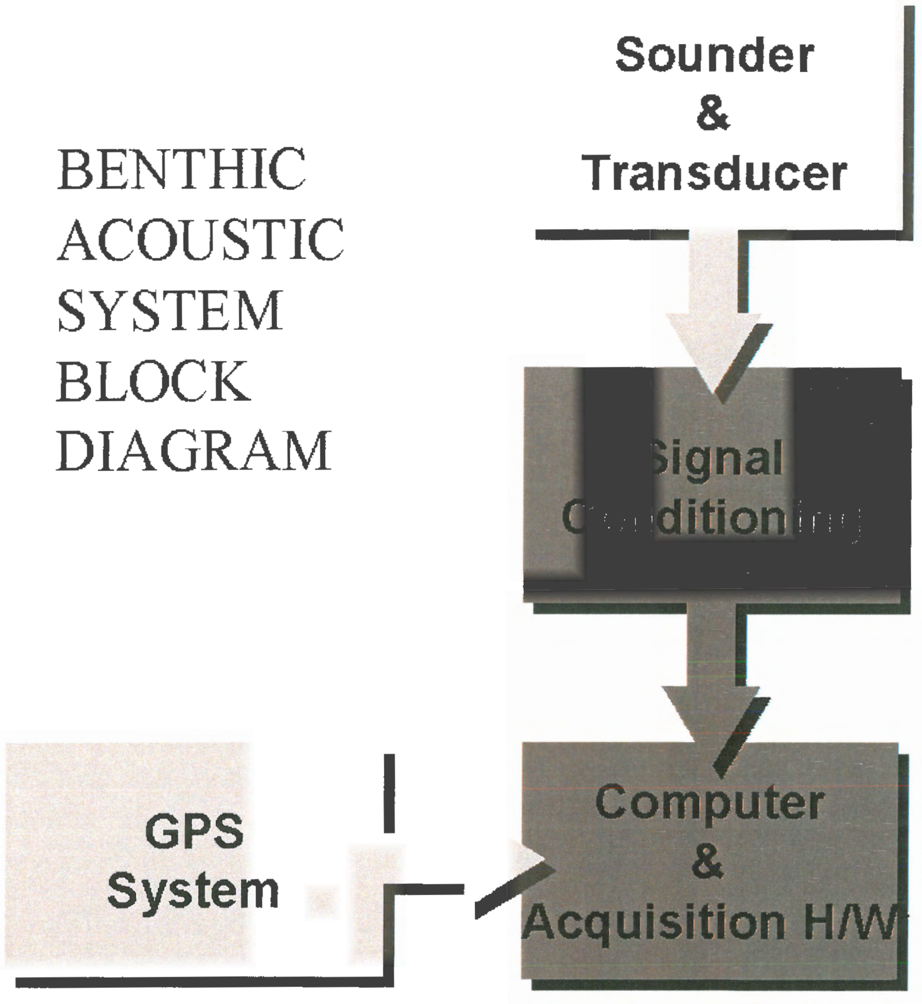


Figure 1 : Benthic acoustic system - block diagram, showing major components of the benthic acoustic system. The system uses a vessels existing echosounder and navigation system or GPS (shown in light gray), while components assembled for this project are (shown in dark gray) the signal conditioning electronics of the "BAS" acoustic receiver and computer acquisition system.

2.1.1 Benthic Acoustic System – Hardware

To allow the storage of the whole water column signal from vertical incidence echo-sounders for the purpose of seabed habitat discrimination, a number of electronics and computer hardware devices have been designed or integrated to form the CSIRO Benthic Acoustic System. The combination of these new software and hardware components allow the benthic acoustic system to acquire and archive high resolution digital acoustic data.

A block diagram for the benthic acoustic system is presented in Figure 1. The system comprises four elements - the echosounder system, GPS navigation system, signal conditioning electronics, and a computer system with data acquisition hardware. The Benthic Acoustic System used a vessels existing host echosounder and GPS navigation system (shown in light gray in Figure 1). The remaining two components, signal conditioning electronics and computer acquisition system (shown in dark gray in Figure 1), were developed for this project and the methods are outlined in subsequent sections 2.1.1.1 Benthic Acoustic Signal Conditioning Electronics & 2.1.1.2 Benthic Acoustic Data Acquisition and Archiving System.

2.1.1.1 Benthic Acoustic Signal Conditioning Electronics

The signal conditioning electronics (or receiver) amplifies the echo and presents the acoustic signal in a form compatible with the data acquisition system (described in 2.1.1.2 Benthic Acoustic Data Acquisition and Archiving System). The receiver amplifies the acoustic signal, band-pass filters the signal to exclude out of band noise, rectifies the signal, converting the AC signal to DC, and anti-alias filters the rectified signal to ensure that the magnitude of the reflected echo is properly sampled at the instants of sampling by the acquisition system.

Prior to the start of the Project, a small external electronics R&D company was contracted by CSIRO to manufacture a prototype to basic specifications. This first prototype was completed by mid-1993 and conditioned of the echo-sounder signal by amplifying the echo, filtering to exclude noise, and rectifying the AC voltage to DC. This prototype functioned well enough to serve as a test-bed for subsequent revisions, but its tolerances were not tight enough for recording of data for analysis. Several revisions of the electronics hardware were designed and constructed by CSIRO and the refined system achieved stable calibrated amplification, tighter filtering to exclude unwanted noise and high dynamic range.

Information on the biological organisms associated to the seabed is an important parameter when describing the seabed type. In designing a signal conditioning receiver for seabed classification with a biological emphasis it is important to have sufficient dynamic range to record both the weak above bottom biological scatter as well as the high intensity echo from the seabed. The dynamic range of an acoustic receiver to measure low acoustic ocean noise, to measuring bottom backscatter information of rock at close range and finally the acoustic transmit pulse itself is large.

The design outline of such a high dynamic range system is presented here. Table 1 shows the symbols and design formula appropriate for the design of the signal conditioning electronics, for the benthic acoustic system. These formulae will be referred to in relation to the signal conditioning electronics design.

Table 1: Symbols and design formula used to calculate the dynamic range for the benthic acoustic system (a narrow band normal incident conical beam acoustic system).

	Name	Formula	SI Unit
f	frequency		Hz (hertz)
a	radius	radius of circular transducer	m (meters)
λ	wavelength	sound speed/frequency	m
c	sound speed	sound speed (MacKenzie, 1981)	m s^{-1}
k	wave number	$2\pi/\lambda$	m^{-1}
θ	beamwidth	+/-3dB 28.65λ/a	degrees
DI	directivity	$10\log(ka)^2$ (Clay and Medwin, 1977, p147)	dB (decibels)
Ω	equivalent beam angle	$5.78/(ka)^2$ (Clay and Medwin, 1977, p233)	steradian
p	power	peak rms power	W (watts)
Ξ	efficiency	for ceramic transducers use –3dB	dB
res	resistance	radiating resistance	ohms
Ns	sea noise	spectrum level noise (Clay and Medwin, 1977, p120) (Urick, 1983, p210) (MacLennan and Simmonds, 1992, p41)	dB re $\mu Pa^2 Hz^{-1}$
τ	pulse length	measured to +/- 3dB power points	s (seconds)
bw	bandwidth	measured to +/- 3dB power points	Hz
ρ	density	density of sea water 1026	kg m^{-3}
α	absorption	calculated from Francois and Garrison formula (Francois and Garrison, 1982)	dB m^{-1}
AC	acoustic constant	$10\log(4\pi/\rho c) - 120$ (Urick, 1983, p75)	dB
SL	source level	10log(p) - AC + Ξ + DI (Urick, 1983, p75)	dB re 1μPa
SRT	sensitivity of receiver	AC + Ξ - DI	dB re 1 v μPa^{-1}
r	range	depth to target	m
NE	noise echo	Ns + 10log(bw)	dB re 1μPa
NP	noise power	NE + SRT	dB re 1 v
TS	target strength	$10\log(\sigma/4\pi)$ where σ is the acoustic scattering cross section in m^2	dB re 1 m
SNR	signal to noise ratio		dB
Sv	volume reverberation	Expected reverberation from a volume scatter	dB re 1m
Br	bottom reverberation	Expected reverberation from the bottom	dB re 1m
TSi	target strength intensity	SL - (40logr +2αr) + TS	dB re 1μPa
TSp	target strength power	TSe + SRT	dB re 1v
Vsi	volume scatter intensity	SL + Sv+10log(Ω) - (20logr + 2αr) + 10log(cτ/2)	dB re 1μPa
VSp	volume scatter power	Vse + SRT	dB re 1 v
Bsi	bottom scatter intensity	SL + Br +10log(Ω) - (20logr + 2αr)	dB re 1μPa
BSp	bottom scatter power	Bsi + SRT	dB re 1v

Receiver Specifications & Design

The design criteria of the receiver was specified to operate on a 120 kHz fishing echosounder with an output power of 1kW, pulse length 0.2 – 1.0 ms using a ceramic transducer of 0.059 m diameter. The environmental conditions for the instrument were set at a temperature of 20° C, and salinity of 35 ppt with typical vessel and sea noise (Ns) of 40 dB re 1uPa/Hz.

As mentioned previously (2.1 Benthic Acoustic System – Development & Refinement) the receiver needed to have significant dynamic range to not saturate on flat hard bottom (Bsi = -10 dB) at 5 m depth and to be able to detect (10 dB SNR) weak echos (Vsi = -74 dB) above the seabed to a water depth dependant on vessel and sea noise (Ns). The large instantaneous dynamic range, to resolve the weak echos through to strong echos, as described (above) was provided by using three channels of receive amplification (low, medium and high; see Figure 2).

It was also necessary to digitise the transmit pulse to monitor the output power and impedance of the host fishing vessel sounder. This allows the monitoring of the behavior of the host echo sounder and acts as a data quality flag.

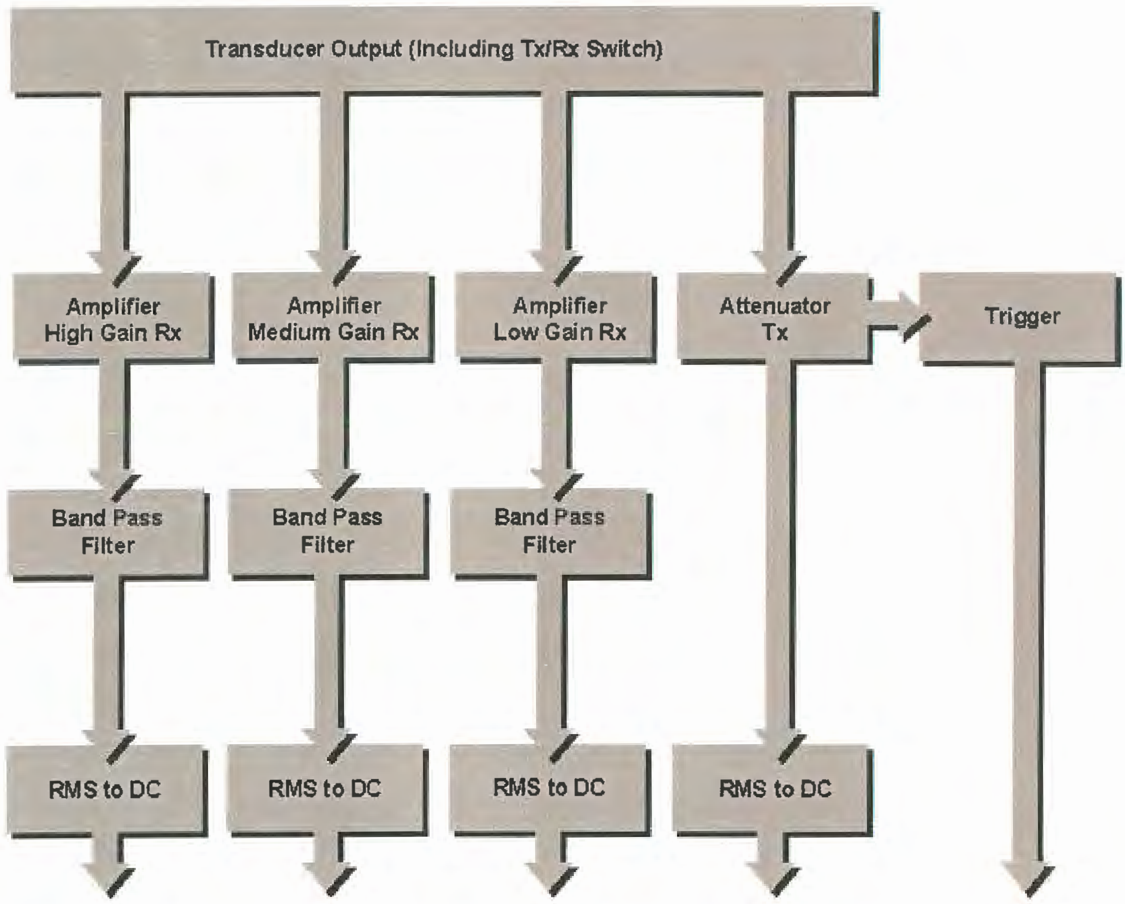


Figure 2 : Signal conditioning receiver electronics — block diagram overview, showing the major functional electronic circuit components of the electronic system designed for this project. The receiver consists of 4 channels of acoustic data (1 transmit and 3 receive) with different levels of amplification or attenuation.

Figure 2 shows the building blocks of the signal conditioning receiver electronics. The system can be divided into four stages (for each receiver channel), first an input stage interfacing to the echosounder transducer, with transmit/receive switch to limit the voltage to the pre amps. The second stage comprises an attenuator for the transmit signal and a series of low voltage preamplifiers, thirdly a band pass filter system and finally RMS to DC conversion stage (consisting of rectifier and low pass filter). There is also a trigger element which synchronises the signal conditioning electronics with the computer data acquisition system. Together these circuit components present the analogue acoustic signal in a form compatible with the data acquisition system, described in the following section 2.1.1.2 Benthic Acoustic Data Acquisition and Archiving System.

2.1.1.2 Benthic Acoustic Data Acquisition and Archiving System

The data acquisition system converted the conditioned analog acoustic signal to a digital form which was then recorded using a computer. The data acquisition system used a high quality analogue/digital (A/D) sampling board — this was an off-the-shelf component that was mounted in the computer. The A/D system had requirements of high speed sampling rate to give high resolution signatures and high quantization resolution and multiple channels (for each of the three receive and one transmit channels of acoustic data) to allow the large dynamic range specified by the BAS. The volume of digital acoustic data, once acquired and recorded to computer hard disk, was quite large, this required a system for archiving this data, for the long term.

2.1.2 Benthic Acoustic System – Software

As well as the designed hardware elements, software was developed to acquire as well as manage and analyse the acoustic data. This software was specially written to control the benthic acoustic system hardware, capture the digital data and record it for subsequent analysis. The software also recorded the latitude and longitude position provided by the vessel's GPS navigation system in order to cross reference with ground truth data collected through independent means (see 2.2 Field Testing & Ground Truth). The first version of the custom software simply acquired and stored the data, then it was re-written in the Windows ™ environment and provided a familiar graphical and mouse driven user interface. The refined software also displayed the shape of the acoustic ping signal, a colour echogram, a plot of the vessel's track and provided data play-back and data manipulation functions, such as bottom-locked data extraction.

The software consisted of two major components. A real time acquisition program which provided an interface to the instrument while collecting the BAS digital acoustic data and a data management, post analysis program. The software code was developed in a modular and flexible manner, such that any future modifications, enhancements or adaptations may be easily incorporated. The software programs have similar user interfaces for consistency and ease of operation. The two software programs are described in the following sections 2.1.2.1 Benthic Acoustic Acquisition & Instrument Control Software & 2.1.2.2 Benthic Acoustic Data Management & Analysis Software.

2.1.2.1 Benthic Acoustic Acquisition & Instrument Control Software

The first version of the acquisition software was written in the 'C' programming language, for the 16-bit DOS operating system, with a text-based user interface. Subsequently a revised second, and much more powerful version of the benthic acoustic acquisition & instrument control software was written in the 'G' programming language and developed using the Lab-View software package. This program provided a familiar windows based user interface. The methods and results for the second version of the software are described.

The acquisition and instrument control software formed the "front panel" to the benthic acoustic system during operation. The software allowed the setup of instrument operating parameters including data acquisition (sampling rate, channels to acquire, acquisition trigger and memory settings) and ancillary data collection parameters (GPS serial data stream settings).

A useful function of the data acquisition & instrument control software was to check on the system performance, through displays of the individual ping signals as well as colour echograms. System function and data quality issues were identified via this software and steps made to correct them (see 3.1 Benthic Acoustic System – Development & Refinement).

2.1.2.2 Benthic Acoustic Data Management & Analysis Software

The benthic acoustic data management & analysis software was also written in the data driven 'G' programming language and developed using the Lab-View software package & provided the means for replaying digital acoustic data acquired with the BAS, for data visualization, data searching, extraction to flat text data files for analysis and quality control purposes.

The BAS digital acoustic data was indexed by time as well as ping and it is these references that allowed the user to search through the data and select sections to be extracted to flat text raw digital acoustic data files for analysis. The data management and analysis software also had a bottom detection and tracking algorithm to allow the extraction of BAS digital acoustic data referenced to the seabed.

2.2 Field Testing & Ground Truth

To test the ability of acoustic echoes to discriminate seabed habitats, it was necessary collect accurate information on seabed type with independent methods. The independent information is called 'ground-truth' data and was used to develop methods of classifying the acoustic data as well as subsequently testing the accuracy of the acoustic classifications. The performance of other methods of remotely sensing seabed habitats can also be compared. The acoustic system was setup on a number of vessels while engaged in research on seabed habitat. While habitat information was being collected, the acoustic system was operated and detailed data on the acoustic signature of the seabed was acquired and stored. The existing RoxAnn unit was run concurrently to record its "hardness" and "roughness" indices. During *Southern Surveyor* cruises, the Simrad EK500 was set up to sample the immediate near-bottom echoes, and geo-referenced ground-truth information on the benthic habitat would be collected regularly, and particularly when the habitat appeared to change, by such methods as remote observation vehicle (ROV) observations, video (sled and net mounted), grab, diving, and benthic dredge.

In this section will describe the methods relating to the field-testing of the acoustic systems and collection of both acoustic and ground truth data. This will include the voyages (dates, locations, related projects), the acoustic instruments and their methods of operation (RoxAnn, Simrad EK 500, CSIRO BAS), as well as ground truth sampling (real-time video, sediment grab sampling, GPS positional data for cross-referencing and habitat coding).

2.2.1 Voyages

The acoustics project collaborated with more than five other projects and participated in field-trips associated with these projects. Most field-trips were undertaken with the GBRMPA/FRDC Effects of Trawling Project in the Far Northern Great Barrier Reef. Other field-trips were undertaken with broad scale habitat mapping Projects in Torres Strait; the FRDC Bycatch Project in the Gulf of Carpentaria; the FRDC SEF Ecosystems Project in the Southeast Fishery (Eden & Gabo Is); and the FRDC Megabenthos Dynamics Project in the Great Barrier Reef off Townsville.

On each of these field trips, the analogue RoxAnn and Digital acoustic (EK500 or CSIRO BAS) systems were setup and operated so that acoustics data and ground truth data could be simultaneously collected and positionally co-registered.

2.2.2 Acoustic Sampling Instruments

Four acoustic instruments were used on field trips during this project. These included the RoxAnn, which was operational prior to this project and was used on nearly all field-trips; the Simrad EK 500 scientific echo-sounder, which was available only on the *Southern Surveyor*; the CSIRO Benthic Acoustic System, which was developed through a series of substantial revisions during this project, and the QTC View seabed classification system, which was tested during this project. The methods of operation for the first three of these acoustic instruments are described.

2.2.2.1 RoxAnn

The RoxAnn is an analogue ultra-sonic processor of echo sounder hydro acoustic signals. The input to the unit is achieved by connection across the transducer cable. The unit amplifies, filters and rectifies the signal, corrects for spreading losses by applying time-varied-gain, then measures the analogue voltage of from two specific portions of the reflected hydro acoustic pulses. This is done by aligning gating switches with the tail of the first echo and around the entire second echo. The two voltage measures are sampled by some digital circuitry and output to a logging computer via communications circuitry. These two numerical indices are called, respectively, seabed roughness and seabed hardness and both can range in values 0–4095. The time lag between the transmit pulse and the first seabed echo return is also output to a logging computer and can be used to measure depth.

Third party software was available to record and display RoxAnn data. However, we wrote our own logging software that also logged GPS position data and displayed colour coded roughness and hardness indices and colour-matched vessel track. Post analysis of index values matched with appropriate "ground truth" data was used to calibrate the RoxAnn (Gordon, 1998) data over known seabed type and produce basic seabed habitat maps (see 0

The remainder of the Analysis of Acoustic Seabed Data section refers to the two types of acoustic data, the processing, analysis and classification techniques appropriate to them.

Analogue Acoustics Data).

2.2.2.2 Simrad EK500

The Simrad EK500 is a digital acoustic echosounder system which records calibrated acoustic echogram data at 3 frequencies (12 kHz, 38 kHz & 120 kHz). The EK500 transmits a pulse of high frequency sound which is reflected by water column and seabed targets including finfish, plankton, epibenthic organisms such as coral and sponges, as well as the seabed itself. The whole reflected digital acoustic signal (including seabed signal) was converted to electrical signals by the echosounder transceiver and stored digitally for later analysis. Position was logged for the acoustic track using GPS.

The Simrad EK500 data is a proprietary format in the form of digital acoustic ping echograms. The CSIRO developed software ECHO (Waring et.al., 1994 & FRDC project T93/237), was used to collect, manage and post process EK500 digital acoustic data. Quality assurance features in ECHO include: editing the echograms for bad data, removing back ground noise (including sea state, man made acoustic and electrical noise), correcting for physical acoustic parameters including sound speed and absorption. Post-processing of the EK500 data included identifying seabed referenced acoustic data of interest, extracting the volume backscatter seabed data for further processing and development of classification techniques.

2.2.2.3 Benthic Acoustic System

The CSIRO Benthic Acoustic System, developed for this project, is a digital acoustic system that when used with an analogue echosounder provides digital acoustic ping data. The input to the unit is achieved by connection across the transducer which converts the acoustic signal to an electrical signal, the BAS then amplifies, filters, rectifies the analogue signal, and converts it to a digital format (see Benthic Acoustic System – Development & Refinement). The whole reflected digital acoustic signal (including seabed signal), as well as position information for the acoustic track obtained using GPS, was stored digitally using the BAS data format.

The BAS data was collected, managed and post processed using the software developed for this project (see Benthic Acoustic System – Software). Post-processing of the BAS data included identifying seabed referenced acoustic data of interest, extracting the information for further processing and development of classification techniques.

2.2.3 Ground Truth Sampling

Up to four methods of collecting ground truth data were used on field trips during this project (see Table 2). These included real-time video, sediment grab sampling, benthic dredge and trawling. GPS positional data was recorded for all sampling methods, for cross-referencing with acoustic data. The methods of operation of these sampling tools are described.

Table 2: Habitat type & ground truth data sources. This table shows the sampling device used as a source of ground truth data for describing seabed habitats. The types of habitat have been divided into two groups, one which relates to sediment and substrate, with the other describing benthic habitats.

Habitat Type & Ground Truth Data Source	
Sediment & Substrate Habitats	**Data Source**
Mud Sediments	Video, Grab
Sand Sediments	Video, Grab
Rubble Substrates	Video, Grab, Dredge
Rock Substrates	Video
Reef Substrates	Video
Benthic Habitats	**Data Source**
Bivalve Shell Beds	Video, Grab, Dredge
Gorgonian Gardens	Video, Grab, Dredge
Sponge Gardens	Video, Grab, Dredge
Coral Gardens	Video, Grab, Dredge
Coral Reefs	Video
Algal Beds	Video, Grab, Dredge
Seagrass Beds	Video, Grab, Dredge

2.2.3.1 Video Sampling

On most field trips that this project took advantage of, ground truth data was collected by using remote video. The two main video systems used were a drop-camera (see Figure 3) and a towed-sled (see Figure 4), both used a colour CCD camera mounted in a water proof housing. Video images were transmitted to the vessel along an umbilical cable, through a genlock device (or "Screen Writer") that continuously overlaid date/time and positional data on the video, into two computer-controlled SVHS video recorders and then to high-resolution video monitors. Operators constantly viewed the video in real time and entered a single digit code (a 1–9 scale, see Table 3), which was recorded every 1-2 seconds along with positional data to indicate the major habitat types that the camera was passing over.

The echo-sounder transducer, from which acoustics signatures were recorded, was typically mounted just ahead of the video camera system. At most ground truth sites, the camera system was run for about 500 m across the seabed to characterise the nature of the bottom. At some sites, longer transects were run to either re-survey sites video at earlier times or to search for particular habitat types in certain areas. Acoustic data was collected continuously between sites.

Figure 3: Video drop camera - used to collect video ground truth data. The drop camera video deployment system allows rapid video habitat mapping, typically over 500m transects.

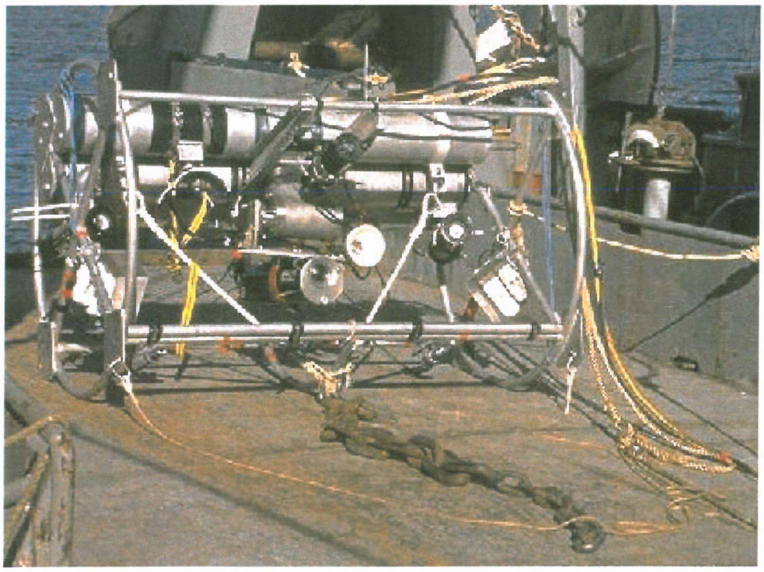


Figure 4: Video camera sled - used to collect video ground truth data. The video sled camera deployment system allows video data to be collected with a constant attitude to the seabed, allowing calibrated image analysis (picture courtesy Bruce Barker).

2.2.3.2 Sediment / Benthic Fauna Sampling

Depending on the objectives of the fieldwork that this project participated in, samples of sediment and seabed fauna may have been taken. Sediments were sampled by deploying a Smith-MacIntyre grab at the beginning or end of video transects for on-site classification of particle-size composition. Grab sediment and infauna samples were preserved for possible later analysis as part of other projects. Seabed epifauna were sampled by deploying a naturalists dredge, typically with a 75 cm wide mouth (alternatively 1.5 m & 3 m dredges) and towed for 100 m to 250 m simultaneously with the video data collection to collect samples of epifauna. The length of the dredge tow was varied depending on the density of the epifauna. If dense epifauna was observed in the video, the tow length was shorted to 150 m; if epifauna was very sparse or absent, the dredge was towed for up to 500 m. On some field trips, prawn trawls or fish trawls were deployed.

Figure 5: Sediment grab - used to collect sediment ground truth data. The sediment grab allows quantitative sediment and infauna samples to be collected. Shown here is a 0.1 m^2 "Smith-MacIntyre" grab, with a sample being sieved.

Figure 6: Small epi-benthic dredge (75 cm) - used to collect epi-benthic ground truth data (other dredges used were 1.5 m & 3 m). Dredges allow sampling of epi-benthic fauna, as well as large substrate components such as rubble and small rocks.

2.2.3.3 Navigational Data Cross-reference & Ground Truth Coding

The position data for the video sled or drop-camera were acquired with the same logging system. An acoustic tracking system (ORE LXT, incorporating a receiver hydrophone mounted on the side of the vessel and a multibeacon model 4330A mounted on the video camera system) with an accuracy of ± 1 m was used to locate the position of the video sled or drop-camera relative to the vessel's position. A DGPS (Differential Global Positioning System) was used to locate the position of the vessel (accuracy 2-5 m). These, in conjunction with the ship's gyro compass heading allowed the position of the tracked remote camera to be calculated in real time and displayed on a navigation plotter and overlaid on the video recording. Waypoint positions of sites were displayed in the navigation plotter window.

The acquired data (GPS, acoustic tracker, gyro heading, sounder depth, and VCR frame count) was logged into an MS Access database table by a customised tracking-navigating-logging software application running on a Windows NT 4.0 Pentium Pro PC. The data recorded consisted of GPS: UTC time/date, latitude, longitude, speed, track; Sounder: depth; Gyro: heading; LXT: acoustic target bearing, slant-range, depression angle; VCRs: tape frame positions; Operator: benthic code (a 0–9 scale). This cross-referenced video and position data allowed acoustic data to be co-located with the video and habitat codes by means of the shared position information.

Table 3: Habitat coding scheme - used to categorise video ground truth data, in real time. The ten classes of habitat, shown below are keyed into a ground truth database which is cross-referenced with acoustic data by a time stamp as well as navigation information. The habitat classes are entered in real time by experienced operators, who monitor the video data in the field during a habitat mapping video transect.

Habitat Code	Habitats
0	Mud / silt
1	Sand
2	Rubble
3	Algae / seagrass
4	Shell beds
5	Sparse soft benthic garden (Sea whips & gorgonians)
6	Dense soft benthic garden (Sparse benthic garden & sponges)
7	Hard benthic garden (Dense benthic garden & hard corals)
8	Rocks & boulders
9	Reef, with live hard corals.

2.3 Analysis of Acoustic Seabed Data

The ultimate objective of this project was to achieve reliable classification of remotely sensed acoustic signatures from major seabed habitat types. Classification was primarily a process of statistical analysis of stored acoustics data. In this section we describe the methods relating to the analysis of acoustic seabed data. This will include various approaches to analysis appropriate for analogue acoustics data (i.e. RoxAnn) and for digital acoustics data (i.e. EK500, BAS). In the case of digital acoustic data, two approaches were taken. The first uses established approaches in that shape features were extracted from each ping and these features were then classified statistically (Prager, 1995; Kavali, 1994). The second approach was entirely original — a recent development in statistical classification methods was applied directly to raw full-ping digitized data.

Prior to analysis, acoustic signatures were standardized to a constant depth so that comparisons between signatures could be made. Signatures corresponding to major habitat types were identified for visual inspection of the major ways that signatures differed between habitats. Measures of the shape of acoustic signatures were also derived. Statistical classification techniques were then applied to the standardised digital signatures and the derived measures by using "training data-subsets" of the benthic habitat information as "predictors" of the acoustic signatures to develop discriminator functions that were subsequently used to test the ability of the acoustic data to discriminate/predict and classify independent "test data-subsets" of the benthic habitat information. The performance of these different classification methods were compared.

2.3.0 Structure of Echo-sounder Signatures

The most familiar view of echo-sounder signatures of seabed would be the paper trace view, or its analogue in the form of a scrolling screen view, to show seabed depth. These views are produced by displaying side-by-side a series of returns from the seabed of the high intensity pulses of sound emitted regularly from the transducer. The view often discussed and presented in this report is that of individual pings — these are like a cross-section of the 'paper trace view' and show how the intensity of sound received by the transducer varies with time after the transmitted pulse.

2.3.0.1 Echo Formation

In order to effectively analyse the acoustic ping signals it is necessary to understand the method by which they are formed by different seabed types. An acoustic ping signal usually consists of a number of signal peaks formed from the reflection and reverberation of the incident acoustic energy on the seabed.

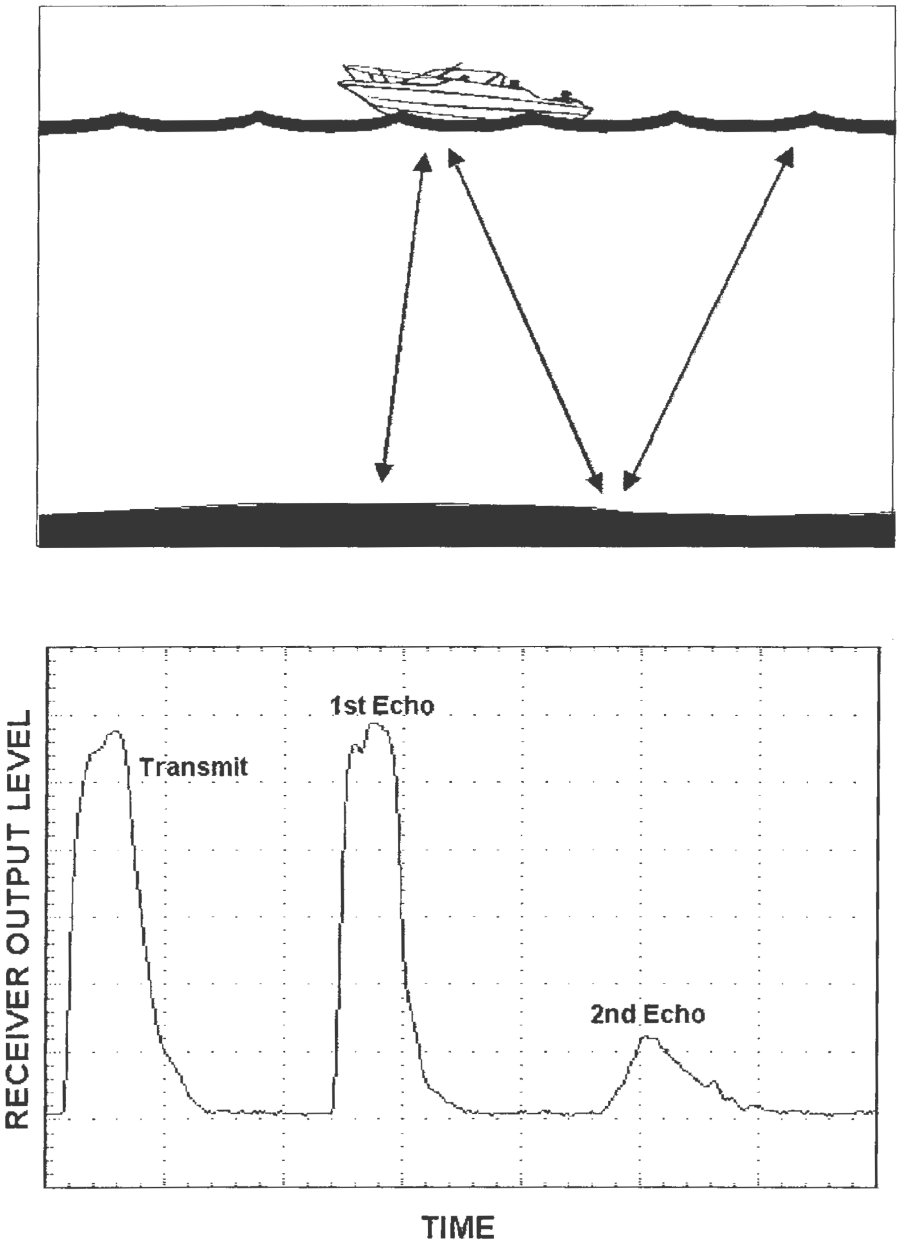


Figure 7: Formation of an echosounder ping (1st & 2nd echos) for a simple seabed (e.g. soft flat sand). The diagram at the top shows the physical reflection mechanisms for the echosounder's acoustic pulse, where sound is reflected from the seabed directly to the transducer, forming a 1st echo, while some acoustic energy may be reflected a second time via the air/sea interface to form a 2nd echo. The diagram at the bottom shows the corresponding ping waveform for these reflections, with the transmit pulse shown initially followed by the 1st echo & smaller 2nd echo.

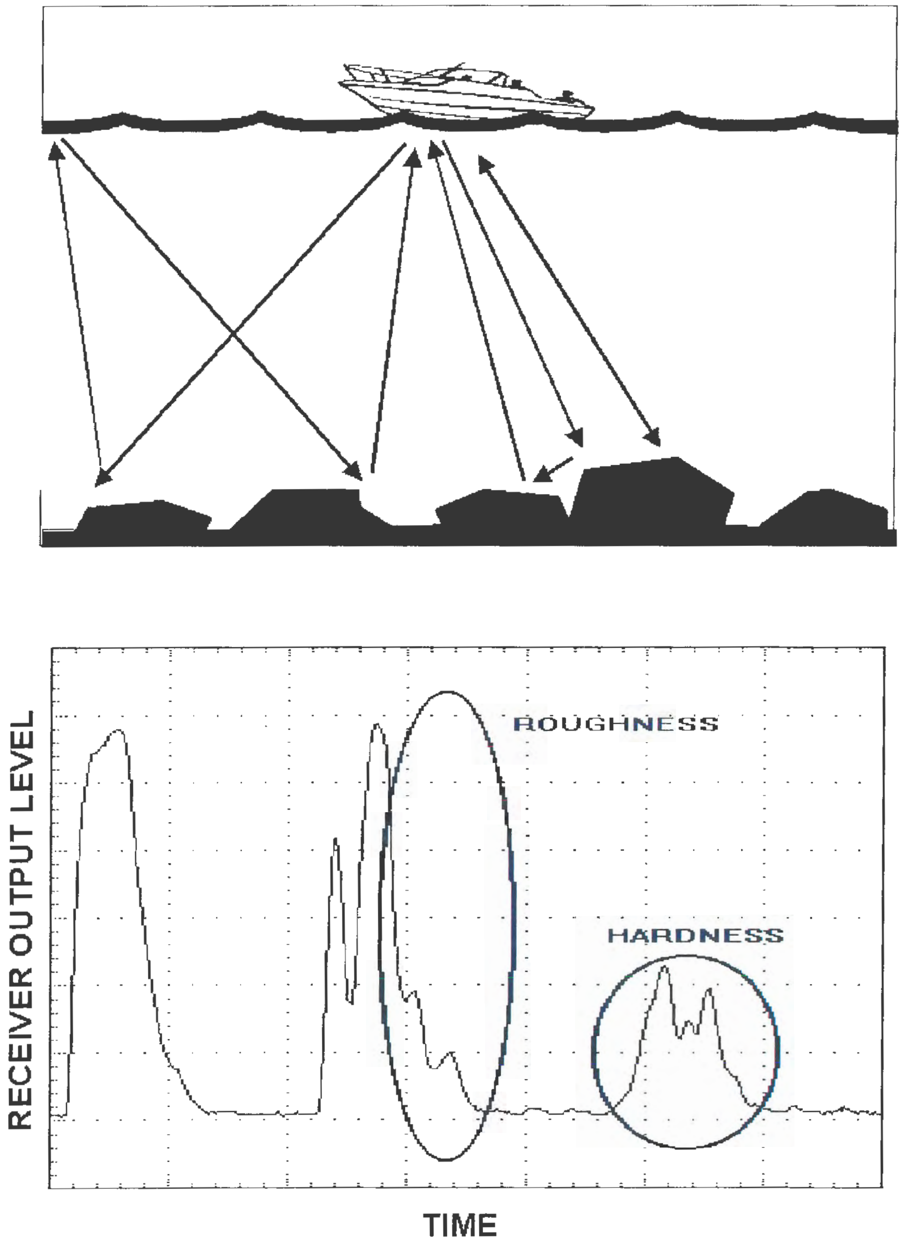


Figure 8: Formation of an echosounder ping (including the roughness & hardness components) for a complex seabed (e.g. rocks or coral reef). The top diagram shows, some of the physical reflection mechanisms for the echosounder's acoustic pulse, where the 1st echo may be scattered by the rough seabed, creating a broader 1st echo return. While the 2nd echo acoustic energy will be affected by the hardness of the seabed. The diagram at the bottom shows the corresponding ping waveform for this complex seabed, with the transmit pulse shown initially followed by the 1st echo including the corresponding tail section of the echo used to measure roughness & 2nd echo used to measure seabed hardness.

The structure of an acoustic ping signal generally consists of three peaks separated by two "roughly flat valleys". The first peak is the transmit pulse which should remain constant given certain output power and pulse length settings. The second peak is the sound returning from the sea-bed to the ships transducer (i.e. the first echo). This sound may reflect off the sea surface to the seabed again and then return to the transducer as a third peak (i.e. the second echo), and in some cases extra multiple echoes (Figure 7) (Chivers et.al, 1990). If, for example, the seabed is acoustically hard, the reflected peaks will be relatively larger. If the seabed is acoustically rough, the peaks would be more diffuse, particularly the trailing tail of the 1st echo. The presence of epibenthos (sponges, gorgonians etc) on the seabed was expected to be detected by changes/patterns in the leading edge of the first echo. Whereas the off the shelf acoustic processing system RoxAnn uses a combination of measures from both the 1st and 2nd seabed echoes and estimates acoustic roughness and hardness (Figure 8). For the development of the benthic acoustic system, 1st echo signals have been analysed (see 2.3.2 Digital Acoustics Data), as they contain the information necessary to discriminate between seabed habitat classes without the influence of mechanisms necessary to form the 2nd echo signal.

2.3.0.2 Effect of Depth

As the depth of the sea floor changes the acoustic ping signal formed by reflection of the echosounder ping from the seafloor will change (dilate in time) even if the "habitat type" remained the same (Pace et.al., 1985). In order to understand why this occurs it is necessary to investigate further, the physical processes by which the returned echo is formed.

For the perfect case where the acoustic reflecting medium (seafloor) is perfectly flat, the signal returned to the receiving transducer will only consist of that formed by the perfectly incident part of the beam. All other components of the acoustic pulse wavefront will be reflected away from the receiving transducer (Chivers et.al, 1990). In this case the received signal will remain exactly the same (i.e. the pulse will not dilate, though there will be some amplitude attenuation due to sound absorption) regardless of the depth of water.

In practical cases, the reflecting medium (seafloor) will have acoustic characteristics (e.g. topographical roughness) (Jackson et.al, 1986) which will reflect elements of the acoustic wavefront back to the transducer other than, and as well as the perfectly incident signal. These non-incident signal returns result in a received echo signal for which the acoustic pulse is stretched somewhat (see Figure 8). This stretching is due to the differing arrival times of different (or incoherent) elements of the receive signal (Caughey & Kirlin, 1995), and is utilised in the case of the RoxAnn instrument for calculating acoustic roughness (Chivers et.al, 1990).

Consequently habitat classification methods which assess echosounder signals over a range of depths, must take into account (or correct for) the influence of depth in the acoustic signal prior to classifying habitats based on this information. The RoxAnn instrument integrates a wider section of the ping waveform as the depth increases, so there is some depth correction provided by the RoxAnn circuitry itself. However, this instrument correction is not adequate as the hardness measure shows significant correlation with depth (Skewes et.al, 1996, Long et.al., 1997), hence a further correction was applied to RoxAnn analogue acoustic data (Long et.al., 1997), see section 2.3.1 Analogue Acoustics Data. The depth effect was taken into account by standardising depths for raw digital EK500 & BAS acoustic data, see 2.3.2 Digital Acoustics Data. Depth correction for raw digital EK500 & BAS acoustic data, may be investigated by re-sampling the acoustic signal (Kavali et.al., 1994; Caughey & Kirlin, 1995) in future work.

2.3.0.3 Acoustic Data Types

As part of this project a number acoustic methods for classifying seabed habitat were investigated. These methods included investigating two distinct acoustic data types (analogue and digital). Specific information about the data stored in each acoustic data base (RoxAnn, EK500 & BAS), the methods of instrument operation and data collection are described in section 2.2.2 Acoustic Sampling Instruments, with the type of acoustic information available summarised in Table 4.

Table 4: Acoustic data types investigated in this project, instruments and the data available for habitat classification. Table 6 describes the analysis & processing methods appropriate for the two types of acoustic data (Analogue - processed & Digital - raw) investigated for this project. QTC View data has not been fully tested within this current project (see 5 Further Developments)

Acoustic Data Source	Data Type	Data Available
RoxAnn	Analogue - processed	Roughness & hardness indices.
QTC View	Digital - processed	Processed ping features.
EK500	Digital - raw	Raw full digital ping data.
CSIRO BAS	Digital - raw	Raw full digital ping data.

The remainder of the Analysis of Acoustic Seabed Data section refers to the two types of acoustic data, the processing, analysis and classification techniques appropriate to them.

2.3.1 Analogue Acoustics Data

RoxAnn analogue acoustic data was recorded, on a number of field testing voyages (see Table 10) for the CSIRO Benthic Acoustic System, and the use of this data with associated ground truth data for the classification of seabed habitats is presented in a number of CSIRO reports (Skewes, 1996; Long, 1997). The RoxAnn data provided a benchmark for existing (analogue) techniques, for comparison with the digital methods developed for the benthic acoustic system (see 2.3.3 Comparison of Classification Techniques).

RoxAnn data was collected over large spatial scales (e.g. ~10 000 km^2 for Voyage 8 & ~5 000 km^2 for Voyage 9, see Table 9) and large range of seabed habitats (see Table 5) and depths (5 m to 120 m) during the course of the project. As an existing technique the analysis of the RoxAnn data, using existing classification methods, was applied across this large range of scales, habitats and depths, with production of results in the form of classified habitat maps possible. The methods for analysis and classification of analogue acoustic RoxAnn data are presented in the following sections.

2.3.1.1 Data Description

The RoxAnn system (as described in 2.2.2.1 RoxAnn) provided two acoustic indices, roughness and hardness, together with seabed depth. This data was logged with navigation to provide a spatial data set which, when linked with ground truth data (see 2.2.3.3 Navigational Data Cross-reference & Ground Truth Coding) provided a means to classify seabed habitat where only acoustic data existed. Ground truth data was collected in the form of video, sediment grab and epibenthic dredge. The sampling protocols for the video are described in 2.2.3.1 Video Sampling, and for the sediment grab in 2.2.3.2 Sediment / Benthic Fauna Sampling.

The collection of RoxAnn data on Voyage 9 (see Table 9) and the analysis presented here, was completed as part of a *Torres Strait marine infill survey* for the *PNG Gas Pipeline Project* (Long, 1997) and outlines the techniques used for seabed habitat classification and mapping using analogue acoustic data.

2.3.1.2 Classification Regimes

The RoxAnn hardness data was corrected for a residual bias with depth (see 2.3.0.2 Effect of Depth), by a regression of the minimum hardness values and depth. The RoxAnn roughness and depth corrected hardness values were then classified, based on ground truth data, from survey video data using a linear discriminant function (see 2.3.2.5 Linear Discriminant Analysis) which maximally separated the habitat types based on roughness and depth corrected hardness values. The linear discriminant function analysis is a method for defining group membership from ancillary data; the rule being defined and evaluated using a training data set with known group membership. This method is described in detail later in the section 2.3.2.5 Linear Discriminant Analysis

To predict substratum habitat type from RoxAnn roughness and hardness indices, the data were first merged by location with the ground truth data in the form of habitat coded transect data (see 2.2.3.3 Navigational Data Cross-reference & Ground Truth Coding). This matched up areas where both RoxAnn and ground truth video data were available and created a training data set where there was information for both substrate type and hardness and roughness values. The discriminant function was developed based on this ground truth data from the real time habitat coding system and grab data. The discriminant function was then applied to the remaining unclassified RoxAnn hardness and roughness data to classify the substrate in areas where we had acoustic data only.

To measure the performance (and to allow the comparison with other methods - see 2.3.3 Comparison of Classification Techniques) of the analogue acoustic classification method, apparent miss-classification error rates were calculated. These were obtained by calculating the proportion of pings that were incorrectly classified using the linear discriminant technique described.

The acoustic data in both raw roughness & hardness from, as well as classified habitat type was then presented as maps, using the Arc/View GIS package.

2.3.2 Digital Acoustics Data

Digital acoustic data (BAS) was recorded, on most field testing voyages (see Table 10) for the CSIRO Benthic Acoustic System, and the use of this data with associated ground truth data for the development of classification techniques for seabed habitats is presented here. This BAS digital acoustic data itself provided feedback for the development and refinement of the BAS system as described in 2.1 Benthic Acoustic System – Development & Refinement, by highlighting instrument errors that were corrected in subsequent instrument revisions . While the ground truth data provided a benchmark for evaluation of the analysis techniques developed and common information for comparison with the existing analogue techniques (see 2.3.3 Comparison of Classification Techniques).

Digital acoustic data (EK500 or BAS) was collected over a number of voyages (Voyages 2-8, 10, see Table 10), at large spatial scales (e.g. ~10 000 km^2 for Voyage 8, see Table 9) and large range of seabed habitats (see Table 5) and depths (5 m to 120 m) during the course of the project. As a developing technique, initial digital acoustic databases provided limited opportunity for development of analysis techniques, due to their quality (see 2.1 Benthic Acoustic System – Development & Refinement), but were useful for refining the system. The data management and analysis overheads for processing large scale high resolution digital acoustic data is restrictive. Accordingly, prototype digital classification algorithms have been developed using, smaller sub-sets collected with later revisions of the BAS system (revision 2.0 & later, see Table 7), from a limited range of habitats and by using standardised depths to eliminate the problem of depth correction (see 2.3.0.2 Effect of Depth). Also through collaboration with the FRDC Project T93/237 *Development of software for use in multi-frequency acoustic biomass assessments and ecological studies*, access to high quality digital acoustic data was possible, at three frequencies.

The seabed classification process was investigated in two stages – feature extraction and classification. With feature extraction, the acoustic data was manipulated prior to classification to summarize information necessary to make a classification. The classification stage, takes the feature or raw data and allocates a seabed habitat type from that data. Results were presented in the form of feature extraction & classification techniques development, application to test data sets, with measures of performance derived from classification error rates and comparison with existing techniques. The methods for analysis and classification of digital acoustic data are presented in the following sections.

2.3.2.1 Data Description

For this project digital acoustic ping data was available from two sources, the CSIRO Benthic Acoustic System and the Simrad EK500 (see Table 4 & descriptions in 2.2.2.2 Simrad EK500 & 2.2.2.3 Benthic Acoustic System). The CSIRO Benthic Acoustic System as a prototype has been developed for a single frequency (120kHz), while the EK500 system uses 3 frequencies (see 2.2.2.2 Simrad EK500). For a more complete investigation of digital acoustic methods for seabed habitat classification, we used data from & present analyses for 3 single frequencies of EK500 data. This data was logged with navigation to provide a spatial data set which, when linked with ground truth data (see 2.2.3.3 Navigational Data Cross-reference & Ground Truth Coding) provided a means to select training sets of digital acoustic data. Ground truth data was collected in the form of video, still photographs and sediment grab. The sampling protocols for the video are described in 2.2.3.1 Video Sampling, and for the sediment grab in 2.2.3.2 Sediment / Benthic Fauna Sampling.

The collection of EK500 data on Voyage 4 (see Table 9), was completed as part of the *South East Fishery ecosystem study* (FRDC Project 94/040), while the analysis and classification techniques development presented here were completed for this project in collaboration with the related research project (Kloser, 1998) investigating the use of three frequencies as an associated multifrequency system (FRDC Project T93/237).

Three seabed habitat classes were selected, with two of the classes being rough habitats (one with a slightly harder substrate), including some epibenthic growth. With the remaining habitat selected from a soft class with little or no epibenthic material. The habitats were chosen from similar depths (~115m to ~125m) to reduce the effect of depth on the classification process (2.3.0.2 Effect of Depth). The habitats chosen were given the classifications Rough/Hard, Rougher & Soft and are summarized in Table 5.

Table 5: Benthic acoustic habitat classes, used as test data for the development of digital seabed habitat discrimination algorithms. These habitat classes were delineated using both inspection of acoustic echograms for data quality and ground truth data via still photographs of the seabed. Source of data - Voyage 4 (see Table 9).

Habitat	Description	Depth
1	Soft	126m
2	Rough & Hard	113m
3	Rougher	115m

Each ping was sampled at a rate of 0.01 m over a bottom referenced layer from a depth of 0.55m above bottom to 12.15m below bottom. This sampling regime resulted in 128 sample points over this extracted bottom layer. There were 128 pings used at each of the three frequencies for each of the four replicates, and three habitat type combinations.

The acoustic ping data was used in two forms for classification, one as a set of features describing the data (see 2.3.2.2 Extracted Ping Features) and the other as the raw data itself (see 2.3.2.3 Full Raw Ping).

2.3.2.2 Extracted Ping Features

As an input to the classification process signal features were calculated for each observation. An observation in this case was one digitised bottom referenced acoustic ping of 128 samples. The signal features were selected to summarize signal properties and encapsulate the information necessary to discriminate between seabed habitat classes. The major ways that signatures differ between habitats, were investigated. Derived measures of the acoustic signatures were investigated; such as ratios of integrals, basic statistical descriptors, slopes of ascending or descending portions of signatures.

For this analysis a vector of 58 features was calculated for each of the 128 pings in each of the four replicate data sets, for each of the 3 frequencies and 3 habitat types. This 58 element feature vector was then used to classify seabed habitat. This 58 element feature vector consists of 5 logical groupings of feature types described in the following sections *Statistics, Shape, Pulse Parameters, Linear Prediction Coefficients, and Echo Integration.*

Statistics

The following group of ping features were generated by calculating a range of basic descriptive and higher order statistics for each ping.

1) *Maximum* – returned the largest S_v value for the ping.

2) *Minimum* – returned the smallest S_v value for the ping.

3) *Mean* – returned the mean S_v value for the ping.

4) *Variance* – returned the S_v variance for the ping.

5) *Median* – returned the median S_v for the ping

6-21) *Ping Histogram* – returned a 16 point histogram of S_v values for the ping. A standard set of histogram bins where used, each of 10 dB width, ranging from –120 dB to 30dB. The histogram bin ranges are parameters for this feature extraction and can be adjusted to suit a classification situation.

22) *Harmonic Mean* – returned the harmonic mean S_v value for the ping. Where the harmonic mean was calculated as the inverse of the mean of the inverses of the ping S_v values.

23) *Skewness* – returned the S_v skewness for the ping. Where the skewness (Keyszig, 1984, p. 922) was calculated as the 3rd central moment divided by the cube of the standard deviation.

24) *Kurtosis* – returned the S_v kurtosis for the ping. Where the kurtosis (Zar, 1984, p. 81) was calculated as the 4th central moment divided by the fourth power of the standard deviation.

25) *Interquartile Range* – returned the interquartile range of the S_v values for the ping. Where the interquartile range was formed by subtracting the 25th percentile of the data from the 75th percentile of the data.

26) *Mean Absolute Deviation* – returned the mean absolute deviation of S_v values for the ping. Where the mean absolute deviation was calculated by subtracting the mean S_v from the S_v values, taking absolute values and finding the mean of this result.

27) *Range* – returned the range of S_v values for the ping. Where the range was calculated by subtracting the minimum S_v from the maximum S_v value.

Shape

This group of ping features was generated as an interpolated reduction of the original ping data.

28-35) *Shape* – returned an 8 point smooth interpolated shape of the ping. Where the ping was represented by an 8 point interpolated version of the raw data. The interpolation used a Fourier transform method, where the input ping signal was periodically extended & the signal spectra was estimated via the Fourier transform (Oppenheim, 1989). The function was then interpolated (or filtered) in the frequency domain & transformed back to time to give the resulting interpolated time signal. The process is equivalent to low pass frequency filtering or smoothing.

Pulse Parameters

This group of ping features was generated by calculating a range of standard pulse waveform measurements defined in the ANSI/IEEE 194-1977 standard on pulse terms & definitions. In order to define a number of these pulse parameters a 50% threshold value was required, and calculated at half the difference of the maximum and minimum S_v values.

36) *Npeaks* – returned the number of valid peaks for the ping. Where a valid peak was considered as a signal peak with a width of at least 2 m, above a the 50% threshold. The valid width value used was a parameter for this feature extraction and can be adjusted to suit a classification situation.

37) *Pulse Width* – returned the width of the ping pulse at the 50% threshold for the ping. The width calculated as the difference between the ping falling edge and the ping rising edge time at which 50% amplitude occurs.

38) *Rise Time* – returned the depth change (time) for the ping to rise from 10% of the peak S_v value to 90% of the peak S_v value on the rising edge of the ping.

39) *Fall Time* – returned the depth change (time) for the ping to fall from 90% of the peak S_v value to 10% of the peak S_v value on the falling edge (tail) of the ping.

40) *Slew Rate* – returned the rate of rise on the ping rising edge. The slew rate was calculated as the ratio between the S_v difference given by (90% of peak S_v amplitude – 10% of peak S_v amplitude) and the *Rise Time.*

41) *Decay Rate* – returned the rate of decay on the falling edge (tail) of the ping. The decay rate was calculated as the ratio S_v difference given by (90% of peak S_v amplitude – 10% of peak S_v amplitude) and the *Fall Time.*

42) *Max Thresh* – returned the peak S_v value, calculated as the largest local ping signal maxima.

43) *Min Thresh* – returned the smallest S_v value, calculated as the smallest local minima before the peak S_v values (bottom signal).

44) *Diff Thresh* – returned the absolute value of the 50% threshold for the ping.

Linear Prediction Coefficients

The following group of ping features were generated by modeling each ping signal as an 8^{th} order auto-regressive linear process, taking into account the correlation structure of the ping waveform. The linear prediction modeled each sample of the signal as a linear combination of previous samples (Makhoul, 1975), that is, as the output of an all-pole IIR (infinite impulse response) filter.

45-53) *LPC* – returned 9 LPC feature parameters – a gain parameter and 8 model coefficients a(n) to the 8^{th} order linear prediction model for the ping. The LPC (linear prediction coefficient) features were calculated as the coefficients and gain of the 8^{th}-order auto-regressive linear process that models the ping signal S_v as

$$\mathrm{Sv}(k) = -a(2)\mathrm{Sv}(k-1) - a(3)\mathrm{Sv}(k-2) - \ldots - a(n+1)\mathrm{Sv}(k-n-1)$$

where S_v was the real input ping signal, and n=8 is the order of the denominator polynomial a(z), that is, a = [1 a(2) ...a(n+1)]. The filter coefficients were ordered in descending powers of z. The LPC model used the autocorrelation method of autoregressive (AR) modeling to find stable filter coefficients or maximum entropy method (MEM) of spectral estimation. The model order used was a parameter for this feature extraction and can be adjusted to suit a classification situation.

Echo Integration

The following group of ping features were generated by calculating integration of values for sea bottom referenced layers for each ping. The integration layer values (i.e. definitions of where the layers start & stop) are parameters for these feature extractions and can be adjusted to suit a classification situation. Echo integration layers may be chosen as a percentage of depth and are listed here for the 100 m depth case.

54) *Above Bottom* – returned the echo integration for the layer from 0.55 m above bottom to 0.05 m below the bottom for each ping.

55) *Below Bottom* – returned the echo integration for the layer from 0.15 m below the bottom to 12.15 m below the bottom for each ping.

56) *Peak* – returned the echo integration for the layer from 0.15 m below the bottom to 2.35 m below the bottom. This corresponded to peak S_v and may be considered an index of acoustic hardness (simulating the RoxAnn hardness parameter).

57) *Tail* – returned the echo integration for the layer from 2.45 m below the bottom to 12.15 m below the bottom. This corresponded to the tail of the ping and may be considered an index of acoustic roughness (simulating the RoxAnn roughness parameter).

58) *Peak to Tail Ratio* – returned the ratio of the *Peak* and *Tail* echo integration features.

When looking at all the 58 extracted features for any frequency, as the groups of features have different scales, the feature groups were standardized by dividing by the value's largest parameter for each group to give feature parameters in the range from -1 to 1.

2.3.2.3 Full Raw Ping

The full raw ping form of digital acoustic data, performed no intermediate extraction of signal features prior to classification. Essentially the raw acoustic ping data were used in the classification process. For the subsequent classification, this method was equivalent to the feature extraction method outlined in the previous section, where the actual 128 elements of raw ping data were considered the "features".

2.3.2.4 Classification Regimes

Traditional statistical pattern recognition approaches were used to classify the data from a vector of extracted features (described in the section 2.3.2.2 Extracted Ping Features) as well as an approach using the raw ping data. Each of these methods uses the Mahalanobis distance to make the classifications and discriminant vectors to graph the separation of the habitats. The Mahalanobis distance measures either the distance between the habitat feature means or the distance of individual pings to habitat means, and the discriminant vectors are linear combinations of the original feature vectors that maximise the between habitat variability relative to the between ping variability. These classification regimes are described in the following sections 2.3.2.5 Linear Discriminant Analysis and 2.3.2.6 Smooth Ping Analysis.

2.3.2.5 Linear Discriminant Analysis

A linear discriminant analysis technique was used to classify a ping into one of the three habitats (see Table 5) using 58 extracted features or the 128 sample points on a raw ping. We defined a feature vector of a ping as a function of the 58 pre-processed features (outlined in section 2.3.2.2 Extracted Ping Features) or the 128 sample points of the ping (outlined in section 2.3.2.3 Full Raw Ping). A collection of these features was put into a data vector and the discriminant analysis developed for this vector. This linear discriminant analysis comprises a classification technique, calculation of discriminant coefficients, and calculation of error rates.

Classification Technique

The Classification of a ping was achieved by allocating a test ping to the habitat with the smallest Mahalanobis distance. This distance was calculated as the square of the difference of a ping data vector to the mean of the ping data vectors (both extracted features & raw data) from training data for a given habitat, scaled by the covariance matrix for the training data.

Discriminant Coefficients

The importance of the features in their contribution to the separation of the three habitats was assessed by examining the coefficients of the best linear combinations of the elements of the data vector. These linear combinations were chosen to maximize the difference in means across habitats (see Hand, 1981, p.150).

To graphically illustrate the separation of the three habitats, we plotted scores on the best two linear combinations on the X and Y axes . On such a plot, the score for a ping on the first linear combination is the value on the X-axis and the score for the same ping on the second linear combination is the value on the Y-axis.

Error Rates

A further measure of the success of classification techniques based on particular data vectors was to compute the miss-classification rate. These were obtained by calculating the proportion of pings that were incorrectly classified using the classification technique described above.

When all the data from any one of the three habitats was used to compute the mean and covariance matrix used in computing the Mahalanobis distance, the resulting error rate for pings in that habitat was called the apparent error rate. It typically overestimates the error rate if the allocation of new pings was performed. To overcome this, we also calculated the cross-validated error rate (Stone, 1974). This was performed by classifying a ping relative to a training data set with that omitted. In fact, eight distinct sets of omitted pings were constructed by selecting a half of each of the four replicates for the three habitats on which to perform the classifications.

In other words, to calculate the cross-validated miss-classification rate, half of the data from each replicate and each habitat was set aside in turn and the discriminant analysis performed on the remaining halves. The data that was set aside was then classified using the Mahalanobis distance, i.e. each withheld observation was assigned the class with minimum Mahalanobis distance when referred to the mean and covariance matrix of the data in the remaining halves. The miss-classification error was calculated as the proportion of incorrectly classified observations when the eight sets of half replicates had been withheld.

2.3.2.6 Smooth Ping Analysis

A typical ping is a smooth function when plotted against the corresponding sequence of points in time. As described earlier, various extracted parameters of the raw ping have been used to form the feature vectors for classifying habitats. We have also used the smooth raw ping curve as an underlying component of the full set of points available for a ping and performed the classification of habitats without relying on using extracted features. This way we hoped to avoid the influence of spurious values that may have made classification unreliable when put into routine use.

So an alternative to using selected features of a ping to form the vector on which to base the classification was performed. Here the property that the 128 points on a ping followed a smooth curve was taken into account. In particular high correlations between adjacent points on a ping usually resulted in linear discriminant functions that highlighted minor fluctuations in the training data. This lead to 1) rough coefficient sequence plots that were not intuitively appealing, and 2) poor miss-classification error rates, as jagged coefficient plots would reflect unimportant local variation that would be highlighted when new data were assessed relative to the classification strategy.

Hence we have adopted a smoothing technique by augmenting the covariance matrix of the full ping data vector with a penalty matrix to dampen the effect of high correlations between points on a ping. The penalty matrix chosen reflected the jaggedness of the curve joining the points on a ping. Different amounts of importance were placed on this penalty matrix by scaling it by a parameter λ. This parameter was chosen to minimize the cross-validated miss-classification error referred to in the previous section.

2.3.3 Comparison of Classification Techniques

In this project we used a number of approaches to the classification of seabed habitat from acoustic data, and the performance of these different methods was compared using error rates and example data selected from ground truth information. For a series of test datasets, we conducted a comparison of the three techniques of classification: analogue roughness/hardness; digital extracted features; and digital full raw ping.

It was possible to use linear discriminant function analysis to analyse the analogue roughness/hardness, digital extracted features and digital full raw ping; but the penalised discriminant function analysis could be used to analyse only the digital full raw ping data (see Table 6).

Table 6: Analysis and processing methods applied to both analogue and digital acoustic data for habitat classification. The table shows that while a linear classification technique is appropriate for all sources of data (acoustic or digital and raw or extracted features), the smooth classification method may only be applied to raw ping digital data, such as that collected by digital acoustic systems like the benthic acoustic system or EK500.

Data Source	Feature Extraction	Linear Classifier	Smooth Classifier
Analogue - processed	Roughness / Hardness	✓	×
Digital - raw	Extracted Features	✓	×
Digital - raw	Raw Full Ping	✓	✓

2.3.3.1 Comparing Analogue and Digital Acoustic Data

Example digital acoustic data from CSIRO BAS, was selected from acoustic data base 8 (see Table 10) where corresponding RoxAnn data existed. For this comparison we selected the BAS data from four of the habitats described using video and sediment grab ground truth described in 2.2.3 Ground Truth Sampling.

To further compare the analogue and digital methods, features were calculated for the digital acoustic data equivalent to those produced by RoxAnn by integrating comparable portions of the digital data as RoxAnn does in its analogue processor, for both CSIRO BAS & EK500 digital acoustic data. These features while calculated from 1st echo data only, simulate the measures of acoustic roughness (tail integration, extracted feature 57, see 2.3.2.2 Extracted Ping Features) and hardness (peak integration, extracted feature 56, see 2.3.2.2 Extracted Ping Features). Error rates for these simulated RoxAnn indices were compared with error rates for digital acoustic methods from EK500 data.

2.3.3.2 Comparing Extracted Features

Cross validated error rates were used to compare the performance of all extracted features & groups of extracted features (as described in 2.3.2.2 Extracted Ping Features), for each of the 3 frequencies.

Discriminant function coefficients were calculated, for individual extracted features (as described in 2.3.2.2 Extracted Ping Features) & the 5 features with the largest discriminant power were identified, for each frequency.

2.3.3.3 Comparing Raw and Smoothed Data

When the full set of points on a ping are used, the benefit of augmenting the covariance matrix with a penalty matrix is also assessed by comparing the classification error rates. Different levels of penalizing are controlled by varying the value of the parameter λ. Interpretation of the importance of the points on a ping based on the smooth ping analysis are again assessed by examining the coefficients of the discriminant functions computed using the augmented covariance matrix.

3 RESULTS & DISCUSSION

This chapter describes and discusses the results for the three major components of the project. These components and their accompanying sub-sections are –

3.1 Benthic Acoustic System – Development & Refinement. In this section we describe and discuss the results for the development and refinement of the CSIRO "Benthic Acoustic System", hardware and software.

3.2 Field Testing & Ground Truth. In this section we describe and discuss the results for the field-testing of the acoustic seabed classification systems and for the collection of both acoustic and ground truth data.

3.3 Analysis of Acoustic Seabed Data. In this section we describe and discuss the results for the analysis of acoustic seabed data, including the results for the development of classification algorithms for digital acoustic data.

3.1 Benthic Acoustic System – Development & Refinement

In this section we describe and discuss the results for development of hardware and software of the CSIRO "Benthic Acoustic System". The refinements made to arrive at the final configurations, choice of hardware and their performance specifications are also described.

3.1.1 Benthic Acoustic System – Hardware

Several electronics and computer hardware components were purchased or developed to form the benthic acoustic system. These included echo-sounders, acoustics receivers, A/D boards, computers and mass storage devices.

The CSIRO Marine Research scientific echo-sounder, the Simrad EK500, was used where possible during the course of this project. Most of the field-work was conducted on charter vessels (see Table 9) and initially we anticipated using whatever echo-sounders were available on these vessels. However, due to the variety of echo-sounders, with different frequencies and other specifications, installed on these vessels it was necessary to purchase a small fishing sounder to provide consistency to the project. The sounders chosen (Fuso MF405 or Sitex LCS-200) had the same frequency as the EK500 (i.e. 120 kHz) and similar beam-width.

The BAS system and receivers (see Table 7) were designed and constructed specifically as part of the project. The first prototype (revision 0.0, see Table 7) was built to basic specifications by a small external electronics R&D company. This prototype functioned well enough to serve as a test-bed for modifications and subsequent revisions, but its tolerances were not tight enough for recording of data for analysis. Subsequently, several revisions of the receiver were re-designed and constructed by CSIRO Revision 1.0 through 2.1 (see Table 7). The design of these Revisions of the BAS system are described here.

Table 7: BAS receiver revision table, showing modifications and refinements implemented in the signal conditioning electronics design, throughout the life of this project.

Revision	Date	Modification / Refinement Notes
0.0	11/93	Original receiver (poor filter, noise & amplifier performance)
0.1	8/94	Included trigger circuit functionality & tuned for A/D specifications
0.2	9/94	Acoustic calibration of channel gains
1.0	12/95	Redesign - improved filter, noise & amplifier performance
2.0	2/96	Correction of design issues (circuit board layout) from revision 1.0
2.1	3/97	Refinement of filter performance & tuning of amplifier gains

Two high performance multi-channel analogue-to-digital-converters (A/D) were purchased for the project. The first was a Data Translation DT2838 and was used with the first DOS version (see 2.1.2.1 Benthic Acoustic Acquisition & Instrument Control Software) of the acquisition software. The second was a National Instruments AD2150C Dynamic Acquisition Board and was more suitable for operation under a modern 32-bit PC operating system such as Windows-NT and the second version of the acquisition software (3.1.2 Benthic Acoustic System – Software).

Several dedicated digital acoustic logging computers were purchased during the course of the project. All had Pentium processors, but as the demands on data transfer rate, and complexity of the acquisition and analysis software, increased so did the requirement for CPU power, memory and hard disk storage capacity. In all cases, the very large volumes of acquired data were backed-up onto 5 Gb EXABYTE tapes (see 3.1.1.2 Benthic Acoustic Data Acquisition and Archiving System).

3.1.1.1 Benthic Acoustic Signal Conditioning Electronics

The acoustic system specification is described in Table 8 for the 120 kHz echosounder used in this study, using the formula in Table 1. To determine the required dynamic range of the system and amplifier gains the equations in Table 1 were used to work through the maximum and minimum signal conditions.

Table 8: Benthic acoustic system performance specifications and design parameters for the 120kHz fishing echosounder used in this project. These parameters in conjunction with design formulae set out in Table 1 were used to design the benthic acoustic system.

Parameter	Value	Units
frequency	120	kHz
transducer diameter	0.059	m
wavelength	0.0125	m
wave number (k)	502.6548	wave number = 2*pi/wavelength(m)
beam width +/- 3dB	13.8	deg
directivity	22.3	dB
ideal beam	-14.7	dBre 1 steradian
power	1000	W
efficiency	-3	dB(50%)
resistance	70	ohms
sea noise	40	dB
ship noise	40	dB
pulse length	0.1	ms (10*(1/frequency as a minimum)
bandwidth	5	kHz(1/(2*pulse length) as a minimum
sound speed	1520	$m\ s^{-1}$
density	1026	$kg\ m^{-3}$
absorption	47	$dB\ km^{-1}$

The maximum return echo signal voltage (154 mV) was measured on acoustically hard bottom (Bsi =-10 dB) echo at 5 m water depth. The noise voltage with a 10 dB SNR is 0.3 uV and the depth at which the system can detect the weak volume back scattered target (Vsi = -74 dB) is 180 m. This yields a dynamic range for the system of 114 dB (for the receive channels of the system). The dynamic range required would change according to the acoustic frequency, power and transducer employed.

This was difficult to achieve in a single amplifier stage as standard 16 bit A/D digitisers would quantise this dynamic range of voltage in steps of 2.35 uV. The 2.35uV voltage steps are far too high when compared to the noise voltage of 0.3uV. It was shown in the design sections that to record high bottom signal at shallow depths and then digitise down to ocean/vessel noise requires a high dynamic range receiver with several gain stages. The best method was to employ several gain stages to increase the dynamic range and reduce the quantised voltage. The system designed in this project addressed these criteria, by having three gain channels (high, medium and low, Figure 2). Also, to record the transmit pulse required that an attenuator be fitted to the system.

The system was designed with four acoustic signal paths of different amplification (transmit, low gain receive, medium gain receive, high gain receive). Several gain stages reduced the quantised voltage to a level far below that of the noise voltage. The receiver was designed with amplification stages meeting these criteria and has gain stages of 8dB, 32dB, and 56dB (low, medium & high), and -40 dB transmit channel, yielding an effective dynamic range of 186 dB (from transmit channel to high gain receive).

The success of the implementation of this design is based on the building of low noise amplifiers and sharp cut off band pass filters. The filters were designed to have the band width (5 kHz, Table 8) to resolve short pulse lengths (0.1 mS, see Table 8). The design outlined here can be generalised to fit to any commercial echo sounder.

For the purposes of this project we were limited to adding a receiver to an existing echosounder with the operating frequency range 120 kHz. This echosounder fitted to a vessel will have all the usual problems associated to acoustic instruments operated at sea. The installation of the transducer at an appropriate location is vital to the success of collecting useful data in reasonable weather conditions. Also the interference from other acoustic devices will greatly effect the operation of the system. To remove all these sources of noise in real time would require an expert system beyond the scope of this project. For this project, the data was stored in raw form to enable the data quality control procedures to remove all known sources of noise and signal degradation.

The electronic circuit schematics for the Revision 2.1 signal conditioning receiver design are shown in APPENDIX E - BAS CIRCUIT SCHEMATICS. These schematics (Figure 33 through Figure 44), show the circuit level design of the BAS system.

Figure 9 shows the implementation of the signal conditioning receiver design (Revision 2.1) described in this section, with two printed circuit boards, one for the amplifier and band pass filter stages, and the second for the rectifier and low pass filter output stages.

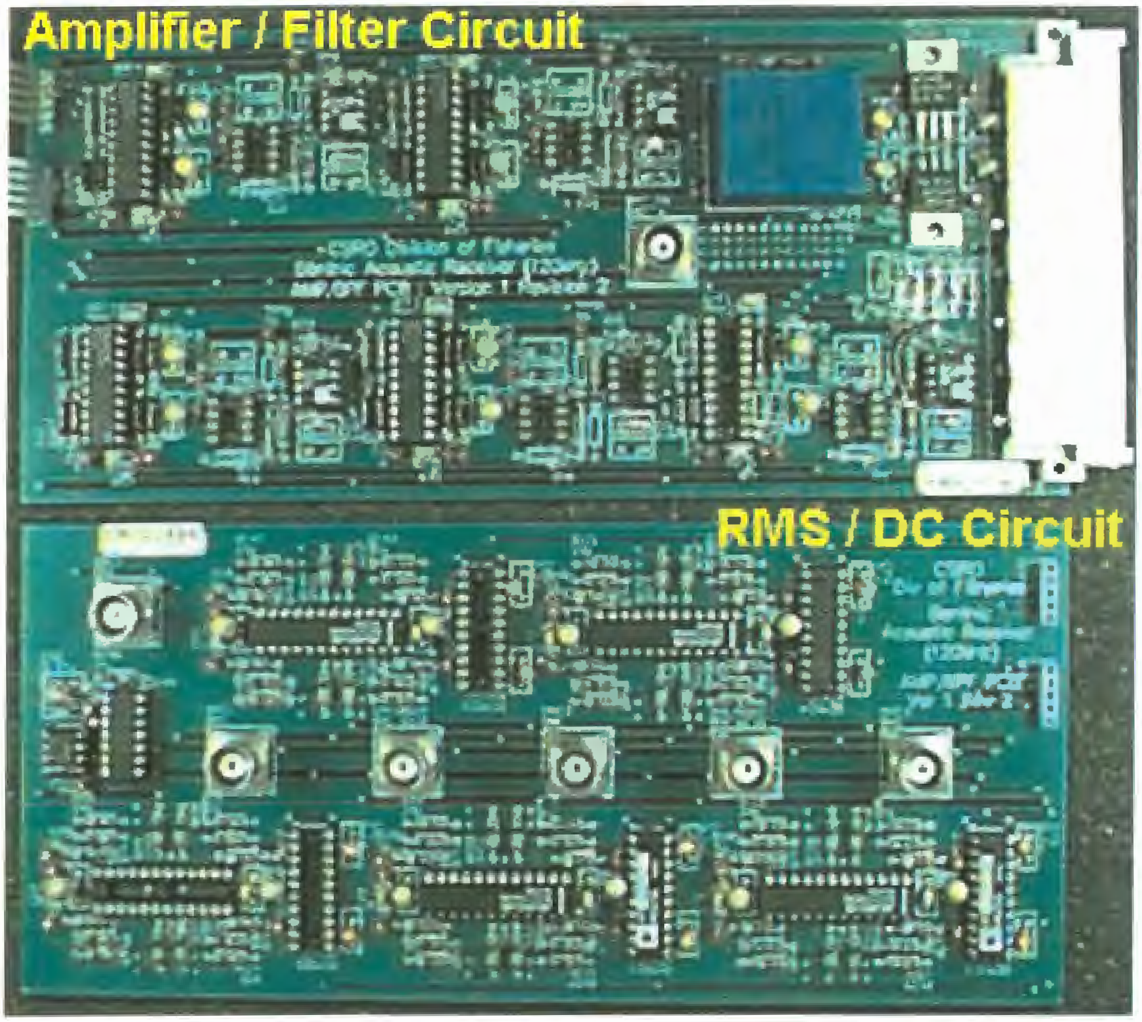


Figure 9: Signal conditioning electronics hardware. This figure shows the two electronic printed circuit boards which comprise the acoustic receiver designed for this project. The PCB at the top consists of the transducer input circuit for both transmit and receive signals, amplifier stages and band pass filter circuits for each channel of the receiver as well as the power supply circuit. The bottom PCB consists of the output RMS/DC circuits and low pass filters for each channel (transmit and receive) as well as the A/D trigger circuit.

3.1.1.2 Benthic Acoustic Data Acquisition and Archiving System

A National Instruments corporation AD2150C dynamic signal acquisition card was used to perform the data acquisition task. The acquisition card has 16 bit resolution, and allowed up to 50 kHz simultaneous sampling on each of the four input channels, which matched the 4 amplification stages of the receiver (see 3.1.1.1 Benthic Acoustic Signal Conditioning Electronics). The acquisition of acoustic data was designed with a high speed sampling rate (up to 50 kHz) to give high resolution signatures up to 30 mm resolution in water, and high quantisation resolution (15 bits - effective) to allow the large dynamic range 114 dB, designed (3.1.1.1 Benthic Acoustic Signal Conditioning Electronics).

With the high speed, high resolution data acquisition system the amount of data captured was very large, up to ~500MB of data per hour of surveying. The digital acoustic data once acquired was then recorded to computer hard disk. All raw digital acoustic data was stored as sampled, because any data reduction at acquisition could lead to corrupt acoustic signals.

Initially the data was stored on the systems hard disk drive and as this drive was filled the data was migrated to the archiving system. For the long term storage of Benthic Acoustic System data very high-capacity high-speed hard disk drives and large capacity tapes were used. The data archiving system stored up to 5 Gb of digital benthic acoustic data on a single Exabyte tape. The data archiving system also made use of recordable CD-Rom's as a read only form of long term data storage.

3.1.2 Benthic Acoustic System – Software

3.1.2.1 Benthic Acoustic Acquisition & Instrument Control Software

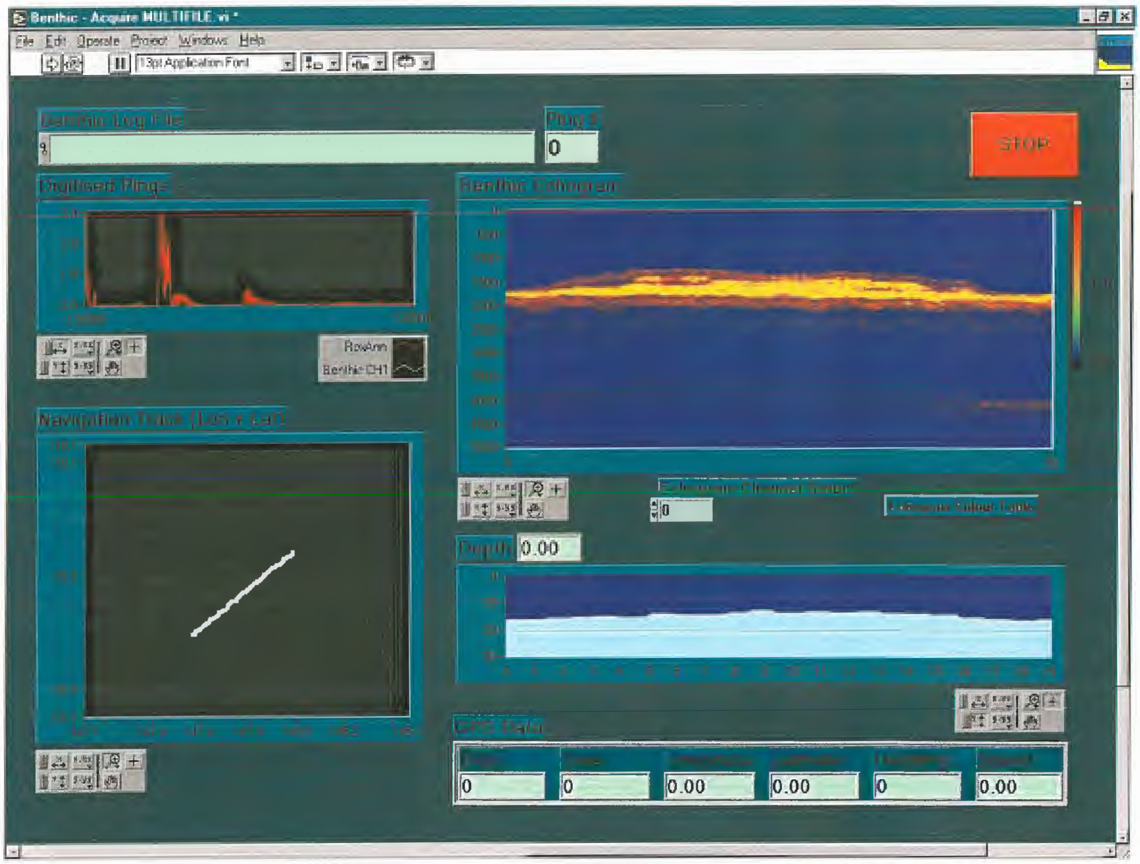


Figure 10: Screen capture of the acquisition & instrument control software user interface, showing computer displays for the digitised echogram (with selector for receiver channel and echogram colour scheme), digitised ping displays (for data integrity checking), depth profile, ship track display diagram and navigation data read-out. The user interface also has controls for data acquisition & control parameters to be set.

The user interface for the acoustic data acquisition and instrument control software is shown in Figure 10. This user interface has graphical displays for both acoustic and navigation data. Acoustic data is displayed for each data channel in the system as a ping time series in the

"Digitised Ping Data" graph window. The colour echogram display provides the familiar echosounder interface as per off-the-shelf echosounders. The echogram display can be selected for each signal conditioning gain channel. The echogram colour scheme can be modified during acquisition to tailor the display to the application. The display also allows the user set ranges and zoom during operation as well.

Navigation data is displayed in text format for date, time, position, heading and speed as well as in graphical form for position. The graphical position indicator shows vessel track. Depth data from the echosounder is displayed graphically to show along track bathymetry.

3.1.2.2 Benthic Acoustic Data Management & Analysis Software

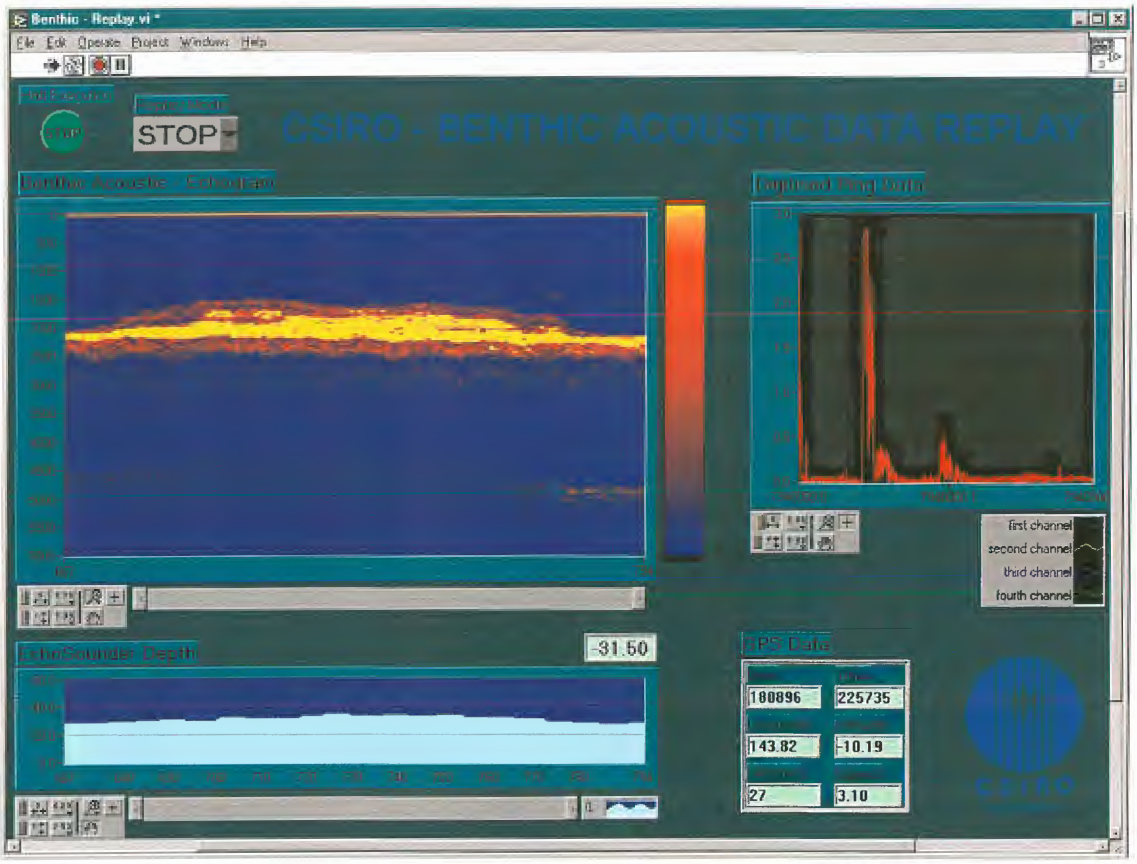


Figure 11: Screen capture of the benthic acoustic data management & analysis software user interface, showing computer displays for the digitised echogram, digitised ping display, depth profile and navigation data read-out. The user interface also has controls for data replay, searching, seabed bottom detection and zooming as well as data extraction for analysis.

The user interface for the benthic acoustic data management and analysis software is shown in Figure 11. The benthic acoustic data management and analysis software has graphical displays similar to those of the acquisition and control software, and include a colour echogram as well as a ping time series display and depth data display.

The benthic acoustic data management and analysis software also contains a sea-bottom pick algorithm, which automatically selects and tracks the seabed echo return (Figure 12). This function allows layers of echogram data to be extracted referenced to the seabed. This is the primary data selection function used in extracting data for use in the acoustic analysis for seabed habitat classification.

The software has the potential to, in the future, be enhanced to take advantage of the discriminator/ predictor functions arising from the analysis phase (3.3 Analysis of Acoustic Seabed Data) — this could provide real-time seabed habitat classification while the vessel is underway (non-research applications would then not require high capacity data storage facilities). The display system could be updated so that the plot of the survey track also provides coded habitat classification information.

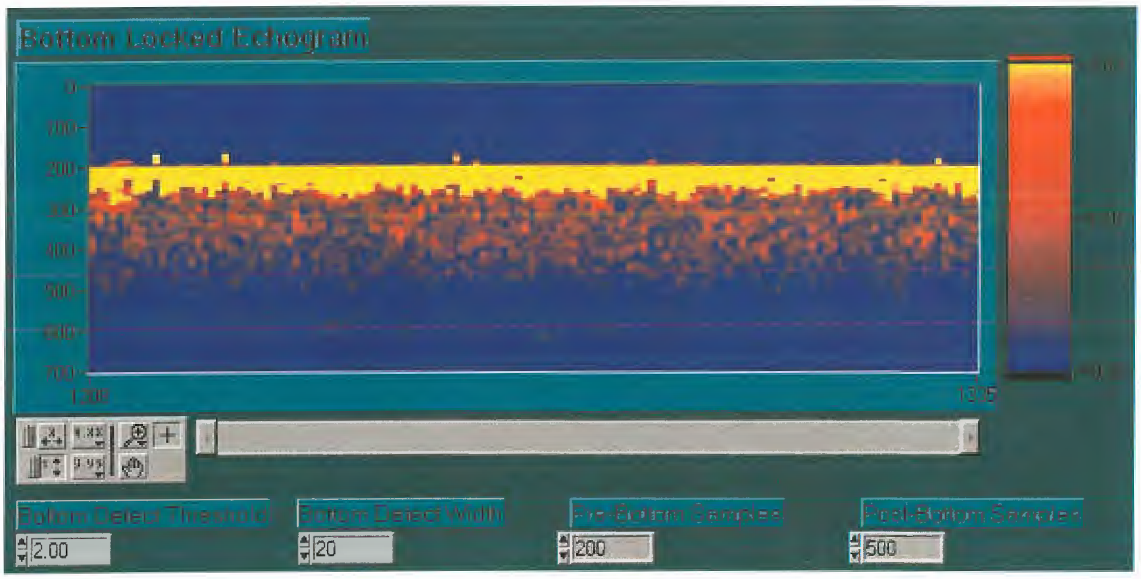


Figure 12: Bottom locked echogram display. This figure shows the user interface for the bottom detection and tracking feature of the benthic data management and analysis software. The user is able to select a seabed locked layer of data to extract for analysis.

3.2 Field Testing & Ground Truth

In this section, we present the results from field-testing of the acoustic systems, in terms of data holdings and metadata statements for both acoustic and ground truth data. This includes results for voyages (dates, locations, related projects), for the acoustic instruments (RoxAnn, Simrad EK 500, CSIRO BAS), as well as for ground truth sampling (real-time video, sediment grab sampling, GPS positional data for cross-referencing and habitat coding).

The habitat mapping information arising from this project is of substantial benefit to the projects for which collaboration has been undertaken for vessel time; e.g. Effects of Fishing, Bycatch, SEF Ecosystems, Torres Strait Habit & Megabenthos Dynamics.

3.2.1 Voyages

Table 9: Habitat acoustic voyages. This table shows the voyages associated with this project for field testing the benthic acoustic system, as well as the collaborating scientific projects, the research vessels used, voyage dates and locations.

Acoustic Voyage	Associated Project	Research Vessel	Voyage Date	Voyage Location
Voyage 1	Effects of Fishing	Sunbird	November 1993	Far Northern Great Barrier Reef
Voyage 2	Bycatch	Southern Surveyor	November 1993	Gulf of Carpentaria
Voyage 3	Effects of Fishing	Sunbird	March 1994	Far Northern Great Barrier Reef
Voyage 4	SEF Ecosystems	Southern Surveyor	September 1994	Southeast Fishery (Eden & Gabo Is)
Voyage 5	Effects of Fishing	James Kirby	November 1994	Far Northern Great Barrier Reef
Voyage 6	Effects of Fishing	James Kirby	April 1995	Far Northern Great Barrier Reef
Voyage 7	Effects of Fishing	James Kirby	January 1996	Far Northern Great Barrier Reef
Voyage 8	Torres Strait Habitat	James Kirby	September 1996	Eastern Torres Strait
Voyage 9	Torres Strait Habitat	James Kirby	April 1997	Central Torres Strait
Voyage 10	Megabenthos Dynamics	Lady Baston	September 1997	Mid Great Barrier Reef

The acoustics project participated in 10 major field-trips associated with more than 5 other projects (Table 9). Ground truth data from voyages 1, 3, & 5–10 was accurately tracked and could be the most closely co-registered, in terms of position, with the acoustic data (i.e. within 5–10 m). Ground truth data from voyage 2 was in the form of trawl catches only, and because trawls integrate over about 3 km, it was difficult to co-register this information except in an overall manner. Ground truth data from voyage 4 was collected from a video sled that was not tracked relative to the vessel, consequently the precision of co-registering was about 50–100 m.

3.2.2 Acoustic Sampling Instruments

The acoustic instruments used to sample acoustic data during this project and the associated acoustic data bases are described in Table 10. Analogue acoustic data was collected on 9 of the 10 field testing voyages in this project, while digital acoustic data from various instruments was collected during 8 of these voyages. The results for specific acoustic sampling instruments are described in the following sections.

The use of the QTC View system, while not in the original scope of this project, is closely aligned with project objectives, consequently the instrument was evaluated during one voyage & subsequently purchased. The experience with QTC while limited, provides scope for further investigation (see Further Developments).

Table 10: Habitat acoustic data bases, showing the type of acoustic data collected during field trial voyages for this project (see Table 9). Data Holdings : RoxAnn 100Mb, QTC View 200Mb, BAS Data 10Gb, EK500 20Gb.

Acoustic Data Base	Associated Voyage	Analog Acoustic Data	Digital Acoustic Data
Data Base 1	Voyage 1	RoxAnn	
Data Base 2	Voyage 2		Simrad EK500
Data Base 3	Voyage 3	RoxAnn	Benthic Acoustic System (Rev 0)
Data Base 6	Voyage 4	RoxAnn	Simrad EK500, BAS (Rev 0.1)
Data Base 4	Voyage 5	RoxAnn	Benthic Acoustic System (Rev 0.2)
Data Base 5	Voyage 6	RoxAnn	Benthic Acoustic System (Rev 0.2)
Data Base 7	Voyage 7	RoxAnn	Benthic Acoustic System (Rev 1.0)
Data Base 8	Voyage 8	RoxAnn	BAS (Rev 2.0), QTC View 3
Data Base 9	Voyage 9	RoxAnn	
Data Base 10	Voyage 10	RoxAnn	BAS (Rev 2.1), QTC View 4

3.2.2.1 RoxAnn

The RoxAnn was operated on all voyages except voyage#2 (Table 10). Each data-set contains USP RoxAnn seabed hardness and roughness indices, as well as ancillary data (including Date/Time, Boat Position, Speed & Water Depth) for each location (Table 12). The Project with which each data-set was associated, and dates, is shown in (Table 9). RoxAnn data holdings are in the vicinity of 100Mb.

USP RoxAnn data was collected using IBM PC based logging software. The data-sets have been filtered for bad records (e.g. bad position fixes, bad seabed depth picks) & corrected for towed body flight depth. The echo-sounder frequency of operation = 120 kHz; Pulse Length = 0.5 ms; Recording Rate = 0.5 Hz (one record every 2 seconds); GPS Mode = Differential or normal (see Table 12); Deployment Method = Towed Body. The total number of records is in the order of 4×10^6.

The data is stored in comma separated value format & includes column headers. The dataset attributes are shown in Table 11.

Table 11: RoxAnn data file format, showing the fields in a RoxAnn data file, their identifiers, the data format of fields & the information they contain.

Field Identifier	Data Format	Information
FILE_NAME	ASCII String	File name for original raw RoxAnn data
DATE	ASCII String	Date DDMMYY
TIME	ASCII String	Time HHMMSS
LONGITUDE	ASCII Number	Longitude in Decimal Degrees
LATITUDE	ASCII Number	Latitude in Decimal Degrees
BOAT_SPEED	ASCII Number	Boat speed in Knots
DEPTH	ASCII Number	Water depth in Meters
ROUGHNESS	ASCII Integer	RoxAnn roughness index (0 to 4096)
HARDNESS	ASCII Integer	RoxAnn hardness index (0 to 4096)

3.2.2.2 Simrad EK500

Simrad EK500 digital acoustic data was collected during two of the Voyages for this benthic acoustic project, these correspond to acoustic databases 2 & 6 (see Table 10). With EK500 acoustic sampling possible at three of echosounder frequencies (12 kHz, 38kHz, 120kHz) for voyage 4, and acoustic data base 6.

Each EK500 data base contains full water column digital acoustic echogram data, including higher resolution seabed referenced data, instrument settings and calibration information, as well as ancillary data (including Cruise, Vessel, Date/Time, Position, & Water Depth). The Project with which each data-set was associated, and dates, is shown in (Table 9).

The EK500 data was collected using the Echo software (Waring et.al., 1994) and was registered with the CSIRO acoustic data base in conjunction with the FRDC project 94/040 Habitat and fisheries production in the South East Fishery ecosystem. This data base 6 provided information for the investigation habitat classification for both this project and the collaborative project investigating multifrequency techniques (FRDC Project T93/237 Development of software for use in multi-frequency acoustic biomass assessments and ecological studies). EK500 acoustic data holdings are in the vicinity of 20Gb.

3.2.2.3 Benthic Acoustic System

The BAS system as the focus of this project was used to collect digital acoustic data during most of the voyages associated with this project (see Table 10). The data was collected from a number of revisions of the system & these revisions are outlined in Table 7. Revisions of the system corresponded with refinements of the design, tested during the course of the projects field trials. As a result of these refinements, data bases 8 & 10 (BAS revision 2.0 & above) provide the highest quality benthic acoustic data for investigation of classification techniques.

Each BAS data base contains full water column digital acoustic echogram data and instrument settings, as well as ancillary data (including, Date/Time, Position, Speed & Water Depth). The Project with which each data-set was associated, and dates, is shown in (Table 9). Higher quality revision 2.0 & above, BAS data holdings are in the vicinity of 10Gb.

3.2.3 Ground Truth Sampling

The different ground truth and navigational cross-reference techniques used during this project and the associated ground truth data bases are described in Table 12. The results for specific ground truth sampling techniques are described in the following sections.

Table 12: Associated ground truth data bases, showing the type of ground truth data (& sampling method) collected during field trial voyages for this project (see Table 9), including the cross-reference method and accuracy of geo-location. Data Holdings: Video 600hrs, Still Photos 150, Sediment & Dredge 450 Samples, Tracking 50Mb

Acoustic Data Base	Associated Voyage	Ground Truth Data	Cross & Geo-reference
Data Base 1	Voyage 1	Video	DGPS
Data Base 2	Voyage 2	Trawl	GPS
Data Base 3	Voyage 3	Video	DGPS
Data Base 6	Voyage 4	Video, Still, Sediment, Dredge	GPS, Tracking
Data Base 4	Voyage 5	Video	DGPS, Tracking
Data Base 5	Voyage 6	Video	DGPS, Tracking
Data Base 7	Voyage 7	Video	DGPS, Tracking
Data Base 8	Voyage 8	Video, Sediment, Dredge	DGPS, Tracking
Data Base 9	Voyage 9	Video, Sediment, Dredge	DGPS, Tracking
Data Base 10	Voyage 10	Video, Sediment, Dredge	DGPS, Tracking

3.2.3.1 Video Sampling

Video ground truth data was collected on all voyages except voyage#2 (Table 12). Each video data-set (except voyage #4) has position reference information overlaid on the recording (including Date/Time, Position, Speed, Direction, Depth, Habitat Code) and an associated video tracking data-set (see *Navigational Data Cross-reference & Ground Truth Coding*)for each location (Table 9). The Project with which each video data-set was associated, and dates, is shown in (Table 9). Video was recorded on SONY Hi8 and/or Panasonic SVHS video cassette recorders. Video data holdings are in the vicinity of 600 hrs.

3.2.3.2 Sediment / Benthic Fauna Sampling

Grab sediment and dredge fauna samples were collected on voyages #4 and #8–10 (Table 12). Each data-set has position reference information recorded (including Date/Time, Position, Depth). The grab sediment data-set has a semi-quantitative classification of fine through coarse sediments (including - mud, sandy mud, muddy sand, sand, coarse sand & rubble), the dredge fauna data-set has weight of fauna — all samples, from each location (Table 9), have been stored for later detailed analysis. Quantitative sediment (including grain size analysis) or detailed dredge species analysis, would not become available within the timeline of this project. The Project with which each grab and dredge data-set was associated, and dates, is shown in (Table 9). Data holdings are in the vicinity of 450 samples each for sediment and dredge.

3.2.3.3 Navigational Data Cross-reference & Ground Truth Coding

Positional tracking and habitat coding data was collected on all voyages except voyage#2 (Table 12). Each tracking data-set (except voyage #4) includes user-entered seabed habitat classification code (0–9 as described in Table 3) as well as ancillary data (including Date/Time, Boat Position, Speed & Water Depth) and can be cross-referenced to the video tape data with an precision of 2-5 m at 1–2 second intervals, for each location (Table 9). The Project with which each data-set was associated, and dates, is shown in (Table 9).

The tracking data was recorded using custom IBM PC based logging software. The total number of records is in the order of 5×10^6. The data is stored in Microsoft Access tables. The dataset attributes are shown in Table 13.

Table 13: Video code / navigation cross reference & habitat coding data file format, showing the fields in a navigation data file, their identifiers, the data format of fields & the information they contain.

Field Identifier	Data Format	Information
FILE_NAME	ASCII String	Table name for individual site tracking data
DATE	ASCII String	Date DDMMYY
TIME	ASCII String	Time HHMMSS
LONGITUDE	ASCII Number	Vessel Longitude in Decimal Degrees
LATITUDE	ASCII Number	Vessel Latitude in Decimal Degrees
BOAT_SPEED	ASCII Number	Vessel speed in Knots
DEPTH	ASCII Number	Water depth in Meters
HEADING	ASCII Number	Vessel gyro heading in degrees
BEARING	ASCII Number	U/W tracking bearing to target in degrees
SLANT_RANGE	ASCII Number	U/W tracking slant range to target in Meters
DEPRESSION_ANGLE	ASCII Number	U/W tracking angle to target in degrees
T_LONGITUDE	ASCII Number	Target Longitude in Decimal Degrees
T_LATITUDE	ASCII Number	Target Latitude in Decimal Degrees
HABITAT_CODE	ASCII Number	Habitat code from video observation

3.3 Analysis of Acoustic Seabed Data

In this section we present the results for the analysis of acoustic seabed data. This includes results for each of the various approaches, for analogue acoustics data (i.e. RoxAnn), and for digital acoustics data (i.e. EK500, BAS). Results for extracting features from each digital ping, and classification methods for analysing fully digital ping data are presented. The results for the comparison of the performance of these different classification methods are also presented.

3.3.1 Analogue Acoustics Data

3.3.1.1 Data Description

There was a significant correlation between the RoxAnn hardness index and depth (see 2.3.0.2 Effect of Depth) so a correction factor was applied to the hardness data. To do this areas of consistent mud seabed were selected to control for possible differences in the relationship between hardness and water depth for different substrates. An investigation of hardness against depth was made and a regression of the minimum hardness values and depth was used to adjust hardness for depth.

Figure 13 shows a map of the field test area with RoxAnn acoustic bottom roughness data. Figure 14 shows a map of the field test area with depth corrected RoxAnn acoustic bottom hardness data. The RoxAnn hardness and roughness data (Figure 13 & Figure 14) corresponded with the pattern observed with the video data with soft smooth bottom in the muddy depauperate area east of Warrior Reef to hard rough bottom in most of the reef passages. Also associated with the Passages was bottom that was hard but relatively smooth (e.g. the western approaches to Missionary Passage). This represents the hard pavement bottom found in some high current areas, as seen in ground truth video.

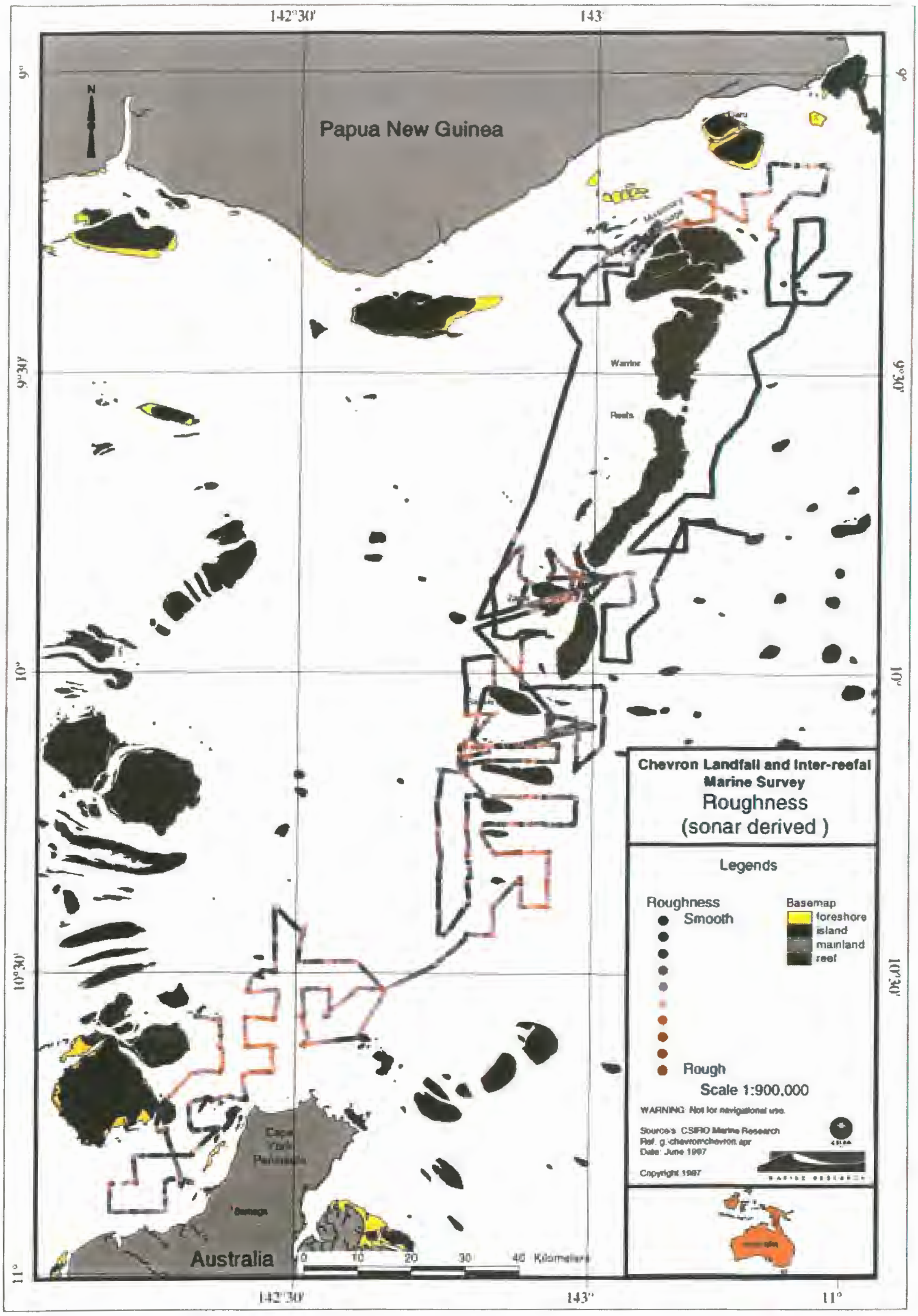


Figure 13: Map of acoustic roughness (Voyage 9 - See Table 9), showing raw analogue RoxAnn acoustic roughness data, with the roughness index shown from dark blue (for smooth habitats) through to dark red (for rough habitats).

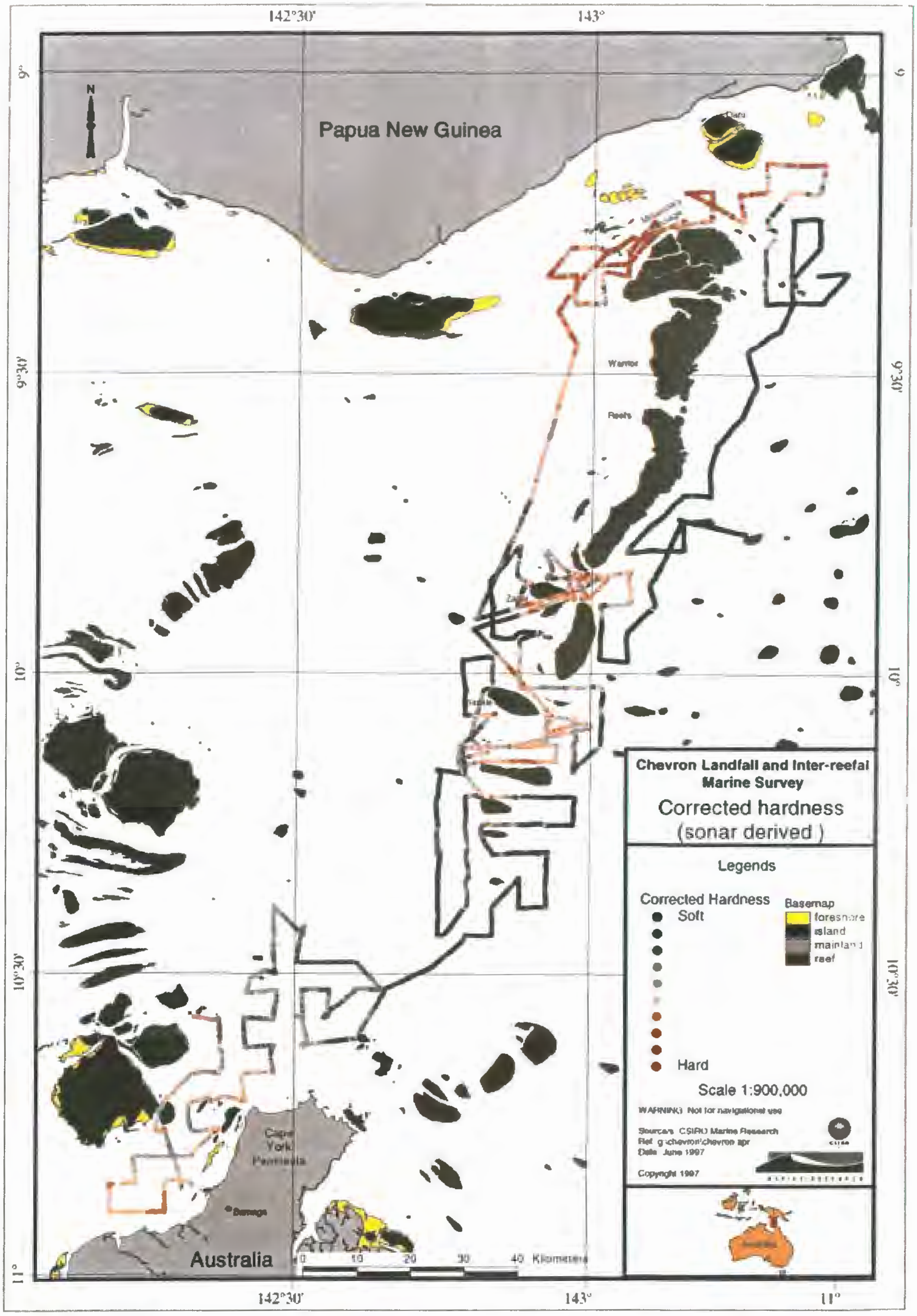


Figure 14: Map of acoustic hardness (Voyage 9 - See Table 9), showing raw analogue RoxAnn acoustic hardness data, with the hardness index shown from black (for soft habitats) through to dark red (for hard habitats).

3.3.1.2 Classification Regimes

The linear discriminant function analysis indicated that the RoxAnn was able to discriminate primarily among five substrate types. Consequently the habitat classes, developed from the ground truth video and grab data (see Table 5), were reduced to 5 substrate types representing mud, sand, rubble, rock/reef and a mixed epibenthos dominated substrate. The analysis was repeated with the five substrate types and the discriminant function was applied to the remaining unclassified RoxAnn hardness and roughness data to classify the substrate in areas where we had acoustic data only.

The results from the linear discriminant function analysis are presented in Figure 15. The figure shows classification space of roughness versus hardness, with the 5 habitat classes, Mud, Sand, Rubble, Rock and Epibenthos.

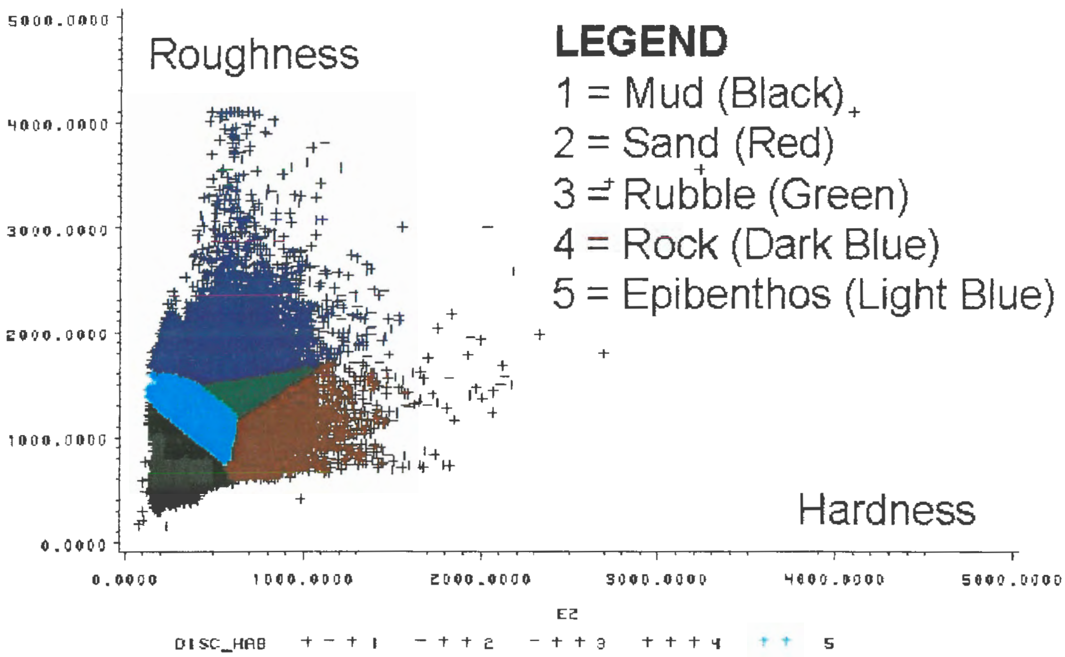


Figure 15: RoxAnn habitat classification : roughness / hardness space. This figure shows the results of the linear discriminant classification of analogue acoustic data, hardness against roughness for each acoustic sample, coloured according to habitat class. The ground truth information is used to form the 5 classes of habitat (Mud, Sand, Rubble, Rock and Epibenthos).

Table 14 shows the results of the linear discriminant function classification of the RoxAnn data, and the apparent error performance. The number of samples is shown for each of the classes, where the observed data is classified into predicted habitat classes.

Table 14: The results of linear discriminant classification of analogue RoxAnn data are shown, with the number of samples from each observed ground truth habitat class and the predicted habitat they are classified into. The apparent error rates for the classification are shown also, giving an indication of performance.

Classification Table		Observed					Apparent Error Rate
		Mud	Sand	Rubble	Rock	Epibenthos	
Predicted	Mud	689	261	13	2	36	0.264
	Sand	66	1194	70	23	33	0.428
	Rubble	42	229	148	20	14	0.591
	Rock	92	188	78	63	17	0.488
	Epibenthos	48	214	53	15	97	0.508
Total		937	2086	362	123	197	0.409

The linear discriminant function analysis of the RoxAnn acoustic data and the matching ground truth data from benthic video codes (see Table 3) indicated that there was a separation between substrates shown by the differences in roughness and hardness values. There was an overall apparent error rate of 40.9% (Table 14). Many of the miss-classified data were due to rubble and rock classified as sand, and rubble classified as rock and vice versa (Table 14). The mixed/epibenthos substrate class was not well described and represented a variable bottom type that included dense epibenthic cover overlaying various substrates from rock to rubble with sand or mud intervening.

Even so, the distribution of the five substrate types (Figure 16) closely matched the video bottom interpretations with mud bottom in the north east, sand in the southern open areas, and rocky and mixed epibenthic bottom in the reef Passages. The Missionary Passage in particular is shown to contain high amounts of hard substrate. The acoustic data gathered west of the Warrior reef complex shows much of this area classed as the mixed/epibenthos substrate type, indicating that some epibenthos probably occurs in this area.

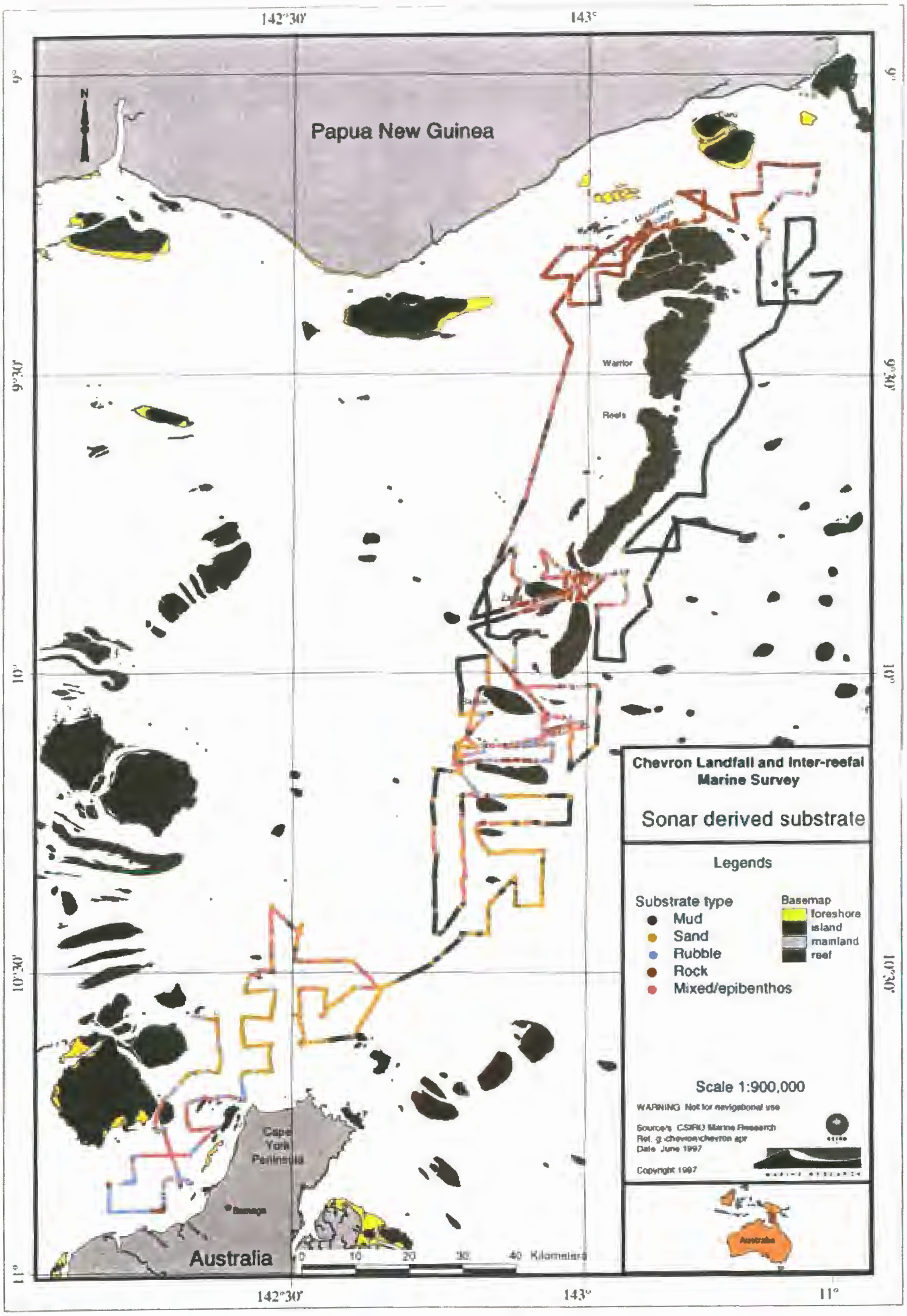


Figure 16: Map of seabed habitat (Voyage 9 - See Table 9), showing linear classified analogue RoxAnn acoustic data, for the 5 habitats described in Table 14 (Mud, Sand, Rubble, Rock & Epibenthos).

3.3.2 Digital Acoustics Data

3.3.2.1 Data Description

The video still ground truth data and associated acoustic data for the three frequencies are described in the figures (Figure 17 through Figure 23) that follow. Figure 17 & Figure 18 show still photographs for the Soft and Rougher habitat classes respectively (Habitat classes 1 & 3, see Table 5). It is clear from the photographs that the seabed habitats were distinctly different. The soft habitat (Figure 17) is characterised by silt, sand and rubble sediments, and shows little or no epi-benthic cover, while the rougher habitat (Figure 18) is characterised by course sediments, large coral boulders & significant epi-benthic cover.

Figure 17: Still photograph of soft habitat (Habitat class 1, see Table 5), ground truth data for the digital acoustic training data set. The soft habitat is characterised by silt, sand and rubble sediments, with little or no epi-benthic cover.

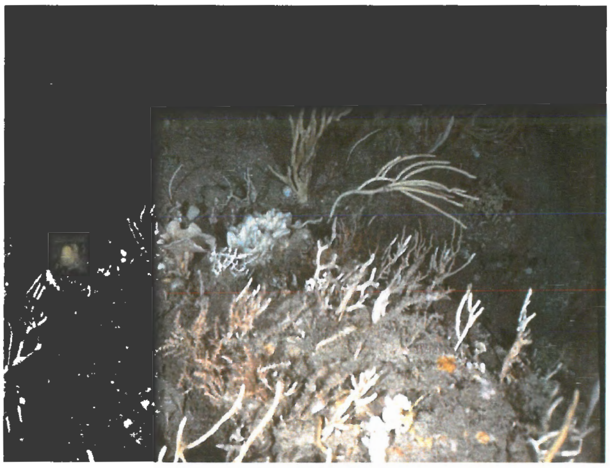


Figure 18: Still photograph of rougher habitat (Habitat class 3, see Table 5), ground truth data source for the digital acoustic training dataset. The rougher habitat is characterised by course sediments, large coral boulders & significant epi-benthic cover.

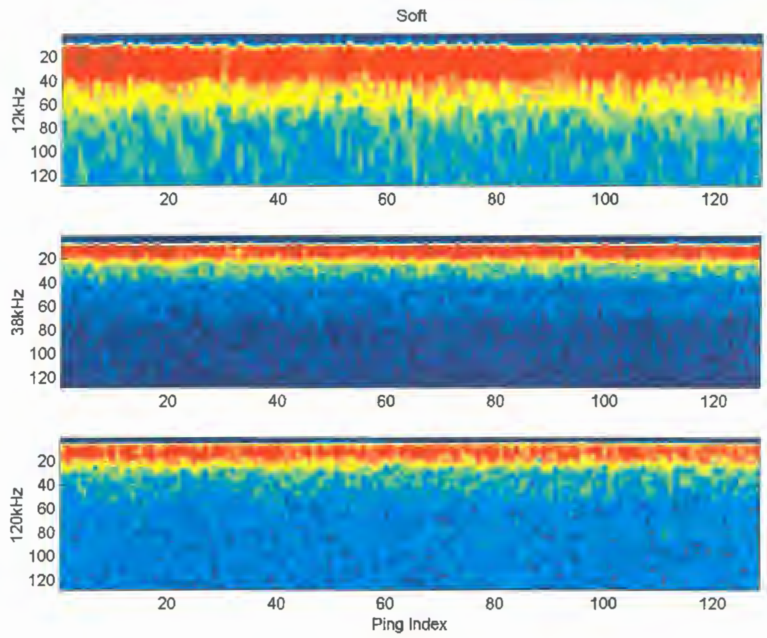


Figure 19: Echogram of soft habitat (see Figure 17), for each of 3 frequencies. The echogram presents the acoustic information for each ping (vertically down the page), coloured according to backscatter intensity (where blue corresponds to low intensity backscatter, through to red for high intensity).

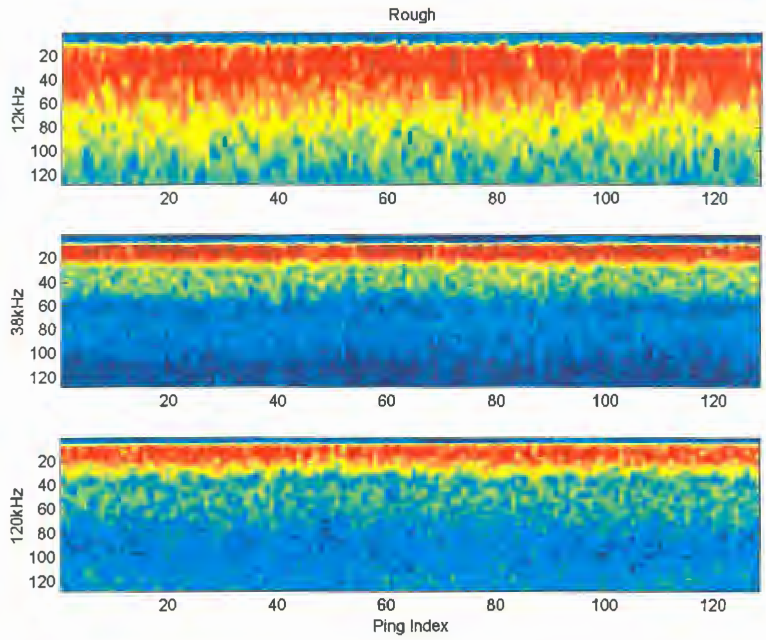


Figure 20: Echogram rougher habitat (see Figure 18), for each of three frequencies. The echogram presents the acoustic information for each ping (vertically down the page), coloured according to backscatter intensity (where blue corresponds to low intensity backscatter, through to red for high intensity).

The colour echograms for each of the 3 frequencies for both the soft and rougher habitat types are shown in Figure 19 & Figure 20 respectively. It is worth noting the increased strength in the signal after the seabed bottom pick (notably increased red/yellow component in the echogram) for the echograms for the rougher habitat. This demonstrates the sound pulse scattering as described in section 2.3.0.1 Echo Formation.

The following three figures (Figure 21 through Figure 23) show the mean ping signal for each of the three frequencies examined and clearly display differences between the signals returned from the three habitats examined in this analysis. The rough/hard habitat type had a ping signal with an increased peak echo strength, and both the rough habitats showed greater post bottom (signal peak) intensity than the soft habitat.

The mean ping signals also display characteristics of transducer beam pattern used for each frequency. The 38 kHz signal showed high levels of side lobe backscattered signal returns associated with its fine beam width of ~7°, the 120 kHz signal displayed some side lobe signal backscatter associated with its ~11° transducer beamwidth and the 12 kHz showed virtually no side lobe backscatter from its ~17° beamwidth transducer.

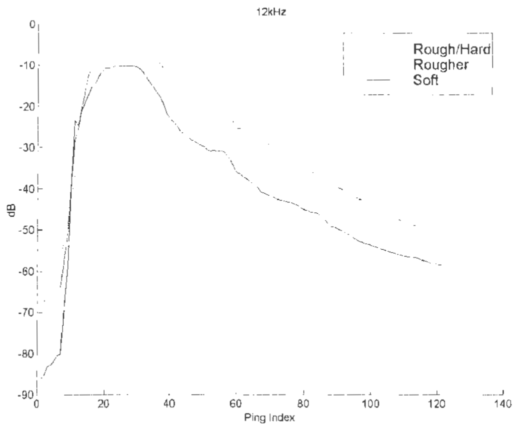


Figure 21: Mean shape of 12kHz bottom locked ping signal, standardised for each habitat (see Table 5).

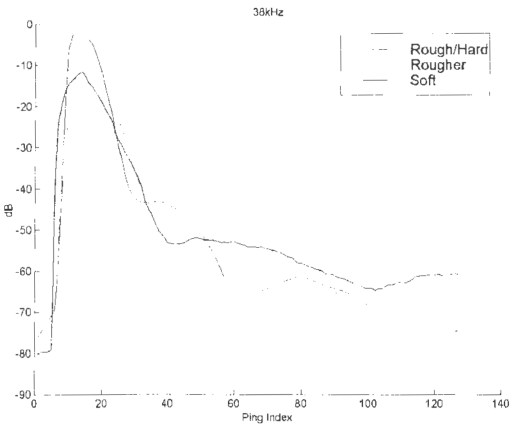


Figure 22: Mean shape of 38kHz bottom locked ping signal, standardised for each habitat (see Table 5).

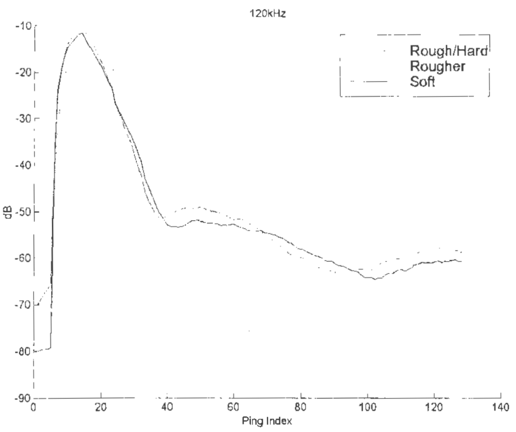


Figure 23: Mean shape of 120kHz bottom locked ping signal, standardised for each habitat (see Table 5).

3.3.2.2 Linear Discriminant Analysis

Extracted Ping Features

In this section, the performance of extracted features (as described in section 2.3.2.2 Extracted Ping Features) was calculated using a cross-validated miss-classification error rate (as described in section 2.3.2.5 Linear Discriminant Analysis) for a linear discriminant classifier. Here we calculated the Mahalanobis distance for the appropriate feature vectors on test subsets of the data relative to their complementary training subset means.

Table 15 shows the results of the linear discriminant function classification of the digital acoustic data, and the cross validated error performance, using all 58 extracted features (as described in section 2.3.2.2 Extracted Ping Features). The number of samples is shown for each of the three classes, where the observed data is classified into predicted habitat classes.

Table 15: Results of linear discriminant classification on All extracted features from digital acoustic data, for each of the 3 frequencies. The table shows the number of samples from each observed ground truth habitat class and the predicted habitat they are classified into. The cross validated error rates for the classification are shown also, giving an indication of performance.

Classification Table			Observed			Cross Validated Error Rate
			Soft	Rough & Hard	Rougher	
Predicted	12kHz	Soft	475	33	0	0.07
		Rough & Hard	17	390	90	0.24
		Rougher	20	89	422	0.18
	38kHz	Soft	512	0	19	0.00
		Rough & Hard	0	449	58	0.12
		Rougher	0	63	435	0.15
	120kHz	Soft	470	55	3	0.08
		Rough & Hard	41	346	96	0.32
		Rougher	1	111	413	0.19

The performance of individual features with respect to classifying the three habitats was represented graphically in Figure 24, where discriminant coefficients were plotted and features having the highest weight in discrimination between the habitats were identified by larger discriminant coefficient values, appearing as positive or negative peaks on the graph.

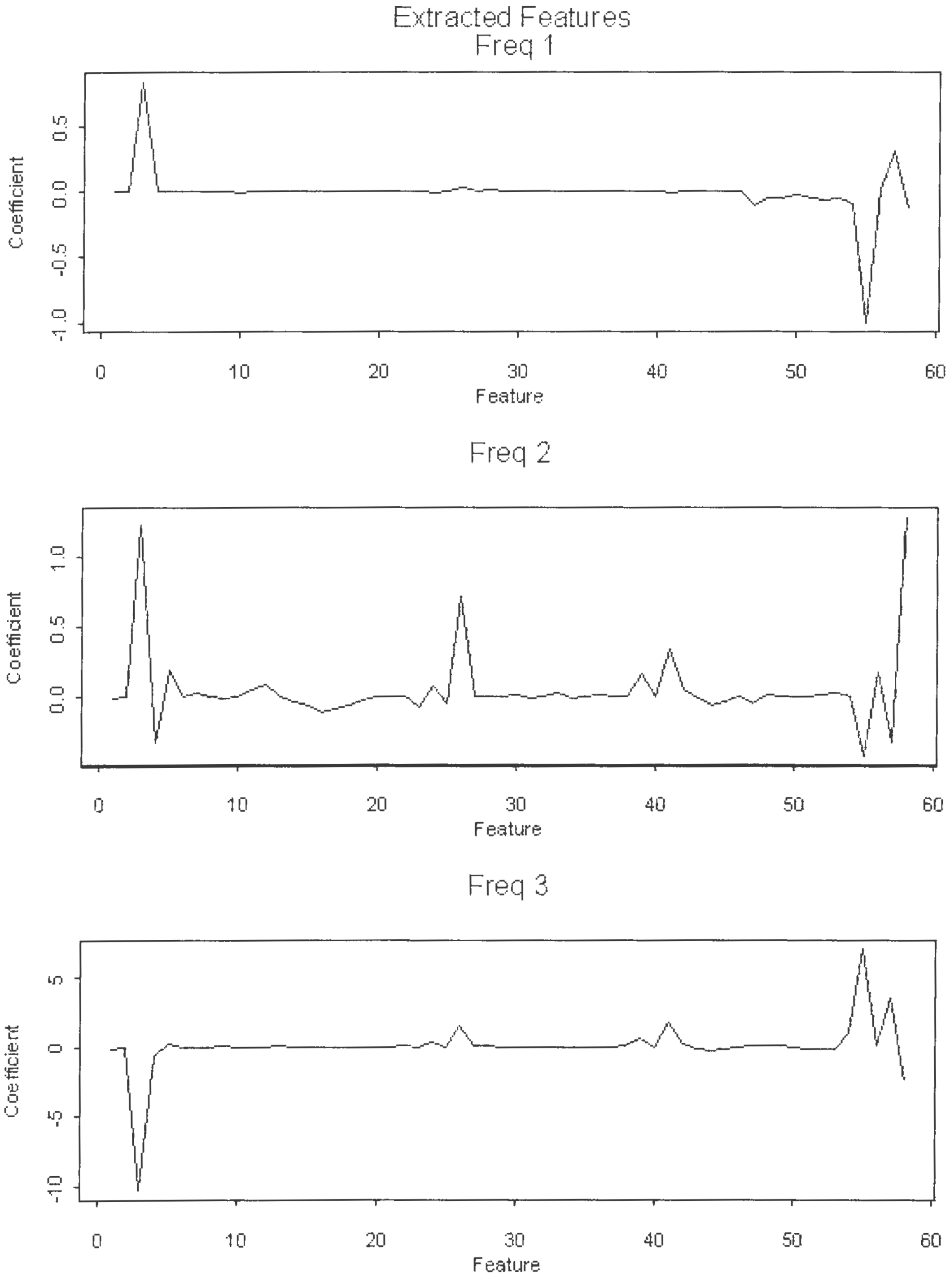


Figure 24: Discriminant coefficients for all extracted features (see 2.3.2.2 Extracted Ping Features), for each of 3 frequencies, showing the features having the highest weight in discrimination between the habitats (increased classification weight is represented by larger discriminant coefficient values). Feature numbers shown on the X-axis are described in 2.3.2.2 Extracted Ping Features.

The performance of logical groups (Statistics, Shape, Pulse Parameters, Linear Prediction Coefficients and Echo Integration) of extracted features (as described in section 2.3.2.2 Extracted Ping Features) was also calculated (Table 16). This showed that the Echo Integration and Shape groups of features performed consistently well across all three frequencies. The 38 kHz frequency provided better discrimination than the 12 kHz and 120 kHz frequencies. The Peak & Tail group of features performed poorly in each case.

Table 16: Cross validated miss-classification rates for the linear classification method applied to extracted features from digital acoustic data, for each of the 3 frequencies. The groups of extracted features are described in 2.3.2.2 Extracted Ping Features, with extra feature groups Peak & Tail (Features 56 & 57) simulating acoustic hardness & roughness, All Extracted describing the use of the full suite 58 extracted features and PCA(10) using the 10 most significant principle components of all extracted features.

Data	12kHz	38kHz	120kHz
Peak & Tail	0.2728	0.2253	0.4902
Statistics	0.2201	0.1361	0.3802
Shape	0.1862	0.1549	0.2572
Pulse Parameters	0.2337	0.2233	0.2650
LPC's	0.1784	0.2109	0.2331
Echo Integration	0.1810	0.1361	0.2363
All Extracted	0.1621	0.0911	0.1999
PCA(10)	0.1992	0.1087	0.2259

To graphically illustrate the separation of the three habitats, we plotted principle component analysis scores on the best two linear combinations of all extracted features on the X and Y axes . On such a plot, the score for a ping on the first linear combination is the value on the X-axis and the score for the same ping on the second linear combination is the value on the Y-axis (see Figure 25 through Figure 27). These plots showed that the soft habitat separates most clearly, where the rough/hard and rougher habitats tend to overlap. Also the 38 kHz frequency seems to separate the physically different habitats the best. These graphical results are consistent with the quantitative error rates shown in Table 15.

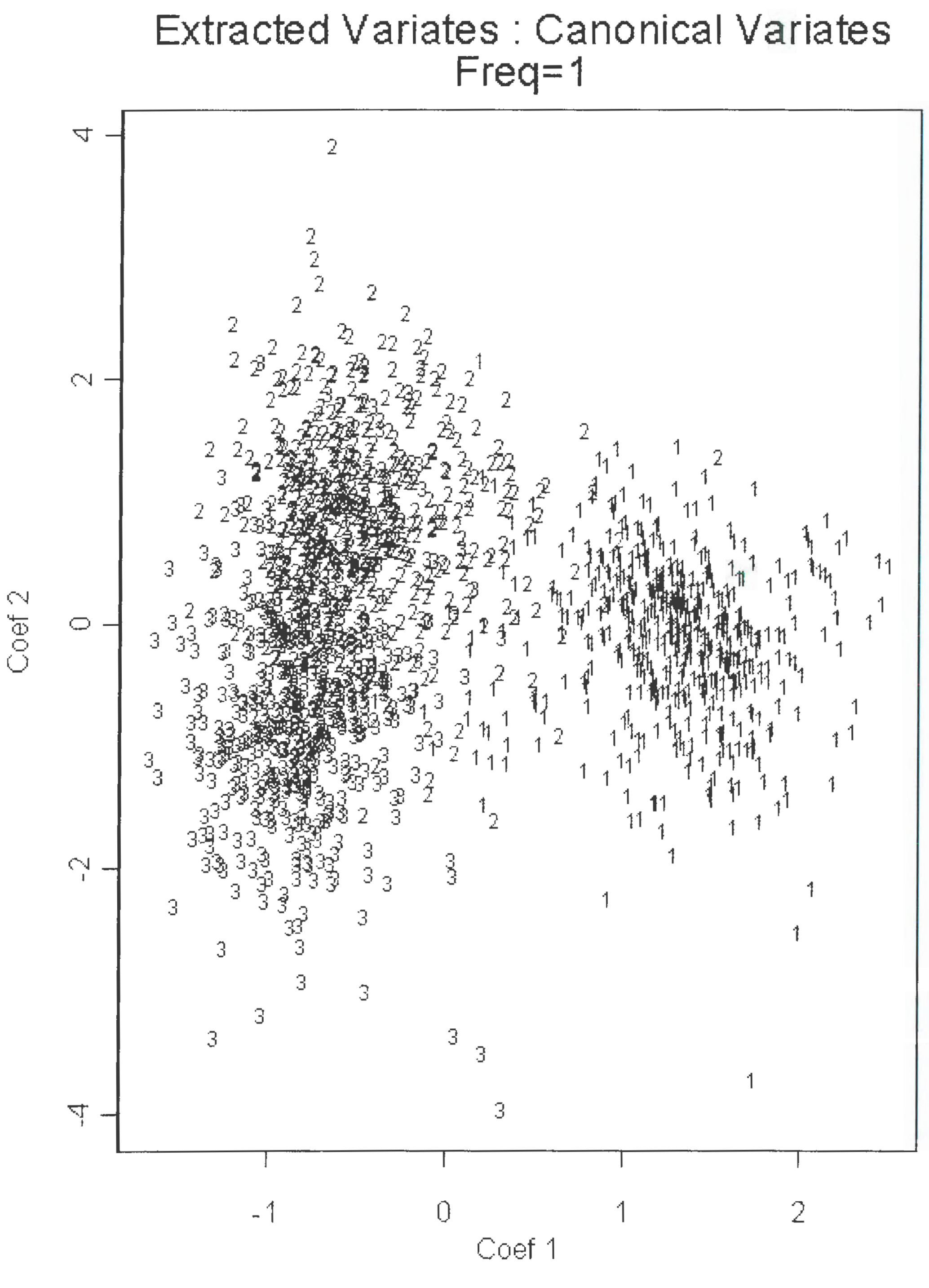


Figure 25: Canonical variate scores for all extracted features for 12kHz. Graphically illustrates the separation of the three habitats (designated 1, 2, & 3 on the graph), plotted against the best two linear combinations of the extracted features.

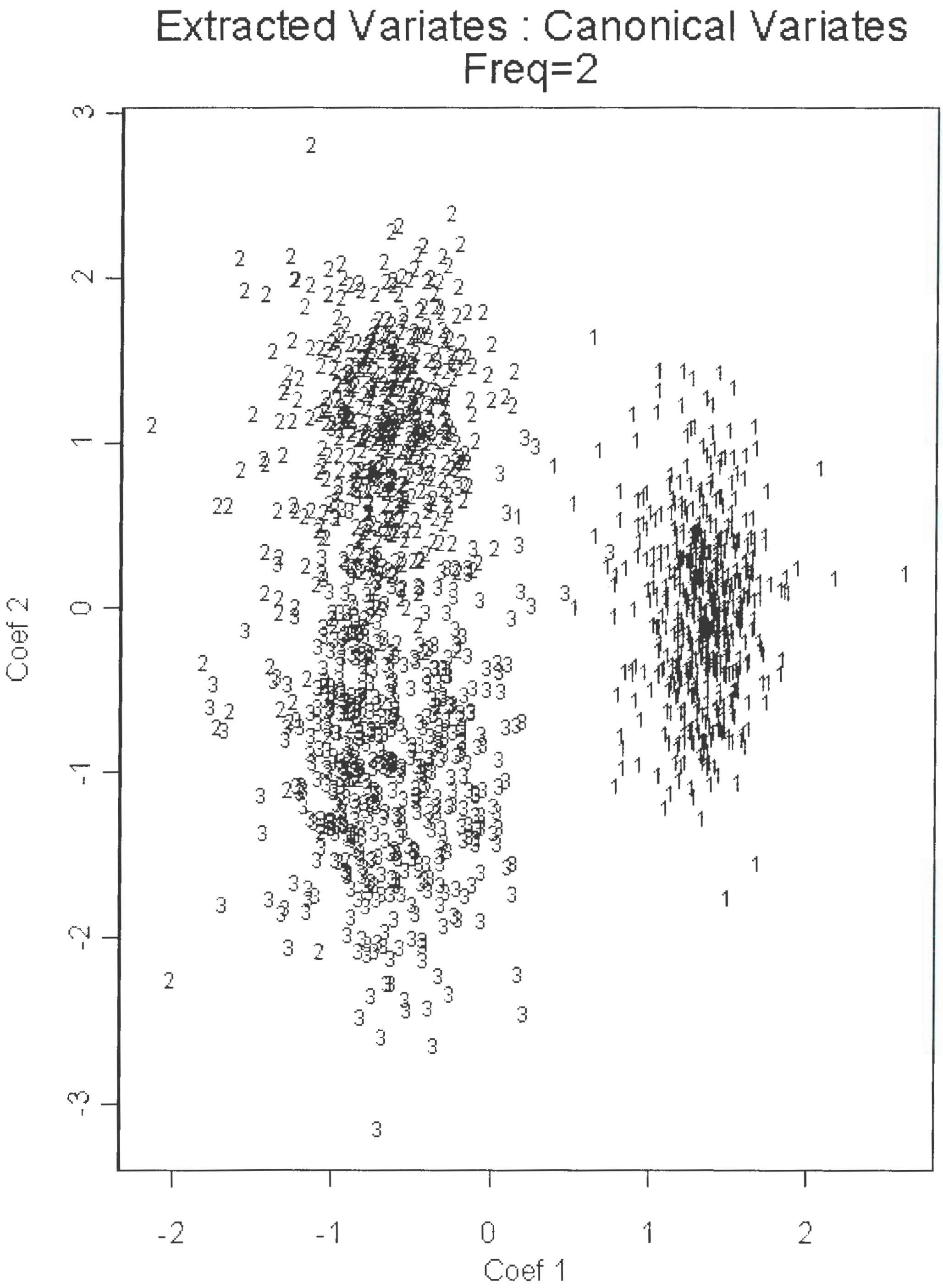


Figure 26: Canonical variate scores for all extracted features for 38kHz. Graphically illustrates the separation of the three habitats (designated 1, 2, & 3 on the graph), plotted against the best two linear combinations of the extracted features.

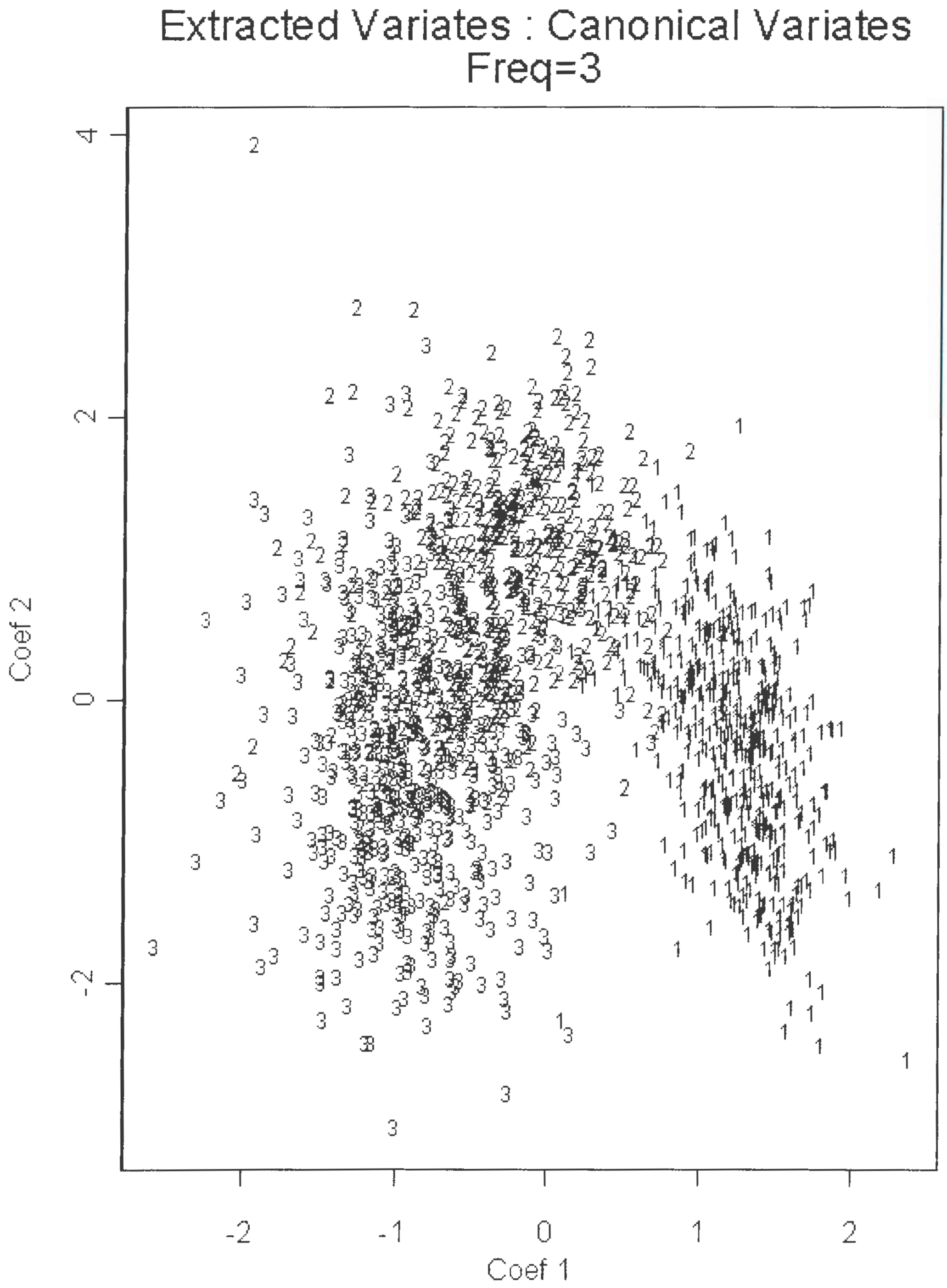


Figure 27: Canonical variate scores for all extracted features for 120kHz. Graphically illustrates the separation of the three habitats (designated 1, 2, & 3 on the graph), plotted against the best two linear combinations of the extracted features.

Full Raw Ping

The full raw ping linear discriminant technique is equivalent to the smooth ping analysis with a smoothing parameter of zero (i.e. no smoothing penalty). The cross-validated miss-classification performance results for the linear discriminant analysis using the full raw ping are given in Table 18 and apparent miss-classification rates are shown in Table 17. It can be seen from the apparent and cross-validated results that the apparent error rate underestimates the actual error value for the linear discriminant classifier. These results showed that the 38 kHz frequency had the lowest error rate compared with the 12 kHz and 120 kHz frequencies.

3.3.2.3 Smooth Ping Analysis

Table 18 shows the classification performance for the smooth ping analysis, for the three frequencies and three values of the smoothing parameter ($\lambda = 0, 0.5, 0.9$). The performance is shown as the cross-validated miss-classification rates, with Table 17 showing performance with the apparent error rate. These results again showed that the 38 kHz frequency had the lowest error rate for all values of smoothing parameter, where as the 12 kHz frequency performed poorly.

Table 17: Apparent miss-classification rates for the smooth classification method using raw digital acoustic data for each of the 3 frequencies and 3 levels of smoothing parameter λ.

Data	12kHz	38kHz	120kHz
Full Smooth(0.0)	0.1745	0.0775	0.1497
Full Smooth(0.5)	0.1595	0.0827	0.1556
Full Smooth(0.9)	0.1530	0.0898	0.1595

Table 18: Cross-validated miss-classification rates for the smooth classification method using raw digital acoustic data for each of the 3 frequencies and 3 levels of smoothing parameter λ.

Data	12kHz	38kHz	120kHz
Full Smooth(0.0)	0.1862	0.1016	0.1660
Full Smooth(0.5)	0.1751	0.0898	0.1647
Full Smooth(0.9)	0.1771	0.0977	0.1686

Table 19 shows the classification table for the smooth ping analysis, for a smoothing parameter λ=0.5, which provided the best classification performance. The number of samples is shown for each of the classes, where the observed data is classified into predicted habitat classes. The cross-validated error rates are shown for each of the three habitat classes.

Table 19: Results for the smooth classification method (smoothing parameter λ=0.5) using raw digital acoustic data, for each of the 3 frequencies. The table shows the number of samples from each observed ground truth habitat class and the predicted habitat they are classified into. The cross validated error rates for the classification are shown also, giving an indication of performance.

Classification Table			Observed			Cross Validated Error Rate
			Soft	Rough & Hard	Rougher	
Predicted	12kHz	Soft	480	30	1	0.06
		Rough & Hard	20	388	112	0.24
		Rougher	12	94	399	0.22
	38kHz	Soft	511	9	5	0.00
		Rough & Hard	1	448	68	0.13
		Rougher	0	55	439	0.14
	120kHz	Soft	495	61	5	0.03
		Rough & Hard	15	353	72	0.31
		Rougher	2	98	435	0.15

Plots of the discriminant coefficients for the smooth ping analysis, for various values of the smoothing parameter are shown in Figure 28 through Figure 30. The plots become progressively smoother as the smoothing penalty parameter λ was increased from 0 to 0.9.

The apparent error rate when using the full smooth curve approach with λ at either 0.5 or 0.9 was higher for two of the three frequencies, than when the covariance matrix was not augmented with the penalty matrix (i.e. λ=0). Also, the apparent error was consistently less than the cross-validated error rate for the three frequencies and three values of λ (0, 0.5, and 0.9). However, the more realistic cross-validated error appeared to have consistently lower values when λ=0.5, than when using a linear discriminant technique (i.e. λ=0). Also of interest is the fact that the 38 kHz frequency performed better with respect to cross-validated errors than 12 kHz & 120 kHz. This may be due, more to the characteristics of the transducer beam pattern than the frequency itself (see 3.3.2.1 Data Description), and could be investigated in further work, using different transducer configurations.

The full smooth curve approach with λ=0.5 and 38 kHz gave the smallest cross-validated misclassification error rate when compared with the other feature extraction techniques, for 38 kHz and 120 kHz. From the plots of coefficients for the full smooth curve approach with λ=0.5, 38 kHz appears to suggest that the first ten sample points and possibly the last five of a ping are the most important for discriminating between the habitats, as these coefficients have the largest magnitude. These first ten samples correspond to the leading edge of the bottom return. The last five points seem to represent the gain in discriminating ability for 38 kHz when compared to the other frequencies 12 kHz & 120 kHz, as the these frequencies do not have importance placed on those points. The statistical significance of the magnitude of these extra points could be tested with further computing via jackknife techniques (Efron, 1982).

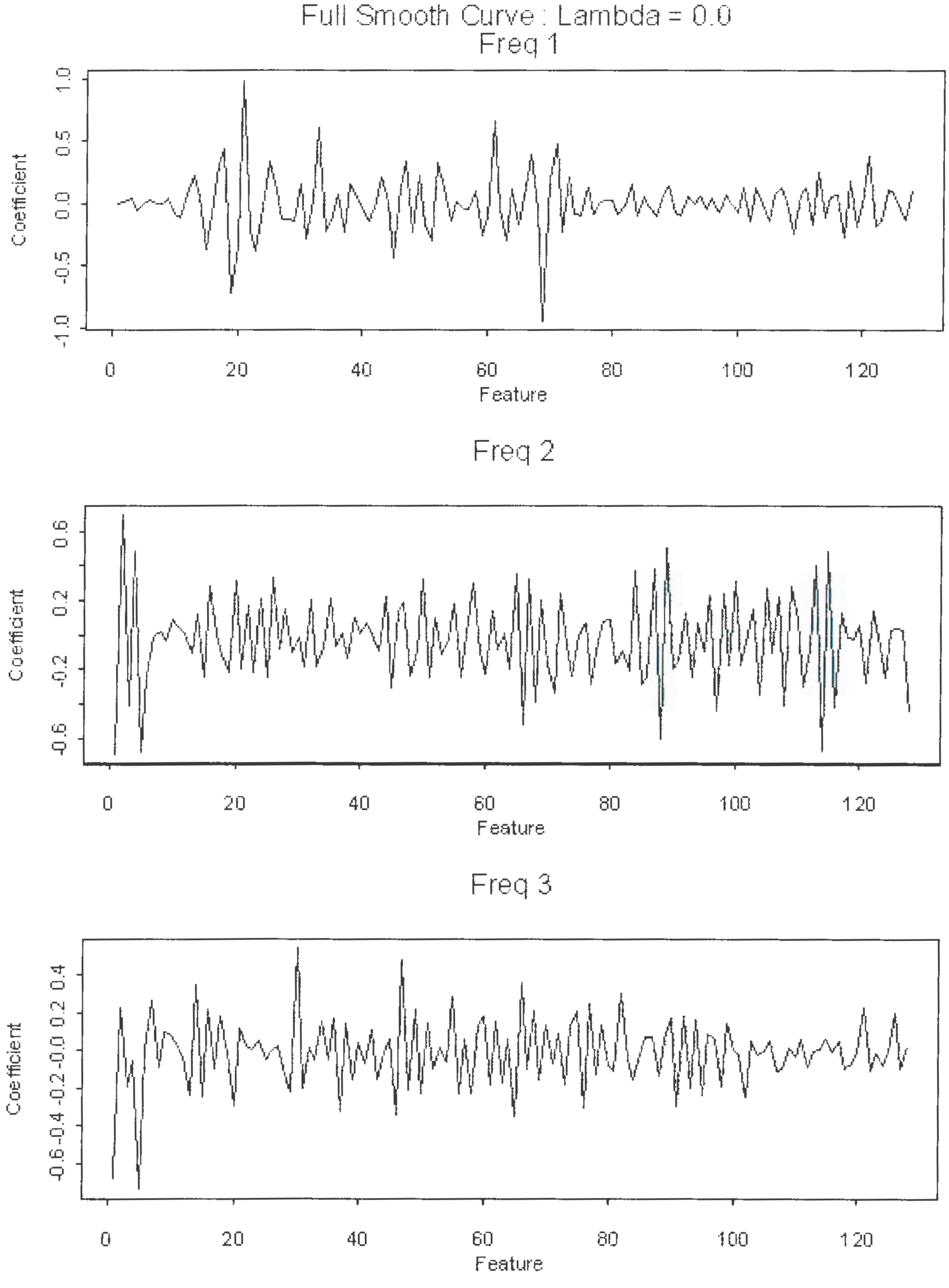


Figure 28: Discriminant coefficients for smooth ping classification analysis (with smoothing coefficient λ=0, equivalent to linear classification), for each of 3 frequencies. Features here refer to samples in the sequence of raw digital data, see section 2.3.2.3 Full Raw Ping. Larger discriminant coefficient values show the raw data elements which have the highest weight in discrimination between the habitats.

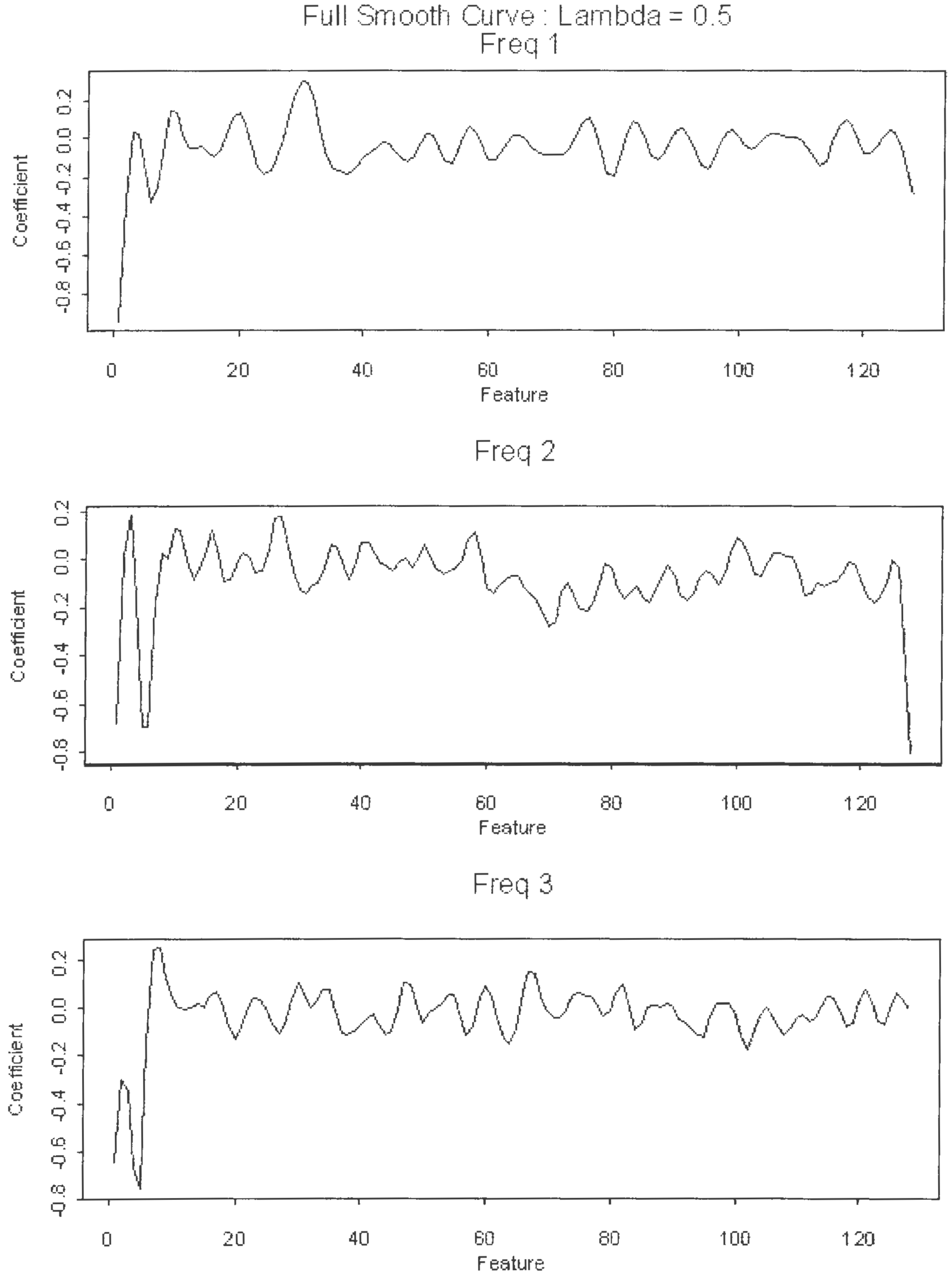


Figure 29: Discriminant coefficients for smooth ping classification analysis (with smoothing coefficient λ=0.5), for each of 3 frequencies. Features here refer to samples in the sequence of raw digital data, see section 2.3.2.3 Full Raw Ping. Larger discriminant coefficient values show the raw data elements which have the highest weight in discrimination between the habitats.

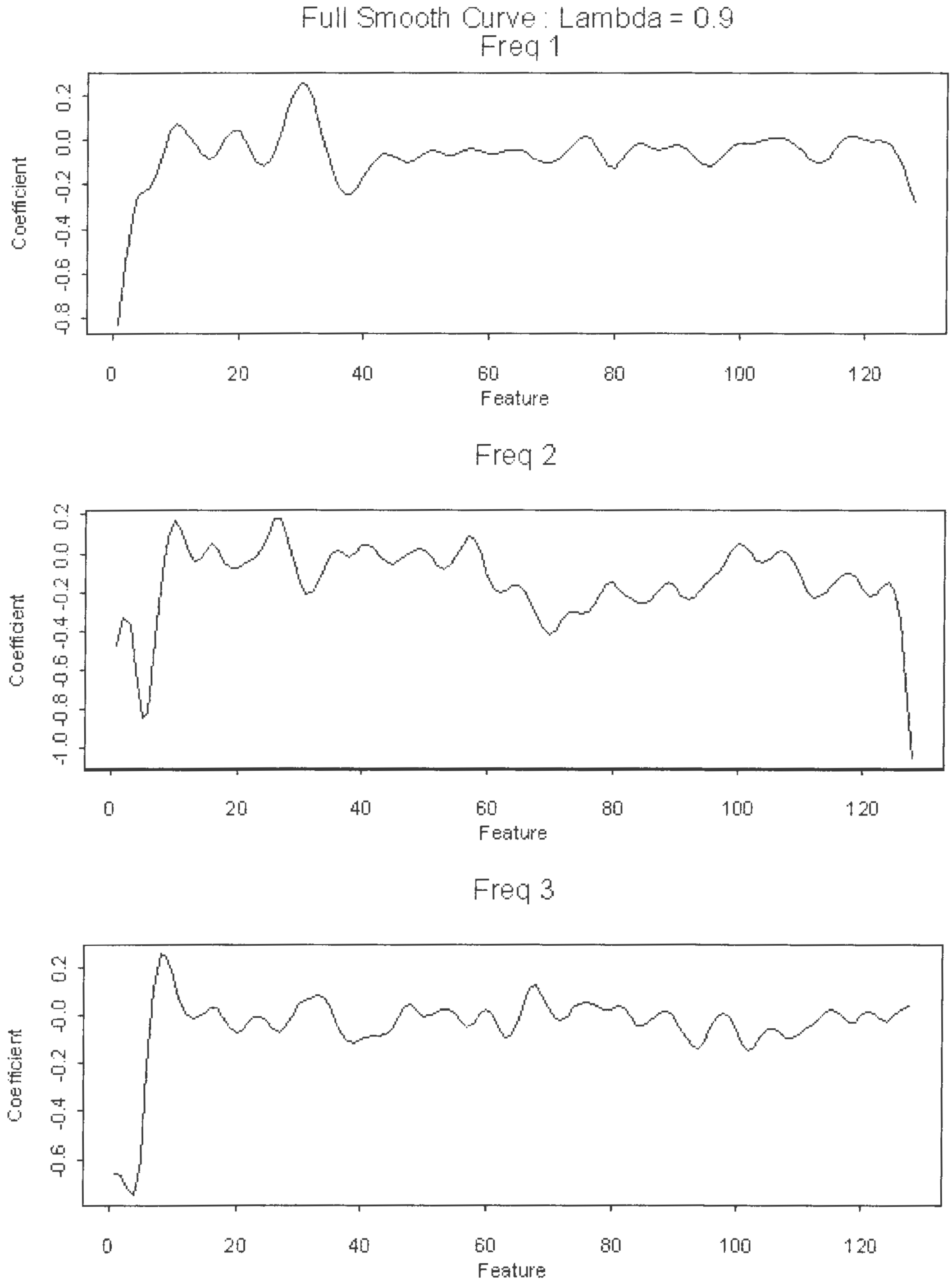


Figure 30: Discriminant coefficients for smooth ping classification analysis (with smoothing coefficient λ=0.9), for each of 3 frequencies. Features here refer to samples in the sequence of raw digital data, see section 2.3.2.3 Full Raw Ping. Larger discriminant coefficient values show the raw data elements which have the highest weight in discrimination between the habitats.

Further work on use of the full smooth curve technique could involve investigating how robust it is to a more extensive range of habitats, and how it performs with data collected from different depths. Whether depth effects could be incorporated into a model for the augmenting of the covariance matrix would of also be of substantial interest if it could improve the performance of the technique that could otherwise only be rationalised from ad hoc design approaches.

3.3.3 Comparison of Classification Techniques

3.3.3.1 Comparing Analogue and Digital Acoustic Data

Where the data provided by RoxAnn (and QTC View) is processed by the instrument, the digital raw data methods (see Table 4) provide the full acoustic signal that may then be processed. The advantages of digital methods are numerous, especially since the actual acoustic data is preserved and may be checked for errors. Processing of these acoustic signals is currently a progressing field of research and techniques are changing quite rapidly. The digital acoustic method provides a means by which, as new and more powerful analysis techniques are developed, they may be implemented on archived digital acoustic data. This means that old surveys can be re-processed so that more recent surveys and maps can be comparable. Digital acoustic methods apply minimal processing reduction of the actual acoustic data and therefore have the most scope for developing successful processing and classification techniques because information reduction is also minimised.

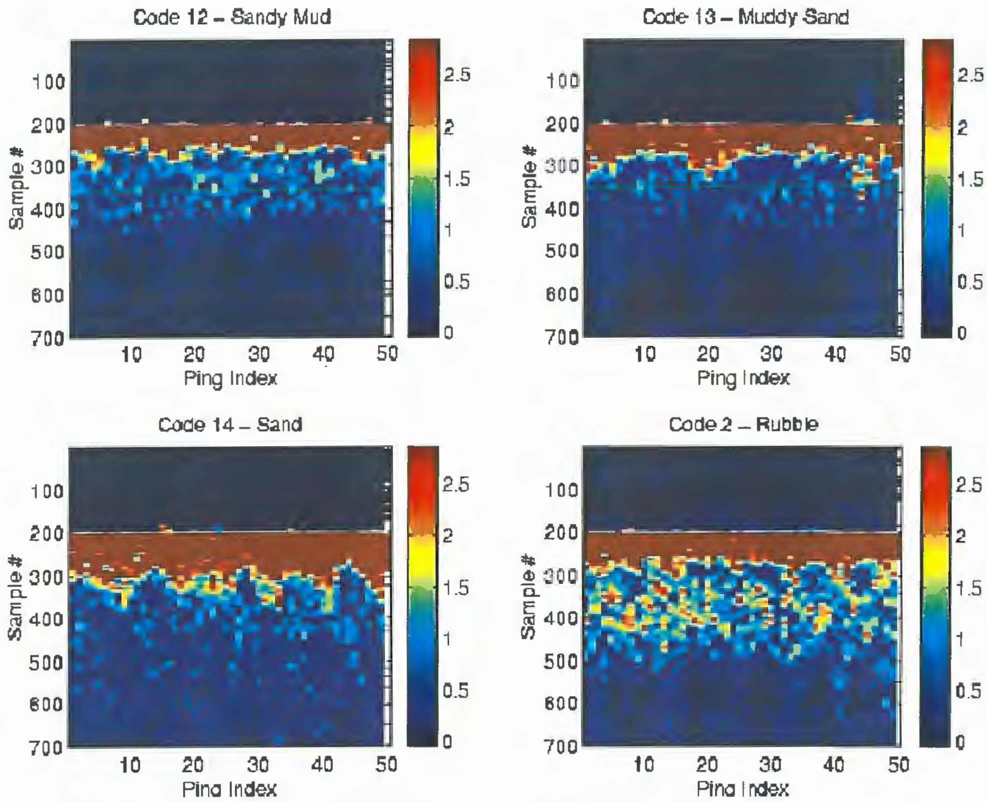


Figure 31: Benthic acoustic echograms from digital acoustic BAS data for 4 seabed types, described using the video ground truth coding scheme & sediment grab information (Sandy Mud, Muddy Sand, Sand & Rubble).

Figure 31 shows example BAS digital acoustic echogram data for 4 habitat classes described in section 2.2 Field Testing & Ground Truth. We can see that there is a clear difference in the echograms for each of these habitat classes, with the rubble habitat exhibiting many of the characteristics of the rough habitat described in Table 5, with the mud habitat closely resembling the soft habitat. Figure 32 shows the peak and tail features (see 2.3.2.2 Extracted Ping Features) calculated from BAS digital acoustic data which simulate the measures derived from the analogue acoustic processor RoxAnn (but using 1st echo data only). The digital processing techniques as described in 2.3.2 Digital Acoustics Data for EK500 data, may be implemented with BAS data.

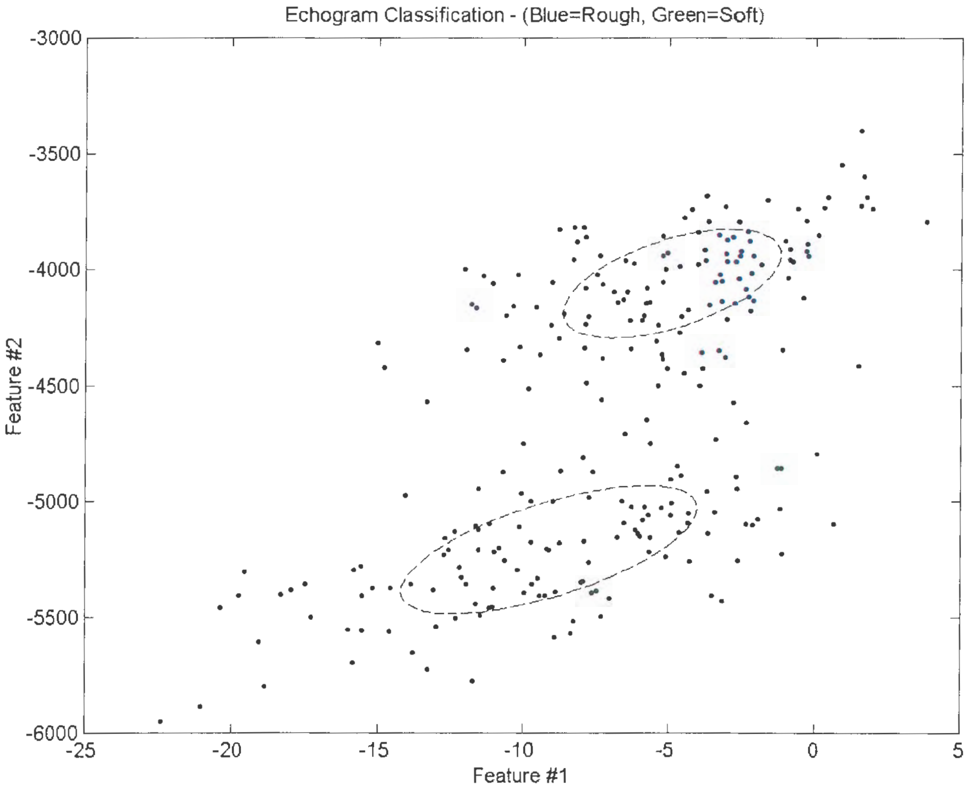


Figure 32: Echogram classification using the features, peak (Feature #1) & tail (Feature #2) as described in 2.3.2.2 Extracted Ping Features. These integration features simulate roughness & hardness, for digital acoustic BAS data from two habitat classes - rough (rubble) & soft (mud). The figure shows classification ellipsoids as dotted lines (1 standard deviation) about class means.

Table 16 shows the cross-validated error performance for digital acoustic data using all 58 extracted features (described in 2.3.2.2 Extracted Ping Features), as well as for the Peak and Tail echo integration features which simulate RoxAnn (but using 1st echo data only). The classification performance is greatly improved for all frequencies, when using all extracted features, rather than two simple echo integration features. It should be noted, that while the Peak extracted feature will simulate the RoxAnn hardness index, it is not equivalent as the RoxAnn value uses 2nd echo measures, while digital acoustic data uses 1st echo data.

3.3.3.2 Comparing Extracted Features

From Table 16, we see that the use of all extracted features gives the smallest misclassification error rate. Echo integration is the next best subset grouping of extracted features when comparing error rates, and this is consistent across the three frequencies. It should also be noted that when only two indices such as peak and tail features (which simulate RoxAnn) are used the classification performance is significantly degraded in comparison to other groups of features.

We see from Table 15, that frequency 38 kHz performs best in terms of habitat classification, also, that the soft habitat is most easily separated from the rough/hard and rougher habitats.

Table 20 shows the five extracted features for each of the three frequencies which provide the most power to the discrimination between the habitat classes. These are the features that have the highest weight on the discriminant function coefficient plots for the three frequencies shown in Figure 24. While some groups of features perform better than others for all frequencies, there are individual features in these groups (as described in 2.3.2.2 Extracted Ping Features) which perform well. We can see from Table 20 that at least one feature from all of the logical groups of extracted features are represented in the 5 most significant contributors to the habitat discrimination, for at least one of the frequencies investigated.

Table 20: Table of extracted features performance, showing the top 5 extracted features contributing the most discrimination power to the habitat classification for each of 3 frequencies (refer to section 2.3.2.2 Extracted Ping Features).

12kHz	38kHz	120kHz
55) Echo Integration - Below Bottom	58) Echo Integration - Peak to Tail Ratio	3) Statistics - Mean
3) Statistics - Mean	3) Statistics - Mean	55) Echo Integration - Below Bottom
57) Echo Integration - Tail	26) Statistics - M.A.D.	57) Echo Integration - Tail
58) Echo Integration - Peak to Tail Ratio	55) Echo Integration - Below Bottom	58) Echo Integration - Peak to Tail Ratio
46) Linear Prediction Coeff - LPC 1	41) Pulse Parameters - Decay	41) Pulse Parameters - Decay

The complex ping feature of linear prediction coefficients provide significant discriminant power to the habitat classification (see Table 20 for 120 kHz). The simple statistical feature of mean (feature number 3 as described in 2.3.2.2 Extracted Ping Features) also provides significant discriminant powers, as seen in Table 20, as well as the bellow bottom echo integration feature and peak to tail echo integration ratio (features number 55 & 58 as described in 2.3.2.2 Extracted Ping Features).

3.3.3.3 Comparing Raw and Smoothed Data

There is an observed benefit in augmenting the covariance matrix with a smoothing penalty matrix when performing the discriminant analysis for the smooth ping approach as shown by the reduction in misclassification error rates for λ=0.5 and λ=0.9. This is consistent over the three frequencies. There is typically an optimal value of λ, for each frequency, lying between 0 and 0.9 that would minimise misclassification error rate. These values of λ can be estimated with a search technique and some further computing. There is no analytic formula for computing the optimal choice of λ, but we have based our calculations on choosing a nominated set of values and comparing the corresponding cross-validated error rates. This criterion could be refined to incorporate different weightings for specific habitat miss-classifications. Once the classification has been optimised, implementation of the technique would require minimal electronic hardware and computer power and would perform on-the-fly discrimination rapidly because it uses raw data directly and there is no need for data pre-processing.

3.3.3.4 Comparing Extracted Features and Smoothed Data

The smooth ping analysis gives the lowest misclassification error rates of all the techniques examined, as can be seen from the separate error tables for the two techniques (Table 16 & Table 18). Further, there is less computing required for implementation of the smooth ping technique in classifying habitats compared to using extracted features. As the use of means and covariance matricies is required by both in computing the Mahalanobis distance, the extracted feature approach requires a preliminary pre-processing step for before a ping before it can be classified.

4 BENEFITS

The results from this project are in several forms, including: hardware prototypes of the receiver/acquisition system; plans of the electronic components; associated acquisition/data management software; maps of seabed habitat produced in collaboration with other projects; and reports and presentations to scientific conferences and workshops.

At the start of this project, techniques for automated remote sensing of the seabed were extremely limited. The available, conventional (above water) remote sensing techniques (e.g. satellite image analysis) are still limited to shallow clear water at best, but even in these optimum conditions it usually has not been possible to separate changes in seabed-habitat from changes in depth. This project has made significant advances in the development of technology for remotely sensing seabed habitat and has provided benefits in the form of an advance prototype acoustic receiver and acquisition software, high resolution ground-truth methods and sensitive new techniques for classification of seabed acoustic signatures. The acoustic data are recorded continuously, at vessel survey speed, and are stored in a form suitable for high-speed digital analysis and production of maps.

Acoustics has been demonstrated to provide a very high resolution proxy for seabed habitat type. The accuracy and repeatability of this system is ensured by recording the whole of water column and seabed echoes and removing noise biases prior to analysis. Current commercial benthic acoustic systems can not perform this function and are unable to provide data quality control. Our approach has been to ensure repeatability of measurement, which is a fundamental requirement for long term monitoring and mapping applications. Digital data from prior surveys can be reprocessed with data from new and additional surveys as they are conducted and as classification techniques improve.

Benefits have already arisen from this project as a result of collaboration with other projects. For example, the environmental effects of trawling in the Great Barrier Reef (FRDC 93/096), mapping trawl grounds in the Northern Prawn Fishery (FRDC 95/014 & 96/257), mapping fishery habitat in Torres Strait and in the South East Fishery (FRDC T93/237 & 94/040). Some acoustic maps of large areas of seabed, particularly in Torres Strait and more recently in the Timor MOU Box, have been produced as a result of collaboration with this project.

The beneficiaries will be management, research and fishing agencies concerned with managing multiple uses of the seabed environment. The benefits will be realised in the form of seabed habitat maps, which will assist with spatial methods of management. Some examples may include spatial management of the potential impacts of fishing or the potential impacts of other activities or events on the productivity of fisheries (e.g. sedimentation of nursery habitats from dredging, agricultural run-off, or mine tailings). Benefits will also flow to other agencies such as GBRMPA and state environment departments that have interests in mapping the distribution of representative seabed habitat types for conservation purposes. Industry will be made aware of the results through publications in appropriate media and through CSIROs membership on scientific and management advisory committees.

The prototype system developed by this project has the potential to be commercialised and be more widely available as an instrument for research and the fishing industry. Because the system can use a conventional echo-sounder for sending and receiving acoustic signals, it could be useable on any suitable vessel equipped with a suitable echo sounder and power supply suitable for a computer. If commercialised, such a system would have potential as a cost-effective search instrument for use on commercial fishing vessels for identifying seabed habitat supporting the most productive stocks thus improving the efficiency and reducing the costs of fishing.

Project results have been presented at a number of forums, and a list of conference and workshop papers relating to this project, is given below –

Gordon, S.R. (1998) Experience Using Acoustic Seabed Classification Systems with Associated Ground Truth Data. *Presented at Managing Seabed Data from Acoustic Classification Devices Workshop, Sydney, Australia 1998*

Gordon, S.R., Kloser, R., Pitcher, C.R. (1997) A Digital Acoustic System for Benthic Habitat Mapping. *Presented at International Conference on Marine Benthic Habitats and their Living Resources: Monitoring, Management and Application to Pacific Island Countries, Noumea, New Caledonia 1997*

Kloser, R., Gordon, S., Ryan, T., Sakov, P., Waring, J. (1997) Development of Normal Incidence Multi-Frequency Acoustics Methods for Seabed Habitat Mapping on the Continental Shelf (Poster). *Presented at International Conference on Marine Benthic Habitats and their Living Resources: Monitoring, Management and Application to Pacific Island Countries, Noumea, New Caledonia 1997*

Pitcher, C.R., Skewes, T.D., Smith, G.P., Gordon, S.R., Long, B.G., Taranto, T. (1997) Methods for Rapid Characterisation, Quantification and Mapping of Shelf Seabed Habitats. *Presented at International Conference on Marine Benthic Habitats and their Living Resources: Monitoring, Management and Application to Pacific Island Countries, Noumea, New Caledonia 1997*

Gordon, S.R. (1994) A Digital Hydro-Acoustic Instrument for Benthic Remote Sensing. *Presented at Joint Scientific Conference on "Science, Management and Sustainability of Marine Habitats in the 21st Century", Townsville, Australia 1994*

5 FURTHER DEVELOPMENTS

As expected, the functional system now has scope for further development. The receiver hardware would benefit from improved signal/noise performance and EMI shielding. The implementation of the mathematical discriminatory functions for real time processing would produce on-the-fly classification of seabed type. Nevertheless, we consider that post-analysis of quality-checked fully digital acoustic data will provide the highest quality seabed classification. The optimisation of the critical smoothing parameter λ in the new penalised classification method is not straightforward and further development is required. Biases due to changing depth can be addressed with fully digital acoustic data — these biases continue to be an issue with off-the-shelf systems and further development is also required. Multi-frequency approaches also appear to demonstrate great promise. Collaboration with another FRDC project (T93/237, Kloser *et al.* 1998), which developed software called "ECHO" to manage and analyse multi-frequency acoustic data, showed that the new mathematical functions developed in this project were even more powerful with three-frequencies of acoustic data. Error rates better than 10% were achieved in preliminary tests, which is extremely encouraging for future applications.

At the start of this project, the Marine Microsystems RoxAnn™ (UK) ultrasonic processor was the only other "black-box" system for classifying seabed acoustics that we were aware of. As emphasised in this report, the digital system developed in this project is entirely different in its method of data acquisition and analysis. However, during the course of this Project, in 1996, we became aware of another "black-box" system, the Quester Tangent (Canada) QTC View™ system. The QTC View (Prager, 1995) is a digital sampling system that implements ping shape and classification algorithms in a microprocessor and outputs three parameters that index habitat types in a seabed classification catalogue. The details of the QTC View operation are trade secrets; nevertheless its basic principles of operation appear to be analogous with those used in this project. Unfortunately the black box implementation of this and similar commercial systems makes them prone to both vessel and sea noise that can corrupt the acoustic signals prior to it being analysed by these systems. The main differences that we can identify are that our system digitises entire pings and stores entire raw datasets for subsequent analysis. The raw digital data can be quality assured, eg. using the ECHO software developed in the FRDC project T93/237 (Kloser *et al.* 1998), to remove areas of signal degradation so they are not included in the seabed classification process. This also means that as we inevitably improve our parameterisation and analysis techniques, we can reprocess older datasets, with additional new seabed types, and merge them with newer datasets to extend mapping of any given area with the best classification methods. QTC View does not record digital ping data, so data quality cannot be verified, and its normal operation requires the unit to develop a reference catalogue of seabed types before any surveying is conducted. It is difficult to add new seabed types into the QTC View catalogue and if the catalogue is changed then all subsequent data will be incomparable with prior data.

We have not fully tested the QTC View system, but in many ways, it may fill the role we originally anticipated for a commercial development of our prototype. Nevertheless, we believe our analysis techniques are more advanced and it is still conceivable that our prototype system could be commercialised in Australia and thus made more widely available as an instrument for research and the fishing industry. Due to the simplicity of operation required for non-specialist commercial use, it would be likely that a real-time classification version of our system would only store a reduced classified data set and thus be subject to some of the limitations of the QTC View system. If our system is commercialised, commercial fishers may potentially use a developed system as an instrument for identifying seabed habitat supporting the most productive stocks thus improving the efficiency, and reducing the costs, of fishing.

6 CONCLUSIONS

The outcome of the project was the completion of the original overall objective to develop a digital hydroacoustic system, in the form of an advanced functioning prototype, acquisition software and classification methods, that can discriminate seabed habitat type. With appropriate survey design and post-analysis of the data, the system can be used for mapping seabed habitats, and potentially for monitoring and impact assessment particularly in cases of significant changes in physical habitat type due to eg. sediment movement or dredge spoil dumping. The project had three sub-objectives that were completed successfully, including: (1) construction of electronics hardware for receiving and digital sampling of analogue acoustic signatures and writing of software to control data acquisition and storage; (2) field test the system against the off-the-shelf RoxAnn™ system and against seabed ground-truth data collected concurrently; and (3) analyse the data to develop more sensitive methods for classification of seabed habitats. The hardware, software and analysis methods were refined appropriately throughout the course of the project. The outcomes of the project are summarised in terms of the three sub-objectives/main tasks.

6.1 Summary of outcomes

Electronics hardware and software: The first prototype was built to basic specifications prior to the start of the Project, by a small external electronics R&D company. This prototype functioned well enough to serve as a test-bed for subsequent revisions, but its tolerances were not tight enough for recording of data for analysis. Subsequently, several revisions of the receiver were re-designed and constructed by CSIRO. The refined hardware achieved stable calibrated amplification, tighter filtering to exclude unwanted noise and high dynamic range. The conditioned analogue echo-sounder signal was captured into digital form by a high performance analogue/digital (A/D) acquisition board. Software was specially written to control the A/D board, capture the digital data and record it for subsequent analysis. The amount of data captured was very large up to ~500MB of data per hour of surveying. All raw data was stored as sampled, because any data reduction at acquisition could lead to corrupt acoustic signals. Several computers were assembled specifically for the project, each with progressively higher performance in terms of CPU power and hard disk drive capacity. High capacity tape backups were used for long term storage. The software also recorded the latitude and longitude position provided by the vessel's GPS navigation system. The first version of the custom software simply acquired and stored the data, then it was re-written in the Windows™ environment and provided a familiar graphical and mouse driven user interface. The refined software also displayed the shape of the acoustic signal, a colour echogram, a plot of the vessel's track and provided data play-back and data manipulation functions, such as bottom-locked data extraction.

Field testing: To test the ability of the system to discriminate seabed habitats, it was compared with other methods of sensing seabed habitat type. The system was operated on several research vessels and recorded digital acoustic signals while samples were being taken from the seabed, by such methods as remote video (eg. sled mounted), grab, and benthic dredge. The RoxAnn unit was run concurrently to record its "hardness" and "roughness" indices. On CSIROs FRV Southern Surveyor, the Simrad EK500 scientific echo sounder sampled the immediate near-bottom echoes. Field trials were conducted in the central and far northern Great Barrier Reef, the Torres Straits, the Gulf of Carpentaria, and parts of the SE Fishery region.

Data analysis: Different types of seabed changed the shape of the reflected acoustic signals and data analysis required mathematical methods of describing these shapes and statistical methods for discriminating among them. The basic shape of an acoustic signature may consist of three peaks of sound intensity separated by two relatively quiet flat areas. The first peak was the transmit pulse and it remained constant. The second peak was the sound returning from the seabed to the transducer (i.e. the first echo). The sound sometimes reflected off the sea-surface to the seabed again and then returned to the transducer as a third peak (i.e. the second echo). On hard seabed, the reflected peaks were relatively larger; on rough seabed, the trailing tail of peaks were scattered more. Objects on the seabed caused back-scatter on the leading edge of the first echo. Initially, signals were standardised to a constant depth and "type-signatures" of the first echo were examined for major habitat types. Then, more than 50 measures of first echo shape were investigated for several sets of sample data. A statistical technique called discriminant function analysis (DFA) was applied to the standardised shape measures of the signals. In addition, a new statistical analysis technique (penalised DFA) was applied to these first echo signals for the first time — this method was applied directly to the fully digitised signal without first having to calculate shape measures. Tests of the ability of the acoustic data and these statistical methods to discriminate seabed habitats showed that RoxAnn type indices could lead to incorrect classifications in 25%–50% of cases. This compared with measures of shape from digital signals, which had a 10%–25% error rate, and with the analysis of full digital signals, which had an error rate of only 10%. The analysis of fully digitised signals was clearly the most powerful method, and though it was a computationally intensive analysis to perform, it has a further major benefit in that would be the easiest to implement, and would perform the fastest classifications, in a real-time system.

6.2 Project summary

This Project has completed development of a hydroacoustic instrument in the form of a functioning system of hardware and software that acquires and stores digital acoustic signatures. New methods of analysis were also developed that provide more powerful and sensitive classification of seabed type from remotely-sensed acoustic data.

There is significant intellectual property in the form of the results, including plans of the electronic circuitry, revised system hardware prototypes, sophisticated computer software code and innovative new procedures for analysis of acoustic data.

As was expected at the start, and as with any new technology, this new system is still complex to operate and in its present form is suitable for operation by skilled technicians. There is significant potential for further development, particularly the new methods of analysis. Also, as noted at the start, the benefits available immediately include use by researchers to map the distribution of seabed habitats to provide information for spatial management of demersal fisheries and of other multiple uses of, or impacts on, the seabed. These benefits have already been demonstrated in the form of tangible outcomes for other collaborative projects.

APPENDIX A - REFERENCES

1. Anderson, T.W. (1958) An introduction to multivariate statistical analysis. Wiley, London.

2. Barker, B., Helmond, I., Bax, N., Williams, A., Davenport, S., Wadley, V. (In press) A vessel-towed camera platform for sea-floor surveys of the continental shelf. *Continental Shelf Science.*

3. Bax, N.J., Kloser, R., Williams, A., Gowlett-Holmes, K., Ryan, T. (In review) Seafloor habitat definition for spatial management in fisheries: a case study on the continental shelf of southeast Australia using acoustics and biotic assemblages. *Oceanologica Acta.*

4. Bax, N.J., Williams, A. (Eds.) Habitat and Fisheries production in the South East Fishery Ecosystem. Report to FRDC on Project 94/040.

5. Caughey, D.A., Kirlin, R.L. (1994) Blind Deconvolution of Echosounder Envelopes.

6. Chivers, R.C., Emerson, N., and Burns, D.R. New Acoustic Processing for Underway Surveying. *The Hydrographic Journal.* (56):9-17, April, 1990.

7. Clay, C.S., Medwin, H. (1977) Acoustical Oceanography: Principles and Applications. John Wiley and Sons, Inc. New York.

8. Efron, B (1982) The Jacknife, the Bootstrap, and Other Resampling Plans. SIAM, Philadelphia.

9. Francois, R.E., and Garrison, G.R. (1982). Sound absorption based on ocean measurements. II. Boric acid contribution and equation for total absorption. *Journal of the Acoustical Society of America* 72, 896-907.

10. Gordon, S.R. (1998) Experience Using Acoustic Seabed Classification Systems with Associated Ground Truth Data. *Presented at Managing Seabed Data from Acoustic Classification Devices Workshop, Sydney, Australia 1998.*

11. Hand, D.J (1981) Discrimination and Classification. Wiley, London.

12. Hastie, T. J., Buja, A., and Tibshirani, R. (1995) Penalized Discriminant Analysis. *Annals of Statistics,* 23(1), 73-102.

13. Jackson, D.R., Winebrenner, D.P., Ishimaru, A. (1986) Application of the composite roughness model to high-frequency bottom backscattering. *Journal of the Acoustical Society of America* 79, 1410-1422.

14. Jackson, L.B. (1989) Digital Filters and Signal Processing. Kluwer Academic Publishers, Boston. 255-257.

15. Kavali, T., Weyer, E., Carlin, M. (1994) Real time seabed classification using multi frequency echo sounders. *Proceedings of Oceanology International 94.* Brighton, UK, March 1994, Vol. 4

16. Kloser, R. et al (1998) Development of Software for use in Multi-frequency Acoustic Biomass Assessments and Ecological Studies. Final Report to FRDC, *CSIRO Division of Marine Research Report.*

17. Kreyszig, E. (1983) Advanced Engineering Mathematics 5th Ed. Wiley, New York.

18. Long, B.G., Skewes, T.D., Taranto, T.J., Smith, G.P., McLeod, I., Pitcher, C.R. Poiner, I.R. (1997) PNG Gas Project : Torres Strait marine infill survey, Report to NSR Re: Papua New Guinea – Queensland gas project. *CSIRO Division of Marine Research Report*, July 1997.

19. MacKenzie, K.V. (1981) A nine-term equation for sound speed in the oceans. *Journal of the Acoustical Society of America* 70, 807-812.

20. MacLennan, D. N., Simmonds, E.J., (1992) Fisheries Acoustics, Chapman and Hall.

21. Makhoul, J. (1975) Linear Prediction : A Tutorial Review. *Proc. IEEE,* Vol. 63.

22. Oppenheim, A.V., Schafer, R.W. (1989) Discrete-Time Signal Processing. Prentice Hall, New Jersey.

23. Pace, N.G., Al-Hamdani, Z.K.S., Thorne, P.D. (1985) The range dependence of normal incidence acoustic backscatter from a rough surface. *J. Acoust. Soc. Am.* 77, pp. 101-112, 1985.

24. Prager, B.T., Caughey, D.A., Poeckert, R.H. (1995) Bottom Classification : Operational Results from QTC View. *Proc. Oceans '95*

25. Shibata, K. (1987) Fluctuation of seabed echo due to ship's motion. *International Symposium of Fisheries Acoustics*, Seattle, Washington, June 22-27, 19pp.

26. Skewes, T.D., Pitcher, C.R., Long, B.G., McLeod, I., Taranto, T.J., Gordon, S.R., Smith, G.P., Poiner, I.R. (1996) Torres Strait infill survey, Report to IPC Re : Pandora gas development project. *CSIRO Division of Marine Research Report*, September 1996.

27. Stone, M (1974) Cross-validatory choice and assessment of statistical predictions. *J. Roy. Stat. Soc.,* B,36: 111-148

28. Urick, R.J. (1983) Principles of Underwater Sound. 3rd Edition. McGraw – Hill, New York.

29. Waring, J.R., Kloser, R.J., and Pauly, T. (1994). Echo – Managing Fisheries Acoustic Data. *In 'Proceedings of the International Conference on Underwater Acoustics* University of New South Wales, Dec. 1994'. pp.22-24. (Australian Acoustical Society: Darlinghurst Public School, NSW.)

30. Zar, J. H. (1984) Biostatistical Analysis. Prentice-Hall, New Jersey.

APPENDIX B - RELATED RESEARCH

FRDC Project T93/237 Development of software for use in multi-frequency acoustic biomass assessments and ecological studies.

CSIRO/QDPI Project on the environmental effects of prawn trawling in the far northern section of the Great Barrier Reef Marine Park. Funded by CSIRO, QDPI, GBRMPA, FRDC, FRRF

FRDC Project 94/040 Habitat and fisheries production in the South East Fishery ecosystem.

FRDC Project 97/205 Natural dynamics of sessile megabenthic fauna that comprise living structural habitat on the seabed, and use of these habitats by important fish resources.

FRRF/EA Project, Timor MOU Box Coral Reef and Shoal Banks Marine Resources and Habitat Mapping Survey.

IPC Pandora gas development project, Torres Strait infill survey.

NSR/Chevron PNG gas development project, Torres Strait infill survey.

APPENDIX C - INTELLECTUAL PROPERTY

This Project has completed a functioning system of hardware, software and analysis that now provides powerful and highly sensitive classification of seabed type. There is significant intellectual property in the form of the results including: plans of the electronic circuitry, revised system hardware prototypes, sophisticated computer software code and innovative new procedures for analysis of acoustic data.

The prototype system developed by this Project has the potential to be commercialized and be widely available as an instrument for research and the fishing industry. Because the system can use a conventional echo-sounder for sending and receiving acoustic signals, it could be usable on any suitable vessel equipped with a suitable echo sounder and power supply suitable for a computer. If commercialised, such a system would have potential as a cost-effective search instrument for use on commercial fishing vessels for identifying seabed habitat supporting the most productive stocks thus improving the efficiency and reducing the costs of fishing.

If the project is approved for a sharing of the intellectual property between CSIRO and FRDC, the two organisations will need to negotiate in this regard.

APPENDIX D - STAFF

Table 21: Project staff, showing the allocation of staff resources and skills.

Staff Member	Time/Year	Skills / Responsibilities
C.R. Pitcher, PhD	25%	Project leader / benthic habitat ecologist / experimental design
S. Gordon, BEng	100%	Electronics engineer (acoustics & signal processing) / hardware development / software development / field operations / data management & analysis / algorithm development
R. Kloser, BEng	10%	Acoustician / electronics engineer / acoustics & electronics hardware design.
P. Jones, PhD	10%	Mathematician / statistician / analysis / algorithm development
A. Poole / G.P. Smith, Elec Cert	15%	Electronics technician / field operations
R. O'Connor, BSc	10%	Database management / analysis
I. McLeod, BSc	10%	Remote Sensing / GIS / spatial modeling
T.D. Skewes, BSc	10%	Benthic ecologist / field operations / GIS mapping
T. Taranto, BSc	10%	GIS Mapping

APPENDIX E - BAS CIRCUIT SCHEMATICS

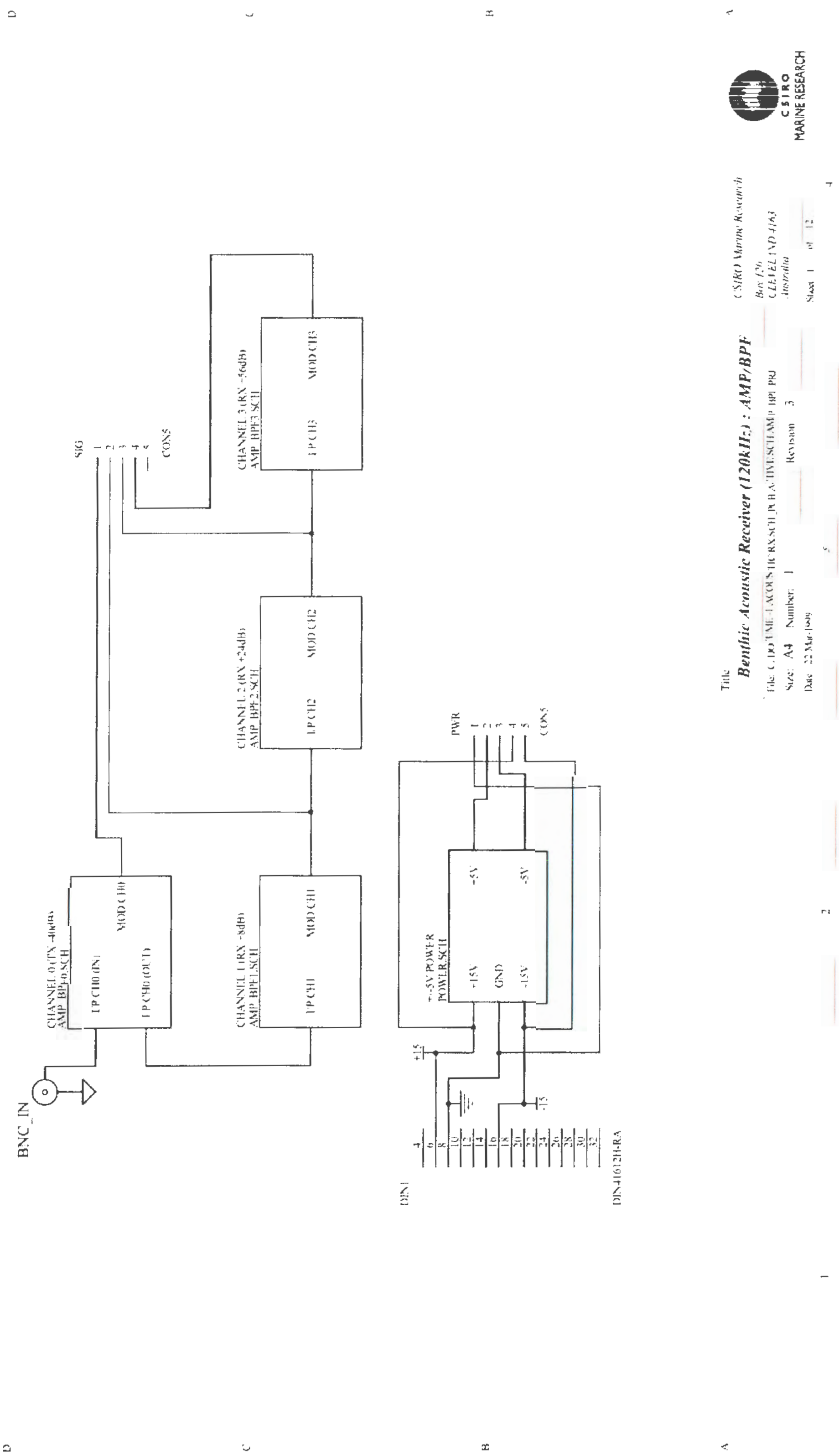


Figure 33: BAS circuit schematic diagram - amplifier & band pass filter circuits.

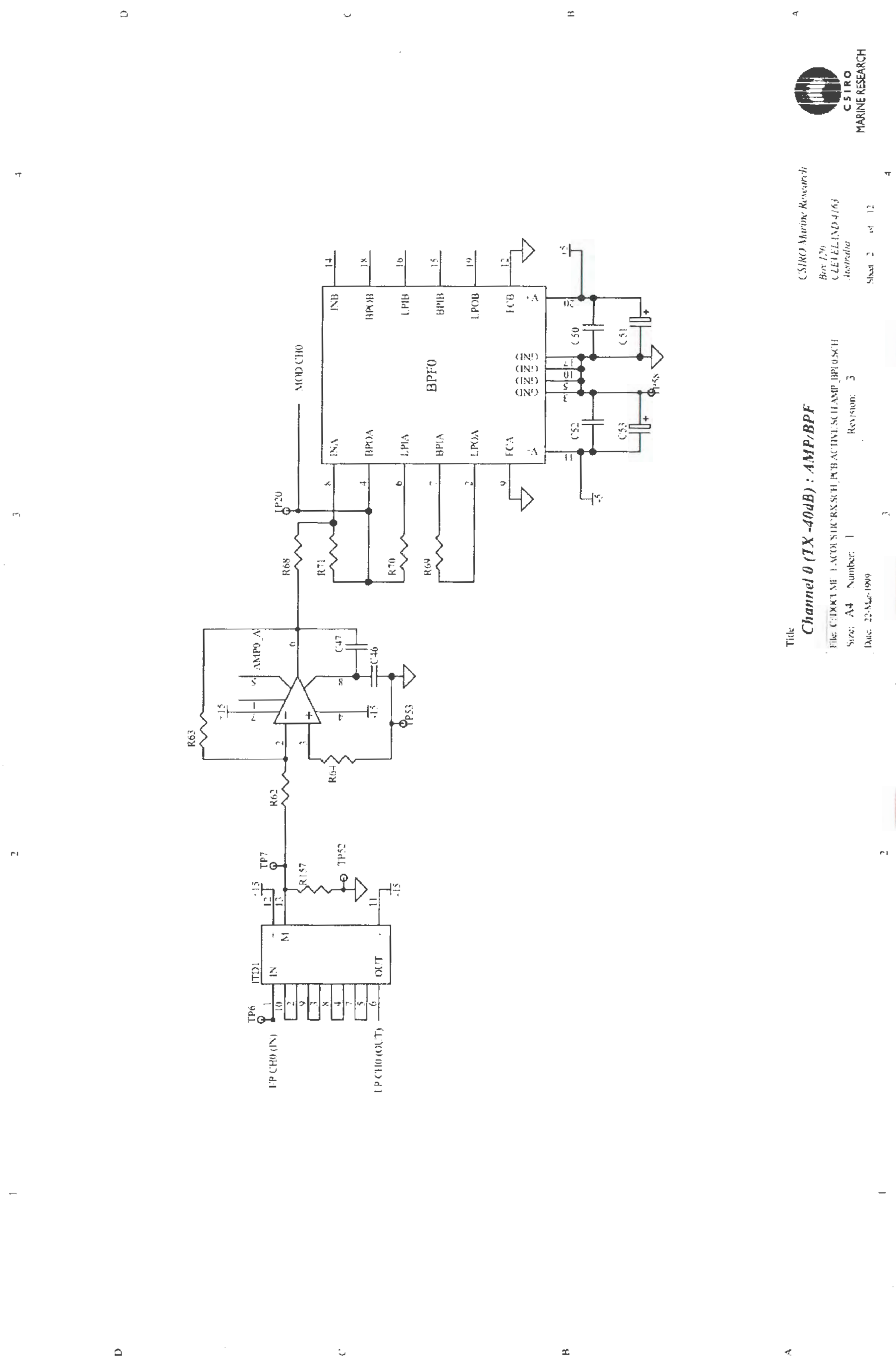


Figure 34: BAS circuit schematic diagram - amplifier & band pass filter circuit, channel 0 (transmit channel), -40dB gain.

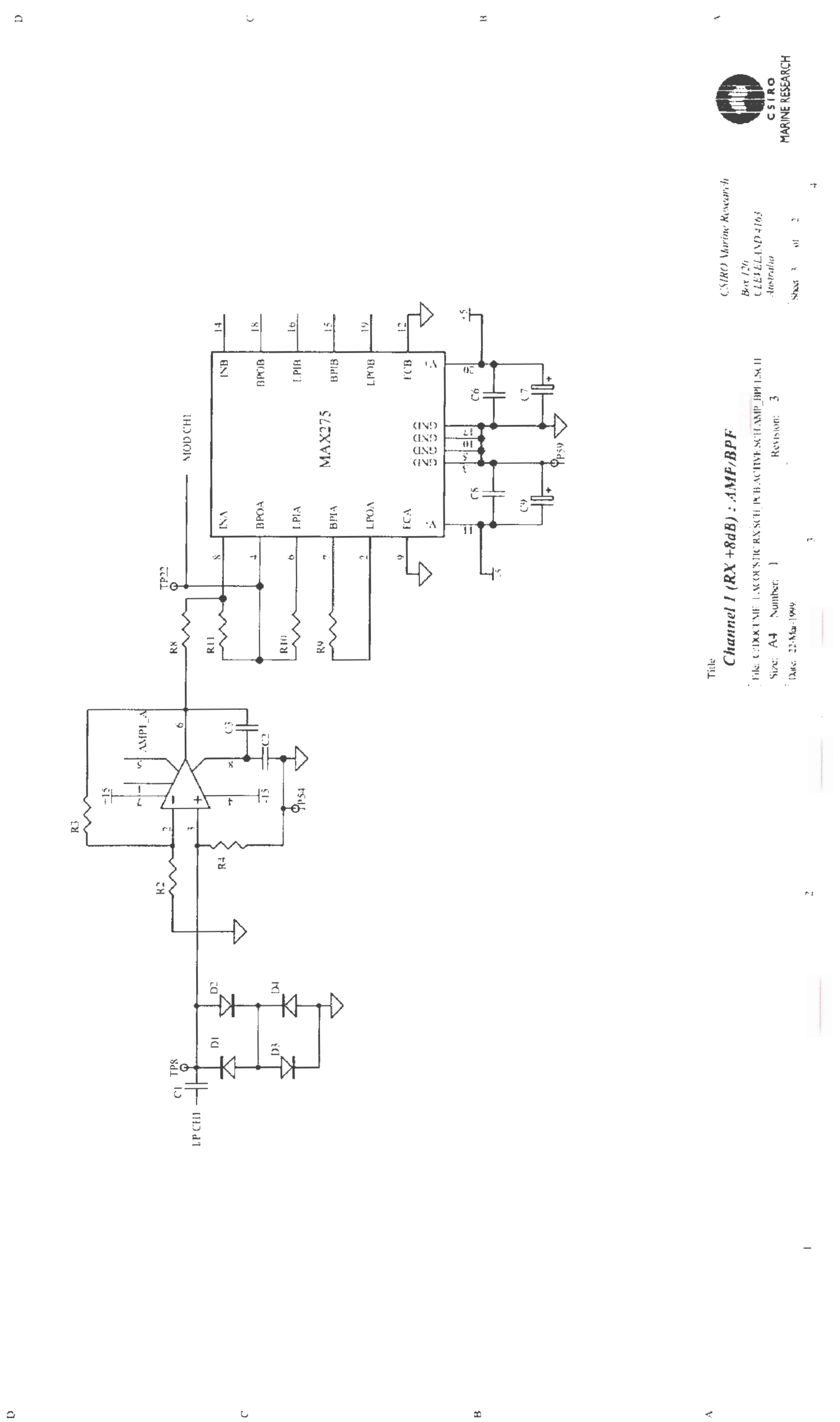


Figure 35: BAS circuit schematic diagram - amplifier & band pass filter circuit, channel 1 (receive channel), 8dB gain.

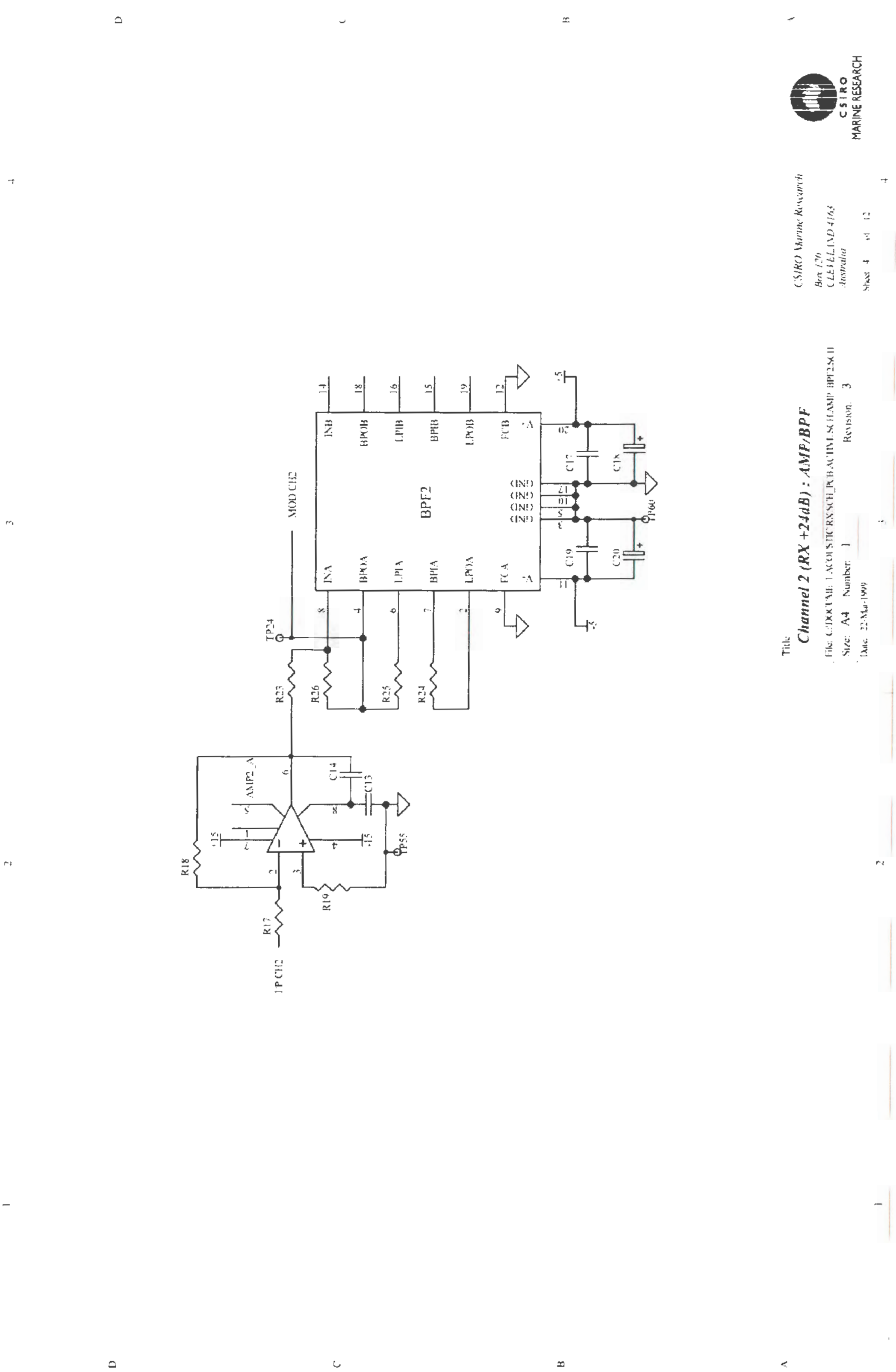


Figure 36: BAS circuit schematic diagram - amplifier & band pass filter circuit, channel 2 (receive channel), 24dB gain.

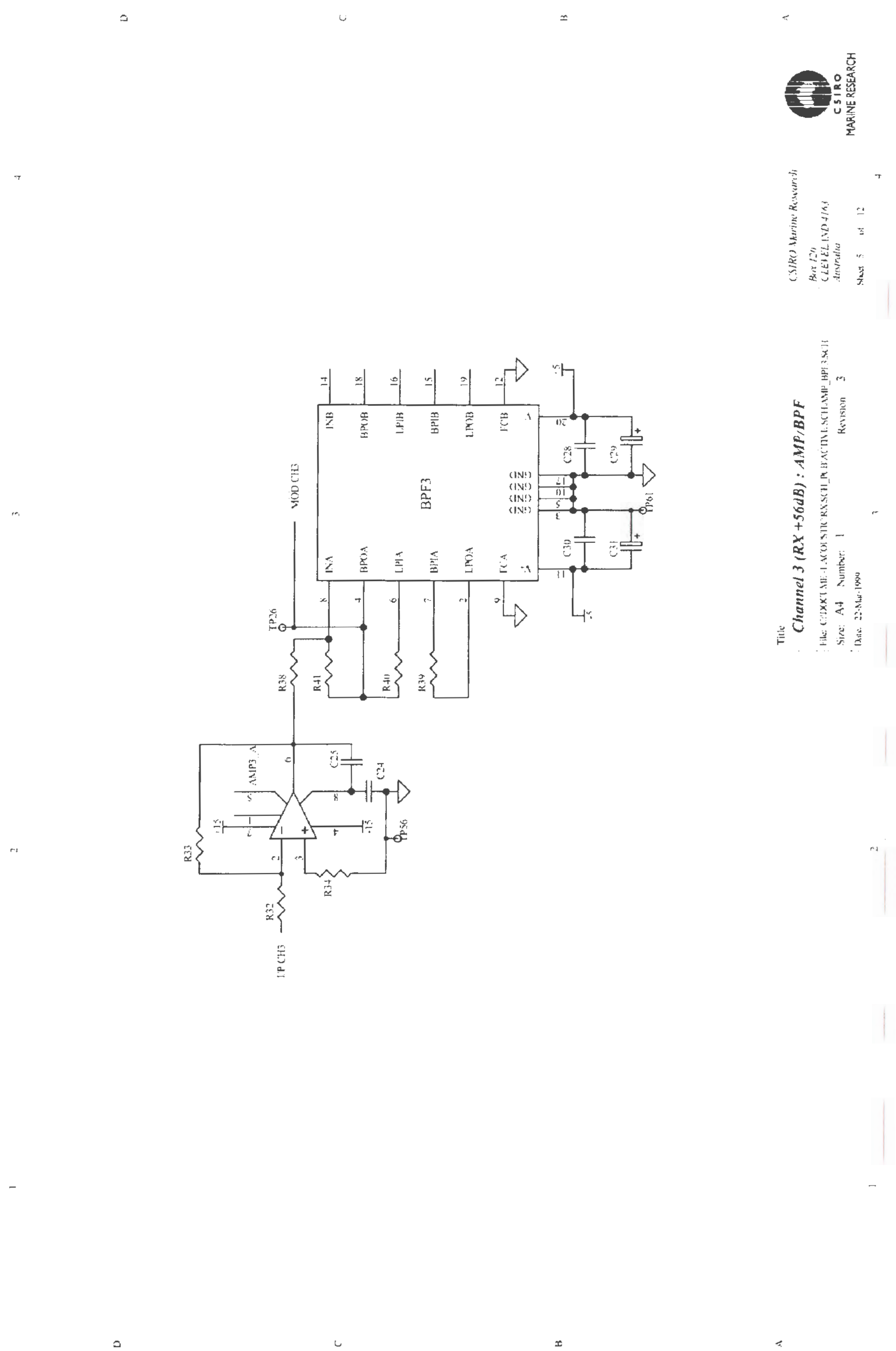


Figure 37: BAS circuit schematic diagram - amplifier & band pass filter circuit, channel 3 (receive channel), 56dB gain.

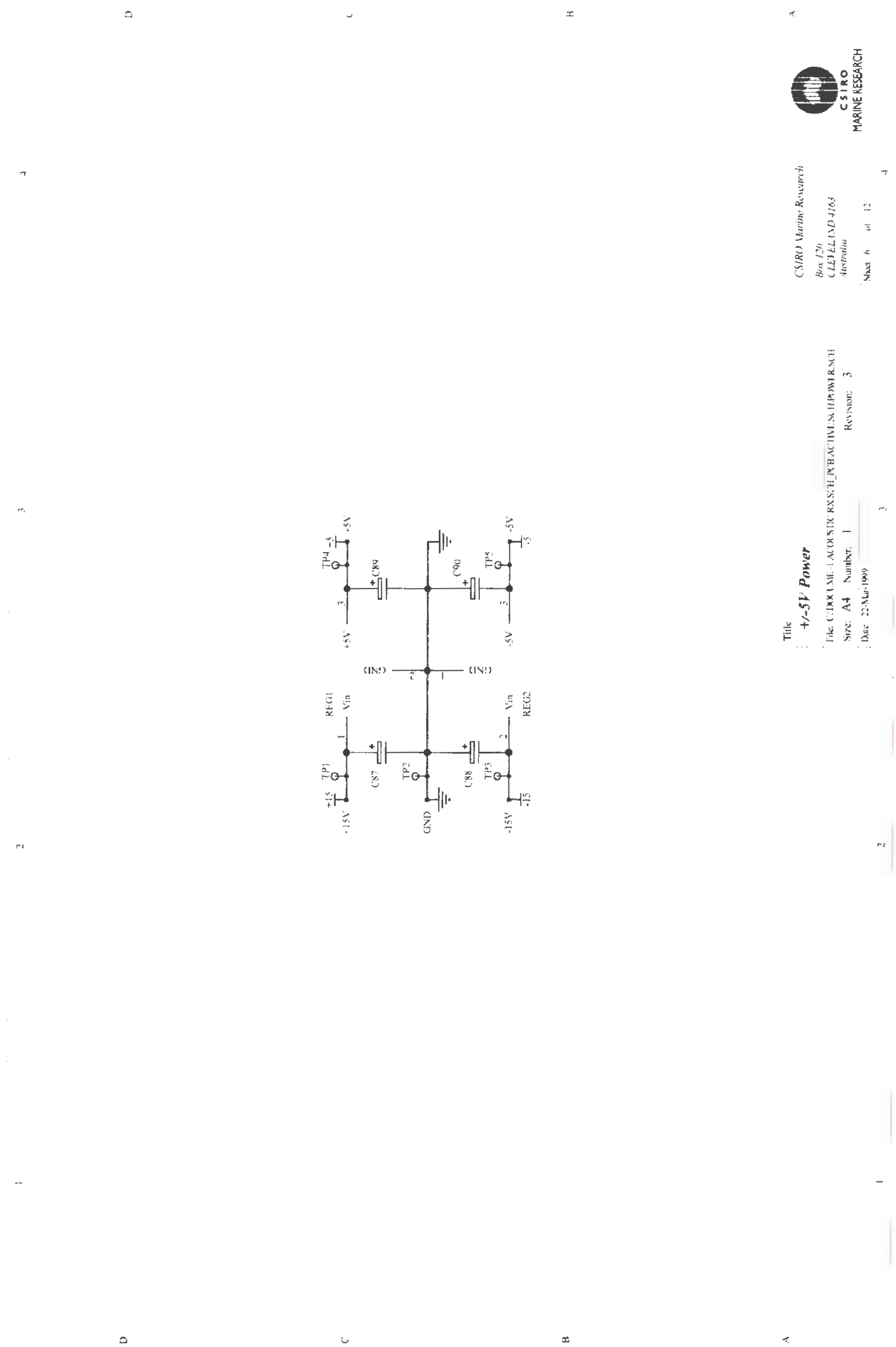


Figure 38: BAS circuit schematic diagram - power circuit, provides +/- 15v & +/- 5v power for integrated circuits.

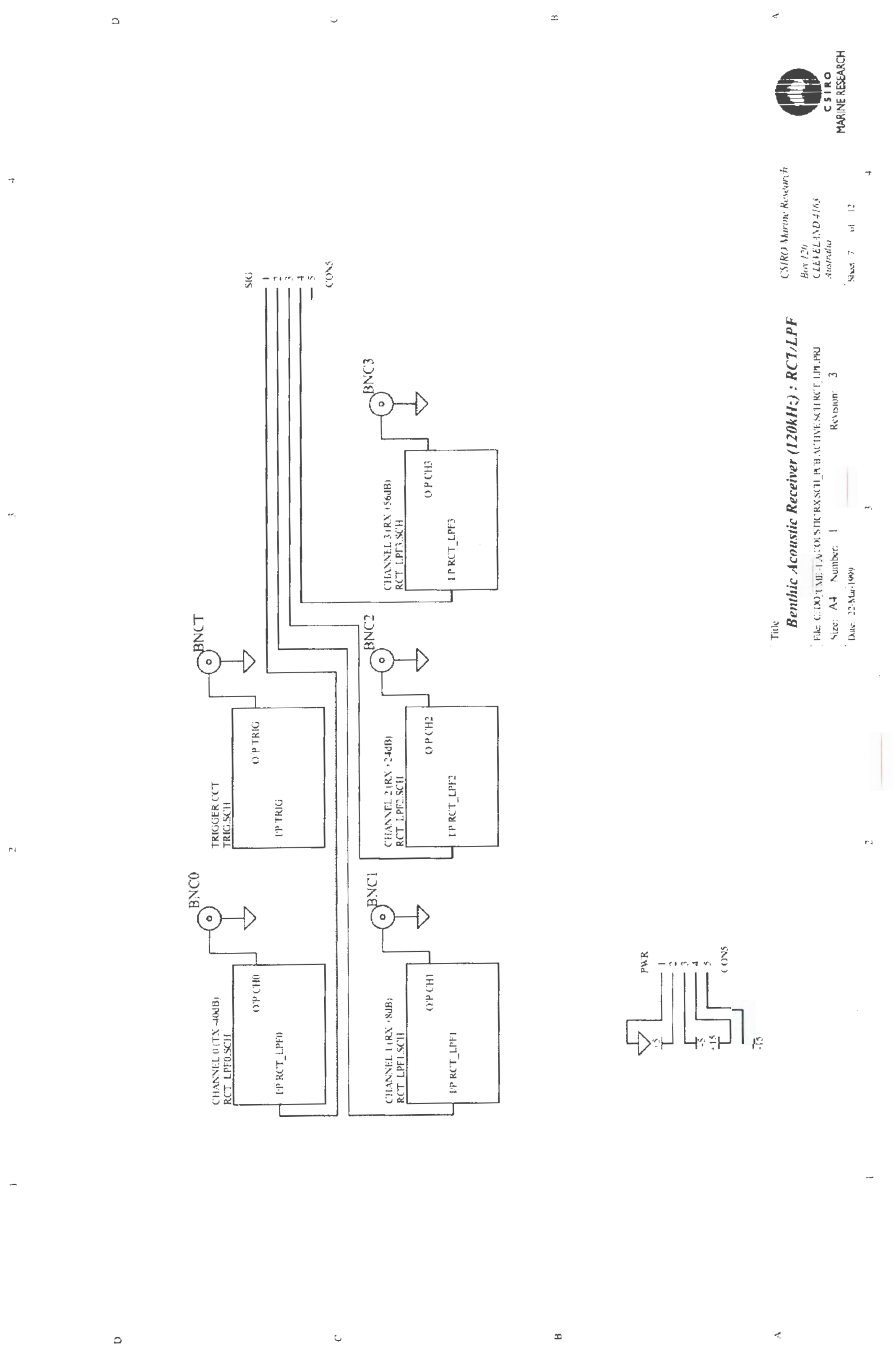


Figure 39: BAS circuit schematic diagram - RMS to DC & low pass filter circuits.

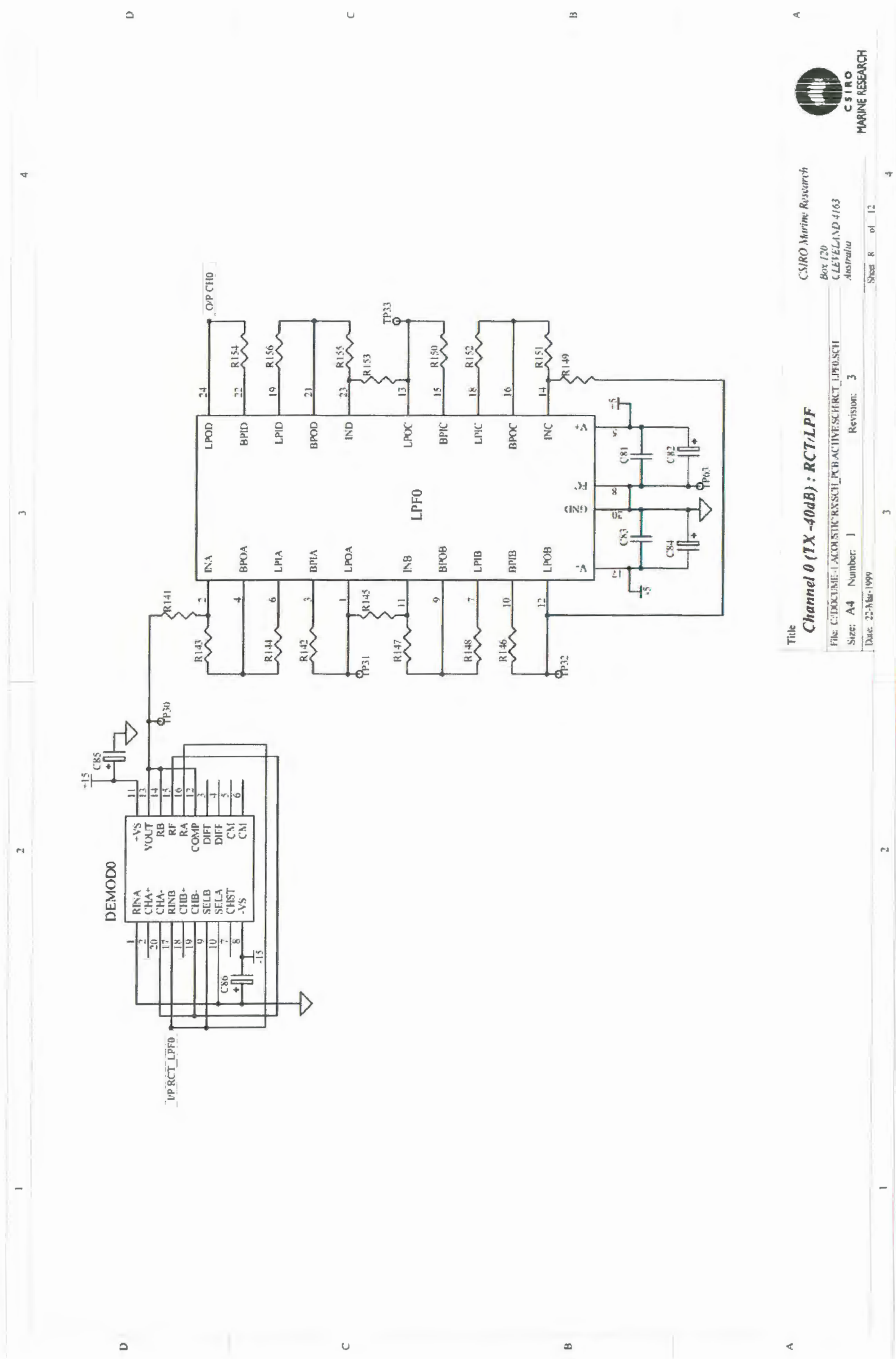


Figure 40: BAS circuit schematic diagram - RMS to DC & low pass filter circuit, channel 0 (transmit channel) -40 dB gain.

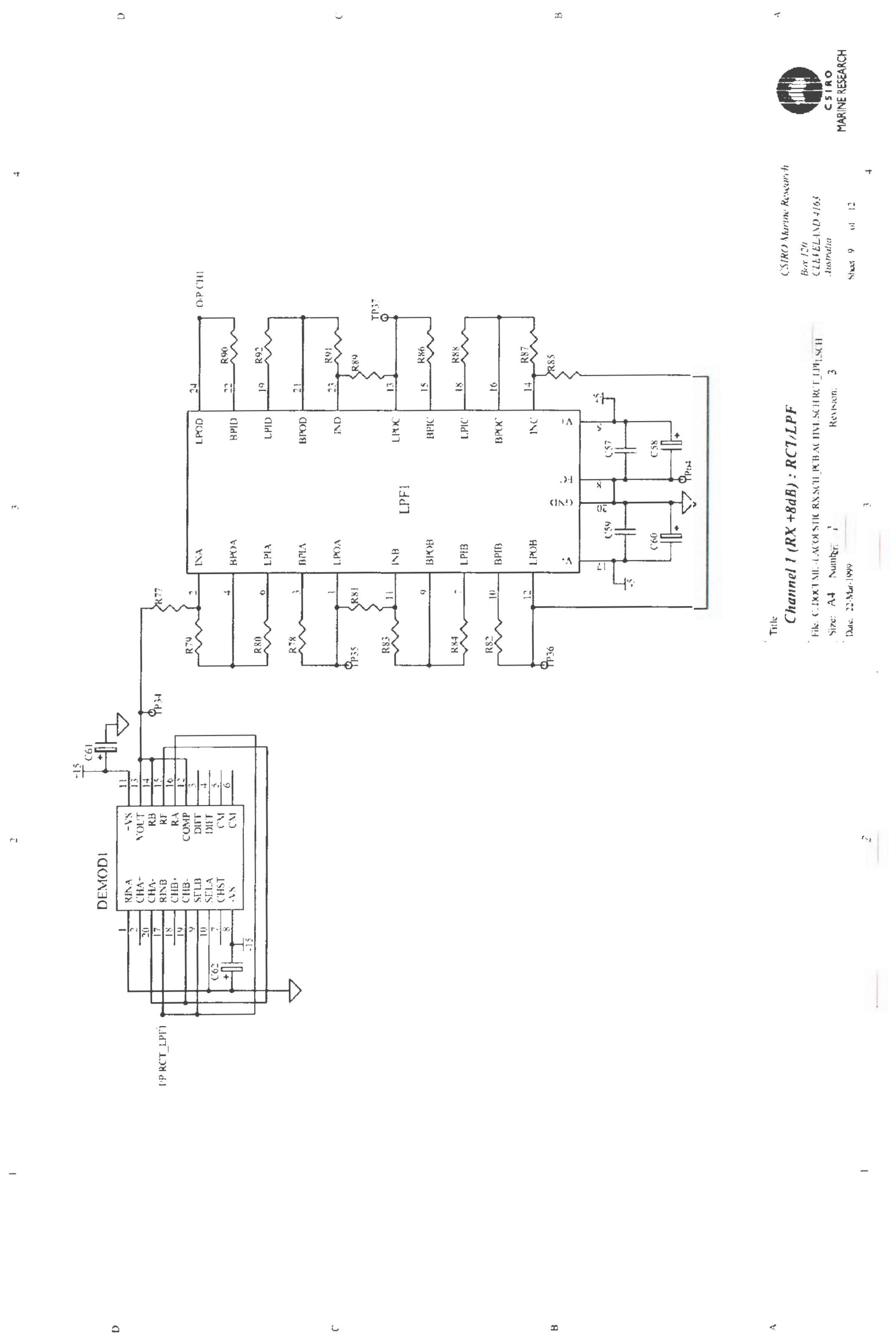


Figure 41: BAS circuit schematic diagram - RMS to DC & low pass filter circuit, channel 1 (receive channel) 8 dB gain.

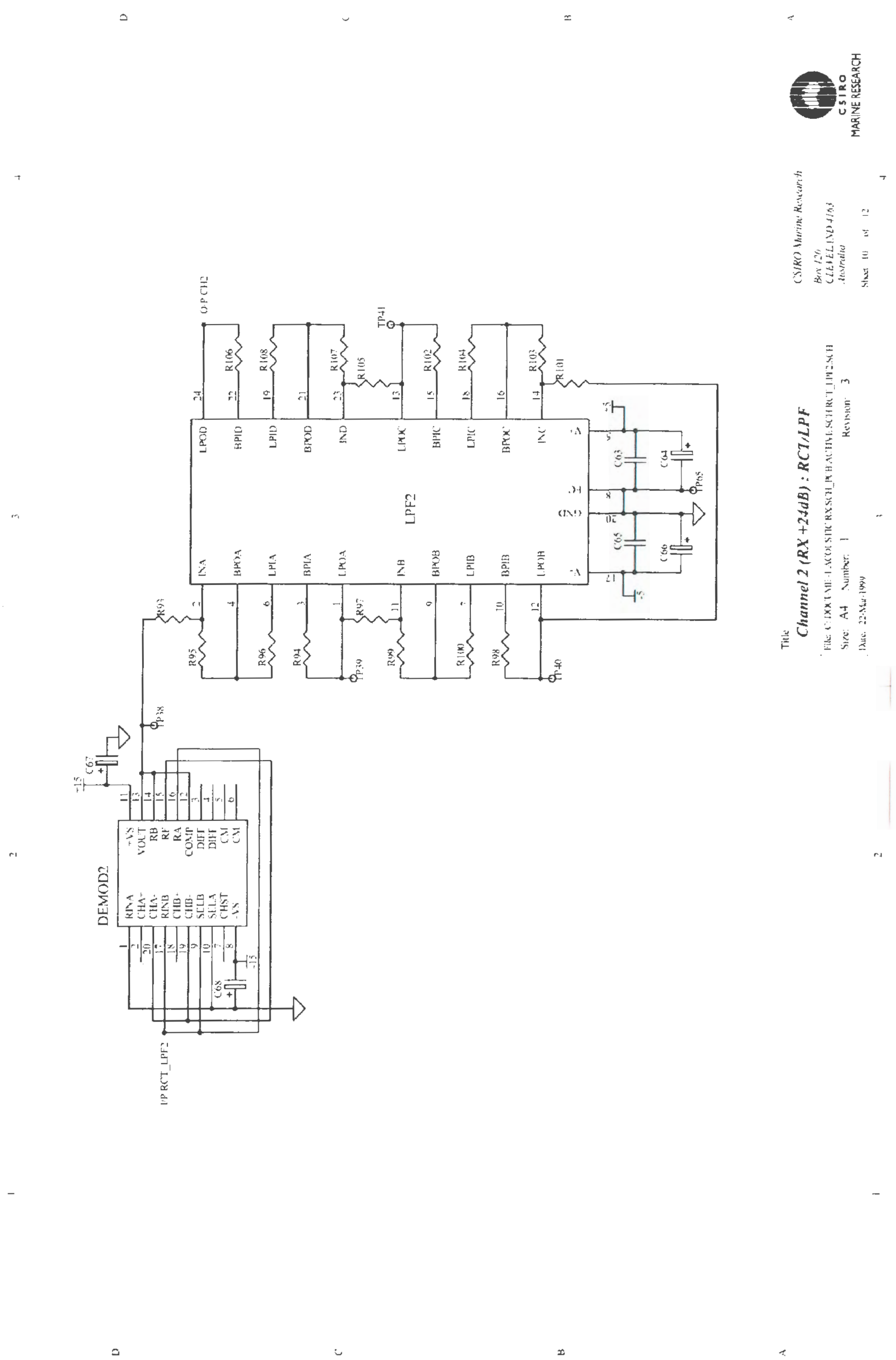


Figure 42: BAS circuit schematic diagram - RMS to DC & low pass filter circuit, channel 2 (receive channel) 24 dB gain.

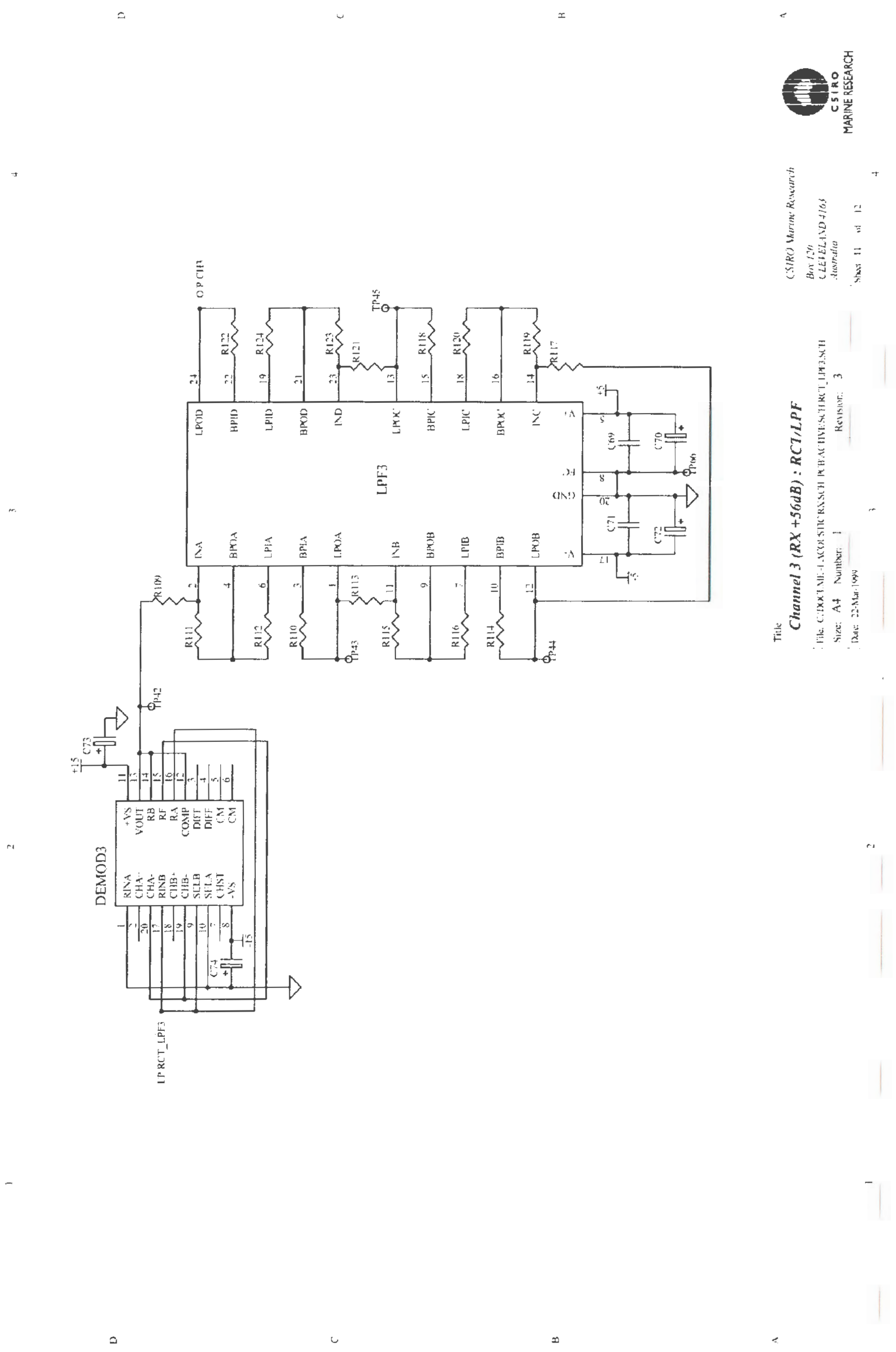


Figure 43: BAS circuit schematic diagram - RMS to DC & low pass filter circuit, channel 3 (receive channel) 56 dB gain.

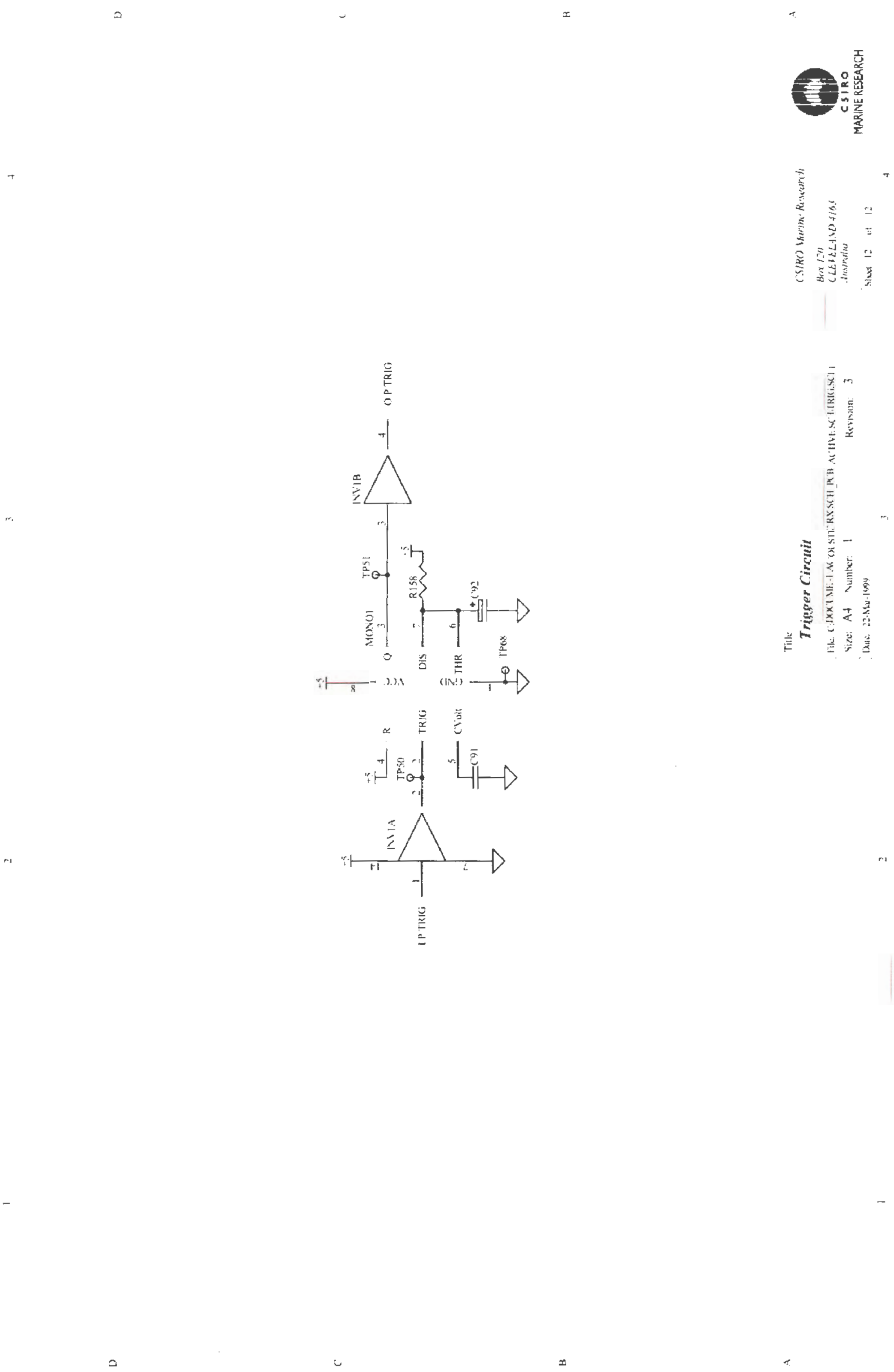


Figure 44: BAS circuit schematic diagram - trigger circuit, provides TTL pulse for synchronisation of A/D.