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THE PASSIVE ACOUSTIC CODING AND TRACKING OF CETACEANS

by

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Abstract

The objective of the work presented in this thesis was to develop a means of passive acoustic monitoring of cetaceans, in particular the smaller dolphins and porpoises. These small cetaceans are very difficult to monitor using other techniques such as photo-identification or visual line transits, which have been successfully employed when monitoring larger cetaceans like the humpback whale. These techniques do not lend themselves to the smaller, faster cetaceans such as dolphins. This is due to the difficulty in spotting them and in counting them more than once due to their fast movements compared to the observation platform. Many of the larger whale species have been individually identified from these techniques allowing the social interactions of the whales to be monitored. It is unfortunately virtually impossible to use photo-identification techniques on the smaller cetaceans due to the difficulty in getting a clear enough picture and the sheer numbers of dolphins that can be present during an encounter.

These smaller cetaceans are however known to be highly vocal underwater where their sounds can travel for substantial distances. This thesis presents an underwater acoustic monitoring system which exploits this characteristic in order to gain individual information about smaller cetaceans from their vocal repertoire.

The Ligurian Sea was chosen for conducting the experimental trials presented in this thesis due to the abundance of striped dolphins known to inhabit the area. Surprisingly little is known about the vocal repertoire of the striped dolphin since most researchers tend to concentrate on the larger bottlenose dolphin. Therefore an initial trial was conducted to assess the vocal repertoire of this mammal.

The promising results obtained from this initial trial prompted the development of a more sophisticated acoustic monitoring system, which replaced the labour intensive method which was used to analyze the initial data set. Once perfected it was hoped that this system would be able to automatically detect, extract and compare cetacean sounds against a database of previously collected individual sounds. The sounds database could them be used to infer census, social and migratory paths of the smaller cetaceans.

The novel algorithms developed for detection, extraction and comparison of dolphin sounds have been compared with the current methods employed and a substantial improvement has been shown. The extension of these algorithms into a real time system is also a novel addition to the current methods employed for acoustically monitoring cetaceans. Also during analysis of the vocalizations of the striped dolphin sounds, a harmonic low frequency sound was discovered which has not been previously reported in the literature.

The author has hypothesized that this sound could be employed by the dolphin as a Doppler sensitive pulse and the ambiguity function is used to demonstrate the Doppler-range sensitivity of the pulse. This new sound is a harmonic tonal pulse of approximately 0.25 - 0.75 seconds duration. The sound tends to be emitted, before, after or in between echolocation tasks performed by the striped dolphins. The regularity of the pulse and it's emission during these tasks suggest that it complements the echolocation information.

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Notation

SL	Source level	dB re: 1μPa @1m
SE	Signal Excess	dB
DI	Directivity Index	dB
DI_T	Transmitter Directivity Index	dB
DI_R	Receiver Directivity Index	dB
DT	Detection Threshold	dB
NL	Noise Level	dB
NSL	Noise Spectrum Level	dB
B	Bandwidth	Hz
TL	Transmission Loss	dB
TS	Target Strength	dB
f	Frequency	Hz
SNR	Signal to Noise Ratio	dB
R	Range	m
α	Absorbtion Coefficient	dB/m
R_{xy}	correlation function	
R_{xx}	Auto correlation function	
S_{xx}	Cross Power spectrum	
S_{xy}	Auto Power spectrum	
h	Doppler scaling factor	
$\lvert\chi(\tau,\eta)\rvert^2$	Ambiguity Function	

Chapter 1 - Introduction

This thesis considers the detection and analysis of the underwater sounds of cetaceans. Cetaceans are the order of mammals of which whales, dolphins and porpoises are members. This group of mammals have the ability to emit and receive underwater sound over a large frequency range, typically 10's of Hertz for the larger whales to 100's of kilohertz for the dolphins and porpoises. Many species of dolphin are known to use the sounds they produce as a form of active sonar. It has also been speculated that the low frequency sounds emitted by the baleen whales is also used as a long range sonar.

The research presented in this thesis concentrates on the underwater sounds produced by one particular species of dolphin, the striped dolphin. Extensive recordings of the vocal repertoire of this dolphin were taken during a field trial in June 1994. Acoustic monitoring equipment was used in the dolphins natural environment which in this case was in the Ligurian Sea off the coasts of France, Italy and Corsica. Most scientific research on the acoustic behaviour of dolphins presented in the literature is for captive dolphins rather than for free ranging specimens.

In this thesis safe acoustic monitoring practises are first investigated. These practices when employed allow striped dolphins to be monitored acoustically without the dolphin detecting the presence of the observation platform using it's echolocation system. An investigation of this type, has not, to the author's knowledge, previously been presented in the literature.

In order to collect and analyse the vocal repertoire of the striped dolphin the development of new equipment was required. A preliminary study of one week duration was conducted in July 1993, to ascertain the likely frequency content and source levels of the striped dolphin's vocal repertoire in order that suitable monitoring equipment could be developed or acquired. Once the initial survey was completed and the requirements known, the main trial was conducted. This trial was conducted during the summer of 1994. During the trial 90 hours of recordings were taken. The recordings were then analysed to assess the vocal repertoire of the striped dolphin.

Different configurations of hydrophone arrays were also used to try to triangulate on the dolphin positions in order to track their movements. Limited success was achieved in tracking the short term movements of dolphins using this method. The problems encountered were; errors introduced from movements in the array, as well as acute cross bearings in front and behind the boat The striped dolphins were found to emit echolocation 'clicks' which were similar to the ones recorded from captive dolphins.

These dolphins also emitted pure tonal, frequency modulated sounds which have been described in the literature for other species of dolphin as 'signature whistles'. Due to the frequent emission of the 'signature whistles' a detection algorithm and a contour extraction algorithm was developed in order that these sounds could be further investigated. It was hoped that the data extracted from these whistles could be used to identify individual dolphins and therefore provide valuable statistics on abundance and geographical location, to zoologists who are interested in the behaviour of these animals in their natural environment.

During the analysis of the signature whistles the striped dolphin was also found to emit a low frequency harmonic pulse that is not thought to have been previously reported in the literature. This purpose of this pulse is hypothesised by the author to be a Doppler sensitive pulse useful to the dolphin for detecting the speed of objects.

1.1 Historical Background

SONAR is the acronym used to describe the SOund NAvigation and Ranging systems that were employed during World War II to detect enemy submarines. Two distinct systems were used, active sonar and passive sonar. An active sonar emits short pulses of sound into the water and waits for echoes to return from targets. The sound emitted is usually an amplitude modulated constant frequency pulse, termed a 'ping'. Passive sonars were used because active sonars have the disadvantage of revealing the location of the search vessel to the enemy. Passive sonars listen for the natural sounds that are emitted by a target, such as propeller noise of a boat.

Echolocation is the term used to describe the process used by animals who emit sounds and receive echoes for the purpose of navigation and detection of objects. The echolocation of animals is also sometimes called bio-sonar. Only two groups of animals are known to possess this capability, cetaceans and bats. The bio-sonar of bats was discovered before that of cetaceans.

Bio-sonar was first noted in bats, in 1773, by an Italian scientist, Spallazani, who noted that bats were able to fly freely in total darkness and were able to avoid obstacles. However, he was unable to explain the process being used. His work was continued by a Swiss scientist Charles Jurine who in 1798 conducted experiments on blinded

bats. He discovered that the bat was able to fly freely when blinded but was unable to orientate itself when deafened. One of his conclusions was that hearing played a major role in the ability of the bat to navigate itself. In 1912 Maxim suggested that bats used the reflection of low frequency sounds emitted from the flapping of their wings, but, was unable to substantiate his theories. High frequency sound emissions, above the human hearing range, were detected by Pierce and Griffin (1938). They used a newly developed piezoelectric crystal microphone and superhetrodyne receiver. The sounds they detected were between 30 and 70 kHz and lasted for 1 to 2 ms.

Cetacean bio-sonar was discovered shortly afterwards by Arthur McBride in 1947, although his work was not published until after his death, in 1956. Kellogg and Kohler (1952) were the first to suggest in the literature that the dolphin possesses a bio-sonar.

Interdisciplinary symposia on animal sonar systems have been held in subsequent years since the discovery of bio-sonar. The first symposium was held in 1966, in Frascati, Italy. The second symposium was held in 1979, in Jersey, The Channel Islands and the third symposium was held in 1986, in Helsingor, Denmark.

While research into bat bio-sonar has expanded rapidly, similar research into cetacean bio-sonar has progressed at a much slower pace. The reason for the slower progress of research into cetacean bio-sonar is because of the difficulty in observing these animals. Studies of captured animals provide a great proportion of the knowledge in the literature. Bats are far easier to capture and house than cetaceans and are of lower cost to maintain. This is reflected in the abundance of published research on bat bio-

sonar compared with the cetacean bio-sonar. The smaller cetaceans are the only animals that it is feasible to capture which can be housed in pools or oceanariums at reasonable cost.

The largest cetaceans to be held in captivity are killer whales, sometimes called orcas from the scientific Latin name (*Orcinus orca*). Many researchers opt to use the Atlantic bottlenose dolphin because of its relatively small size and greater abundance than other species of dolphin. Much of the literature, therefore, reports on the bio-sonar of the Atlantic bottlenose dolphin. Investigations into the sonar capabilities of the larger whales are only possible through field studies and therefore progress in this area is slow.

The difficulty with sighting and identifying cetaceans visually in the field, has led to the development and use of underwater acoustics in order to obtain cetacean statistics from their vocalisations. Many species of cetacean are known to produce underwater sounds. Passive acoustic monitoring of cetaceans is a technique of increasing interest to zoologists who are keen to study their behaviour. The technique also allows observation to continue at night or times of poor visibility. Up to the present, the area of underwater acoustics has been dominated by engineers and as such, interdisciplinary collaboration is required for the study of cetacean vocalisations.

Dr. Jonathan Gordon, of the Oxford Zoology Department, is the co-ordinator of a group of zoologists who are interested in sperm whale behaviour and their acoustic vocalisations. The group has a sailing yacht converted for cetacean research, with particular emphasis on acoustic monitoring. A collaboration between the author, (a

member of the Acoustics and Sonar group at The University of Birmingham) and the team led by Dr. Jonathan Gordon enabled the work presented in this thesis to be completed. The yacht is funded by the International Fund for Animal Welfare (IFAW).

A trial was conducted during the summer of 1994 to collect acoustic data on cetacea in the Ligurian Sea. This area had recently been declared a sanctuary to cetaceans. The simultaneous collection of acoustic and conventional sightings data were obtained. This allows a comparison of the two techniques to be made. The cetacean population in this area is known to consist of the following species: fin whales; sperm whales; striped dolphins; grampus dolphins and Atlantic bottlenose dolphins.

The striped dolphins are the most abundant species in this area with frequent sightings. The other species are generally only seen in small numbers and not at frequent intervals.

The work presented in this thesis is of particular interest because all of the recordings were taken of dolphins in their natural environment. The purpose of obtaining the recordings was to investigate the possibility of using only the underwater sounds produced by cetaceans to gain useful data for the zoologists.
Many aural acoustic detections are made of cetaceans when no sightings are made. This can be for a number of reasons, i.e. poor visibility; cetacean at depth; night time survey; cetacean at too long a range. The acoustic data is useful to help validate the sightings data and sometimes is the only data available to the zoologist. Interpreting the acoustic data is difficult since the vocalisations of most cetaceans are unknown.

Some species are known to emit sounds of various types and at different frequencies to other species. Each species would appear to employ a vast repertoire of sounds. Many species emit a 'click' which is known to be used for echolocation. Apart from echolocation 'clicks', the purpose or relevance of most of the other sounds produced by cetaceans is unknown. A limited summary of the available acoustic repertoire of cetaceans is shown in Table 1.1.

Table 1.1

Cetacean	Sonar Capability	Vocalisations	Duration	Frequency range	Reference
blue whale	Unknown	low frequency moaning	36.5 seconds	12.5-200 Hz	[42,86]
		buzzes/rasps			
fin whale	Unknown	20 Hz pulses	1 second	23-18 Hz sweep	[86]
humpback whale	Unknown	songs / moans	variable long sequences of sounds	500 Hz-2 kHz	[33,34,61,80]
		pulses	300-400ms	25-80 Hz	
sperm whale	Highly developed	sonic pulses		5 kHz peak frequency	[72]
killer whale	active				[43]
false killer whale	active				[16]
beluga whale	active				[7,66,67]
bottlenose dolphin	active	ultra sonic pulses	120μs	120 kHz peak frequency	[3,4,5,9,10,12,14]

The acoustic recordings used in this thesis were obtained from the sailing yacht 'Song of the Whale'. This yacht was already equipped with a passive acoustic monitoring system. This consisted of a stereo towed hydrophone array (3m spacing) linked to a recorder, which had been designed and built by Dr. Jonathan Gordon's team. The stereo array was based upon hydrophone elements supplied by Benthos Ltd. The pre-amplifiers were designed by Oliver Chappel (a member of IFAW). The housing for the hydrophone was also constructed by Dr.Gordon's team. This system enables recordings to be taken over the 200 Hz - 20 kHz frequency range. The frequency range is restricted at the lower end by the pre-amplifiers to prevent overloading due to low frequency flow noise, and at the higher frequency end by the recorder. This system had been used extensively in previous expeditions to collect sperm whale

recordings. Sperm whales produce short duration clicks which have a peak frequency of around 5 kHz. Since this array was tried and tested and the crew were familiar with its use and deployment, it was also used for these trials. As can be seen from Table 1.1 the system is suitable for the frequency range of interest for recording dolphin whistles. However it is unsuitable for recording the low frequency pulses of fin whales or for the recording of the echolocation clicks of dolphins and porpoises. Due to the broad band nature and high sound level of the echolocation clicks produced by dolphins they are detectable in the recordings taken over this frequency range and so can be placed into context with any other sound emissions produced. Even though they cannot be properly analysed due to the limits on bandwidth.

The signal-to-noise ratio of the passive acoustic monitoring system can be increased by filtering out the noise in the frequency bands which do not contain cetacean vocalisations. These filters need to be selectable so that they can be adjusted to give the best filtering characteristics for the vocalisation of interest. There were no commercially available modules which were able to meet the required specification. The author has therefore, developed custom amplifier and filter modules that have been used in these trials and subsequently in other trials (indicating the lack of suitable commercially available equipment). These were needed to reduce noise levels by filtering out noise in unwanted frequency bands and to amplify the vocalisations when the cetaceans were at large distances from the yacht. Using this equipment a preliminary study was conducted to establish which acoustical cues could be exploited in order to gain information about each species of cetacean. This study concentrated upon collecting acoustic census information about striped dolphins from their whistle vocalisation.

The results of this preliminary study were promising since it showed that the striped dolphins encountered emitted a vocalisation known as a signature whistle similar to the ones reported by Caldwell & Caldwell (1965) for the bottlenose dolphin. This type of vocalisation is a pure tonal frequency and amplitude modulated sound for which the frequency modulated contour when mapped in the time-frequency domain is characteristic of an individual dolphin. By extracting these contours from the whistles and comparing them it is possible that useful census information can be extracted. The preliminary study developed the necessary mathematical and statistical techniques in order to achieve this.

The process of detecting, mapping, extracting and comparing contours is computationally expensive, and therefore a faster method than the one used in the preliminary study was required. A real time system for performing the census calculation was therefore developed based around an ADSP 21020 digital signal processor, with an IBM PC used for the front end. This system required the design and build of high speed interrupt driven interface hardware in order that real time processing could be achieved. The software was written in assembler on the DSP and in C on the IBM-PC.

1.2 Thesis Outline

Chapter 1 introduces this thesis and also provides the historical background to the subject.

In Chapter 2 the relevant research conducted in the area of cetacean acoustics is explored. This research is divided into six sub sections:

1. An overview of the current dolphin literature is described in the first section.
2. The current knowledge of the anatomy relating to sound production is described in the second section.
3. The mechanisms proposed for sound reception in dolphins are reviewed in the third section.
4. The sonar performance of dolphins, mainly the bottlenose dolphin is reviewed in the fourth section.
5. The fifth section presents the current understanding of dolphin whistle production and also describes the signature whistle hypothesis. This hypothesis suggests that dolphins possess a unique whistle which they emit for 90% of their whistle repertoire.
6. The final section reviews the very latest developments.

Chapter 3 uses the sonar equations and characteristics of the cetacean sonar given in the literature to perform predictions of the propagation distances of dolphin vocalisations. These predictions give guidance for cetacean monitoring. The signature whistles which are of interest for this thesis are detectable at distances greater than the cetaceans echolocation system. Therefore non-invasive research is

possible by keeping the observation distance greater than the detection range of the cetacean. The signature whistles can be detected without the cetacean detecting the sailing yacht.

Chapter 4 reviews the signal processing techniques which have been used for collection and data analysis for this thesis. The mathematics of the signal processing techniques are described. The statistical analysis techniques which were used for the study are also described.

Chapter 5 describes the experimental locations at which acoustic recordings were taken during the trials work. The equipment that was developed for collecting cetacean recordings during these trials is described. A custom amplifier filter module was designed and constructed, which was necessary to collect the recordings presented in this thesis. This amplifier filter module has also found uses in other research and commercial projects. The towed array and the methods used to collect the recordings are described. After the preliminary study was carried out, a real time system for analysis of the signature whistles was developed. The hardware and software developed for this analysis system is also described.

Chapter 6 presents the results obtained from the preliminary study conducted to evaluate the potential to exploit dolphin vocalisations for collecting zoological information. Techniques are developed for tracking cetaceans from the echolocation clicks that some species produce such as dolphins and sperm whales. A technique to detect and extract dolphin signature whistles automatically is also developed which can be used to extract the dolphin signature whistle contours. These contours are

individual to each dolphin and so have the potential of yielding census information as well as social interactions between dolphin groups.

A new sound which was heard throughout the recording of the striped dolphins is described. This sound is not thought to have been reported in the literature. Investigation of the sound during one encounter with striped dolphins has resulted in 77 occurrences being detected in a 10 minute period by listening. The sound is a harmonic pulse of approximately 0.25 - 0.75 seconds duration. The frequency and duration of this pulse suggests that it has the capability of encoding Doppler information sensitive enough to detect the speed of a dolphin's prey, although no data was collected which could validate this.

Chapter 7 evaluates the detection and extraction algorithm against decreasing signal-to-noise ratio using a simulated dolphin whistle which has been corrupted by varying amounts of white noise and also by simulated echolocation clicks. This algorithm is compared to work presented by Buck and Tyack (1993) and found to be superior for all conditions especially when the signal-to-noise ratio is low and also when the whistles are corrupted by echolocation clicks. The developed algorithm is also able to automatically find the start and end points of dolphins whistles which was not possible with the algorithm developed by Buck & Tyack.

Chapter 8 describes the results of using the real time dolphin whistle contour detection and extraction system. The extracted whistles from one tape are given in Appendix A. The performance of the signature whistle detection algorithm is explored in terms of the Receiver Operating Characteristics (ROC).

Chapter 9 investigates the characteristics of the new sound which was recorded during encounters with striped dolphins. The sound is a harmonic pulse which is used by the dolphins in-between their click trains. It is hypothesised that the pulse is Doppler sensitive which allows dolphins to estimate the speed of objects. The ambiguity function is used to determine the Doppler-range sensitivity of the harmonic pulse as well as the echolocation click and the signature whistle.

Chapter 10 is the Discussion

Chapter 11 presents Conclusions & Suggestions for Future Work

Chapter 2 - Literature Review

2.1 Literature search overview

There are many published papers relating to dolphin subjects covering a wide diversity of topics. For the purposes of this thesis the current literature has been divided into twelve categories:

2.1.1 Anatomy

The following papers relate to the current knowledge on the anatomy of dolphins and the sound productions mechanisms employed to produce underwater sounds. [60,71,108,141]

2.1.2 Sound Production Mechanisms

Very little knowledge is available on the physical mechanisms employed by cetaceans to produce their underwater sounds, these three papers detail the current understanding, [1,48,78].

The anatomy and sound production mechanisms are explored in more depth in section 2.2.

2.1.3 Hearing

It is very difficult to assess the hearing capabilities of cetaceans, however three captive cetacean experiments have been conducted and the auditory thresholds for the beluga, [66,67], and bottlenose dolphin [75] have been measured. No other data for other species could be found in the literature. This subject is covered in more depth in section 2.3.1

2.1.4 Local Ligurian Sea Literature

During the course of collecting data for presentation in this thesis several trials were conducted in the Ligurian Sea area off the coasts of France, Italy and Corsica. The following papers describe the local cetacean population and the work being conducted in the area, [26,55,57,58,100,102,105,107,110,118]. Many of these papers were produced by members of the Tethys Research Institute with whom a collaborative trial was performed to collect some of the data presented in this thesis.

2.1.5 Cetacean acoustic beam patterns

The following papers describe experiments that have been performed on trained captive cetaceans. These experiments were conducted to measure the directional nature of the underwater sounds that cetaceans produce and to map both the transmitting and receiving beam-patterns. These papers describe the beam-patterns of the Atlantic bottlenose dolphin [9,12], the beluga [19] and the false killer whale[16]. A computer generated beam pattern has also been calculated for the common dolphin

[2]. No other literature on other species of dolphin is known to exist. This subject is covered in more depth in section 2.3.2

2.1.6 Cetacean Echolocation

Many papers describe experiments conducted on captive cetaceans to assess the sonar capabilities of these animals. Most subjects tend to be Atlantic bottlenose dolphins [10,13,18,20,23,27,35,82,89,117,123,129] with limited data existing for false killer whales [16,117], and belugas [7,19,129]. These experiments are conducted to measure various parameters of the echolocation signals such as, maximum detection range, frequency content, bandwidth, adaption, target detection in noise or reverberation. These experiments are described in more detail in sections 2.4.1 & 2.4.2.

2.1.7 Cetacean sonar discrimination experiments:

Cetaceans are able to discriminate between a wide variety of underwater targets by just using their echolocation system without any other sensory cues, such as sight. These papers describe experiments conducted to assess these cetacean capabilities, [6,8,22,24,28]. Most of the data that exists is for the Atlantic bottlenose dolphin, and this species has shown the ability to discriminate objects of the same physical dimension and target strength but with different material compositions.

2.1.8 Cetacean Sonar Performance

The following papers describe various experiments which have been performed to assess the performance of cetacean sonars. Some of this work is described in section 2.4

[5,11,14,15,17,20,21,69,70,79,93,101,103,128,130,131]

2.1.9 Classification

The following papers describe various techniques employed to classify the sounds produced by cetaceans, [43,63,88,90,106,133,134].

2.1.10 Cetacean tracking and population estimation experiments

Detecting and analysing the underwater sounds of cetaceans provides the researcher with an extra avenue to exploit in order to gather more information about these animals. Many different techniques have been used to detect the presence of cetaceans from the sounds they produce [36,37,100,111,133,134, and in some cases tracking of the movements of cetaceans has also been performed using their underwater sounds, [40,56,72,86,91,92,120,136,137,138,139].

2.1.11 Sound source levels and sightings of cetaceans

The following papers detail underwater sounds recorded from cetaceans in their natural environment as well as visual sightings that have been recorded for various species.

[4,33,34,41,42,45,49,50,59,61,62,65,76,77,80,124,125,140,142,143]

2.1.12 Signature whistle

Signature whistle production in dolphins was first hypothesized in 1965, [30] and reviewed at various times afterwards [31,32,85], since then many researchers have presented techniques for measuring and comparing these sounds, [29,64,83,84,109,112,113,115,119,122]. This area of research is described in more detail in section 2.5.

2.2 Anatomy Relating to Sound Production

Sounds produced by dolphins originate from the head area. The exact source and the method of production of the different sounds is a matter of contention between different researchers. The dolphin produces sound without the need to open it's mouth or exhale air through it's blowhole. However, sometimes air bubbles are emitted from the blowhole at the same time as sound production. The physical structures thought to be associated with sound production have been investigated by Green et. al. (1980). They have taken lateral and cross-sectional dissections through the head of a bottlenose dolphin (*Tursiops truncatus*), Figures 2.1 & 2.2. The physical structure of the head area of a dolphin is very different from other mammals, many major adaptations are apparent. Some adaptations are for respiratory reasons and others appear to be associated with sound production. The two most striking differences between dolphins and other mammals is the location of the nostrils (or blowhole) at the top of the head and the bulbous area in what would be the top lip in other mammals (melon). This location of the nostrils allows the dolphin to breathe without the need to fully surface. Dolphins possess two nasal passageways which fuse into one opening.

The melon is thought to be used in sound production as an acoustic lens, this was first suggested by Wood (1968). The melon has a varying sound speed profile, a lower velocity core is surrounded by a higher velocity shell which is closely matched to the speed of sound in water. The melon has mild focusing properties as shown by the ray trace diagrams in Figures 2.3 & 2.4, Au (1993).

2.2.1 Source of Sound Production in Dolphins

Most researchers have focused upon two areas which they have proposed as the source of sound production in dolphins. Dormer (1979) compiled a table of twenty entries summarising the different theories and techniques used to substantiate them of the different researchers.

Reference	Sound type	Species	Origin	Investigative technique
Blevins and Parkins (1973)	whistles, clicks	*Tursiops truncatus*	larynx	anatomy
Diercks et al. (1971)	clicks	*Tursiops truncatus* *Inia geoffrensis* *Orcinus orca*	nasal plugs	acoustics
Evans and Dreher (1960)	whistles clicks	*Stenella graffmani* *Stenella graffmani*	larynx premaxillary sacs	acoustics, anatomy
Evans and Maderson (1973)	clicks	*Tursiops truncatus*	nasal plugs, tubular sacs	microanatomy
Evans and Prescott (1962)	whistles, clicks	*Tursiops truncatus* *stenella graffmani*	nasal plugs, larynx	anatomy, acoustics
Lilly and Miller (1961)	whistles, clicks	*Tursiops truncatus*	air sacs, nasal passages	anatomy, acoustics
Lilly (1968)	whistles or clicks	*Tursiops truncatus*	left or right nasal plug	anatomy, acoustics
Lilly (1968)	clicks (high frequency)	*Tursiops truncatus*	larynx	anatomy, acoustics
Mead (1972)	whistles, clicks	18 Delphinidae	mostly right nasal passage	anatomy
Murie (1870)	unspecified	*Lagenoryhnchus albirostris*	larynx	anatomy
Murie (1871)	unspecified	*Grampus rissoanus*	larynx	anatomy
Norris et al. (1961)	clicks	*Tursiops truncatus*	forehead region	anatomy, acoustics
Norris et al. (1971)	whistles	*Stenella longirostris*	left nasal plug	cineradiography, anatomy
Norris and Harvey (1972)	clicks	*Physeter catodon*	museau de singe	anatomy, acoustics
Norris and Harvey (1974)	clicks	*Tursiops truncatus*	nasal plugs	anatomy, acoustics
Purves (1967)	whistles	*Tursiops truncatus*	larynx	anatomy, acoustics
Schenkkan (1973)	clicks	19 species	larynx	anatomy
Tomlin (1955)	whistles, clicks	*Delphinus delphis*	diaphram between right, left air sacs	anatomy, acoustics
Turner (1868)	whistles	*Globicephala svineval*	larynx	anatomy
Wood (1968)	unspecified	*Kogia* sp.	museau de singe	anatomy

The two main areas of contention are the larynx and the nasal air sac regions labelled 'A' and 'B' respectively in Figure 2.1. The dolphin does possess a larynx which is known to be the sound production mechanism in most other mammals. The larynx is the favoured site of sound production by researchers who use anatomical techniques. The acoustical techniques tend to point towards the nasal air sac region. Dormer (1979) used cineradiographic techniques upon live specimens and concluded that the larynx provided the air supply to the nasal sac region in which the sound production originated. He arrived at this conclusion by correlating the movements of the various structures with the sounds recorded from the specimens. He presents the schematic shown in Figure 2.5 as way of explanation of the air movements within dolphins during sound production.

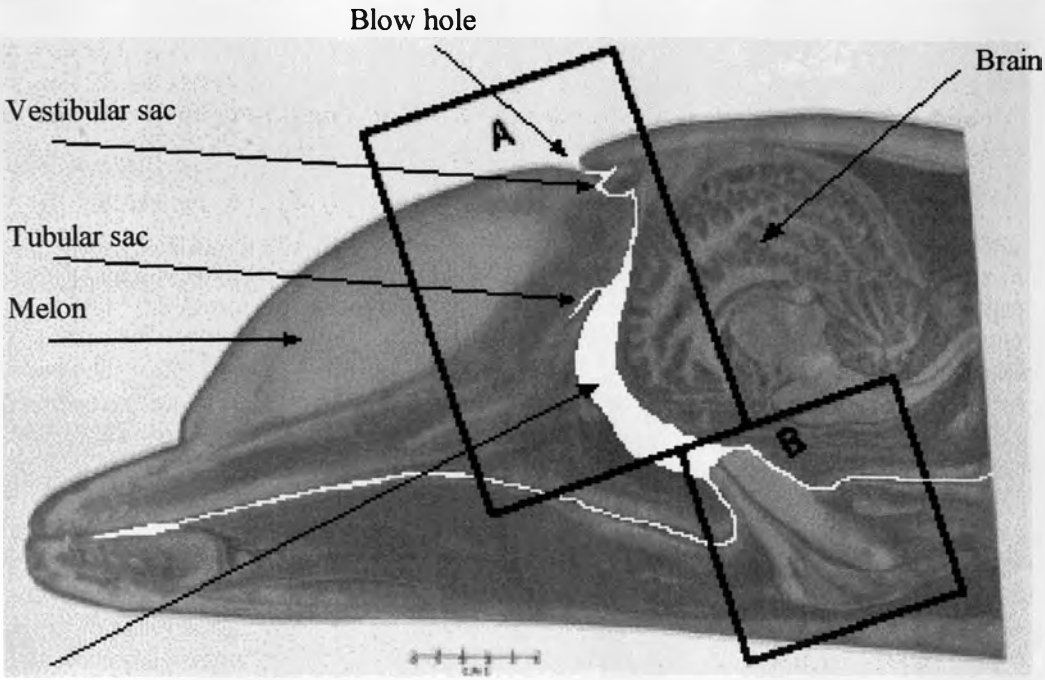


Figure 2.1 - Lateral dissection through the head of a dolphin.

Reproduced from Green *et al.* (1980)

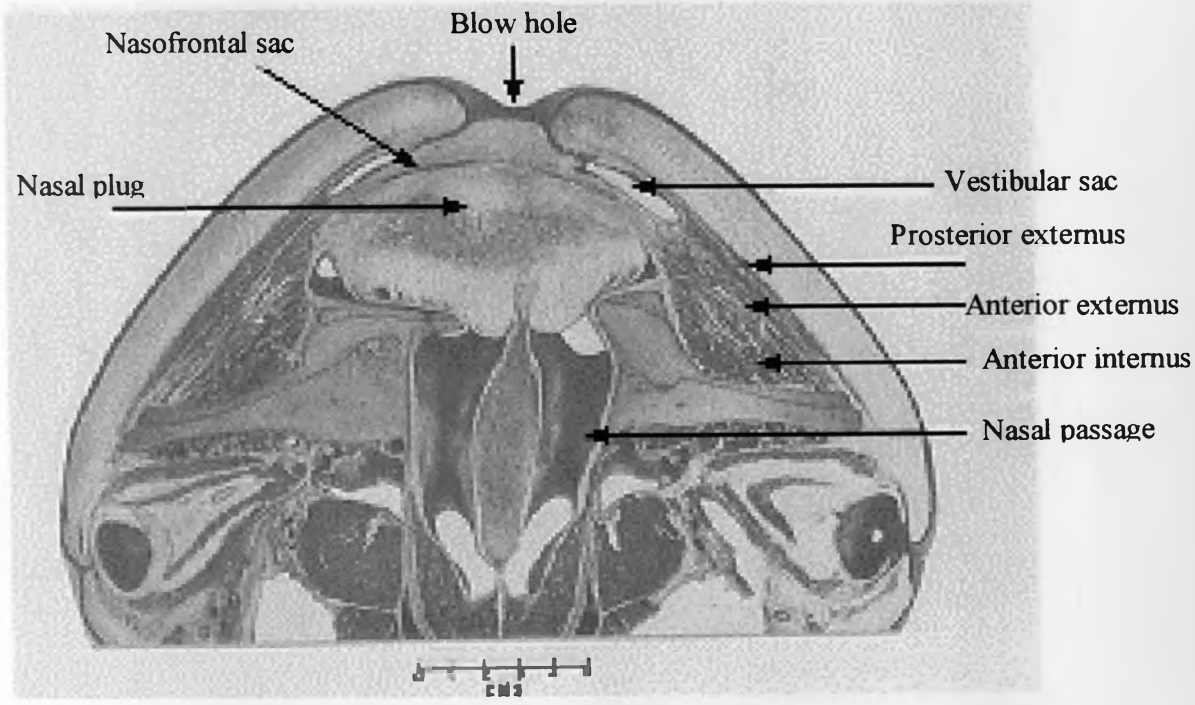


Figure 2.2 - Cross-sectional dissection through the head of a dolphin.

Reproduced from Green et al. (1980)

Side view

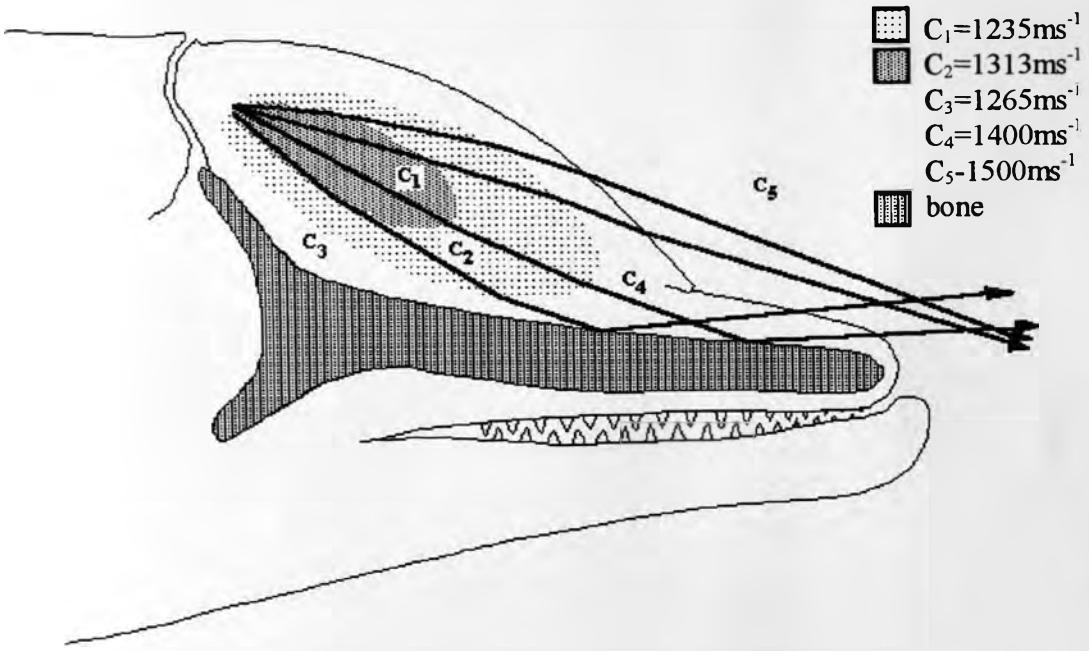


Figure 2.3 - Raytraces through the melon of a dolphin, side view.

Reproduced from Au W.W.L. (1993)

Top view

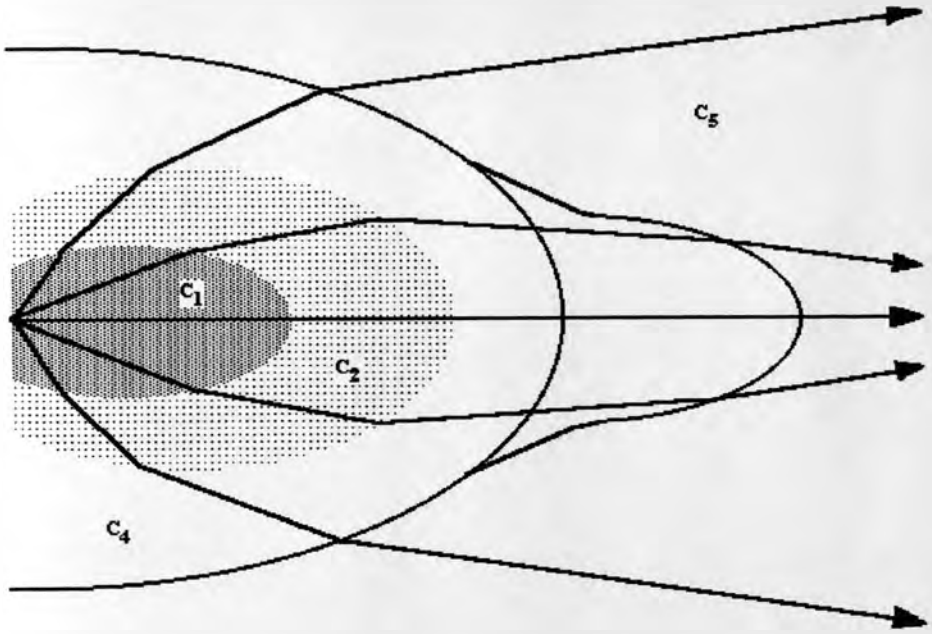


Figure 2.4 - Raytraces through the melon of a dolphin, plan view.

Reproduced from Au W.W.L. (1993)

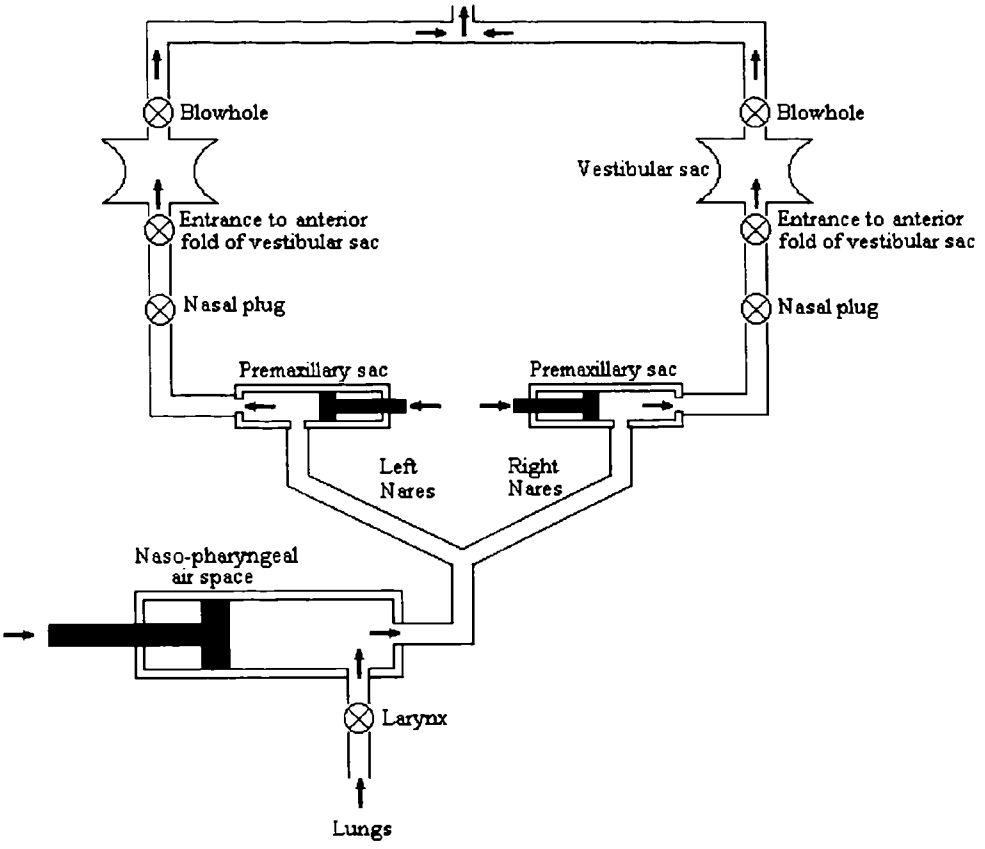


Figure 2.5 - Schematic diagram showing the air passageways of a dolphin.

Reproduced from Dormer (1979)

2.3 Hearing in dolphins

The hearing in dolphins is not well understood. Much speculation has been made about the actual mechanism of hearing in dolphins. Dolphins do posses an external ear which has an opening behind the lower jaw. Norris (1964) has suggested that dolphins use the lower jaw to receive sound and then channel it to the inner ear see Figure 2.7. There is a fatty channel which runs along the line of the jaw and is attached to the inner ear. This fatty channel has an acoustic impedance closely matched to that of sea water. A study by Brill and Harder (1991) sought to clarify the sound reception mechanism in dolphins by attenuating the dolphins echolocation signals in the region around the lower jaw. Two 'hoods' were used to cover the lower jaw of the dolphin. One hood called the control hood was made from gasless neoprene whilst the experimental hood was made from closed cell neoprene. The experimental hood greatly attenuated the echolocation signals. Brill and Harder (1991) found that the dolphin was able to emit useful echolocation clicks whilst wearing the hoods however the dolphin was 'significantly hindered in it's ability to echolocate.'

2.3.1 Auditory threshold

A study on the auditory thresholds of a captive bottlenose dolphin, *Tursiops truncatus*, was conducted by Ljungblad *et. al* (1982). Behavioural response techniques were used to test the hearing of the dolphin over the 1 kHz – 160 kHz frequency range. The dolphin responded to signals in the 2 kHz – 135 kHz frequency range. The sensitivity

is recorded as the minimum sound intensity level at which the dolphin responded to the signal. This sound intensity was determined by attenuating the signal in 5 dB steps until the dolphin failed to respond. The signal was then increased by 15 dB and then attenuated again until there was no response. Figure 2.6 shows the hearing threshold measured over this range, this work shows the dolphin to be most sensitive to sound in the band 27 to 60 kHz.

2.3.2 Dolphin receiving beam patterns

The receiving beam patterns of the Atlantic bottlenose dolphin, *Tursiops truncatus*, have been measured by Au and Moore (1984). The measurements were made using tones of 2 s duration at frequencies of 30, 60 and 120 kHz at varying angles to the dolphin. The beam patterns are reproduced in Figure 2.8. The beam patterns show that maximum sensitivity occurred in the vertical plane between 5° and 10° above the midline of the dolphins mouth, whilst in the horizontal plane maximum sensitivity occurred at 0°. The vertical beam pattern is asymmetric, the sensitivity dropping off more quickly above the head than below it. The horizontal beam pattern is reasonably symmetric. Au and Moore (1984) also calculated the receiving directivity index as used in the sonar equations described by Urick (1975). The directivity indices were found to be 10, 15 and 21 dB for frequencies of 30, 60 and 120 kHz respectively.

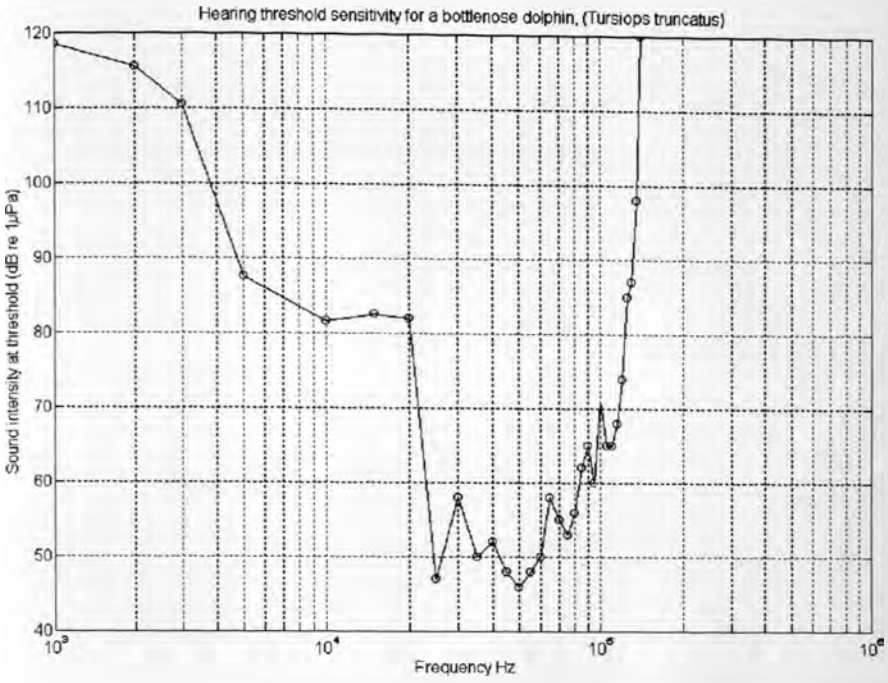


Figure 2.6 - Auditory threshold of an

Eastern Pacific bottlenose dolphin, (Tursiops truncatus)

reproduced from data presented by Ljungblad *et. al* (1982)

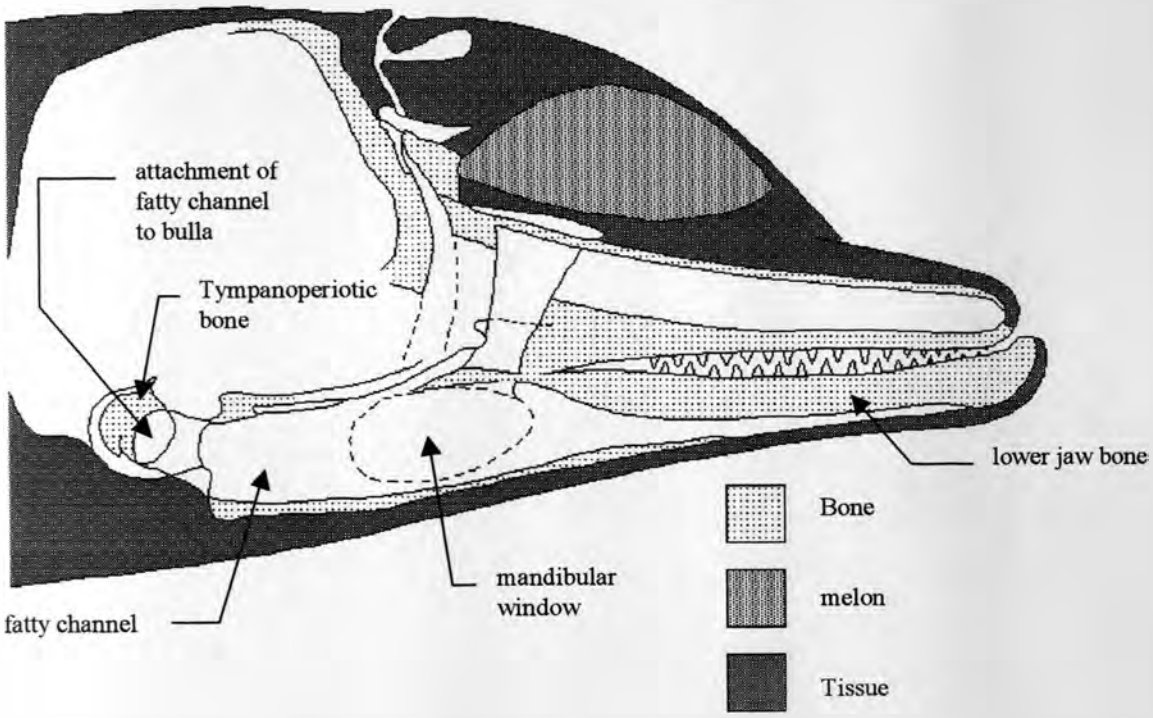


Figure 2.7 - Locations of the structures associated with sound reception.

Reproduced from Au W.W.L. (1993) [7]

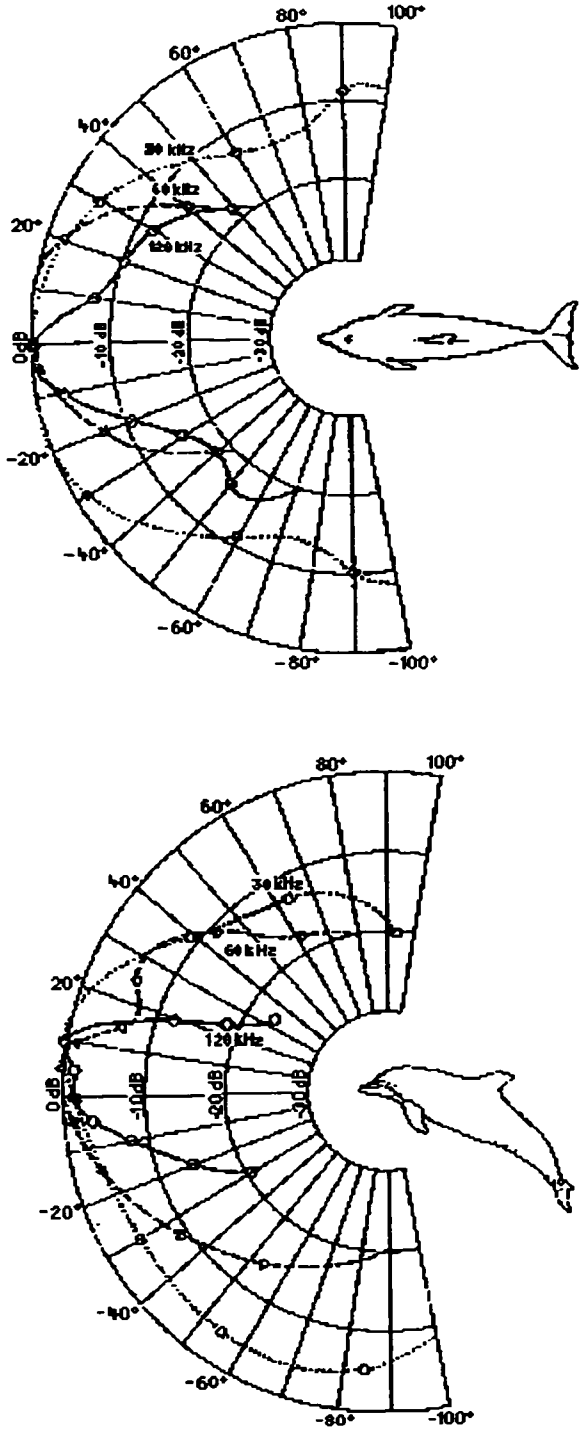


Figure 2.8

Above: **Horizontal receiving beam pattern**

Below: **Vertical receiving beam pattern**

reproduced from Au and Moore (1984)

2.4 Cetacean Sonar Capabilities

Captive dolphins have been the subjects used by many researchers. Dolphins, especially the bottlenose dolphin, have been the favoured choice for study. These small cetaceans are readily housed in pools or corals at costs which are not too prohibitive. The largest cetacean held in captivity is the killer whale. Many experiments have been performed in order to quantify the capabilities of a cetaceans sonar. Trained dolphins are used to respond to different stimuli in order that the researcher can gauge the performance. The typical experimental set-up is shown in Figure 2.9. This shows a floating pen which is located inside the pool or sometimes experiments are conducted in more natural conditions such as in a lake, wide river or bay. The dolphin is constrained to the pen and under command of the researcher orientates itself below the water with it's head through a hoop, it then performs an echolocation task and responds via paddles located on the side of the pen. The paddles represent a YES/NO response which is dependent upon what task the dolphin has been trained to perform. For example the dolphin may be performing a maximum range experiment where a target is placed at ever increasing distances until the dolphin is no longer able to detect it. The maximum range is found when the dolphin responds NO to the presence of a target when one is there. Training is performed by means of reward, the dolphin receives a food reward when it touches the correct paddle, i.e. YES when the target is present or NO when the target is absent.

Early researchers used the hoop station to locate the dolphin, this technique affords the dolphin restrictive movement of the head. Experiments to measure the beam patterns

of a dolphins sonar requires the dolphins head to remain in the same orientation. This is achieved by training the dolphin to bite onto a plate thereby restricting it's ability to move it's head, Figure 2.10.

Murchison (1980) has used this technique in Kaneohe bay to measure the maximum detection range of a bottlenose dolphin. Murchison found that the dolphin was able to detect with 90% accuracy the presence of a 7.62 cm diameter water filled steel sphere at a range of 73m. Several other researchers have attempted to measure the maximum range of a dolphins sonar, the results of their experiments are shown in Table 2.2.

Table 2.2 - Maximum detection range for different targets

Author	Target	Maximum range
Ayrapet'yants & Konstantinov (1974) 90% detection bottlenose dolphin	metal cylinder (75mm height 75mm diameter plastic cylinder (115mm height no diameter given) wooden cylinder (115mm height no diameter given)	11m 7.3m 6.8m
Morozov et al. (1972) 100% detection bottlenose dolphin	20cm fish (dead mackerel)	30m
Titov (1972) bottlenose dolphin	rubber sphere 50mm diameter wax sphere 50mm diameter lead sphere 50mm diameter steel sphere 50mm diameter	5.9m 7.8m 11.1m 12.4m
Babkin & Dubrovskiy (1971) bottlenose dolphin	steel sphere 4mm steel sphere 12.3mm lead sphere 3mm lead sphere 12.7mm mackerel 13.5cm long	3.5m 7.5m 3m 9m 9.8m

The different targets used in each of these experiments makes it difficult to compare results. The target strength of each of these targets is not given by the authors. All of the targets used in the above table are much smaller than the one used by Murchison(1980) which accounts for the discrepancy in the maximum range. The two experiments involving dead mackerel have very different results, but again the targets are of varying size. The theoretical maximum range derived from the sonar equations can be calculated and this is performed in Chapter 3.

Murchison (1980) also performed a resolution experiment in order to find the maximum distance that a dolphin is able to distinguish the presence of one or two targets. The dolphin was trained to respond YES if it detected two targets and NO if it detected only one. The targets were placed together at ever increasing distances and then moved apart until the dolphin responded YES. The results of this experiment are shown in Figure 2.11. The dolphin was able to detect two targets with at least 90% accuracy as long as they were more than 6 cm apart.

Since 1980 an Hawaiian researcher, Whitlow W.L. Au, with access to the American naval dolphin research facility has published many papers and a book on the sonar of captive dolphins. Au's work has concentrated on the high frequency echolocation clicks produced by dolphins and he has not speculated upon the purpose of other sounds produced by these cetaceans such as the signature whistle. The echolocation clicks used in a target detection task are described by Au (1980) as exponentially decaying sinusoidal pulse of peak frequency ~110 kHz and duration ~150μs as shown in Figure 2.12. The source levels quoted by Au (1980) are peak to peak levels measured from the time pressure waveform. Appendix D describes the conversion to

the usual rms source level. Peak to peak levels are used due to the difficulty in measuring the rms level. RMS meters have too long an integration time to be used for dolphin clicks.

2.4.1 Beam Patterns

Dolphin echolocation clicks are directional. The sound is projected from the head of the dolphin forwards into the water. A directional acoustic source of this nature has a directivity index associated with it. The directivity index (DI) is described by Urick (1975). A directional source requires less energy to produce the same intensity at a particular point along an axis than an equivalent omni-directional source. The directivity index is calculated by comparing the intensity of the directional source to the intensity that an omnidirectional source would produce, were it to radiate the same acoustic power, see Figure 2.13. It is calculated from the following equation:

$$\mathrm{DI} = 10\log\left(\frac{I_D}{I_{NOND}}\right)$$

where, I_D is the Intensity of the directional receiver and I_{NOND} is the intensity of the omni-directional receiver.

2.4.2 Atlantic bottlenose dolphin transmitting beam pattern

Au et al. (1986) have measured the transmitting beam patterns of Atlantic bottlenose dolphins in the horizontal and vertical planes. These beams are measured for the emission of the 120 kHz echolocation pulses. Figure 2.14 shows the transmitting beam patterns. Au et. al. (1986) has also calculated the directivity of these beams, and found it to be approximately, $DI_T = 26.5$ dB.

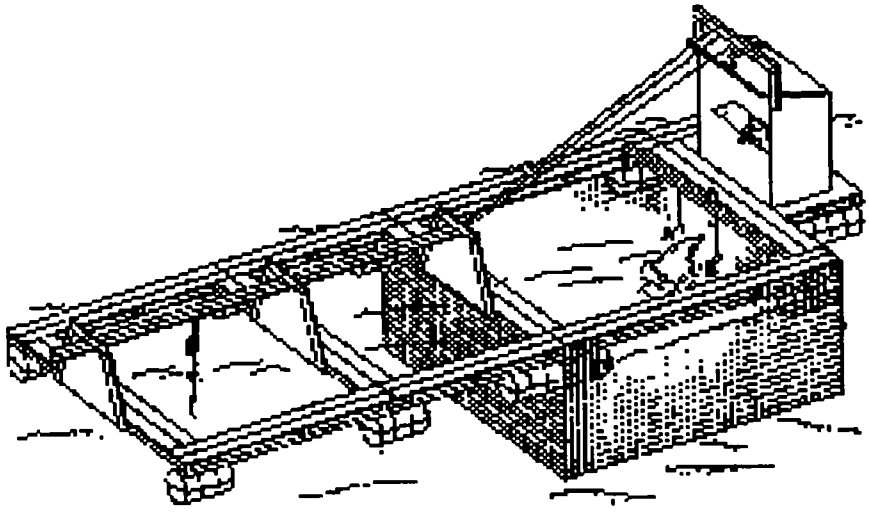
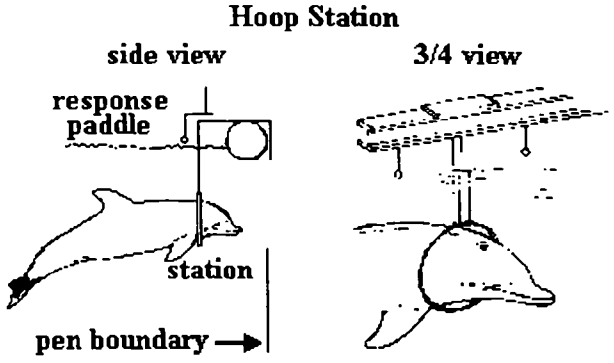


Figure 2.9 - Floating pen used in captive dolphin experiments.

Redrawn from a sketch produced by Schusterman (1980)

(a)



(b)

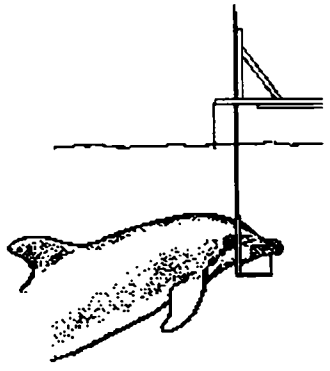


Figure 2.10 - (a) Hoop station orientation method

(b) Bite plate orientation method.

Reproduced from Schusterman (1980)

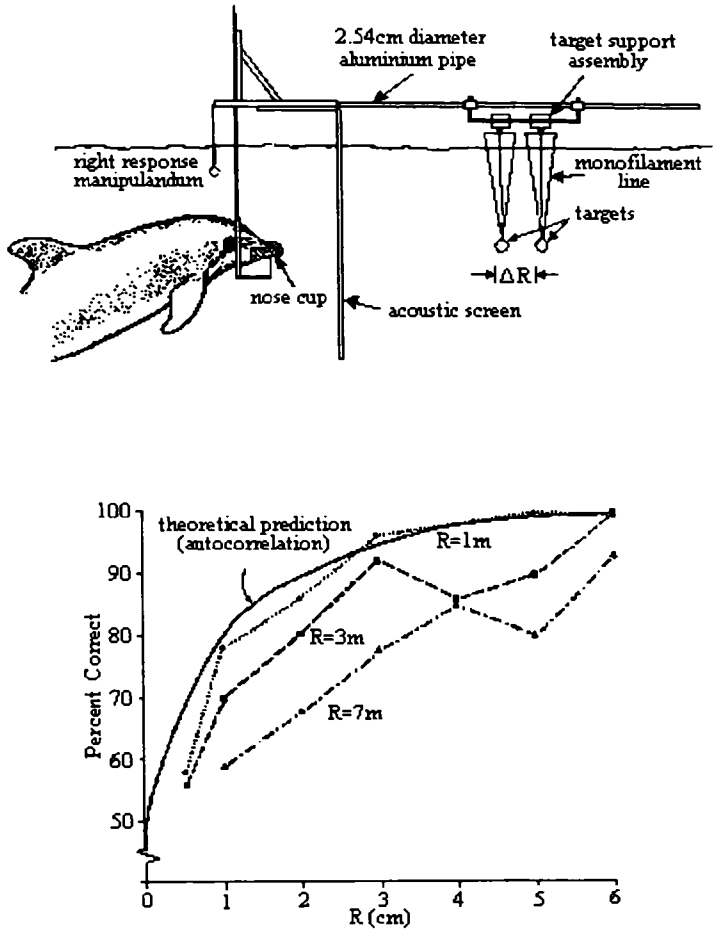


Figure 2.11 - Resolution experiment performed by Murchison (1980)

(a) Experimental set-up.

(b) Results of sonar resolution experiment.

Reproduced from Murchison (1980)

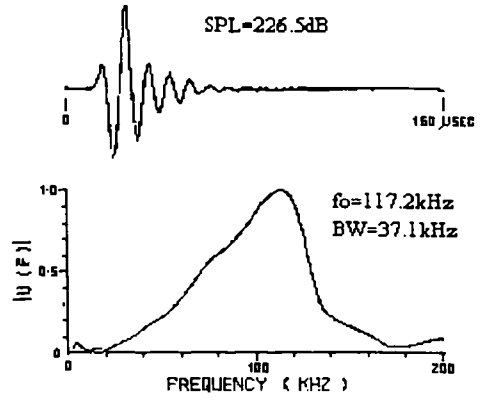


Figure 2.12 - Average click waveform and spectrum of a bottlenose dolphin.

Reproduced from Au W.W.L. (1993) [7]

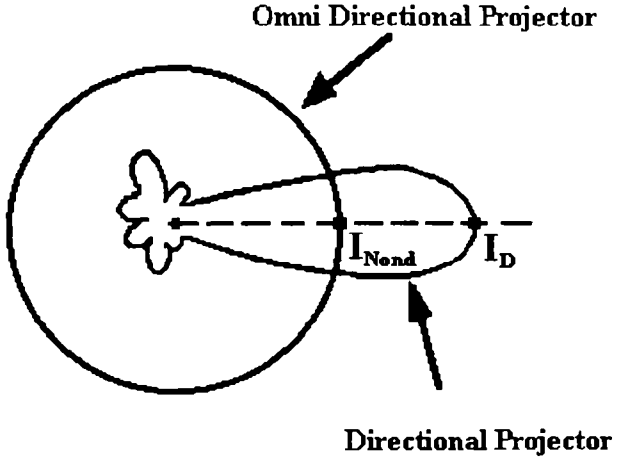
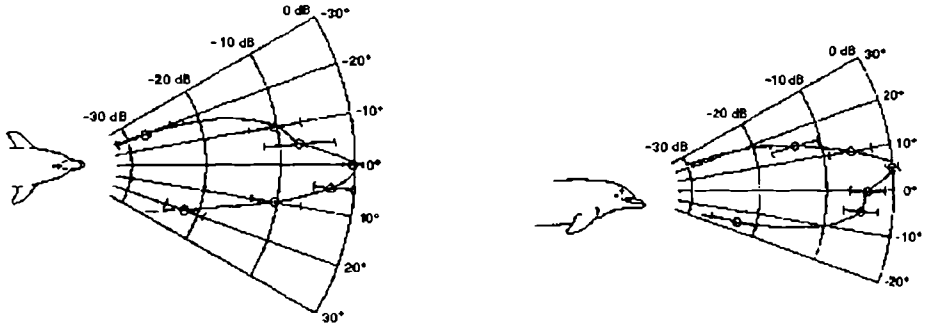


Figure 2.13 - Beam patterns of directional and omni-directional projectors radiating the same acoustic power.

Reproduced from Urick (1975)



a) b)

Reproduced from Au *et al.* (1986)

Figure 2.14 -

a) Horizontal transmitting beam pattern of the echolocation clicks of a bottle nose dolphin.

b) Vertical transmitting beam pattern of the echolocation clicks of a bottle nose dolphin.

2.5 Whistle production amongst dolphins

Essapian (1953) is credited with suggesting that individual bottlenose dolphins are able to produce distinctive 'notes' which are recognisable by other dolphins. Caldwell and Caldwell (1965-1990) produced the first scientific work on the signature whistle. Their first paper in 1965 presented the hypothesis that bottlenosed dolphins produced whistles with individualised contours. An experiment was performed on five freshly captured dolphins over a three week period. During this time the whistles emitted from the dolphins were recorded and played back at 1/8th speed. Caldwell and Caldwell (1965) report that 90% of whistles emitted by the dolphins were their own distinctive whistle. The five whistles were categorised in Table 2.3.

Table 2.3:

Dolphin Number	Description	Repetitions	Notes
1	sharply rising single upsweep	1-9	
2	falling inflexion with a break at the lower end	never more than twice in series	
3	single unbroken up-and-down sweep	1-7	also distinctive series of breaks resembling a musical scale
4	falling inflexion then a rise and fall at least once	the rise and fall at the end sometimes continued up to four more times	
5	same as four except that it begins with a rise rather than a fall	the rise and fall at the end continued between two and five times	

Summarised from Caldwell & Caldwell (1965)

They also report that the whistles show signs of variability, however the contours stay consistent. Different whistles were sometimes recorded but were infrequent. Others sounds emitted by the dolphins were described as, squeals, chirps, squeaks, squawks, barks, yelps, grating sounds and echolocation clicks. No attempt was made to give these sounds any relevance, apart from the echolocation clicks which had been extensively investigated at the time by many other researchers.

Species specific differences in the whistles of five species of dolphin were investigated by Steiner (1981). The five species were: *Tursiops truncatus*, *Stenella longirostris*, *Stenella plagiodon*, *Lagenorhynchus acutus*, and *Globicephala melaena*. The recordings were taken of free ranging dolphins along the Eastern coast of America, from Nova Scotia to the Caribbean, during the period August 1964 to April 1977. Steiner (1981) measured six features from the whistles produced by these dolphins: maximum frequency, minimum frequency, beginning frequency, final frequency, duration and the number of points of inflexion. The number of whistles measured for each species of dolphin was as shown in Table 2.4.

Table 2.4:

Dolphin species	Date range (years)	Number of whistles
Tursiops truncatus	1964-1971	858
Stenella longirostris	1967 &1977	1691
Stenella plagiodon	1969 & 1971	1529
Lagenorhynchus acutus	1966 &1967	567
Globicephala melaena	1973	2088

There is no mention in the paper as to how the recordings of the dolphins were identified as belonging to the above species, presumably this was done from visual sightings. The statistics measured from these whistles were used to perform a

canonical correlation analysis. The results of this technique are plotted in Figure 2.15. These results show that, *Tursiops truncatus* and *Globicephala melaena* are the easiest to distinguish, due to their separation on the canonical map. The other species are much closer on the map and are therefore more difficult to distinguish from each other.

Weight has been given to the signature whistle hypothesis proposed by Caldwell & Caldwell (1965) by research performed on a small community of bottlenose dolphins, by Sayigh *et. al.* (1990). Approximately 100 bottlenose dolphins have been studied over a fourteen year period in the waters off Sarasota, Florida. The ages, sex and matrilineal relationships of these dolphins have been documented since 1970. The recording of whistles from 12 mother calf pairs has been conducted over a twelve year period. The study of these whistles have shown that individuals favour their own distinct whistle which has remained stable over the period of the recordings. Recordings were generally taken using a contact hydrophone on restrained dolphins and therefore large signal-to-noise ratio was achieved. The study was performed on mother calf pairs and so little data was collected on adult male dolphins. The relationship between the mother and calf whistles was also investigated. Calves produced their own distinctive whistle in the first year and this whistle remained stable over the period of the recordings. The male calves tended to produce similar whistles to their mothers, whilst the female calves tended to produce distinctly different whistles. This preliminary study was extended and Sayigh *et. al.* (1995) published the results from a study of 42 mother calf pairs. This later study validated the earlier hypothesis.

The use of signature whistles by wild bottlenose dolphins during separations and reunions has been investigated by Smolker *et. al.* (1993). This was a behavioural study which produced subjective conclusions. The infants were found to produce more whistles during separations than when they were close to their mothers, however the mothers were found not to produce a greatly increased rate of whistle production.

Buck and Tyack (1993) present a method for determining a quantitative measure of similarity for *Tursiops truncatus* signature whistles. They develop an algorithm to automatically extract the contour of a whistle from it's spectrographic representation. They also compensate for variability within the duration of the whistles by describing a non-uniform time dilation algorithm which is used to align contours for comparison. A least squares comparison is used to test for similar whistles. Only thirty examples of whistles were used in this study. The whistles were taken from the same group of dolphins studied by Sayigh *et. al.* (1990). The algorithm presented was able to distinguish twenty nine whistles only failing to correctly identify one whistle.

Statistical analysis of two species of dolphin found in the waters off the East coast of Australia has been presented by Shultz and Corkeron (1994). The two species of dolphin recorded were *Tursiops truncatus* and *Sousa chinensis*. The recordings were taken over an eleven day period during the summer of 1990. Twelve hours and 34 minutes of recordings were taken and analysed. Eight variables were used for the analysis which were extracted using an overlay placed upon the spectrographic representation of the whistles. The results of plotting the first two canonical discriminant variables is shown in Figure 2.16. The two species do produce different whistle types and clustering can be seen from the canonical plot. However there is

overlapping of the two species which would result in errors when trying to classify an unknown whistle.

A technique for quantitative contour similarity measurement is presented by McCowan (1995). This technique extracts 20 frequency variables from the spectrographic representation of captive *Tursiops truncatus* dolphins. These measurements are made by hand from the spectrogram. Five captive dolphins all from Marine World Africa USA (Vallejo, CA) were the subject of this experiment. Twenty whistles from each were used for the comparison.

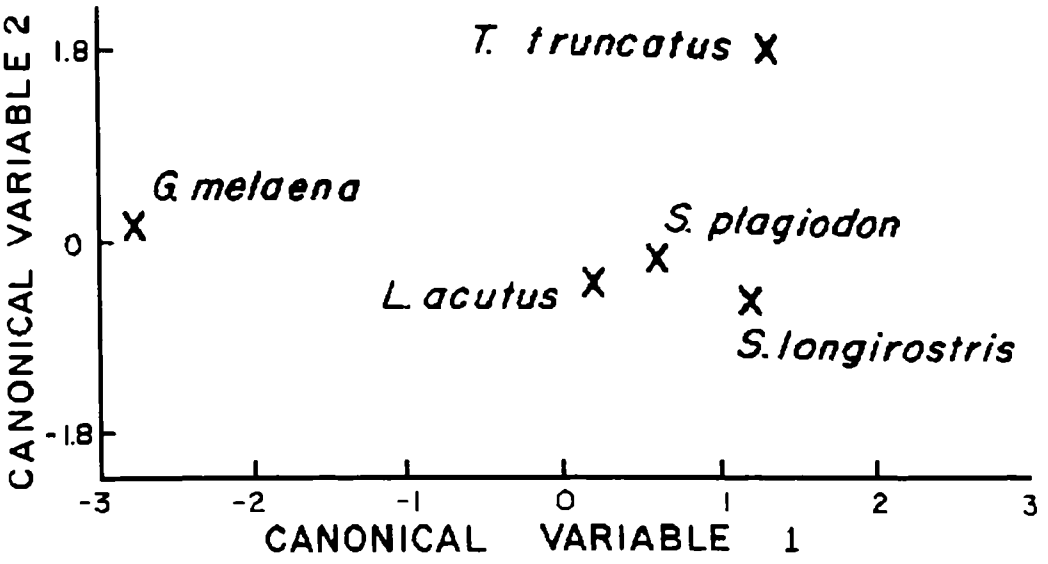


Figure 2.15 - Plot of the first two canonical variates.

Reproduced from Steiner(1981)

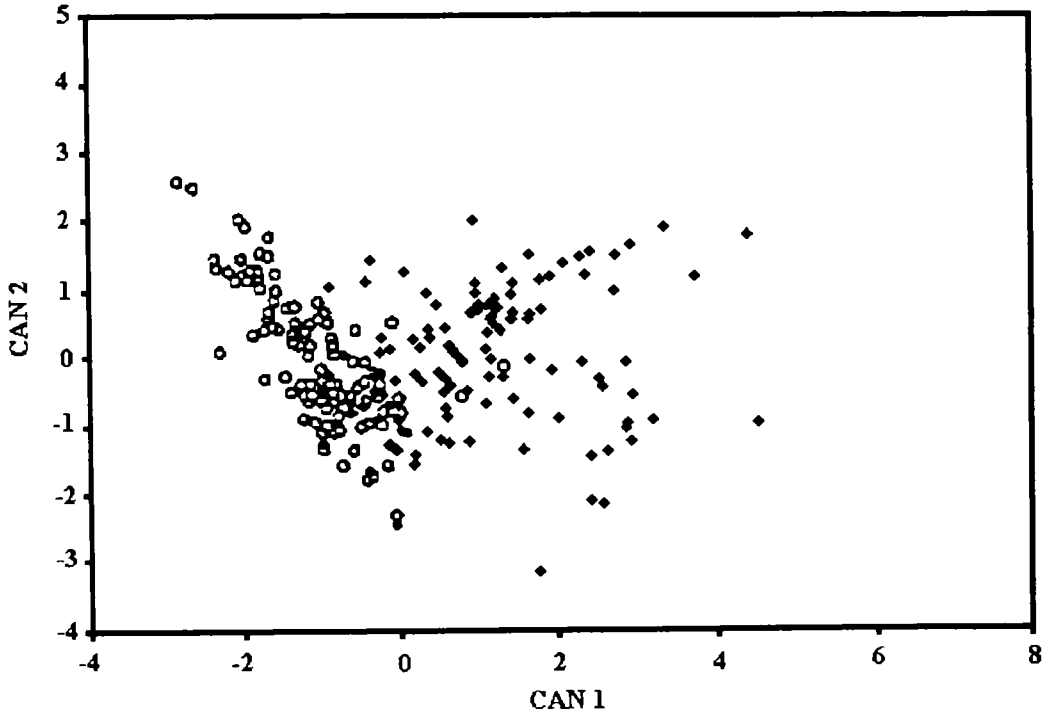


Figure 2.16 - Canonical discriminant analysis plot of Tursiops truncatus and Sousa chinensis whistles.

reproduced from Shultz and Corkeron (1994)

2.6 Current developments

During the write up period for this thesis a paper was found which also describes a similar pulse to that presented in Chapter 9. This paper by Shultz et al. (1995) describes a low frequency narrow band sound produced by bottlenose dolphins. The sound described is similar to those presented in Chapter 9 of this thesis and also in the authors M.Phil, for the striped dolphin. The sound described by Shultz et al. is for a different species of dolphin. Shultz et al. do not put forward any hypothesis for the use of the sound. This finding suggests that the harmonic pulse sound may be present in other species than the one studied in this thesis and that perhaps many other species posses the capability to produce this sound.

Also during the write up of this thesis a paper appeared supporting the signature whistle hypothesis and is detailed below:

Janik & Slater (1998) describe experiments on captive bottle nose dolphins and presented the following conclusions:

> "Each dolphin produced one stereotyped signature whistle when it was separated from the group. Similarly the remaining group in the other pool also used primarily their signature whistles if one animal was in a separate pool. Signature whistle copying was rare and did not initiate reunions or specific vocal responses. The results strongly support the hypothesis that signature whistles are used to maintain group cohesion."

A Ph.D. thesis has been produced on signature whistle extraction and analysis by Loughborough University which was conducted concurrently with the work presented

in this thesis. The work presented by C.R. Sturtivant (1997) in that thesis does not however compare the algorithms which he has developed with those in the current literature or indeed make reference to them. It is therefore difficult to assess any potential improvement in his algorithm design compared with those in the literature and indeed with the ones presented in this thesis. Chapter 7 of this thesis compares the algorithms of Buck & Tyack (1995) with the ones presented in Chapter 6 to show an improvement using simulated dolphin sounds so that a fair comparison could be made. Due to time constraints it has not been possible to perform a similar study of the algorithms presented by C.R. Sturtivant. The omission of references to the work by Buck and Tyack and others in Strutivant's thesis is strange since the conclusions drawn imply the work produced is of a novel nature:

> "The *raison d'etre* behind this research was to provide a novel research tool which would aid in the study of changes in behaviour over time of dolphins in the wild. No such acoustic tool previously existed for the quantitative measurement of differences in whistle structure."

Chapter 3 - Theoretical propagation distances of dolphin vocalisations

3.1 Introduction

When using a passive acoustic array to record cetacean sounds an understanding of how these sounds propagate through the ocean is essential. If the maximum range of detection that a dolphin can perform can be evaluated then measures can be taken to evade a dolphins sonar thereby rendering the dolphin oblivious to the observation process. This is only possible if the signals of interest propagate further than the range of the dolphins sonar. The high frequency clicks of dolphins are attenuated more severely than the lower frequency signature whistles. The signature whistles are the signals of interest for this project. It is possible to detect and record the signature whistles whilst observing from a distance outside the range of the dolphins sonar. The maximum distance of propagation of the signature whistles has not, to the knowledge of the author been presented in the literature, either experimentally or from theoretical predictions.

Theoretical predictions are presented to validate the hypothesis that recordings of signature whistles can be performed without the knowledge of the dolphin. The sonar equations developed by Urick (1975) have been applied to dolphin sounds described in the literature. This gives a better understanding of how the sounds which are emitted by dolphins propagate. The more frequently emitted high frequency echolocation click sounds used by dolphins has a maximum range of detection on a passive array. The range of detection of these clicks is limited by the background noise and the

sensitivity of the receiver. The characteristics of the array and the dolphins sonar can be estimated, which yields a reasonable approximation to the maximum range of detection of a dolphin click sound. The whistle sounds emitted by dolphins are much lower in frequency than the click sounds but are of a lower intensity. The sonar equations presented later in this chapter show that although the whistle and click sounds emitted by dolphins are of different intensities the propagation distances are similar due to the different attenuation rates of the ocean. The vocalisations are often heard before the dolphin is detected by any other means including visual sightings. The intensity of the emitted sound is also important when designing amplifiers and filters for dolphin detection. Overloading of amplifiers when cetaceans are near to the array will render the recordings useless, unless the gains and sensitivities are properly set.

The clicks emitted by dolphins are known to be used for echolocation purposes as described in a series of papers by Au *et al.* (1980-1995). The effective range of echolocation by a dolphins' sonar has been determined experimentally (see Table 2.2). Artificial targets, i.e. targets the dolphin would ordinarily be unlikely to encounter in it's natural environment, are usually used in the experiments. Some experiments however, have involved the use of dead fish (Morozov *et al.* (1972), Babkin & Dubrovskiy (1971)) which is more representative of the type of target the dolphin would normally be trying to detect.

3.2 Background Noise levels

The received signal at the hydrophone consists of the desired signal and the background noise. The noise level NL, sometimes called the ambient noise level, is a measure of the undesired portions of the received signal. If sufficiently large the noise level can completely mask the desired signal. In this case the desired signal would be undetectable, unless a correlation process can be used.

There are many factors which contribute to the background noise detected at a particular location. Each contributor of noise tends to occupy a distinct band in the frequency spectrum. When noise sources overlap one or other tends to dominate. Table 3.1 gives the frequency bands and the major contributor to the noise in each band.

Table 3.1

Noise source	Frequency range
Tides and waves	1 or 2 cycles per day
Seismic disturbances	1/7 Hz (microseisms)
Oceanic turbulence	1 - 10 Hz
Ship traffic	50 - 500Hz
Surface noise	500Hz - 25kHz
Thermal noise	above 100kHz

As well as the noise sources described in the above table intermittent noise can also be present from a variety of sources. Rain and storm weather, crustacea in shallow water and wind speed all contribute to increased noise levels.

Coates (1990) gives empirical formulae for estimating the noise spectrum level from the four main contributors,

Turbulence Noise

$$NSL_1 = 17 - 30(\log f) \text{ dB re } 1\mu\text{Pa} \tag{3.1}$$

Shipping Noise

$$NSL_2 = 40 + 20(D - 0.5) + 26(\log f) - 60(\log(f + 0.03)) \text{ dB re } 1\mu\text{Pa} \tag{3.2}$$

Surface Agitation Noise

$$NSL_3 = 50 + 7.5\sqrt{W} + 20(\log f) - 40(\log(f + 0.4)) \text{ dB re } 1\mu\text{Pa} \tag{3.3}$$

Thermal Noise

$$NSL_4 = -15 + 20\log(f) \text{ dB re } 1\mu\text{Pa} \tag{3.4}$$

The overall noise spectrum level can be calculated thus,

$$NSL = 10\log\left(10^{\frac{NSL_1}{10}} + 10^{\frac{NSL_2}{10}} + 10^{\frac{NSL_3}{10}} + 10^{\frac{NSL_4}{10}}\right) \text{ dB re } 1\mu\text{Pa} \tag{3.5}$$

Where f is the frequency measured in kHz, W is the wind speed in ms^{-1} and D is the level of shipping density from 0 (very light) to 1 (heavy). Figure 3.1 shows the noise spectrum levels calculated from the formulae above.



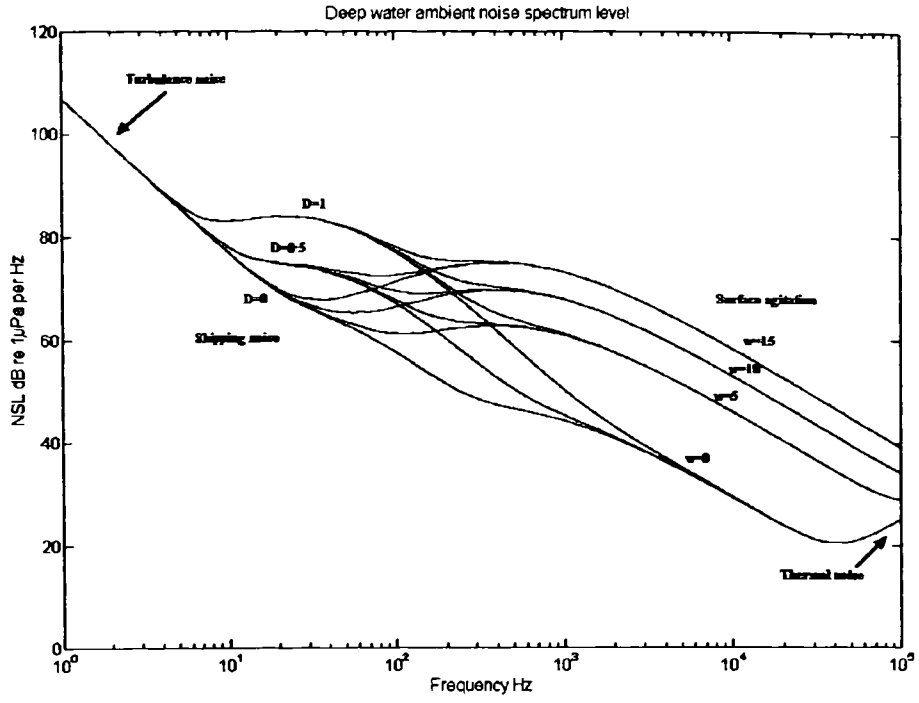


Figure 3.1 - Deep water ambient noise spectrum level.

The background noise levels for the experimental location in the Ligurian Sea were measured for different locations and varying boat speeds (with and without the engine running). The water depths in this area are around 1.5 to 2 km.

The recording acquisition system introduces gain at various stages. In order to calculate the ambient noise level these effects must be taken into account. The hydrophone has a sensitivity of -201dB/V re 1μ Pa. The preamplifier introduces a gain of 28dB. The DAT recorder also amplifies or attenuates the signal depending upon the input source and the input gain level, see Figure 3.2. Calibration charts for the DAT players and the preamplifier are given in Appendix E and Chapter 5 respectively.

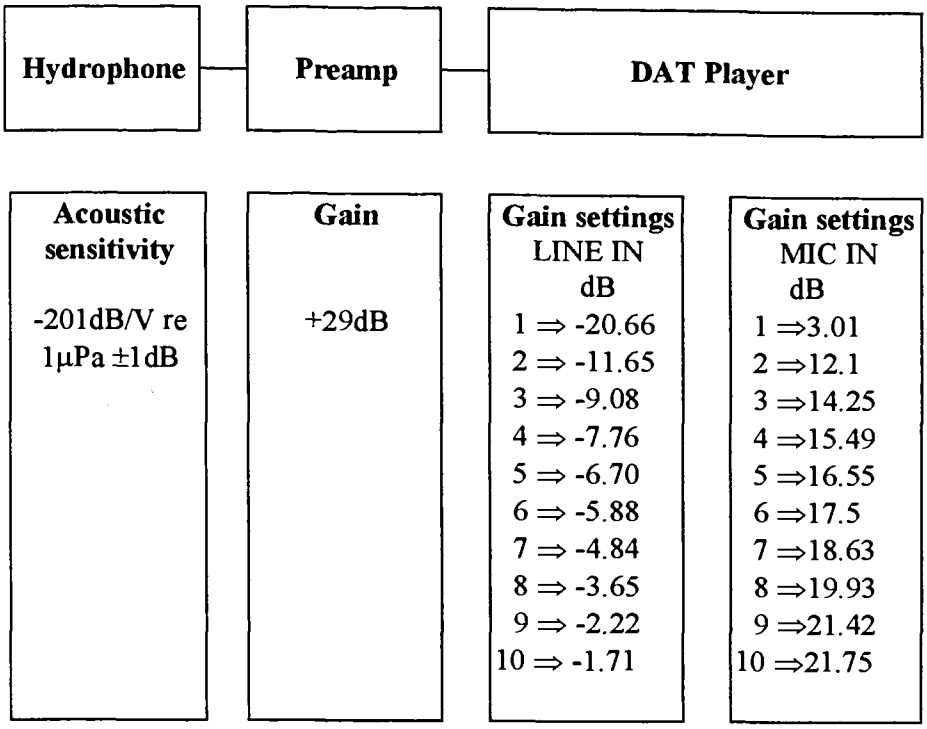


Figure 3.2 - Ambient noise level signal conditioning.

3.2.1 Hydrophone sensitivity

The acoustic sensitivity of the Benthos AQ4 elements used in the towed array have a sensitivity of -201dB/V re 1μ Pa. Therefore

$$-201 = 20\log\left(\frac{V_{out}}{P_{in}}\right)$$

and

$$\frac{V_{out}}{P_{in}} = 8.912 \times 10^{-11} \qquad \frac{\text{V}}{\mu\text{Pa}}$$

where V_{out} is the potential produced at the element terminals when the input pressure P_{in} = 1μ Pa. The noise spectrum level was calculated from the recordings by digitising them using a sound card and then taking 1024 point FFT in Matlab© to obtain the noise spectrum. The effects of the system were compensated for so that the voltage output

at the hydrophone element and therefore the sound pressure level could be calculated. The ambient noise levels with the engine on were calculated at speeds from 1-6 knots, see Figure 3.3. Also shown on the same figure are the typical deep water ambient noise spectrum levels for comparison. In the frequency band below 2 kHz the noise spectrum from the towed array is much greater than the typical ambient levels. This is as expected and is due to the close proximity of the array to the boat (100 m). As the boat speed increases, the noise spectrum level from the towed array increases. The noise spectrum increases by almost 20 dB as the tow speed is increased from 1 to 6 knots. In the frequency band where dolphin whistle production occurs, 5 kHz to 20 kHz, the towed array spectrum levels are within the typical ambient noise levels. The noise level due to increasing boat speed does not significantly increase the noise spectrum level in this band.

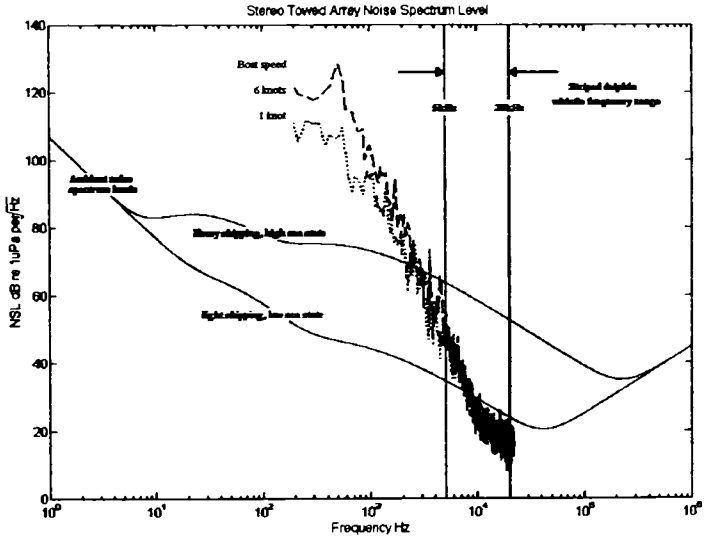


Figure 3.3 - Noise spectrum levels at varying speeds from the stereo towed array.

dotted line (———), ambient noise spectrum at a tow speed of 1 knot.

dashed line (———), ambient noise spectrum at a tow speed of 6 knots.

solid line (———), typical ambient noise levels.

solid vertical lines (| |), frequency band of whistle vocalisations.

3.3 Propagation of dolphin signature whistles

It is useful to have an estimate of the maximum propagation distance of the dolphin whistle. The passive sonar equation can be used to give a prediction of the maximum range at which a dolphin signature whistle can be detected. Very little data has been published on the source levels of dolphin signature whistles. To the knowledge of the author, to date only one report has been published recording the source levels for free ranging dolphins, Fish & Turl (1976). This is probably due to the difficulty in accurately determining the position and indeed the origin of the sound. The passive sonar equation used to determine the range of propagation of a signature whistle is given by Urick (1975) as,

$$SE = SL + DI_R - NL - TL\text{-}DT$$

where

SE is the Signal Excess, measured in dB re 1μPa

SL is the Source Level measured in dB re 1μPa @ 1m. The source level SL also includes the transmitting directivity.

DI_R is the directivity index of the receiver, measured in dB.

NL is the background noise level, measured in dB re 1μPa.

TL is the transmission loss due to propagation of the sound through the water, measured in dB.

DT is the Detection Threshold of the receiver, measured in dB.

The source levels of a dolphin's signature whistles has been reported in the literature by Fish & Turl (1976), and was measured from a sample of whistles from a group of approximately 10 free ranging dolphins.

The source levels measured by Fish & Turl (1976), measured in a bay were:

SL = 150 to 173 dB re: 1μPa @ 1m (8 kHz)

The bandwidth of these sounds is between 5kHz and 15kHz, therefore B=10kHz.

Background noise levels can be estimated from empirical formulae presented by Coates (1990), equation 3.5. These are typical noise levels experienced in deep water environments, and at 8 kHz the Noise Level (NL) is:

$$NL_{8k} = NSL_{8k} + 10\log(B) \text{ dB re } 1\mu Pa$$

$$NL_{8k} = 54 + 40 = 94 \text{ dB re } 1\mu Pa$$

The directivity of the receiving array is omni-directional at these frequencies. Therefore,

$$DI_R = 0 \text{ dB}$$

The transmission loss is estimated from the equation:

$$TL = 20 \times \log(R) + \alpha R$$

where, R is the range in metres at which the sound is emitted from the receiver.

α is the attenuation coefficient in dBm^{-1} calculated from empirical formulae presented by Coates(1990).

The attenuation coefficient depends upon the frequency of the signal, higher frequencies being more severely attenuated than lower frequency ones.

Using Coates' formula an estimate of the attenuation coefficient can be made for the frequency range of interest, at 8 kHz the attenuation coefficient is:

$$\alpha_{8k}=2.2\times10^{-4}\ dB/m$$

Substituting these values into the passive sonar equation allows us to calculate the range of propagation for an 8 kHz whistle as if we assume the signal excess (SE) to be zero at maximum detection range and assuming spherical spreading:

$$SE = 173 - 94 - 20\log10\ R - \alpha R - DT$$

Therefore if a 10 dB detection threshold (DT) is required for detection, then the range to which the signature whistle propagates, is: R =2.6 km

The decay of the dolphin signature whistle with range is plotted in Figure 3.4. This figure can be used to estimate the detection range if the detection threshold (DT) required for detection is known. A detection threshold of 10 dB has been assumed for the purposes of estimating the range of propagation of the whistle.

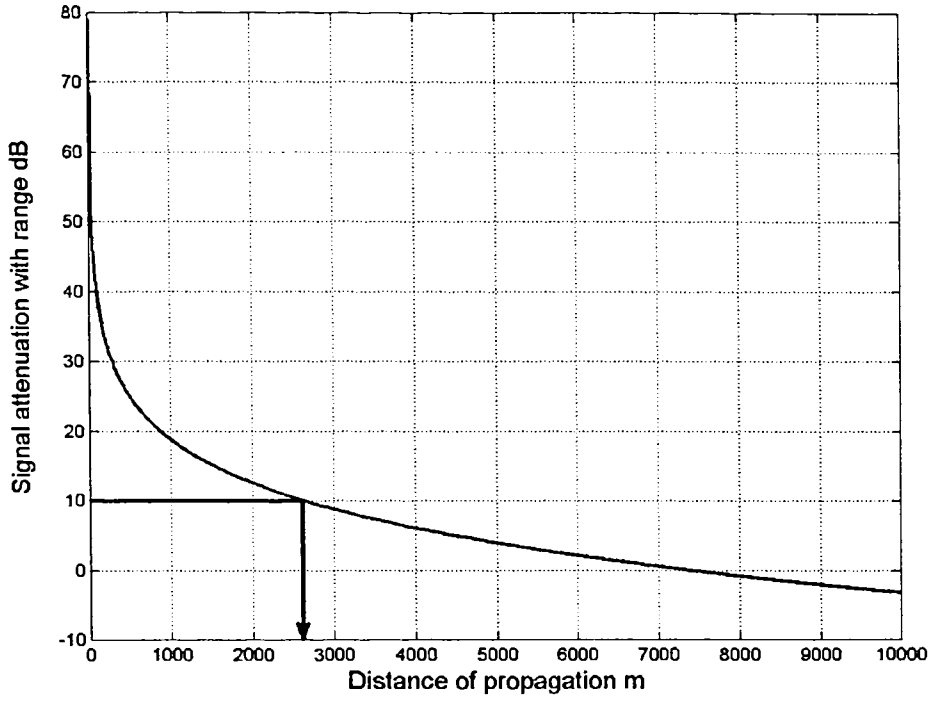


Figure 3.4 - Signal excess against range of propagation for a dolphin signature whistle. The arrow shows the range below which the signature whistle can be detected.

The following assumptions are made to estimate this range:

Water temperature = 14 °C
Salinity = 35 %
Spherical spreading
Noise Level NL calculated using equation 3.5. Assuming D=0.5,W=10ms^{-1}
Omnidirectional source and receiver

3.4 Propagation of Dolphin Echolocation Clicks

The whistle sound of a dolphin can be detected without revealing the presence of the boat to the dolphin only if the maximum range that the dolphin can use its sonar is less than the propagation distance of the whistle.

The active sonar of the dolphin operates as follows. The click is produced in the head of the dolphin and propagates into the water, it then radiates out from the dolphin according to the transmission beam pattern of the dolphin. The click will undergo absorption and attenuation in water. Once the sound encounters an object, (the target), it is reflected. The strength of the reflected sound depends upon many factors such as the size, shape and composition of the target and also on the frequency of the sound. This reflected part of the sound then radiates back towards the dolphin again being absorbed and attenuated by the water and reaches the dolphin. However, the dolphin's reception of sound depends upon the receiving beam pattern of the dolphin, i.e. it is dependent upon the orientation of the dolphin with respect to the incident sound. The dolphin can only hear the reflected echo if the intensity of it is greater than the background noise assuming it is not performing some form of signal processing. The intensity of sound above the background noise after all these effects have been taken into account is known as the signal excess and is effectively a measure of the signal-to-noise ratio. This signal excess can be calculated from the following equation, known as the active sonar equation.

$$SE = SL_{rms} - 2\times TL + TS - (NL - DI_R) - DT$$

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Experiments conducted by Au et al on captive dolphins have calculated the maximum range of a bottlenose dolphin's sonar using two different targets. The targets are small spheres 2.54cm and 7.62cm with target strengths of –41.6 dB and –28.3 dB respectively. The maximum detection range for the larger target was 113m and 73m for the smaller one. If these figures are plugged into the sonar equation then they give an estimate of the detection threshold of the dolphin.

$SL = 220 - 15.5 = 204.5$ dB

$TL = 20\times\log_{10}(R) + \alpha R$ (assuming spherical spreading)

TS = -41.6 dB Measured for the 2.54cm sphere

NL =79 dB (Calculated from equation 3.5)

$DI_R = 20.2$ dB (Measured by Au (1993) in an earlier experiment)

Inserting these values into the sonar equation yields:

$DT = 204.5 - 2\times(20\times\log_{10}(73) + 0.0159\times73) + (-41.6) - (79 - 20.2)$

$\underline{DT = 27.2 \text{ dB}}$

Repeating the calculation for the larger sphere:

$SL = 220 - 15.5 = 204.5$ dB

$TL = 20\times\log_{10}(R) + \alpha R$

TS = -28.3 dB Measured for the 7.62cm sphere

NL = 79 dB (Calculated from equation 3.5)

$DI_R = 20.2$ dB (Measured by Au (1993) in an earlier experiment)

$DT = 204.5 - 2\times(20\times\log_{10}(113) + 0.0159\times113) + (-28.3) - (79 - 20.2)$

$\underline{DT = 31.7 \text{ dB}}$

Average detection threshold is: DT = 29.5 dB

Now that we know what the average detection threshold is we can apply these results to the dolphin detecting a sailing vessel such as the one used to collect data for this thesis. This detection threshold is significantly higher than the +12dB figure usually quoted for commercial sonar systems. The implication is that the SL used in the preceding sonar equation is possibly 17dB greater than in reality. However, since the figures are based on experimental data any error in the measurement of SL_{pp} or the conversion of SL_{pp} to SL_{rms} does not affect the validity of the following calculations.

The target strengths of surface ships are generally difficult to estimate due to surface effects, but limited data does exist and is given by Urick (1975). A small sailing vessel such as 'Song of the Whale' would have a target strength varying from 0 dB to 10 dB between the bow and beam aspects respectively.

$SL = 220 - 15.5 = 204.5$ dB

$TL = 20\times\log_{10}(R) + \alpha R$

$TS = 0$dB, 10 dB

$NL = 79$ dB (Calculated from equation 3.5)

$DI = 20.2$ dB (Measured by Au (1997) in an earlier experiment)

$0 = 204.5 - 2\times(20\times\log_{10}(R) + 0.0159\times R) + (0) - (79 - 20.2) - 29.5$

$R = 400$ m for the bow aspect

$0 = 204.5 - 2\times(20\times\log_{10}(R) + 0.0159\times R) + (10) - (79 - 20.2) - 29.5$

$R = 550$ m for the beam aspect

Therefore, the boat can detect the dolphin before the dolphin can detect the boat using its echolocation system.

3.5 Passive detection distance of the Dolphin click

The dolphin click will be detectable by the sailing vessel at larger distances than these because the signal will not suffer from reflection and the return attenuation path. However the receiver will be omni-directional and therefore does not have the advantage of a directivity index. If a detection threshold of 15 dB for the array on the sailing vessel is assumed then the sonar equation becomes:

$$SE = SL - TL - NL - DT$$

$$0 = 204.5 - (20\times\log_{10}(R) + 0.0159\times R) - 79 - 15$$

$R = 2600$ m

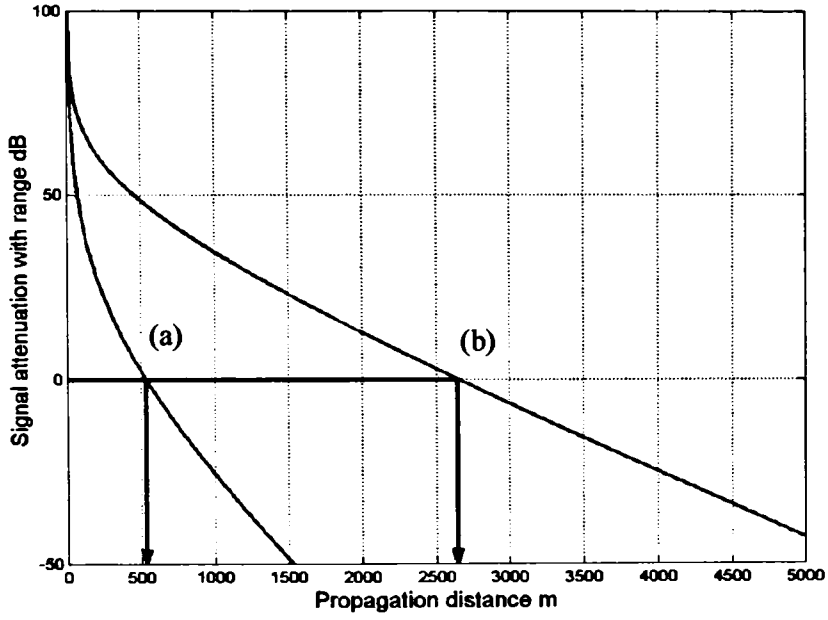


Figure 3.5 - The signal excess plotted against range for a dolphin echolocation click. The left arrow shows the range below which the dolphin can detect a target and the right arrow shows the distance at which the same echolocation click can be detected passively

3.6 Propagation of self-noise

The analysis of the self-noise generated from 'Song of the Whale' is described in section 3.2 of this chapter. The propagation distance of the self noise of Song of the Whale is calculated from the passive sonar equation and shown in Figure 3.6:

$$SE = SL - NL - 20\times\log10(R) - \alpha\times R - DT$$

where:

SL = 120 dB re 1uPa @ 1m
f = 500 Hz
NL = 69 dB
$\alpha = 2.1 \times 10^{-5}$ dB/m @ 500Hz

Assuming a 10 dB detection threshold for detection yields a passive propagation distance of 120m.

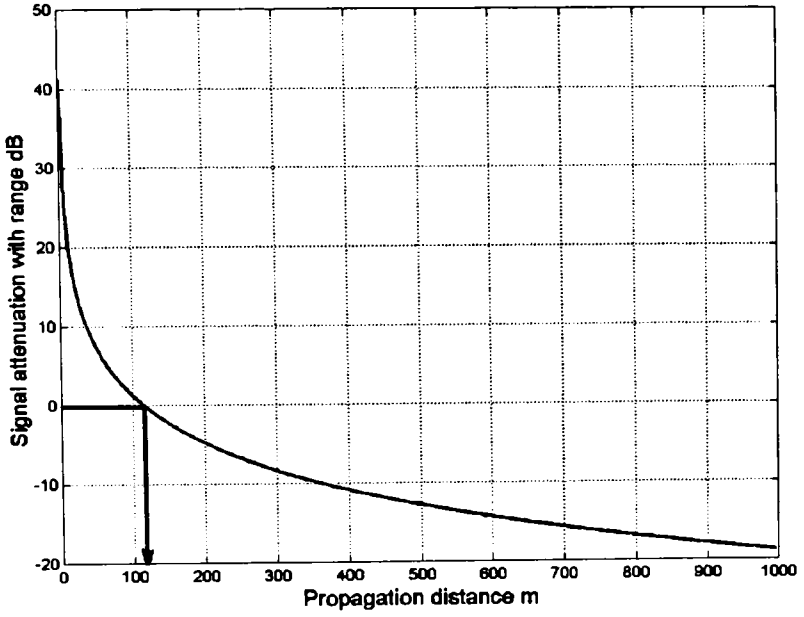


Figure 3.6 - Propagation distance of the noise from the sailing vessel 'Song of the whale' when running on engines (5 knots).

3.7 Propagation zones of dolphin vocalisations

Figure 3.7 shows the zones of propagation of each of the dolphin vocalisations as calculated in the preceding sections. The receiving array is located at position (0,0) in the centre of this figure. These zones have been labelled A, B and C. If a dolphin enters zone A then the whistle sounds can be detected on the array. Although it is possible to also detect the click sounds at this range the appropriate equipment was not available to do this, since the equipment had been designed in order to collect the whistle sounds. The whistle detection equipment does allow the click sounds to be heard but at much shorter distances than calculated earlier due to the much reduced energy concentrated in the frequency range that the equipment was designed for, (200 Hz - 20 kHz). If a dolphin enters zone B then it will be able to use its echolocation system to detect the prescence of the boat. The dolphin will detect the boat sooner if approaching from the beam aspect since the target strength is larger in this direction and hence more energy will be reflected back towards the echolocating dolphin. Once inside zone C the dolphin will be able to passively detect the presence of the boat from the self-noise it generates. This may occur if the dolphin is not performing regular echolocation.

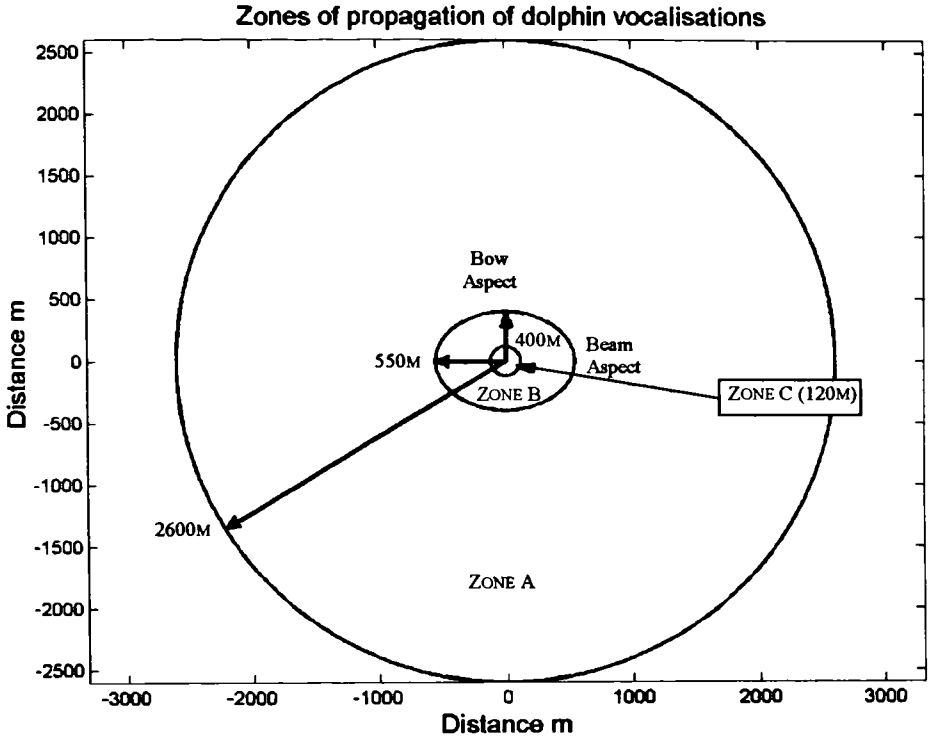


Figure 3.7 - Theoretical propagation ranges of the dolphin sounds.

3.8 Summary

The dolphin vocalisations will be detected by the boat providing the dolphin is within zone A. As the boat gets closer to the dolphin then the signal to noise ratio of the recording will increase. Once the dolphin is within zone B then it will be able to detect the precence of the boat by using its echolocation system. If for whatever reason the dolphin is not echolocating then it will not detect the precence of the boat until it enters zone C. Therefore in order to be sure of conducting non-invasive research the boat should be operated so as to keep the acoustically observed dolphins within zone A but not so close as to be within zone B.

The boat used for collection of dolphin recordings, 'Song of the Whale', is operated in such a manner so as to keep the self-noise to a minimum. If a noisier platform is used then the dolphin may be able to passively detect the presence of the vessel before being able to use its echolocation system.

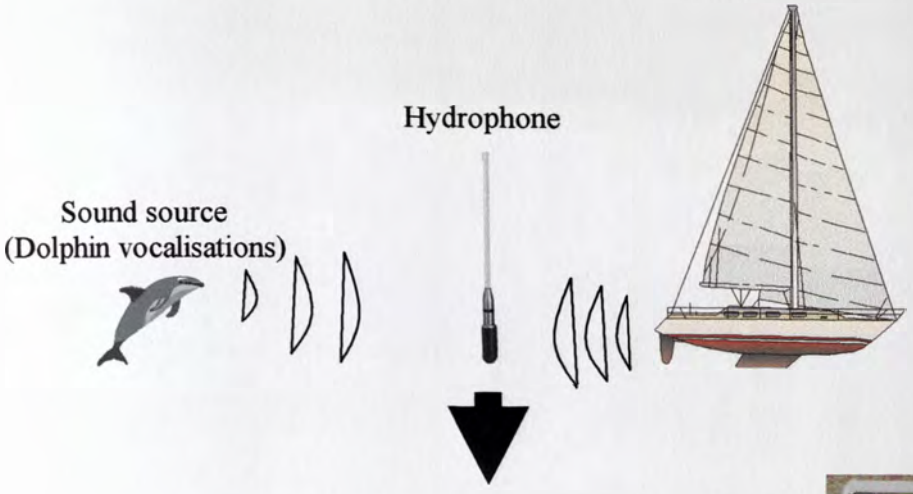
Chapter 4 - Signal Processing, and statistical Data Analysis

4.1 Introduction

This chapter describes the various signal processing and statistical analysis techniques used to analyse and interpret the recordings of the striped dolphins. These signal processing and statistical methods were first developed during the preliminary study conducted in June 1994. Since the data did not need to be analysed in real time Matlab v4.0 running on a Pentium 100 MHz PC was used for this purpose. These algorithms were later developed to run in real time on an ADSP 21020 processor, which was interfaced to a Pentium PC, this PC was used as the controller and graphics display.

During the preliminary study the recordings were digitised using a sound card connected to the Pentium PC. Sections of the recordings were sampled at 44100Hz in order to capture the full human audio bandwidth. Digital signal processing techniques could then be used to manipulate and transform the data. Several techniques are available for digitally filtering data, the Infinite Impulse filter design method was employed for its simplicity and ease of implementation. The detection and extraction algorithms operate in the frequency domain. The frequency content of the vocalisations is therefore very important and Fast Fourier Transform (FFT) algorithms were used to calculate the spectrum and also the Short Time Fourier Transform (STFT or spectrogram) of the recordings. This chapter describes the algorithms used and also the windowing functions employed. The power spectrum is also used to calculate the background noise levels.

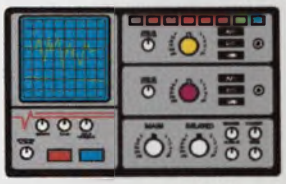
4.1.1 System Diagram



Custom built amplifier and filter circuitry for conditioning of dolphin vocalisations prior to recording.



Preliminary analysis and data monitoring during recording, using oscilloscopes



Further real time processing using Digital Signal Processors implementing digital filters and FFTs.



Display, comparison and classification of results using statistical methods



Once the digital processing is complete, statistical methods are used to interpret the data. Natural clusterings of the data are found from the measured variates using k-means cluster analysis and principal component analysis.

4.2 Infinite Impulse Filter Design

The Infinite Impulse Response filter (IIR) is type of digital filter which was used as part of the digital signal processing. A digital filter may be defined as a computational process or algorithm which converts a sampled input signal into an output signal which changes the character of the signal in some manner. The filter is usually the digital equivalent of an analogue filter. High, low, band pass and band stop filters are all realisable using the IIR filter design method. The bilinear transformation method used here tries to approximate an analogue filter as closely as possible by calculating the coefficients of the IIR digital filter transfer function $H(z)$ from the corresponding coefficients of the analogue transfer function $G(p)$, defined by,

Analogue transfer function

$$G(p) = \frac{A_0 + A_1 p + A_2 p^2 + \cdots + A_k p^k}{B_0 + B_1 p + B_2 p^2 + \cdots + B_k p^2} \tag{4.1}$$

Digital transfer function

$$H(z) = \frac{a_0 + a_1 z^{-1} + a_2 z^{-2} + \cdots + a_k z^{-k}}{b_0 + b_1 z^{-1} + b_2 z^{-2} + \cdots + b_k z^{-k}} \tag{4.2}$$

where,

z - digitised sample number
p - time

4.2.1 Bilinear Transformation Method

The bilinear transformation method is one of the many ways a digital filter can be designed. It produces a frequency response similar to analogue filters and is relatively simple to design, Stanley (1975).

Notation

p = analogue prototype Laplace variable
s = digital final Laplace variable
λ = steady-state radian frequency corresponding to p ($p = j\lambda$)
ω = steady-state radian frequency corresponding to s ($s = j\omega$)
f = cyclic frequency corresponding to ω ($f = \omega/2\pi$)
v = normalised frequency (with respect to folding frequency) = f/f_0
G(p) = analogue prototype transfer function
H(z) = discrete transfer function

The z-transform pair of a discrete time signal $x(n)$ is denoted $X(z)$ and given by,

$$X(z) = \xi[x(n)] \tag{4.3}$$

and its inverse is given by,

$$x(n) = \xi^{-1}[X(z)], \tag{4.4}$$

these denote the transform pair. Where $\xi[]$ denotes the z-transformation given by,

$$X(z) = \sum_{n=0}^{\infty} x(n) z^{-n} \tag{4.5}$$

where,

$$z = e^{sT} \tag{4.6}$$

The desired digital transfer function H(z) is obtained by replacing p in G(p) by an equation expressing p in terms of z. This is given by

$$p = \frac{C(1-z^{-1})}{(1+z^{-1})} \tag{4.7}$$

where C is a mapping constant. Substituting (4.6) in (4.7) yields,

$$p = \frac{C(1-e^{-sT})}{(1+e^{-sT})} = C\tanh\frac{sT}{2} \tag{4.8}$$

If we now substitute for $s = j\omega$ and $p = j\lambda$ in equation (4.8) and using the relationship, $\tanh jx = j\tan x$, where $j = \sqrt{-1}$ and cancelling the j's results in

$$\lambda = C\tan\frac{\omega T}{2} \tag{4.9}$$

Rewriting in terms of the folding frequency, f and the normalised frequency, f_0 (4.9) can be written as

$$\lambda = C\tan\frac{\pi}{2}\frac{f}{f_0} = C\tan\frac{\pi}{2}v \tag{4.10}$$

This expression shows how the frequency scales are mapped as a function of normalised frequencies.

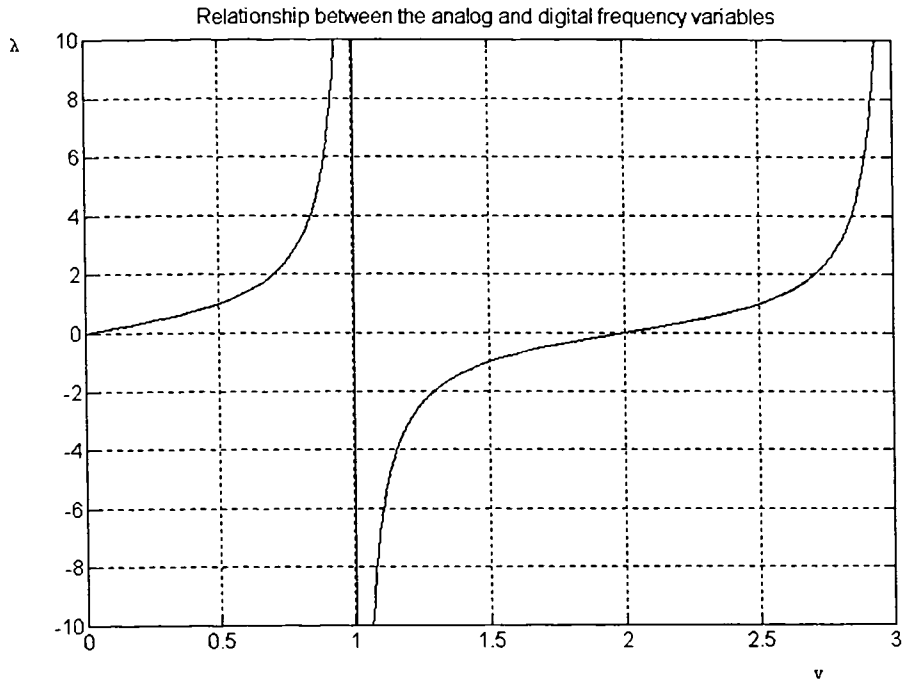


Figure 4.1 - Relationship between frequency variables of the analogue and digital functions

The graph, in Figure 4.1, shows a linear relationship between the variables below half the normalised frequency. The constant C is chosen so as to align the frequency variables of the filter at a particular point. Usually the -3 dB point is chosen.

To align the variables for a particular frequency, digital frequency = ω_r and analogue frequency = λ_r. Let $v_r = f_r/f_0$.

$$C = \lambda_r \cot\frac{\omega_r T}{2} = \lambda_r \cot\frac{\pi}{2}\frac{f_r}{f_0} = \lambda_r \cot\frac{\pi}{2}v_r \qquad (4.11)$$

4.3 Short Time Fourier Transform

The Short Time Fourier Transform (STFT) combines time-domain and frequency-domain information onto the same graph. It provides useful information about how the frequency content of a signal varies over time. A Fourier transform does not yield this information, since there is only one transform for the entire signal. A STFT is calculated by dividing the whole sequence into smaller sequences. This process is known as windowing. The analysis window (sometimes called the analysis filter) is moved through the data. The Fourier transform is taken of each of these windows and plotted in sequence. The resulting graph of frequency against time is known as a spectrogram.

The Fourier transform of a signal x(n) is given by,

$$X(\omega) = \sum_{n=-\infty}^{\infty} x(n) e^{-j\omega n} . \tag{4.12}$$

where ω is a variable denoting frequency. The STFT is calculated from such Fourier transforms taken from sections of x(n). The section for time n_0 is obtained by multiplying by a shifted window $w(n_0 - n)$. The STFT at time n_0 is then given by

$$X(n_0, \omega) = \sum_{n=-\infty}^{\infty} x(n) w(n_0 - n) e^{-j\omega n} . \tag{4.13}$$

The sequence $f_{n_0}(n) = x(n)w(n_0 - n)$ is known as the short-time section of x(n) at time n_0. Each of these short-time sections are transformed and the window is then

shifted along the x(n) sequence. The fixed variable n_0 is replaced by the variable n. The summation variable is now changed to m to avoid confusion.

$$X(n,\omega) = \sum_{m=-\infty}^{\infty} x(m)w(n-m)e^{-j\omega m} \tag{4.14}$$

4.4 The window function

The window function is an important part of the STFT. Its purpose is to select the appropriate part of the signal to be transformed. If the section is selected without modification of the coefficients then the window is said to be rectangular. Since multiplication in the time domain corresponds to convolution in the frequency domain, the window function is multiplied by the signal in the time domain so therefore it is convolved with the signal in the frequency domain. The Fourier transform of a rectangular window has significant oscillations and poor high frequency convergence. Therefore, when it is convolved with the Fourier transform of the desired signal, poor representation of the signal may result. An ideal window is not possible since this would be an infinitely long window. Therefore, a compromise is required. The spectrum of a window should consist of a narrow main lobe and small side lobes. Windows which have these properties are displayed in Figure 4.2.

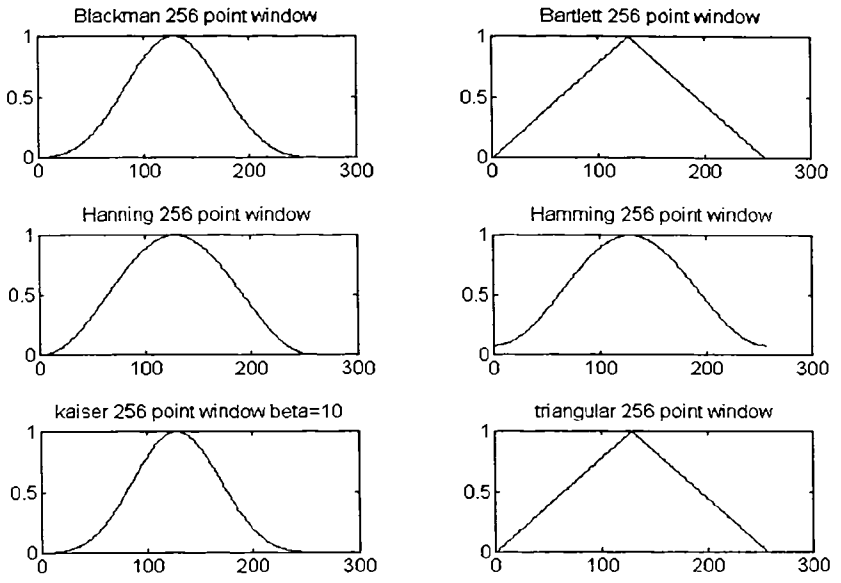


Figure 4.2 - Windowing functions

4.5 Cross Correlation

The cross correlation of two signals indicates how well the two signals are correlated for a particular delay. In the time domain the cross correlation function $R_{xy}(\tau)$ is given by,

$$R_{xy}(\tau) = \overline{x(t)y(t-\tau)} \tag{4.15}$$

where τ represents a delay between the two signals $x(t)$ and $y(t)$.

The autocorrelation function is a special case of the cross correlation in which the two signals are the same, $x(t) = y(t)$,

$$R_{xx}(\tau) = \overline{x(t)x(t-\tau)} \tag{4.16}$$

4.6 Power spectrum

The power spectrum of a signal can be calculated from the autocorrelation of the signal. It can be shown that the Fourier transform of the autocorrelation function is the square of the magnitude of the Fourier transform, $X(f)$, of the signal, $x(t)$. This is called the auto power spectrum $S_{xx}(f)$ and is calculated as,

$$S_{xx}(f) = F\left[R_{xx}(\tau)\right] = X(f)\tilde{X}(f) = \left|X(f)\right|^2 \tag{4.17}$$

where $\tilde{X}(f)$ denotes the complex conjugate of $X(f)$ and $F[]$ the Fourier transform. The cross power spectrum is calculated in a similar way from the cross correlation function,

$$S_{xy}(f) = F\left[R_{xy}(\tau)\right] = X(f)\tilde{Y}(f) \tag{4.18}$$

The application of the cross correlation function is useful for finding the time delay of a signal. With a line array consisting of two spatially separated hydrophone elements, H1 and H2, there will be a delay dependent on the bearing of the sound source. The result of cross correlating a dolphin click arriving on the two hydrophone elements is shown in Figure 4.3. The maximum peak in the cross correlation indicates the time delay between the two signals. In this case the click arrives on H2 before arriving on H1, this results in a negative time delay, which means the source of the click was from the rear of the array.

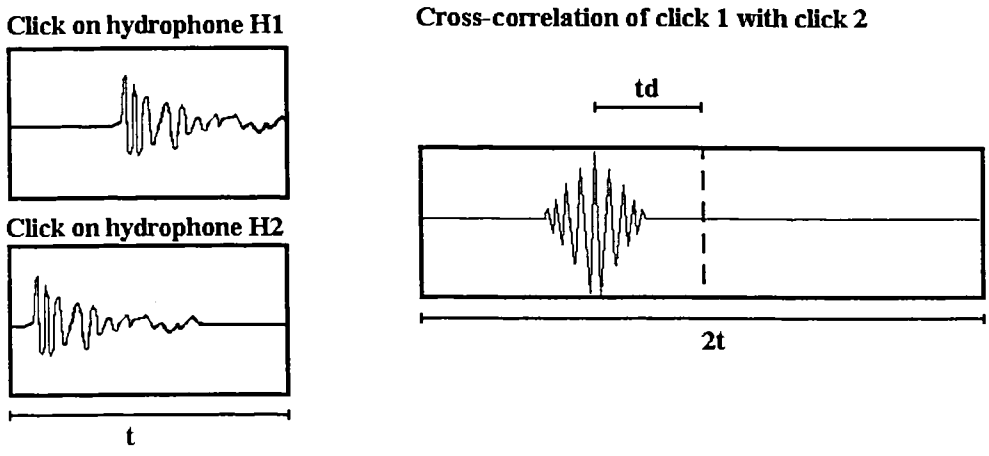


Figure 4.3 - Cross correlation of two signals giving a negative time delay.

Observing the arrival of the click on element H1 first, Figure 4.4, indicates that the click has a source originating from in front of the array. This results in a positive time delay.

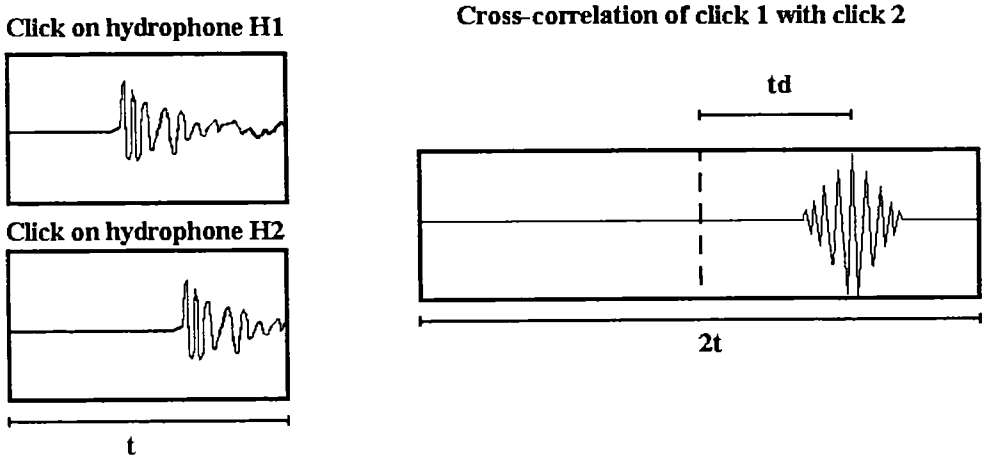


Figure 4.4 - Cross correlation of two signals giving a positive time delay.

4.7 Multivariate analysis

A multivariate data set consists of several variables recorded on a number of objects or individuals. In the context of this thesis the objects or individuals are dolphins and the variables are features of the dolphins signature whistle. Multivariate techniques can be used to examine relationships between the variables such as Principal component analysis. Principal component analysis is known as a variable-directed method as it seeks to find new variables which are linear combinations of the observed variables such that they have maximum variance and are uncorrelated with each other. Principal component analysis is described more fully later in this section.
Other multivariate techniques such as cluster analysis are used to examine the relationship between the individuals and are known as individual-directed methods.

4.7.1 Variable-directed methods

A set of p variables are collected on a set of n individuals, the resulting data set is an n by p matrix. Each variable $x_1,x_2,x_3,\ldots,x_p$ describes a different characteristic of the individual. Variable directed methods are used to find linear relationships between the variables with the aim of reducing the dimensionality of the problem.

4.7.1.1 Principal Component Analysis

With this method new variables are found which are linear combinations of the original p observed variables so that the new variables have maximum variation and are uncorrelated with each other. These new variables or 'principal components' are found using the following method:

If S is the p by p variance-covariance matrix of the n by p data matrix then a vector a_1 of length p can be found such that it satisfies the following condition:

$a_1^T S a_1$ is maximised subject to $a_1^T a_1 = 1$.

The first principal component is then given by,

$$z_1 = \sum_{i=1}^{p} a_{1i} x_i$$

this provides the linear combination of the variables that gives maximum variation.

The second principal component can be found in a similar way,

$$z_2 = \sum_{i=1}^{p} a_{2i} x_i$$

such that $a_2^T S a_2$ is maximised subject to $a_2^T a_2 = 1$ and $a_2^T a_1 = 0$

The other p principal components can be found in the same way.

The vectors a_i are the eigenvectors of the matrix S. Associated with each eigenvector is an eigenvalue. The eigenvalue is the proportion of variation given by the ith principal component.

Usually fewer than p principal components are required to represent most of the variance within the data. A test on the smaller eigen values can be performed to investigate the number of dimensions needed.

4.7.2 Individual-directed methods

The same n by p data matrix is used for the input to the individual-directed methods. These methods have their emphasis on the relationship of the individuals. A distance measure is applied to each of the variables against all the other variables resulting in an n by n matrix which is called a similarity matrix (if the distance scores show how close the variables are related) or dissimilarity matrix (if the distance scores show how far apart the variables are). The Euclidean distance score is usually suitable although other scores can be used,

$$D=(x_{ki}-x_{ji})^2$$

Given the distance scores between the individuals there are three types of analysis that can be performed.

1. Grouping the individuals; i.e. collecting the individuals into groups so that those within a group are closer to each other than to members of another group.
2. Classifying the individuals; i.e. if some are known to belong to a particular group then others can be compared to see if they belong in that group.

3. Mapping the individuals; i.e. graphing the distances between the individuals on a map.

4.7.2.1 Cluster Analysis

There are two types of cluster analysis. Hierarchical cluster analysis and Non-Hierarchical analysis (or more commonly known as k-means cluster analysis).

4.7.2.2 Hierarchical cluster analysis

This analysis proceeds as follows. The distance matrix is first formed using a suitable distance measure. The n individuals are then grouped in pairs with the closest individual based on the distance score. A new distance score is then calculated for the remaining groups. This new distance score is then used to group the pairs of individuals into larger groups. This process continues until one group is formed containing all the individuals. The groups formed along the way show the relationship between each of the variables i.e. the most similar ones are grouped together first. The hierarchical information produced can be used to group the individuals into a chosen number of clusters. This method has the disadvantage of needing to know the number of clusters in the data set.

4.7.2.3 k-means cluster analysis

Non-hierarchical cluster analysis can be used to form a given number of clusters from the data. The data is partitioned into clusters again using the distance score. The

quality of the chosen number of clusters can be tested and an optimum number of clusters established. One commonly used criterion is the within cluster sum of squares.

$$SS_c = \sum_{k=1}^{K} \sum_{i=S_k} \sum_{j=1}^{p} (x_{ij} - \bar{x}_{kj})^2$$

where, S_k is the set of objects in the kth cluster, $\bar{x}_{kj}$ is the mean of the variable j over cluster k. SS_c is minimised by reallocation of the objects into different clusters.

4.7.2.4 Discriminant analysis

Discriminant analysis is concerned with the allocation of individuals to a number of known groups. The rule used to test if an individual belongs to a specific group is obtained from a training set of data in which the group membership is known.

Chapter 5 - Experimental Location, Equipment and procedures.

5.1 Introduction

This chapter is divided into three sections. The first section describes the trial locations. The second section describes the existing equipment available for the collection of cetacean recordings. The third section describes the new equipment that was developed.

5.2 Section 1 - Trial locations

The data presented in this thesis was collected during collaborative trials with IFAW from their research vessel 'Song of the Whale'. These trials were conducted in different geographical locations. The trial locations and dates are shown in Table 5.1.

Table 5.1

Trial Number	Location	Date	Purpose	Trial Vessel
1	Ligurian Sea, Italy/Corsica	7th-21st June 1994	Evaluation and assessment of existing acoustic monitoring equipment	'Song of the Whale'
2	Dominica, W. Indies	7th Jan - 31st March 1995	Testing and evaluation of developed equipment	'Song of the Whale'
3	Ligurian Sea, Italy/Corsica	June 1995	Installation of equipment and training of crew for continued collection of dolphin recordings in the Ligurian Sea area.	'Gemmini'
4	Grenada, W. Indies	February 1996	Collection of data using 4 hydrophone system	'Song of the Whale'

5.2.1 Trial 1 - Ligurian Sea

This trial was conducted during the first year of the research programme and served to familiarise the author with the complex issue of obtaining and interpreting free ranging cetacean vocalisations. This first trial also allowed the existing acoustic monitoring equipment used on board 'Song of the Whale' to be evaluated and assessed in order that future developments to the system would be compatible. This chapter begins by describing the existing acoustic monitoring equipment that was in use on 'Song of the Whale' prior to the authors' development of new equipment. The opportunity was taken to obtain recordings of striped dolphin vocalisations for later analysis.

This trial illustrated the potential for exploiting the acoustics for detection, tracking, identification and counting of the cetaceans. The trained human listeners were able to distinguish between several different types of dolphin and whale vocalisations. How this was achieved is not easily identified or well understood. The human listeners were possibly taking cues from; frequency composition, time variations and also from the grouping of sounds which were known to be emitted by certain cetaceans.

The need for the development of the existing equipment to enhance the recorded vocalisations was also noted. The existing system did not allow the sounds to be conditioned. The propagation of sound in the oceans varies with frequency, the low frequency sound being attenuated less than higher frequency sounds. The result of this is that the lower frequency sounds can overload the amplifiers in the system therefore rendering it useless for recording a lower level higher frequency sound. It is desirable

to be able to adjust the gain and frequency band selection of the system so that sounds of interest can be enhanced and unwanted sounds can be rejected. Thereby maximising the signal to noise ratio of the sounds of interest. Since the vocalisations vary widely depending upon the cetacean currently being detected the system also needs to be flexible.

A custom built variable amplifier and filter module was designed, constructed and tested. The module is described later in this chapter. This module was used successfully for all subsequent collections of recordings in the Ligurian sea during 1994.

Over 90 hours of recording were collected during this trial over a three month period. The extensive use of the first amplifier / filter module highlighted the need for an improved, more robust design. The constant use and harsh environment that the module was subjected to was not fully considered during the initial design stage. Also during use a number of features were suggested which would make the module easier to use. These considerations were taken into account during the design of the next module.

5.2.2 Trial 2 - Dominica, W. Indies

The second module to be designed is described more fully later in this chapter and is referred to as prototype 'B'. The module was constructed and tested on the bench and then later tested during trial 2. This trial was much longer in duration allowing the author to fully test and modify the design where necessary in the field. A base station was set up at Springfield Plantation, Dominica, W. Indies which was used as a 'make shift' electronics lab see Figure 5.1. During this trial the design of the module was finalised.



Figure 5.1 - 'Make shift' electronics laboratory set up at Springfield, Dominica, W. Indies.

This trial also provided the opportunity to experiment with different array configurations and also with hydrophone design. As part of the collaboration with IFAW hydrophones were constructed which were given to local Whale Watch Enterprises. This initiative was intended to raise the awareness of the public into the acoustic vocalisations of these animals when they are taking part in whale watch excursions. One of the hydrophones which was supplied to a whale watch operation in the West Indies is shown in Figure 5.2.

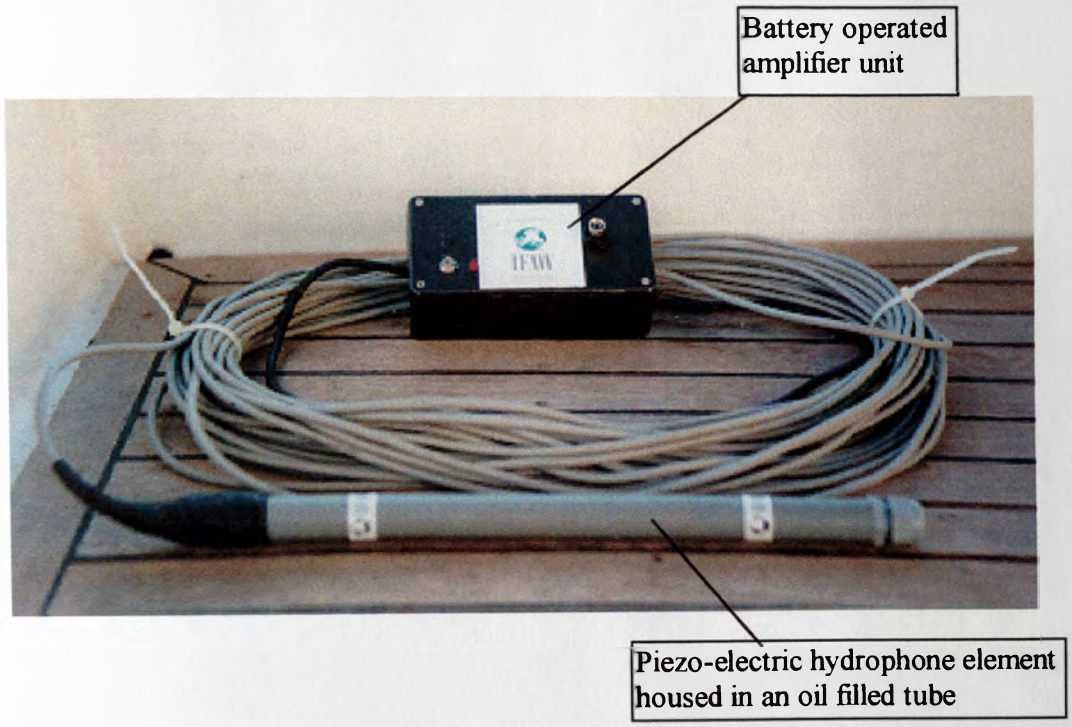


Figure 5.2 - Mono channel hydrophone supplied to a whale watch organisation in the West Indies

5.2.3 Trial 3 - Ligurian Sea

To complement the recordings taken during the first trial another research vessel, 'Gemmini' which is permanently based in the Ligurian sea was enlisted. The Tethys organisation which operate 'Gemmini' did not have an acoustic capability. The author installed an acoustic monitoring system on 'Gemmini' which they used to collect cetacean recordings. The crew were trained in the use of the system so that they would be able to continue to collect recordings during 1995. This set of recordings were unfortunately stolen from their offices along with the DAT recorder and other equipment. These recordings were never recovered.

5.2.4 Trial 4 - Grenada, W.Indies

A two week trial was conducted in Grenada in the West Indies using equipment which had been designed to collect four track recordings of sperm whales from a linear array. Figure 5.3 shows the 4 channel amplifier and filter module that was constructed for this trial.

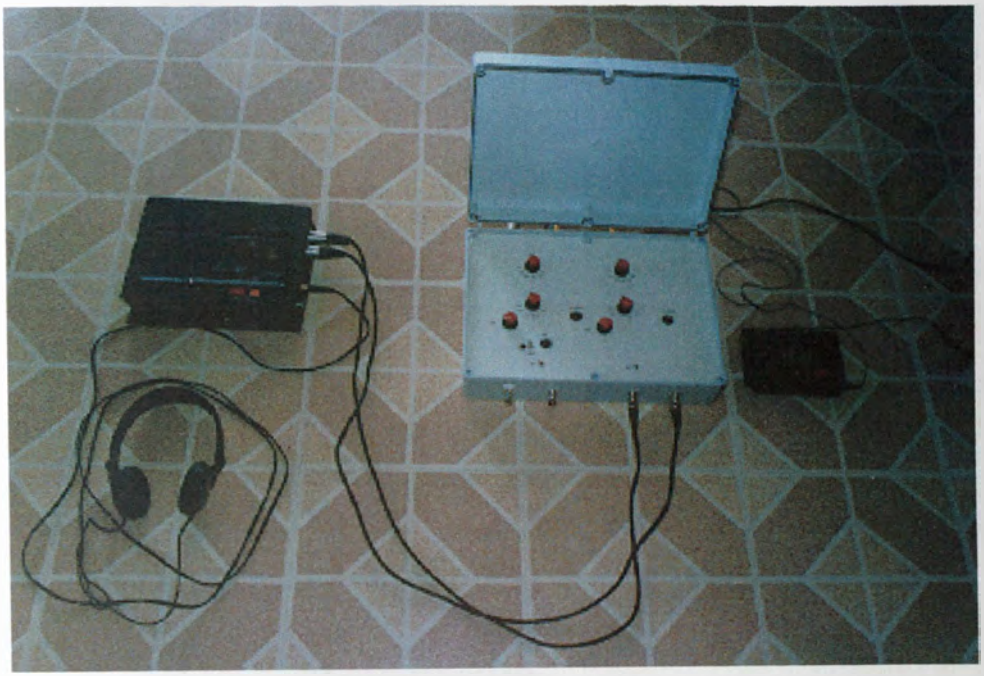


Figure 5.3 - Four channel amplifier filter module and recording equipment.

5.3 Section 2 - Existing Equipment

This section describes the research vessel 'Song of the Whale', the equipment, and also procedures used for previous acoustic monitoring of cetaceans by Dr Gordons' team. This equipment is evaluated and the design and construction of new equipment is described in the next section, which integrates with the existing equipment to provide enhanced capabilities. This chapter goes on to describe the complete system used for collection and analysis of the cetacean sounds presented in this thesis.

5.3.1 Experimental Vessels

The platform used for collection of dolphin recordings was a 46 ft sailing ketch called 'Song of the Whale', Figure 5.4. This is a research boat operated by IFAW[1] for the purpose of investigating cetacean acoustics. Sperm whale acoustics was previously the principal area of research.

Trial 3 was conducted from a different vessel called 'Gemini'. Tethys, the organisation which operated 'Gemini' were mostly interested in fin whale behaviour.

[1]IFAW is the acronym for the International Fund for Animal Welfare.



Figure 5.4 - 'Song of the Whale' at anchor.

The cruising speed of the yacht when running on the engine is 5 knots. Sailing speeds in excess of this are obtainable. There is room for seven crew members on board. Permanent crew members are the skipper, the science officer and the mate, the other positions are filled by interested students. 'Song of the Whale' has been modified for use as a research vessel. A number of acoustic monitoring systems have been installed which are described later in this section. Environmental monitoring equipment is also installed, from which the data is automatically logged via a portable PC. The Global Positioning System (GPS) is also linked to the PC for automatic position logging when desired. There is a 'crow's nest' 3/4 of the way up the main mast, which can be used for visual surveys during clement conditions. This vantage point is useful for identifying the different cetaceans.

5.3.2 Existing underwater acoustic monitoring equipment.

In order to keep an acoustic record of cetacean encounters, acoustic recordings of one minute duration were taken every 15 minutes whilst the boat is at sea. These recordings were taken using a single towed hydrophone, connected directly to a Sony Pro DAT (Digital Audio Tape) machine. The hydrophone, which is shown coiled on deck in Figure 5.5, has two elements separated by 3 m to give an equivalent stereo effect in water as would be experienced in air, taking into account the difference in the speed of sound between the two mediums. This array is described in more detail later in this section. The elements and pre-amplifiers are mounted in an oil filled tube 10 m long and towed on 100 m of strengthened cable with a 6 m rope tail. The rope tail helps to keep the oil filled tube straight. The pre-amplifiers have a gain of 30 dB and a lower cut-off frequency of 200 Hz, which prevents saturation of the amplifier due to flow noise. Listening is performed via headphones connected to the DAT recorder which has a frequency response of 20-20000 Hz.

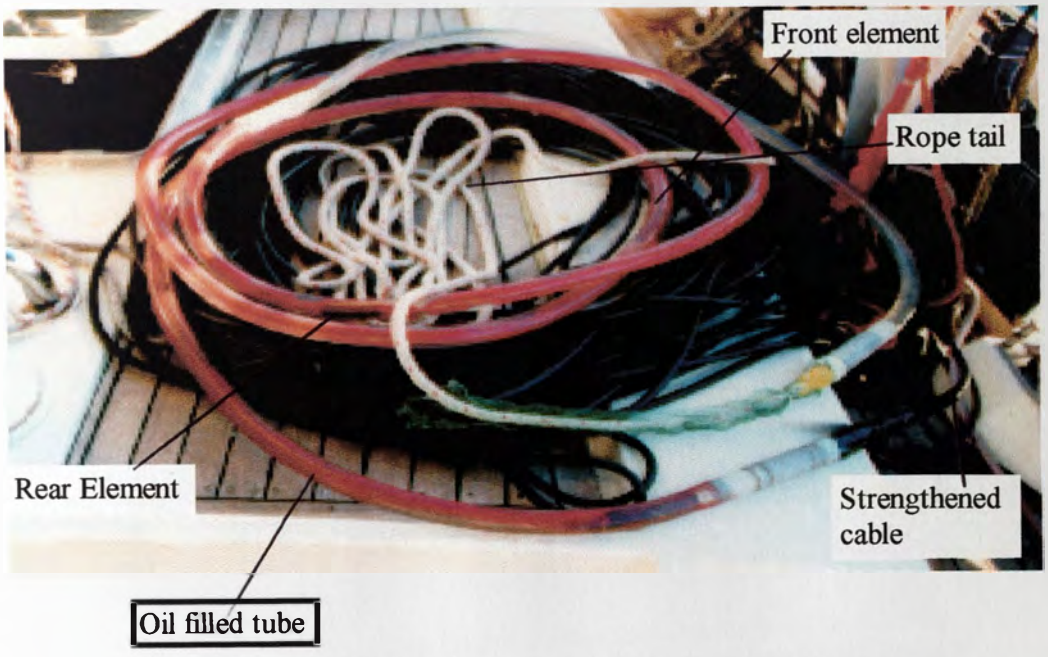


Figure 5.5 - Stereo towed hydrophone coiled on deck.

The towed hydrophone is supplemented by other underwater acoustic monitoring equipment installed on the boat:

5.3.2.1 Depth sounder

A depth sounder gives information on scattering layers within the sea structure and can also be used to watch the descent of deep diving sperm whales to a maximum depth of 200 fathoms.

5.3.2.2 Active sonar

An active sonar system is mounted on the aft of the boat alongside a directional hydrophone, as shown in Figure 5.6. The active sonar and the directional hydrophone cannot be used unless the boat is stationary and the weather calm, this is because they would become detached from their mountings.

5.3.2.3 Radar

The radar is used to track the movement and locations of other vessels in the vicinity of 'Song of the Whale'.

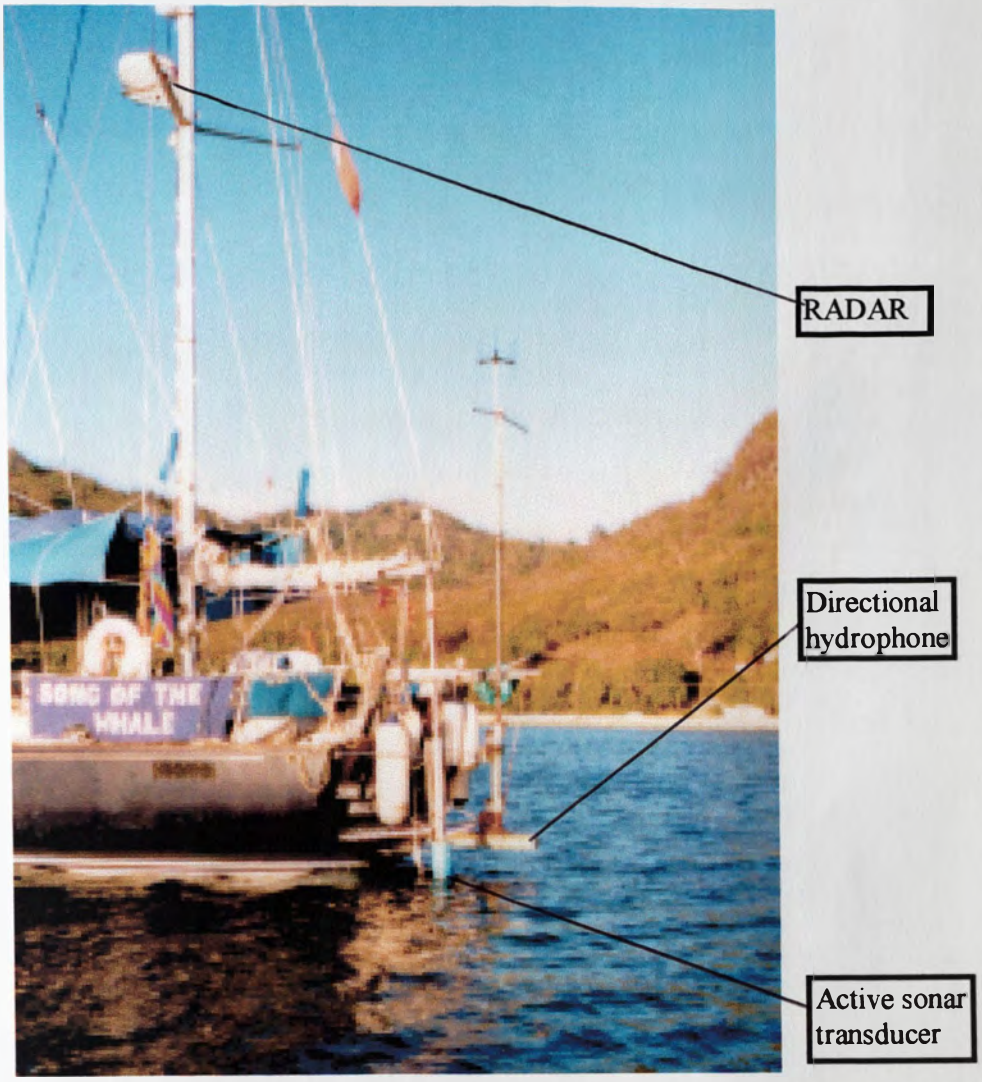


Figure 5.6 - Aft view of 'Song of the Whale'.

5.3.2.4 Directional hydrophone

The directional hydrophone is used for obtaining bearings to vocalising sperm whales during their long dives. This acoustic contact is kept with sperm whales so that they can be photographed upon surfacing.

5.3.2.5 Environmental data collection

In order to correlate the acoustic data, other information is also collected on an Amstrad portable IBMPC XT 8 MHz compatible, see Figure 5.7. Boat position is logged whenever a sighting or a recording is made using the GPS (Global Positioning System) which is connected to the computer via the serial interface. The computer also automatically logs, on request, the wind speed and direction, along with the temperature of the sea and air, also via the serial interface. Sea state is recorded manually.

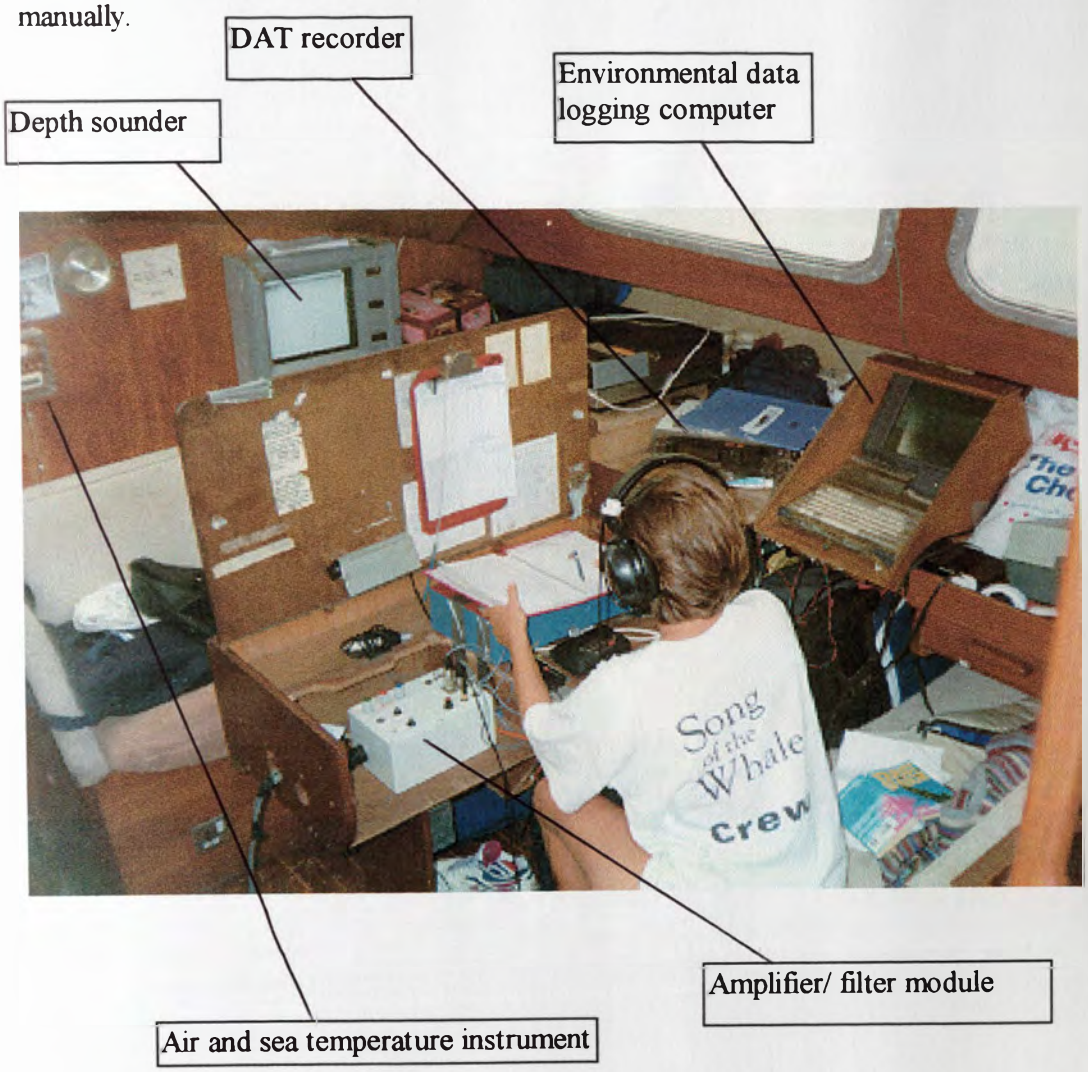


Figure 5.7 - Acoustic recording and data collection area on 'Song of the Whale'.

5.3.3 Method of collection of recordings

The array is towed from the stern of the boat and the speed determines the depth at which the array is towed. When the boat is stationary the towed array is negatively buoyant and starts to sink. Recordings taken for the survey operations are made by idling the engine (reducing propeller noise) and the boat starts to drift. The inertia of the boat keeps it moving forwards so the hydrophone still maintains it's horizontal orientation. The one minute survey recording is taken during this period.

5.4 Section 3 - Data Analysis Hardware

5.4.1 Introduction

The following section describes in more detail the acoustic monitoring equipment used for data collection and the analysis of these data recordings. Some of the equipment is commercially available whilst other pieces of equipment have been custom built. The descriptions of the commercially available equipment is limited to how it was used during the experiments and where relevant the specification, all other data being available from the manufacturers. The design, construction, testing and use of the custom built equipment is fully documented. Some of the custom built equipment have been utilised in other research and commercial projects which indicates the lack of commercially available equipment.

Figure 5.8 shows, in block diagram form, the equipment used during the collection and subsequent analysis of the recordings. The following sections describe each component of this data collection and analysis hardware and software. The equipment already in operation on the boat are the items labelled 'Recording Equipment' in Figure 5.8. The items labelled 'Data Analysis Equipment' were custom built equipment except for the PC and the DSP board which were both running custom written software. All the hardware and software was designed and tested by the author.

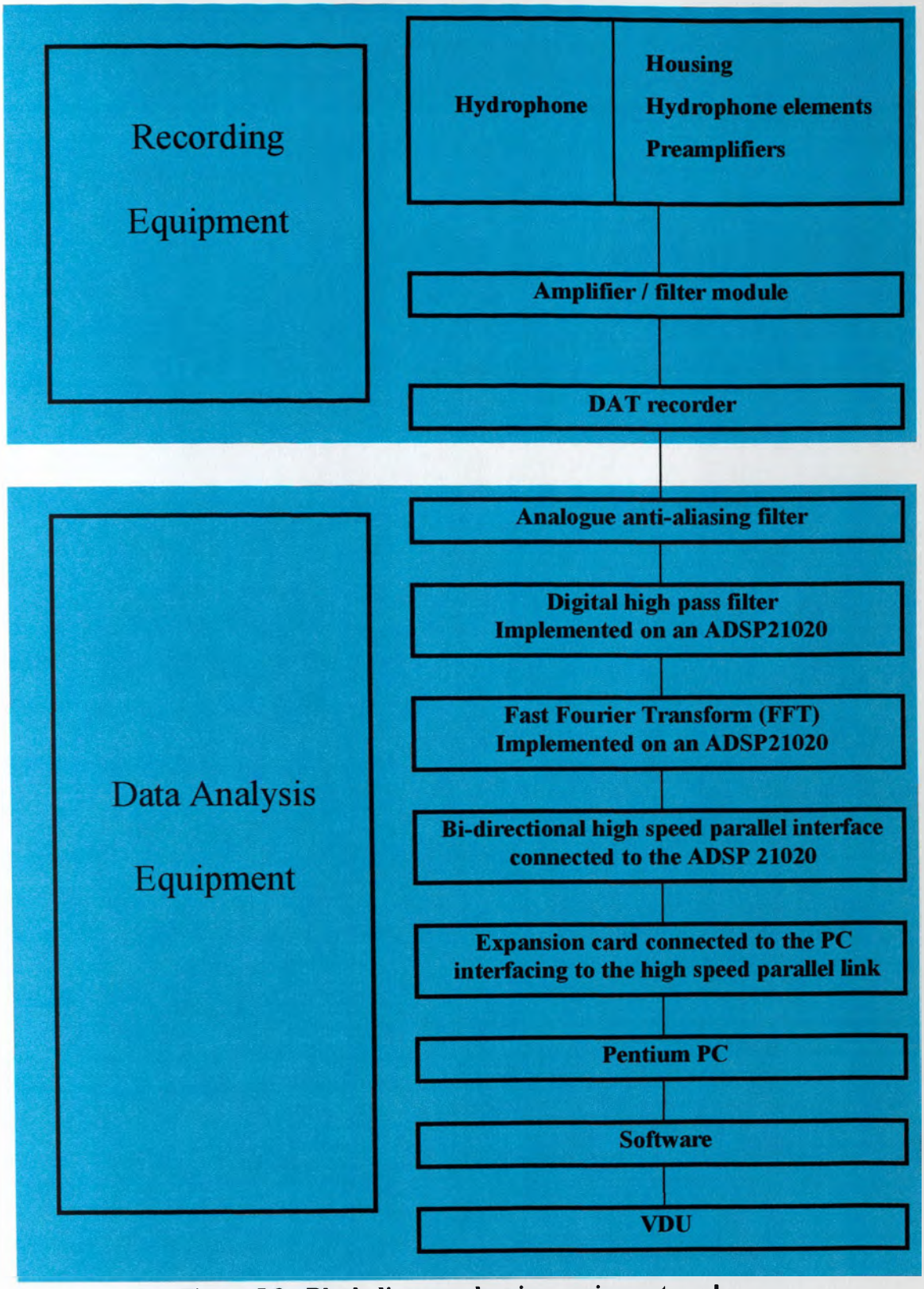


Figure 5.8 - Block diagram showing equipment used for data collection and analysis.

5.4.2 Stereo Towed Array

A two element linear towed array was used to collect the cetacean vocalisations. This array was towed astern of the boat at speeds up to 6 knots. Recordings were taken when the engine was out of gear and the boat was drifting, thus reducing the self noise generated by the boat. The elements are spaced 3m apart inside an oil filled plastic tube 10m long. This tube was towed on 100m of 6 core & screen strengthened cable. Figure 5.9 shows the construction of the hydrophone. This hydrophone was designed and built by Dr. Jonathan Gordon's team of researchers.

5.4.2.1 Hydrophone elements

The hydrophone elements were supplied by Benthos Ltd. and have the following specification.

Table 5.2 : Hydrophone element specification, type AQ4.

Acoustic Sensitivity dB/v re 1μPa±1dB	-201dB
Acceleration Sensitivity dB/v/G	-70dB A -60dB T
Frequency Response ±1.5dB	1Hz-15kHz
Directivity ±1dB on axis	15kHz
Sensitivity vs. Depth loss@ 1732 meters	0.8dB
Depth - meters rated / destruct	3300 / 6600
Size - cm dia. / length	1.30 / 3.30
Weight - grams air / water	4.0 / 2.9
Capacitance - pfd ±25%	2400

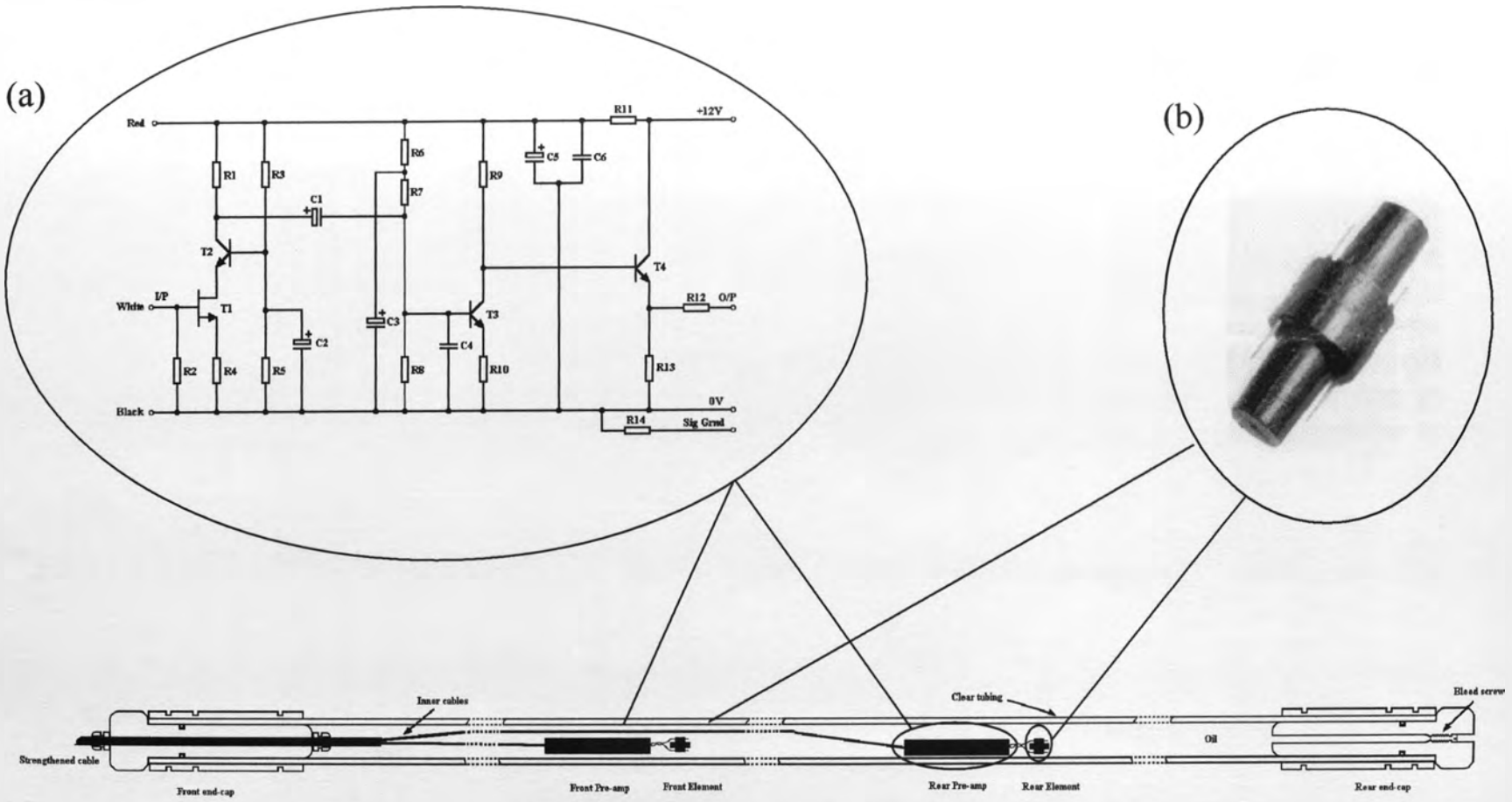


Figure 5.9 - Cross-section through stereo towed array.

(a) Preamp circuit diagram

(b) Benthos AQ4 hydrophone element.

5.4.2.2 Pre-amplifiers

The pre-amplifiers are constructed from discrete components and encapsulated in potting compound to protect them from the oil. They are tuned amplifiers with a gain of 30dB in the passband and a frequency response that rolls off at 20dB per decade below 200Hz. These preamplifiers require +12v DC power. Figure 5.10 shows the amplitude and phase response of these preamplifiers. The preamplifiers are mounted in the oil filled tube close to the hydrophone elements, (it was designed by Oliver Chappel, a member of Dr. Jonathan Gordon's team.)

Component values in Figure 5.9 (a)

Resistors

R1	1KΩ
R2	10MΩ
R3	15KΩ
R4	22Ω
R5	15KΩ
R6	120KΩ
R7	100KΩ
R8	22KΩ
R9	5K6Ω
R10	470Ω
R11	47Ω
R12	22Ω
R13	680Ω
R14	47Ω

Capacitors

C1	47nF (50Hz)
C1	1uF (7Hz)
C2	100nF
C3	1uF
C4	220pF
C5	100uF
C6	10nF

Transistors

T1	J231
T2	BC109
T3	BC109
T4	BC109

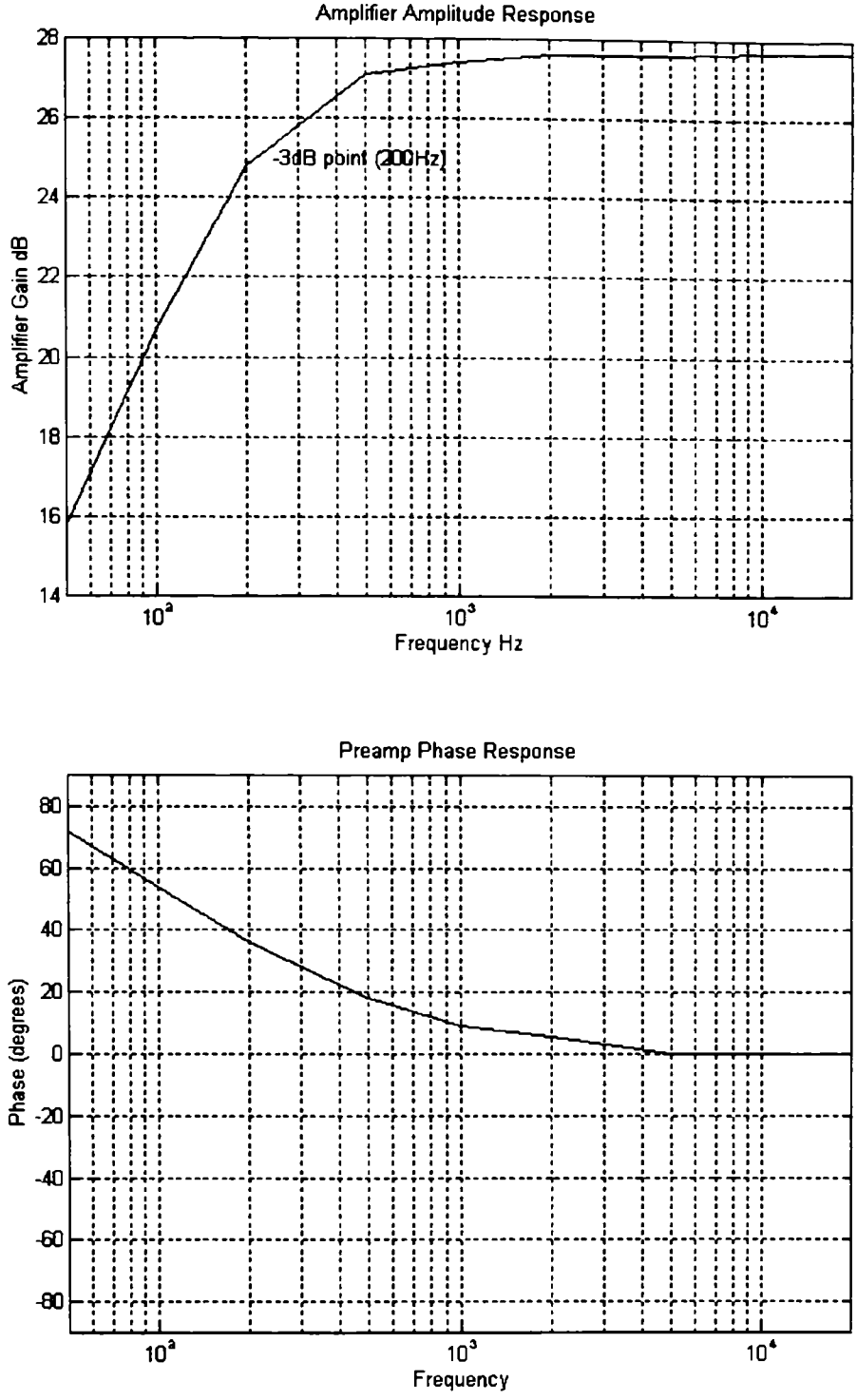


Figure 5.10 - Amplitude and phase responses of the preamplifier.

5.4.3 Amplifier/Filter module.

It is possible to improve the signal to noise ratio in a frequency band of interest by filtering out unwanted frequency bands. Once the unwanted frequency bands have been filtered out it is then possible to amplify the desired frequency bands to obtain a better signal to noise ratio. The dolphin signature whistles of interest for this thesis lie between 5kHz and 20kHz, therefore it is possible to filter below 5kHz to remove boat noise without affecting the signature whistles. The boat noise is dominant in the frequency band 0-5kHz. A fixed filter would not be appropriate because the system is used for monitoring other cetaceans apart from striped dolphins. For example sperm whales emit high intensity sonar clicks which are centred around 5kHz so a fixed filter would render the system useless for monitoring sperm whales. A flexible system is therefore required which allows filtering to be performed across a range of frequencies. Although filters are available commercially, none are suitable for this task, for a number of reasons:

1) To the knowledge of the author all commercial filters are designed to run from mains electricity. Although there is a 110V generator on board 'Song of the Whale' it is not possible to run it whilst cetacean monitoring. The generator creates electrical noise in the boat which interferes with other systems and can be detected on the cetacean monitoring equipment.

2) The environment on board a boat is harsh for electronic equipment. Moisture, vibration, temperature changes and corrosive salt water all create

problems for electronic equipment. It is therefore necessary to seal electronic equipment as fully as possible. Commercially available filters are designed for laboratory bench work and do not adapt well to this environment.

3) Commercially available filters tend to be bulky and as space on board a boat is a premium requirement, small modules are much more desirable.

4) Amplifiers tend to be sold separately to filter modules which means that two units are required. Amplifier units have the same problems associated with them as described above for the filter modules.

The specification of the amplifier/filter modules was carefully discussed with Dr. Jonathan Gordon so that the boat's requirements could be incorporated into the design. It was intended to leave the amplifier / filter modules on board 'Song of the Whale' for their future use after the collection of the cetacean recordings for this research project. In order to increase the flexibility of the system the amplifier and filter module was developed keeping in mind the frequency bands that cetaceans use. The design construction and testing was performed by the author.

5.4.4 Specification for the amplifier / filter module

Power source:

The unit was required to run from batteries. Two 12V lead acid batteries were used for the power source. Power supply conditioning and protection was required.

Signal inputs:

The unit was required to accept inputs from balanced line drivers.

Outputs:

The unit was required to output the amplified and filtered signal via balanced line drivers.

Power supply for hydrophone pre-amplifiers was required from the module.

Two headphone outputs were needed for dual monitoring.

Controls:

The filters required for cetacean monitoring were chosen as follows:

Table 5.3: Amplifier / Filter settings

High pass settings	Low pass settings	Gain settings
no filter	20kHz	0dB
200Hz	15kHz	5dB
500Hz	10kHz	10dB
1kHz	5kHz	15dB
2kHz	1kHz	20dB
5kHz	500Hz	30dB

On/Off switch and power indicator.
Volume control for headphones.

5.4.5 Design and construction of hydrophone amplifier-filter module, prototype 'A'

Previous to the use of the amplifier / filter module the hydrophone was connected directly to a DAT recorder. This provided the only means of controlling the level of the signal, which was achieved by attenuating the incoming signal. The only amplification in the system was provided by the pre-amplifier in the hydrophone which was fixed at 30dB. The signal often exceed the dynamic range of the system when the boat was motoring or when cetaceans were vocalising very close to the boat. The amplifier filter module enables the removal of high levels of unwanted noise whilst still retaining the signals of interest as long as they occur in separate frequency bands. Once filtered the signal can be amplified because clipping would no longer occur due to the boat propeller and flow noise. This allows the monitoring of fainter more distant cetaceans. The prototype was designed to have switchable high and low pass filters and also switchable gain settings. This allowed maximum flexibility. The schematic diagram and the designed circuit diagram for one channel is shown in Figure 5.11 and Figure 5.12 respectively.

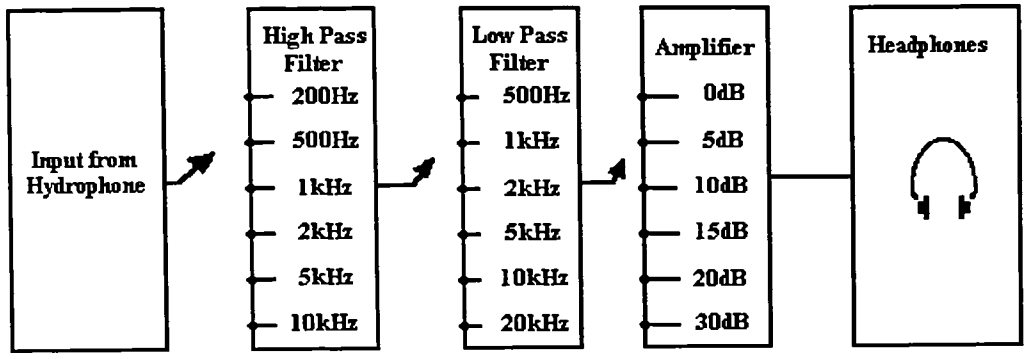


Figure 5.11 : Schematic of amplifier-filter module.

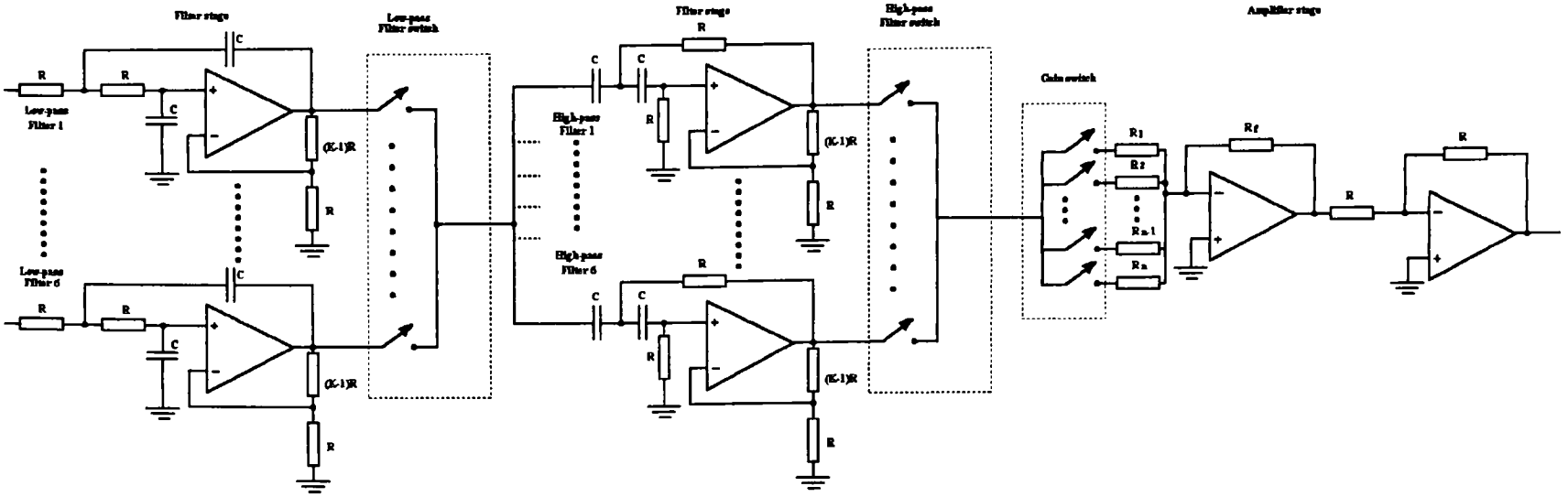


Figure 5.12 - Circuit diagram of one channel of the amplifier -filter module.

Component values for the circuit in Figure 5.12 are chosen from the formulae in the following sections.

5.4.5.1 Low pass filter analysis

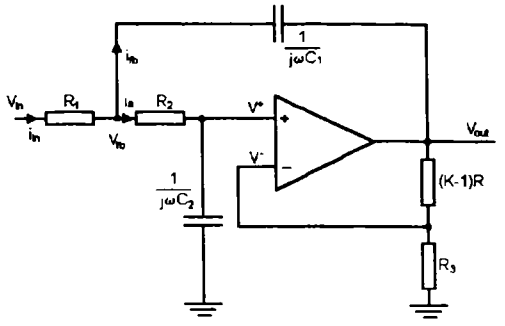


Figure 5.13 - Low pass filter circuit.

The voltages and currents are as labelled in Figure 5.13.

If the gain is chosen to be unity (K=1) then the resistor labelled (K-1)R becomes a short circuit.

For ease of analysis choose:

$$R=R_1=R_2=R_3 \text{ and } C=C_1=C_2$$

Vout will appear at the inverting input of the opamp, therefore:

$$V^+=V^-=V_{out}$$

The current through C_2 will be

$$i_a=j\omega CV_{out}$$

Therefore,

$$V_{fb}= i_a(R+1/j\omega C) \Rightarrow V_{fb}= j\omega CRV_{out}+V_{out}$$

$$i_{fb} = j\omega C(V_{fb}-V_{out}) \Rightarrow i_{fb} = (j\omega C)^2RV_{out}$$

$$i_{in} = (V_{in}-V^{fb})/R \Rightarrow i_{in} = V_{in}/R - j\omega CV_{out} - V_{out}/R$$

$$i_{in}=i_{fb}+i_a$$

therefore,

$$V_{in}/R = j\omega CV_{out} + V_{out}/R + (j\omega C)^2RV_{out} + j\omega CV_{out}$$

$$V_{in}/V_{out} = (j\omega CR)^2 + 2j\omega CR + 1$$

$$V_{out}/V_{in} = 1/(1+j\omega CR)^2$$

Choice of R and C determine the cut-off frequency of the filter which is defined as the -3dB point, the cut-off frequency occurs when $20\log10(1/(1+j\omega CR)^2) = -3dB$, therefore,

$$20\log10(1/(1+j\omega CR)^2) = -3dB \text{ when } 1+\omega CR=2$$

$$\text{ie } \omega_c=1/CR \text{ where } \omega=2\pi f_c$$

$$f_c = \frac{1}{2\pi RC} \tag{5.1}$$

The amplitude and phase responses of this filter are shown in Figure 5.15.

5.4.5.2 High pass filter analysis

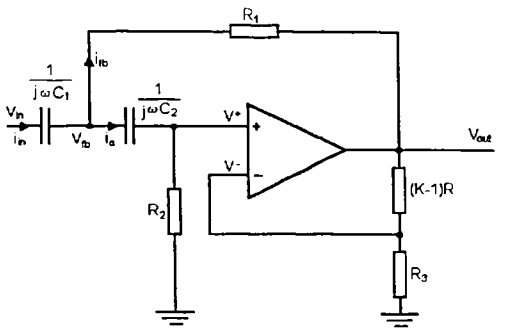


Figure 5.14 - High pass filter circuit.

The analysis of the high pass filter is virtually identical to the low pass filter analysis, since the resistors and capacitors are swapped over. The result of the circuit analysis is

$$V_{out}/V_{in} = 1/(1+ 1/(j\omega CR)^2)$$

The amplitude and phase responses of this circuit are shown in Figure 5.16

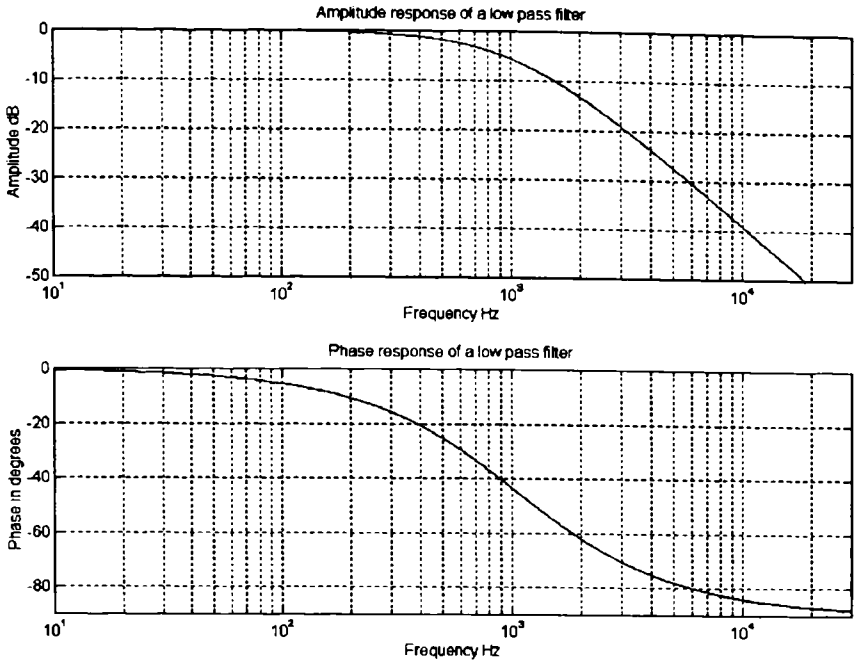


Figure 5.15 - Low pass filter amplitude and phase responses.

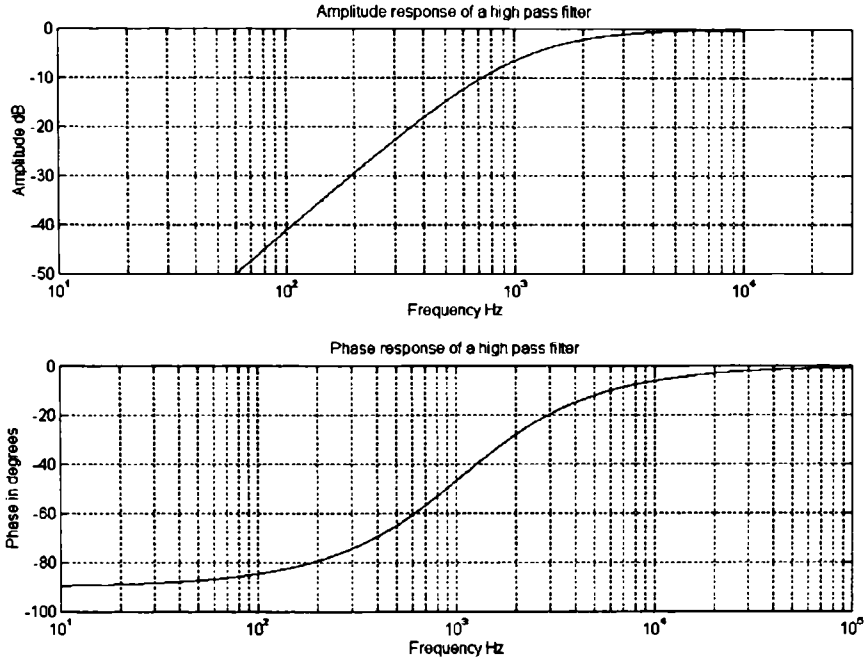


Figure 5.16 - High pass filter amplitude and phase responses.

5.4.5.3 Amplifier component selection

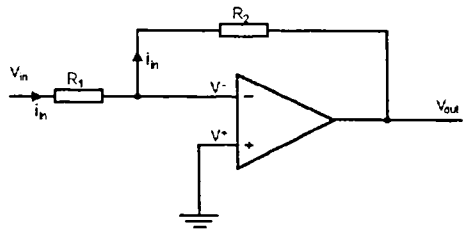


Figure 5.17 - Amplifier Circuit diagram.

The analysis of this circuit is as follows:

The current i_{in} flowing into the amplifier flows around the feed back loop via R_2 due to the high input resistance of the inverting terminal.

$$V^+ = V^- = 0V$$

Therefore,

$$(V_{in}-V^-)/R_1 = (V^--V_{out})/R_2$$

$$V_{out}/V_{in} = -R_2/R_1$$

Gain values $G = V_{out}/V_{in}$ are determined for the amplifier by the ratio of R_1 to R_2.

Gain is usually measured on the decibel scale = 20 log G

The designed amplifier-filter module, prototype 'A' is shown in Figure 5.18.

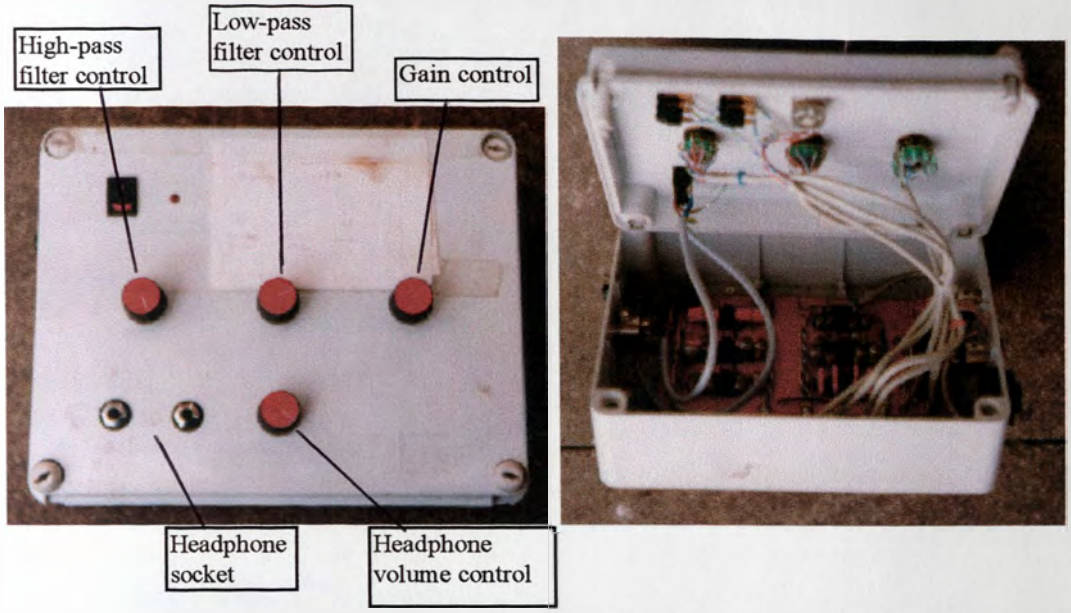


Figure 5.18 - External and internal photograph of the first prototype amplifier-filter box

5.4.5.4 Advantages of prototype 'A'

The high pass filter shown in Figure 5.14 has a cut off frequency of 2kHz. This cut off frequency can be changed by selecting another filter. For the 2 kHz filter the high levels of boat noise are highly attenuated. The boat noise is generally strongest at approximately 200Hz. The use of this filter attenuates the boat noise at this frequency by 30dB. Below 100Hz this filter attenuates the noise by more than 40 dB. The boat noise tends to mask the cetacean vocalisations so by reducing the noise in this manner the cetacean sounds can be more easily heard.

When the boat is stationary and self boat noise is lower, the gain can be increased to listen for distant cetaceans. The fixed gain nature of the previous system did not allow this.

The reduction of the boat noise allows the recording of cetacean sounds without overloading the DAT recorder. The filter /amplifier module therefore allows recordings to be taken in more situations than was previously possible with the original system.

The switchable high pass filter banks of the amplifier-filter module are very effective at removing the propeller and flow noise. The settings most frequently used were a 200 Hz high pass filter with 20 dB gain. The 2 kHz high pass filter with a higher gain of 30 dB was also frequently used because it was ideal for detecting faint dolphin whistles.

In practice the low pass filters were rarely used. The 20 kHz setting of the low pass filters was always used. This setting help to prevent aliasing when the signals are later digitised. The DAT recorder has an anti-aliasing filter built in.

5.4.5.5 Deficiencies in the performance of prototype 'A'

A problem with the prototype was the cross-talk between the two channels. This occurs when signals on one of the channels, are picked up by the other channel. Cross-talk occurs whenever signal paths pass close together. This occurred in prototype 'A', because the signal path of the two channels goes from the circuit board into the same filter or gain switch. Another design flaw which also introduced cross talk was the use of multiple OP-Amps in the same IC package. Using quad OP-Amp packages reduced the amount of space required in the circuit board. However both channels passed through the same Op-Amp package so cross-talk was introduced within the Op-Amp package.

Electrical noise is also introduced into the module through cables connecting different parts of the circuit. It is usual to send a balanced signal along cable runs to reduce the noise. The components required to perform balanced line driving and receiving were not available during this trial, so instead a common ground was established between the various equipment.

As well as the problem of cross talk due to the signals from both channels passing through the same switches, another problem occurred which involved the switches. Due to the corrosive salt water environment in which the box was operated, corrosion of the contacts of the switches took place, resulting in a degradation of the signal over a period of time. As the switch contacts corrode, the resistance of the contact increases and so the signal is attenuated. This problem, however, only occurred after

several months of operation after these trials were completed and while the module was being used for other survey operations.

5.4.5.6 Improvements to prototype 'A'

A number of improvements became apparent after extensive use of the first prototype 'A'. The conclusions from using this prototype were,

1. that the two channels should be kept isolated where possible
2. that the sound signal should be confined to the circuit board to reduce pick up of noise. Switching of the signal path should be performed using relays.

A PCB design would give more control over the signal paths which was not available with the veroboard design. Relays should be used to switch the different settings of the gain and filters so that the sound signal path could be constrained to the circuit boards. The relays should also be sealed so that corrosion of the contacts does not occur. The switches will then control the relays by grounding the operating coil, the other side of the coil is connected to +12V. Resistance due to corrosion of the switches will not affect the quality of the signal. Another amplifier-filter box was designed and constructed to include these improvements.

5.4.6 Hydrophone amplifier-filter module, prototype 'B'

Externally there are minimal differences between prototypes 'A' and 'B'. These differences are, a 'balanced line out' connector which has been added to send the signal to the balanced 'LINE IN' on the DAT player. The switch for the low pass filter bank was omitted. Instead of having a bank of low pass filters the upper frequency range of the box was set at 25 kHz to prevent aliasing when the recording was digitised. A switch to change the survey setting was included, the survey setting control is described later in the manuscript.

Inside the module each circuit was separated from the others by constructing them on different printed circuit boards. The two channels were separated by using a two tier stacking system for the PCBs. Between the boards are ground planes to prevent noise being introduced from radio transmissions. The top layer of boards is for the left channel and the bottom layer is for the right channel. Each of the circuits is labelled in Figure 5.19, which also shows the connectivity of the complete system. The first stage is a balanced line receiver, which subtracts the noise introduced by the hydrophone cable. The second stage is the high pass filter banks. Relays controlled by the switches select the appropriate filter. The third stage amplifies the signals. Again relays control the gain of the non-inverting amplifier so the signal never leaves the board. Stage four, the output stage, is via the headphone amplifier and also the balanced line receiver. The circuit diagram for prototype 'B' is shown in Figure 5.20. The circuit diagram shown is for one channel, the circuit diagram for the other channel is identical.

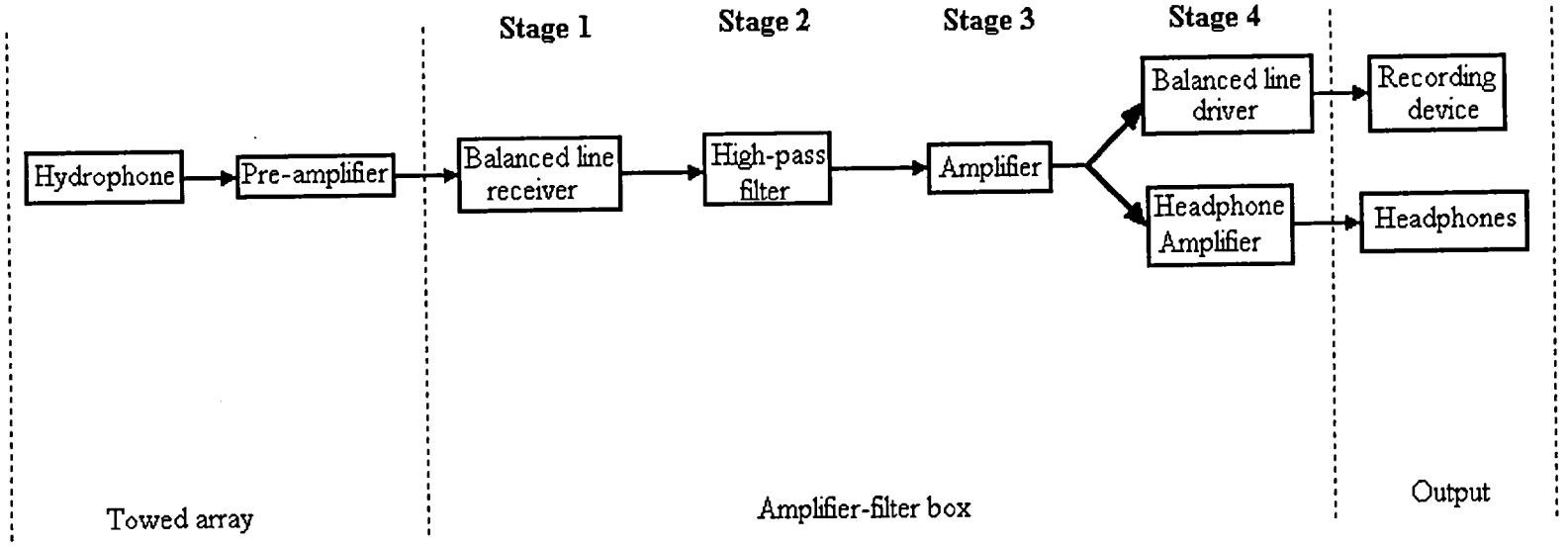


Figure 5.19 - Schematic of complete hydrophone system

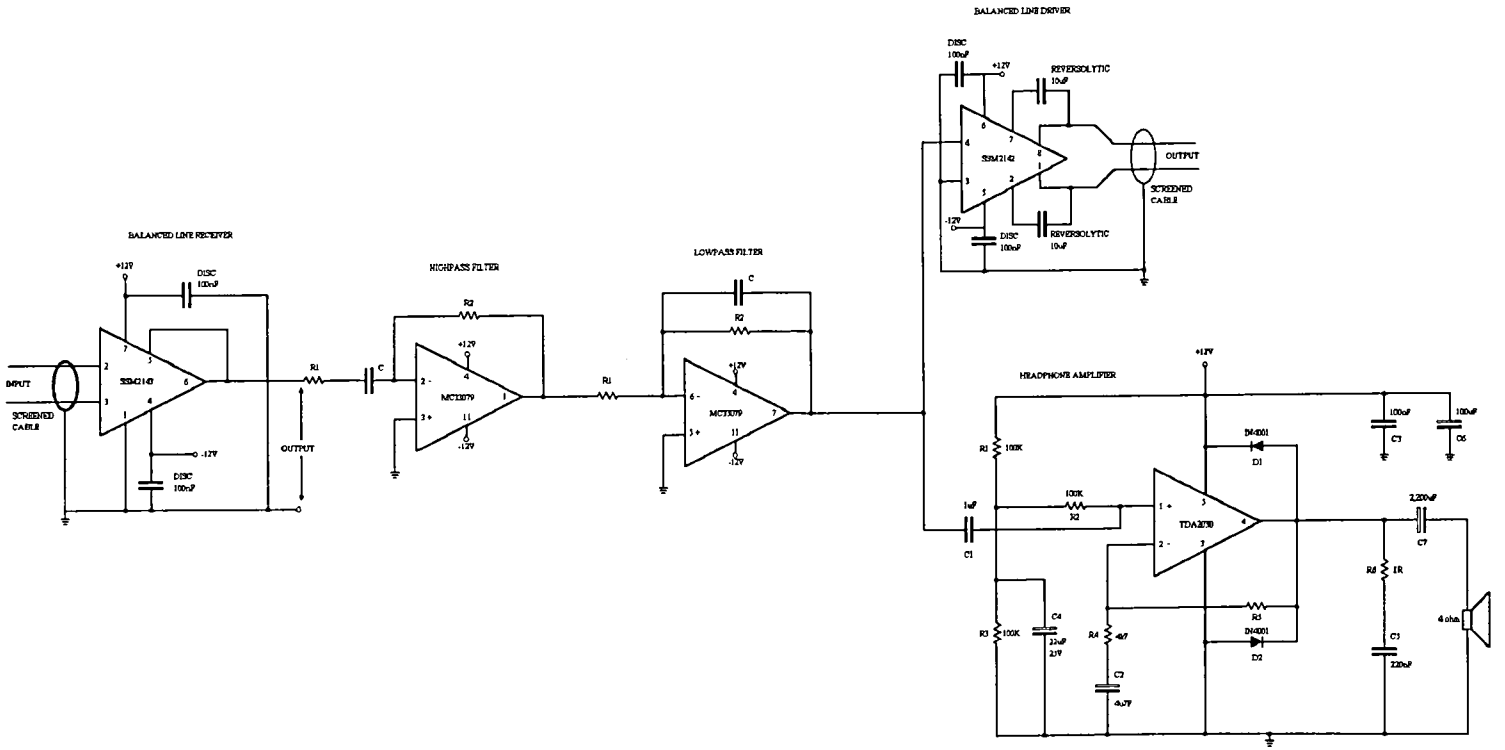


Figure 5.20 - Circuit diagram of prototype 'B'- One channel

The power distribution board is located on the right wall of the box. This contains a dc-dc converter which allows the circuitry to use split voltage supplies whilst only requiring one 12 V battery. The original module required two 12 V batteries which means that four batteries were required so that one pair could be charged whilst the other pair were being used. The 12 V batteries are separate from the boat systems because noise is introduced by other navigational instruments and cannot be charged whilst being used due to electrical noise introduced by the charger.

5.4.6.1 Survey setting

'Song of the Whale' conducts survey operations in which it follows defined tracks and records for 1 minute every fifteen minutes throughout the day and night. The 1 minute recording consists of two different settings for each half minute. For general listening a 200 Hz filter with 20 dB of gain proved to be the best setting. However, when listening for dolphin whistles a 2 kHz filter with 30 dB of gain proved the most effective. The recordings were taken at these two different settings.

Faint whistles often gave the first indication of the presence of dolphins. The survey operations provide the best way of finding dolphins in order to collect recordings during experimental trials. The survey control in the module allows the recording to continue and the settings of the gain and filters to be switched between these two settings with one switch, half way through the recording. This survey control is a new development which was not present in prototype 'A'. The completed hydrophone amplifier-filter module, prototype 'B' is shown in Figure 5.21.

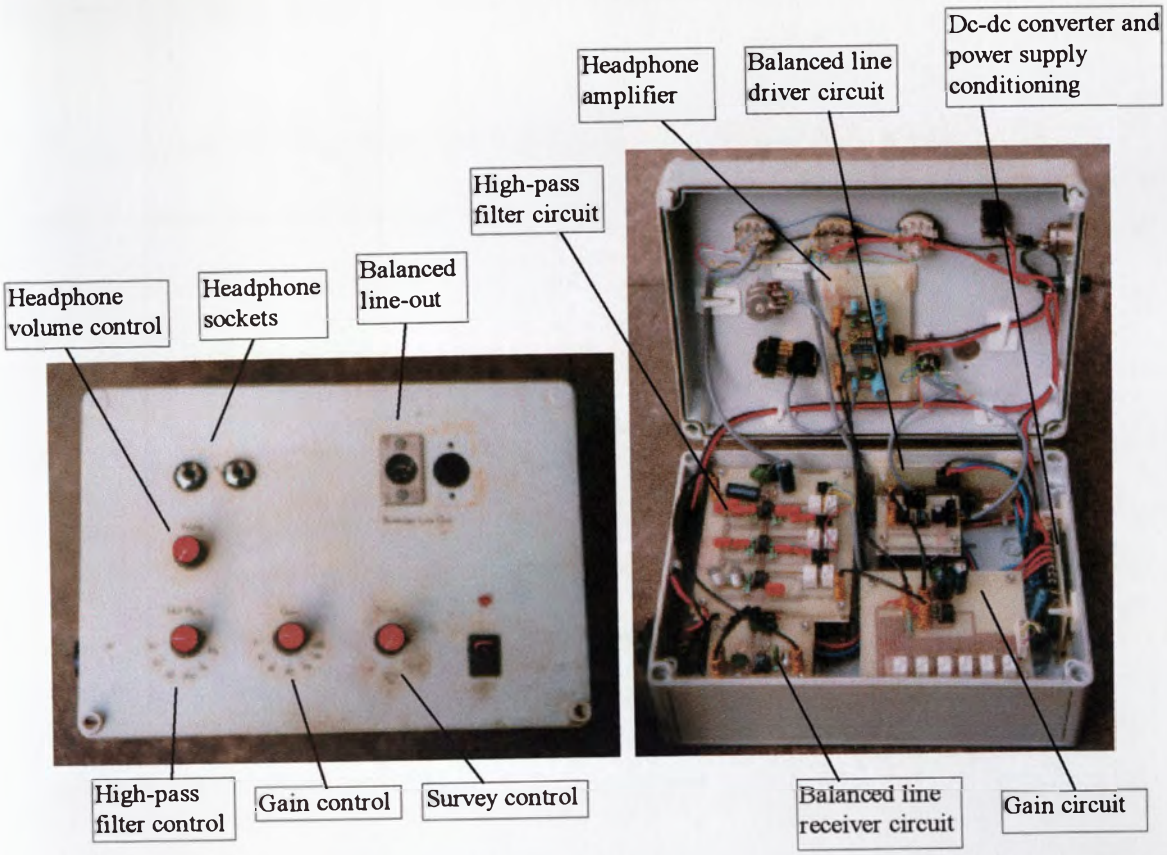


Figure 5.21 - External and internal photographs of amplifier-filter module, prototype 'B'

5.4.7 Final design for hydrophone amplifier-filter module

The prototype 'B' design reduced the problems of cross talk between channels and also the introduction of electrical noise from cables. However, due to the amount of connections which are made between boards, problems occurred which resulted in complete failure of one of the channels. The problem was traced to the connections between boards. The crimp type connectors used were not reliable for this application. Direct soldering of the connections cured the problem. A third hydrophone amplifier-filter module was designed to resolve these problems. Two printed circuit boards were used, one for each channel. This reduced the number of connections within the circuit and the problem was cured. Otherwise the circuit is identical to the circuit in prototype 'B'. This third and final prototype is shown in Figure 5.22.

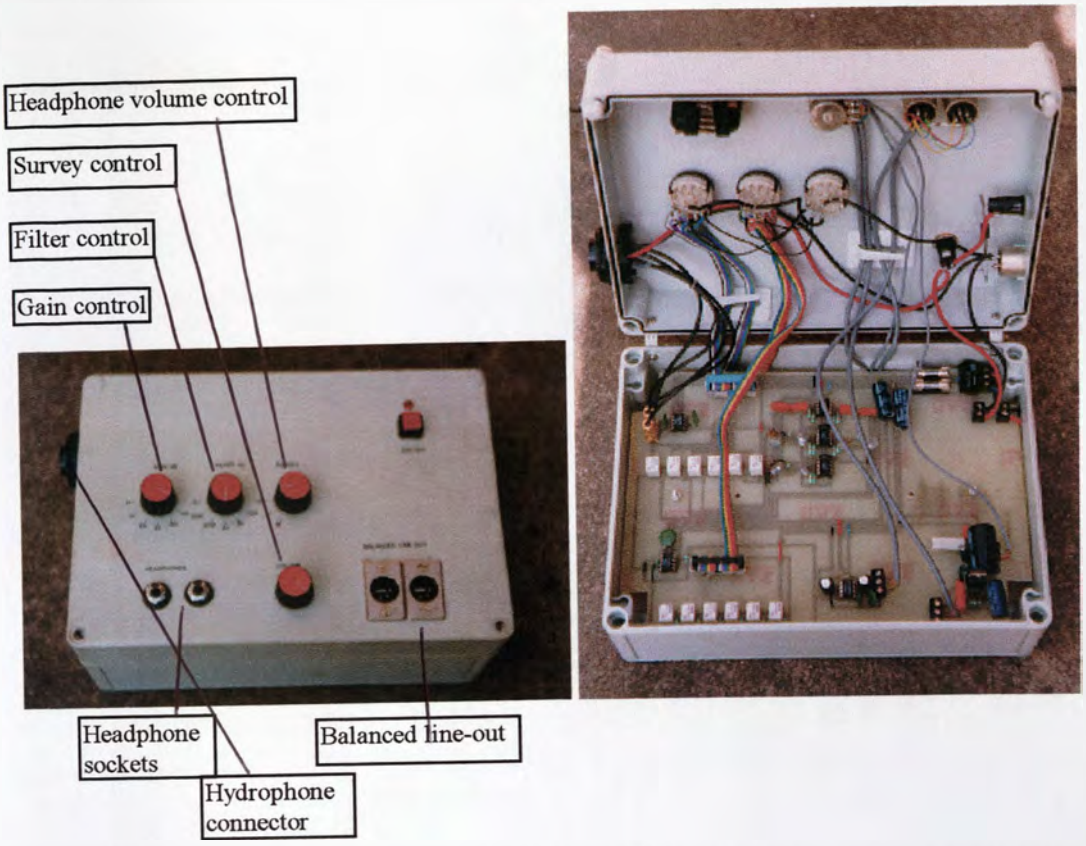


Figure 5.22 - External and internal photographs of final hydrophone amplifier-filter module.

5.4.8 Application of the designed amplifier-filter module in other research projects

The success of the amplifier-filter module in collecting cetacean data during the current project has enabled the module to be provided for use in other research projects. These are listed below:

1. The amplifier-filter module was used for the collection of striped dolphin recordings during the Ligurian Sea trial, in the summer of 1994, on board 'Song of the Whale'. It was continually used throughout the winter 1994-95 in Dominica and again in the Azores, in the summer of 1995.

2. The survey operation in the Ligurian sea to collect striped dolphin recordings was continued by TETHYS, during summer 1995. TETHYS is an Italian research institute interested in fin whale research. They generously offered to collect recordings for the current project. Therefore an identical hydrophone and amplifier-filter module was installed on their research boat 'Gemini'.

3. The amplifier-filter module has also been used on other cetacean projects. Morgan film productions who were shooting a film for a BBC sperm whale documentary in Dominica, during the winter 1994-95, used one of these modules during the second location shoot which was in the Azores, in the summer of 1995.

4. The boat chartered by Morgan productions 'Silvery Light', which operates in the Azores during the summer, are now using one of the amplifier-filter modules for whale watch excursions.

5. During the winter 1995-96 two amplifier-filter modules were used in an IFAW project in Antarctica. These modules were a modified version so that the gain and filter settings could be set externally from a computer, which allowed the recording to be done automatically.

6. Another amplifier-filter module was used by a French film company for an artistic film on sperm whales in Dominica during the winter 1995-96.

7. During June-July 1996 a cetacean monitoring contract between Research and Development Ltd. and Shell Oil is using one of the modules to detect cetaceans that may be in the immediate location before seismic surveying is commenced, so that government guidelines can be adhered to.

5.4.9 Audio Recorder

Recordings were taken using a commercially available Sony TCD-D10 PROII DAT recorder. This audio recorder stores the recording in a digital format. As well as the audio sounds, the time and date of the recording is automatically marked on the tape and index marks can also be made. The recordings are stereo, the left channel records the hydrophone nearest to the boat and the right channel records the hydrophone furthest from the boat. The frequency response of the DAT recorder is flat from 20Hz to 22050Hz, and this has been verified by the author, see Appendix E. The incoming signal can be recorded through either the line or microphone inputs, more gain is available through the microphone input. There are 10 gain settings. The calibration curves, calculated by the author, for the DAT player can be found in Appendix E.

5.4.10 Anti-Aliasing Filter

When digitising signals the sample rate must be selected at twice the highest frequency of interest. This is to prevent aliasing which occurs when there is energy present above half the sample rate. When the sample rate is twice the frequency of interest then this is known as the Nyquist rate. Sampling rates above the Nyquist rate are desirable due to increased accuracy, however, keeping the sample rate low allows more storage on a particular medium. The result of aliasing is to fold down the frequencies above half the Nyquist rate, therefore giving erroneous results. To overcome aliasing a low pass filter is used to limit the frequency range to below half the Nyquist rate. In this analysis an 8-Pole Low Pass Bessel filter is implemented in analogue electronics with a cut-off

frequency of 22kHz. The circuit diagram, design equations and response of this filter are given in Appendix J. This filter was designed and constructed by the author.

5.4.11 Digital Signal Processing Hardware

An Analog Devices Digital Signal Processor was used for the real time signal analysis. This development board is shown in Figure 5.24. The development board consists of the main processor (ADSP 21020, 25MHz) which has separate data and program memories. The board supports a sound port (AD1849) which has stereo audio inputs, also a 2 channel ADC/DAC (AD7769) is available, this allows a total of four acquisition channels. Figure 5.23 shows the interconnection of the DSP boards and also the internals of the DSP board in block diagram form. DSP programs were written in assembler and then downloaded from a host PC via the RS232 port. Once development is complete the program can be blown onto EPROM which dispenses with the need to download the software. The RS232 port is driven by the processor controlling the soundport which has the draw back that the RS232 port cannot be used for data transfer whilst running a program which uses the sound port.

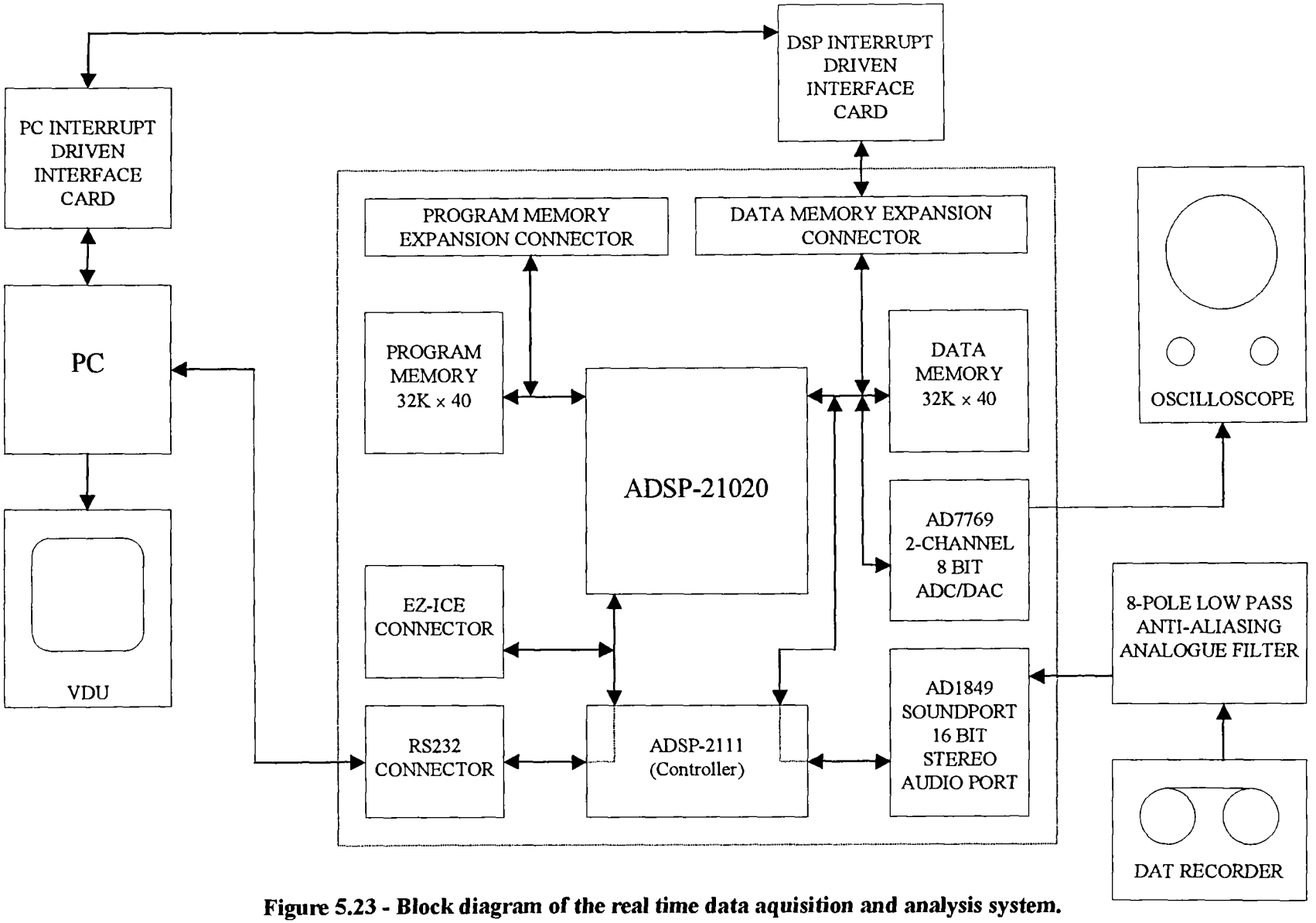


Figure 5.23 - Block diagram of the real time data aquisition and analysis system.

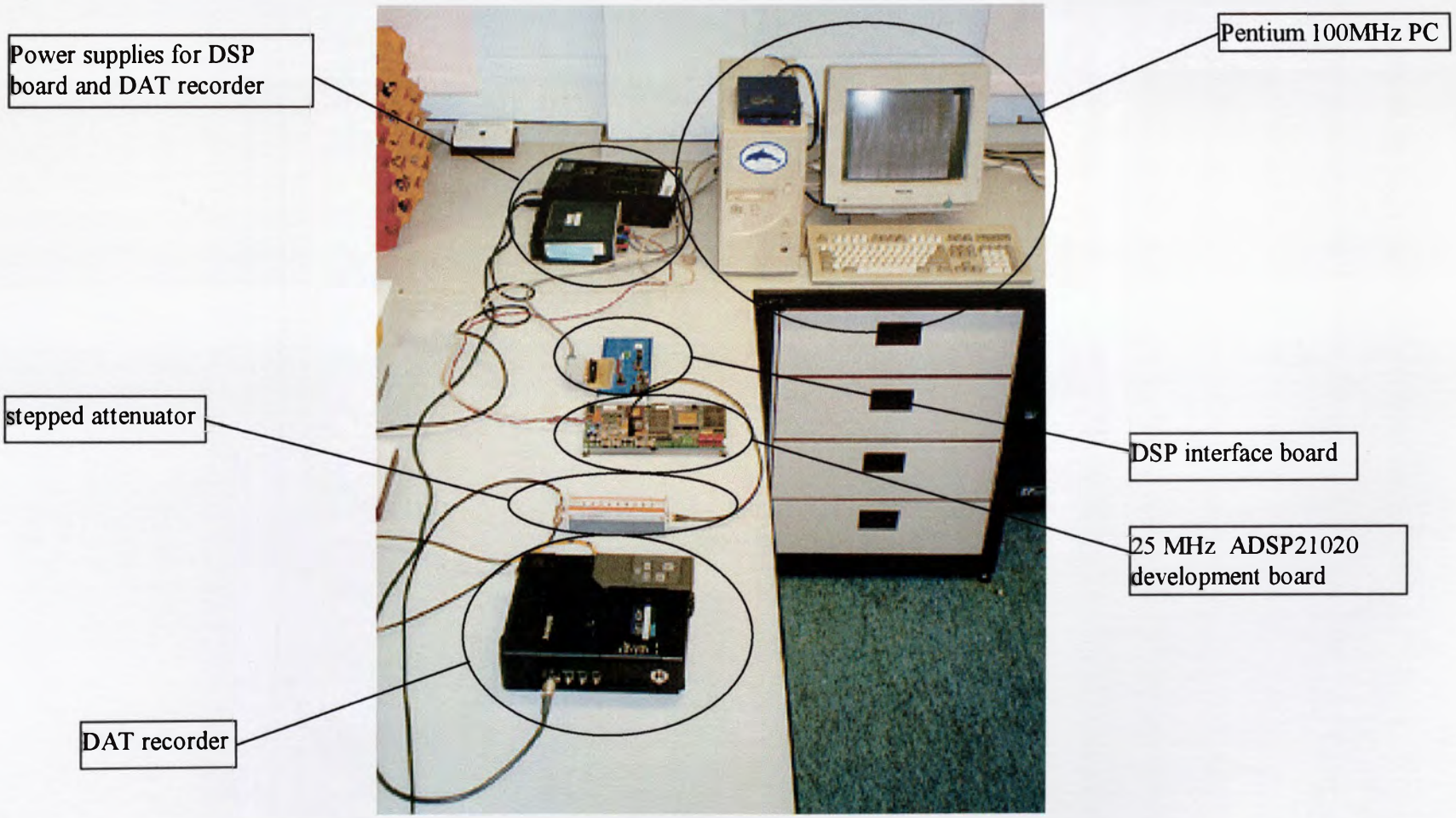


Figure 5.24 - Real time signal processing system.

5.4.11.1 High Pass Digital IIR Filtering

Digital filtering using the ADSP21020 was performed in real time. The incoming signal was digitised via the AD1849 analogue to digital converter. An IIR cascaded biquad algorithm was used to calculate the filtered data which was then output via the AD7769 digital to analogue converter. The cut off frequency of the high pass filter was selectable via an input to FLAG0 of the processor. Five cut off frequencies were available: 200Hz, 500Hz, 1kHz, 2kHz and 5kHz. These cut off frequencies were chosen after pre-analysis of the vocalisations.

5.4.11.2 Spectral Analysis

An ADSP 21020 digital signal processor development board was used to develop a real time analysis tool for automatic detection, extraction and analysis of the dolphin vocalisations. The schematic in Figure 5.23 shows the components of the system. Analogue data is converted to digital data by the AD1849 analogue to digital converter at a sample rate of 44100 Hz. This data is stored in a buffer ready for FFT analysis. The buffer size chosen was 1024. Once the FFT is complete the results are output via the data expansion port. These data are then sent via a high speed custom built parallel data link to a PC for display analysis and storage. Table 5.4 shows the number of machine cycles and time taken for each length of FFT to be performed

Table 5.4

FFT Length	cycles	time ms
64	636	0.026
128	1226	0.049
256	2504	0.100
512	5286	0.211
1024	11331	0.453
2048	24418	0.977
4096	52608	2.10
8192	113054	4.52

5.4.11.3 High Speed Interrupt Driven Parallel Data Link

Data transfer rate:

The DSP is acquiring data at a rate of 44100 samples per second. This data is being fed into a buffer which is 1024 samples long. The buffer therefore takes 23.2 ms to fill. Once the buffer is full a 1024 pt FFT is performed. This produces a 512 byte frequency spectra. This frequency spectra needs to be transferred to the PC for display. The rate at which the data needs to be transferred is therefore: 22050 bytes per second.

The output rate of the FFT data from the DSP is too high for a serial data link to be used. A serial link running at 57.6kHz baud rate can only transfer data at a rate of 4800 bytes per second.

A custom built parallel data link was constructed by the author which received the data into a PC under interrupts. The ISA expansion port of a PC can be clocked at the maximum rate of 40kHz. Therefore 40 kbytes of data can be transferred every second. Therefore allowing the display to run in real time.

The components of the interface are shown in Figure 5.25. The data is acquired and analysed by the DSP, this data is then sent via the expansion connector to the interface card. A cable then transfers the data to the PC via the PC interface card.

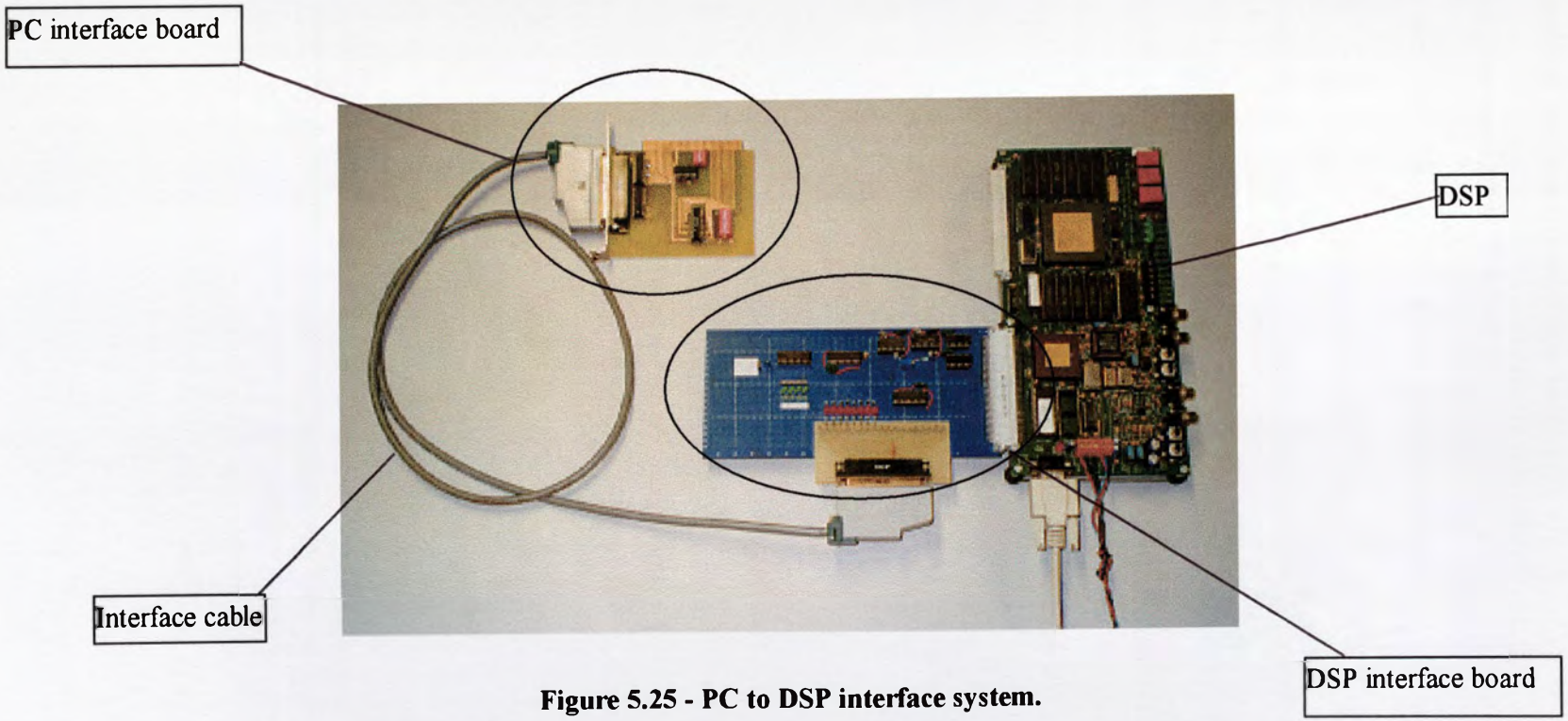


Figure 5.25 - PC to DSP interface system.

5.4.11.4 PC Interface card

An expansion card was designed and constructed to fit into the ISA bus of the PC. The schematic diagram of the PC interface card is shown in Figure 5.26. Figure 5.27 (a), shows the PCB schematic which was developed from the circuit shown in Figure 5.26. Figure 5.27 (b) shows the PC interface card installed in the ISA slot of a Pentium PC. This interface was designed to be bi-directional allowing data to be transferred from the DSP to the PC and control commands to be sent to the DSP from the PC. The speed of the parallel link was determined by the maximum speed that the PC can read from it's expansion bus.

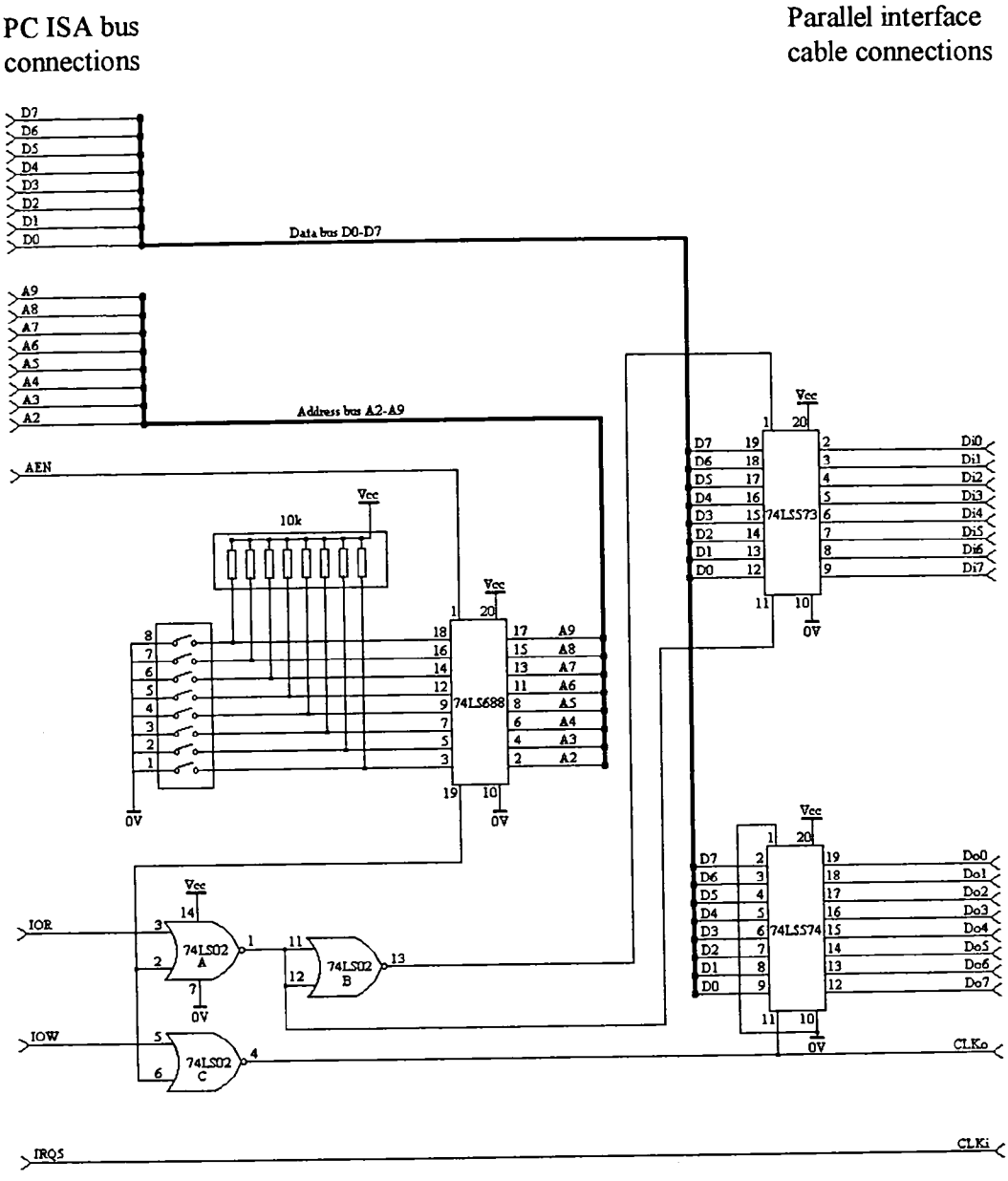
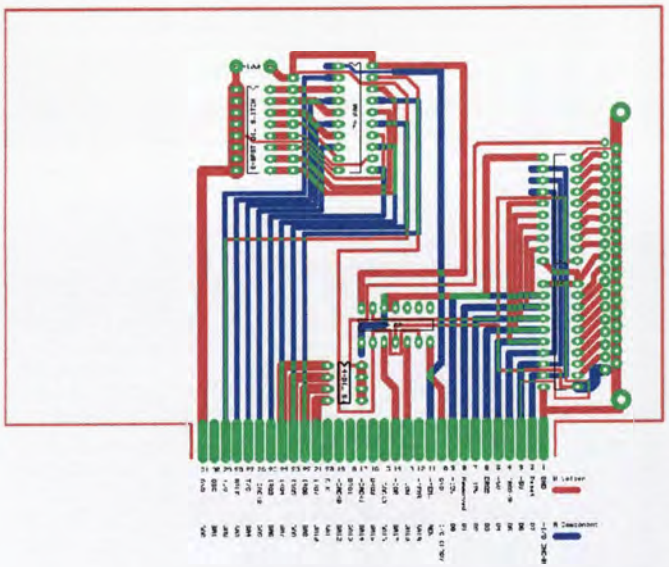


Figure 5.26 - Circuit diagram of the PC ISA interface card.



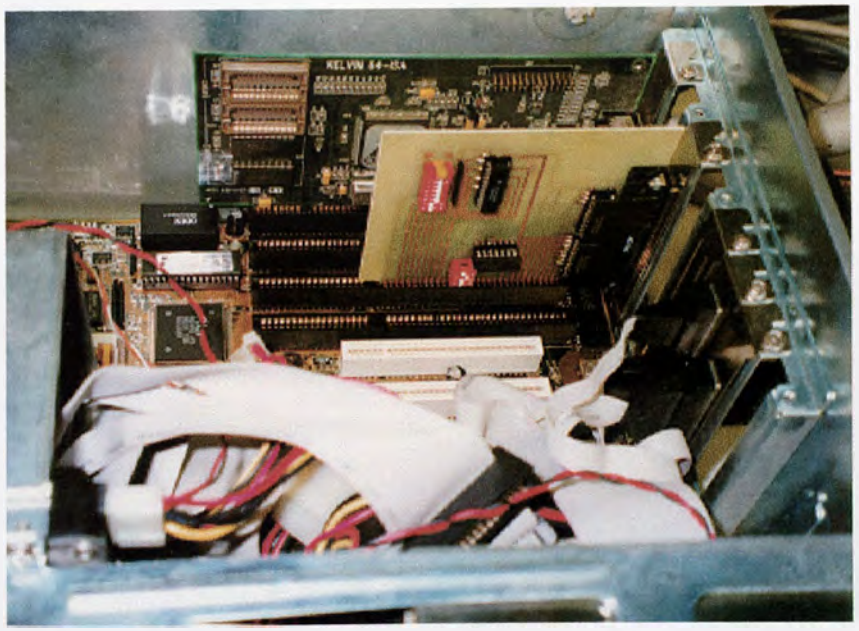


Figure 5.27 - PC Interface card.

(a) PCB schematic

(b) Interface card installed in the expansion slot of a PC

5.4.11.5 DSP Interface card

An interface card was also designed and constructed for the DSP, the circuit diagram is shown in Figure 5.28. A parallel cable linked the PC interface card to the DSP interface card. The read and write cycle timing diagrams are shown in Figures 5.29 & 5.30 respectively. A read cycle is initiated by an interrupt on the IRQ1 line of the ADSP. The ADSP 21020 responds by pulling the DMS3 and DMRD lines low for approximately 0.3 μs. The circuitry on the interface card then AND's these signals together to produce the clocking pulse for the 8 way D-Type Latch. The data can then be read from the latch into memory.

The read cycle is more complicated due to the slower speed at which the PC can read data compared to the ADSP21020. The ADSP 21020 initiates a data write by pulling DMS3 and DMWR low. These signals are ANDed together to produce the rising edge of the IRQ5 signal this initialises the interrupt handler of the PC. The data is then loaded into the D-Type latch using lengthened clock pulses due to the slower speed of the latches for accepting data. The data is then read from the latch when the IRQ5 pulse goes low again 12.5μs after the data transfer was initiated. The interface is then ready to begin another data write cycle.

ADSP 21020 data expansion port connections

Parallel interface cable connections

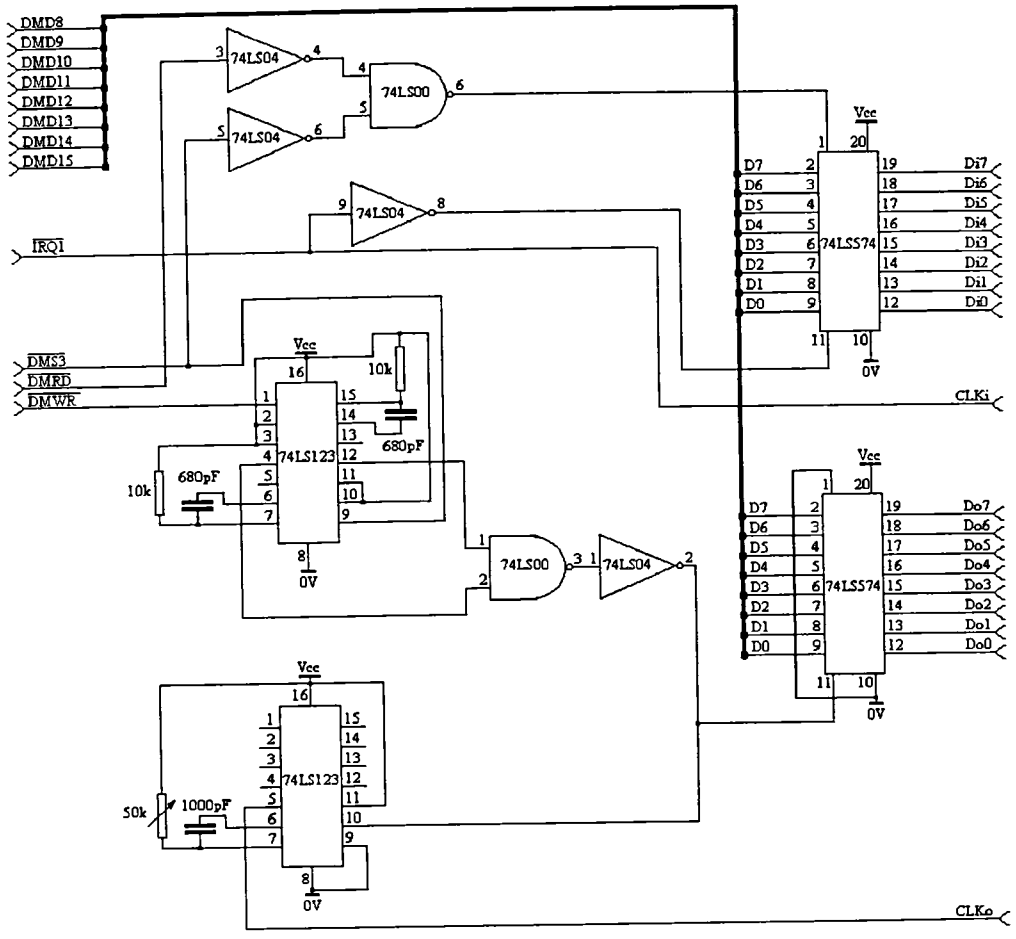


Figure 5.28 - Circuit diagram for the ADSP interface card.

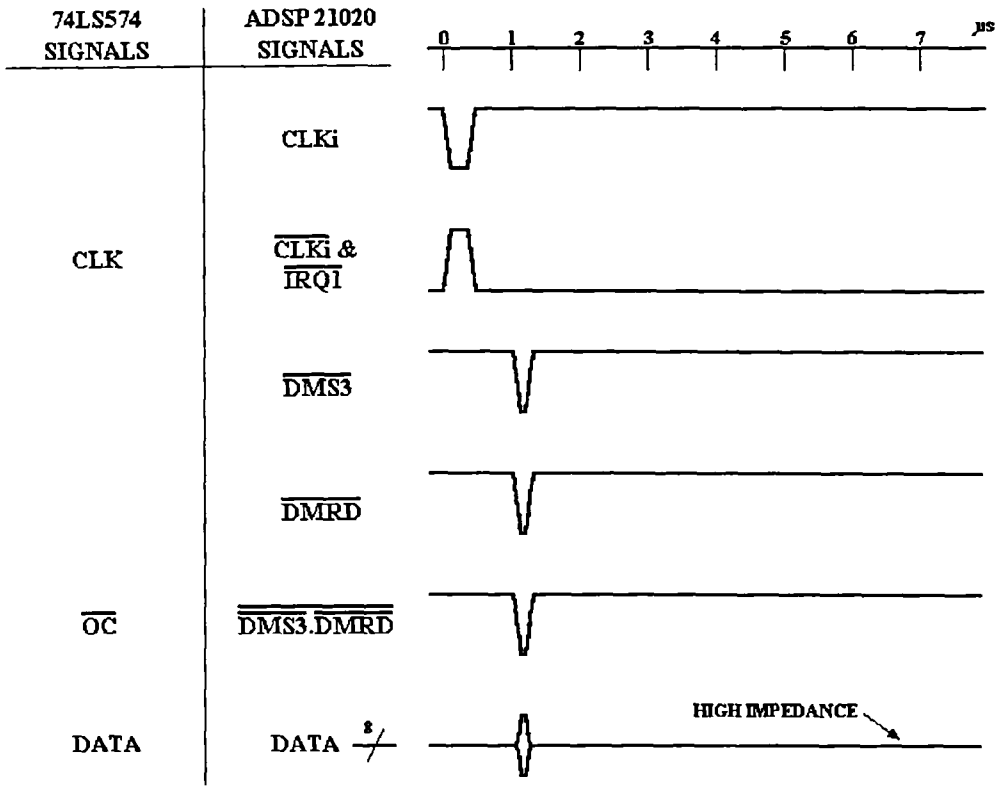


Figure 5.29 - Read cycle of the ADSP 21020.

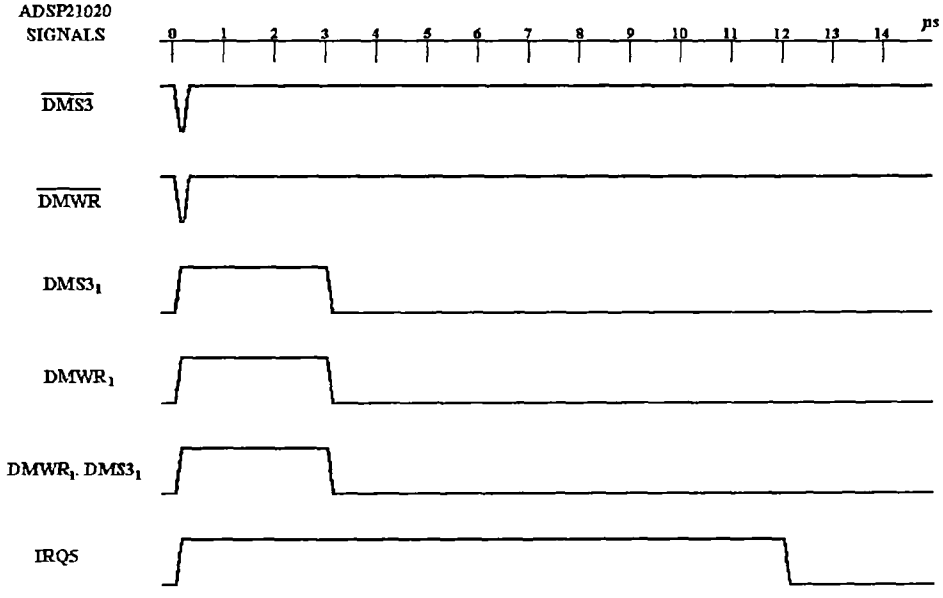


Figure 5.30 - Write cycle of the ADSP 21020.

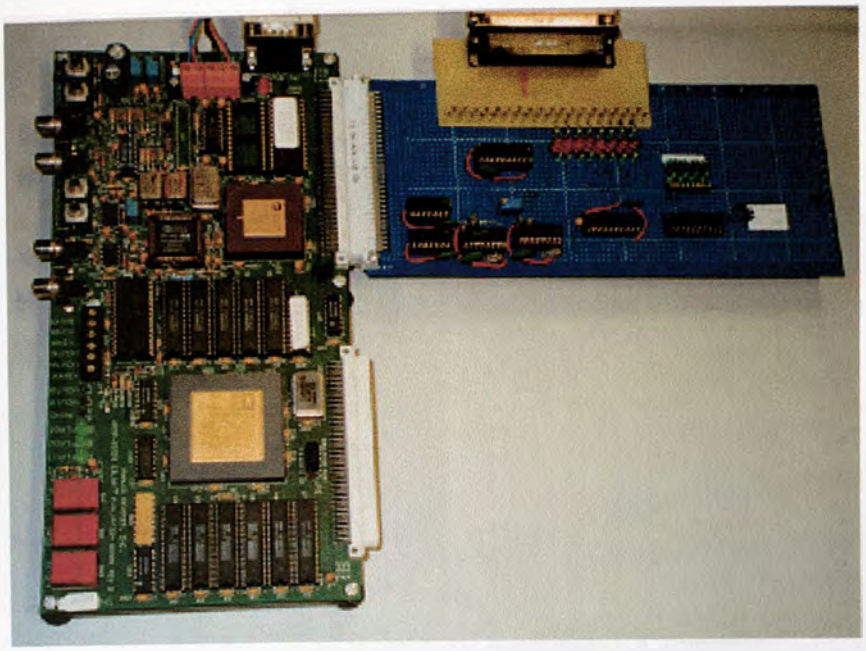


Figure 5.31 - DSP Interface card shown plugged into the data expansion port of the ADSP 21020.

The timing diagram for the transfer of data and also the handshaking signals are shown in Figures 5.29 & 5.30.

5.4.11.6 Display

Once the data had been acquired from the ADSP 21020 via the high speed data link the output was displayed using the VDU of the Pentium PC. The display produced is shown in Figure 5.32.

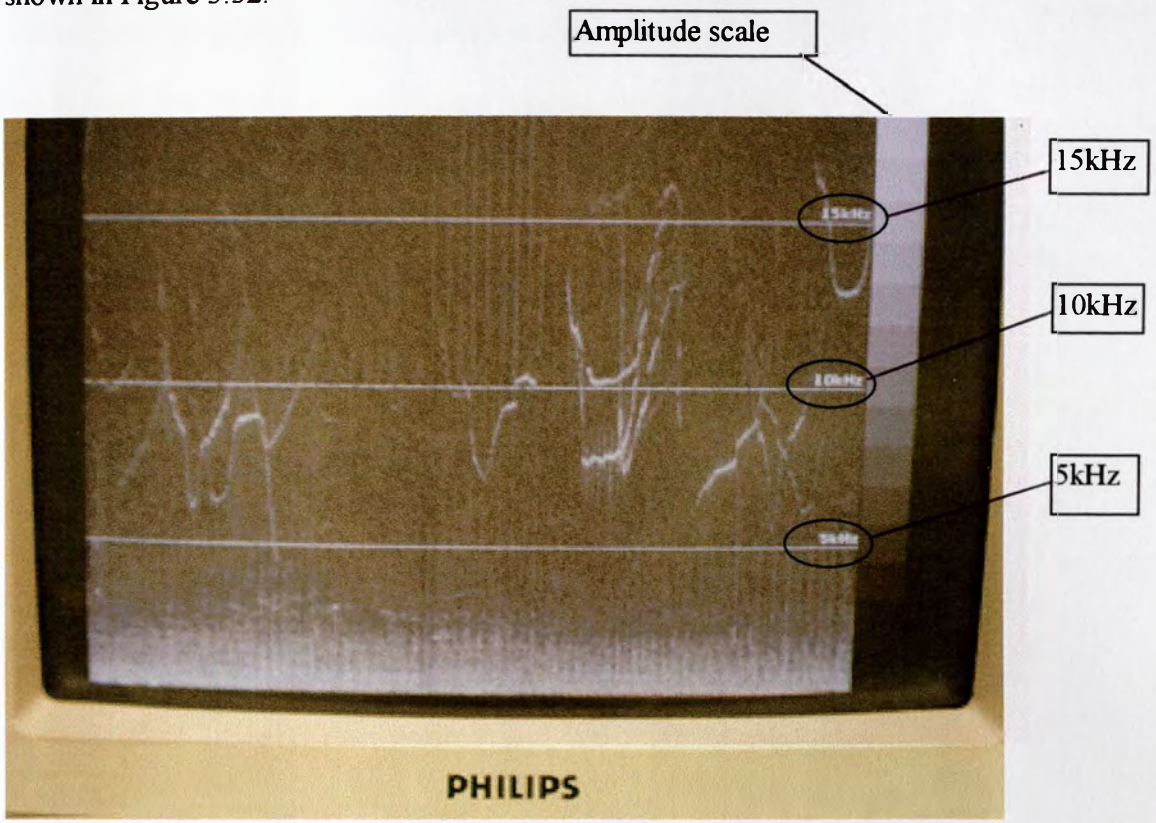


Figure 5.32 - Spectral display of data from the ADSP 21020.

5.4.12 Digital Signal Processing Software

5.4.12.1 Spectral analysis routine

The spectral analysis routine is shown in block diagram form in Figures 5.33 & 5.34. The spectral analysis routine was written in assembly language which was complied on the PC and downloaded to the program memory of the ADSP 21020 via the serial interface. The source code for this routine is given in Appendix I.

5.4.12.2 Interrupt driven data collection and display routine

The data collection routine was written in 'C' under the MSDOS operating system. The block diagram representation of the program is given in Figure 5.35. The source code for the data collection and display routine is given in Appendix I.

DSP Program Flow Diagram

Main Routine

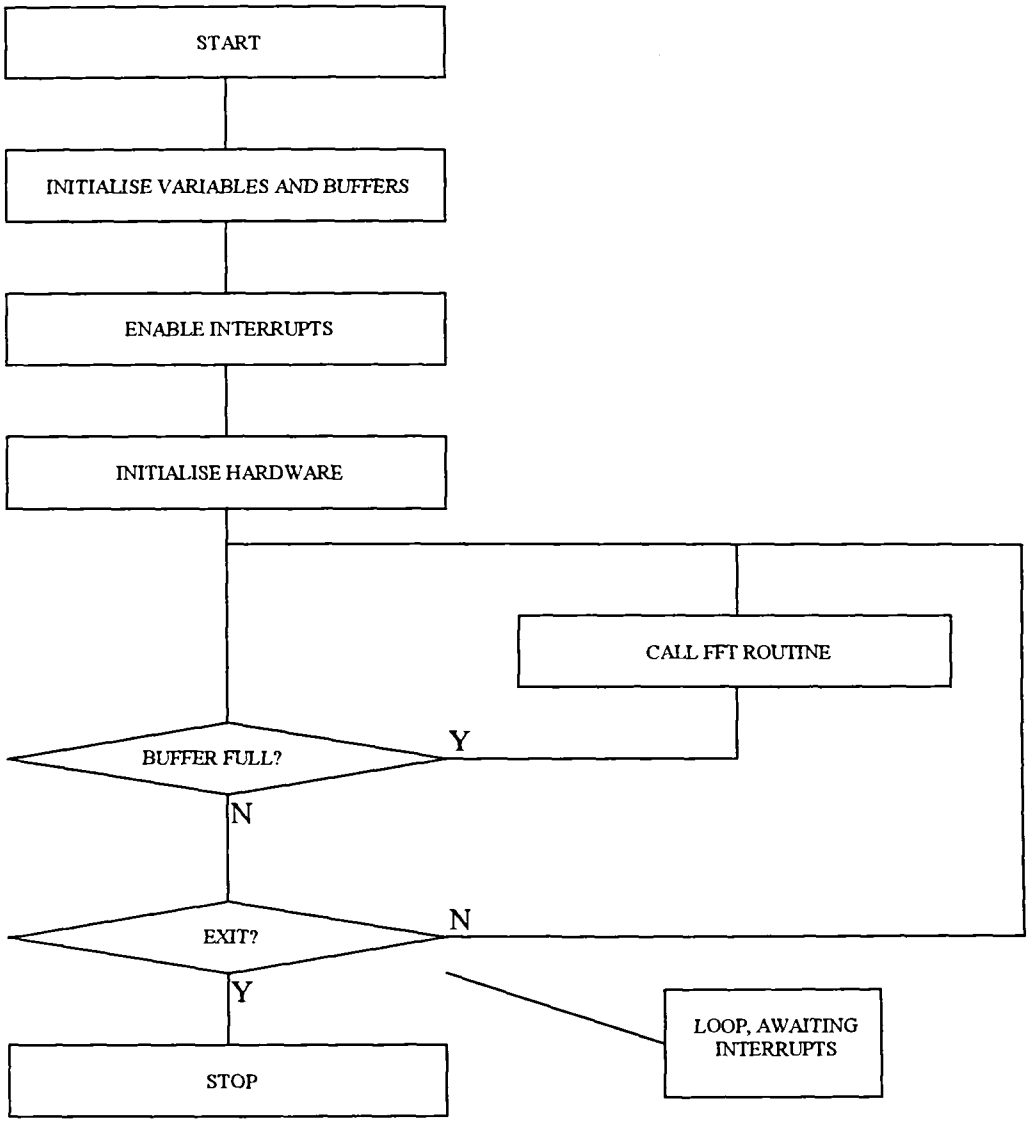


Figure 5.33 - Block flow diagram of the DSP main routine.

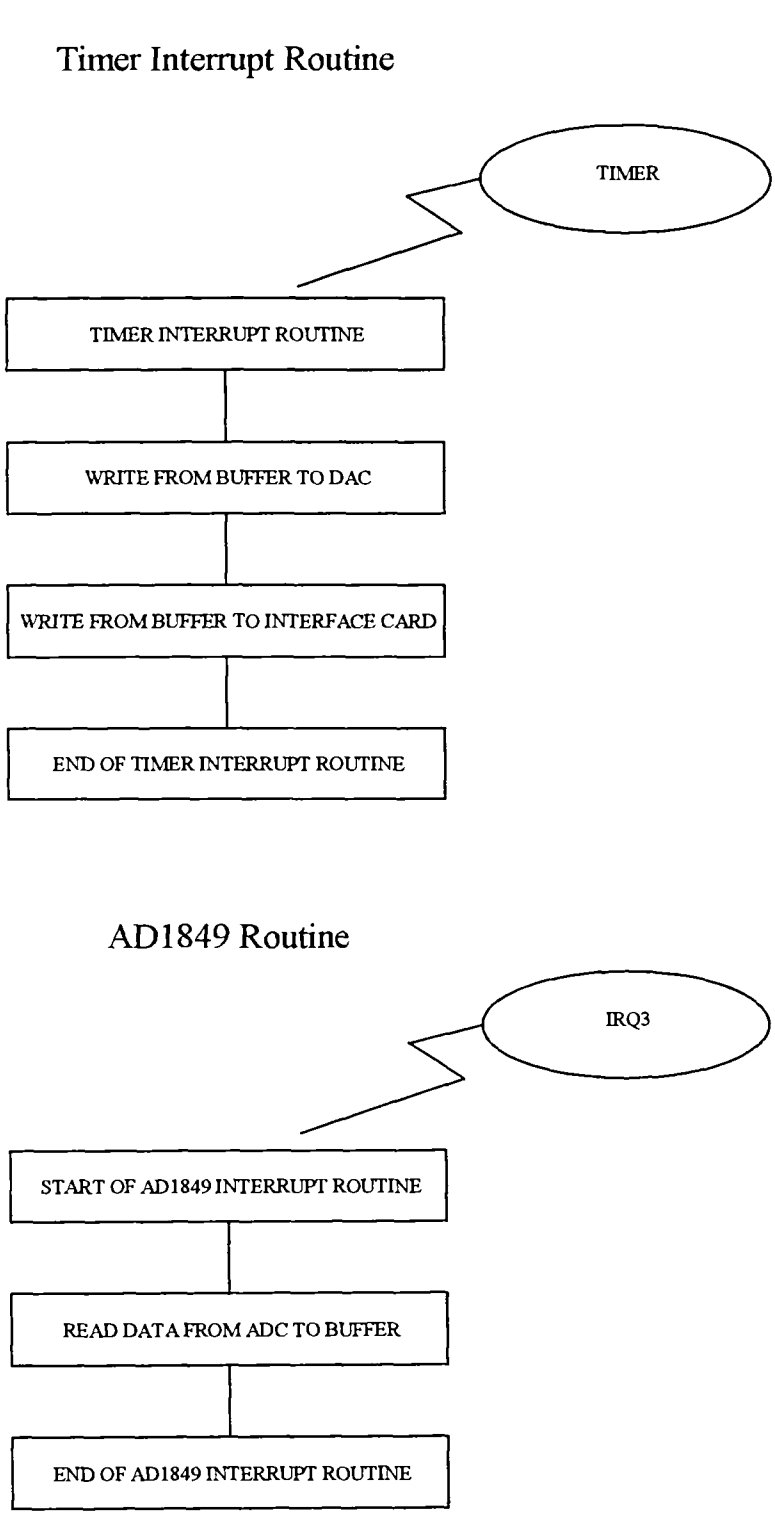


Figure 5.34 - Block flow diagram of the DSP interrupt routines.

PC Program Flow Diagram

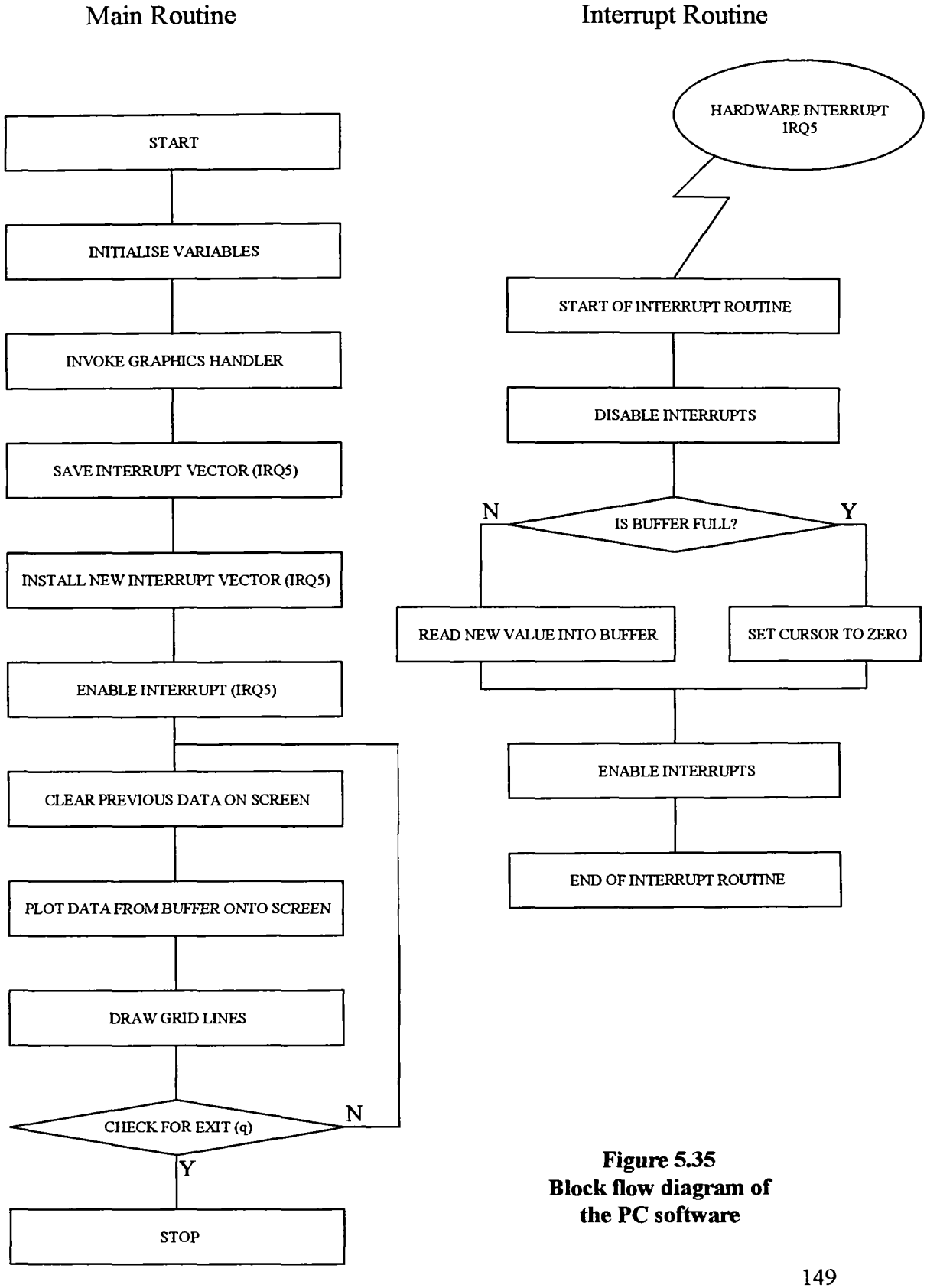


Figure 5.35
Block flow diagram of the PC software

Chapter 6 - Preliminary Experimental Results - Trial 1

6.1 Introduction

The recordings taken during the first trial are presented in this chapter. These recordings were used to explore the ways in which information could be extracted from acoustic recordings of cetaceans. The Ligurian Sea area is inhabited by striped dolphins (*Stenella coeruleoalba*) and this species was recorded on numerous occasions. This species of dolphin is relatively small and are similar in skin patternation to other dolphins which are closely related such as the spotted dolphin. The striped dolphin is known to produce echolocation clicks and also pure tone frequency modulated whistles. These sounds have been reported in the literature Steiner (1981).

The echolocation clicks which dolphins are known to emit were detected from the striped dolphins encountered. These clicks have a peak source level at 120 kHz. Unfortunately due to limitations in the bandwidth of the recording equipment used only the energy in the frequency band below 20 kHz was detectable. Even with this limitation the echolocation clicks can be identified above the background noise. The short duration of these clicks of typically 120 μs was exploited by using a spatially separated array to track the movements of the dolphins from calculations on the time difference of arrivals of the clicks on the elements of the array. This experiment is described in section 1.

The dolphins also produce a pure tone frequency modulated whistle which is thought by many researchers to have an individual frequency - time contour. This was

investigated during an encounter with four dolphins during which time, seventeen whistles were detected. An algorithm for detecting and extracting these whistles from the background noise is presented, this is an original contribution which builds on work conducted by Buck and Tyack (1985) on a different species of dolphin. The testing and evaluation of these algorithms can be found in chapter 7. Comparison of the extracted whistles was performed by the use of multivariate analysis methods. This analysis then yields information on the number of cetaceans present during the encounter and enables a database of individual dolphins whistles to be collected for future reference. This database could then be interrogated when an encounter occurs to determine the individual dolphins present within a group and therefore a history of the individuals movements and associations with other dolphins can be collected. This work is presented in section 2.

Section 3 investigates a sound which has not previously been reported in the literature. This sound was found to be emitted frequently by the striped dolphins usually before, after or during echolocation click trains. The sound is a short pulse, typically less than 0.5 second in duration, with a harmonic frequency structure. Section 3 describes this sound and presents a possible explanation for it's use.

6.2 Section 1 - Dolphin Clicks

6.2.1 Introduction

The recording of the group of striped dolphins was performed on two stereo towed arrays as described in Chapter 5. The reason for recording the dolphins on two of these arrays is to obtain positional information about the dolphins. The dolphins emitted a constant stream of clicks during the acoustic contact. By triangulating on the clicks from each pair of hydrophones in the two arrays a position for the vocalising dolphin can be determined.

6.2.2 Positional information from two elements

Analysis of a click on each element of one array shows that there is a time difference of arrival of the click on one element compared to the other which is dependent on the angle of the array to the dolphin. This is shown schematically in Figure 6. 1.

Where,

H1 is the front element of the array and H2 is the rear element of the same array.

L is the length of cable that the array is being towed upon.

s is the separation of the two elements H1 and H2 which is fixed and is 3 m.

W is the position of the vocalising dolphin.

a is the distance that the click has to travel in the water to reach the element H2

d is the extra distance that the click has to travel in the water in order to reach the element H1.

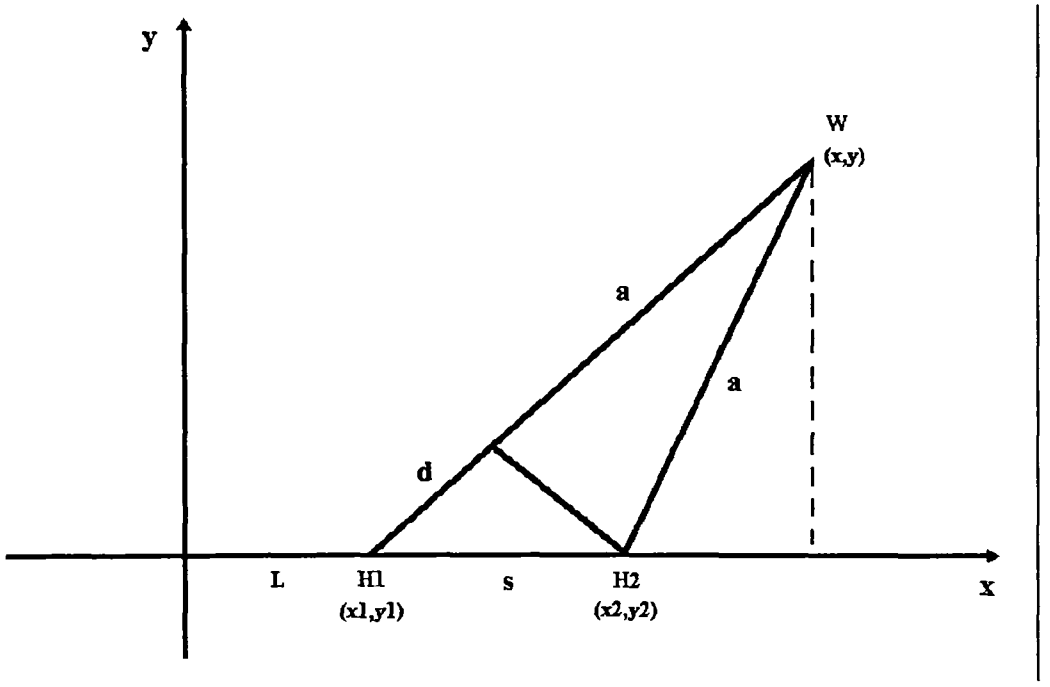


Figure 6. 1- Propagation paths of dolphin clicks

With two elements there exists a three dimensional surface on which the dolphin can vocalise and still produce the same time delay between the two elements. The surface resembles a cone orientated with the apex of the cone at the midpoint between the two elements, as shown in Figure 6. 3. If the problem is considered in two dimensions, then the vocalising dolphin can produce the same time delay if it is anywhere on a hyperbolic curve. The derivation of this curve of possible locations can be found in Appendix F. The result is quoted here,

$$y = \sqrt{\left(\frac{(x-L)^2 - (x-L-s)^2 - d^2}{2d}\right)^2 - (x-L-s)^2} \qquad (6.1)$$

Now by choosing values of x, y can be plotted to find the locations of possible vocalisations. This hyperbolic curve of possible locations are plotted as the continuous line in Figure 6. 2.

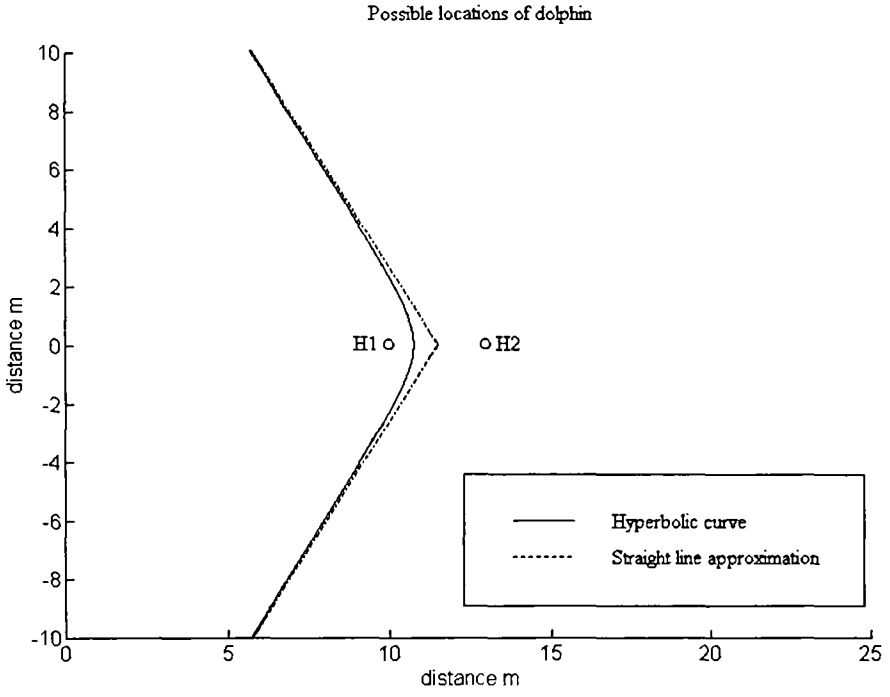


Figure 6. 2 - Possible positions of a vocalising dolphin using two array elements.

Although the possible positions of the location of the sound are on a hyperbolic curve the curve can be represented by a straight line. This approximation is valid once the position is beyond 2m.

The straight line approximation yields a bearing to the vocalising dolphin. The bearing, which is only an approximation can be found as,

$$\tilde{\mathbf{B}} = \cos^{-1}\left(\frac{d}{s}\right) \tag{6.2}$$

where d and s are as described for equation (6.1) and $\tilde{\mathbf{B}}$ is the estimate of the bearing to the vocalising dolphin. This straight line approximation is plotted as the dashed line in Figure 6. 2.

The two dimensional solution can be extended to three dimensions. Because there are two elements the solution to the position using the time delay between elements is a position on the surface of a hyperbolic cone as shown in Figure 6. 3.

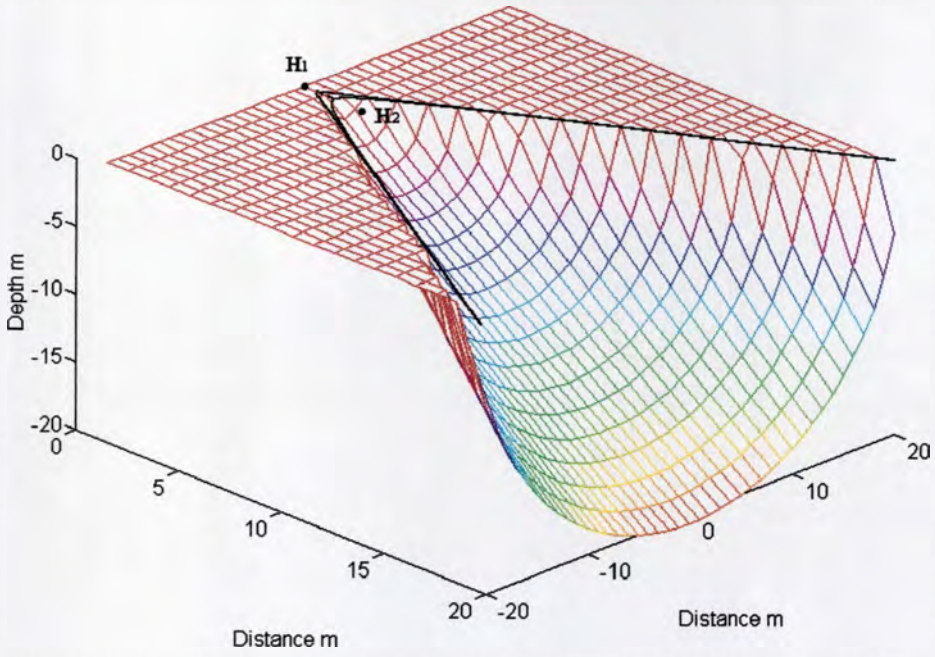


Figure 6. 3 - Hyperbolic cone of possible dolphin locations using two elements.

The solid black line represents the two dimensional solution.

With dolphins, assuming that they are near to the surface when they are travelling, the problem is reduced back to the two dimensional case.

6.2.3 Click detection

Echolocation clicks of the striped dolphins were detected from the spectrogram. The clicks are broadband and of short duration. When displayed as a spectrogram a click train is a series of vertical lines. Figure 6. 4 shows a section of a striped dolphin's click train fourteen clicks occur in a one second interval which gives an interclick interval of 71 ms.

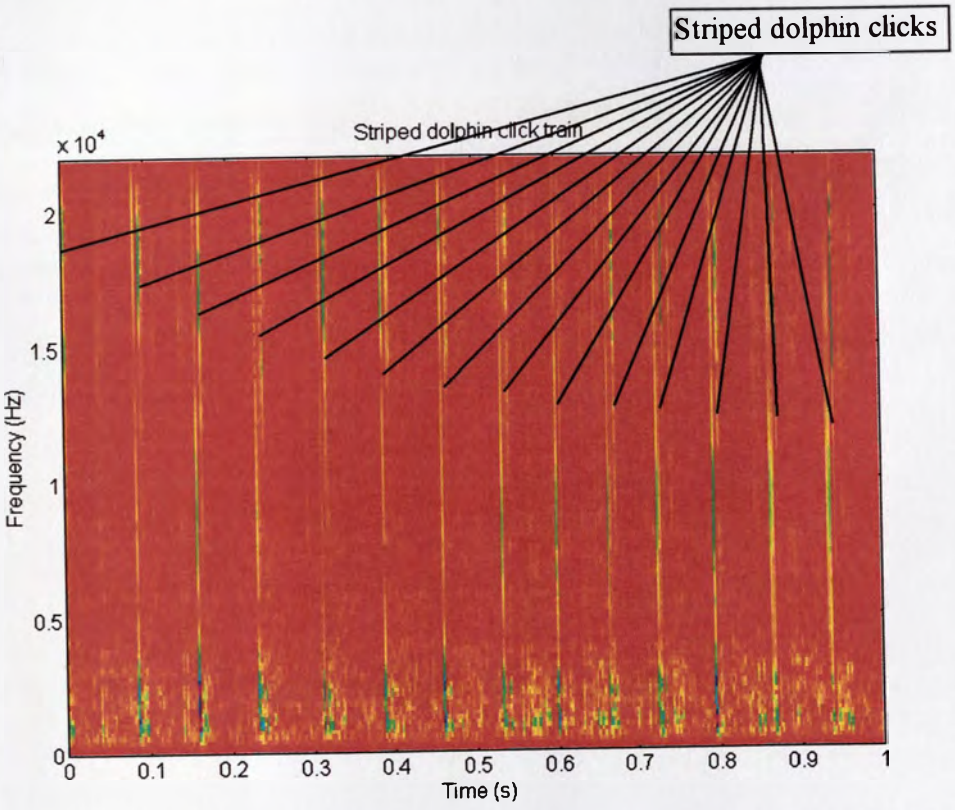


Figure 6. 4- Striped dolphin click train

6.2.4 Dolphin bearing estimation

The bearing to the vocalising dolphin can be estimated from the time difference of arrival of the click on the two elements of each of the arrays. A bearing is obtained for each of the arrays and a position can be found by taking the cross bearing. For each of the clicks detected the bearing is estimated and then plotted against time (shown as samples), in Figure 6. 5. Zero degrees corresponds to the front of the boat and 180 degrees corresponds to the rear of the boat.

The first visual sighting of the striped dolphins was off the starboard side to the rear of the boat. The dolphins then swam past the boat and rode on the bow wave. Four dolphins were counted and identified as striped dolphins.

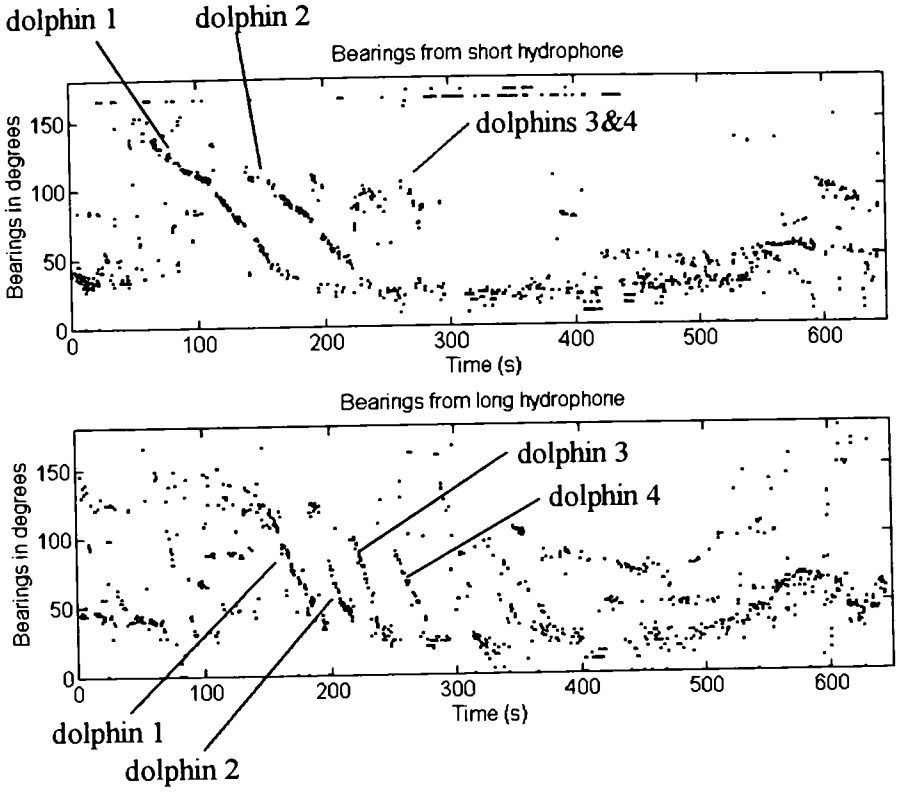


Figure 6. 5 - Bearings calculated from time differences in signal arrival times.

6.2.5 Bearing accuracy

The bearing is estimated from the time difference of arrival of the click sound on each of the array elements. The relationship between the time difference of arrival and the bearing is given in equation (6.2). Since this relationship is not linear then the bearing will be more accurate at points were the time difference varies more quickly as shown in Figure 6. 6. The top graph shows the relationship between the bearing and the time difference of arrival of the clicks on each of the elements. The bottom graph shows the rate of change of time difference with respect to the bearing. The maximum occurs at 90 degrees to the array and so bearings measured in this area will be more accurate than those towards the front or rear of the array.

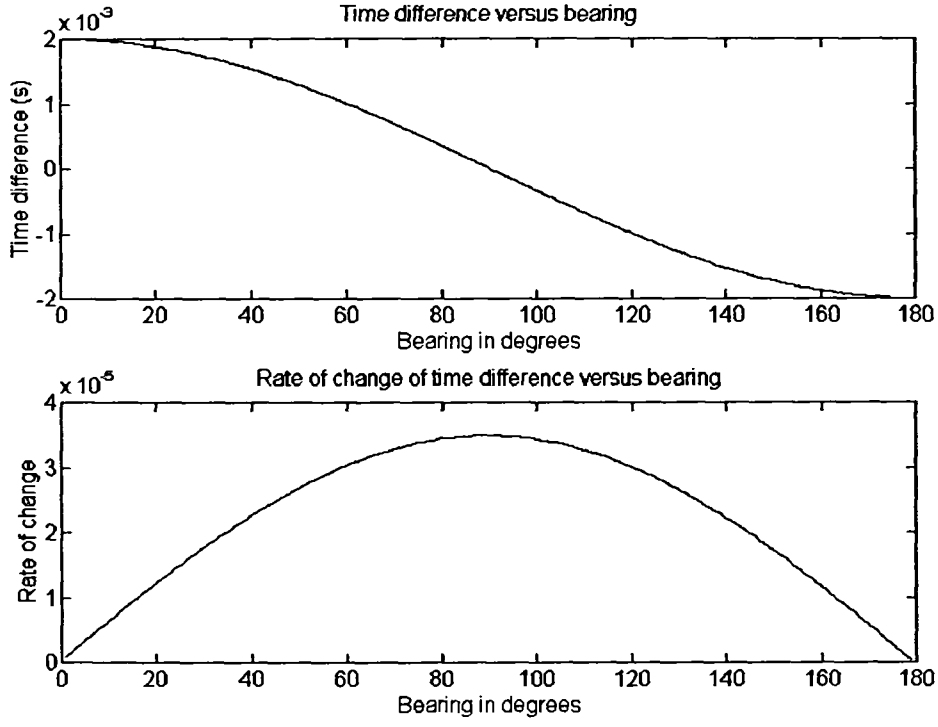


Figure 6. 6 - Relationship between bearing and time difference

6.2.6 Summary

Four dolphins were sighted visually behind the boat and identified as striped dolphins. They then swam past the boat on a parallel course and then disappeared out of sight in front of the boat.

The acoustic track data shown in Figure 6. 5 shows bearings plotted against time for each of the arrays. The bearing is relative to the boat where 0 degrees is in front of the boat and 180 degrees is behind the boat. The short array plot, indicates that the dolphins started from behind the boat and then travelled faster than the boat on a near parallel course. This is indicated by the bearing reducing with time with the best results obtained when the dolphins are broadside to the arrays. The dolphins then swim until they are in front of the boat. The longer hydrophone array shows the same bearing data, four tracks are visible indicating the presence of four dolphins. The shorter array shows only two tracks and a confused pattern for the other two. The reduced signal to noise ratio due to the proximity of the shorter array to the boat and propeller has reduced the effectiveness of the detection of the clicks. Overall the acoustic track data corresponds well with the visual data. The arrays were found to perform well for clicks detected broadside to the arrays. The array would perform better if it were towed further behind the boat, which would decrease the self noise emitted from the boat. This was not possible due to the restriction on obtaining a longer cable length.

6.3 Section 2 - Dolphin Signature Whistles

6.3.1 Introduction

Each dolphin is known to produce it's own distinctive signature whistle for a large proportion of it's whistle repertoire (typically > 90%). This vocalisation is therefore potentially very useful for collecting census information about dolphins. The signature whistle hypothesis is described more fully in chapter 2.

6.3.2 Whistle detection

A database of signature whistles would seem to be a natural extension where by new signature whistles could be added as they become available. However, there are many problems to be resolved before this would be possible. This type of database has been highly successful for photographic identification of the larger whales. The populations of the different species of larger whales are much smaller by comparison and so lends itself more readily to this type of identification.

The problems of creating such a database are:-

1. detection of the whistles from the background noise
2. extraction of the contour of the whistle
3. a measure of similarity of the whistle to others

Automatic detection of signature whistles has not been presented in the literature, the start and end points of the whistles being found manually before analysis. A novel method for detection of signature whistles is presented here.

Signal detection theory is widely used for finding a known signal from noise. However, when trying to detect whistles, although some knowledge of the signal is available, the variability between whistles prevents a model encompassing all whistles from being formulated.

Recordings of dolphin whistles were taken with the experimental equipment described in Chapter 5 in the 200 Hz - 20 kHz frequency band. Detection of the whistles was performed from the spectrogram given by

$$X(n,\omega) = \sum_{m=-\infty}^{\infty} x(m)w(n-m)e^{-j\omega m} \tag{6.1}$$

where $X(n,\omega)$ is the spectrogram, x is the sampled signal, and w is the window. A fuller description of the Short Time Fourier Transform (STFT), or spectrogram as it is more commonly known, was given in Chapter 4

A one second segment of the recording was analysed at each iteration. The recordings were then digitised at 44.1 kHz, each segment being 44,100 samples long. The data was filtered using a digital high-pass infinite impulse response (IIR) filter with a cut-off frequency of 4 kHz. See Chapter 4 for a description of filter design. A 256 point Hanning window, w, was used as the STFT window. An overlap of 128 points was used which is half the window length.

Dolphin echolocation clicks typically occurred at the same time as the whistles, as shown in Figure 6. 7. The spectrogram consists of short time Fourier transforms which are stacked vertically from left to right. The length of the STFT is 256 samples. Broad-band sounds, such as clicks appear on the spectrogram as vertical lines, whereas a pure tone would appear as a horizontal line. The whistle shown in Figure 6. 7 starts at 7 kHz and sweeps up in frequency till it reaches 14 kHz before sweeping back down to 6 kHz. The second harmonic of this whistle is visible but is weak. The whistle is 1.2 seconds in duration.

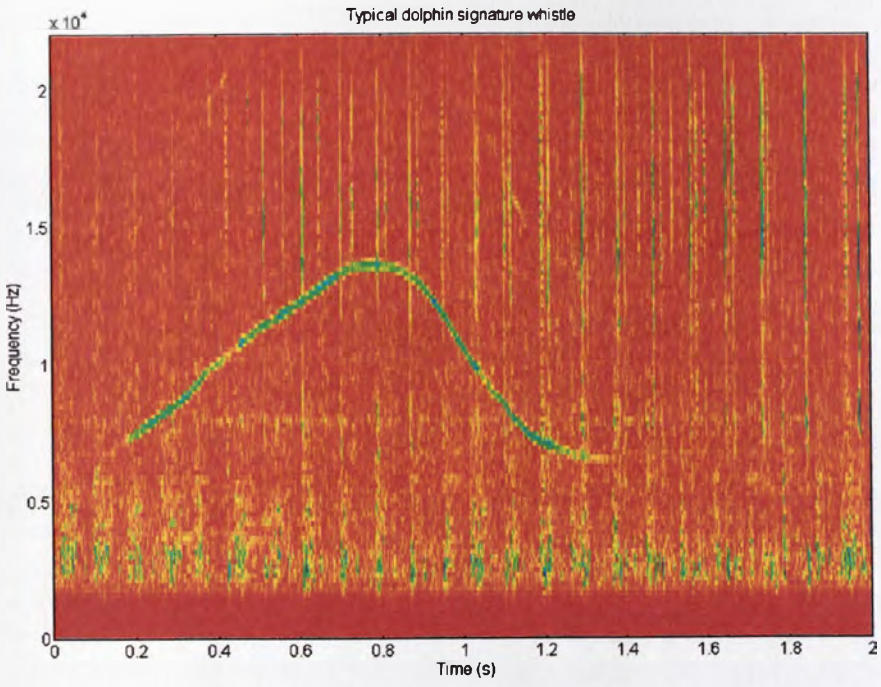


Figure 6. 7 - Spectrogram of a dolphin signature whistle

Each block of the spectrogram was examined to see if clicks were present. Firstly, the background noise was measured for the spectrogram,

$$b = \frac{N}{w/2} \tag{6.2}$$

where b is the number of STFT's, which is calculated from the window size w and the number of samples N, the window size is halved because the windows overlap by 50%, the average noise for the spectrogram is therefore,

$$Noise = \frac{1}{b}\sum_{m=1}^{b}\frac{2}{w}\sum_{\omega=1}^{\frac{w}{2}} X(m,\omega). \tag{6.3}$$

Each STFT is then averaged and normalised as follows,

$$A(m) = \frac{\sum_{m=1}^{b}|X(m,\omega)|}{\max\left(\sum_{m=1}^{b}|X(m,\omega)|\right)}, \tag{6.4}$$

a threshold is set half way between the background noise level and the maximum value occurring in the spectrogram. The spectrogram was digitally filtered with a high pass IIR filter with a cut-off frequency of 4 kHz.

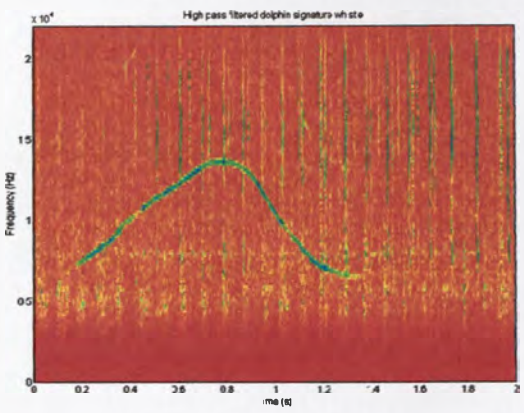


Figure 6. 8 - Filtered dolphin whistle

The contour of the signature whistle was extracted by taking the peak value in each of the STFT's once the clicks had been filtered, this process is described in equation 6.1, and shown in Figure 6. 9.

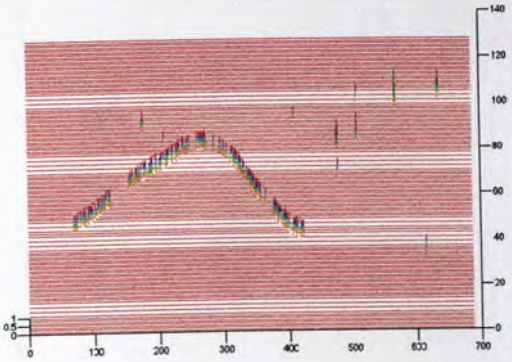


Figure 6. 9 - Spectrogram of whistle extraction

The graph in Figure 6. 10 shows the extracted waveform when a signature whistle is present in the recording. The same process was applied to the whole recording and Figure 6. 11 shows the result when there was no signature whistle present.

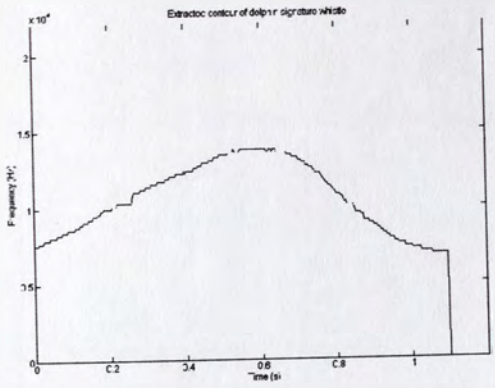


Figure 6. 10 - Extracted contour of dolphin whistle

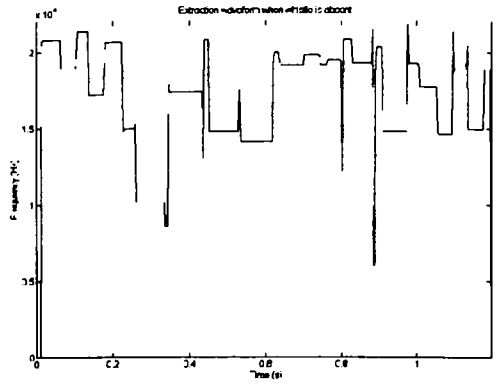


Figure 6. 11 - Extracted waveform for whistle absent

The previously described method for finding whistles was applied to the striped dolphin recording. The contours were detected by using an analysis window of 0.25s duration. This window was slid through the extracted waveform. The window was then differentiated and if no large changes in gradient occurred then a detection was recorded. The graph in Figure 6. 12 shows the detection score for each second of the file.

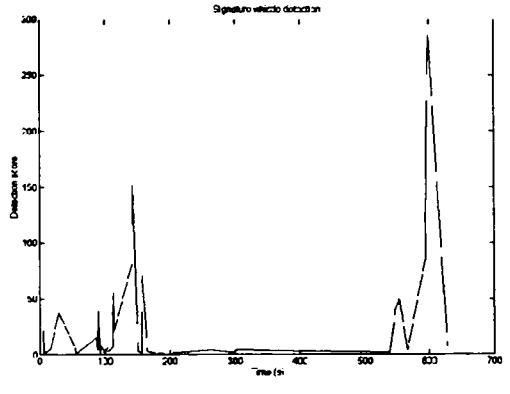


Figure 6. 12 - Detection scores of signature whistles

Forty detections were recorded, although some had low detection scores. Seventeen signature whistles were identified at the locations indicated in Figure 6. 12. The detection scores are recorded in Table 6.1.

Table 6.1: Detection scores

Detection Number	Location in recording (s)	Detection score	Sound found
1	5	22	whistle
2	6	1	whistle
3	17	5	whistle
4	29	38	whistle
5	55	5	whistle
6	56	1	whistle
7	87	15	whistle
8	88	11	whistle
9	89	4	whistle
10	90	39	whistle
11	93	1	whistle
12	94	8	whistle
13	100	1	noise
14	101	4	noise
15	104	7	grunt
16	106	3	noise
17	112	7	whistle
18	113	81	whistle
19	114	30	whistle
20	115	22	whistle
21	142	82	grunt
22	143	152	grunt
23	151	3	whistle
24	155	2	whistle
25	156	2	whistle
26	157	75	whistle
27	165	3	grunt
28	184	1	clicks
29	264	4	noise
30	300	2	noise
31	301	4	noise
32	538	2	noise
33	545	31	whistle
34	546	39	whistle
35	553	50	whistle
36	566	4	noise
37	594	86	whistle
38	595	192	whistle
39	599	286	noise
40	628	7	noise

The detection method described had 73% detection of dolphin sounds with 86% of those being signature whistles. The other sounds which have been called 'grunts' are described later. The other 27% of detections appeared to be background noise. The algorithm did not miss any signature whistles which were picked up by listening. Some of the whistles overlapped the analysis window of one second and so multiple entries for the same whistle appear in Table 6.1.

6.3.3 Multivariate Analysis

Once the signature whistles have been extracted from the recording as shown in Table 6.1, a measure of similarity is required so that the whistles can be classified and assigned to a particular dolphin. The contours can easily be compared by eye and a decision made by the observer as to whether or not the dolphin has been encountered before. This is, however, subjective and labour intensive. The problem of repeatability is also present. A mathematical and repeatable method for comparing whistles is therefore required. Multivariate analysis is a useful way of representing data. For each of the whistles five properties were measured from the spectrogram. These were recorded and are shown in Table 6. 2. From this data it is possible to perform a cluster analysis.

Table 6. 2 : Data matrix of whistles

Whistle number	Position (s)	Maximum frequency (Hz)	Minimum frequency (Hz)	Beginning frequency (Hz)	Final frequency (Hz)	Duration (s)
1	5-6	14523	6469	7261	6469	1.18
2	16-17	13731	6601	6865	6601	0.88
3	29-30	13467	7129	8186	7129	1.02
4	45-46	13335	6733	7129	6733	1.11
5	55-56	13731	6601	7658	6601	1.18
6	87-88(1)	13995	7922	7922	8186	0.48
7	87-88(2)	13467	7261	7261	10034	0.46
8	89-90	20861	6733	11619	6733	1.19
9	93-94(1)	13467	7394	7394	10826	0.48
10	93-94(2)	13995	8450	7922	10298	0.58
11	112-113	17428	9902	10826	17428	0.93
12	114-115	20333	8450	14259	8450	1.15
13	150-151	20333	10958	13203	10958	0.83
14	156-157	19013	10958	12411	12807	0.90
15	545-546	17692	9770	11091	17692	1.00
16	553-554	16372	9902	11619	16372	1.06
17	594-595	18749	8186	11487	18749	1.15

6.3.3.1 Cluster Analysis

Cluster analysis is an exploratory technique which seeks to identify natural groupings or clusterings in the data. No prior knowledge of the groupings within the data are required before commencing cluster analysis.

The procedure for a cluster analysis is as follows:-

1. For each subject p variables are measured, producing the data matrix **x**, see Table 6. 2.
2. A measure of similarity or difference between the subjects using the measured variables is then performed. The resulting matrix which compares each whistle with all of the others is called a distance matrix **d**, see Table 6.3. Different measures of distance can be calculated, the Euclidean distance is used in this example.
3. Each of the subjects are then compared to see how similar they are based on the distance score. A low distance score indicates that the two whistles are similar. A distance score of zero means the whistles are identical.

The distance matrix **d** for the whistles in Table 6. 2 is shown in Table 6.3. The two most similar whistles using this distance measure are whistles 11 and 15 indicated by the lowest score.

Table 6.3 : Squared Euclidean distance between pairs of whistles

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	0																
2	81892	0															
3	284196	237230	0														
4	156816	26136	144830	0													
5	81972	62884	90604	47150	0												
6	577500	544421	209457	458937	439665	0											
7	1445162	1244760	931207	1121023	1244839	456773	0										
8	5930180	7347226	6677035	7680077	6656126	6433469	8483878	0									
9	2097189	1882901	1436529	1727721	1861886	780595	66264	8971143	0								
10	1930130	1827355	1213608	1672176	1722600	473932	219912	7646707	195148	0							
11	15303342	15747786	13641805	15484604	15182456	10955367	9004486	13683992	7734461	7316390	0						
12	9057682	10509524	8751336	10570508	9399720	8067629	10003674	1314456	10103069	8374291	10293730	0					
13	10936571	12172355	10163473	12156673	11230033	8496048	9697090	3848909	9360595	7478486	5706519	1369526	0				
14	10700397	11615553	9550966	11488331	10798842	7590238	7863795	5878646	7255486	5791659	2749322	3043101	578846	0			
15	16156379	16660144	14484150	16400394	16052785	11748951	9745957	13964440	8430576	8012400	22704	10416807	5819352	2876201	0		
16	13226586	13594444	11334709	13233635	12903344	9024893	7457631	12310400	6333783	5831971	285912	8752550	4862510	2142650	378100	0	
17	18946464	19662934	17493777	19479903	18992769	14695641	12256545	15097343	10805337	10679884	687165	11633214	7383737	4391482	490037	1426233	0

6.3.3.2 Distance measure

There are many different ways to measure distance between the whistles.

Euclidean distance $$d_{ij} = \sum_{k=1}^{p} (x_{ik} - x_{jk})^2$$

City block distance $$d_{ij} = \sum_{k=1}^{p} \left| x_{ik} - x_{jk} \right|$$

'Canberra' metric $$d_{ij} = \sum_{k=1}^{p} \frac{\left| x_{ik} - x_{jk} \right|}{\left(x_{ik} + x_{jk} \right)}$$

Angular separation $$d_{ij} = \frac{\sum_{k=1}^{p} x_{ik} x_{jk}}{\left[\sum_{k=1}^{p} x_{ik}^2 \sum_{k=1}^{p} x_{jk}^2 \right]^{\frac{1}{2}}}$$

Mahalanobis D^2 $$d_{ij} = (\mathbf{x}_i - \mathbf{x}_j)' \mathbf{S}^{-1} (\mathbf{x}_i - \mathbf{x}_j),$$

where S is the covariance matrix, and $\mathbf{x}_i$, $\mathbf{x}_j$ are the vectors of measured variables.

A k-means method for clustering the data was used, Daly et al.(1995). The procedure for a k-means clustering is as follows.

1. The number of clusters is chosen.
2. The first four whistles are chosen as the cluster centres.
3. Each whistle is then compared with the cluster centre score by taking the mean pattern.
4. The whistle is assigned to the cluster which has the closest mean pattern.
5. The centre of the cluster is recalculated from all members now in the cluster.
6. Because the cluster centres move during the assignments the process is iterated until no movements between clusters of the whistles is made.

Because the number of clusters is chosen at the beginning of the analysis it appears to be of little use, since we were looking for the analysis to find the natural grouping present in the data. We can, however, perform the analysis for different numbers of clusters and then check to see what the quality of the cluster is.

6.3.3.3 Cluster Quality

Although no *a priori* knowledge is required the number of clusters has to be set before analysis can proceed. A measure of the quality of a cluster set would ensure the correct number of clusters were chosen. The number of clusters which maximises C in the following expression will be the closest estimate, Everitt (1993).

$$C = \frac{\text{trace}(\mathbf{B})}{g-1} \Big/ \frac{\text{trace}(\mathbf{W})}{n-g} \tag{6.7}$$

where g is the number of clusters and n is the number of whistles. The matrices **B** and **W** are the pooled between-groups covariance matrix and pooled within-groups covariance matrix respectively. The covariance matrix S can be calculated as follows,

$$\mathbf{S} = \frac{1}{n-1}\sum_{i=1}^{n}(\mathbf{x}_i - \bar{\mathbf{x}})(\mathbf{x}_i - \bar{\mathbf{x}})' \tag{6.8}$$

The scores for C for the cluster analysis performed on the 17 whistles are recorded in Table 6.4

Table 6.4 : Cluster quality

Number of Clusters	C
1	-
2	-2.6487
3	0.2788
4	1.9660
5	1.3225
6	-0.9251
7	-1.1986
8	-0.9246

Therefore the four cluster is the best natural grouping for the data. The separation of the whistles into four clusters is shown in Table 6.5.

Table 6.5: Clustering of whistles

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
cluster 1								1				1	1	1			
cluster 2						1	1		1	1							
cluster 3											1				1	1	1
cluster 4	1	1	1	1	1												

6.3.3.4 Principal Component Analysis

Principal component analysis is another multivariate technique which focuses on the variables themselves and on the relationships between them. Principal component analysis transforms the original variables **x**, into a new set of variables **y**. The new variables are linear transformations of the original variables with the following properties,

$y_1, y_2, \ldots, y_p$ are uncorrelated with each other.

$y_1, y_2, \ldots, y_p$ account for decreasing portions of the variance of the original variables.

where p is the number of variables.

The analysis procedure is to find a set of weights **w** which when multiplied by the original variables **x**, yields the new variables **y**.

$$\mathbf{w}=[w_1+w_2+w_3+w_4+w_5],$$

It seeks the set of weights **w** which give the maximum differences between the variables. The weights are constrained so that,

$$w_1^2+w_2^2+w_3^2+w_4^2+w_5^2=1,$$

this is so that the weights are not made arbitrarily large.

As an example the scores on the first whistle, from Table 6. 2 are,

$$\mathbf{x}_{i,j}=[x_1\ x_2\ x_3\ x_4\ x_5]$$

$$\mathbf{x}_{1,j}=[14523\ 6469\ 7261\ 6469\ 1.18]$$

These variables are used to form a weighted sum,

$$y_1 = w_1x_1+w_2x_2+w_3x_3+w_4x_4+w_5x_5$$

$$y_1 = 14523w_1+6469w_2+7261w_3+6469w_4+1.18w_5$$

The y-scores for all the whistles are calculated in the same way. The set of weights which achieve maximum variability in all the y-scores is known as the first principal component and the corresponding y-score for each whistle is known as the score on the first principal component. The second principal component is found in the same way but must be uncorrelated with the first. The other principal components are calculated with the same constraints, there are as many principal components as there are variables.

The principal components for Table 6. 2 can be calculated from the correlation matrix. The correlation matrix is shown in Table 6.6.

Table 6.6 : Correlation matrix

	1	2	3	4	5
1	1	0.5762	0.9434	0.3825	0.4090
2	0.5762	1	0.7178	0.6911	-0.0957
3	0.9434	0.7178	1	0.4839	0.3656
4	0.3825	0.6911	0.4839	1	0
5	0.4090	-0.0957	0.3656	0	1

The principal components are found from the eigen values and vectors of the correlation matrix. These are found by solving equation (6.9).

$$\mathbf{A}x = \lambda x, \tag{6.9}$$

where **A** is the correlation matrix from Table 6.6 and λ is the set of eigen values that satisfy equation (6.9).

Table 6.7 : Eigen values and eigen vectors

Principal component	PC5	PC4	PC3	PC2	PC1
	0.5862	0.4411	0.3576	-0.2568	0.5177
	0.2443	-0.7356	0.0966	0.3982	0.4810
eigen vectors	-0.7693	0.0623	0.2788	-0.1476	0.5521
	-0.0215	0.3824	-0.7238	0.4098	0.4019
	0.0672	-0.3380	-0.5110	-0.7654	0.1852
eigen values	0.0349	0.1905	0.5324	1.2576	2.9847

The largest eigen value indicates the first principal component. The amount of variance of each principal component can be found by dividing the eigen value for that

principal component by the number of variables. The variance of each principal component is given in Table 6.8.

Table 6.8 : Variance of each principal component

Principal Component	% of variance
PC1	60
PC2	25
PC3	10
PC4	4
PC5	1

The principal components can now be plotted against each other to show natural groupings within the data. Plotting PC1 against PC2 will show the maximum variance between the whistles. Plots of the other variables are also useful. The first three plots of the principal components are shown in Figure 6. 13.

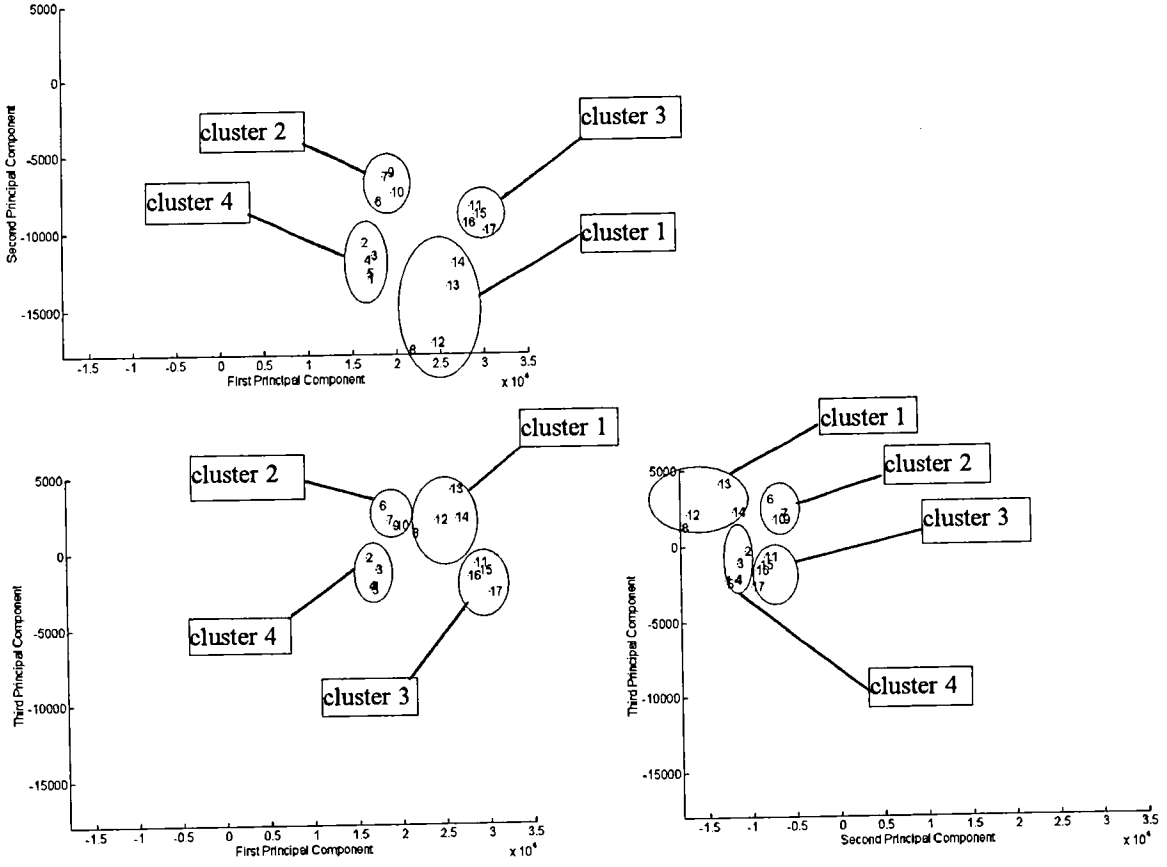


Figure 6. 13- Scatter plots of the first three principal components

6.3.4 Summary

The detection of signature whistles of dolphins has previously been performed by listening to slowed down recordings. A method for detecting the presence of signature whistles was developed. The method did not miss any whistles which were detected by listening, however, it did report detections when no signature whistle was present. Some of these detections, where no signature whistle was found, were a sound which in this thesis has been called a harmonic pulse. This sound seems to be stereotypical between the different individuals in this group. This pulse is a short tone of approximately 4 kHz, typically 0.5s duration, see Figure 6. 14. It is not frequency modulated like the signature whistles, and shows little variation. It does contain a large number of harmonics which extend all the way up to 20 kHz, which is the limit of these recordings.

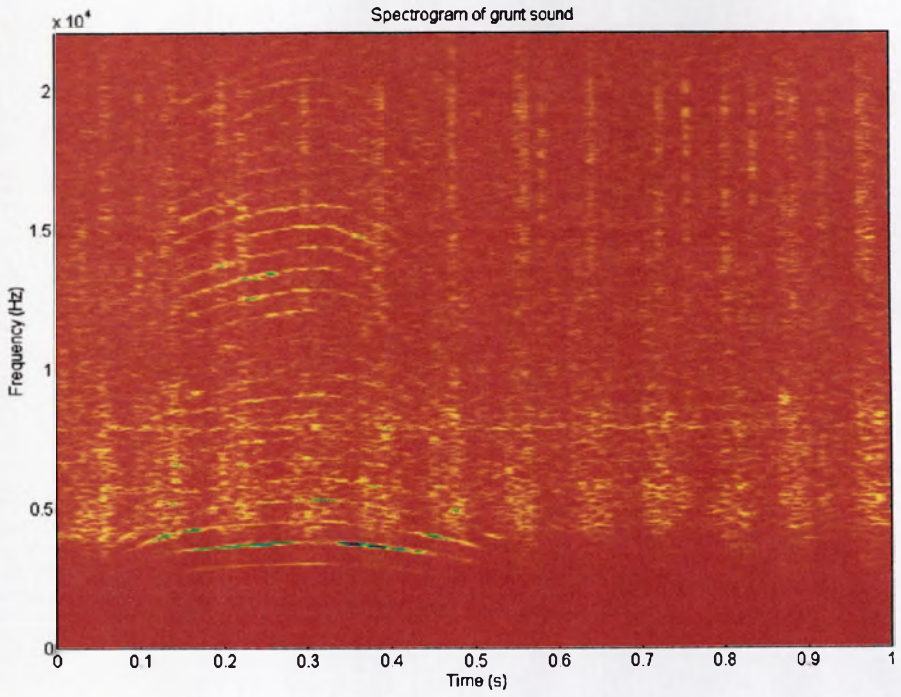


Figure 6. 14 - Spectrogram of harmonic pulse

The other false signature whistle detection reports seemed to contain only noise. The scores for the noise detections are low when compared to the signature whistle detection scores and so application of a threshold may produce a better result. The score for detection 39 is surprisingly high. Inspection of the spectrogram at this location shows that the entire second is very quiet. The boat engine was in idle and the dolphins were becoming distant. The use of the threshold being half way between the maximum value and the background noise needs attention to ensure more false detections of this nature are not reported by the algorithm.

The seventeen signature whistles detected in the recording have been analysed using cluster and principal components analysis. These techniques seek to display natural groupings that are present in the data and the analysis has shown that there are four distinct groups. This suggests that there were four dolphins present when the recordings were taken.

6.5 Section 3 - Doppler sensitive pulse

6.5.1 Introduction

During the analysis of the striped dolphin recordings a harmonic pulse sound was found during the detection process of the signature whistles. Four of these pulse sounds were detected during this process. Upon further analysis this sound was found to be very common, and a further 77 examples of the sound were found in a 10 minute segment. These sounds were found by listening. This equates to a harmonic pulse being emitted approximately every 7 seconds. This sound is obviously important to the dolphin. The purpose of the sound, however, has not been recorded in the literature. The spectrogram of the sound is shown in Figure 6. 15.

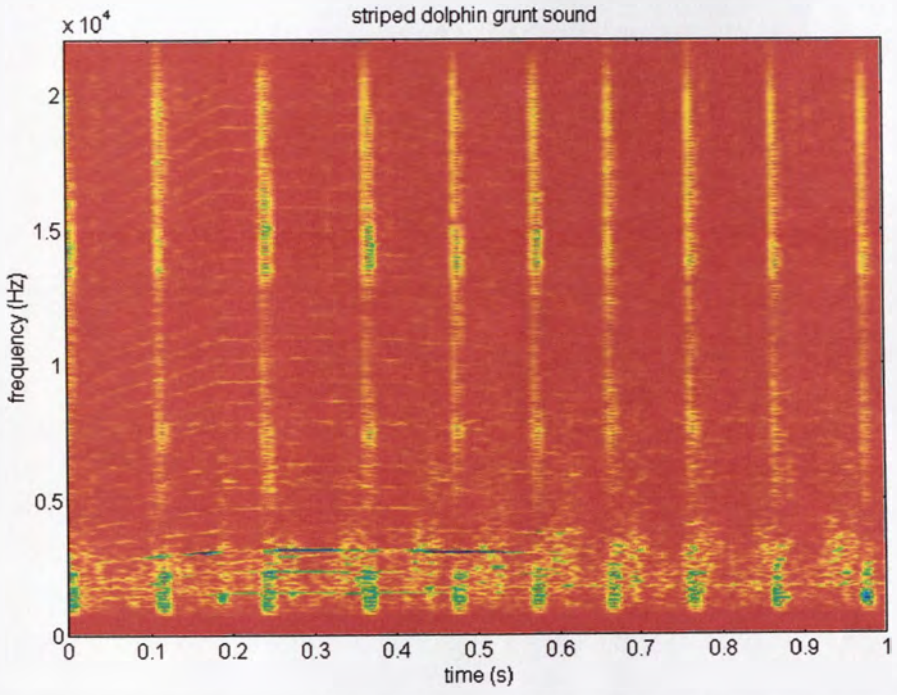


Figure 6. 15 - Striped dolphin Harmonic pulse

The peak frequency of the 'grunt' sound is 3 kHz which can be found from the power spectrum shown in Figure 6. 16. The duration of this signal is 0.55 seconds.

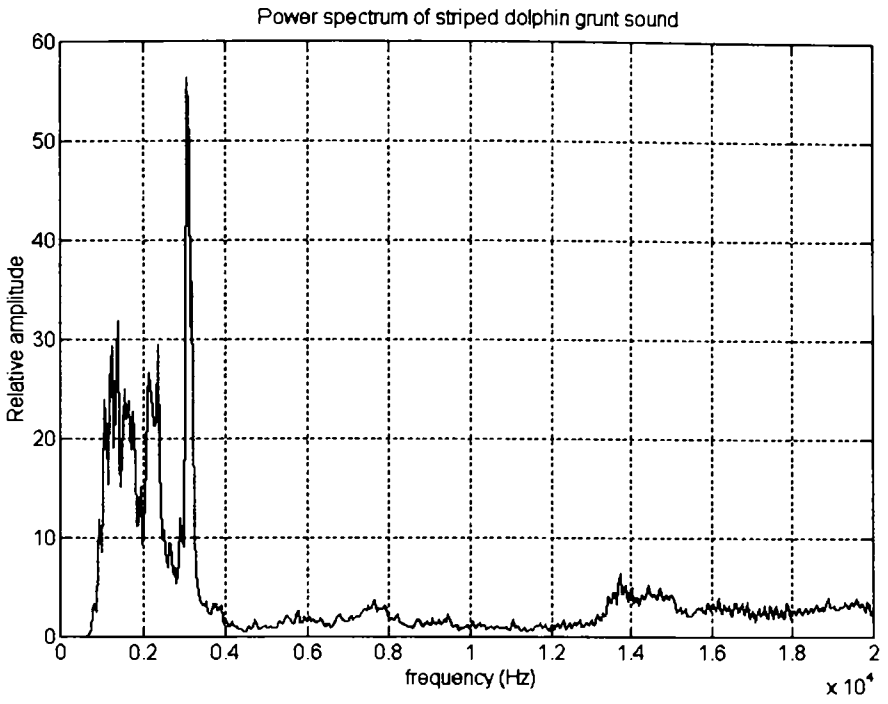


Figure 6. 16 - Power spectrum of dolphin Harmonic pulse sound

Dolphins are reported in the literature as not having the capability of producing a harmonic pulse of the type recorded during these experiments by Au (1993). Au's experiments are all performed on captive dolphins and as such he has made the admission:

"Our perception of how dolphins utilise their sonar in the wild is based on extrapolation of knowledge obtained in "laboratory" experiments - we do not have the foggiest idea of how dolphins utilise their sonar in a natural environment"

The discovery of this harmonic pulse in wild dolphins opens a new avenue for research into the sonar capabilities of dolphins. The possibility exists that the dolphins in captivity have not had cause, or may not have the ability, to produce this pulse which may explain the lack of detection of this sound by Au.

6.5.2 Doppler Sensitivity of the pulse

The harmonic pulse is Doppler sensitive which means that the returning echo from such a pulse will be useful for finding the velocity of a target. The Doppler resolution of a pulse can be calculated from the following expression,

$$f_{echo} = f_{trans}\left(1 + \frac{2V_R}{c}\right) \tag{8.1}$$

where f_{echo} and f_{trans} is the frequency of the echo and the transmitted pulse respectively, V_R is the relative velocity of the target and receiver and c is the velocity of sound in water (1500 ms^{-1}).

Expanding equation (8.1) we obtain,

$$f_{echo} = f_{trans} + f_{trans}\left(\frac{2V_R}{c}\right) \tag{8.2}$$

Therefore,

$$f_{echo} - f_{trans} = f_{trans}\left(\frac{2V_R}{c}\right) \tag{8.3}$$

The bandwidth of the pulse is equal to the difference in frequency of the transmitted and echo of the pulse. Therefore,

$$B = \frac{1}{T} = f_{trans}\left(\frac{2V_R}{c}\right) \tag{8.4}$$

where T is the duration of the pulse.

The velocity resolution ΔV, of the pulse can now be calculated by rearranging equation (8.4),

$$\Delta V = V_R = \frac{Bc}{2f_{trans}} \tag{8.5}$$

For the dolphin pulse shown in Figure 6. 15,

B = 1.818 Hz

f_{trans} = 3 kHz

c = 1500 ms^{-1}

which gives a velocity resolution of

ΔV = 0.454 ms^{-1}

= 1.634 km/h

= 2.452 mph

6.5.3 Summary

The presence of the harmonic pulse during the recording of the striped dolphins raises questions as to the purpose of the pulse. The pulses were all stereotypical. Each of the dolphins emitting very similar pulses unlike the dolphin signature whistles which are very different from each other and from the pulse. The pulse has the ability to encode Doppler information which would make it useful to the dolphin for estimating the speed of a target. The frequency of the emission suggests that the dolphins were dependent upon the echo for information. The purpose of the dolphins behaviour was unknown. Maybe they were feeding, in which case they may have been in pursuit of fish or other prey, or maybe they were investigating the boat. The velocity resolution of the pulse, which is calculated from the Doppler frequency shift of the pulse in equation (8.5), shows that it is able to detect objects moving at speed above 1.634 km/h. This resolution is more than adequate to detect fish.

Chapter 7 - Evaluation of dolphin signature whistle detection and extraction algorithms

7.1 Introduction

In order that the detection and extraction algorithm could be evaluated is was necessary to corrupt the signal to be detected by noise. This evaluation is performed using a simulated dolphin signature whistle which can be added to noise in order that the algorithms can be evaluated for varying signal to noise ratios. Often echolocation clicks from other dolphins are emitted concurrently with the signature whistle of interest. The algorithms are therefore tested with simulated dolphin echolocation clicks to ensure they do not adversely affect them.

7.2 Simulated dolphin signature whistle signals

In order to test detection and extraction algorithms, simulations of dolphin signals were constructed. A signature whistle (pure tone, frequency modulated signal) was constructed which sweeps up in frequency from 5 kHz to 13 kHz and then down in frequency to 7 kHz. The spectrogram representation of this simulated whistle is shown in Figure 7. 1.

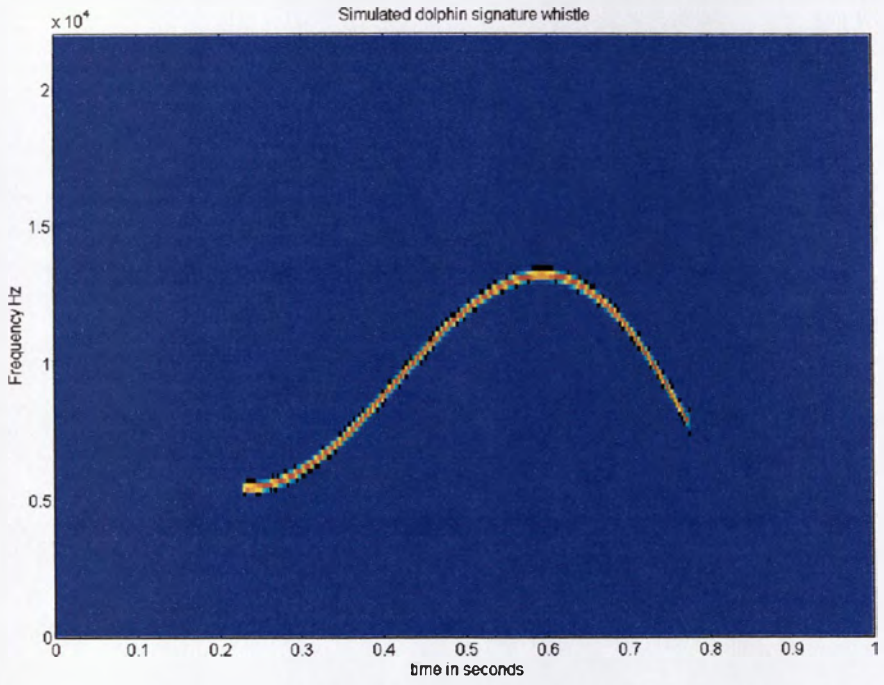


Figure 7. 1 - spectrogram showing a simulated dolphin signature whistle.

7.3 Noise masking

This signal was then corrupted with white noise of increasing level in order to decrease the signal to noise ratio. The power spectra of the simulated whistle and the various levels of white noise are plotted in Figure 7. 2. The signal to noise ratio was decreased from 50 dB signal to noise, until the signature whistle was completely masked by the noise (-10 dB signal to noise) in 5 dB increments. The varying levels of white noise can be added to the simulated dolphin whistle in order to mask it. Figure 7. 3 & Figure 7. 4 show the spectrogram of the signature whistle with additive white noise to give a signal to noise ratio of 10 dB and 0 dB respectively.

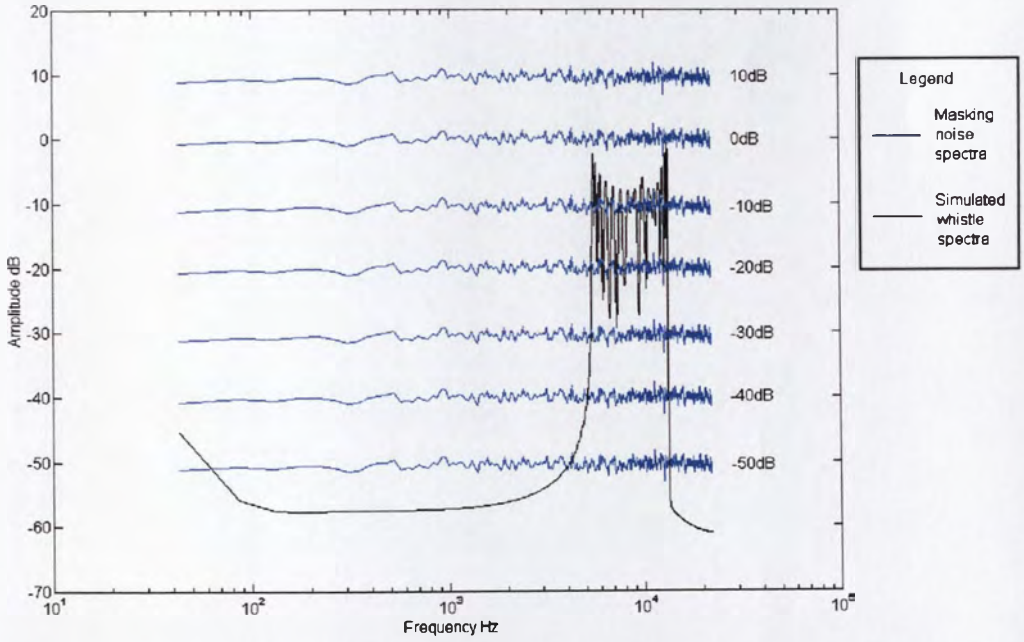


Figure 7. 2 - power spectra of the simulated dolphin signature whistle and the spectra of the increasing levels of masking white noise

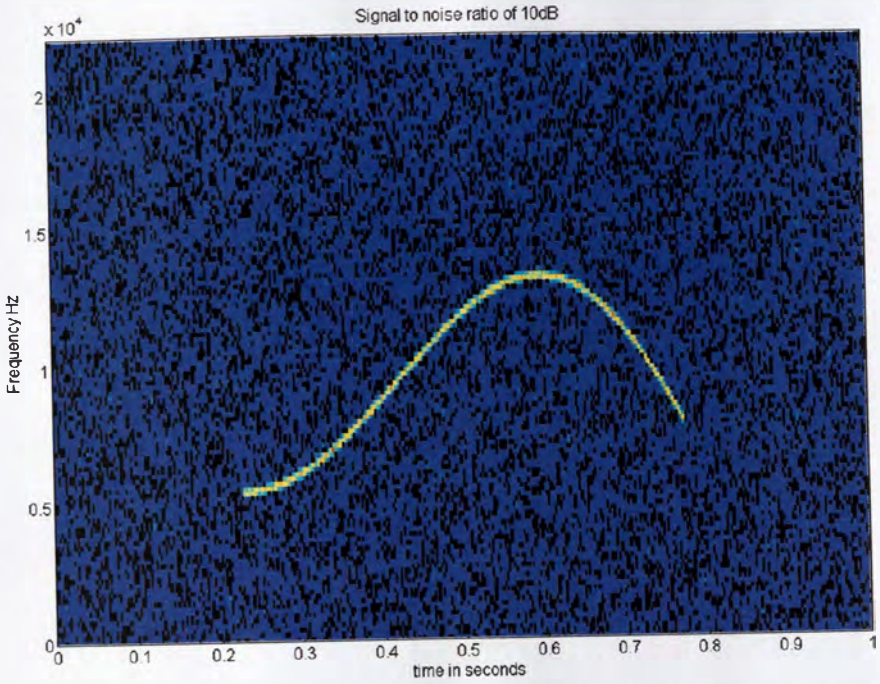


Figure 7. 3 - spectrogram showing a simulated dolphin. signature whistle corrupted by white noise 10 dB below the level of the whistle

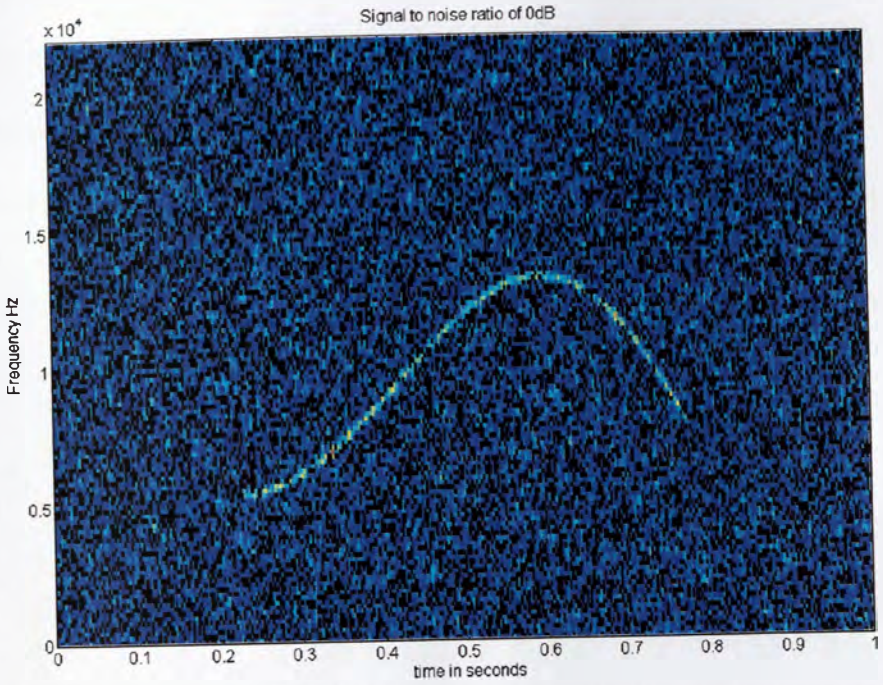


Figure 7. 4 - spectrogram showing a simulated dolphin signature whistle corrupted by white noise of a similar level.

7.4 Contour extraction algorithm performance

The performance of the whistle contour extraction algorithm was then plotted against decreasing signal to noise ratio. The simulated whistle occupies 187 blocks of the spectrogram and the detection score is the percentage of blocks that the algorithm correctly detects the whistle above the masking noise. The extraction algorithm performs at 100% correct detection when the signal to noise ratio is above 15 dB, this falls to approximately 85% correct when the signal to noise ratio falls to 5 dB. At zero signal to noise ratio the detection algorithm performs at 50% correct detection.

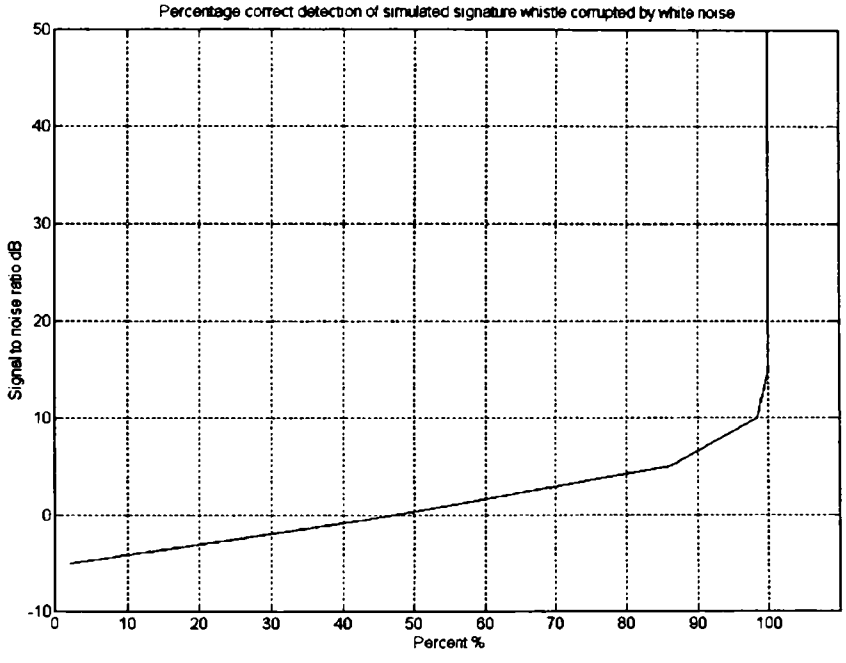


Figure 7. 5 - performance of the extraction algorithm as the signal to noise ratio is decreased.

7.5 Comparison of this extraction algorithm with the one used by Buck and Tyack (1993)

Buck and Tyack (1993) describe a method for comparing contours of signature whistles. Firstly, the whistle begin and end points are found by listening. The whistle is then digitised and the spectrogram calculated. The contour is then extracted from the spectrogram by taking the peak frequency in each block of the spectrogram.

The algorithm described by Buck and Tyack (1993) for finding the contour is,

$$f[m_0] = \left(\frac{f_s}{N}\right)\left(\max\left| X[m_0,k] \right| \right), \tag{7.1}$$

where $f[m_0]$ is the frequency of the strongest peak in block m of the spectrogram $X[m_0,k]$, f_s is the sampling frequency and N is the length in samples of the whistle.

A quantitative measure of similarity of the contours is computed by differencing the contours and then summing the squares of the differences.

$$D(s,r) = \left(\frac{1}{N}\right)\min\left\{\sum_{n=0}^{N-1}(s[n] - r[\omega[n]])^2\right\}, \tag{7.2}$$

where $D(s,r)$ is the distance measure between the two contours, $\omega[n]$ is the warping function, s and r are the two contours to be compared.

Dynamic time warping of the signal is used to align contours prior to the measurement of similarity.

Author's Extraction Algorithm

Detection of the whistles was performed from the spectrogram which is calculated thus,

$$X(n,\omega) = \sum_{m=-\infty}^{\infty} x(m)w(n-m)e^{-j\omega m}$$

where $X(n,\omega)$ is the spectrogram, x is the sampled signal, and w is the window. See Chapter 4 for a full description of the Short Time Fourier Transform (STFT), or spectrogram as it is more commonly known.

A running average, $N_{BG,}$ of the background noise is measured for the spectrogram over a one second interval,

$$N_{BG} = \frac{1}{b}\sum_{m=1}^{b}\frac{2}{w}\sum_{\omega=1}^{\frac{w}{2}}\left|X(m,\omega)\right|$$

where b is the number of blocks in the spectrogram,

$$b = \frac{N}{w/2}$$

which is calculated from the window size w and the number of samples N, the window size is halved because the windows overlap by 50%.

Each STFT is then averaged and normalised as follows,

$$A(m) = \frac{\sum_{m=1}^{b} |X(m,\omega)|}{\max\left(\sum_{m=1}^{b} |X(m,\omega)|\right)}, \tag{7.6}$$

a threshold is set half way between the background noise level and the maximum value occurring in the spectrogram.

The rejection of clicks and background noise is performed by differentiating with respect to time and removing spectrogram blocks which exhibit a large gradient changes.

The three plots in Figure 7. 6 show a comparison between the authors' algorithm and the one used by Buck and Tyack (1993). The upper plot shows the spectrogram of the simulated whistle. The middle plot shows the points extracted by this algorithm and the lower plot shows the points extracted by the Buck and Tyack (1993) algorithm. At 5 dB signal to noise ratio the Buck and Tyack algorithm extracts all the points (red circles) along the whistle however it requires that the start and end points of the whistle are known for the contour to be extracted (black solid line). If the start and end points of the whistle are unknown then the contour extracted is the one shown by the black line. The authors' algorithm detects 86% of the points (red circles) however it correctly rejects all the noise resulting in the correct contour being extracted for the whistle (black line).

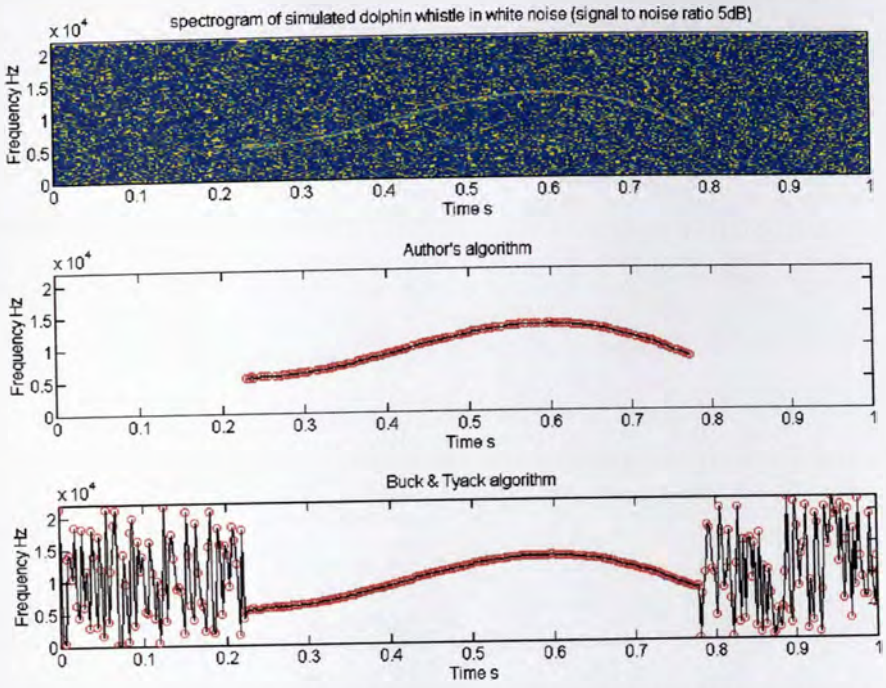


Figure 7. 6

red circles - **detection points**

black line - **extracted whistle contour**

Top: **spectrogram of the simulated dolphin whistle with 5 dB signal to noise ratio**

Middle: **Authors' extraction algorithm**

Bottom: **Buck and Tyack's extraction algorithm**

As the signal to noise ratio is decreased the noise starts to dominate the whistle and the algorithm by Buck and Tyack starts to fail, Figure 7. 7. At 0 dB signal to noise ratio the Buck and Tyack algorithm incorrectly chooses the noise over the whistle at many points throughout the whistle, the extracted contour is therefore no longer a representation of the actual contour. The performance of the authors' algorithm is much reduced, now down to 44% of the possible number of points. However because these points are spread throughout the duration of the whistle the extracted contour is still a close representation of the whistle. The noise is again correctly rejected.

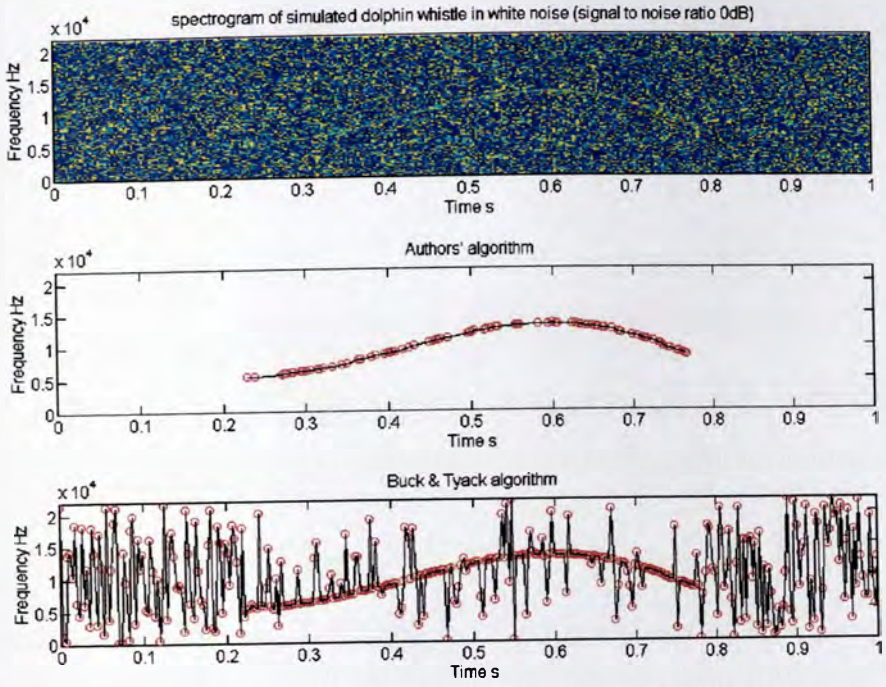


Figure 7. 7

red circles - **detection points**

black line - **extracted whistle contour**

Top: **spectrogram of the simulated dolphin whistle with 0 dB signal to noise ratio**

Middle: **Authors' extraction algorithm**

Bottom: **Buck and Tyack's extraction algorithm**

7.6 Corruption of the signature whistle with white noise and simulated echolocation clicks

The algorithm by Buck and Tyack was developed for whistles, recorded from temporarily captured dolphins, with large signal to noise ratios and also with no other corrupting noises. The recordings taken in a more natural environment such as those from groups of free ranging dolphins are often corrupted by the echolocation clicks of other nearby dolphins in the acoustic vicinity. Buck and Tyack's algorithm does not perform well when there are echolocation clicks occurring at the same time as whistle emissions. These clicks appear as vertical lines in the spectrogram i.e. they are of short duration and are broad band across the audio frequency range. These clicks have been simulated in order that the detection algorithm can be tested when these clicks are present in the recording. A comparison is shown in Figure 7. 8 of the two algorithms for a signal to noise ratio of 5 dB. The Authors' algorithm detects 68% of the possible points, therefore giving a good representation of the contour. The algorithm by Buck and Tyack incorrectly chooses the dolphin clicks instead of the whistle which results in an incorrect contour being extracted.

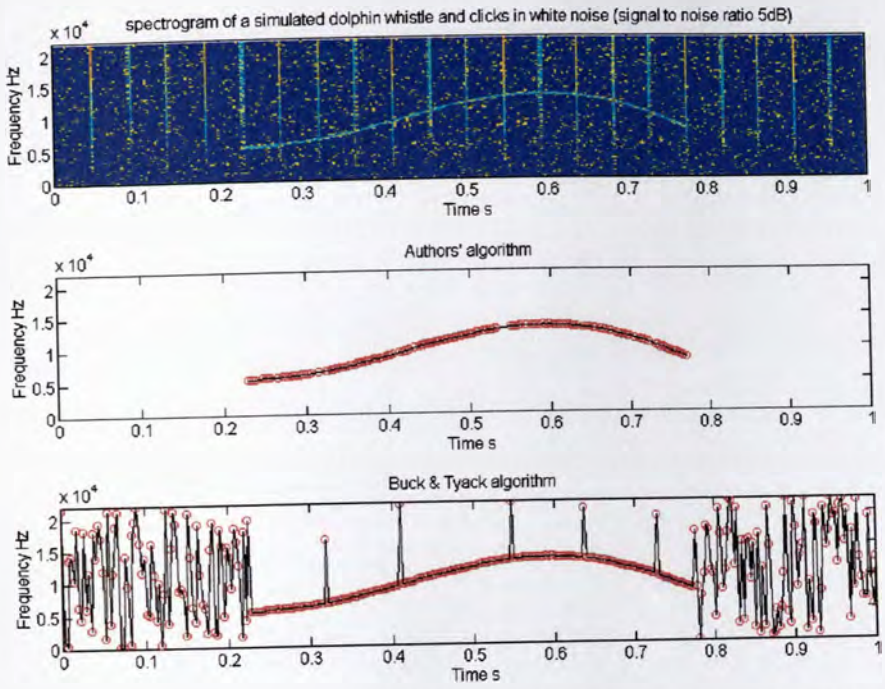


Figure 7. 8

red circles - **detection points**

black line - **extracted whistle contour**

Top: **spectrogram of the simulated dolphin whistle with 0 dB signal to noise ratio**

Middle: **Authors' extraction algorithm**

Bottom: **Buck and Tyack's extraction algorithm**

Again as the signal to noise ratio is reduced to 0 dB the Buck and Tyack algorithm no longer extracts a contour which represents the whistle, Figure 7. 9. The authors' extraction algorithm although now only detecting 26% of the possible points still manages to extract a contour which is representative of the whistle whilst still not producing any false detections.

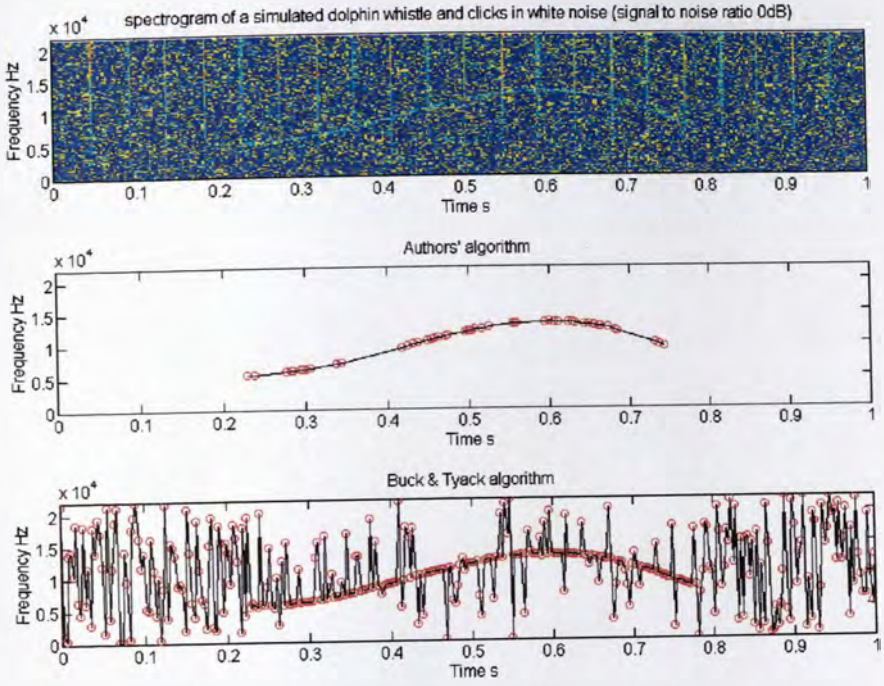


Figure 7. 9

red circles - **detection points**

black line - **extracted whistle contour**

Top: **spectrogram of the simulated dolphin whistle with 0 dB signal to noise ratio.**

Middle: **Authors' extraction algorithm**

Bottom: **Buck and Tyack's extraction algorithm**

7.7 Detection scores for the algorithms when the whistles are corrupted by both noise and dolphin clicks.

The detection scores for the authors' algorithm is shown in Figure 7. 10 for varying levels of masking noise. The algorithm performs at approximately 95% correct detection for signal to noise ratios above 15 dB and rapidly decreases below 10 dB signal to noise level.

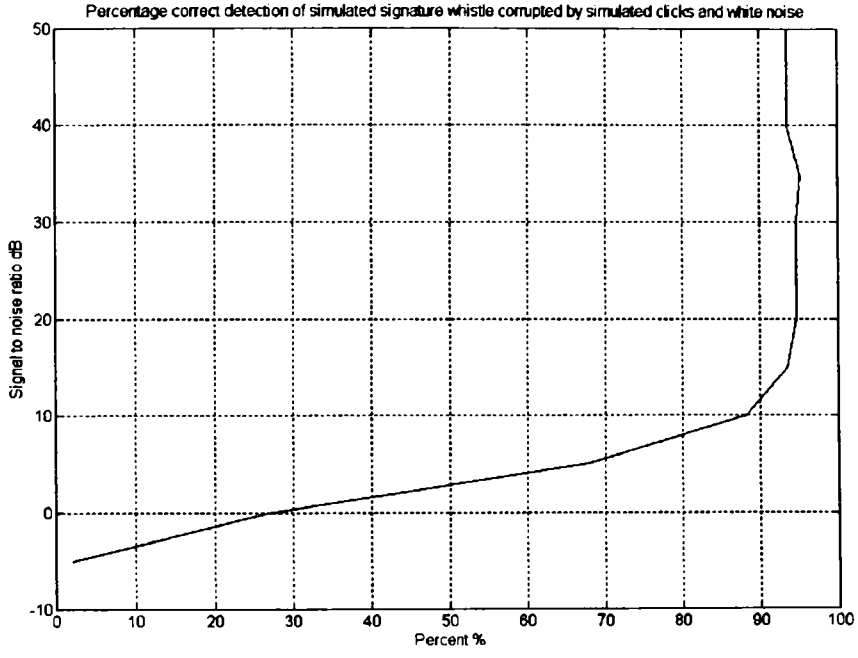


Figure 7. 10 - Detection score of the algorithm when the signature whistle is corrupted by white noise and simulated dolphin echolocation clicks.

7.8 Summary

The detection and extraction algorithm performed well in the presence of masking background noise. The start and end points were correctly identified even when the signal to noise ratio was as low as 0 dB. The algorithms were able to extract 100% of the whistles when the signal to noise ratio was above 15 dB. The number of extracted points decreases rapidly with decreasing signal to noise ratio below 0 dB. The points which are extracted however are generally spaced along the required contour and so interpolation gives a good representation of the shape of the contour. Buck and Tyack's (1985) algorithm performs well at high signal to noise ratio, however it is unable to identify the start and end points of the whistle. As the signal to noise ratio decreases the contour extracted using Buck and Tyack's algorithm no longer gives a good representation of the whistle contour.

When the signature whistle is also corrupted by echolocation clicks the author's algorithm still extracts the correct contour however the performance in terms of the number of extracts points is reduced. The Buck and Tyack algorithm is unable to extract the correct contour once the whistle has been corrupted by echolocation clicks.

Chapter 8 - Real time signature whistle analysis

8.1 Introduction

A real time stereo analyser based around the ADSP 21020 digital signal processor was developed and used for the analysis of the results presented in this chapter. The real time signal processing system was described in chapter 5. The data presented is from previously recorded DAT tapes, however the system can perform the same analysis in real time on data directly from the array.

Sonar arrays have enabled zoologists to determine if cetaceans are present within the survey area. However often when cetaceans are heard they are not seen for a variety of reasons; survey conducted at night, inclement weather conditions, dolphins too far away. When an acoustic contact is made it is therefore important to extract as much information from the acoustics as possible. This information will help to augment the sightings data and often only the acoustic data is available.

Also during the course of a survey it is unknown if the cetaceans encountered are the same ones encountered earlier during the survey. This obviously leads to incorrect abundance estimates. With the larger cetaceans such as the great whales this problem has been overcome by use of photographic techniques. The photographs are taken of the whales when they raise their flukes before a dive or of the flanks when they surface to breath. Painstaking hand sifting and comparison of photographs yields valuable information on the migratory paths and family structure of the whales. This technique is not suitable for the smaller cetaceans such as dolphins because they are notoriously difficult to photograph especially when they are leaping from the water. Also the numbers of smaller cetaceans is much greater and therefore the time taken to process and compare photographs would be prohibitive.

The techniques developed in Chapter 6 and evaluated in Chapter 7 are used to produce the results presented here. Due to the large number of recordings taken during the trials which have been conducted it is not possible to present all of the results. A selection of results which show the usefulness of this analysis technique are presented. The limitations of the analysis technique are explored and also a comparison is made with other work of a similar nature.

8.2 Ligurian Sea recordings

An extensive set of dolphin recordings were taken in the Ligurian Sea area. These recordings were virtually exclusively from striped dolphins. Very few other species of dolphin were encountered during the trial period.

Two tapes were chosen to demonstrate the techniques which have been developed in this thesis. A total of thirty tapes of three hour duration each were recorded. Tapes 2 and 20 are presented here. The recordings are of one minute duration and are taken every fifteen minutes. Tape 2 was recorded over a three day period and tape 20 was also recorded over a three day period. Tape 2 is representative of the other tapes which were recorded. Tape 20 is also included because it contains recordings of a military sonar at the same time as dolphin vocalisations are recorded.

8.3 Analysis of recordings from Tape 2

Tape 2 recordings cover the period from 22:46 on 7/6/94 till 04:59 on 9/6/94. During these recording periods a total of 36 striped dolphin signature whistles were extracted, see Appendix A (pages A1-A36) . From these 36 whistles only fifteen different whistles are present. It therefore demonstrates the caution which should be exercised when taking information from the acoustics. The whistles need to be compared to see if they are from the same individual, and a count based purely on the number of whistles would be inaccurate. The census count for this period should therefore be estimated at fifteen dolphins and not 32. The visual sightings data which exists for the day time recordings was examined to see if this data correlated with the acoustic data. Some of the recordings are of acoustic contacts during the hours of darkness and so it is not possible to correlate the acoustic data with visual sightings for this period.

The following table 8.1 outlines the acoustic data and cross references it to the visual sightings data.

Table 8.1

Contact Number	Time of contact	Date of contact	Acoustic contact abundance estimate	Number of whistles in contact	Sighting contact abundance estimate
1	22:46	7/6/94	1	1	No sighting due to night time contact
2	23:30	7/6/94	1	1	No sighting due to night time contact
3	7:30	8/6/94	4	6	5
4	9:31	8/7/94	1	1	No sighting
5	12:31	8/7/94	No acoustic contact	0	1 in distance
6	14:01	8/7/94	1	1	No sighting
7	19:30	8/7/94	1	5	2
8	00:45	9/6/94	1	2	No sighting due to night time contact
9	01:15	9/6/94	1	2	No sighting due to night time contact
10	03:30	9/6/94	2	12	No sighting due to night time contact
11	4:30	9/6/94	1	2	No sighting due to night time contact
12	4:45	9/6/94	1	3	No sighting due to night time contact

Three visual sightings (contacts 3,5 & 7) were made during this period which resulted in a sightings abundance estimate of eight dolphins. The contact 3 acoustic abundance estimate was for 4 dolphins which compares favourably with the sighting estimate. Contact 5 was visual and no acoustic contact was made. The dolphin however was reported to be at some distance from the boat when this contact was made. Contact 7 yielded an acoustic estimate of one and a visual estimate of two dolphins. During the whole recording the number of visually sighted dolphins was eight. The acoustic method presented here estimates the number of dolphins encountered during the same period as fifteen. The difference in acoustic and visual estimates of abundance during daylight hours is one extra dolphin detected in favour of the visual sighting method, although both methods have been shown to miss dolphins. If we include the night time period the difference in the two methods is eight extra detections in favour of the acoustics. This suggests that the visual sightings are estimating only half the number of dolphins that are present, due to the inability of the sightings to be conducted at night.

8.4 Analysis of recordings from Tape 20

Tape 20 recordings cover the period from 04:16 on 3/8/94 till 02:0 on 5/8/94. A man made sonar was heard throughout this period. This signal is referred to as a military sonar throughout the rest of this thesis, since this is the most likely source for this sound. There was also a large number of acoustic detections of dolphin signature whistles for this period. Seventy eight whistles were detected during this period, 14 of these whistles are presented in Appendix A (pages A37 - A51).

Two encounters with dolphins are presented. Whistles A37 - A40 are from the first encounter, they indicate the presence of one dolphin since the contours are all the same. The whistles have the same contours and so were emitted from the same dolphin. The recordings for this encounter were taken over a two minute period

The second encounter lasted over 20 minutes and during this time the estimate for the number of dolphins seen visually was in excess of 20. Five of the dolphin whistles were recorded at the same time as a military sonar was sounding. These whistles are on pages A44,A47,A49,A50 & A51. The military sonar shows up on the spectrogram as the red line at 4 kHz, the signal is a frequency swept pulse which lasts 0.25 second usually with over 10 repetitions. The dolphin whistles numbered A47 and A50 start before the military sonar and are not interrupted by the military sonar. The other three whistles, A44, A49 and A51 are emitted by the dolphins after the military sonar has started. This indicates that the dolphins are not perturbed by the military sonar. Figure 8.1 shows the spectrogram of two seconds of the military sonar pulse on an expanded frequency scale (0-10kHz).

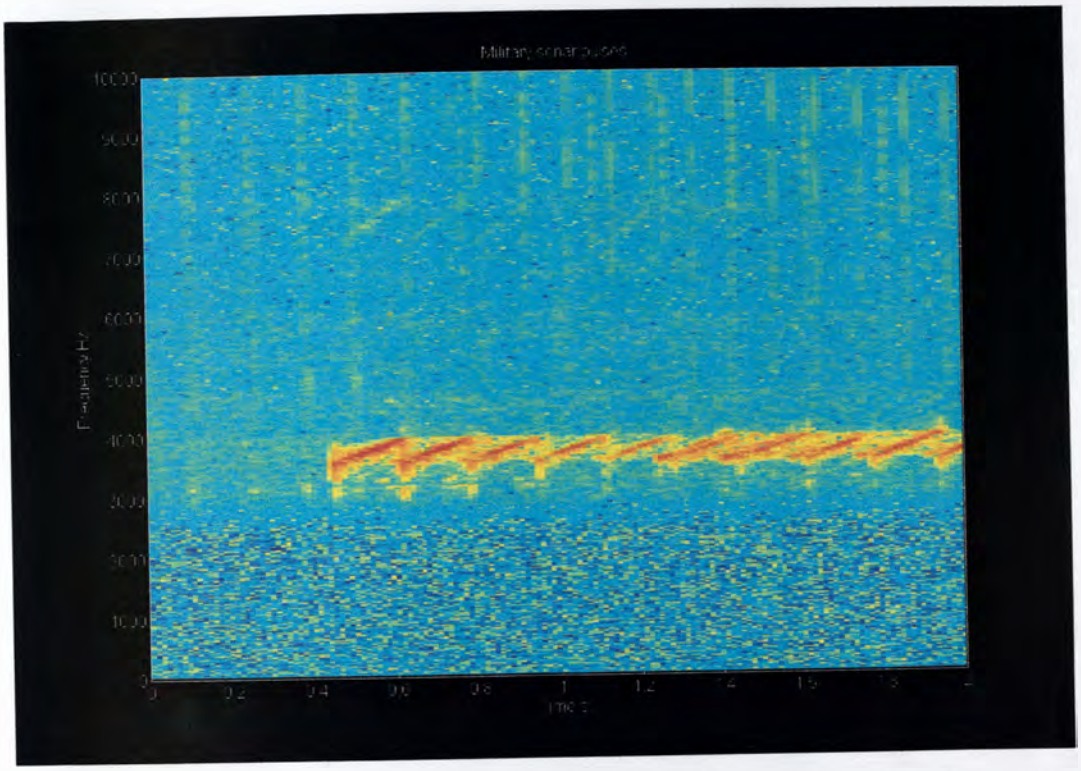


Figure 8.1 - Military sonar pulse

8.5 Signature Whistle Detection Algorithm Performance Analysis

It is normal to assess the performance of a sonar detection system by means of the Receiver Operating Characteristics (ROC). These characteristics usually predict the Probability of False Alarm (PFA) and Probability of Detection (PD) as a function of input signal-to-noise ratio and the decision threshold level. However, the algorithm described in this thesis does not use a conventional decision threshold level, instead it makes use of the largest detected component at any instant. Thus a modified form of the Receiver Operating Characteristics must be derived.

Consider a block diagram of the algorithm employed as shown in figure 8.2

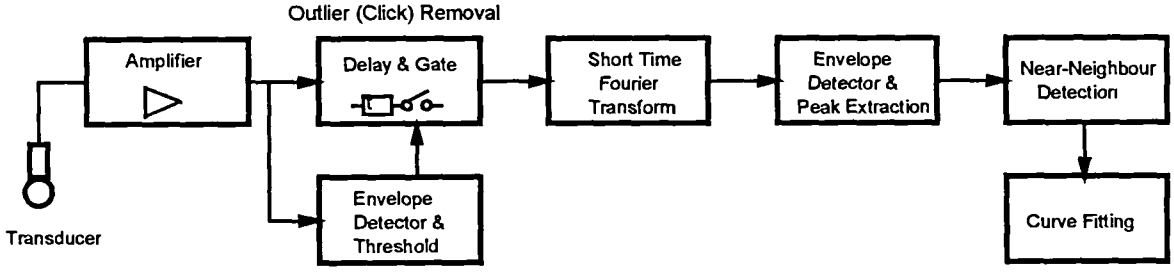


Figure 8.2 System diagram for signature whistle detection algorithm

The received signal is amplified and any impulsive noise is removed using the same techniques as used in high-performance radio receivers. A broad-band detector is used to control a signal gate – the main signal path being delayed to compensate for the time response of the envelope detector and level threshold operations. A short time Fourier transform is used to extract the frequency content of the signal. Envelope (modulus) detection is applied prior to the selection of the largest frequency

component. A number of stages of post-detection processing are then applied in order to reduce the Probability of False Alarm value.

The output of envelope detector will consist of N frequency cells. Assuming that the operational bandwidth is of the order of 500 Hz to 20 kHz, the sampling frequency is 44.1 kHz and the number of points in the short time Fourier transform is 1024, then N is approximately equal to 450. Assuming that the input signal is additive white Gaussian noise then the probability that the largest component is detected in cell n is $P(n) = 1/450$. However, as there are N parallel channels, this stage of the process will have a probability of activation of unity.

Only when a minimum of two independent observations of the signal are made can the Probability of False Alarm be reduced below unity. Consider two observations at time t_1 and t_2 as shown in figure 8.3. The probabilities that the detected maxima will occur in cell n are $P(n,t_1)$ and $P(n,t_2)$. Thus the joint probability that the maximum will lie in the same cell during two different observations is $P(n,t_1) \cdot P(n,t_2)$. The algorithm discussed in this paper is designed to detect frequency modulated signals and thus the maxima are likely to occur in cells corresponding to similar, but not necessarily identical, frequencies. For this reason a near-neighbour acceptance window of width W is introduced. The joint probability that the maximum will occur in this acceptance window will now vary between $(W+1)/2N^2$ at the extremes of the frequency range and W/N^2 in the middle of the frequency range. Note that W is assumed to be odd and for the results presented in this thesis $W = 5$. As there are N

possible occurrences of this event, the Probability of False Alarm is obtained by integrating the joint probability with respect to n. For the values given above this implies that the PFA = 0.011, or that about 1% of observations will falsely pass through the near-neighbour detection section of the algorithm.

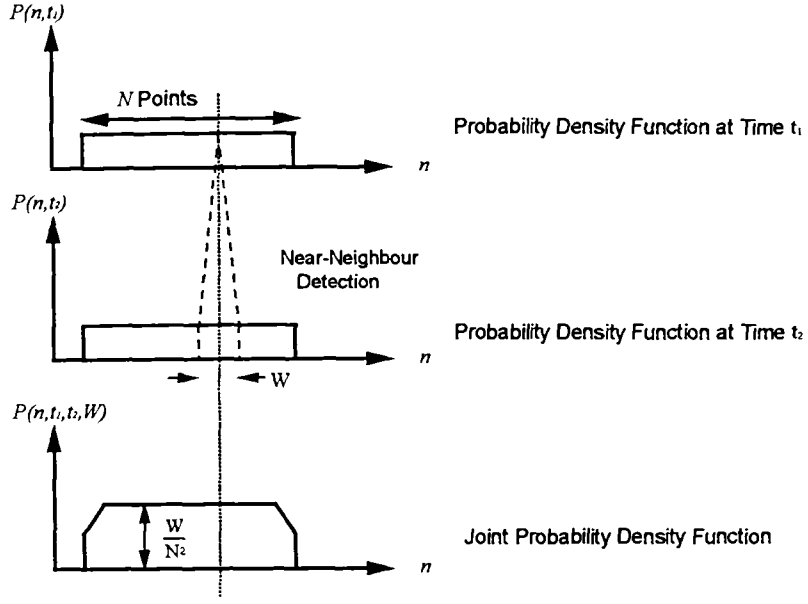


Figure 8.3 Probability density functions for detection algorithm

The above derivation of the PFA values assumes that there is no signal present in the water. Now let us consider the case of a deterministic input signal contaminated by additive white Gaussian noise.

First, consider the case of the output of a single cell of the short time Fourier Transform. For the case of no signal present then the statistics of the envelope of the output become Rayleigh distributed. The probability density function is

$$p(r) = \frac{r}{N}\exp\left(\frac{-r^2}{2N}\right)$$

where r is the output signal level and N is the noise variance.

When a sinusoidal signal is present ($A\cos\omega t$), the probability density function for the envelope is given by the Rician distribution

$$p(r) = \frac{r}{N}\exp\left(\frac{-(r^2+A^2)}{2N}\right)\cdot \mathrm{I}_0\left(\frac{r\cdot A}{N}\right)$$

The probability density function includes the modified Bessel function of the first kind and of zero order.

$$\mathrm{I}_0(x) = \frac{1}{2\pi}\int_o^{2\pi} \exp(x\cos\theta)\, d\theta = 1 + \frac{\frac{1}{4}x^2}{(1!)^2} + \frac{\left(\frac{1}{4}x^2\right)^2}{(2!)^2} + \frac{\frac{1}{4}\left(x^2\right)^3}{(3!)^2} + \ldots$$

The ratio $A^2/2N$ is equivalent to the signal-to-noise ratio of the received signal in a single cell of the output of the short time Fourier transform.

Now consider the case where the noise level exceeds the signal level in two independent samples, which is given by

$$p(noise > signal) = \int_0^{\infty} p_{Rayleigh}(r)\int_0^{r} p_{Rician}(s)\; ds\, dr$$

Thus when considered across N cells

$$p(signal > noise) = \left(1 - p(noise > signal)\right)^{N-1}$$

We now require, as a comparison, the probability that the largest signal detected appears within the near-neighbour window of width W – whether caused by the signal or the noise.

This probability may be determined by calculating the probability that a detection will occur outside the near-neighbour window using the Poisson distribution function.

$$P(x=r)=\frac{e^{-\mu}\mu^{r}}{r!}$$

where μ is the mean of the theoretical distribution

and r is the number of occurrences.

So if there are to be no occurrences outside the near-neighbour window then $r = 0$. Similarly, $\mu=(N-W)P(noise>signal)$ thus the required Probability of Detection is given by

$$PD = e^{-\mu}(1-p(noise>signal))^{N-1}$$

This Probability of Detection value includes the cases where the first observation represented either the signal or noise and the second observation represented the signal. It should be noted that no attempt has been made to allow for more than one signal to occur within the same time period as the proposed system is highly non-linear and will always 'capture' the strongest of the signals.

This Probability of False Alarm is obtained by assuming that the largest value inside the near-neighbour observation window resulted from a component other than the noise.

$$PFA=\left[1-(1-p(noise>signal))^{N-1}\right]\frac{W}{N}$$

This joint Probability of False Alarm and the joint Probability of Detection in two adjacent observations may be plotted as a function of signal-to-noise ratio as shown in figure 8.4. It will be noted that, as with a conventional sonar, the performance of the system improves dramatically for signal-to-noise ratio values in excess of +12 dB. The performance of the algorithm described in this thesis depends on the number of frequency cells used in the short time Fourier transform. For example, the larger the

number of cells the lower the values of PFA and PD for any given signal-to-noise ratio. The acoustic noise is unlikely to be white under the data conditions encountered during the data recording periods. Thus the lower frequency cells are likely to have a higher variance value than those representing the higher frequency components. Figure 8.4 plots the results for two scenarios, the first is $N = 450$ as used earlier and the second is $N = 90$ in order to take some account of the coloured noise background. The signal-to-noise ratios at which the PFA value equals the PD value are 13.2 dB and 13.1 dB respectively. However, at these values of signal-to-noise ratio, the vast majority (>95%) of values would be rejected by the algorithm.

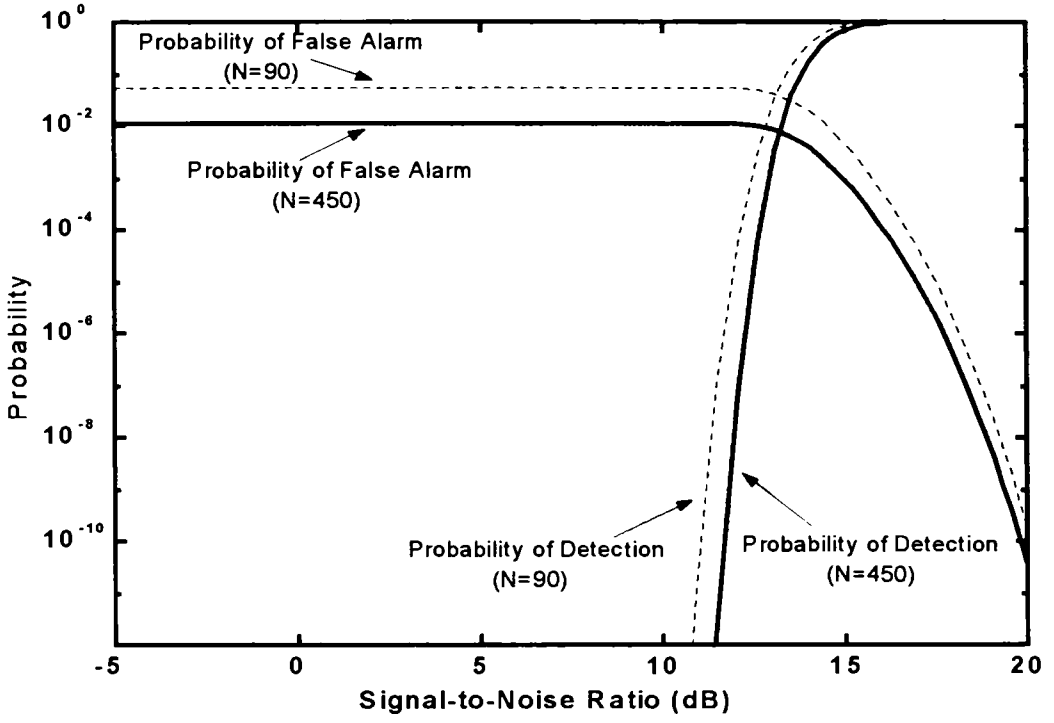


Figure 8.4 Receiver Operating Characteristics for the signature whistle detection algorithm

Chapter 9 - Results of analysis of a pulse discovered in recordings of striped dolphin vocalisations

9.1 Introduction

During the analysis of the dolphin signature whistles another sound was found which was emitted regularly apparently by the dolphins. This sound called a harmonic pulse, was hypothesised by the author as being Doppler sensitive during the preliminary analysis conducted in Chapter 6. As this sound has not been previously reported in the literature a more detailed analysis of this sound is investigated in this chapter. Evidence is presented which suggests that the pulse is emitted by dolphins and not by other man made or biological means. The spectrogram is used to show the time frequency variation of this pulse and the context in which it is used by the dolphin. The frequency content of the signal is analysed using a narrow band analysis to examine the harmonic structure of the pulse. The ambiguity function is then used to measure the Doppler/range sensitivity of the harmonic pulse as well as other commonly emitted sounds produced by dolphins.

9.2 Harmonic Pulse

Figure 9.1 shows the spectrogram of a typical harmonic pulse. The spectrogram shows 3 seconds of a recording taken from tape 2. The dolphin which is vocalising is producing a click train of which the last 10 clicks are shown on the left of the spectrogram (vertical lines). The clicks stop and then the harmonic pulse is emitted. The pulse has harmonics which extend up to 20 kHz and possibly beyond. Confirmation of this is not possible due to the bandwidth limitations of the equipment. Echoes of the previously emitted echolocation clicks can be seen whilst the pulse is being emitted. The harmonics in the region 10 kHz to 20 kHz are of a similar amplitude above the back ground noise. The harmonics between 5 kHz and 10 kHz are either below the back ground noise or are not present. Two stronger harmonics are visible between 3 and 4 kHz. Below 3 kHz the noise from the boat swamps any other harmonics which may be there. The spacing of the harmonics is approximately 700 Hz. This suggests that the fundamental frequency will be 700 Hz. After the pulse the dolphin continues echolocating. A narrow band analysis yields more information about the harmonic structure than the spectrogram, see Figure 9.2.

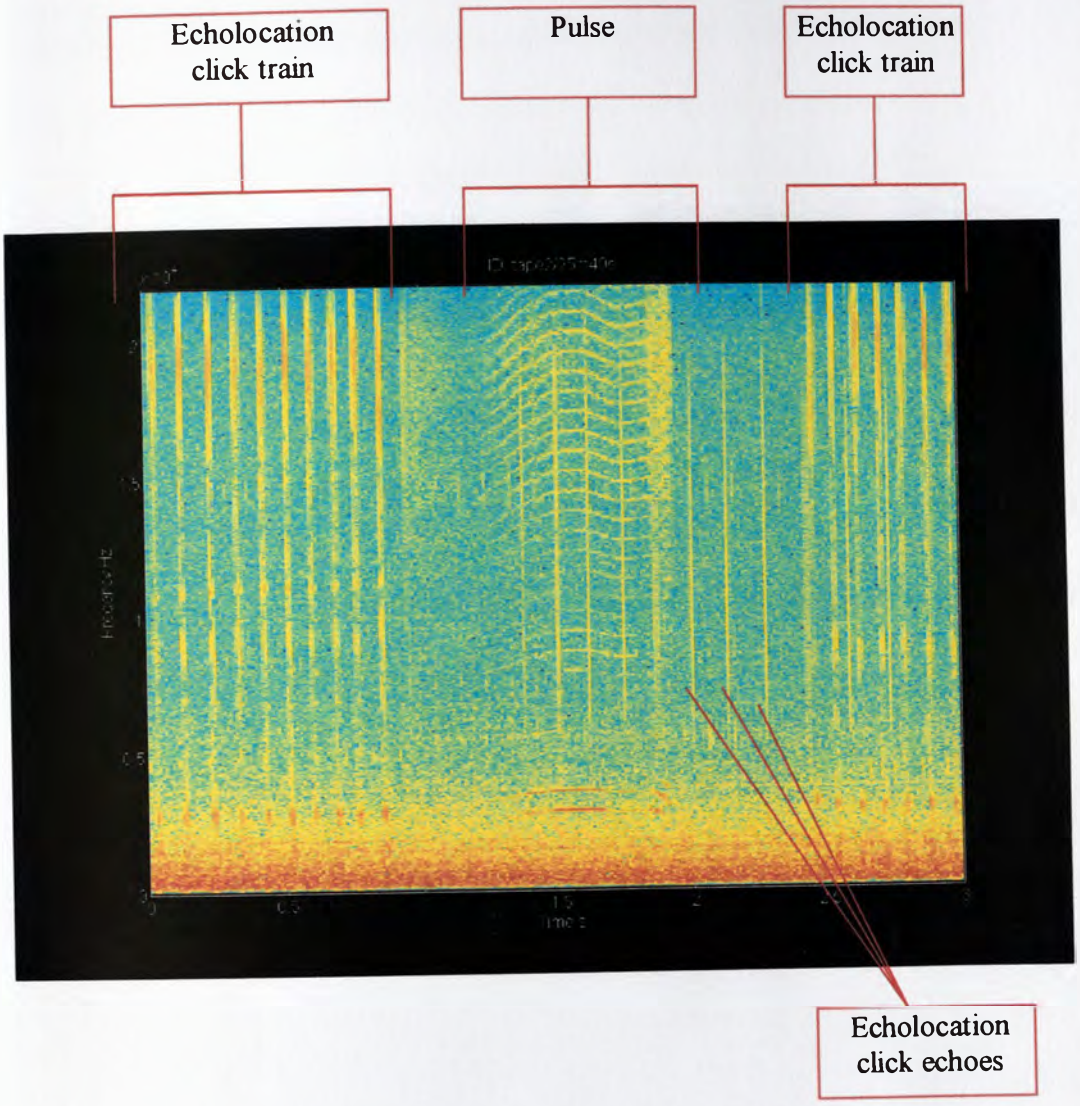


Figure 9.1 : Spectrogram of a typical harmonic pulse

9.3 Narrow band spectral analysis of pulse

A narrow band frequency analysis is shown in Figure 9.2. The frequency resolution of the spectrum is 1 Hz. The harmonics are labelled across the top of the figure. The vertical grid lines are spaced at multiples of the fundamental frequency of 737 Hz. All of the peaks line up exactly with the grid lines. Harmonics 18-30 are more than 6 dB above the background noise. Table 9.1 lists the sound pressure levels of all the harmonics. Harmonics 3 & 4 have the highest SPL this may be because the harmonics below this are destructively interfered with by the background noise. This may also account for harmonics 6 - 10 being below the background noise.

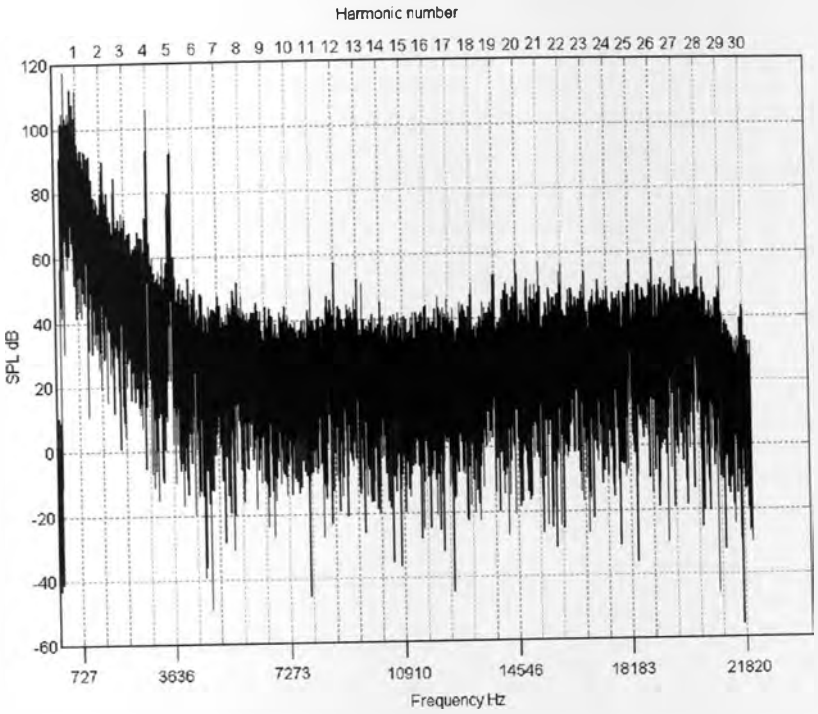


Figure 9.2 : Narrow band frequency spectrum showing the harmonic structure of the pulse.

Table 9.1

Harmonic number	Frequency Hz	SPL dB
1	727	95.3
2	1454	54.4
3	2182	71.9
4	2909	100.8
5	3636	89.4
6	4364	34.6
7	5091	41.9
8	5818	17.1
9	6546	17.5
10	7273	18.2
11	8000	49.1
12	8728	57.0
13	9455	43.8
14	10182	29.6
15	10910	29.8
16	11637	23.3
17	12364	34.4
18	13092	46.0
19	13819	47.7
20	14546	56.4
21	15274	45.8
22	16001	48.7
23	16728	50.5
24	17456	42.3
25	18183	54.3
26	18910	57.7
27	19638	55.0
28	20365	47.4
29	21092	37.6
30	21820	16.1

9.4 Analysis of dolphin sounds using the ambiguity function

9.4.1 Introduction

The ambiguity function can be used to measure the Doppler/range sensitivity of sounds produced by dolphins. The ambiguity function is used to calculate the amount of Doppler/range information contained within the sounds produced by dolphins presented in this thesis. The ambiguity function, $|\chi(\tau,\eta)|^2$, is a two-dimensional function of a correlator output power against range τ and Doppler scaling factor η. The expression for the wideband ambiguity function $\chi(\tau,\eta)$ using an arbitrary pulse design, *s(t)* is given by Lin (1988):

$$\chi_s(\tau,\eta) = \sqrt{\eta}\int_{-\infty}^{\infty} s(t)s^*[\eta(t-\tau)]dt$$

9.4.2 Dolphin Echolocation Click

The click sound is commonly emitted by many species of dolphin, it is very short in time and broadband in frequency therefore it is expected to give extremely good range resolution with virtually no Doppler resolution. The equation used to generate this click sound is presented in Au (1995), and reproduced here.

$$s(t) = A\cos(2\pi f_0 t + \phi)e^{\left(-\pi^2\frac{(t-t0)^2}{\Delta t^2}\right)}$$

where		Value used
A = relative amplitude	(1)	
f_0 = peak frequency		(120 kHz)
t_0 = centroid of the signal		(9.9 μs)
Δt = rms duration of the signal		(29.9 μs)
ϕ = phase shift		($3\pi/4$)

The time history of the click generated from this equation is shown in Figure 9.3. It consists of four cycles of an exponentially amplitude modulated sinusoid. The duration of the click is approximately 30 μs with a peak frequency of 120 kHz.

The ambiguity function is shown in figure 9.4. The x-axis shows the time delay that can be measured using the pulse, which can be interpreted as range. The y-axis shows the velocity to which the sound is sensitive to. The ambiguity function of the click is shown as a narrow ridge orientated along the y-axis with several side lobes. This shows that the time delay can be measured to an accuracy of 0.1 ms and hence the range resolution of the click can be determined to 0.15 m. The Doppler or velocity resolution is essentially zero since the ambiguity function is almost constant for all velocity values.

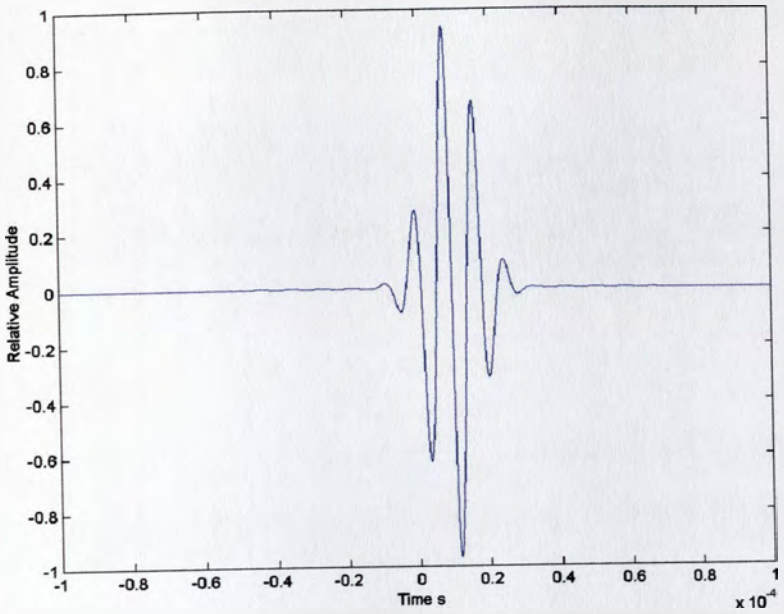


Figure 9.3 Time history of a simulated dolphin echolocation pulse.

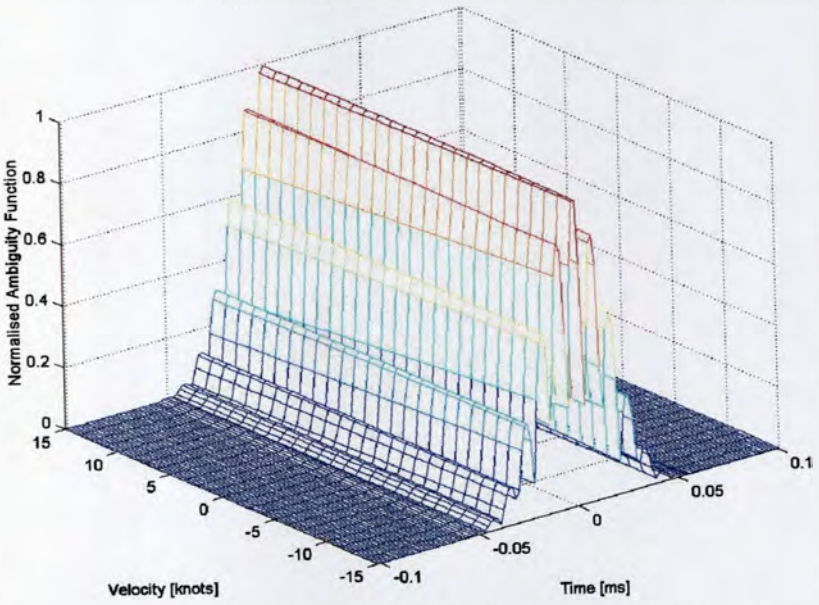


Figure 9.4 Ambiguity function showing the Doppler/range resolution of the simulated dolphin echolocation pulse

9.4.3 Dolphin Signature Whistle

The signature whistle sound is thought to be used for communication and social interactions and does not seem to be used as an active sonar pulse. A typical dolphin signature whistle has been simulated by fitting a polynomial curve to the frequency contour of whistle 1 presented in Appendix C. This whistle consists of a frequency modulated pure tonal sound which sweeps from 7 kHz to 14 kHz over a 0.5 second interval before sweeping back down in frequency from 14 kHz to 6 kHz over a similar period.

The spectrogram for this signature whistle is shown in figure 9.5. The ambiguity function for this sound is shown in figure 9.6. The time resolution of the signature whistle is approximately 60 ms which equates to a range resolution of 90m, which is poor. The Doppler or velocity resolution is approximately 2 knots, which is reasonably good although there are quite large side lobes which will reduce the effectiveness of this sound. The signature whistle hypothesis that this sound is used for communication and social interactions seems to be the most likely since it would have limited use as an active sonar pulse.

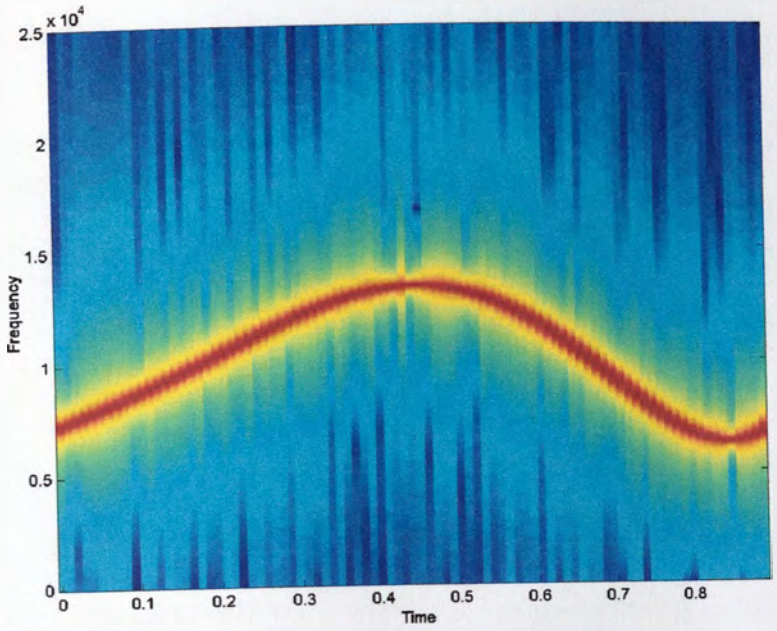


Figure 9.5 Spectrogram of the simulated dolphin signature whistle.

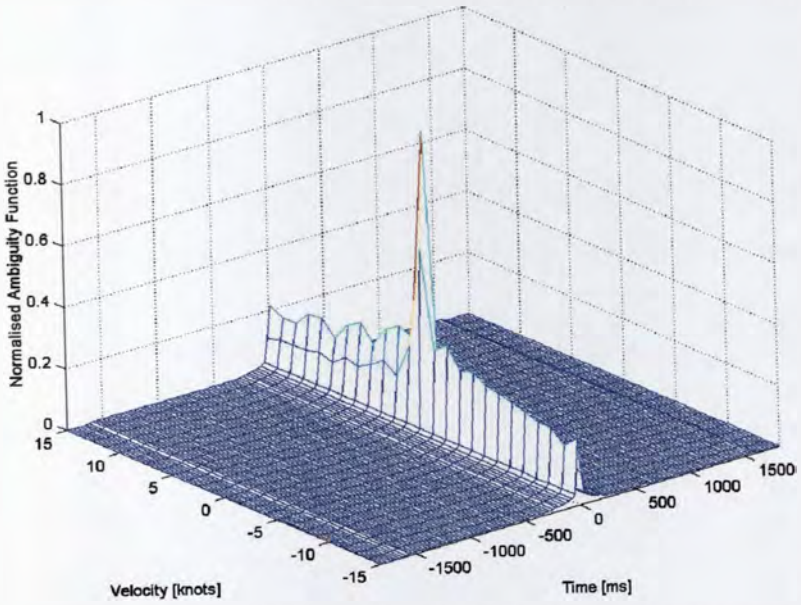


Figure 9.6 Ambiguity function showing the Doppler/range sensitivity of the simulated dolphin signature whistle sound.

9.4.4 Dolphin Harmonic Pulse Sound

The harmonic pulse sound presented in this thesis appears to be used by the dolphin to supplement the information it gains from the echolocation click. The echolocation click is very good at detecting range but unfortunately contains no Doppler information for the dolphin to use to determine target speed. This harmonic pulse sound tends to be emitted between echolocation click trains and is more commonly emitted than the signature whistle. The ambiguity function is used to determine the amount of Doppler/range sensitivity that this pulse sound contains.

The simulated harmonic pulse is based on the recorded sound presented in figure 9.1. The spectrogram of the simulated sound recreates both the frequency modulation as well as the amplitude variation of the various harmonics and is shown in figure 9.7. The ambiguity function, shown in figure 9.8 shows that this sound contains very little time or range resolution but a reasonable amount of Doppler information. The time resolution of 70 ms equates to a range resolution of 105m which is obviously unusable for detecting range. However the velocity resolution is approximately 3 knots.

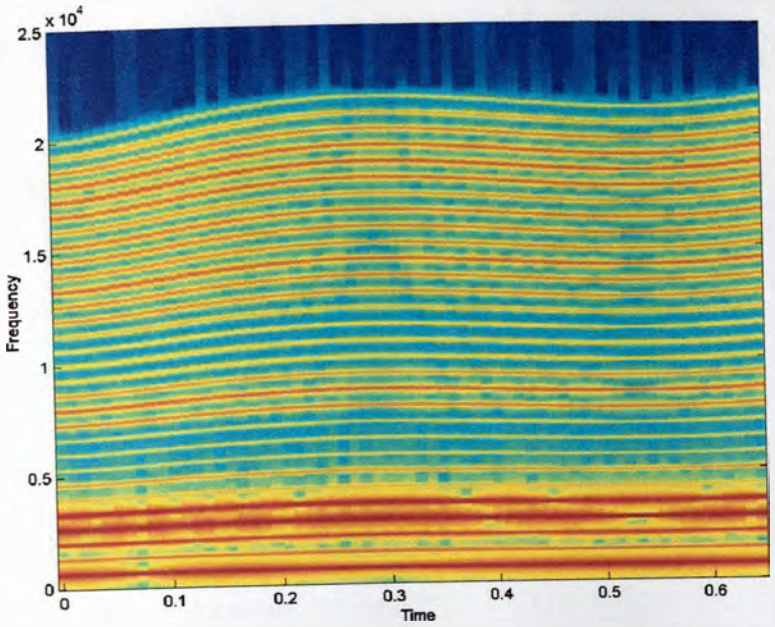


Figure 9.7 Spectrogram of a simulated dolphin harmonic pulse.

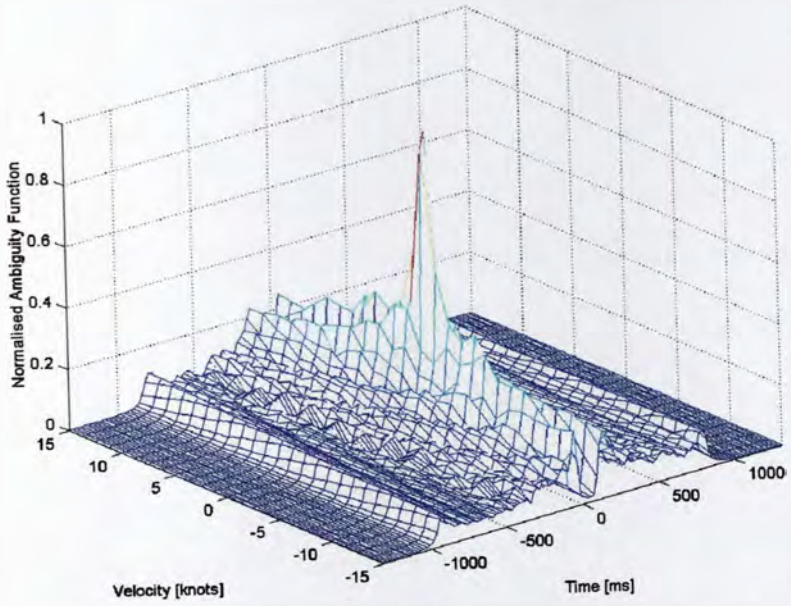


Figure 9.8 Ambiguity function showing the Doppler/range sensitivity of the simulated harmonic pulse.

9.4.5 Summary of ambiguity function analysis

The slice through the center of the ambiguity function for range and Doppler for each of the sounds are shown in figures 9.9 and 9.10 respectively.

Sensitivity to range

The ambiguity function for range resolution, in figure 9.9, shows that the echolocation click is excellent for detecting range. The broader the peak then the worse the sound is for detecting range, both the signature whistle and the harmonic pulse have similar width peaks at the –3 dB point, with the harmonic pulse being degraded by the large sidelobes (skirts of the peak).

Sensitivity to Doppler

The ambiguity function for Doppler, in figure 9.10, shows that the echolocation click contains no useful Doppler information as the ambiguity function shows up as a horizontal line. Both the signature whistle and the harmonic pulse contain Doppler information with the harmonic pulse performing better due to the reduced sidelobes compared to the signature whistle. It is therefore highly likely that the dolphin uses this harmonic pulse to detect the Doppler of moving targets to supplement the excellent range detection it can achieve with the echolocation click.

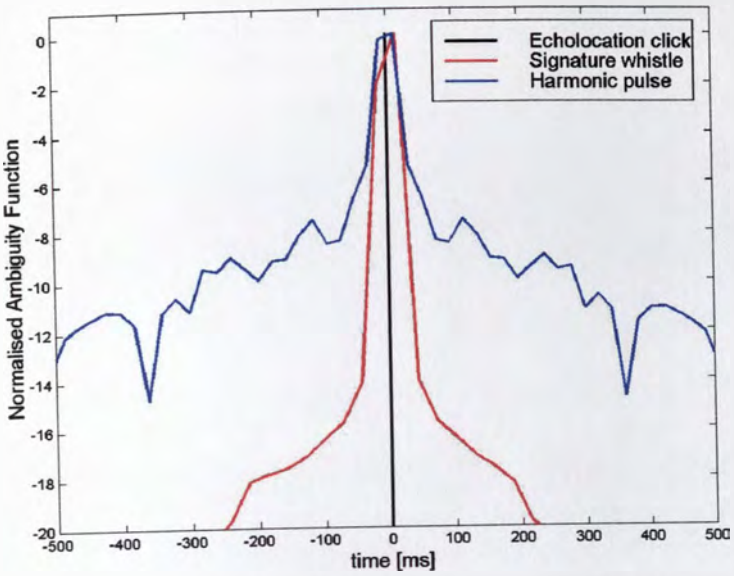


Figure 9.9 Comparison of range ambiguity for the echolocation click, signature whistle and harmonic pulse.

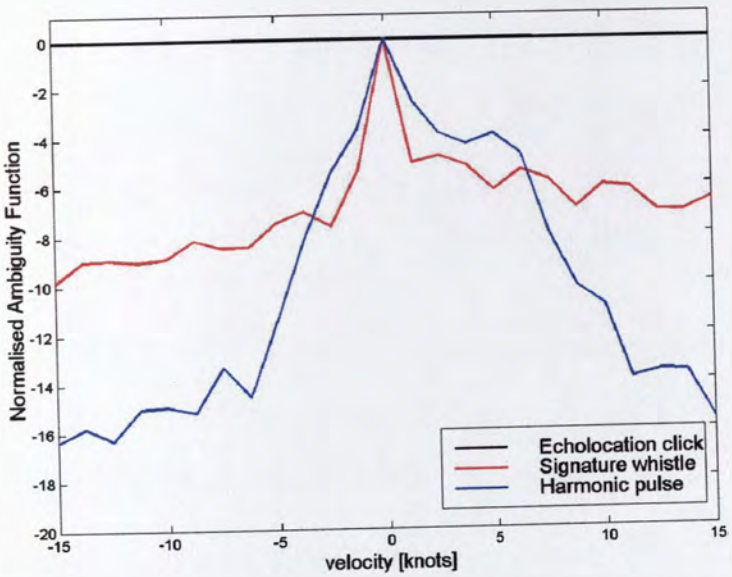


Figure 9.10 Comparison of Doppler ambiguity for the echolocation click, signature whistle and harmonic pulse.

9.5 Discussion

Caution has to be exercised when making acoustic measurements in the open ocean. There are many sources of underwater sound, man made, seismic, weather generated as well as biological noises from a myriad of creatures. Therefore attributing a particular sound to one species is very difficult. Sound can travel large distances underwater and the source of a sound may be remote from the observation site. Just because dolphins are in the vicinity does not automatically mean that all measured sound can be attributed to them.

This pulse has been detected only when dolphins have been in the acoustic vicinity. The sound level of the pulse also varies in accordance with the other sounds which are known to be emitted by dolphins such as the echolocation click and the signature whistle. The pulse is often emitted between click trains which suggests the dolphin is using the pulse to supplement the information from the echolocation clicks.

One could argue that the dolphin is falling quiet when this other sound is being emitted by a different source other than a dolphin. This is unlikely given the amount of evidence that has been collected from recordings which span a 5 month period. In the experience of the author dolphins do not tend to become quiet when other sources of sound are present. Loud boats or ships do not cause dolphins to fall silent, in fact often they are more inquisitive when other sources of sound are in the vicinity and increase their vocalisations. The loudest sounds which have been recorded during this trial were from a military sonar and spectrograms of these sounds can be found in Chapter 8.

This military sonar is very different from the harmonic pulse, see Figures 9.3 and 9.4. These figures show a harmonic pulse and a military sonar on the same scales. The Military pulses are less than 0.2 seconds in duration are is swept in frequency from approximately 4 kHz to 4.2 kHz and have no harmonic content.

Dolphins were also found to be vocalising whilst these sounds were being emitted and did not seem to be discouraged from doing so because of it. The author would therefore suggest that this pulse does come from a striped dolphin and the ambiguity function analysis has shown that it could be used as a Doppler sensitive pulse.

More examples of this pulse can be found in Appendix B. These examples of the pulse have been taken from different times and locations within the Ligurian Sea area. Some variability of the pulse has been observed. The overall harmonic structure of the sound remains reasonably constant. The duration of the sound varies from 0.25s to 0.75s, and the frequency varies by as much as 100 Hz.

The propagation path of the pulse determines what is detected at the receiver. The higher frequencies are attenuated much faster than the lower ones and so the higher harmonics are often not observed. Also multi-path propagation through the ocean can cause interference at particular frequencies depending upon the various path lengths from source to receiver. This interference can be constructive or destructive depending on the phase of the received sounds. This may account for the variability of the sound level of the various harmonics.

This sound requires more investigation firstly to verify beyond doubt that it is a dolphin sound and then to investigate the usefulness of the pulse to the dolphin. This may only be possible by experiments on a captive dolphin in a suitably large tank. Captive dolphin experiments have been described in Chapter 2. These experiments generally use bottlenose dolphins and the researchers have investigated the echolocation clicks of the dolphins. Small tanks and oceanariums are often used to perform these echolocation experiments. Small tanks are a highly reverberant environment in which only high frequency sounds such as the echolocation clicks can be reliably measured. Low frequency sounds are often detected as reverberation and this would certainly be the case for the 700 Hz pulse sound. To reliably detect sounds the receiver needs to be in the far field of the source and as far away as possible from reflecting surfaces. The bottom and walls of a tank are hard reflectors and absorb little of the acoustic energy. The wavelength of sound at 700 Hz is approximately 2m. This means that a tank which is 4m deep will only support one wavelength before reflection if the source is placed equidistant from the reflecting surfaces. Some experiments are conducted in shallow bays or lakes. Kaneohe bay has been used for echolocation experiments conducted by Au (1995). This bay is probably not suitable for detection of this pulse since the depth of water is only 6m.

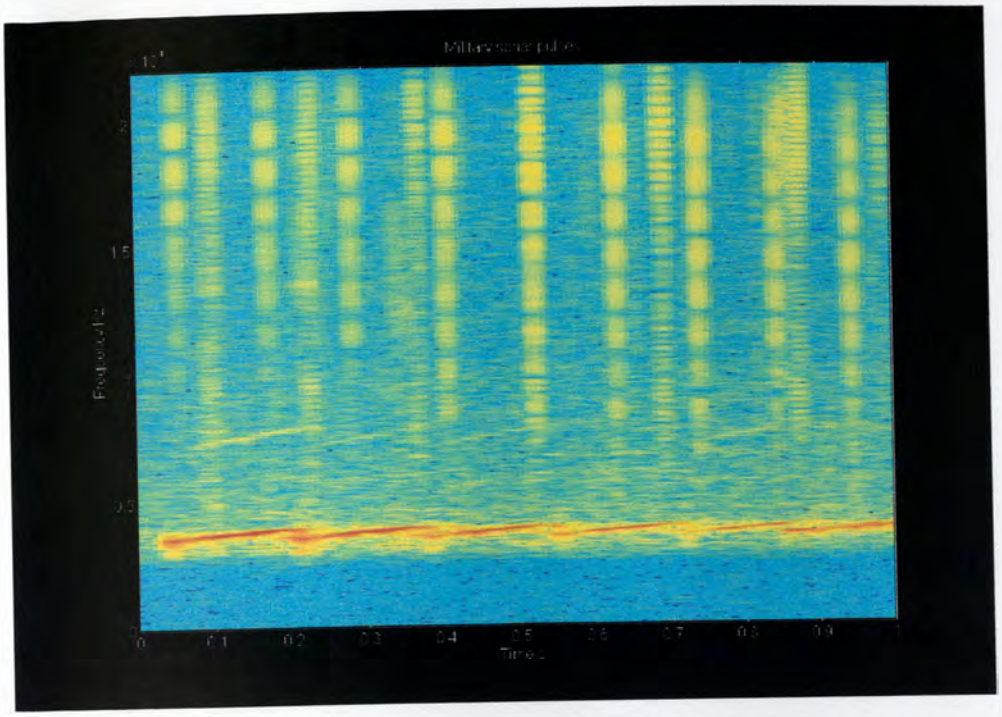


Figure 9.11 - Military sonar pulse.

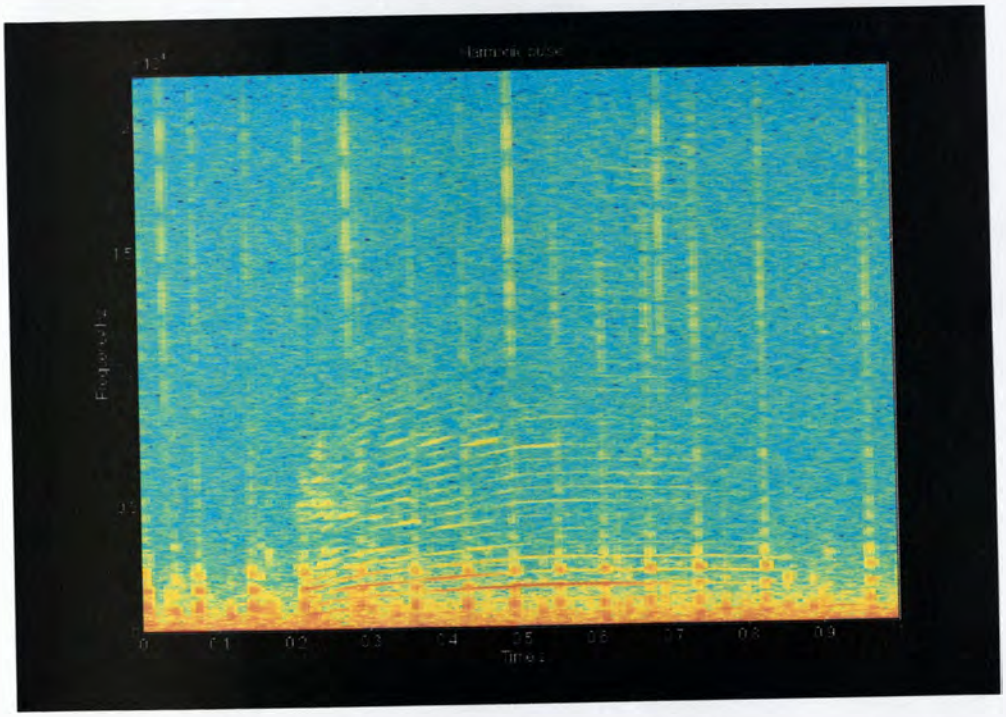


Figure 9.12 - Harmonic pulse.

Chapter 10 - Discussion

10.1 Data collection

The data presented in this thesis was collected during four separate trials. These trials were conducted from the sailing vessels 'Song of the Whale' and 'Gemmini' which were operated by IFAW and Tethys respectively. Over 90 hours of recordings were collected during the first trial which took place in the Ligurian Sea. The objective of this first trial was to experiment with array configurations and also to develop analysis methods which allowed data about the cetaceans to be extracted from the acoustic recordings. The extracted data is intended for further analysis by zoologists who are interested in obtaining information about long term movements of cetaceans and also the social interactions between individuals as well as collecting census information about the abundance of various cetacea. The striped dolphin is common in these waters and this thesis has concentrated on obtaining information about this species.

The data from the first trial was used to develop the following methods of analysis:

1. tracking of striped dolphins by using a spatially separated array to detect and obtain bearings to the dolphins from the time difference of arrival of their echolocation clicks.
2. individual recognition and census information by detection, extraction and comparison of individualised whistle contours emitted by striped dolphins.
3. to investigate other sounds emitted by striped dolphins.

Recordings were obtained during the first trial which were later analysed in the laboratory. The preliminary results, Chapter 6, develops the above techniques for analysis of the striped dolphin vocalisations. The recordings used were from an encounter in which four striped dolphins were known to be present from the visual sightings which were made concurrently with the acoustic recordings. The visual sightings were used to validate the acoustic information.

The acoustic tracking of the movements of the cetaceans from their echolocation clicks was found to be possible. The low signal to noise ratio, due to the restricted bandwidth and high background noise, limited the range over which this technique could be used. A longer tow cable for the array would help to reduce the noise from the boat.

The individual recognition algorithms which were developed were able to detect and extract automatically from the recordings the striped dolphin signature whistle contours. These extracted whistle contours were then compared using multivariate statistical methods to determine the number of individual dolphins within the group.

A sound was recorded which has not previously been reported in the literature. The sound was a short tonal pulse of 0.25s - 0.75s duration which has a harmonic structure, the fundamental of which would be at approximately 700 Hz. This was investigated in greater detail in Chapter 9 and by use of the ambiguity function found to be Doppler sensitive.

10.2 Echolocation click tracking

Striped dolphin (*Stenella coeruleoalba*) sounds were recorded in the frequency band 200 Hz - 20 kHz. These sounds were recorded using two towed arrays, which were towed at a distance of 19.5 m and 92 m to form a linear array of four elements. This configuration of array allows cross bearings to be calculated for the striped dolphin sounds.

Striped dolphins use a broadband 'click' sound for echolocation. This is a short pulse approximately 130 μs long. The 'click' contains a broad range of frequencies. Analysis of striped dolphin 'clicks' have not been recorded in the literature, but they are probably similar to the Atlantic bottlenose dolphin 'clicks' which have been well studied. These bottlenose dolphin 'clicks' have a peak frequency of approximately 120 kHz with a -3dB bandwidth of approximately 37 kHz. The maximum frequency that could be recorded was limited by the tape recorder, which was 20 kHz. The 'click' frequency spectrum of the striped dolphin extends into this region and the clicks are audible throughout the recording. The clicks arrive at different times on the different elements of the array depending on how far they have to travel to reach the elements. The time differences between the same click arriving on the two spatially separated elements is proportional to the bearing to the dolphin. Each array produces a bearing to the dolphin. By triangulating the bearings a position for the dolphin can be found. This technique did not prove to be as useful as was first hoped. The position information found from the clicks was hoped to give the tracks of the individual dolphins. The number of tracks could then be counted and an estimate for the number of dolphins within a group could be found. The results are from a group of four

dolphins, the tracks produced are confusing and overlapping even for this relatively small number. Therefore the technique would not be useful for large numbers of dolphins. Also there are breaks in the tracks when the dolphins are not echolocating which also adds to the confusion. Unpredictable movements in the array and the variable background noise spectrum introduces errors and so inhibits the usefulness of this technique. Other techniques of measuring the number of dolphins within a group have therefore been investigated and a discussion of those techniques follow in the next section.

During Trial 4 which took place in Grenada in the West Indies another attempt was made to use the four element tracking system this time with sperm whales. Sperm whales produce a more intense echolocation click than dolphins and the peak frequency is much lower at 5kHz. This allows much higher signal to noise ratio recordings to be taken for sperm whales. This data was collected but due to time restrictions has not yet been analysed.

10.3 Signature whistle analysis

During the recording of the striped dolphins, seventeen signature whistles were detected. Signature whistles are frequency modulated pure tonal sounds which last between 0.5 s and 1.5 s. The signature whistles occupy the 5 kHz -20 kHz band. These signature whistles have been found to be individually distinctive to the dolphin Sayigh et al. (1990). The signature whistles were analysed using spectrograms and are displayed in Appendix C. Automatic detection of the whistles was performed in the frequency domain from the spectrogram. The recording was filtered using a digital high pass IIR filter with cut off frequency of 4 kHz to remove boat noise. The contour of the whistle was extracted from the spectrogram of the whistle by choosing the peak frequency in each STFT block. The derivative of the contour was then taken. Due to the relatively slow change in frequency of the whistles the derivative of a contour produces a waveform close to zero. Sudden changes in frequency as were found for clicks and other noise sounds produce a rapidly changing derivative. A detection score was produced which was calculated from the number of segments of small gradient change within a whistle. Signature whistle contours produce a high score, whereas noise and other sounds produced low or zero scores.

Multivariate analysis was used to look for natural clusters within measured parameters of the signature whistles. The parameters which were used were the maximum frequency, minimum frequency, beginning frequency, end frequency and duration. Using these measured parameters Cluster Analysis was performed which groups the data into natural clusters. Principal Components analysis was used to verify the clustering of the data. The Principal Components of the data were calculated and the

plots of the first three components were found. Four distinct clusters were found using both methods which indicates the presence of four dolphins during the recordings. This correlates with the visual sightings.

Abundance counts of groups of dolphins are usually performed visually. Estimating the number of dolphins within a group visually, is difficult. The problems are listed below,

1. dolphins do not stay stationary.
2. they are only visible from the deck if they are at or near the surface.
3. multiple counts of the same dolphin are possible.
4. beyond 5 dolphins, estimating the size of a group is purely guess work so, greater and less than, estimates are usually used.

The estimate of the number of dolphins is an important environmental factor to measure. The ability to know if group sizes are consistent or if the abundance of dolphins has changed within a region are important statistics for zoologists.

The estimate of dolphin numbers from the signature whistles complements the visual estimate. The acoustic estimate, however, would not be conclusive since it depends upon whether or not the dolphins are vocalising. If they remain silent or if individuals remain silent then the estimate of the group size will be affected. Obviously only those dolphins which produce their signature whistles can be counted. However, it is usual to hear signature whistles during an encounter so the usefulness of this technique for measuring the number of dolphins is encouraging.

A real time system was developed which was able to perform the spectrogram analysis and also the detection and extraction of the whistle contours. The design and

development of this system is described in Chapter 5. The system was tested using the recorded data from Trial 1. The system was designed to be installed on board an observation platform to automatically detect and extract dolphin whistle contours. These contours could then be downloaded and compared to an international database of whistle contours so that the long term movements of dolphins could be monitored especially at remote sights. Paper 1 describes a system which can be installed in any suitable location on the sea floor. This would enable remote sensing of the dolphin's movements. Extracting just the whistles means that the system can record for longer between downloading the stored information.

A 2GB hard disk would hold approximately 50,000 digitised dolphin whistles, or 2.5×10^6 whistle contours if just the extracted contour data is saved.

10.4 Harmonic pulse analysis

During the analysis of the signature whistles another sound occurred frequently, which can be described as a harmonic tonal pulse. This pulse was approximately 0.5 seconds long and had a frequency of 3 kHz. During a 10 minute segment of the recording the sound was emitted 77 times which equates to one every 7 - 8 seconds. The regular occurrence of this sound suggests that it may complement the echolocation clicks since it occurred usually at the start or end of a click train. The nature of the pulse was examined and found to be Doppler sensitive. The pulse is able to encode enough Doppler information to resolve the speed of a target to 1.634 km/h. This resolution of speed would easily detect most fish. A description of this sound has not appeared in the literature. Whether or not the dolphin is using the pulse to estimate the speed of a target or not is difficult to assess when the recordings are taken in a natural environment. Without knowing the orientation of the dolphin or the target which is being ensonified only speculation about the use of this sound can be made. The presence of this pulse in wild dolphins requires more investigation. Captured dolphins are reported as not having the ability to produce such a sound. The reasons for the lack of detection of this sound in captive dolphins can only be speculated about. Perhaps due to the static nature of the experiments the dolphin does not need to use the pulse. The species of dolphin most commonly held in captivity is the bottlenose dolphin, whereas the subject of this thesis is the striped dolphin, the bottlenose dolphin may not have the ability to produce a pulse of this nature.

10.4.1 Production method for harmonic pulse

Suggestions have been made at ARL Texas that when a dolphin 'homes' in on a target the echolocation pulse interval becomes short and may possibly be interleaved. If the pulse repetition frequency (prf) becomes large then the vertical lines on a spectrogram may merge and when this occurs as a result of the analysis and the recoded bandwidth it might be expected that envelope detection of the rapid clicks is performed. This would show up as vertical lines getting closer together before merging and becoming horizontal the harmonic structure would then appear with harmonic spacing at the prf rate.

The author suggests that this is not occurring to produce these sounds since the prf rate preceding a harmonic pulse does not increase steadily till they merge and that there is a small delay between the end of the click train and the harmonic pulse being emitted. The harmonic spacing of the pulse presented in this thesis is 727 Hz which would equate to a range to target of less than 1m. The dolphin would almost certainly be able to see the target at these ranges and would be unlikely to use its sonar. The mechanism for production of these sounds is at present unknown and further research is required into this area.

Chapter 11 - Conclusions and Suggestions for Further Work

11.1 Conclusions

Passive acoustic monitoring procedures were explored in Chapter 3. These monitoring procedures were based on theoretical predictions of the propagation characteristics of the known dolphin vocal repertoire. They served as guidelines for the data collection during the four trials which were conducted.

A description of the four trials which were conducted was given in Chapter 5. This chapter also presents the design and construction of the hardware which was required for the collection of data presented in this thesis. Signal conditioning modules were developed which allowed the selection of different frequency bands so that the optimum signal to noise ratio could be obtained for the cetacean vocalisation of interest. These modules were also used in seven other research and commercial projects which demonstrates the need for such equipment in this area.

A real time system was developed to interpret the acoustic recordings which were taken. This system was based around the ADSP 21020 digital signal processor. A paper was published in IEE computing and control which describes the system, a copy of this paper is included at the end of this thesis. The system was developed after promising results were obtained from a preliminary study which is described in Chapter 6. It was found to be possible to extract census information based on a count of the number of different pure tonal frequency modulated whistle contours that were emitted by striped dolphins during an encounter. The algorithm which was developed to

detect and extract these tonal whistles of striped dolphins is evaluated in Chapter 7. The results obtained from using this real time analysis system are presented in Chapter 8.

During analysis of the striped dolphin whistle vocalisations another sound was discovered which has not to the knowledge of the author been previously reported in the literature. This vocalisation can be described as a constant frequency harmonic pulse. This pulse was found to be emitted before, after or in between echolocation click trains emitted by striped dolphins. The regularity of the emission of the pulse and the presence of it during echolocation tasks by the dolphins has led the author to suggest that this pulse is employed as an active sonar pulse which complements the echolocation click of striped dolphins. Echolocation clicks have a good range resolution whereas a constant frequency pulse of this nature has a good Doppler or speed resolution. This pulse is described in section 3 of the preliminary results, Chapter 6 and also in greater depth in Chapter 9.

11.2 Suggestions for Further Work

The short range tracking of striped dolphins from arrival times of their echolocation click on a linear array was described in Chapter 6. The results of this analysis showed that this technique would be of limited use for striped dolphin tracking. This was mainly due to the limited bandwidth of the equipment. The dolphin echolocation click has it's peak sound pressure level at 120 kHz. At this frequency sound is severely absorbed in sea water and so it is unlikely that the expense of developing more sophisticated wider bandwidth equipment would yield any significant benefit in terms of range of tracking. This technique, however, may prove to be useful for tracking the movements of sperm whales. Sperm whales emit an echolocation click which has it peak sound pressure level at 5 kHz. The clicks from sperm whales are often detected at large distances in excess of 1 km. Recordings were obtained in Grenada using the two towed hydrophone system. These recordings have not yet been analysed.

It may be possible to track the movements of individual dolphins by creating a database which holds the whistle contours of previously encountered dolphins. This database could then be interrogated when new recordings are taken. The real time system presented in this thesis could be used in remote locations to automatically detect and log the signature whistles of dolphins so that they can be included in the database. A system based around existing equipment developed at Birmingham University is described in a paper which was published at a Bioacoustics Conference in Loughborough, a copy can be found attached at the end of this thesis. The system

consists of a package which is located on the sea bed which can transmit information to the sea surface via a vertical acoustic link. The package in this case would be the dolphin whistle detection system described in this thesis. These packages could then be deployed over a wide area and monitored from one vessel.

The harmonic pulse discovered during striped dolphin vocalisations requires more investigation. The presence of the pulse during echolocation tasks by the dolphin suggest that it may supplement the information obtained by the echolocation clicks. It has been suggested in this thesis that the pulse may be used for detecting the speed of targets. However, this has not been confirmed. This raises questions which require extensive research to answer. What extra information can be obtained using this pulse? Do all species of dolphin have the same capability? Is the pulse used for specific echolocation tasks?

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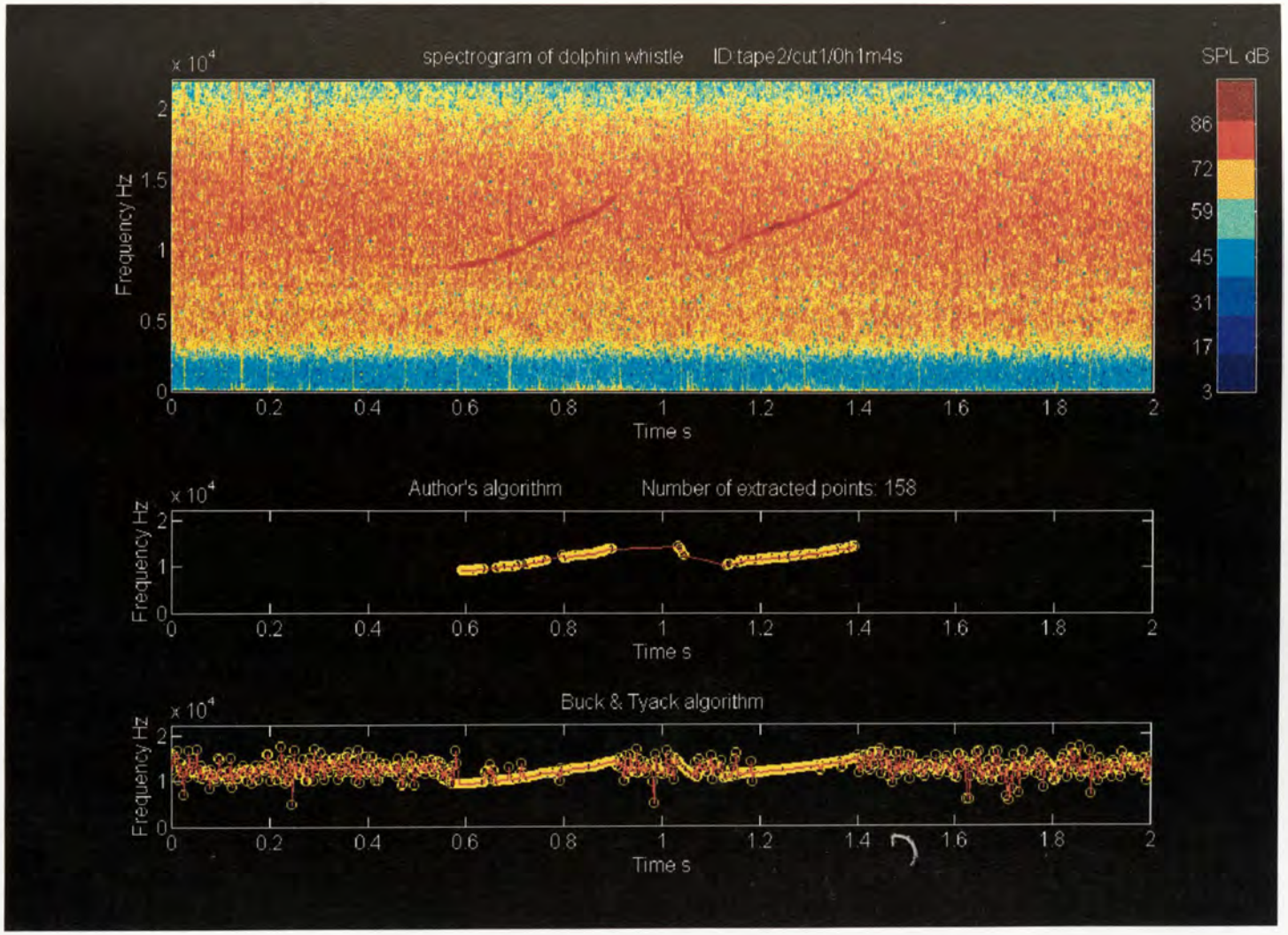
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[Full texts redacted]

Appendix A

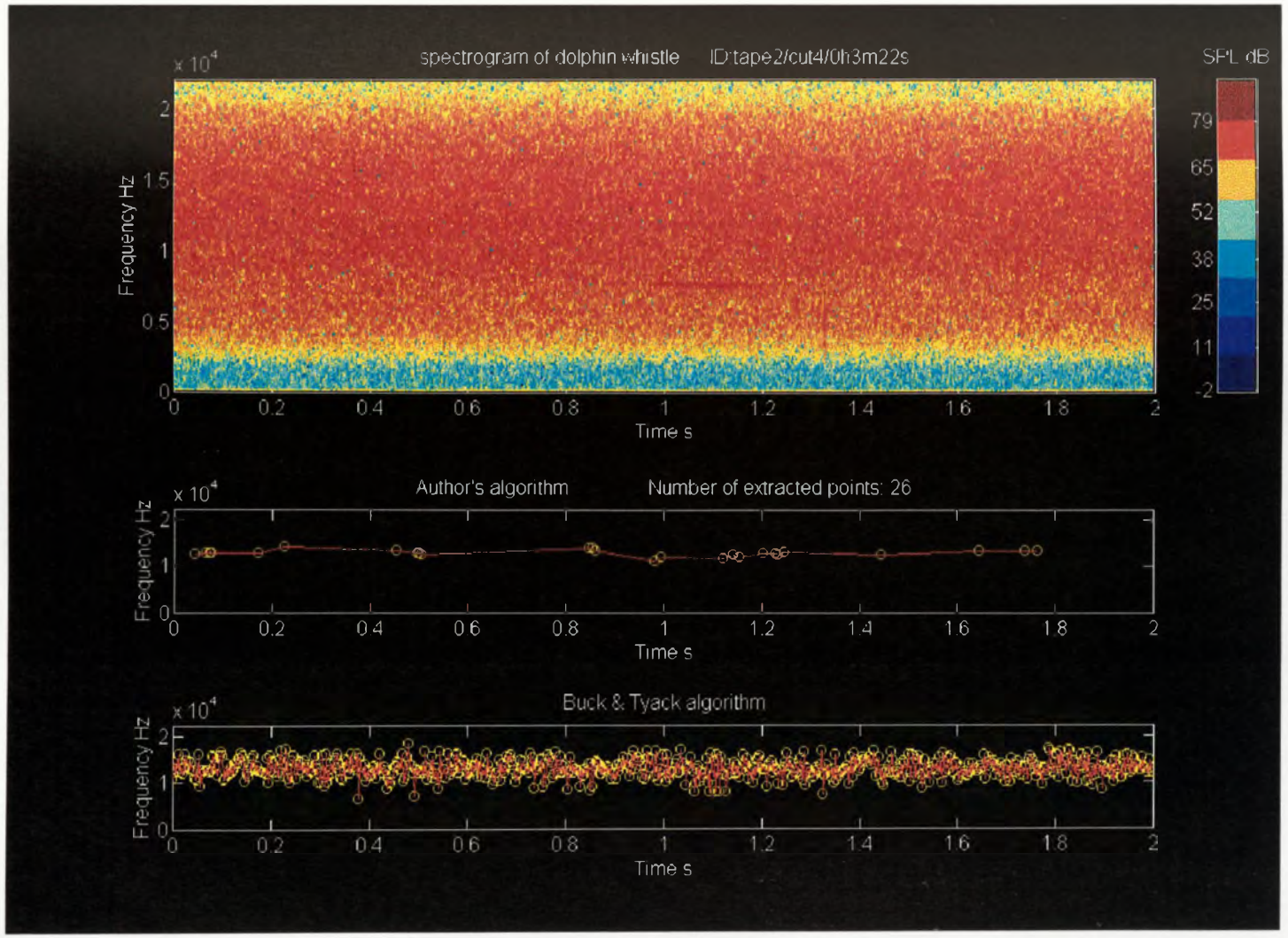


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut1/0h1m4s
Date:	7/6/94
Time:	22:46
Location:	Ligurian Sea
Longitude:	43.5405
Latitude:	7.6455

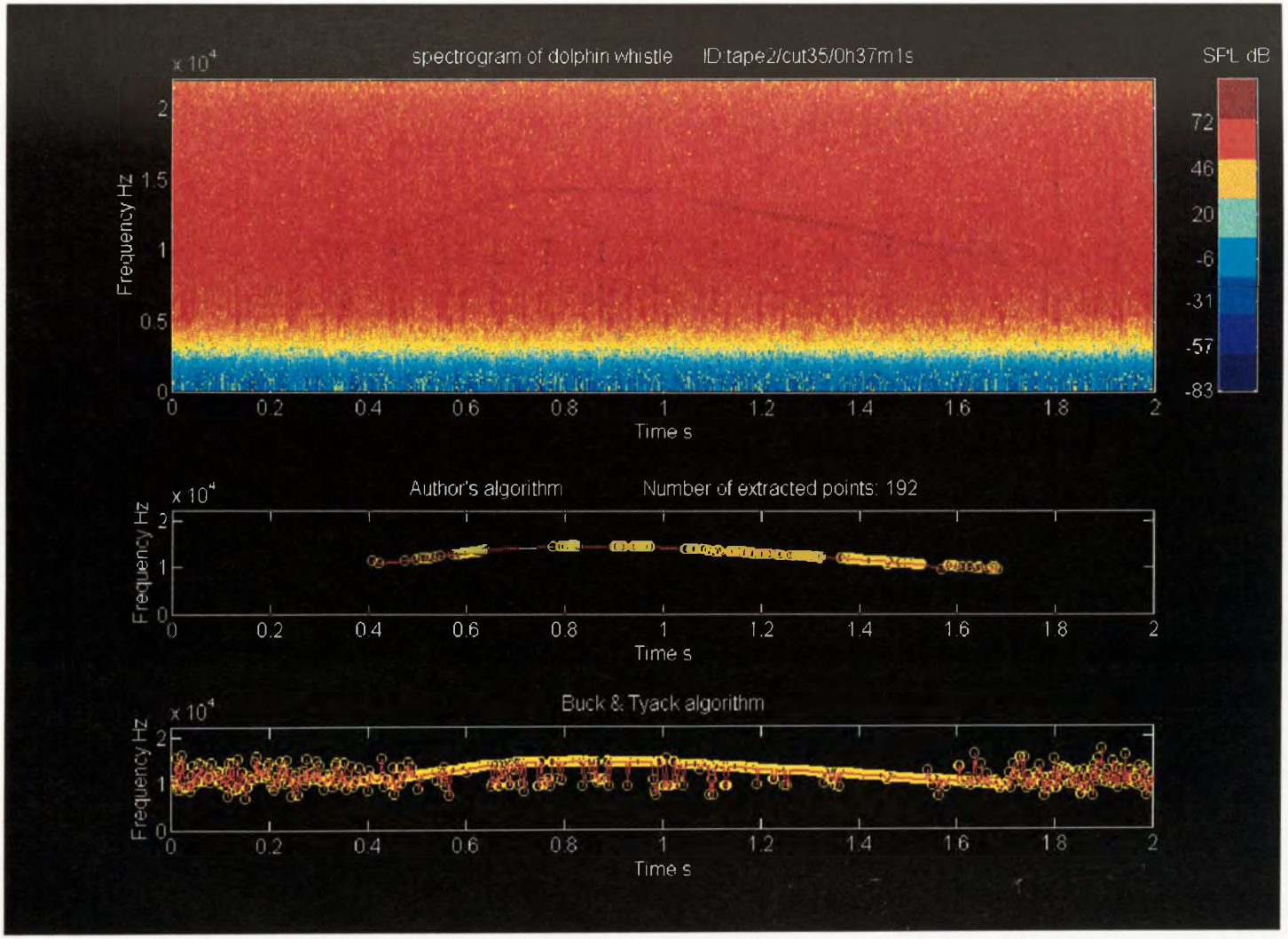


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut4/0h3m22s
Date:	7/6/94
Time:	23:30
Location:	Ligurian Sea
Longitude:	43.5288
Latitude:	7.7303

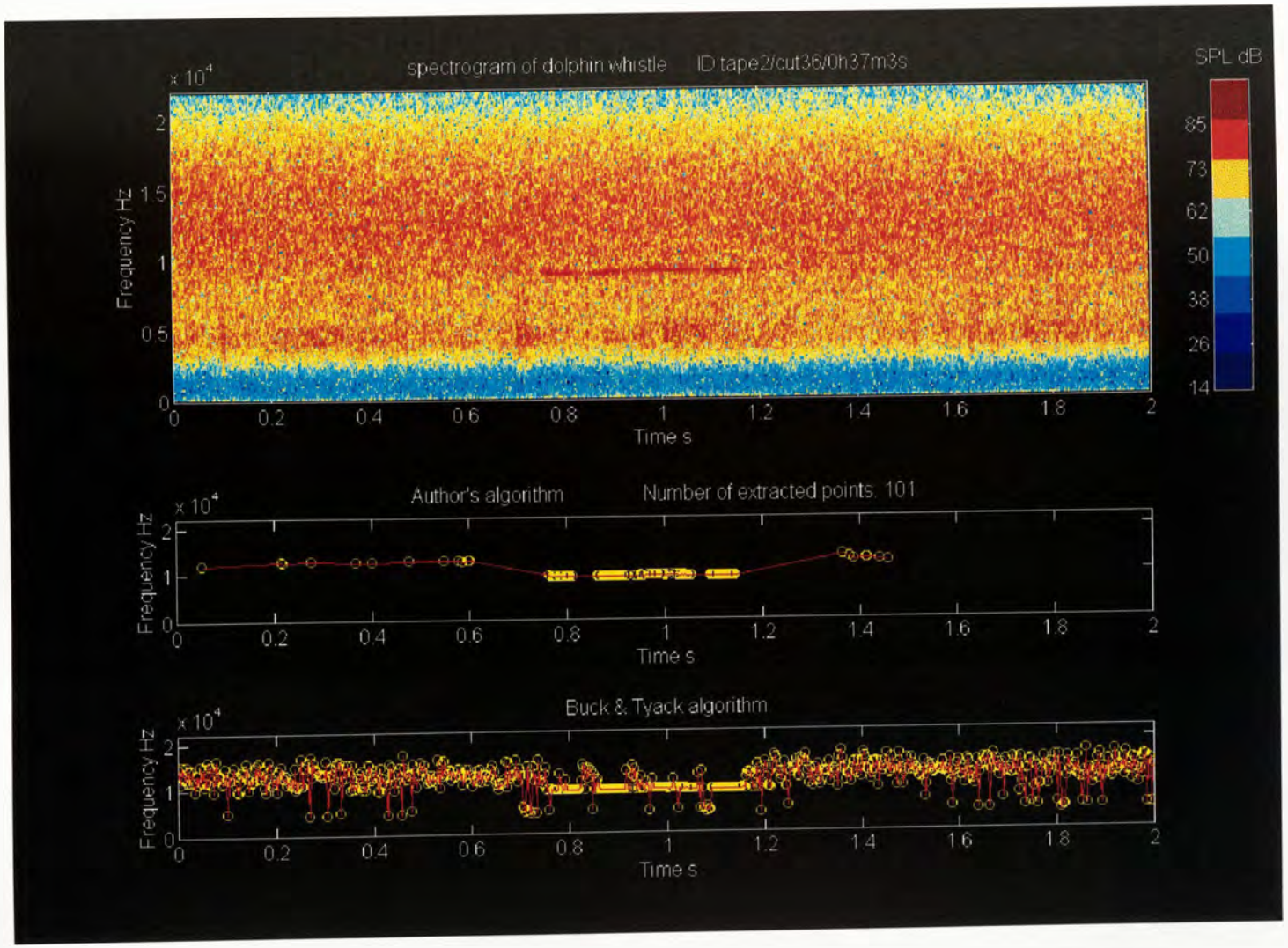


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut35/0h37m1s
Date:	8/6/94
Time:	07:30
Location:	Ligurian Sea
Longitude:	43.4168
Latitude:	7.7563

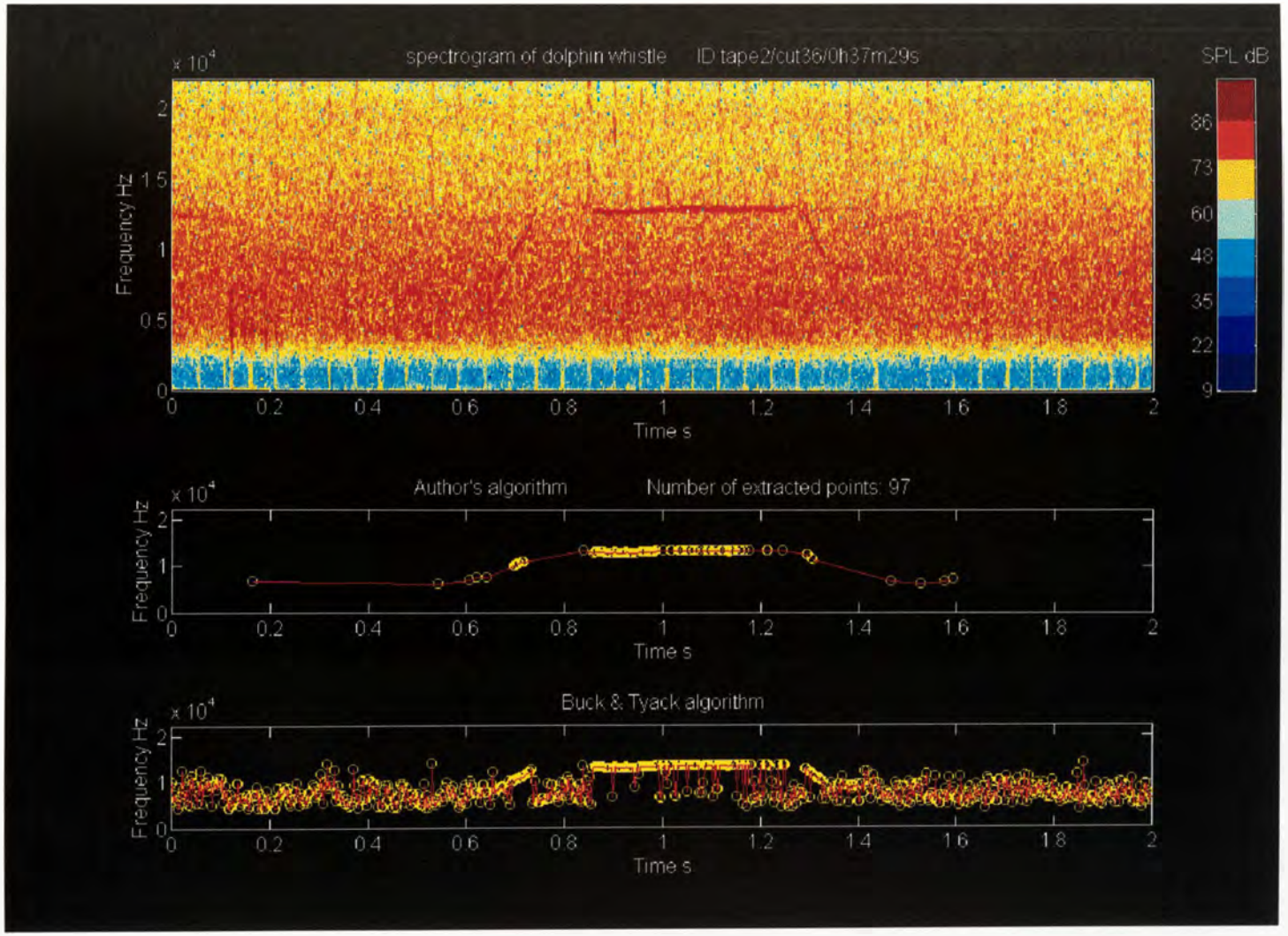


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut36/0h37m3s
Date:	8/6/94
Time:	07:47
Location:	Ligurian Sea
Longitude:	43.4093
Latitude:	7.7928

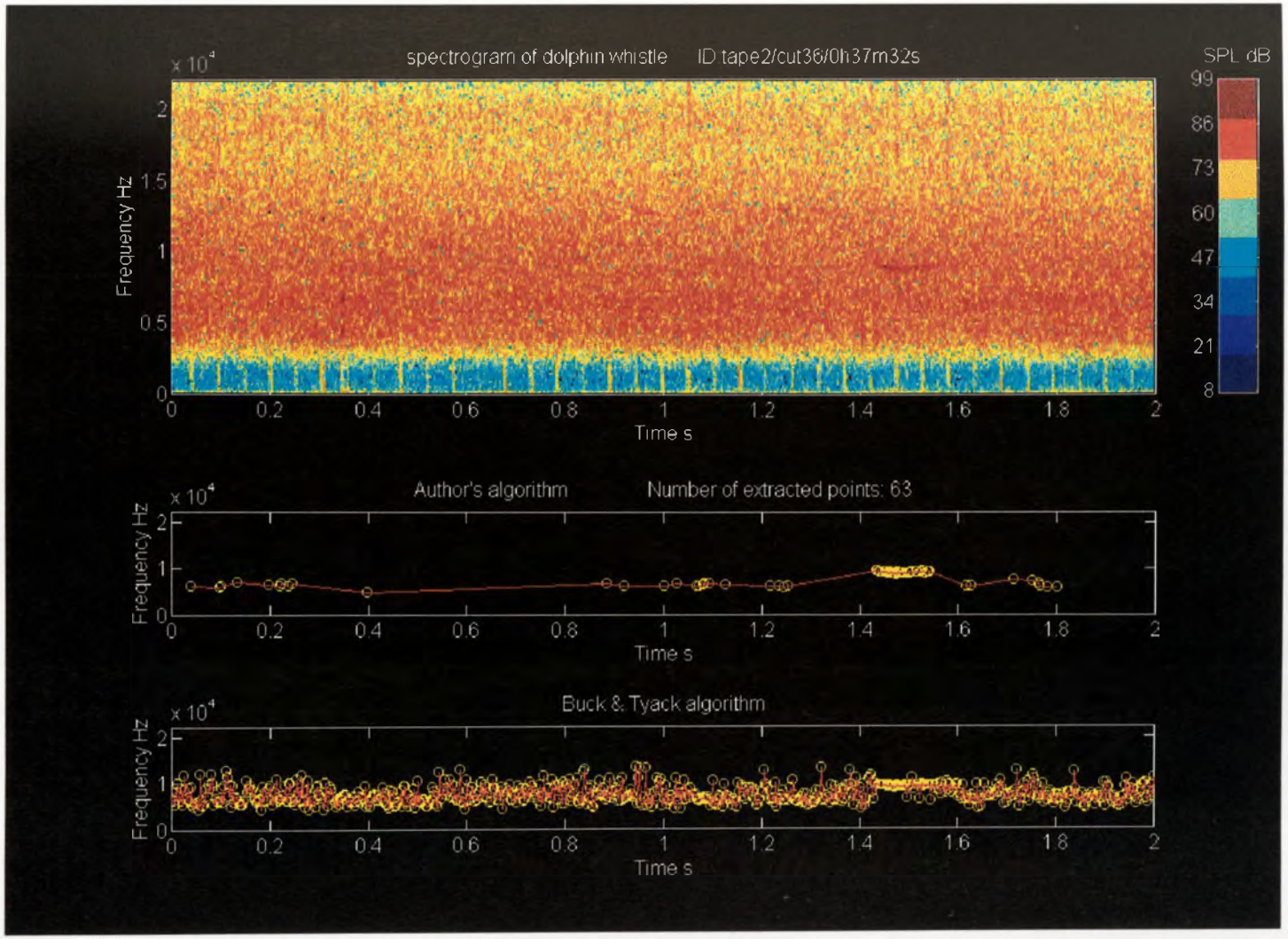


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut36/0h37m29s
Date:	8/6/94
Time:	07:47
Location:	Ligurian Sea
Longitude:	43.4093
Latitude:	7.7928



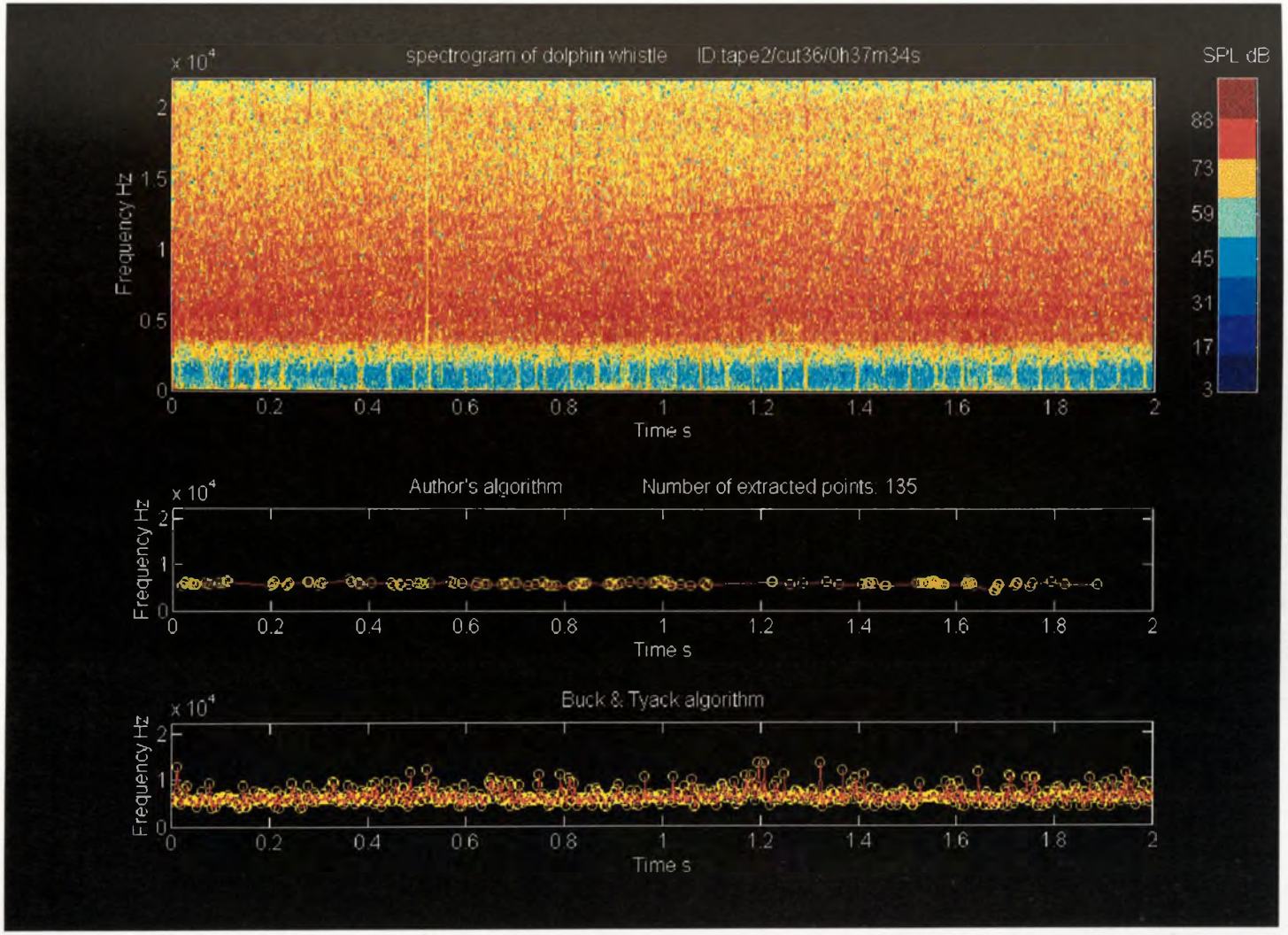
Legend

extracted points

extracted whistle contour

Recording details

ID:	tape2/cut36/0h37m32s
Date:	8/6/94
Time:	07:47
Location:	Ligurian Sea
Longitude:	43.4093
Latitude:	7.7928

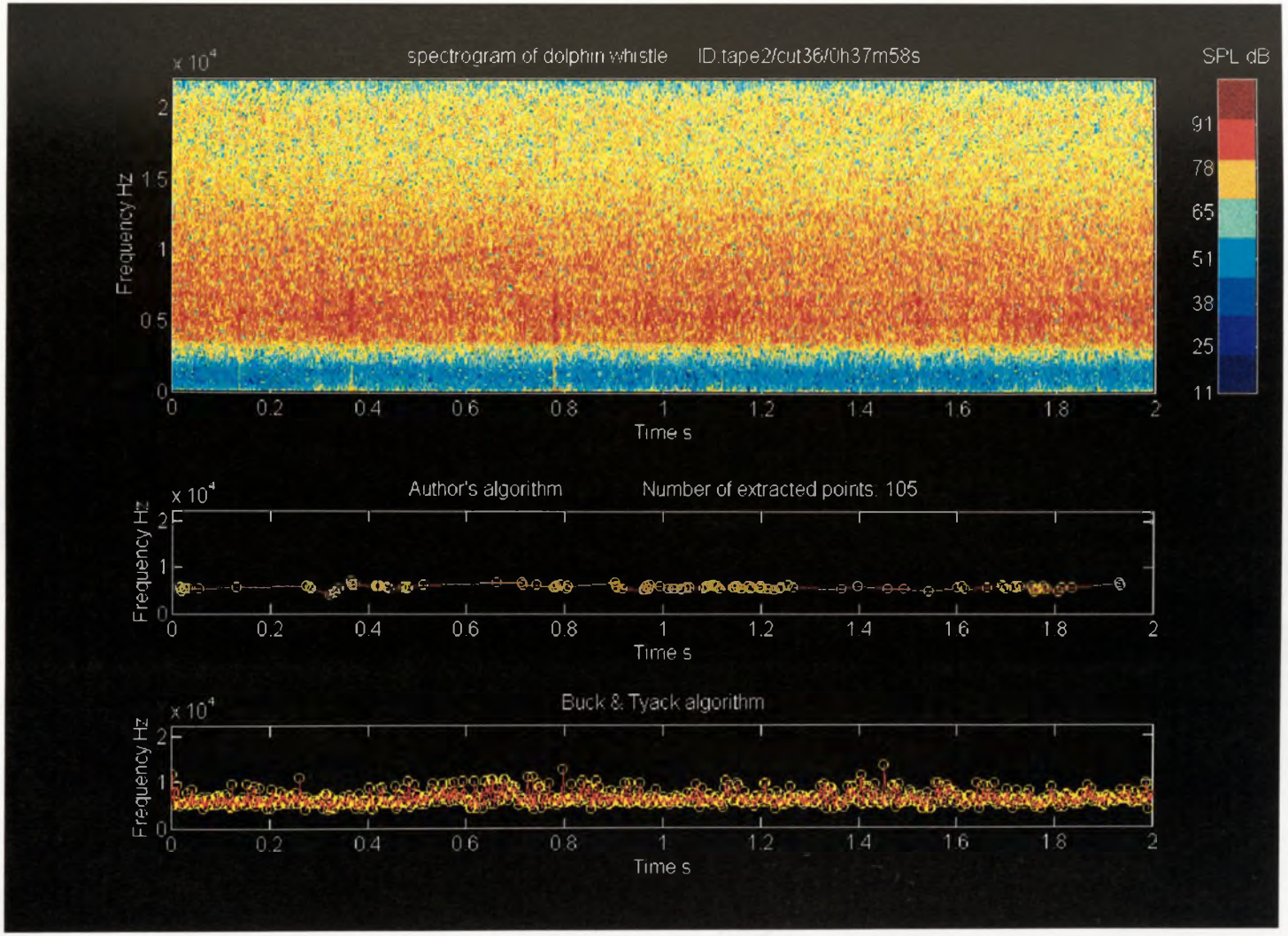


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut36/0h37m34s
Date:	8/6/94
Time:	07:47
Location:	Ligurian Sea
Longitude:	43.4093
Latitude:	7.7928



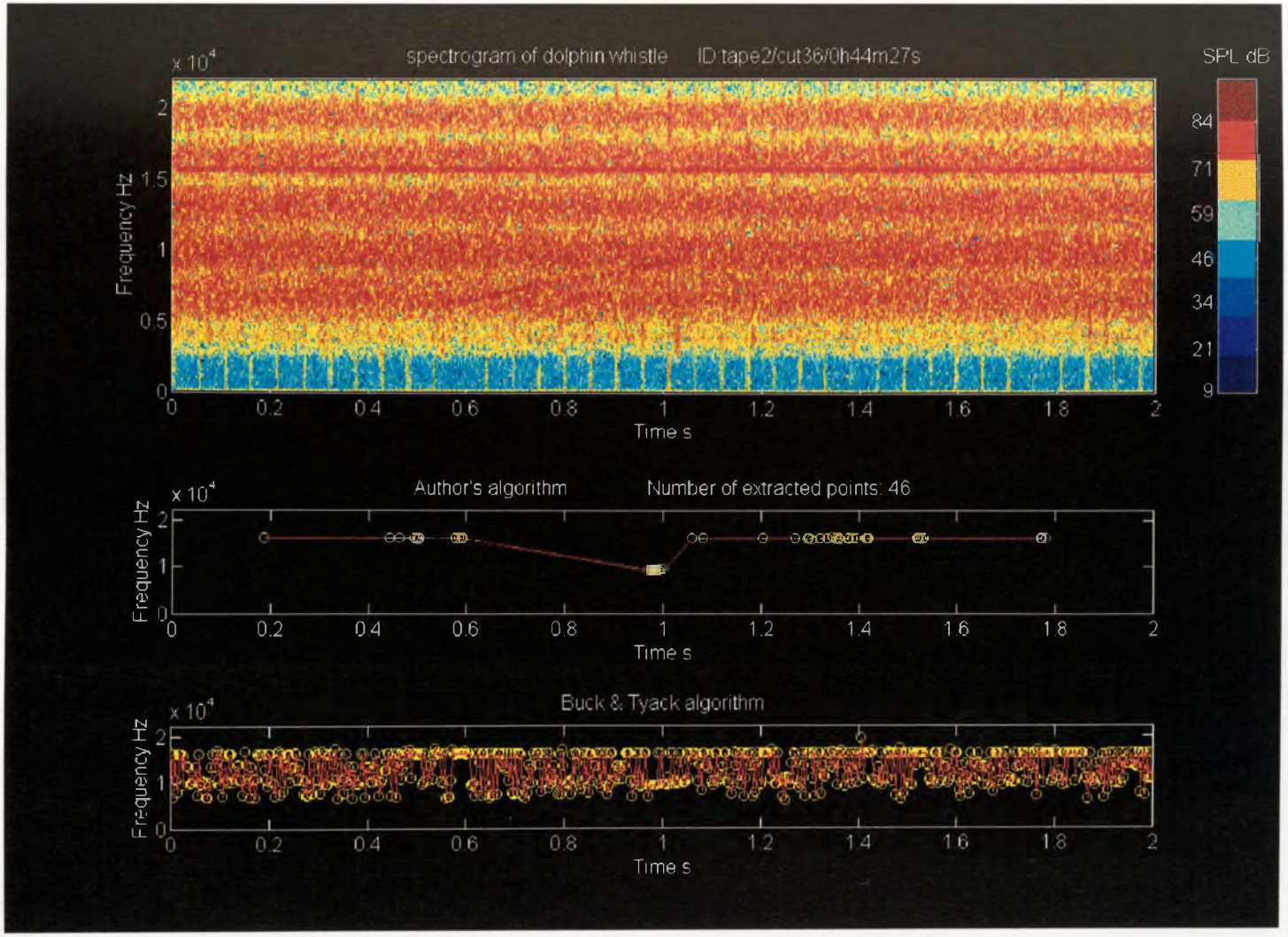
Legend

extracted points

extracted whistle contour

Recording details

ID:	tape2/cut36/0h37m58s
Date:	8/6/94
Time:	07:47
Location:	Ligurian Sea
Longitude:	43.4093
Latitude:	7.7928

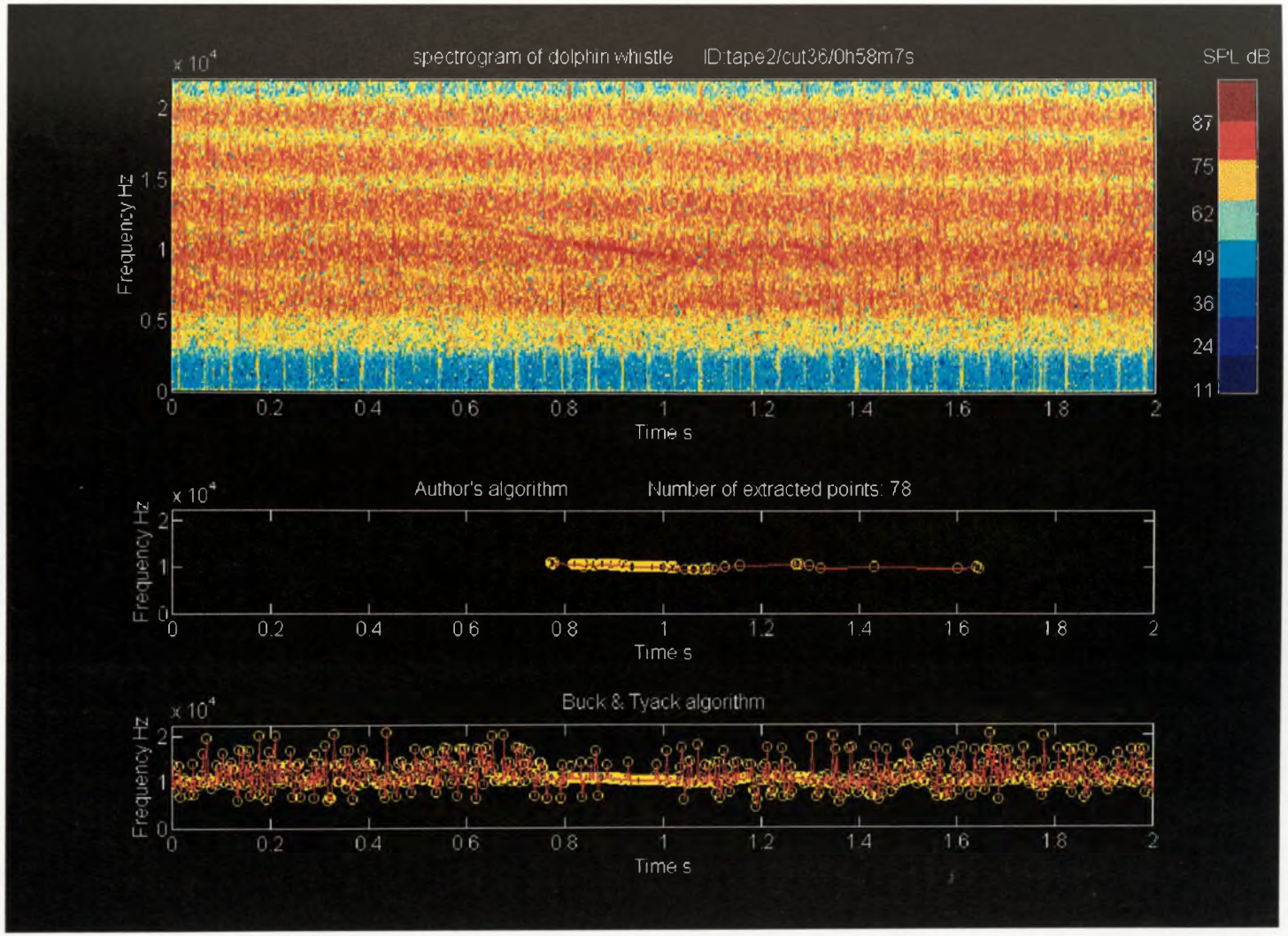


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut36/0h44m27s
Date:	8/6/94
Time:	09:31
Location:	Ligurian Sea
Longitude:	43.3845
Latitude:	7.9877

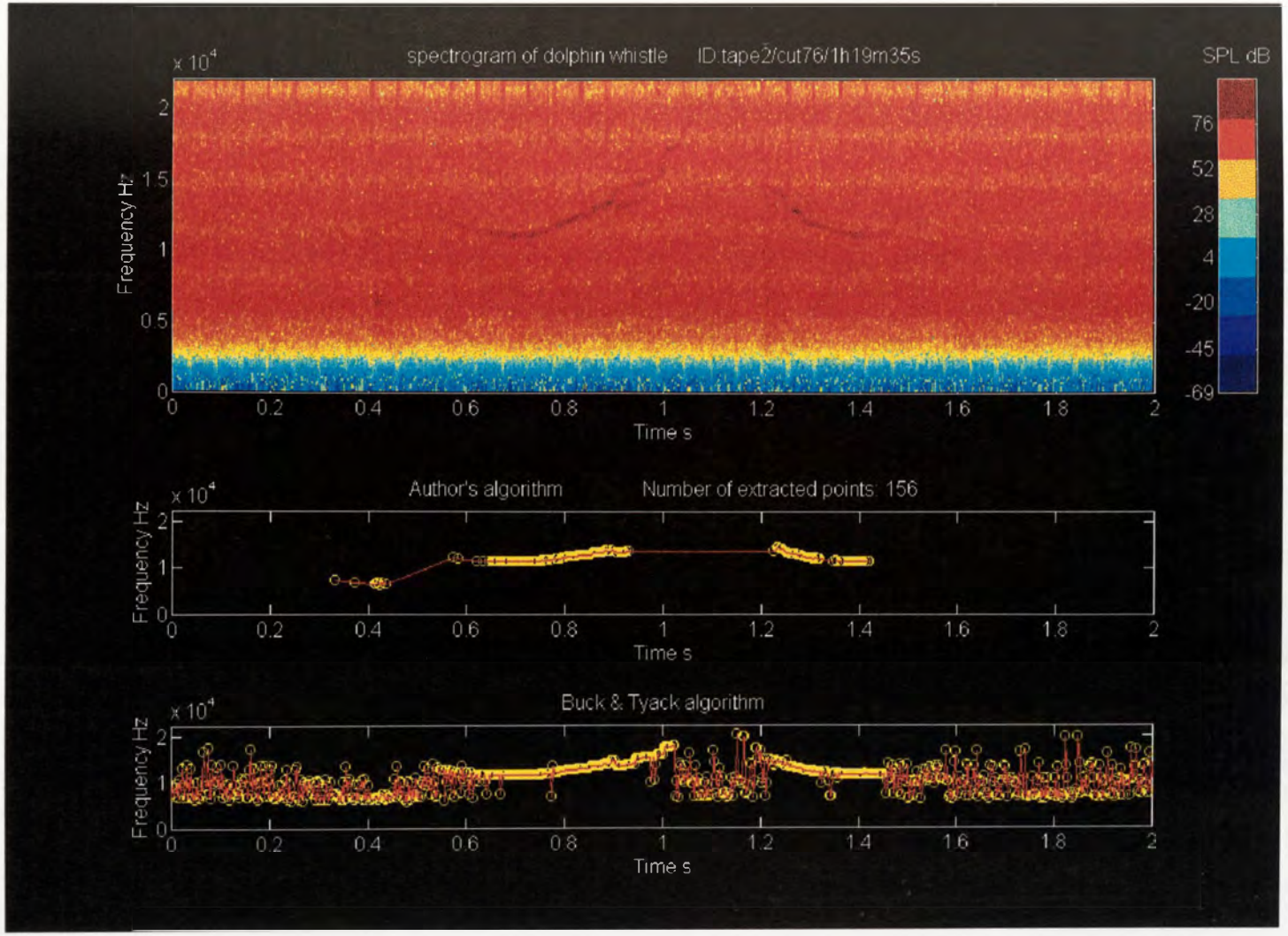


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut55/0h58m7s
Date:	8/6/94
Time:	14:01
Location:	Ligurian Sea
Longitude:	43.2970
Latitude:	9.2873

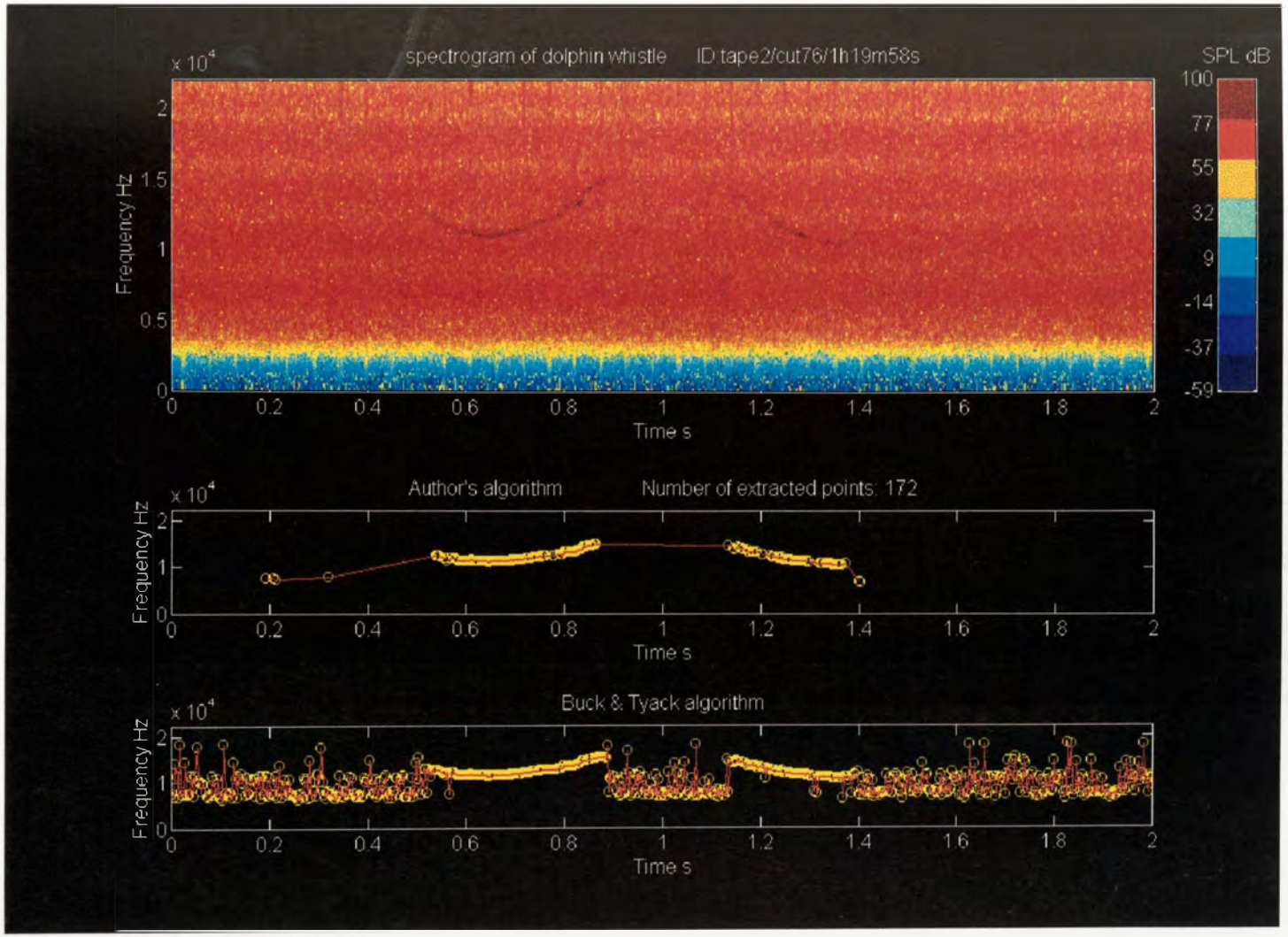


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut76/1h19m35s
Date:	8/6/94
Time:	19:30
Location:	Ligurian Sea
Longitude:	43.0543
Latitude:	9.0713

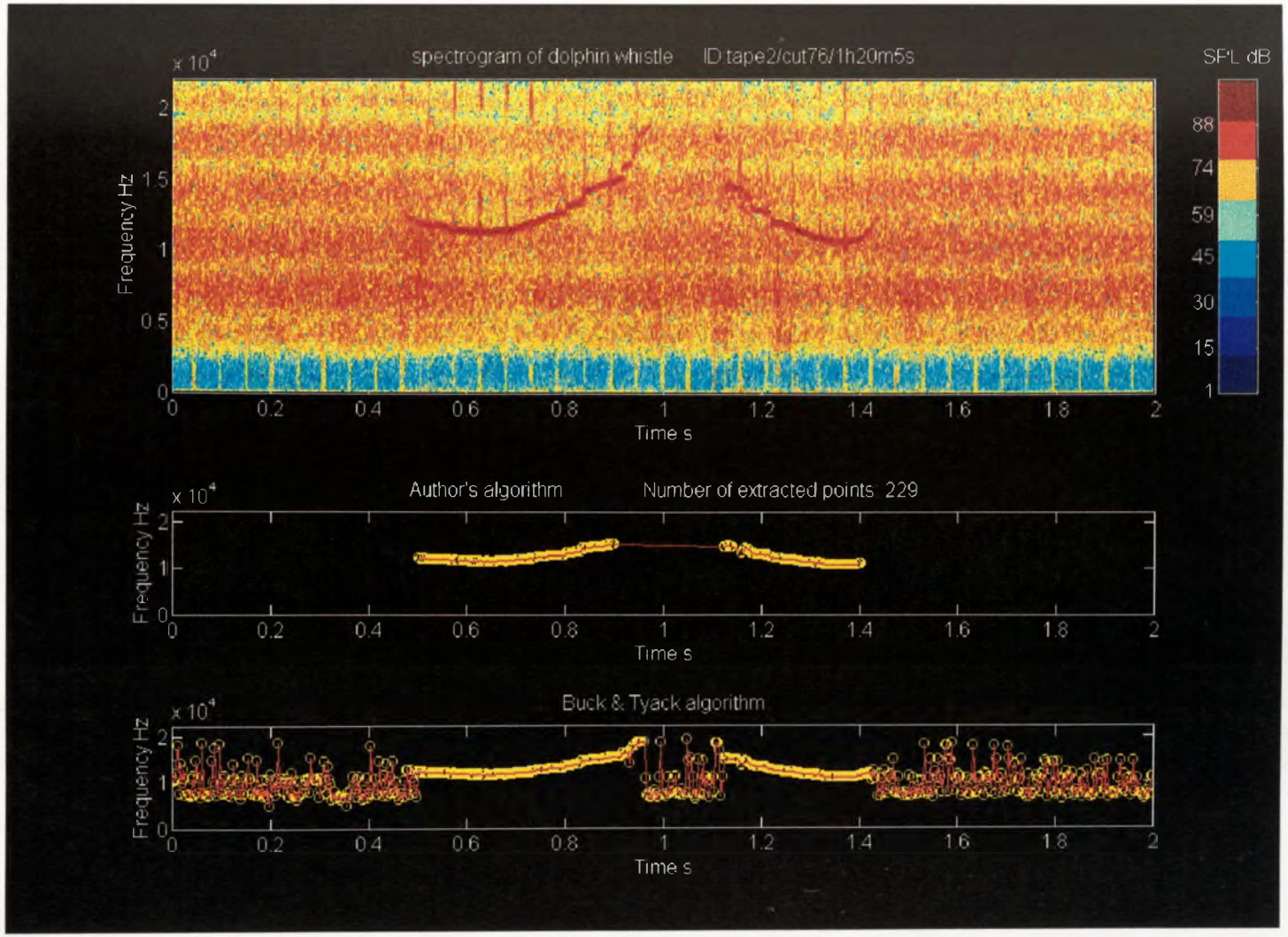


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut76/1h19m58s
Date:	8/6/94
Time:	19:30
Location:	Ligurian Sea
Longitude:	43.0543
Latitude:	9.0713

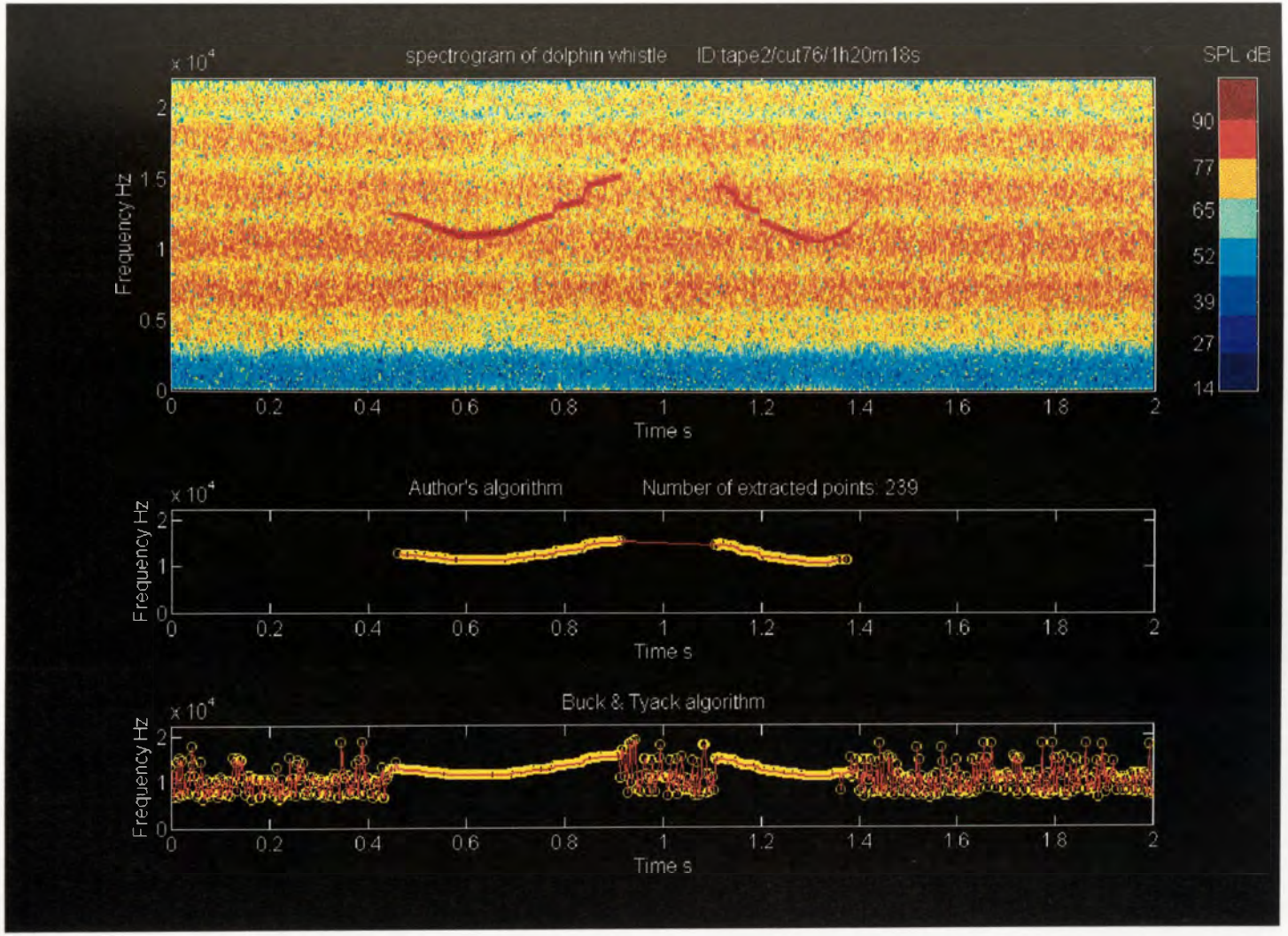


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut76/1h20m5s
Date:	8/6/94
Time:	19:30
Location:	Ligurian Sea
Longitude:	43.0543
Latitude:	9.0713



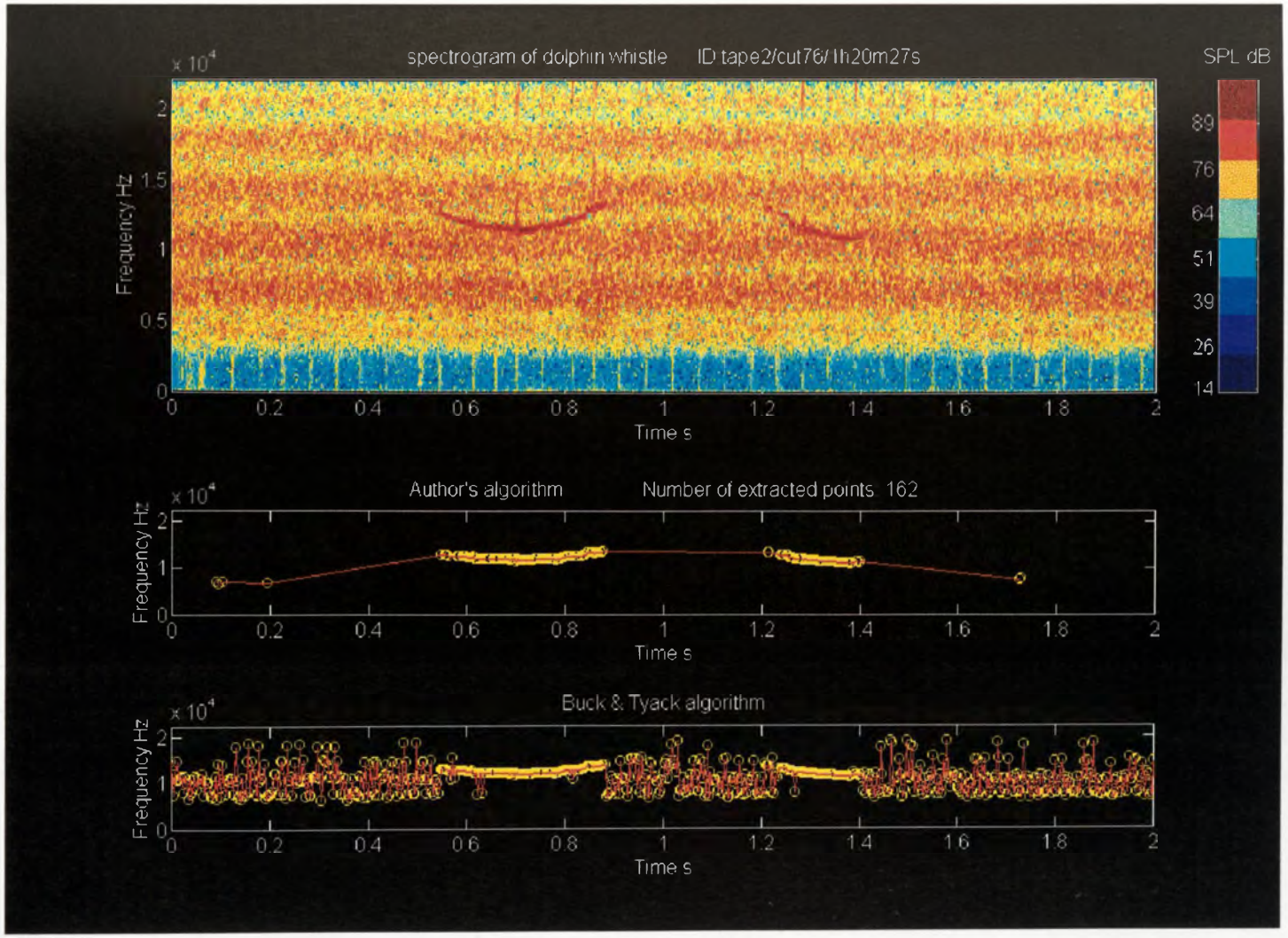
Legend

extracted points

extracted whistle contour

Recording details

ID:	tape2/cut76/1h20m18s
Date:	8/6/94
Time:	19:30
Location:	Ligurian Sea
Longitude:	43.0543
Latitude:	9.0713

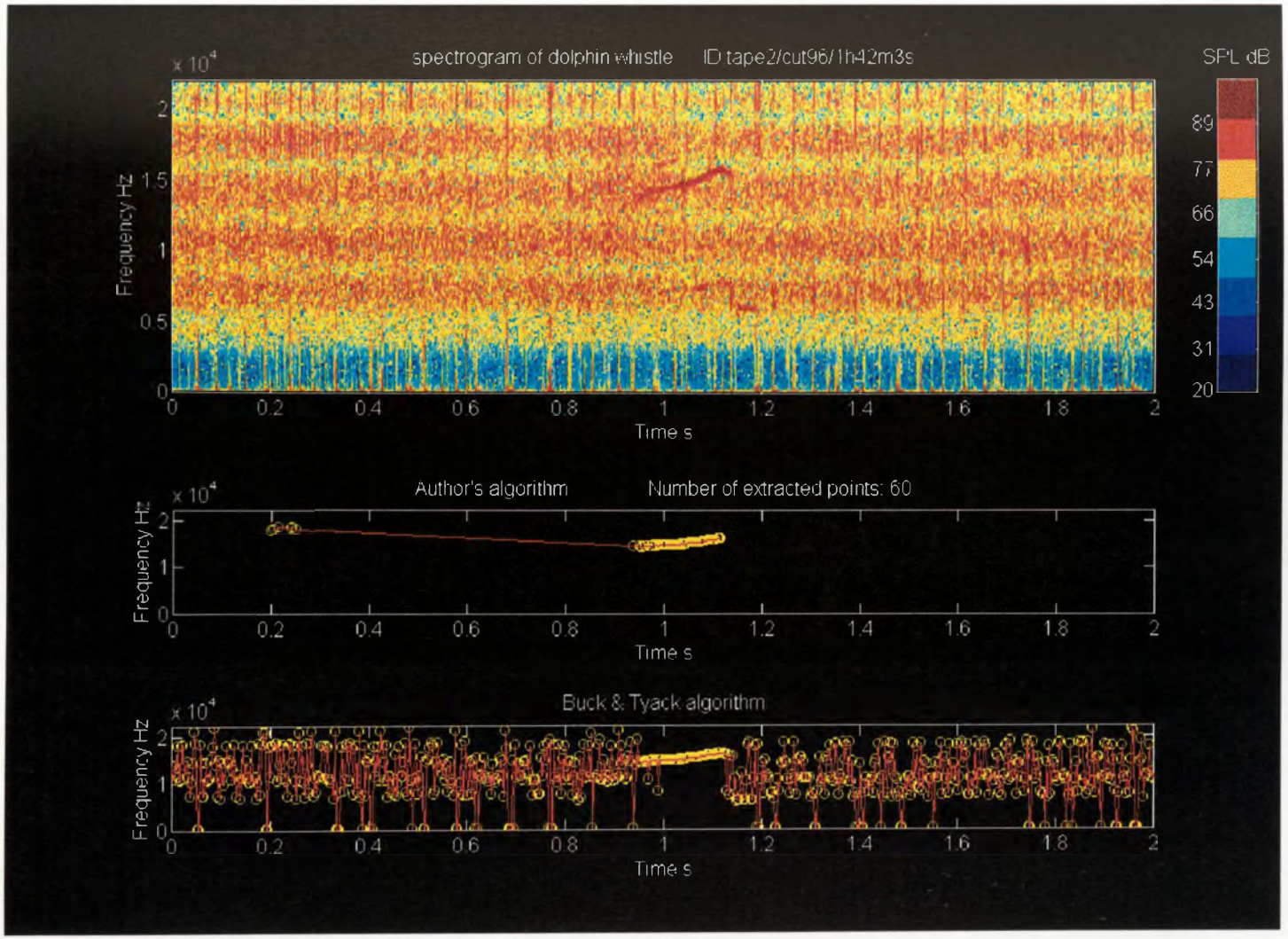


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut76/1h20m27s
Date:	8/6/94
Time:	19:30
Location:	Ligurian Sea
Longitude:	43.0543
Latitude:	9.0713

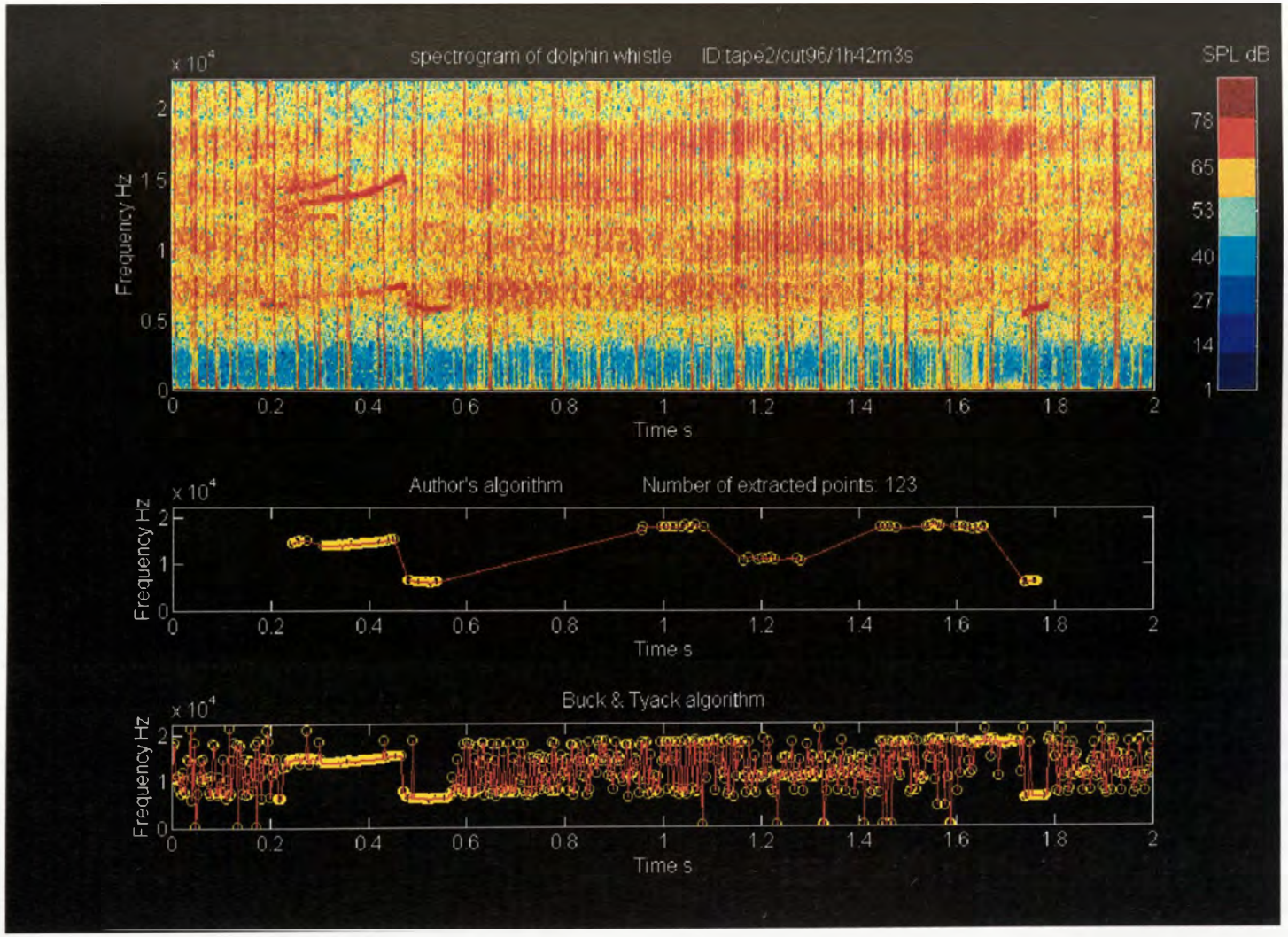


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut96/1h42m3s
Date:	9/6/94
Time:	00:45
Location:	Ligurian Sea
Longitude:	42.8920
Latitude:	9.8002

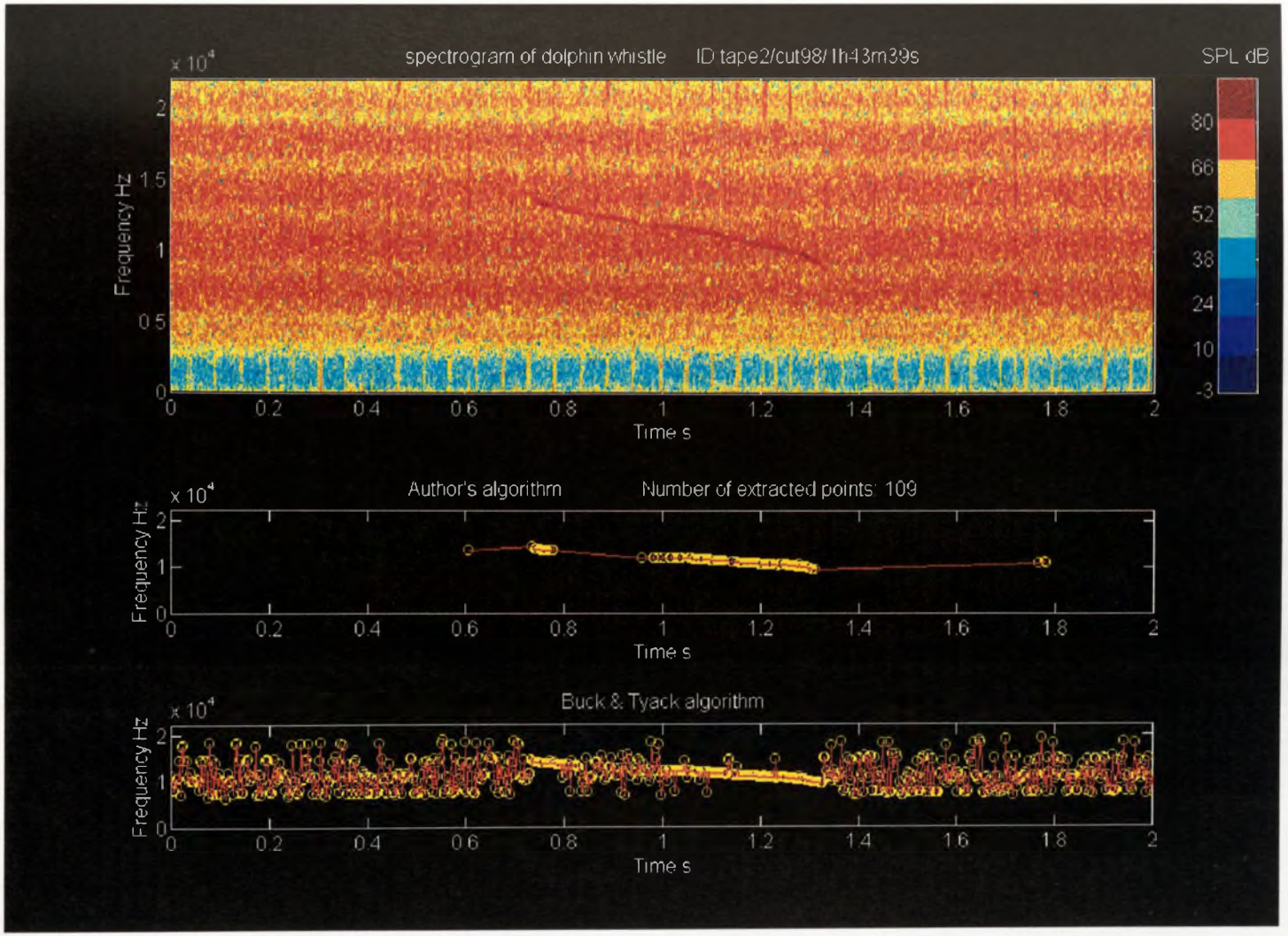


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut96/1h42m18s
Date:	9/6/94
Time:	00:45
Location:	Ligurian Sea
Longitude:	42.8920
Latitude:	9.8002

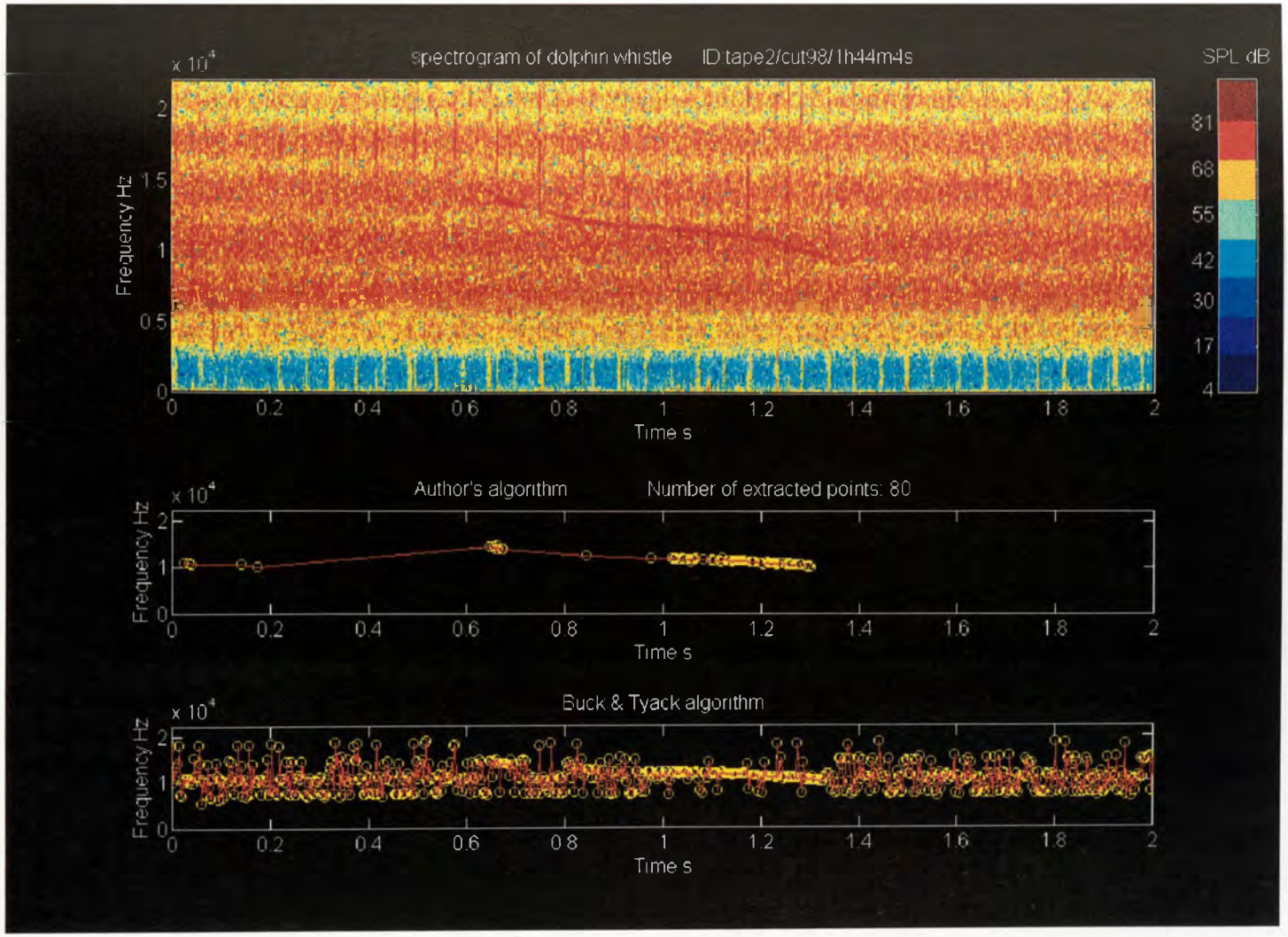


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut98/1h43m39s
Date:	9/6/94
Time:	01:15
Location:	Ligurian Sea
Longitude:	42.8698
Latitude:	8.8437



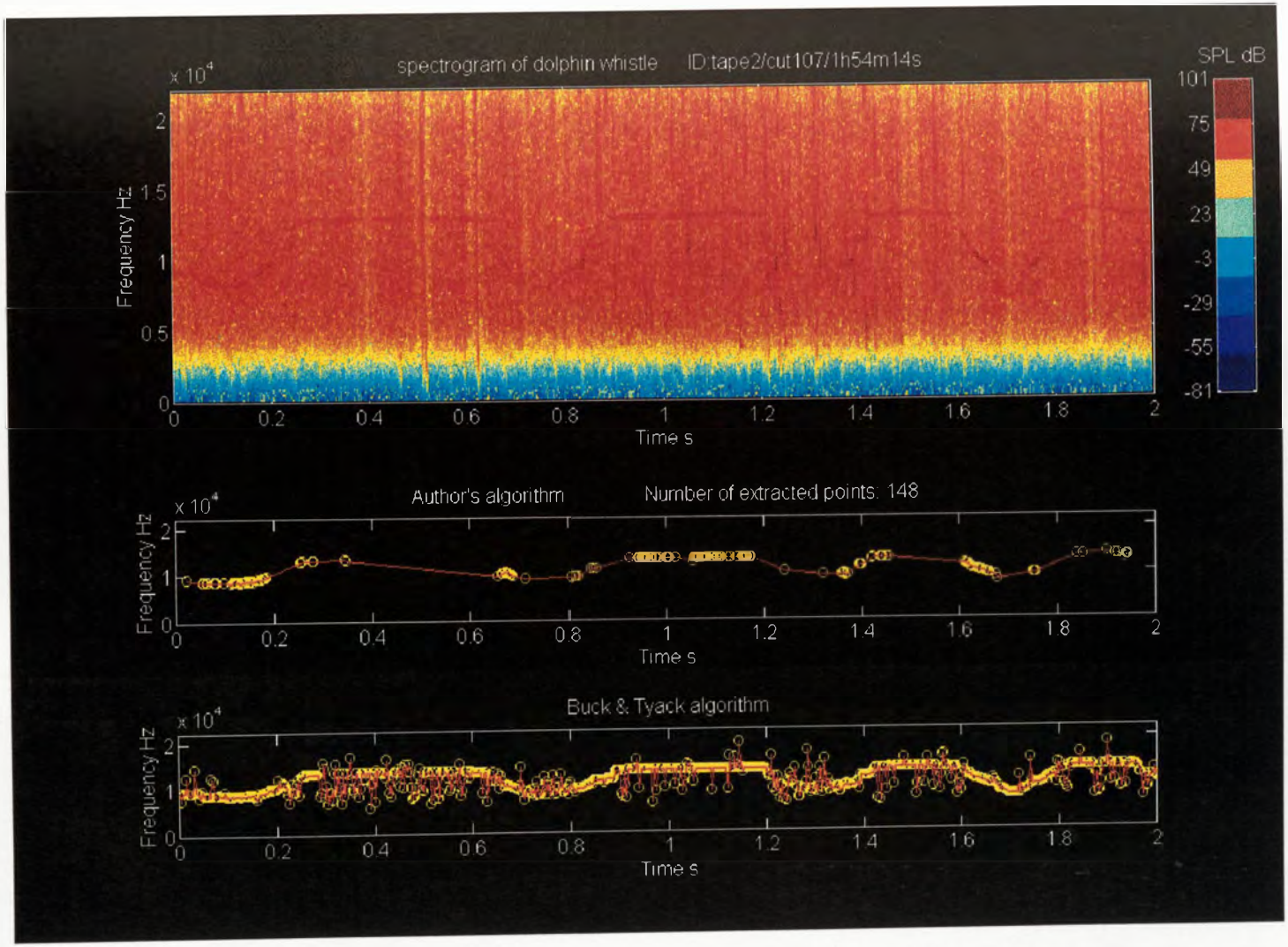
Legend

extracted points

extracted whistle contour

Recording details

ID:	tape2/cut98/1h44m4s
Date:	9/6/94
Time:	01:15
Location:	Ligurian Sea
Longitude:	42.8698
Latitude:	8.8437

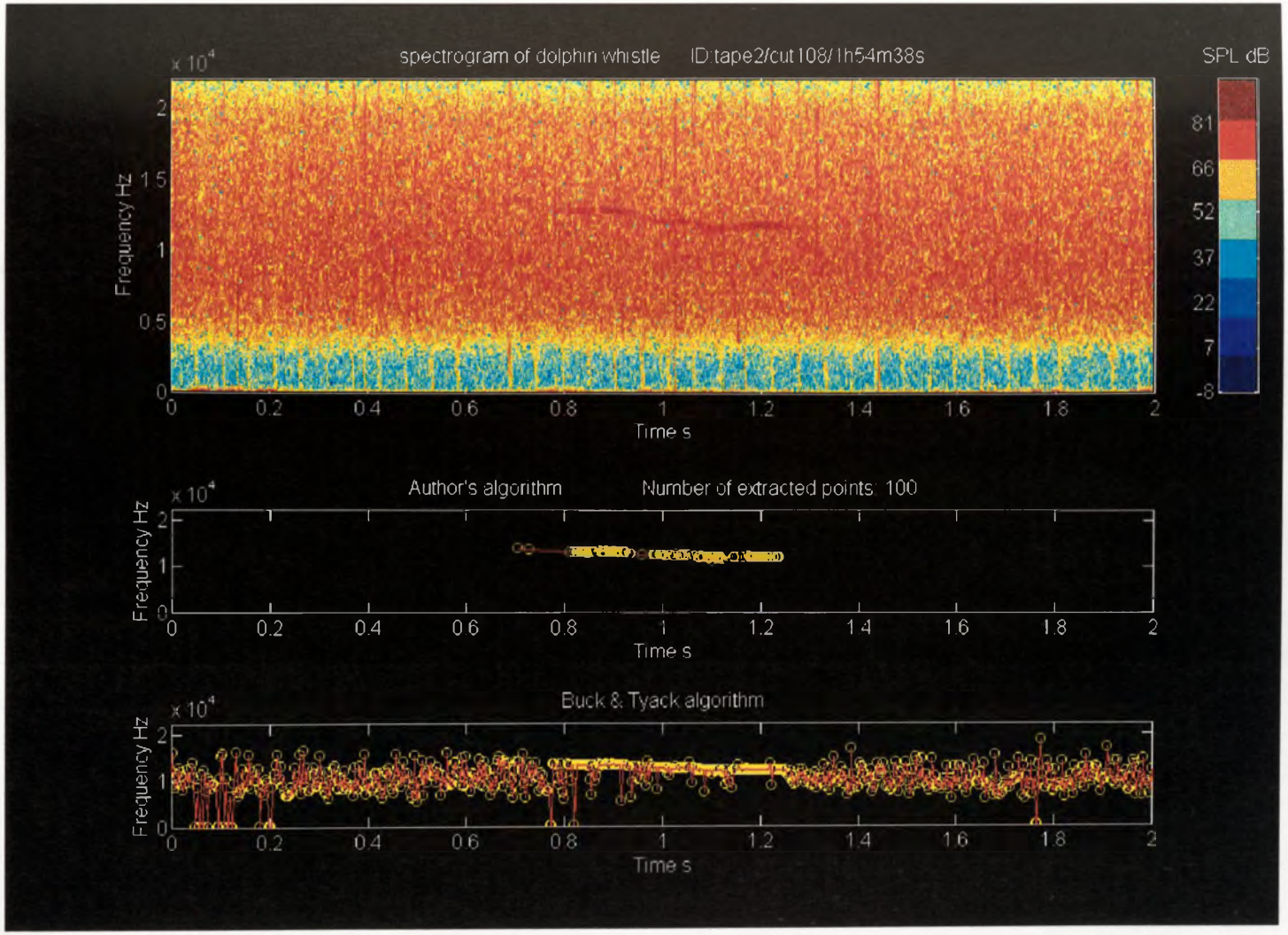


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut107/1h54m14s
Date:	9/6/94
Time:	03:30
Location:	Ligurian Sea
Longitude:	42.7422
Latitude:	9.0203

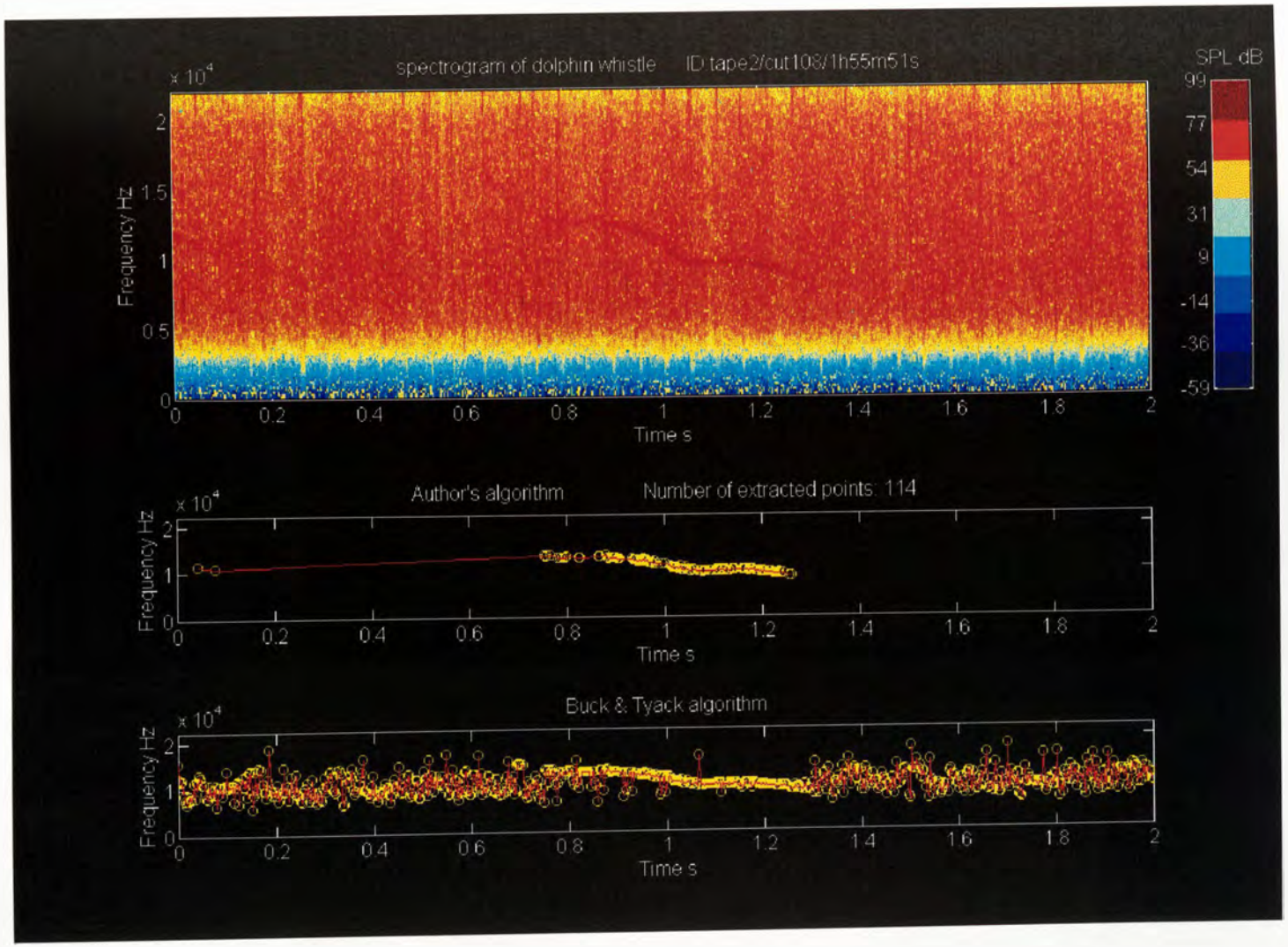


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut108/1h54m38s
Date:	9/6/94
Time:	03:44
Location:	Ligurian Sea
Longitude:	42.7360
Latitude:	9.0378

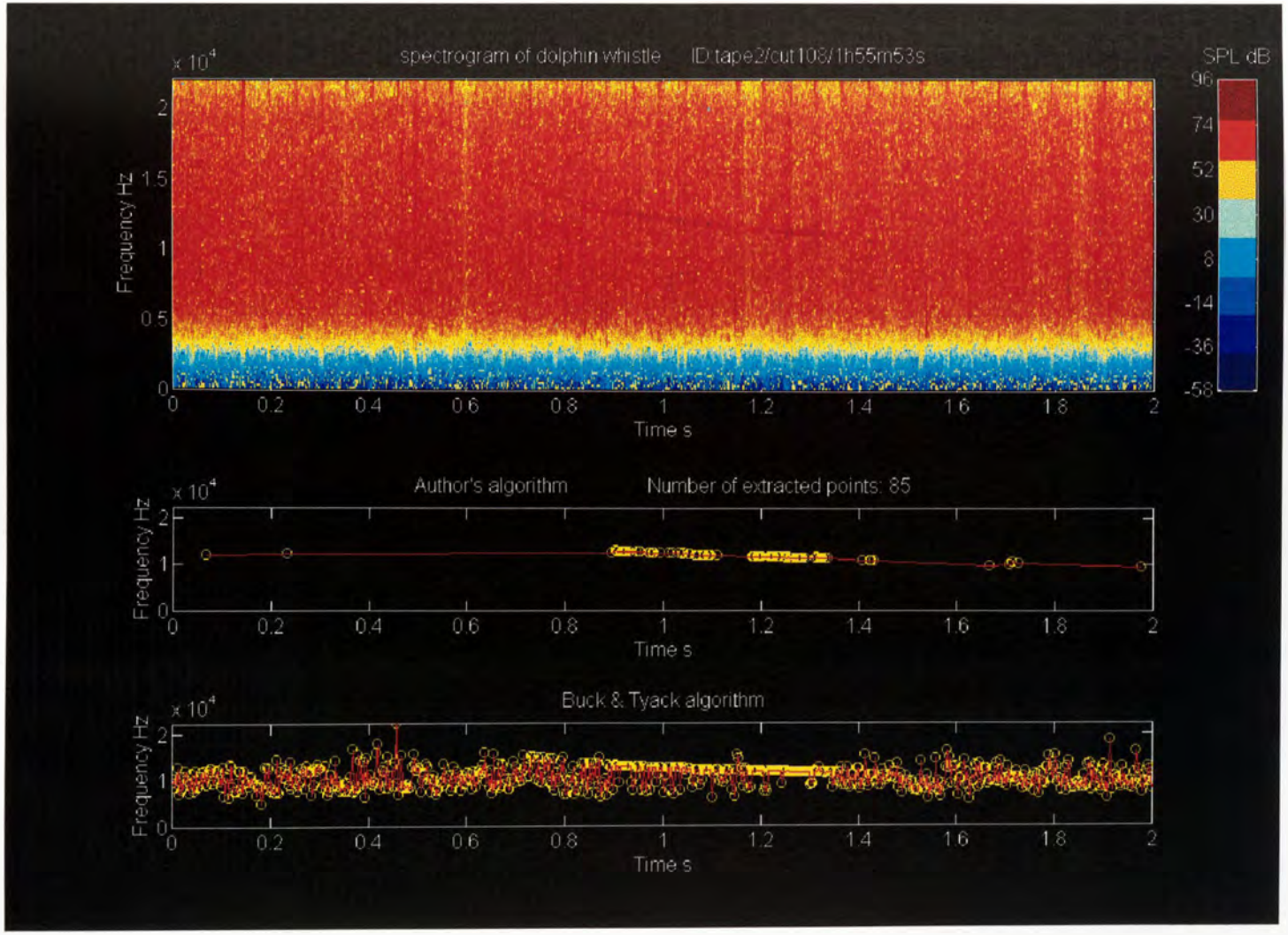


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut108/1h55m51s
Date:	9/6/94
Time:	03:44
Location:	Ligurian Sea
Longitude:	42.7360
Latitude:	9.0378

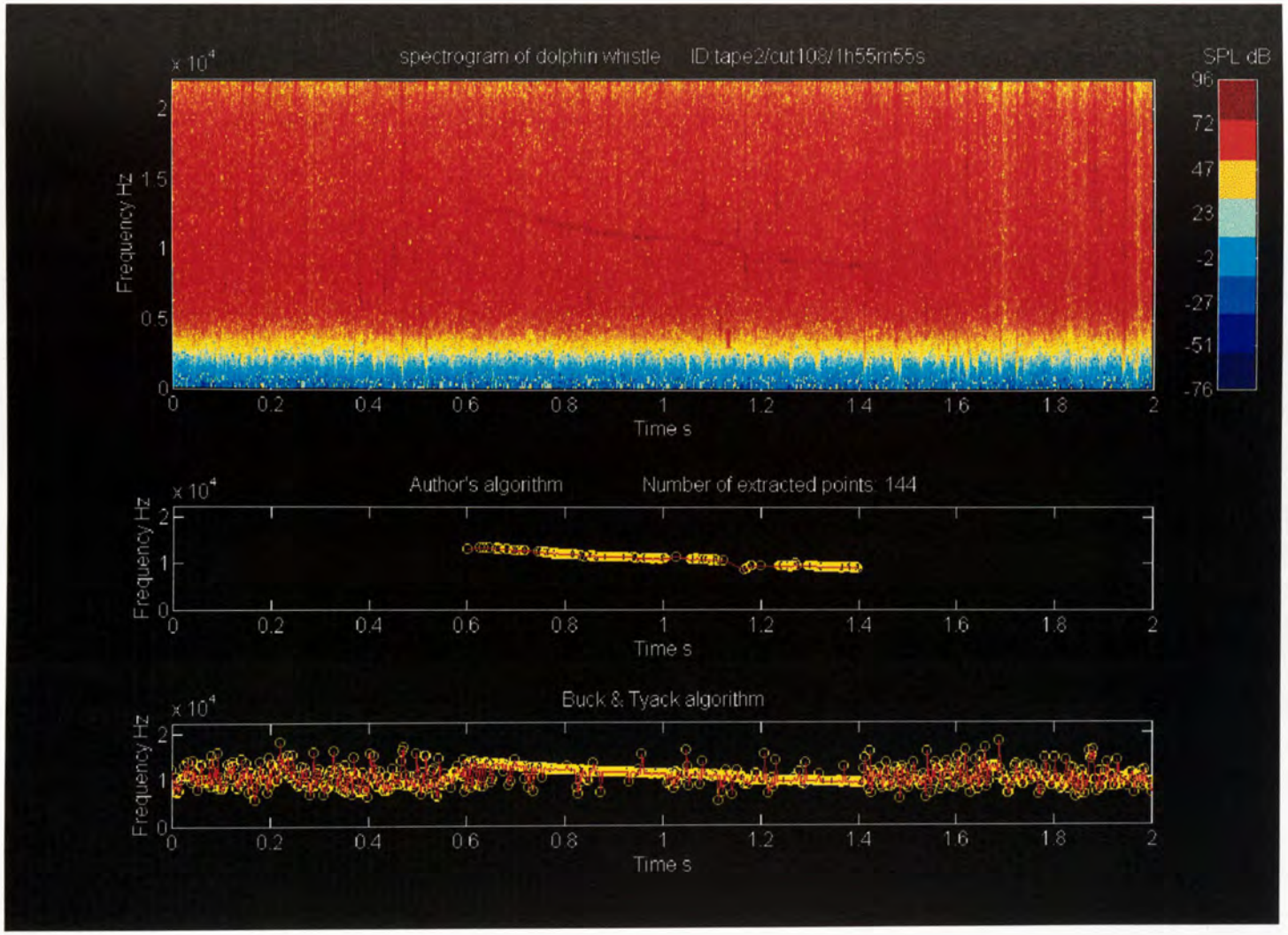


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut108/1h55m53s
Date:	9/6/94
Time:	03:44
Location:	Ligurian Sea
Longitude:	42.7360
Latitude:	9.0378

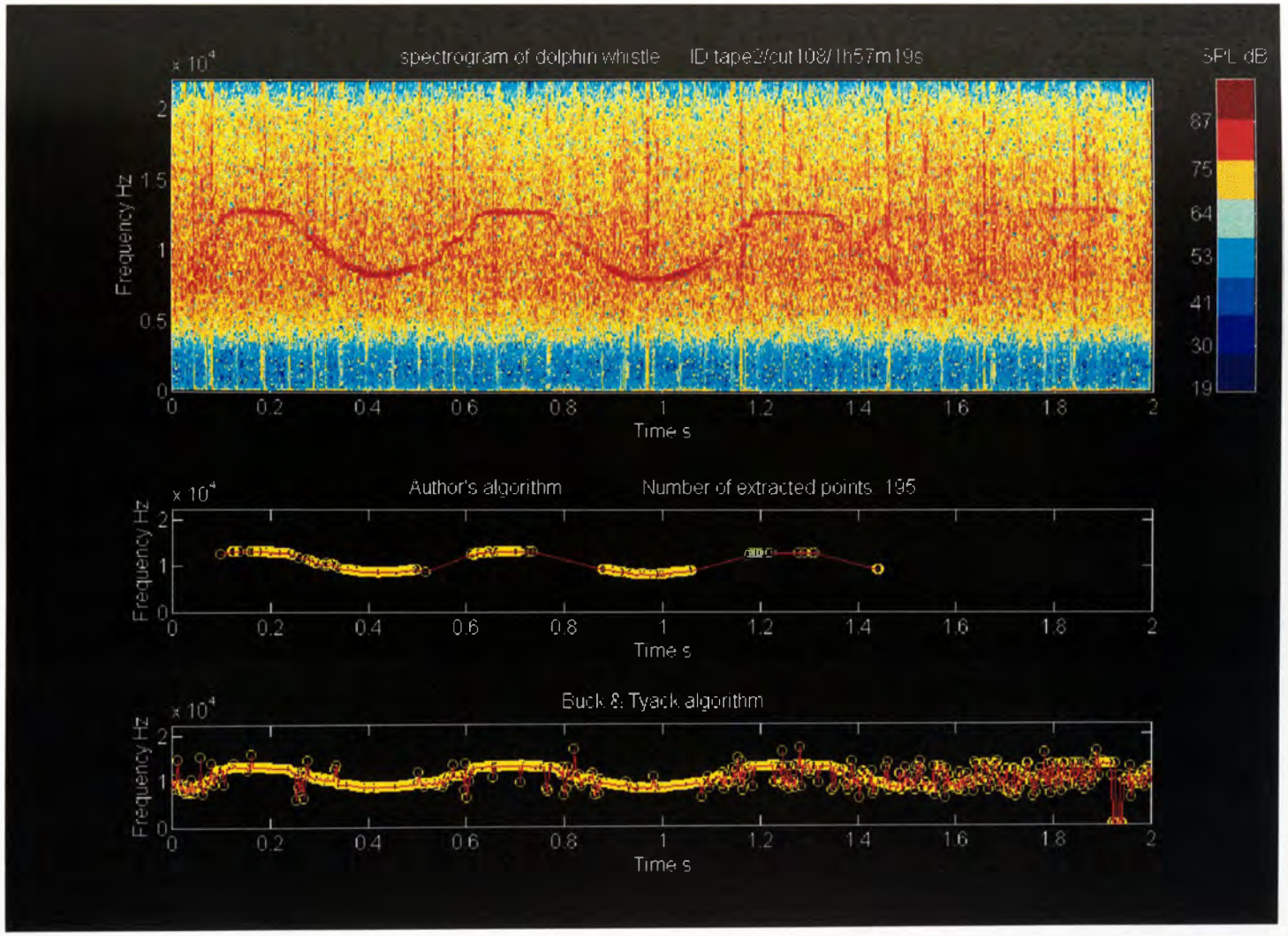


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut108/1h55m55s
Date:	9/6/94
Time:	03:44
Location:	Ligurian Sea
Longitude:	42.7360
Latitude:	9.0378

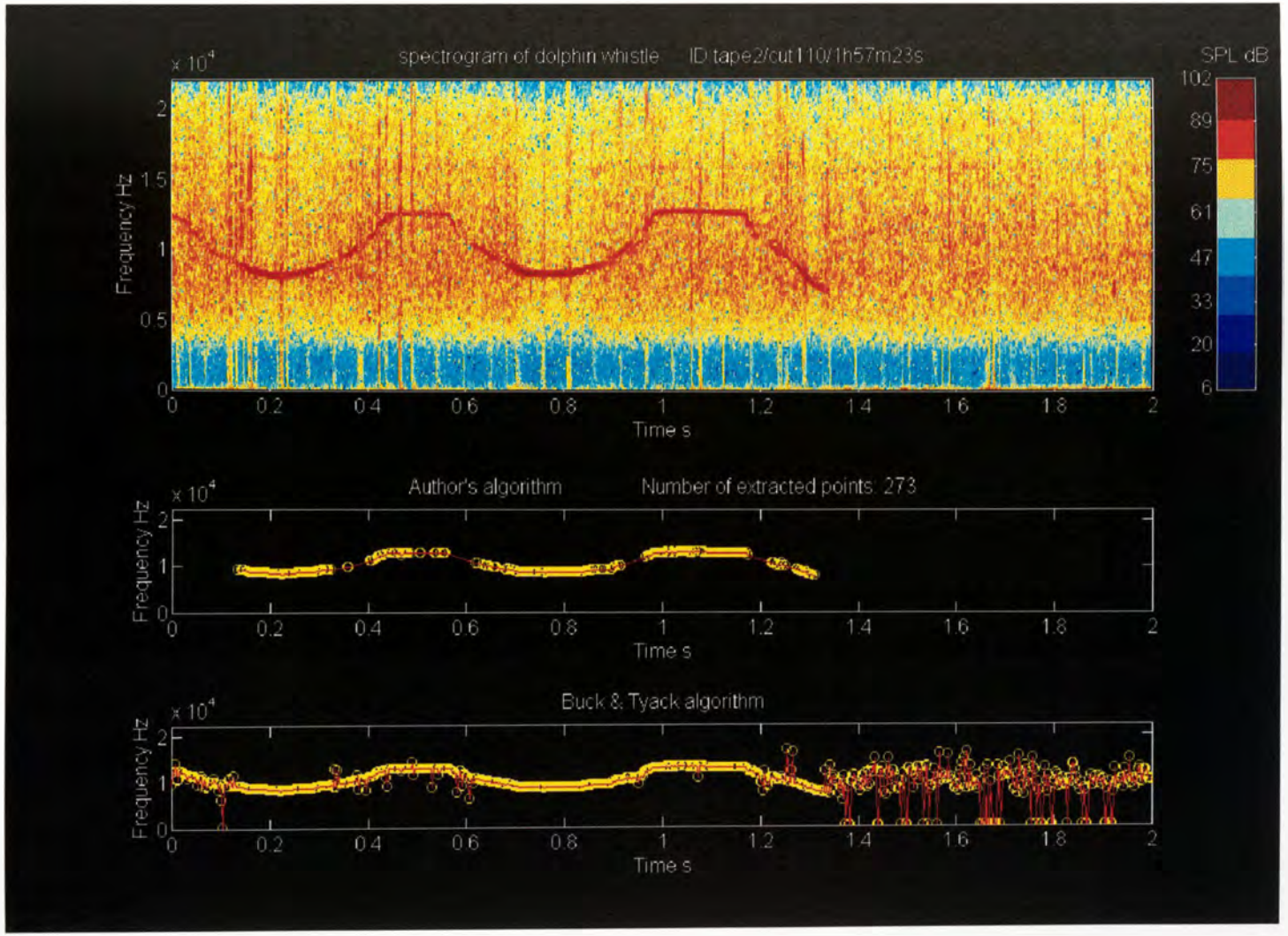


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut110/1h57m19s
Date:	9/6/94
Time:	04:15
Location:	Ligurian Sea
Longitude:	42.7305
Latitude:	8.9970

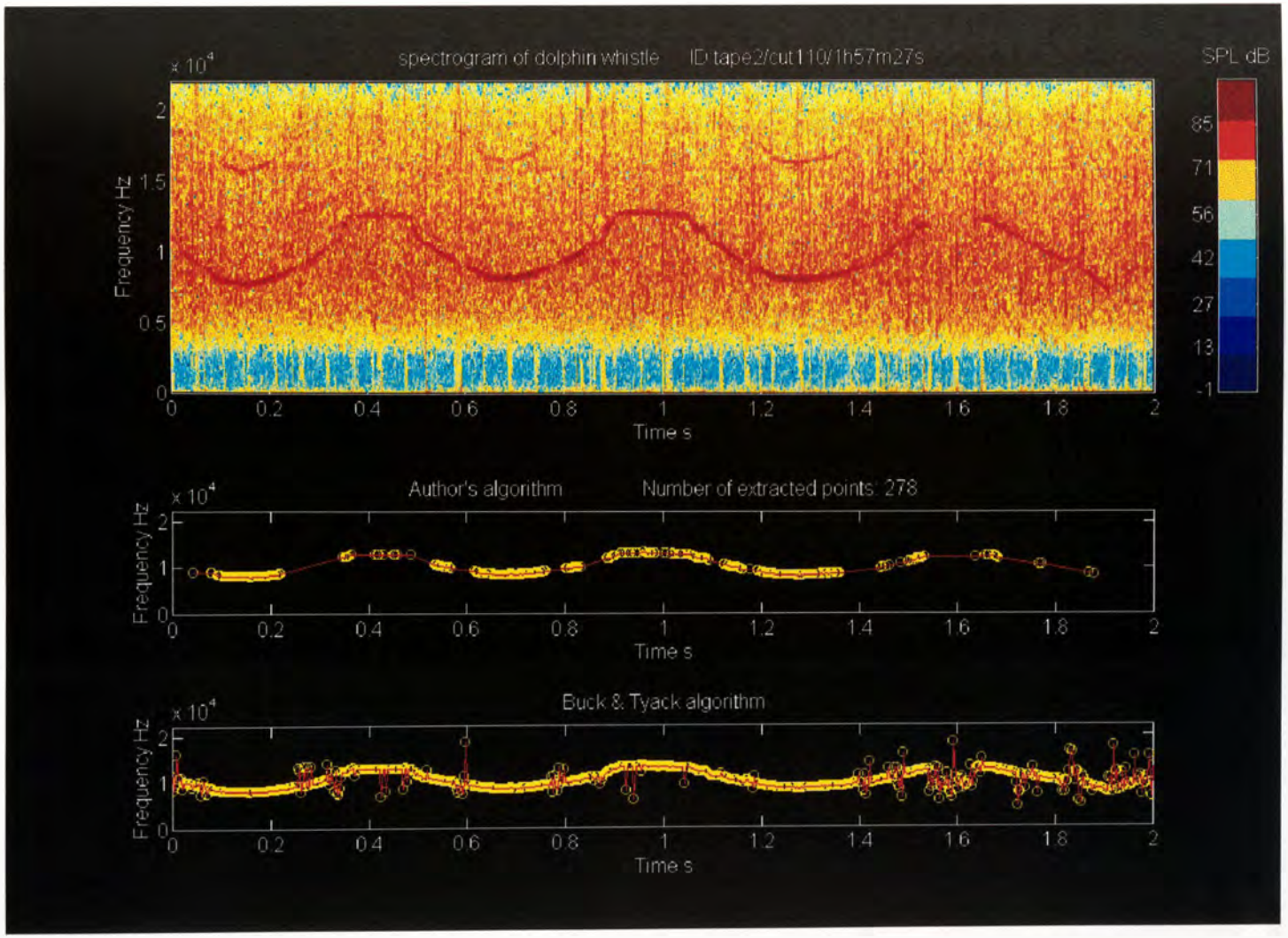


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut110/1h57m23s
Date:	9/6/94
Time:	04:15
Location:	Ligurian Sea
Longitude:	42.7305
Latitude:	8.9970

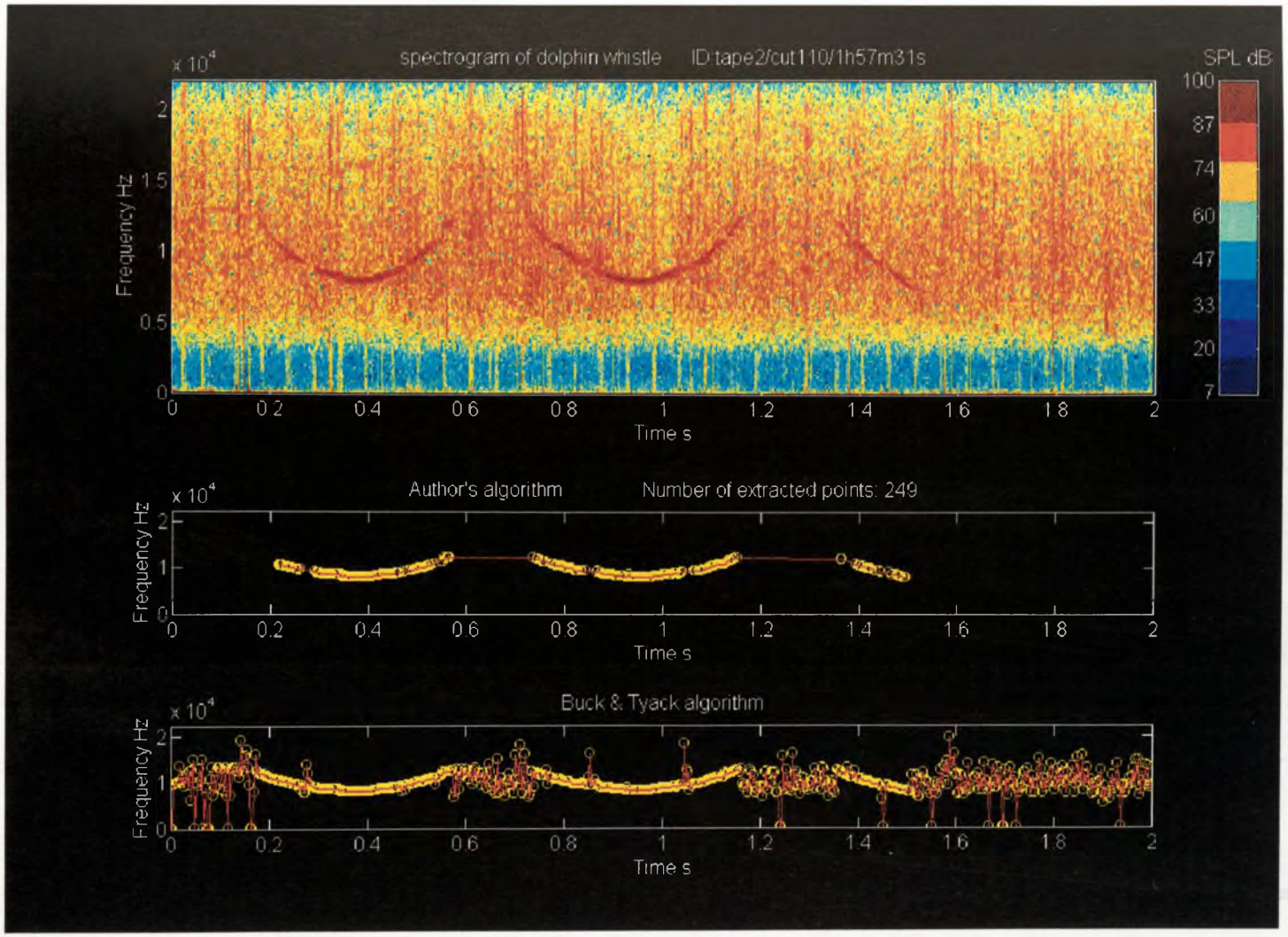


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut110/1h57m27s
Date:	9/6/94
Time:	04:15
Location:	Ligurian Sea
Longitude:	42.7305
Latitude:	8.9970

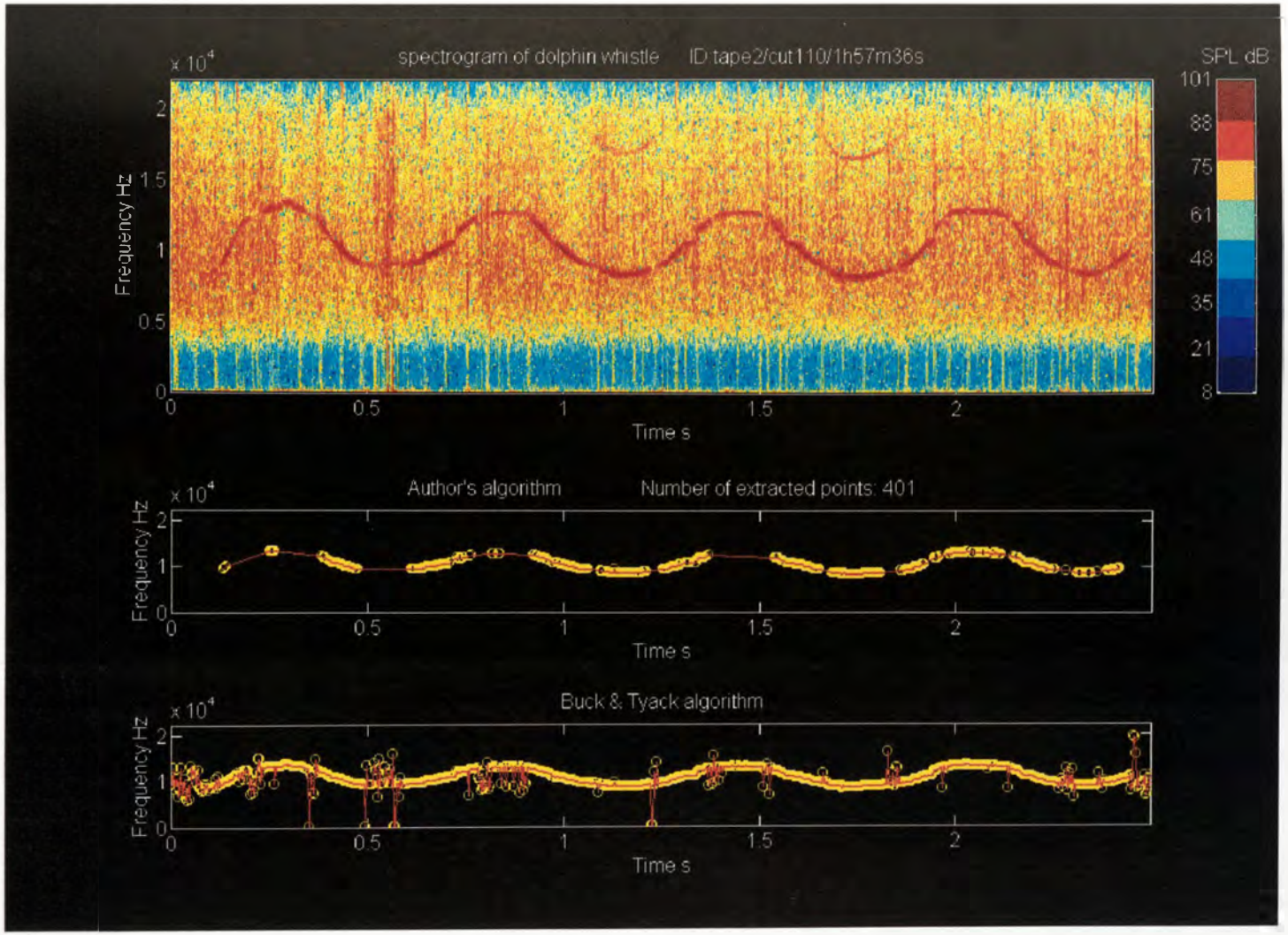


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut110/1h57m31s
Date:	9/6/94
Time:	04:15
Location:	Ligurian Sea
Longitude:	42.7305
Latitude:	8.9970



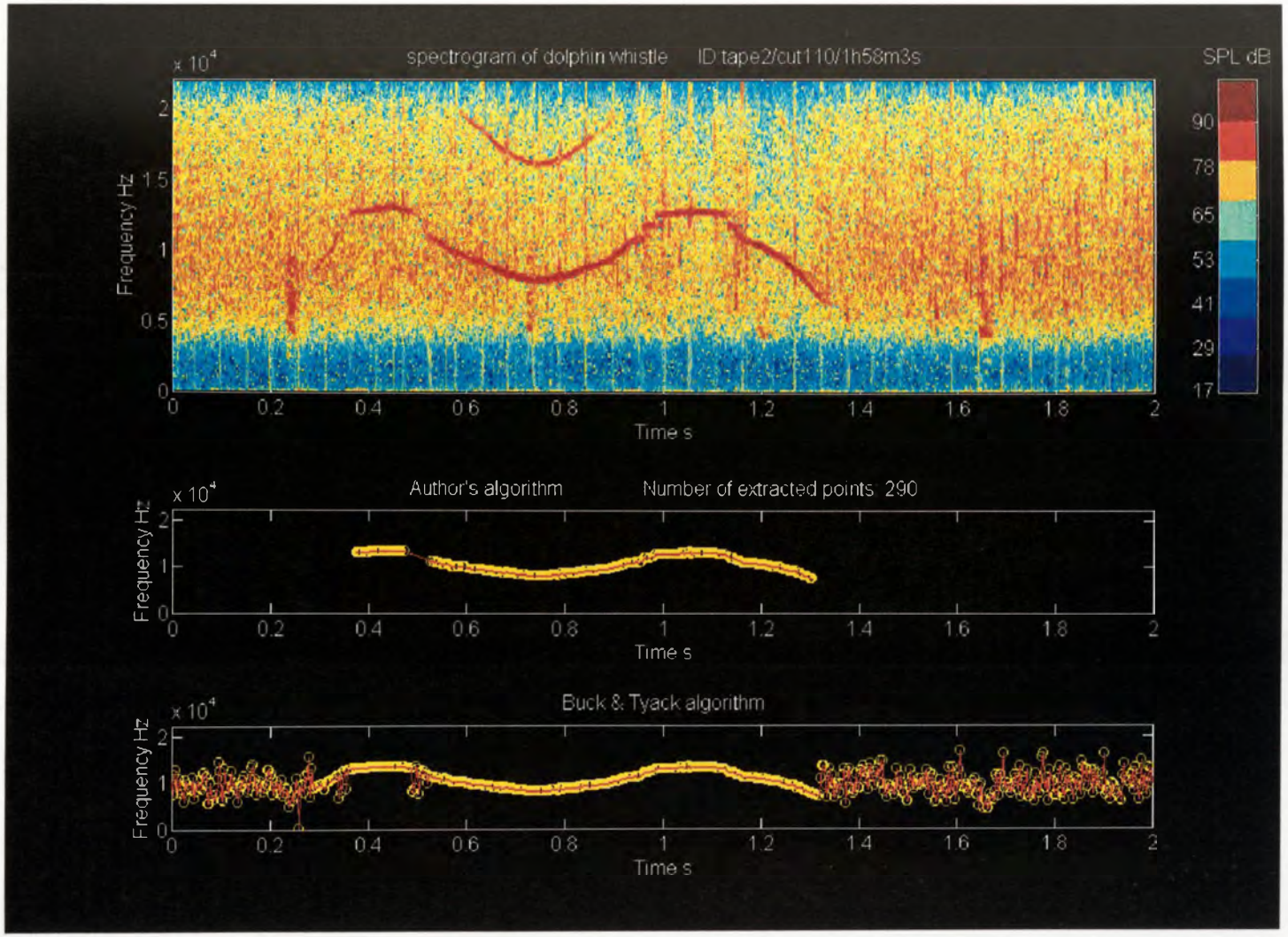
Legend

extracted points

extracted whistle contour

Recording details

ID:	tape2/cut110/1h57m36s
Date:	9/6/94
Time:	04:15
Location:	Ligurian Sea
Longitude:	42.7305
Latitude:	8.9970

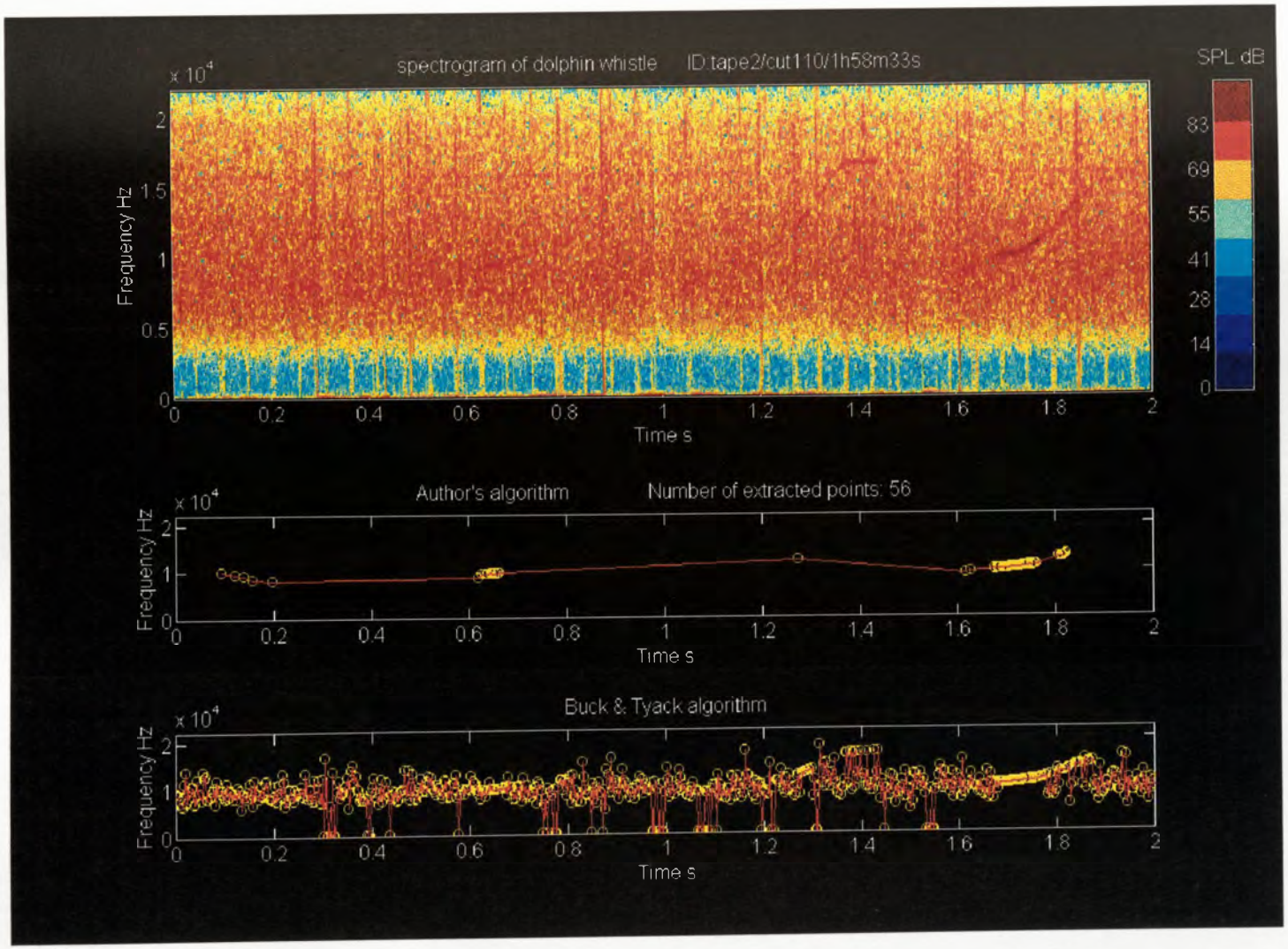


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut110/1h58m3s
Date:	9/6/94
Time:	04:15
Location:	Ligurian Sea
Longitude:	42.7305
Latitude:	8.9970

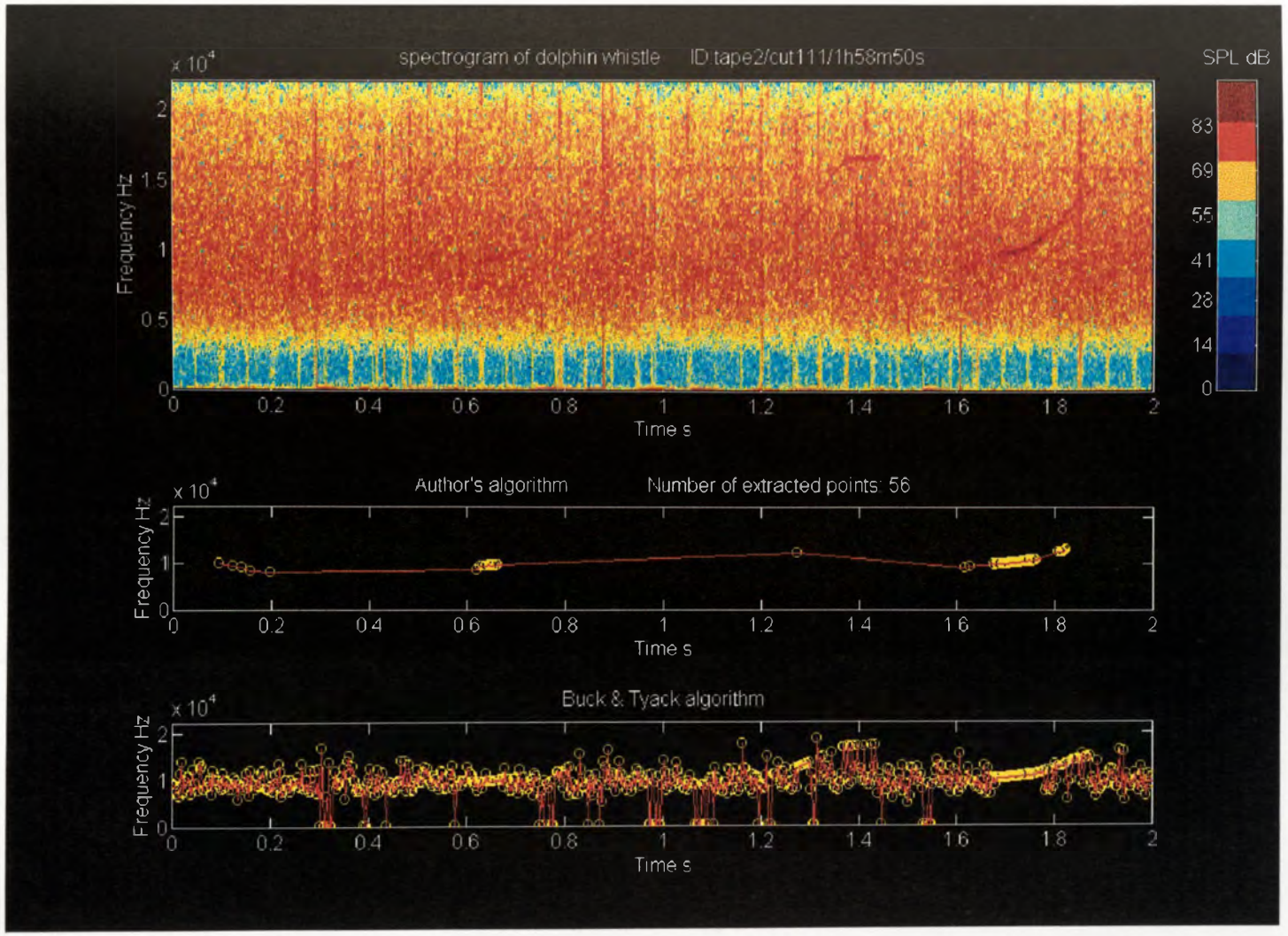


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut110/1h58m33s
Date:	9/6/94
Time:	04:15
Location:	Ligurian Sea
Longitude:	42.7305
Latitude:	8.9970

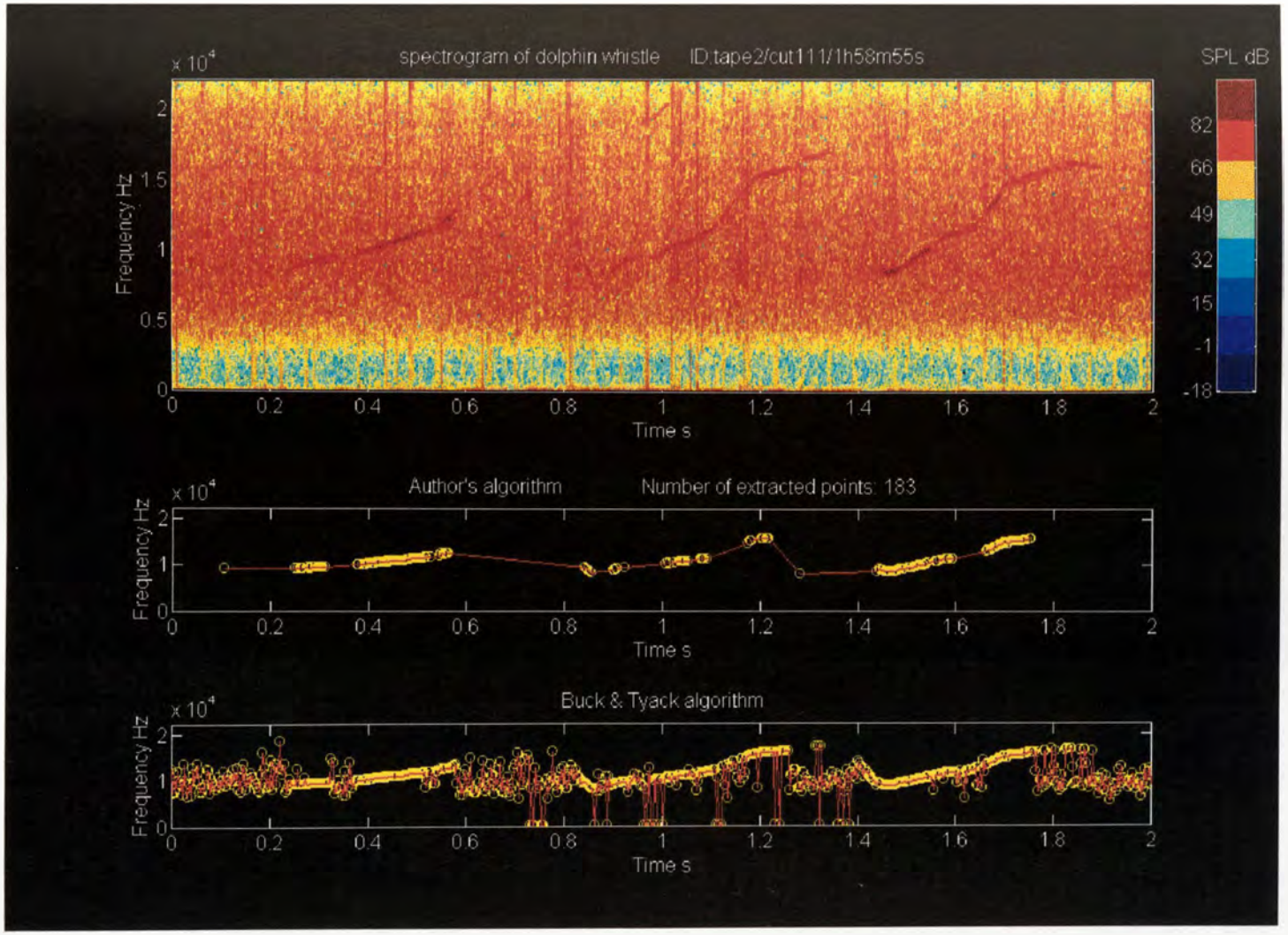


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut111/1h58m50s
Date:	9/6/94
Time:	04:30
Location:	Ligurian Sea
Longitude:	42.7262
Latitude:	8.9798



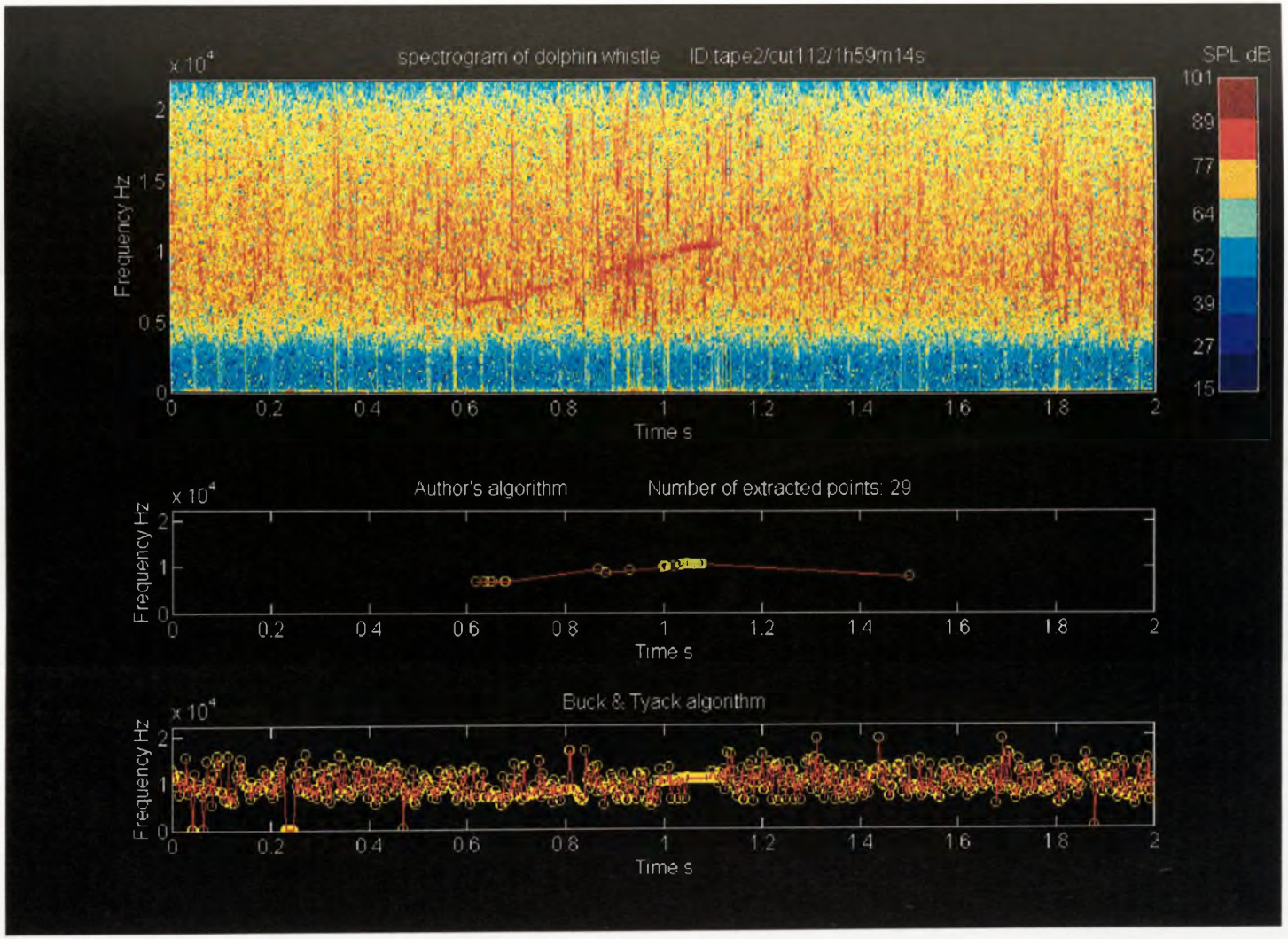
Legend

extracted points

extracted whistle contour

Recording details

ID:	tape2/cut111/1h58m55s
Date:	9/6/94
Time:	04:30
Location:	Ligurian Sea
Longitude:	42.7262
Latitude:	8.9798

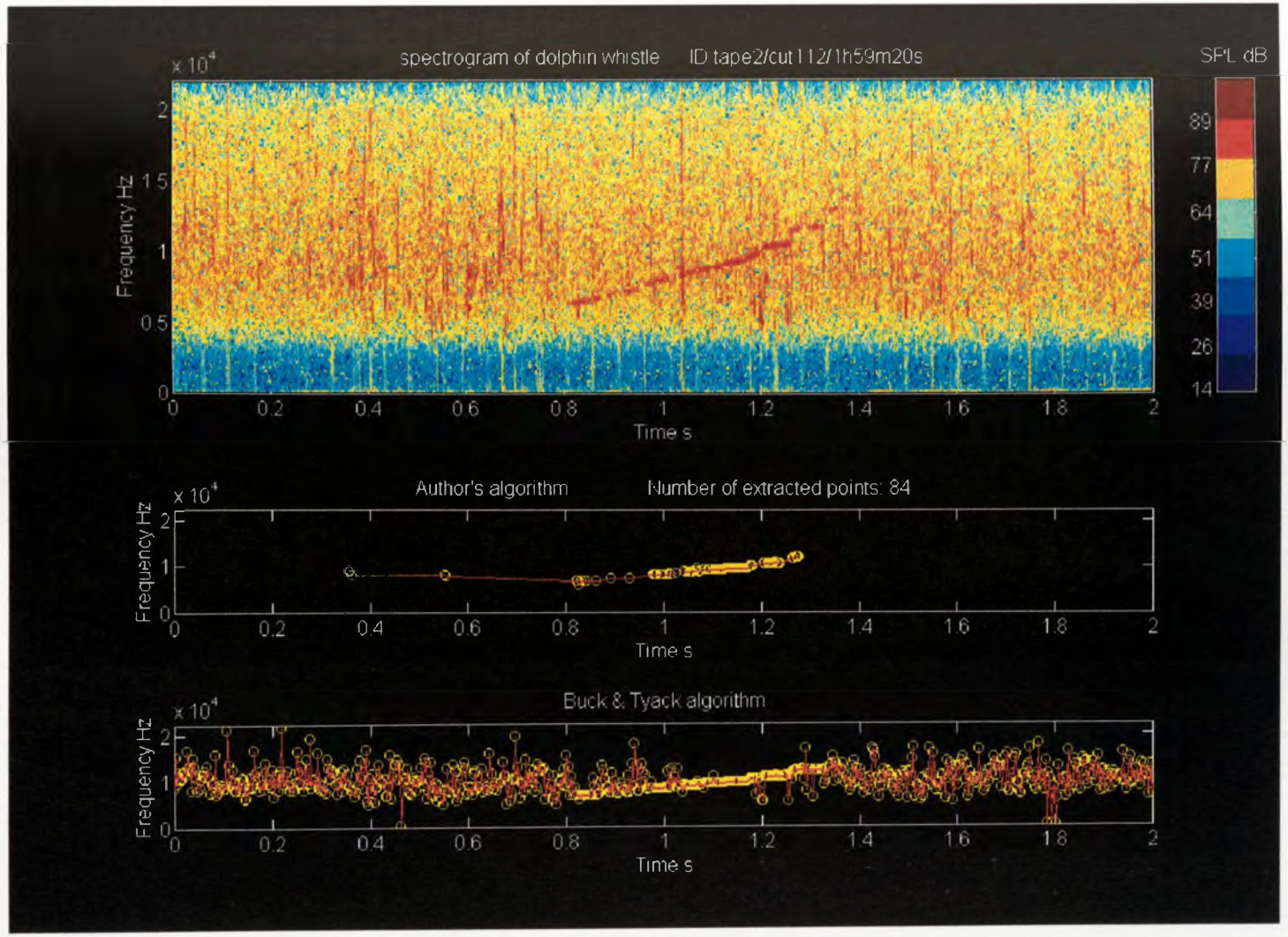


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut112/1h59m14s
Date:	9/6/94
Time:	04:45
Location:	Ligurian Sea
Longitude:	42.7215
Latitude:	8.9547

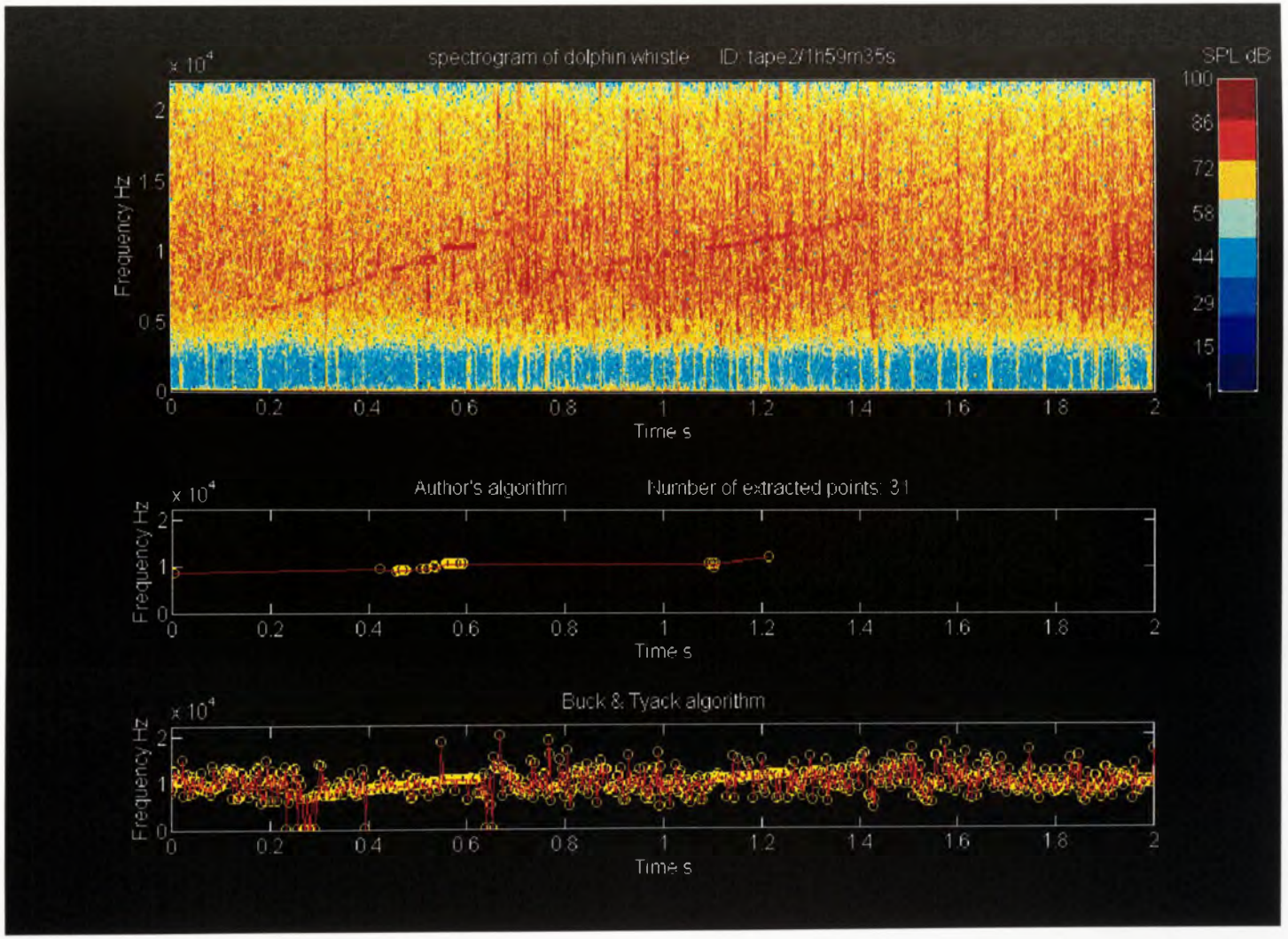


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut112/1h59m20s
Date:	9/6/94
Time:	04:45
Location:	Ligurian Sea
Longitude:	42.7215
Latitude:	8.9547

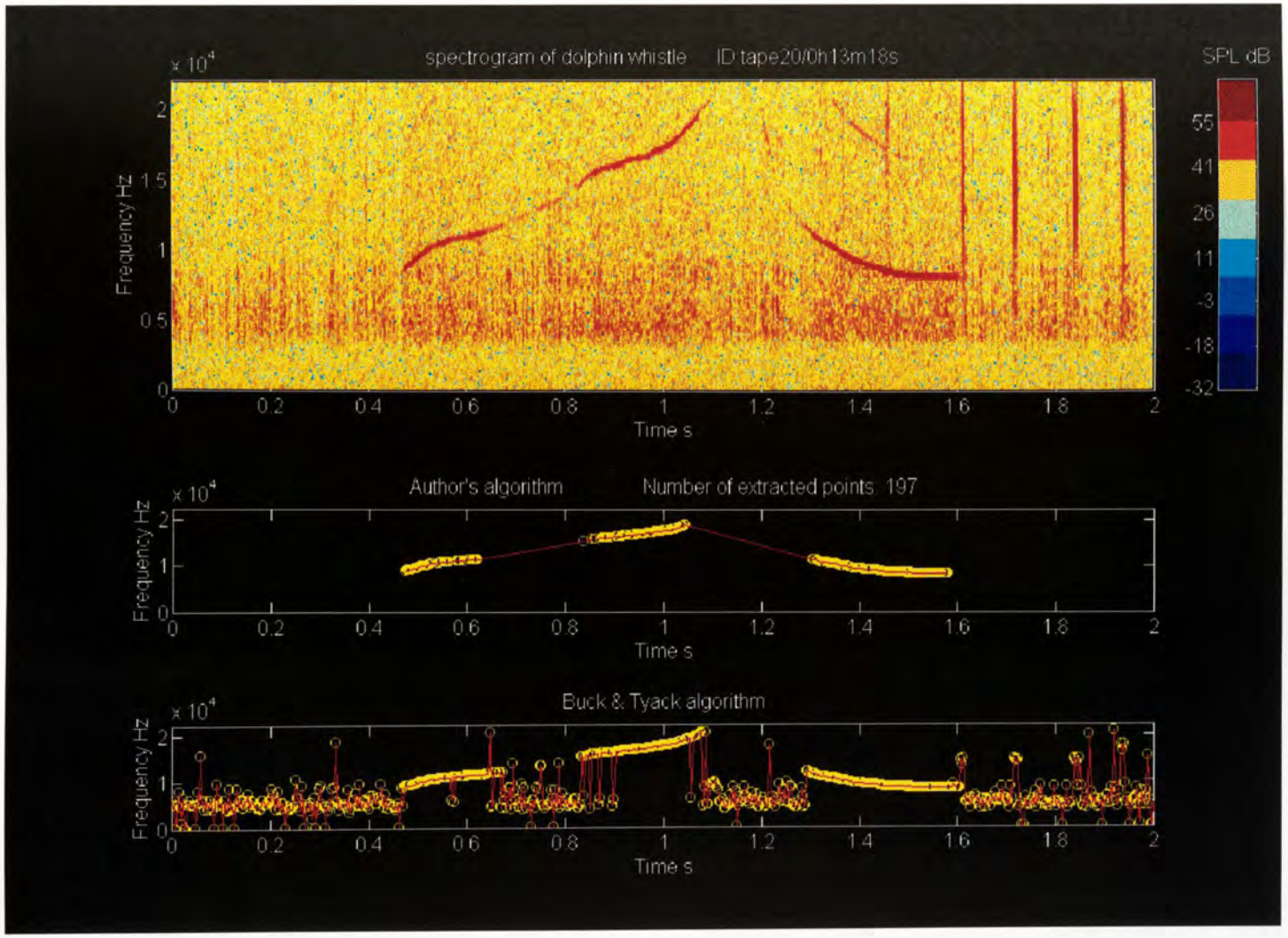


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape2/cut112/1h59m35s
Date:	9/6/94
Time:	04:45
Location:	Ligurian Sea
Longitude:	42.7215
Latitude:	8.9547

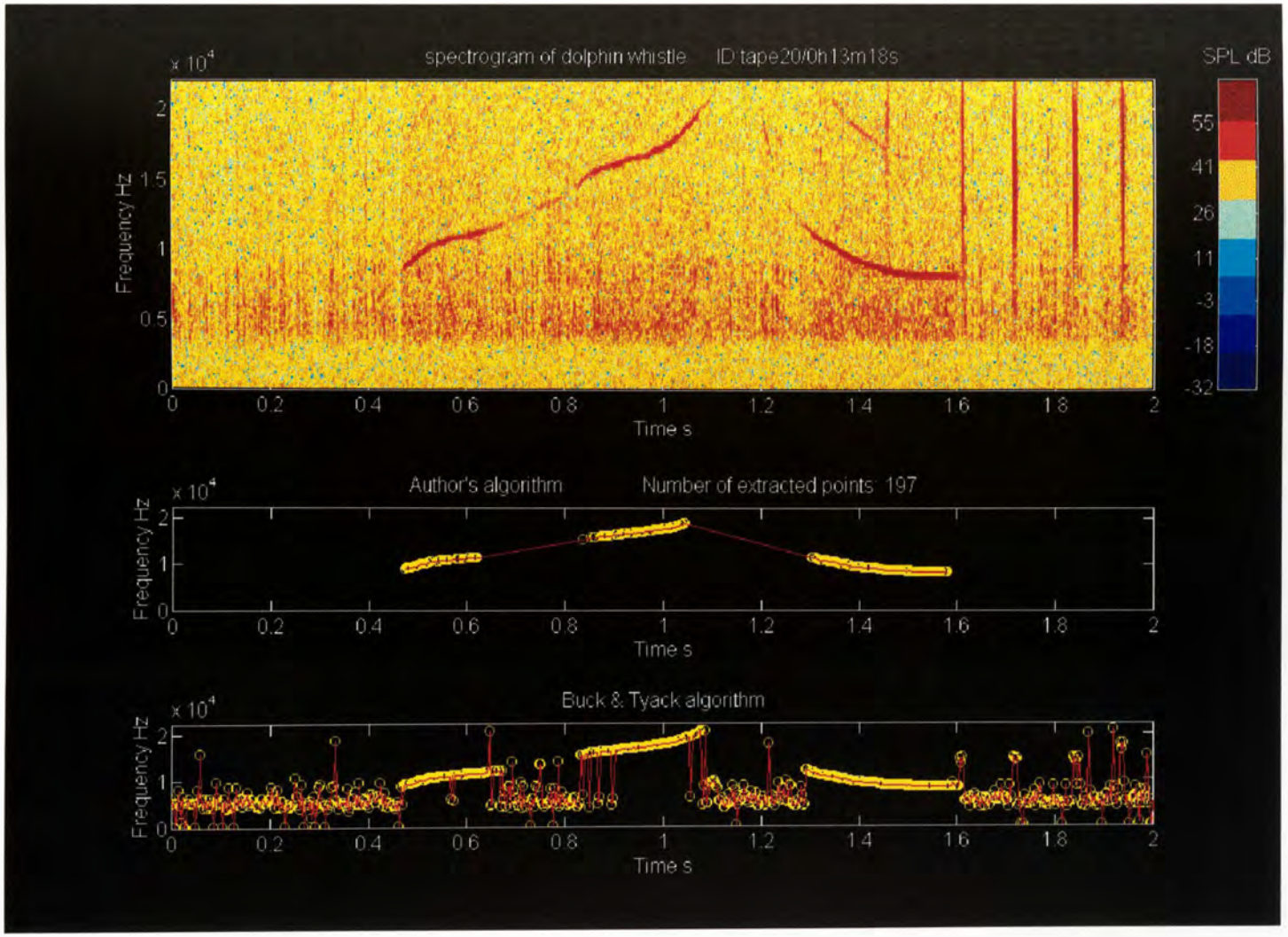


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape20/0h13m18s
Date:	3/8/94
Time:	07:29
Location:	Ligurian Sea
Longitude:	43.2865
Latitude:	7.5622

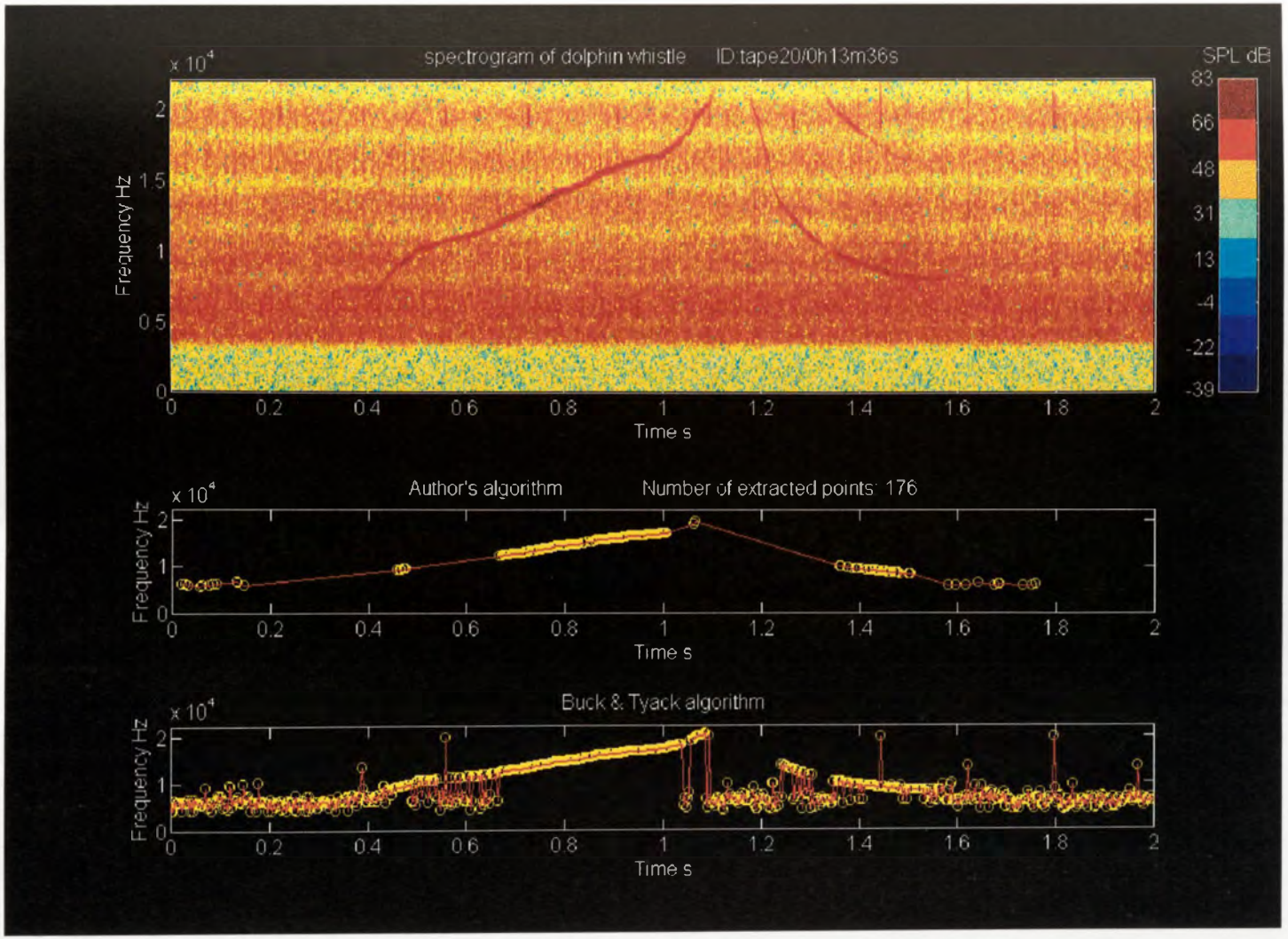


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape20/0h13m29s
Date:	3/8/94
Time:	07:29
Location:	Ligurian Sea
Longitude:	43.2865
Latitude:	7.5622



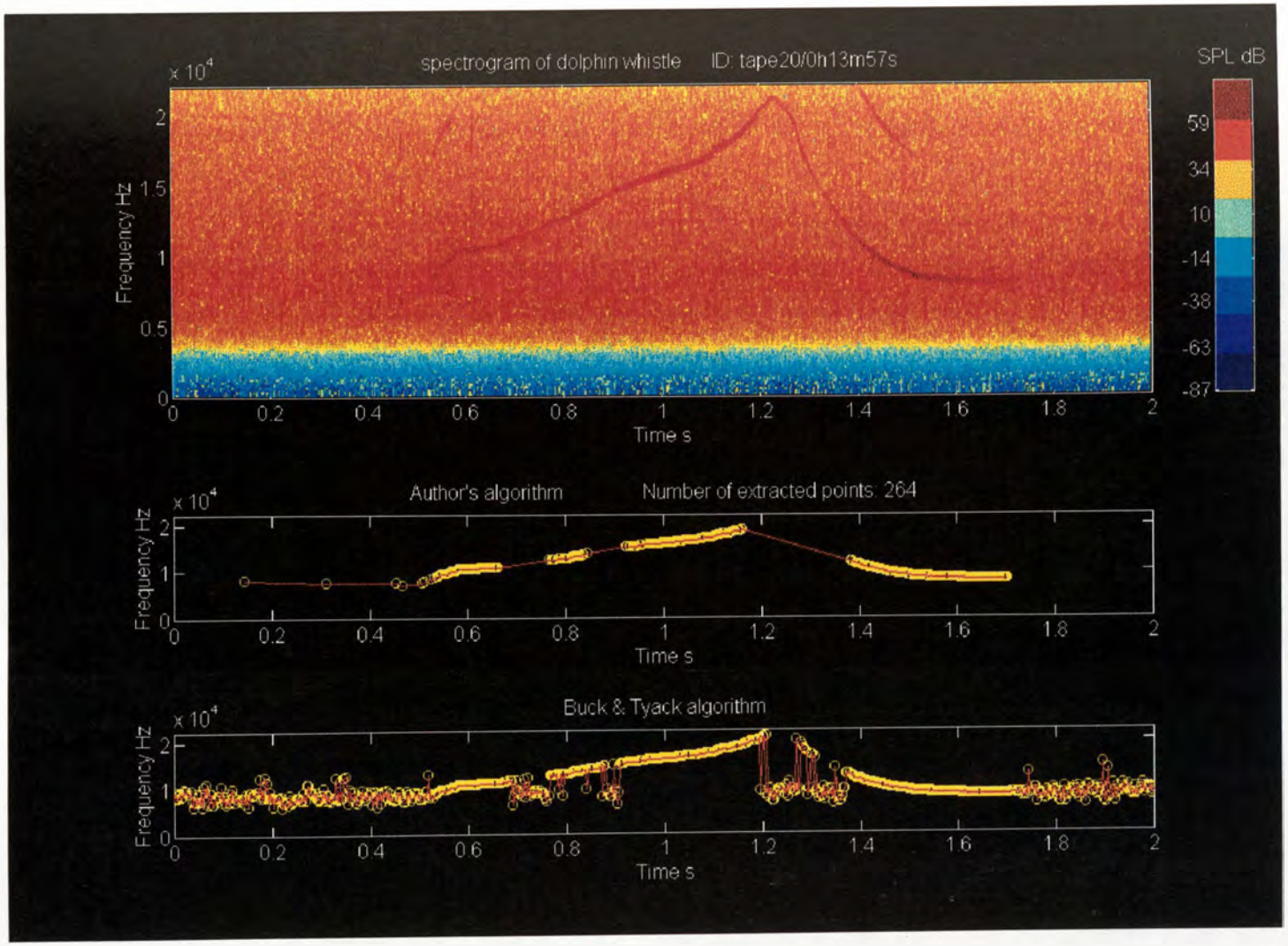
Legend

extracted points

extracted whistle contour

Recording details

ID:	tape20/0h13m36s
Date:	3/8/94
Time:	07:29
Location:	Ligurian Sea
Longitude:	43.2865
Latitude:	7.5622

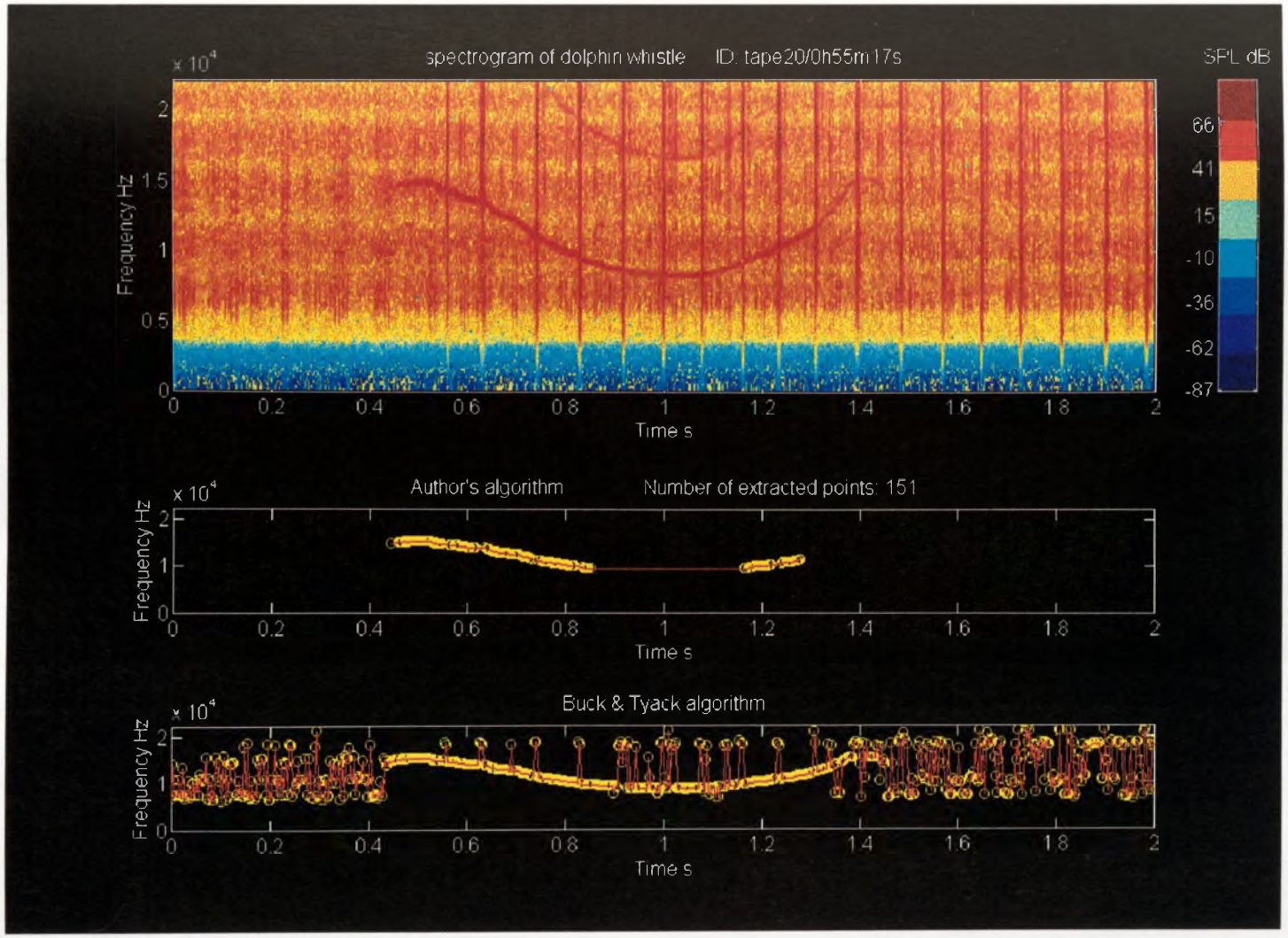


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape20/0h13m57s
Date:	3/8/94
Time:	07:29
Location:	Ligurian Sea
Longitude:	43.2865
Latitude:	7.5622



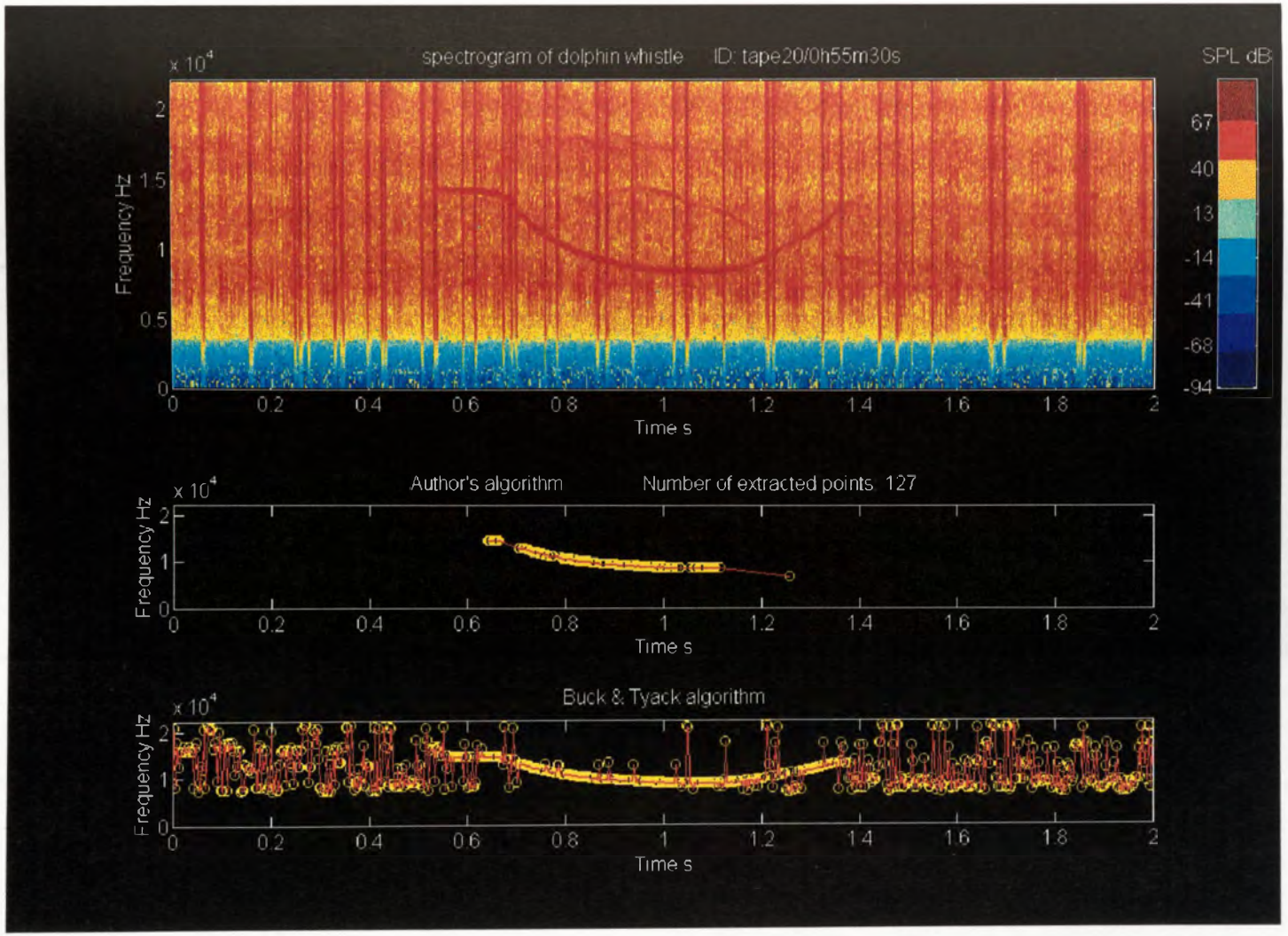
Legend

extracted points

extracted whistle contour

Recording details

ID:	tape20/0h55m17s
Date:	4/8/94
Time:	08:59
Location:	Ligurian Sea
Longitude:	43.2897
Latitude:	7.8748

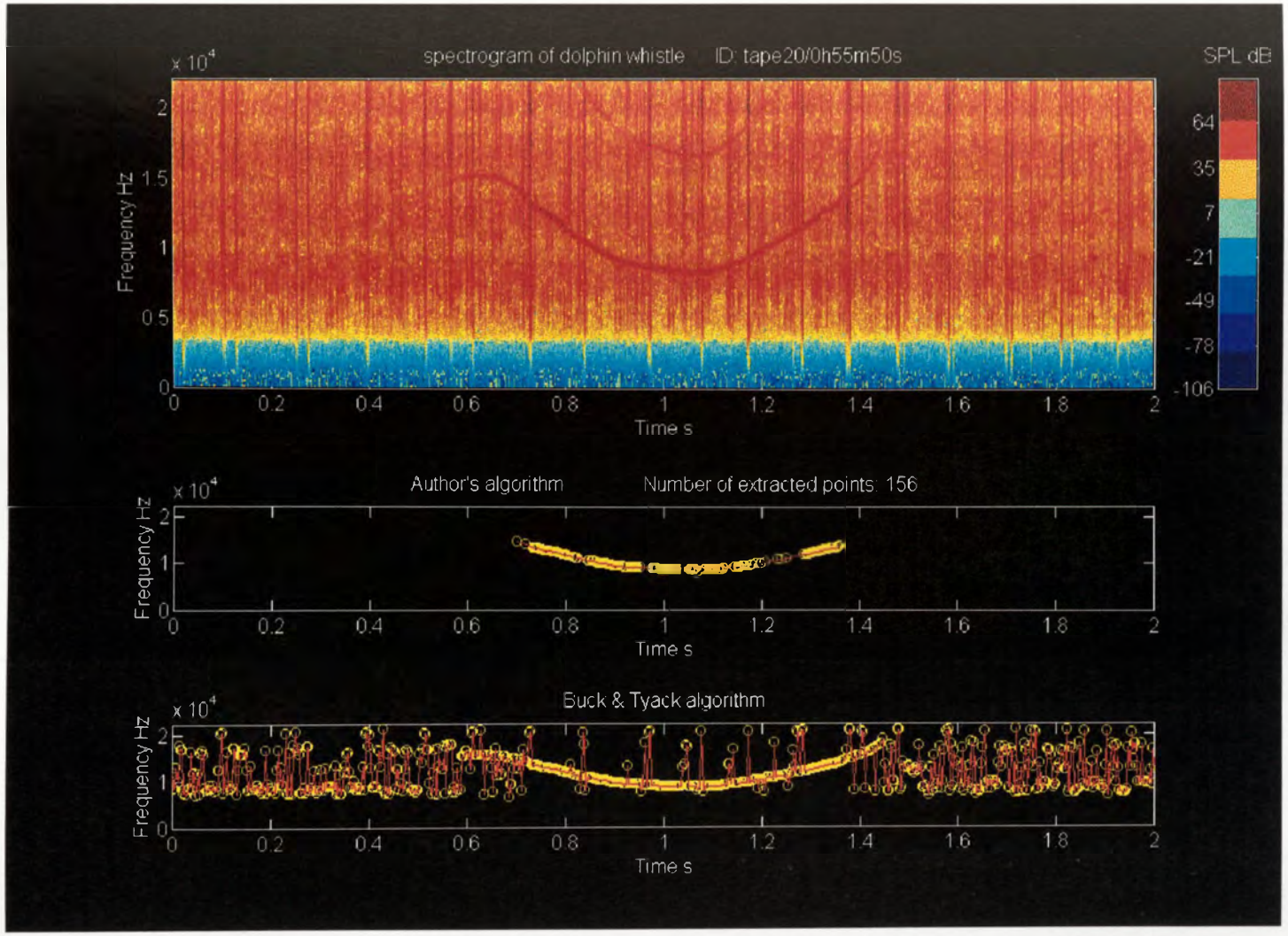


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape20/0h55m30s
Date:	4/8/94
Time:	08:59
Location:	Ligurian Sea
Longitude:	43.2897
Latitude:	7.8748

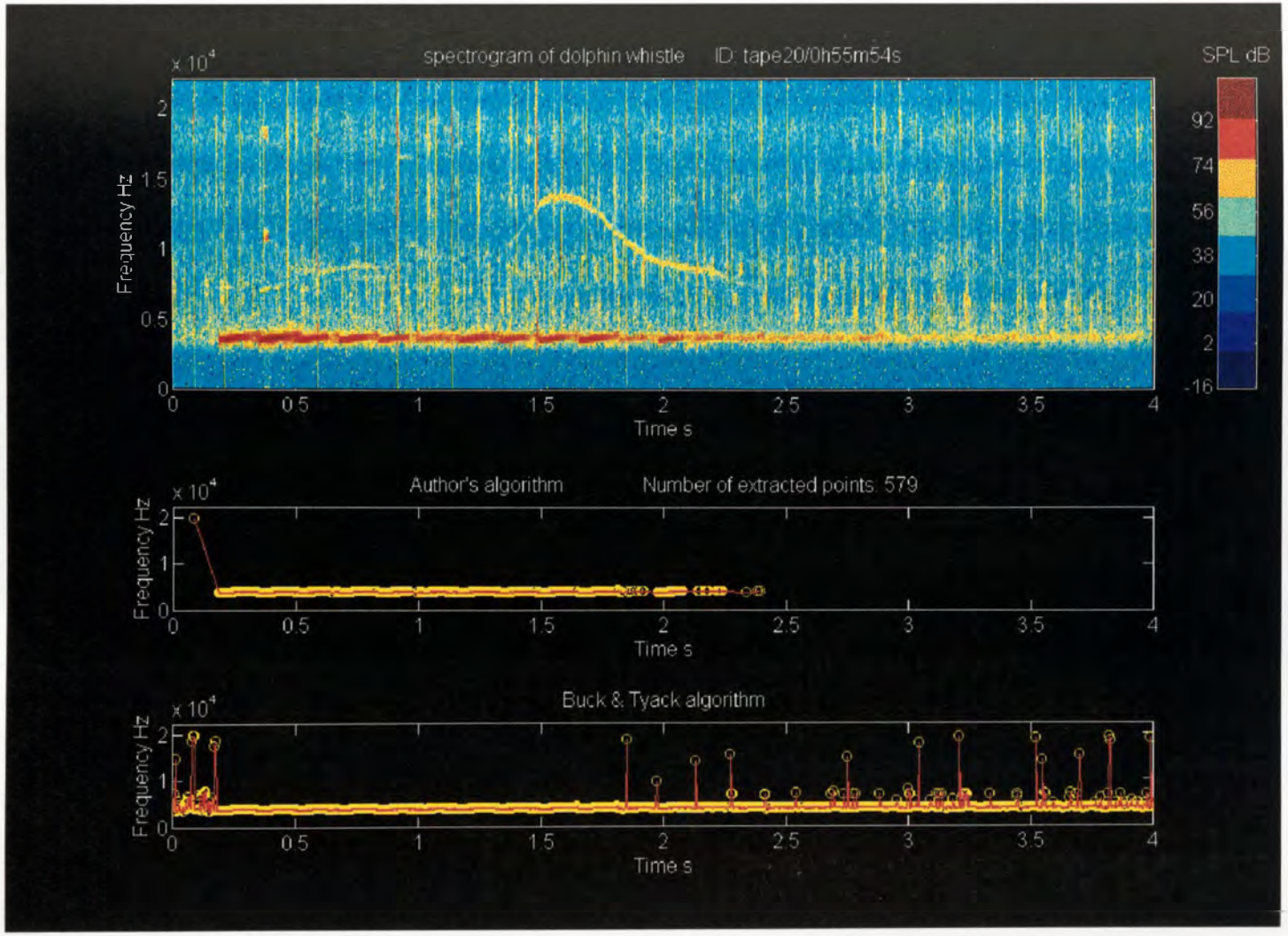


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape20/0h55m50s
Date:	4/8/94
Time:	08:59
Location:	Ligurian Sea
Longitude:	43.2897
Latitude:	7.8748

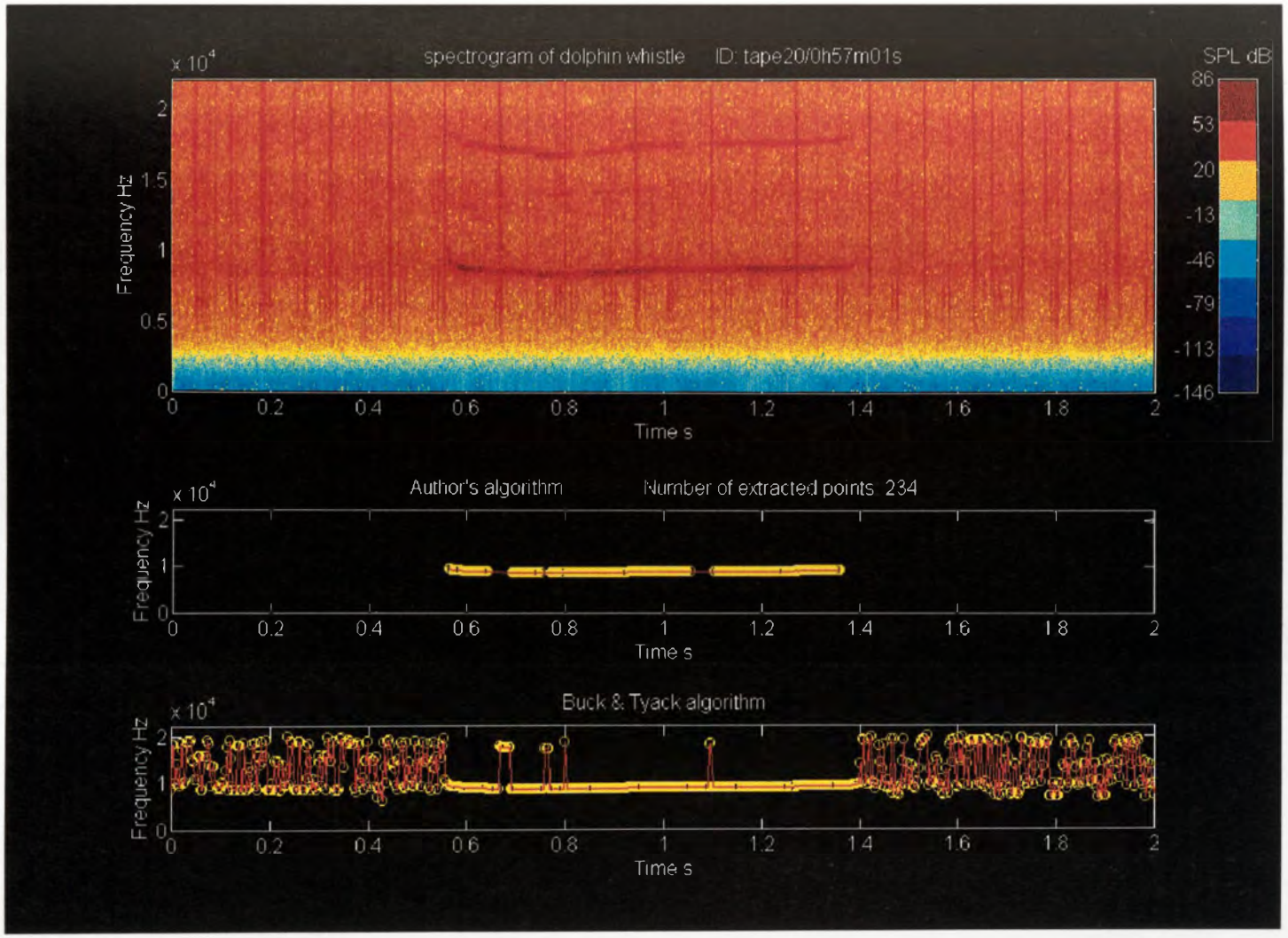


Legend

extracted points
extracted whistle contour

Recording details

ID:	tape20/0h55m54s
Date:	4/8/94
Time:	08:59
Location:	Ligurian Sea
Longitude:	43.2897
Latitude:	7.8748



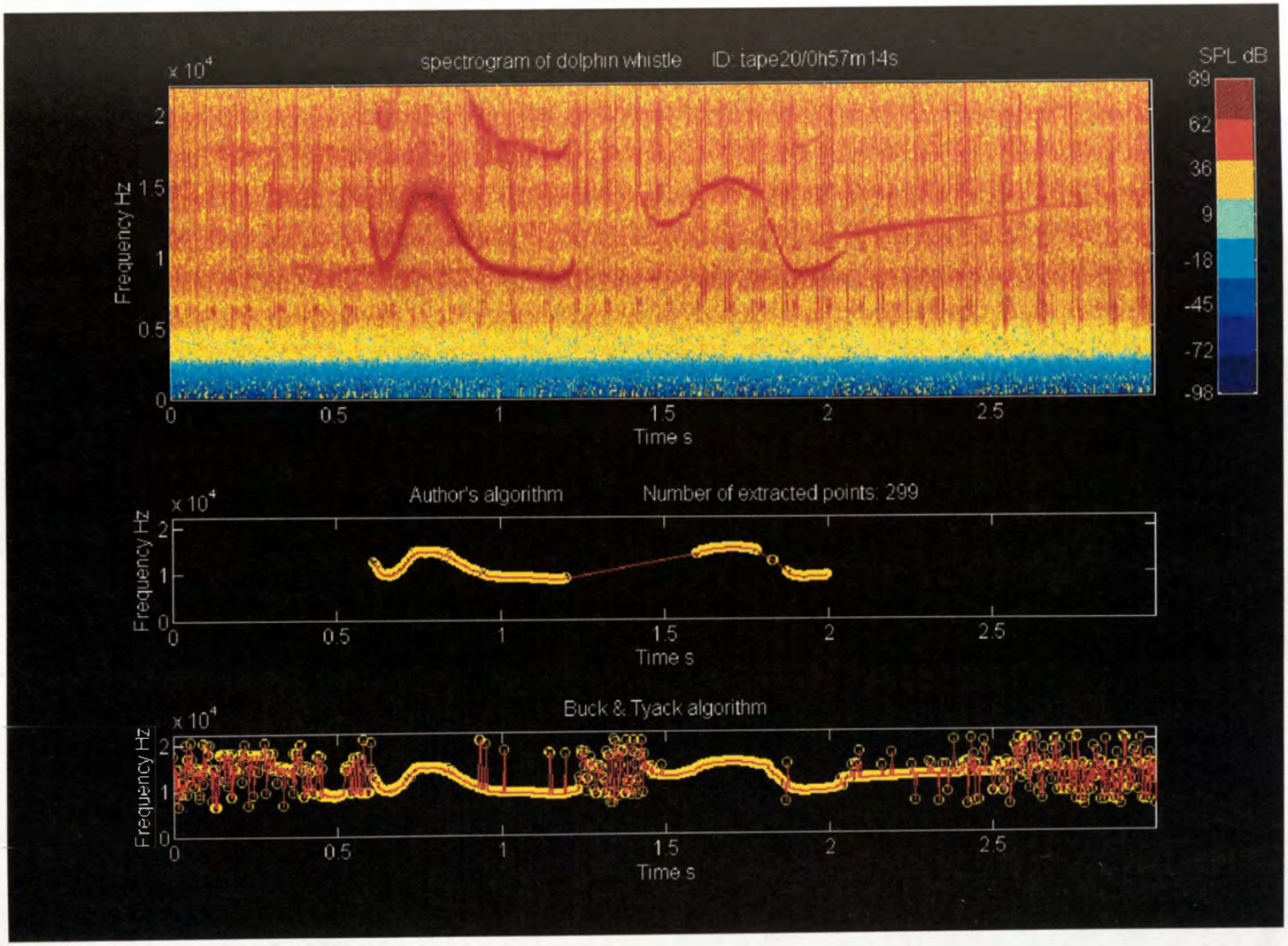
Legend

extracted points

extracted whistle contour

Recording details

ID:	tape20/0h57m01s
Date:	4/8/94
Time:	08:59
Location:	Ligurian Sea
Longitude:	43.2897
Latitude:	7.8748



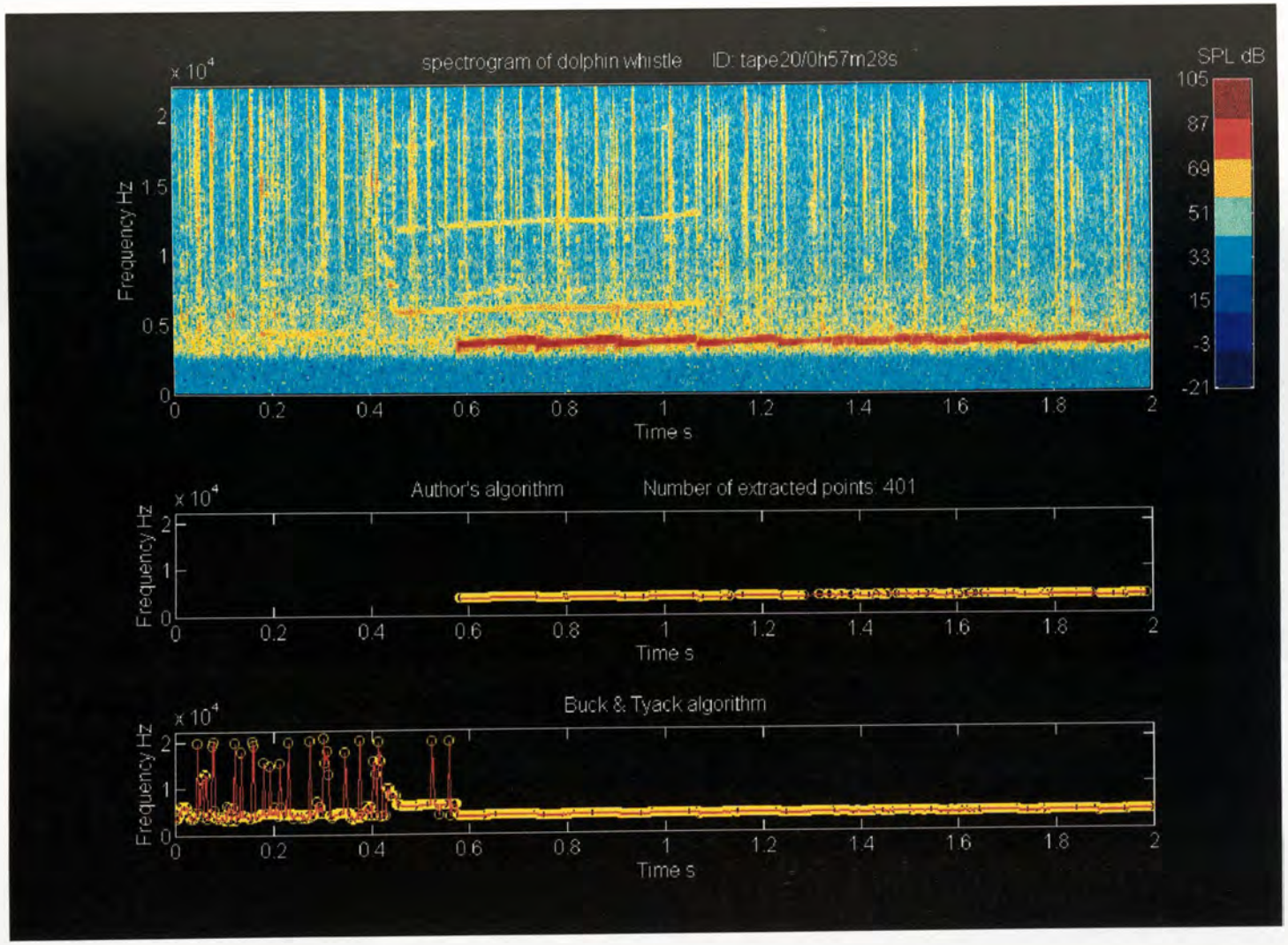
Legend

extracted points

extracted whistle contour

Recording details

ID:	tape20/0h57m14s
Date:	4/8/94
Time:	08:59
Location:	Ligurian Sea
Longitude:	43.2897
Latitude:	7.8748



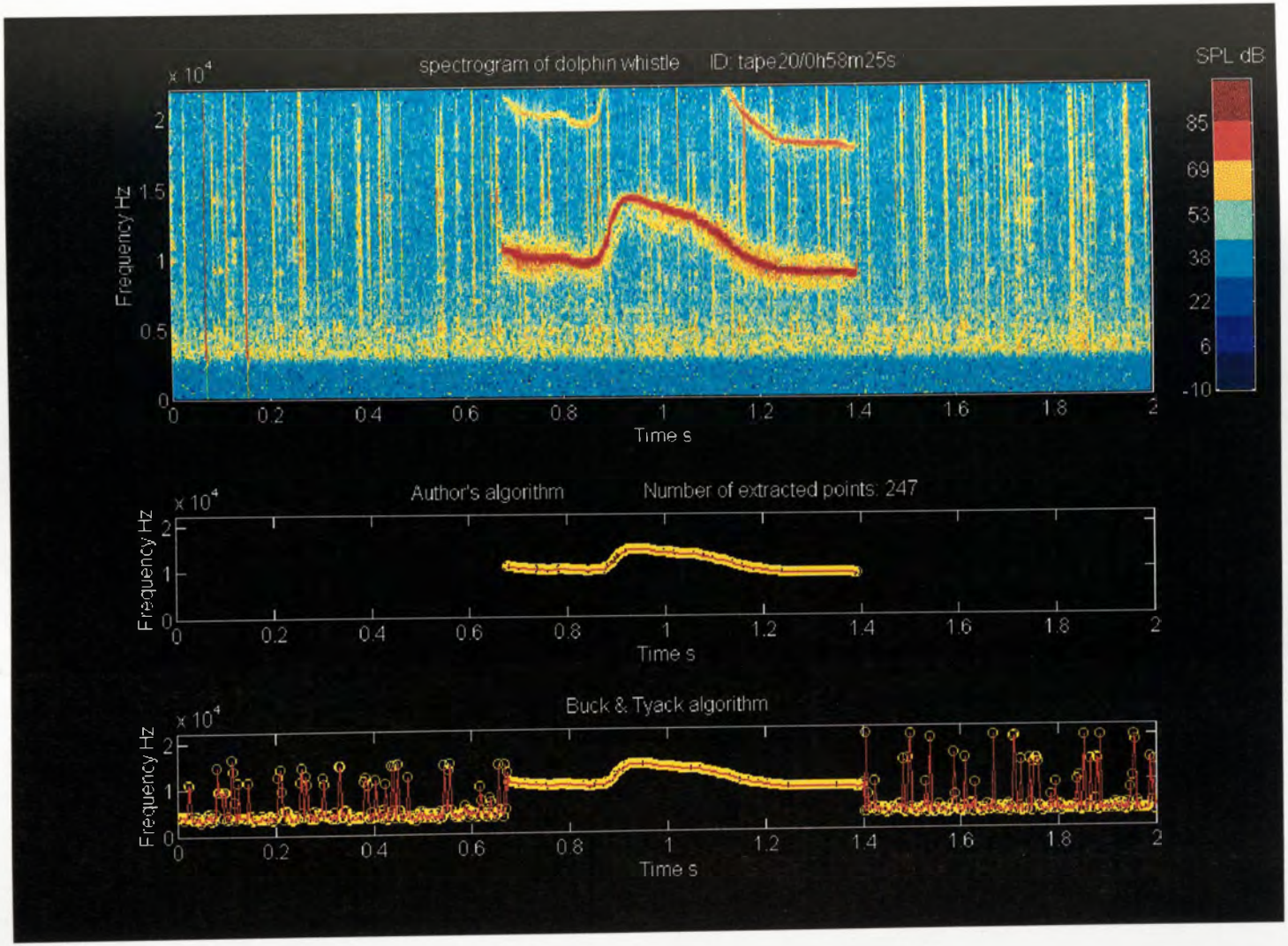
Legend

extracted points

extracted whistle contour

Recording details

ID:	tape20/0h57m28s
Date:	4/8/94
Time:	08:59
Location:	Ligurian Sea
Longitude:	43.2897
Latitude:	7.8748

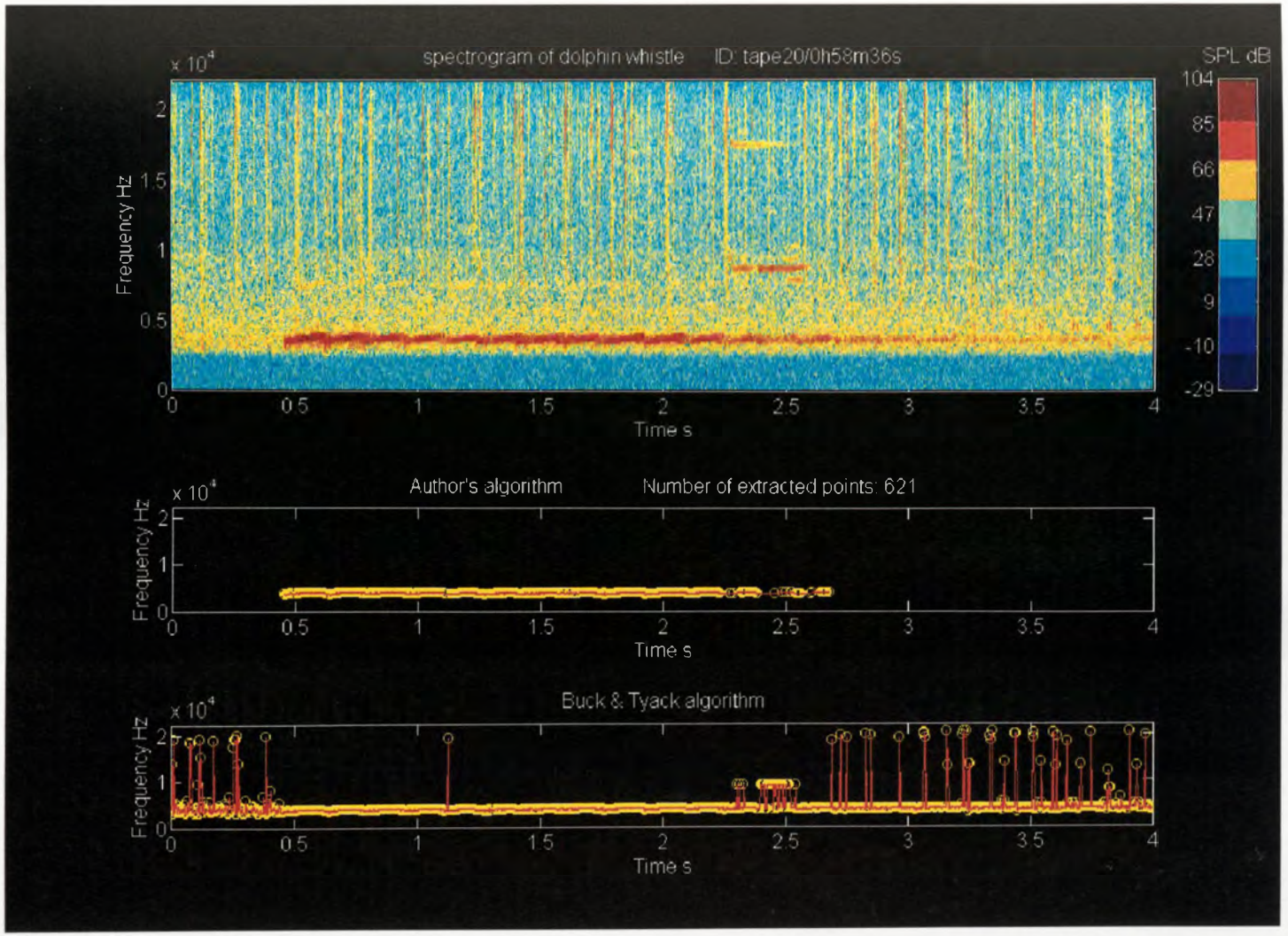


Legend

- extracted points
- extracted whistle contour

Recording details

ID:	tape20/0h58m25s
Date:	4/8/94
Time:	08:59
Location:	Ligurian Sea
Longitude:	43.2897
Latitude:	7.8748



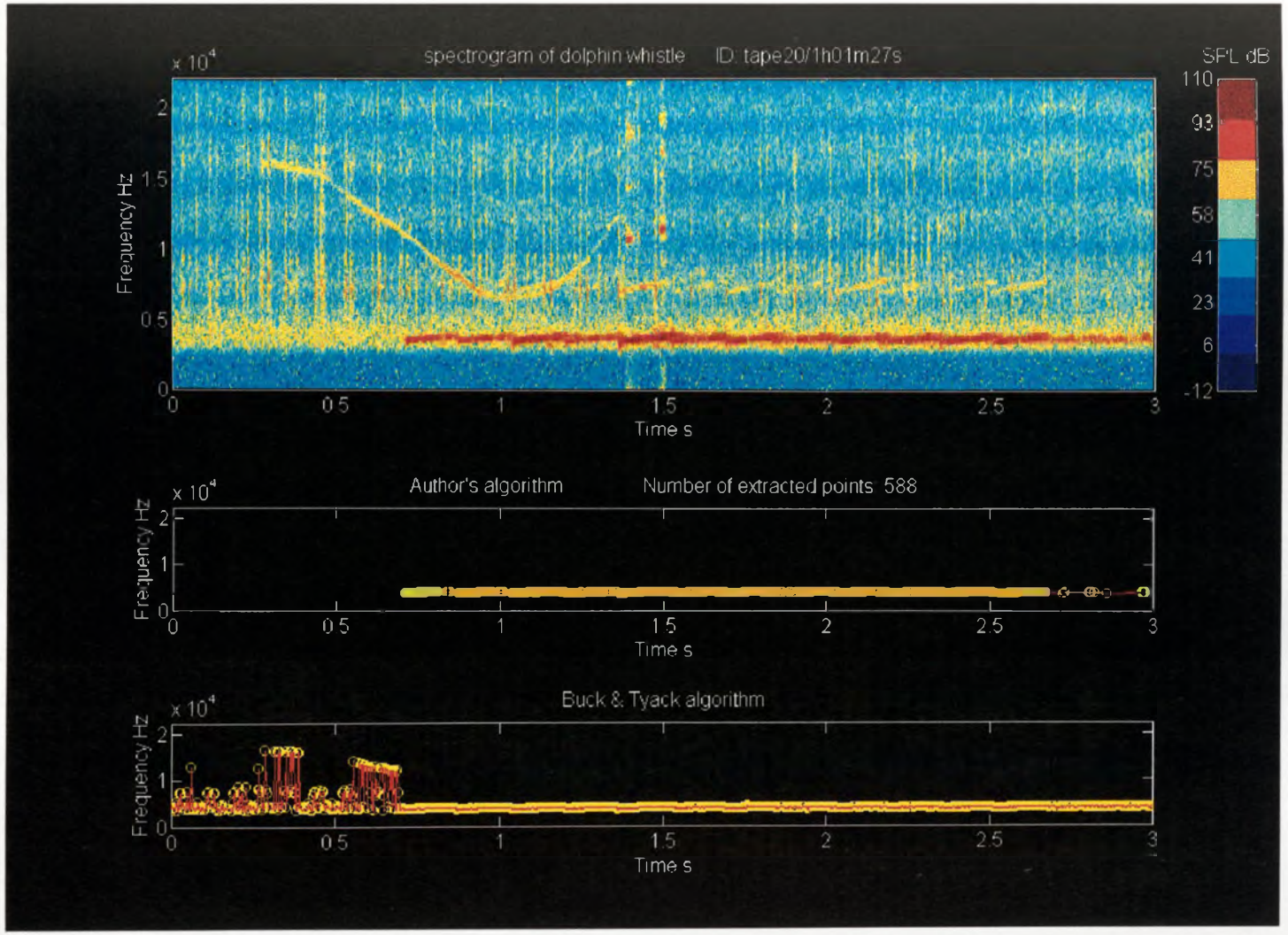
Legend

extracted points

extracted whistle contour

Recording details

ID:	tape20/0h58m36s
Date:	4/8/94
Time:	08:59
Location:	Ligurian Sea
Longitude:	43.2897
Latitude:	7.8748



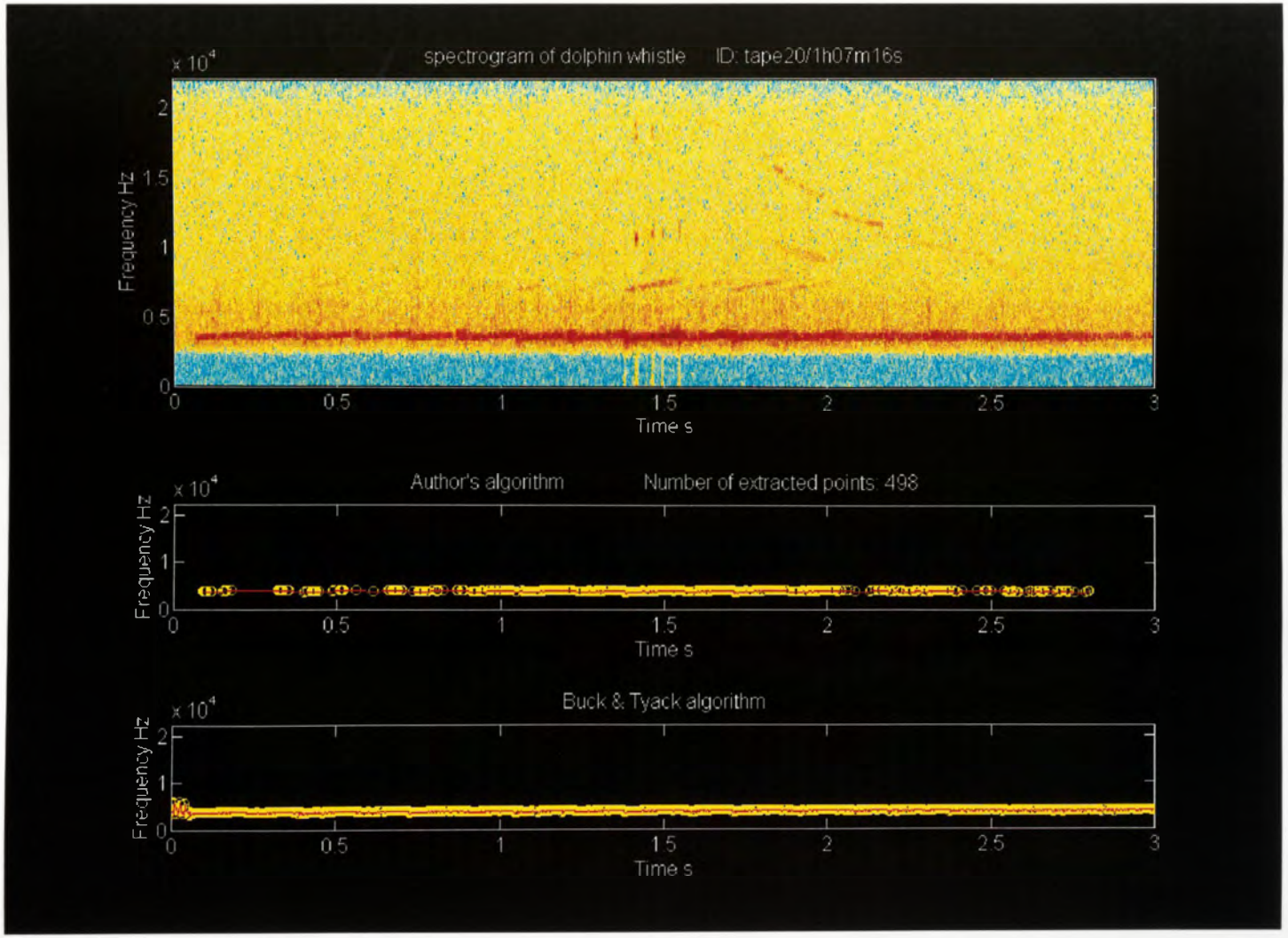
Legend

extracted points

extracted whistle contour

Recording details

ID:	tape20/1h01m27s
Date:	4/8/94
Time:	08:59
Location:	Ligurian Sea
Longitude:	43.2897
Latitude:	7.8748



Legend

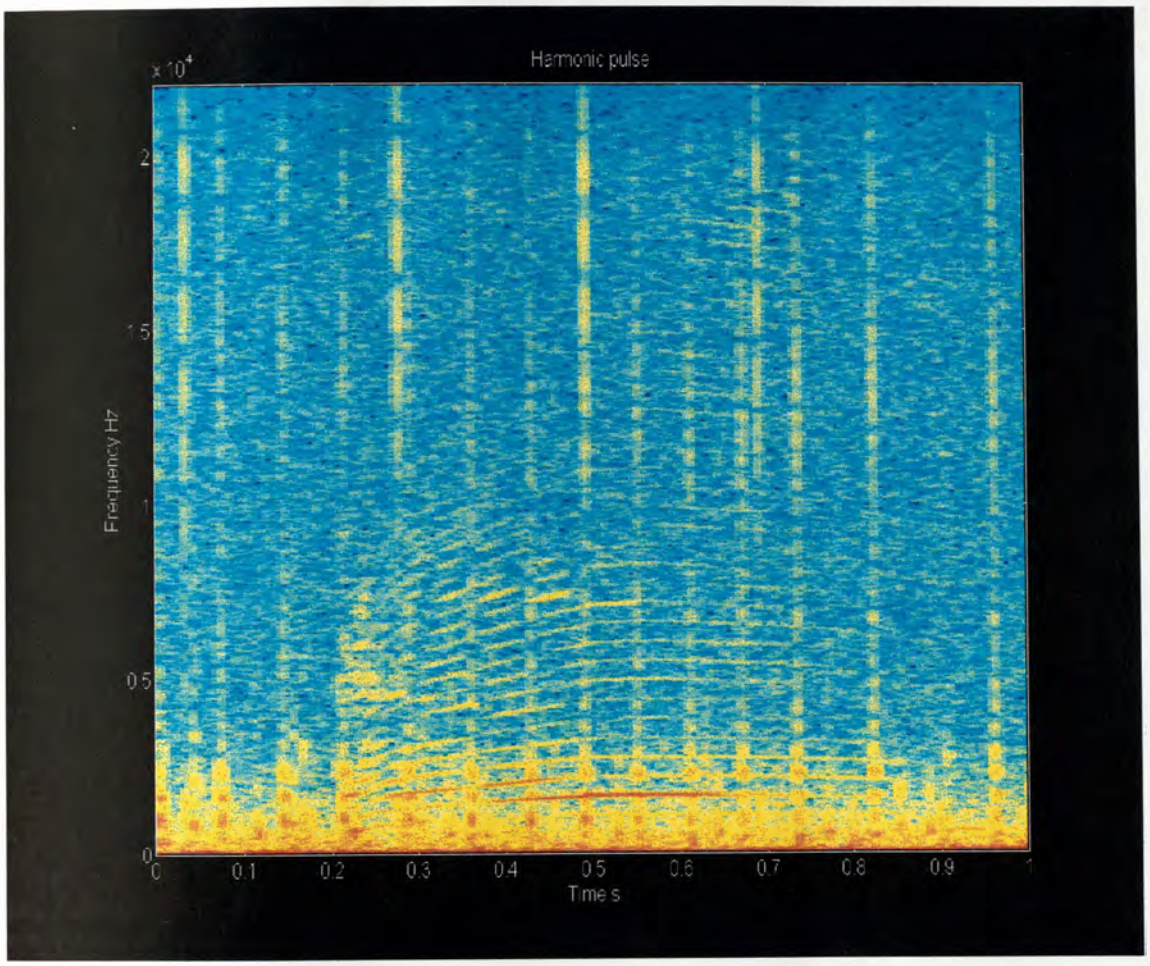
- extracted points
- extracted whistle contour

Recording details

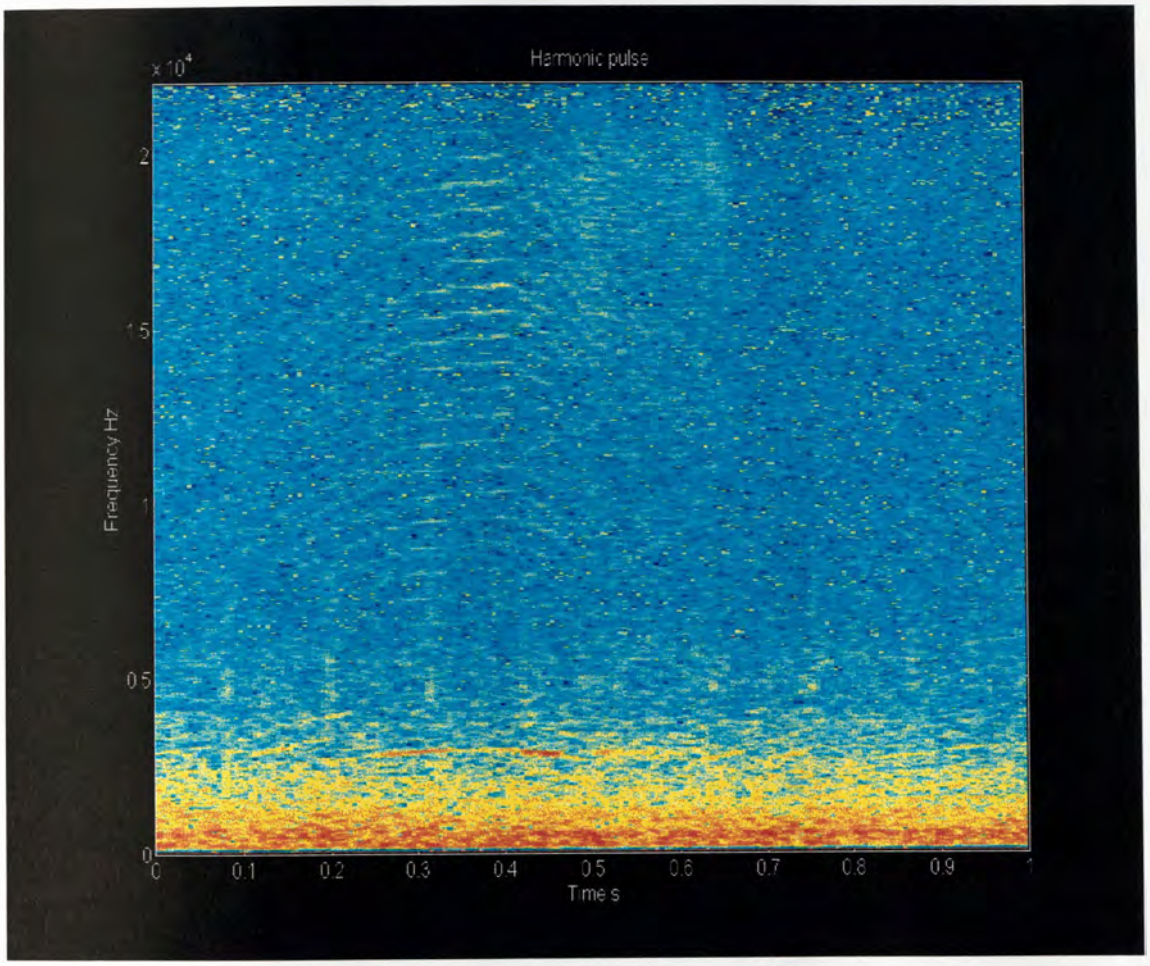
ID:	tape20/1h07m16s
Date:	4/8/94
Time:	08:59
Location:	Ligurian Sea
Longitude:	43.2897
Latitude:	7.8748

Appendix B

Harmonic Pulse 1



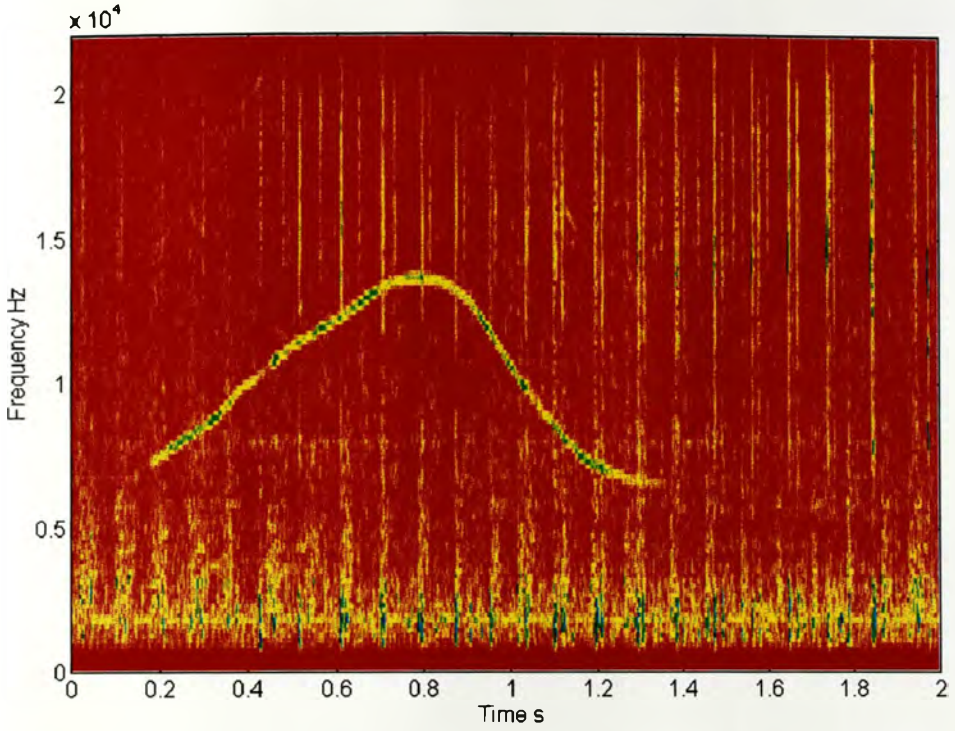
Harmonic Pulse 2



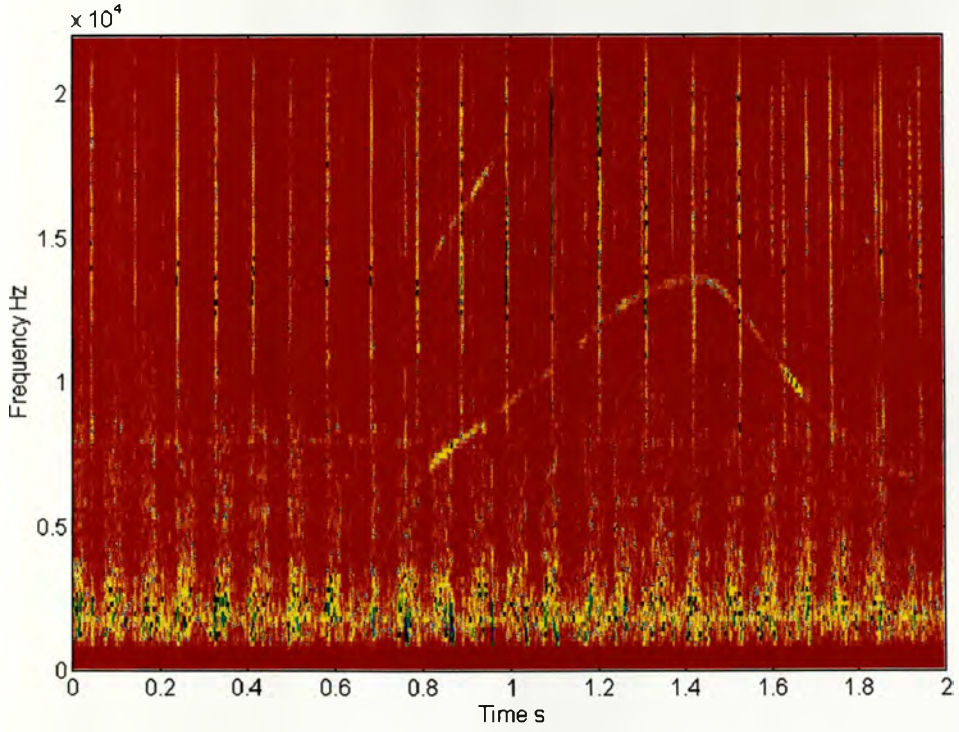
Appendix C

Spectrograms of the signature whistles described in Chapter 6.

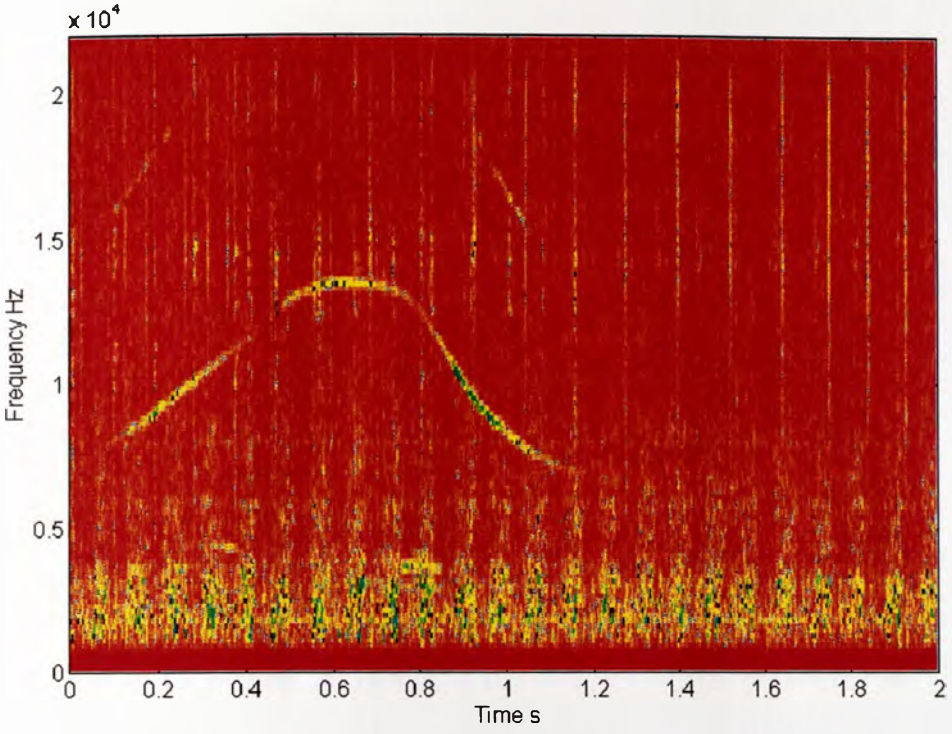
Whistle 1



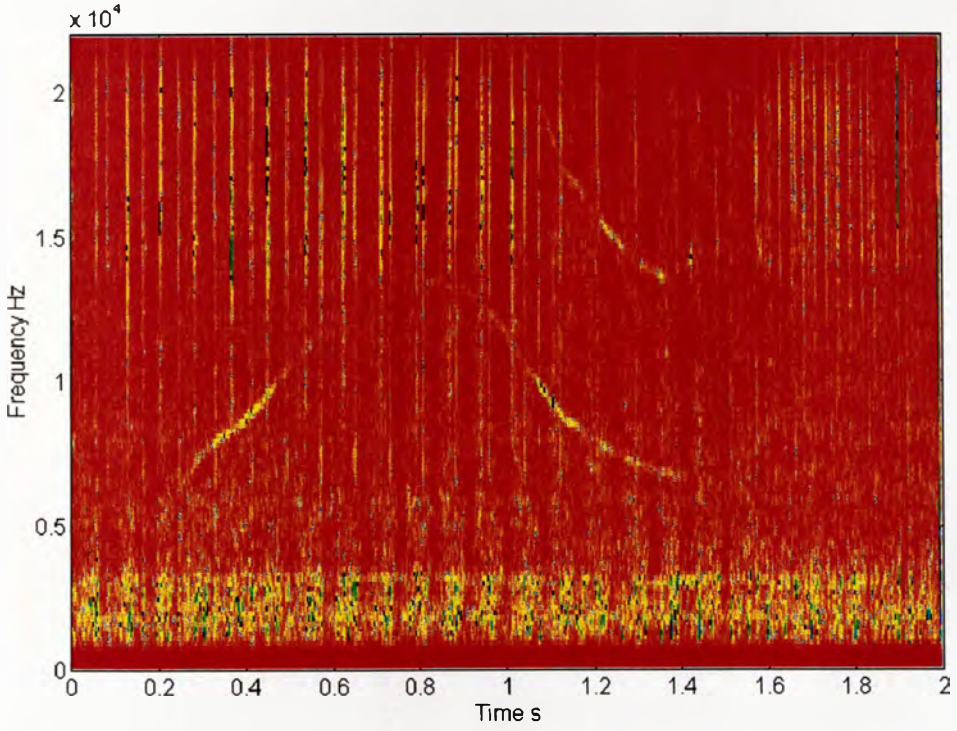
Whistle 2



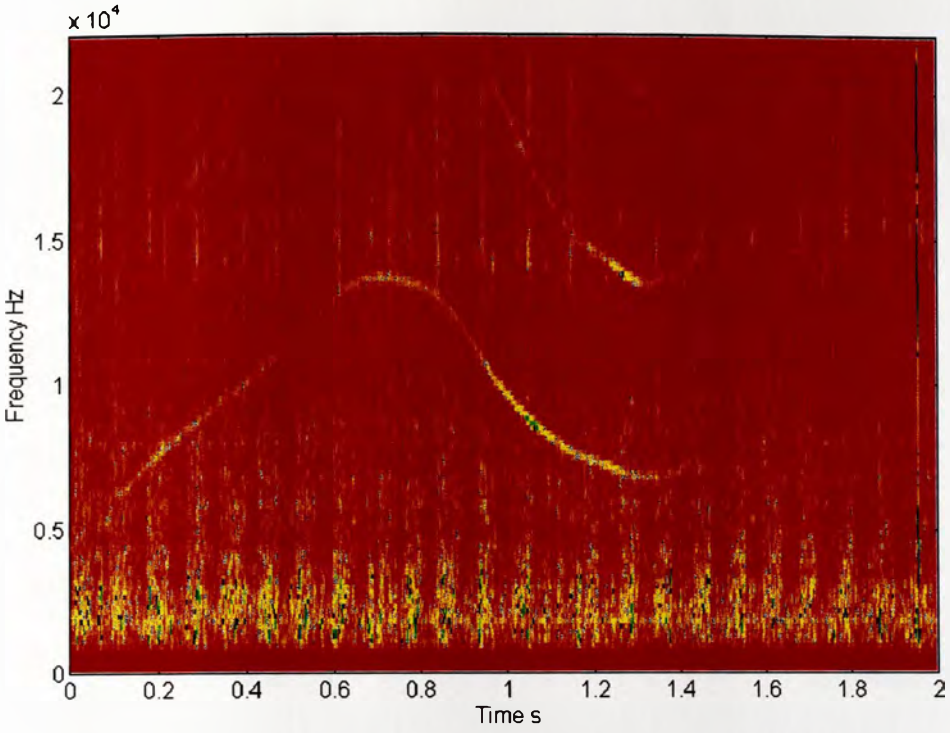
Whistle 3



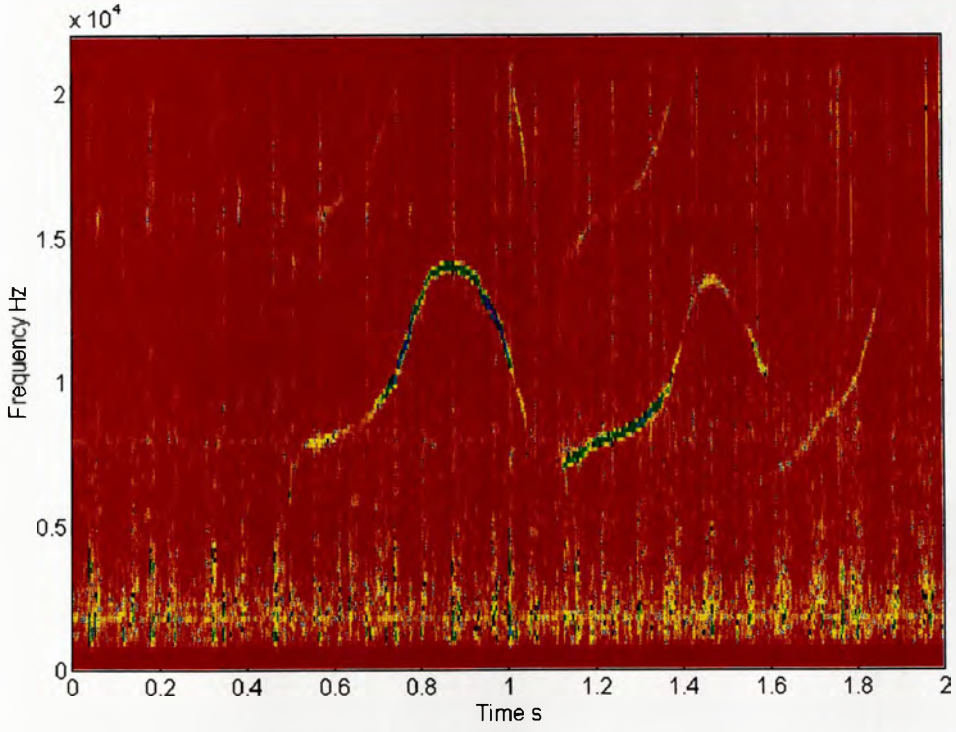
Whistle 4



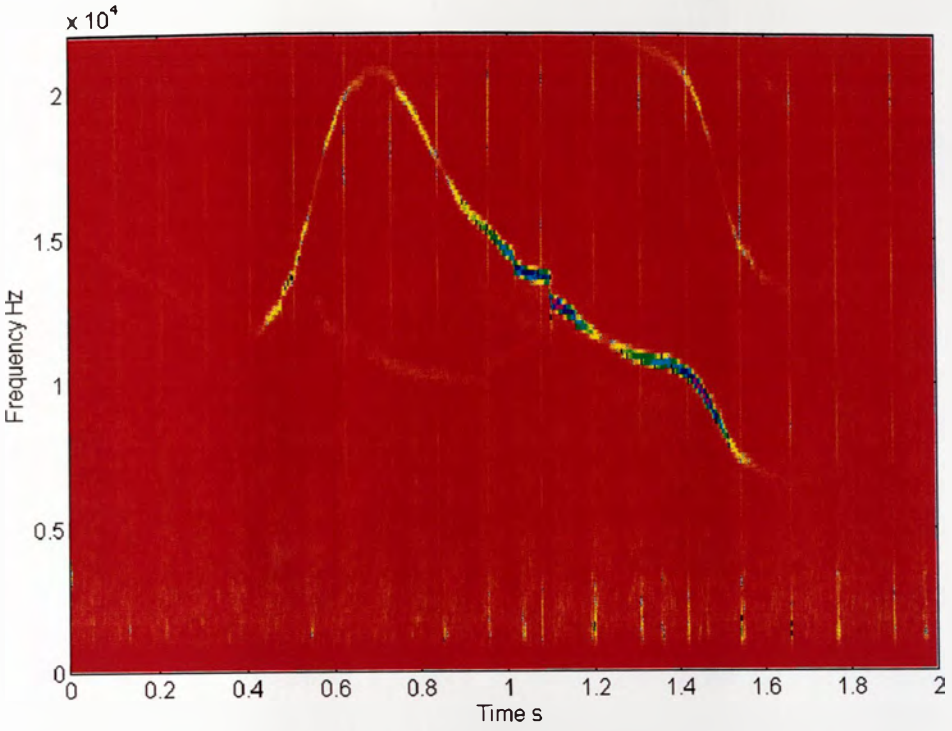
Whistle 5



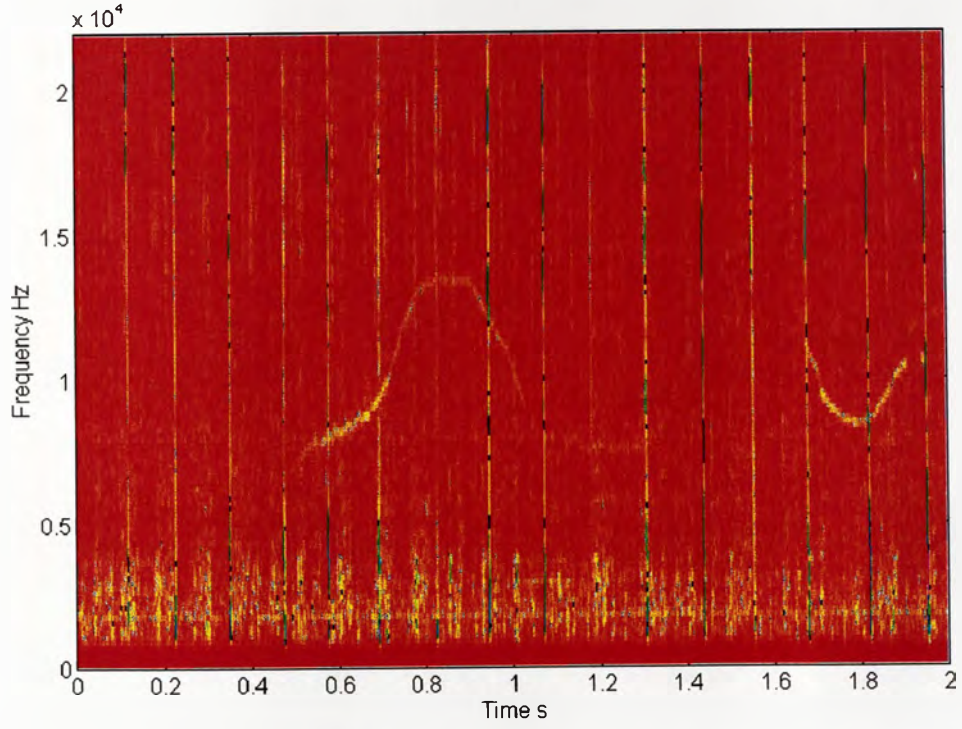
Whistle 6 & 7



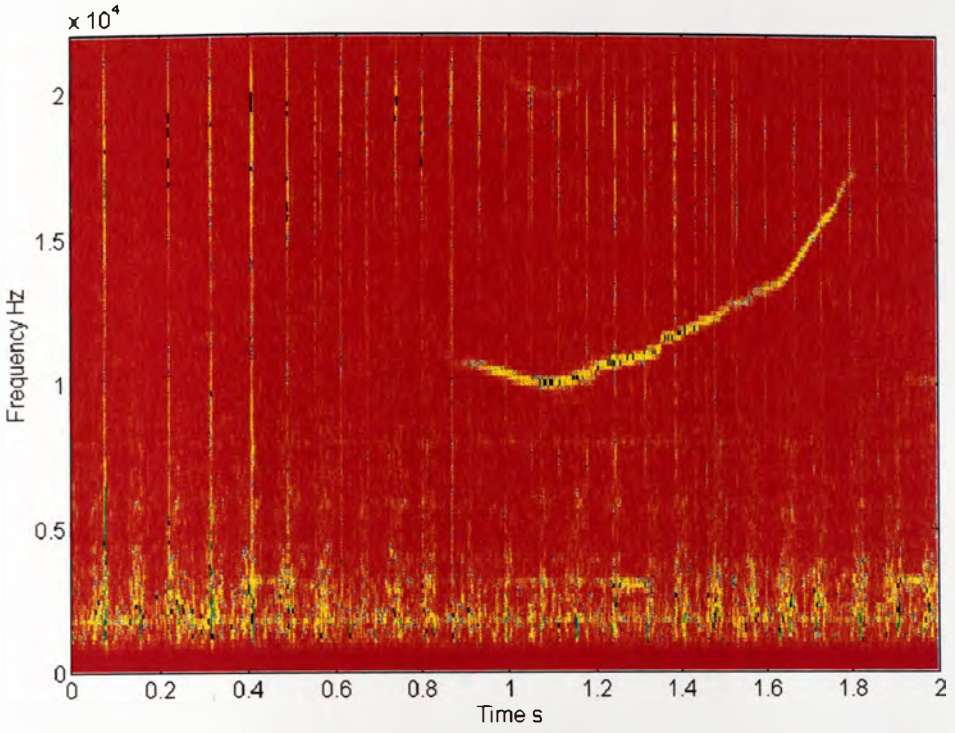
Whistle 8



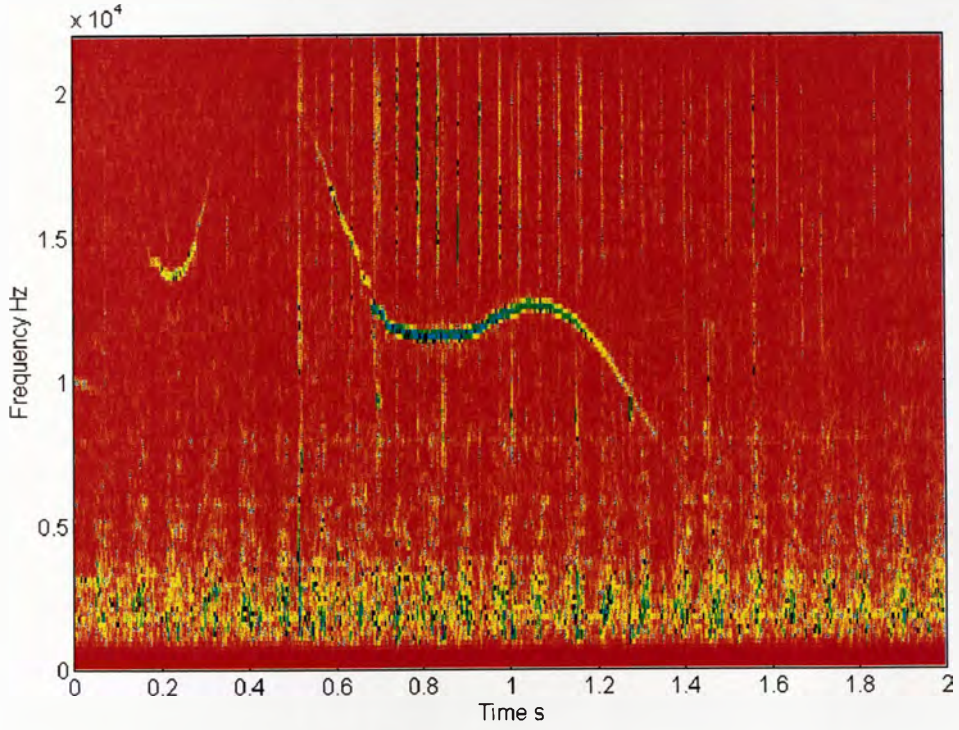
Whistle 9 & 10



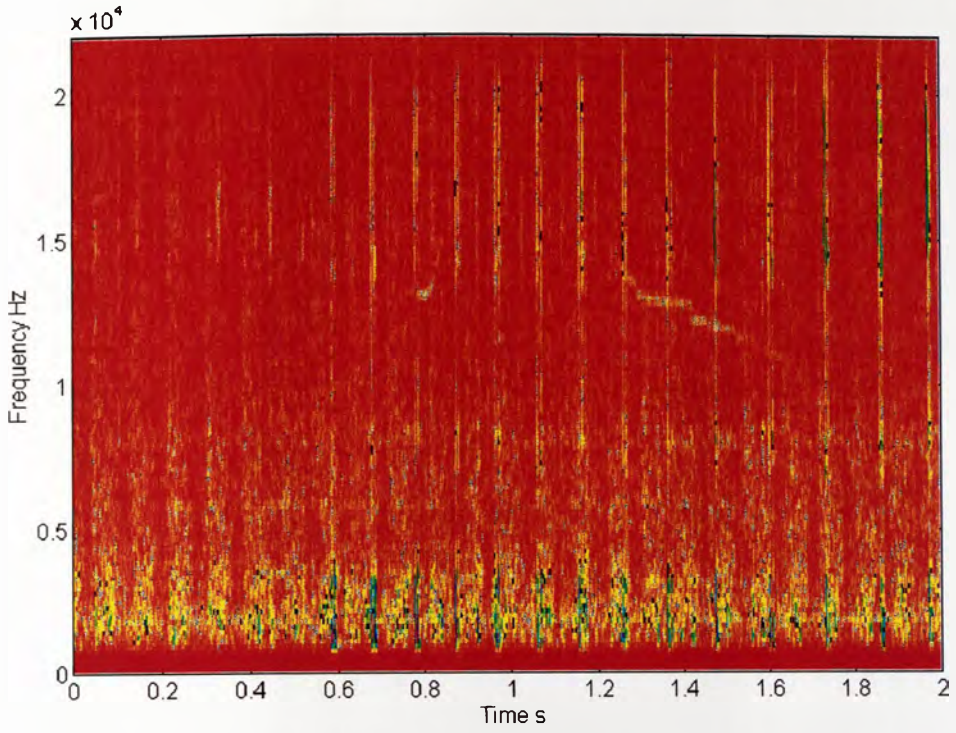
Whistle 12



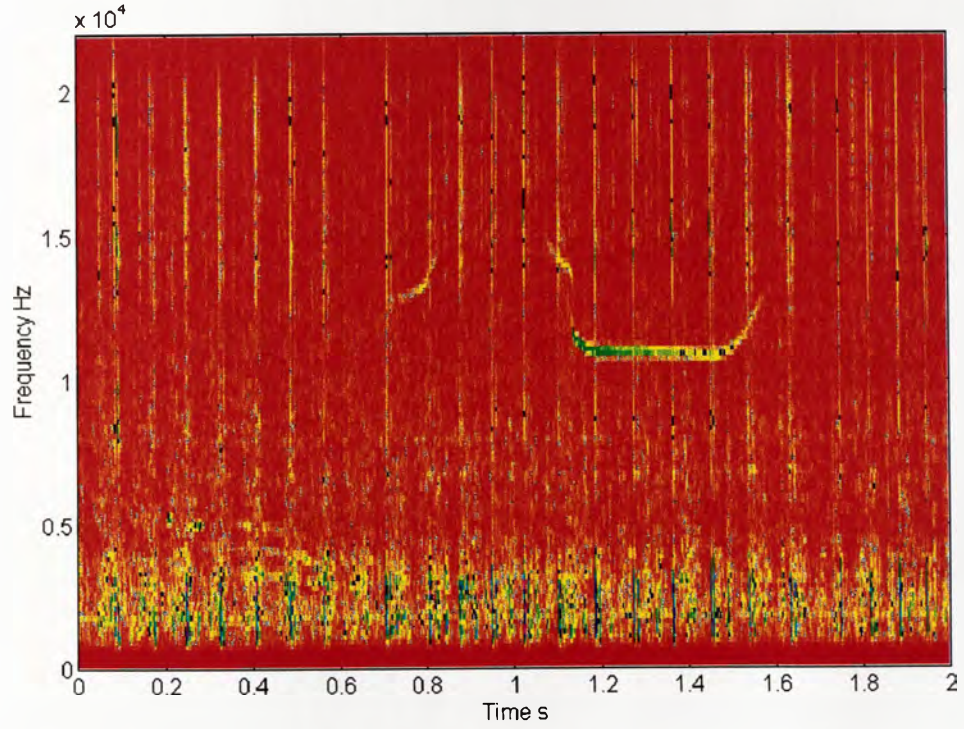
Whistle 13



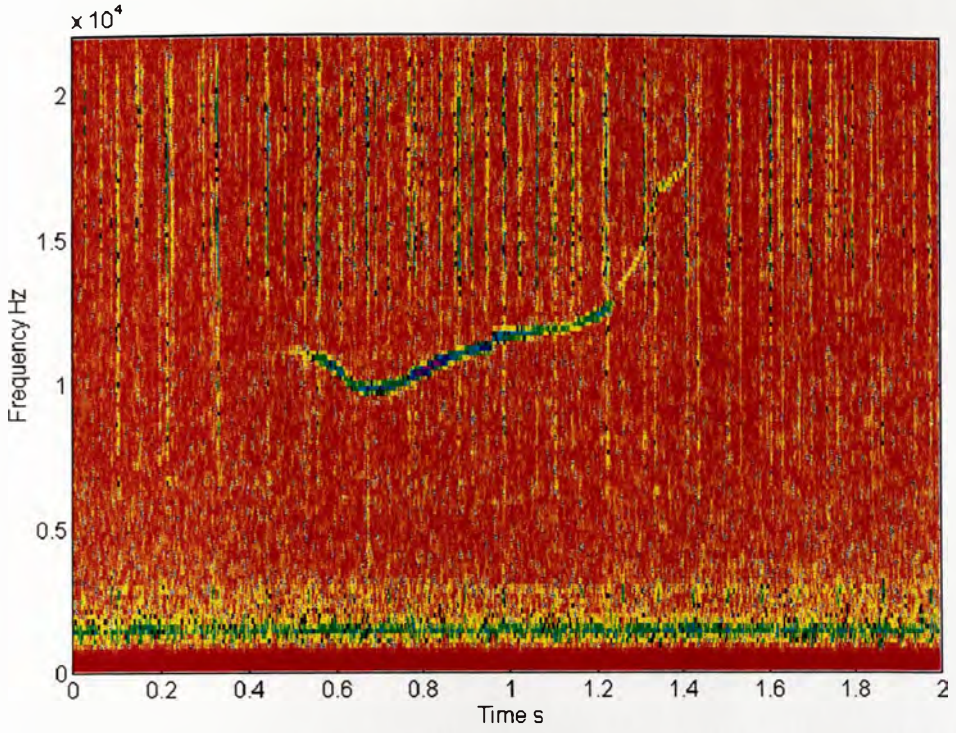
Whistle 13



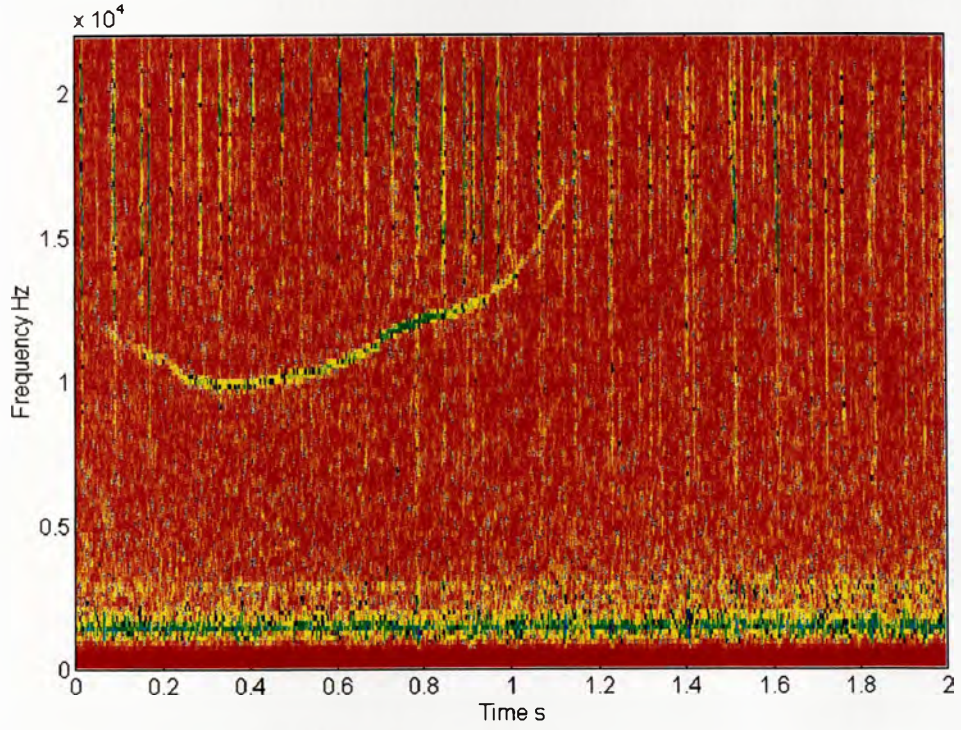
Whistle 14



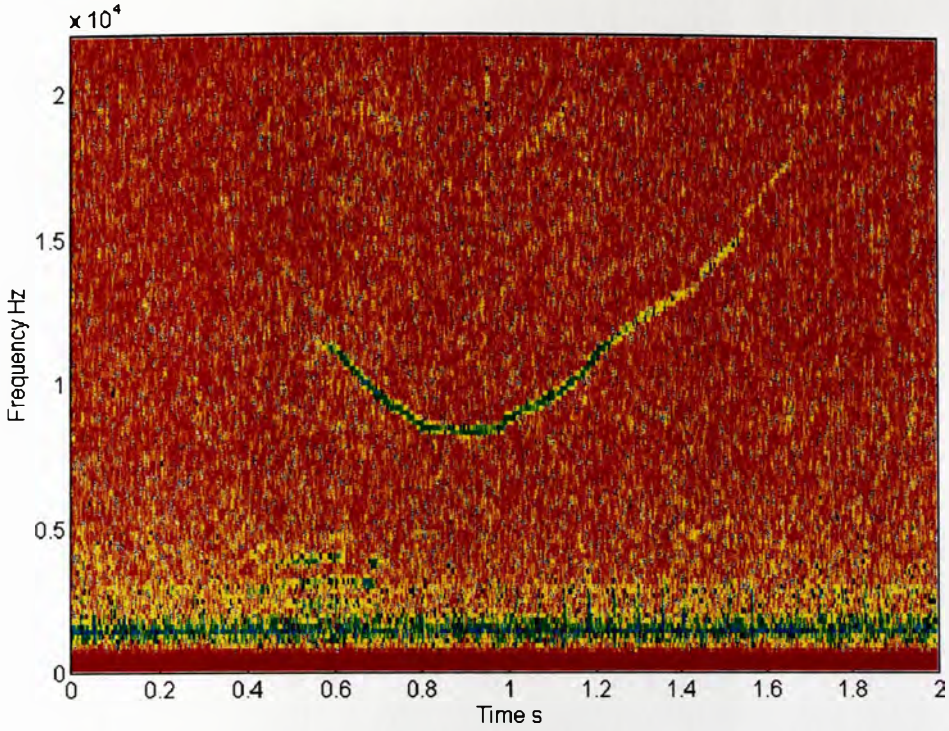
Whistle 15



Whistle 16



Whistle 17



Appendix D

Due to the short nature of the clicks emitted by dolphins there is a difficulty in measuring the rms source level. It is much easier to measure the peak to peak level. This peak to peak level is used by Au (1993) and he has derived the following expression to find the power in the signal from the measured peak to peak value.

$$I_{rms} = \frac{p_{rms}^2}{\rho c} \times 10^{-12}$$

The power of an omni directional source is calculated thus

$$P_0 = 4\pi r^2 I_{rms}$$

Power from an omnidirectional source is related to the power from a directional source by the following expression

$$\mathrm{DI} = 10\log\left(\frac{P_0}{P_D}\right) = 10\log(di)$$

where $di = P_o/P_d$. Therefore the radiated power in watts of a directional source is

$$P_D = \frac{4\pi r^2 I_{rms}}{di}$$

Therefore,

$$110\log P_D = \mathrm{SL}_{rms} - \mathrm{DI} - 171$$

The transmission directivity index has been measured by Au to be 25.8dB for *Tursiops truncatus.*

This relates the rms source level to acoustic power but we need to convert the peak to peak source level to the rms value.

The rms source level is calculated from the time waveform by this expression,

$$\mathrm{SL}_{rms} = 20\log(p_{rms})$$

$$p_{rms} = \sqrt{\frac{1}{T}\int_0^T p^2(t)dt}$$

$$p(t) = As(t)$$

A is the amplitude of the waveform and s is the normalised waveform. The rms pressure is found by integrating the time waveform,

$$\mathrm{SL}_{rms} = 20\log\left(\sqrt{\frac{A^2}{T}\int_0^T s^2(t)dt}\right)$$

The peak to peak source level is shown here,

$$SL_{pp} = 20\log(2A)$$

Therefore, the peak to peak and rms levels are related as follows,

$$SL_{rms} = SL_{pp} - 6 + 20\log\left(\sqrt{\frac{1}{T}\int_0^T s^2(t)}\right)$$

Au has numerically integrated this expression using a typical dolphin click and reports the following result,

$$SL_{rms} = SL_{pp} - 15.5\text{dB}$$

Therefore acoustic power is related to peak to peak source level by this expression.

$$110\log P = SL_{pp} - 212.3\text{dB re 1 Watt}$$

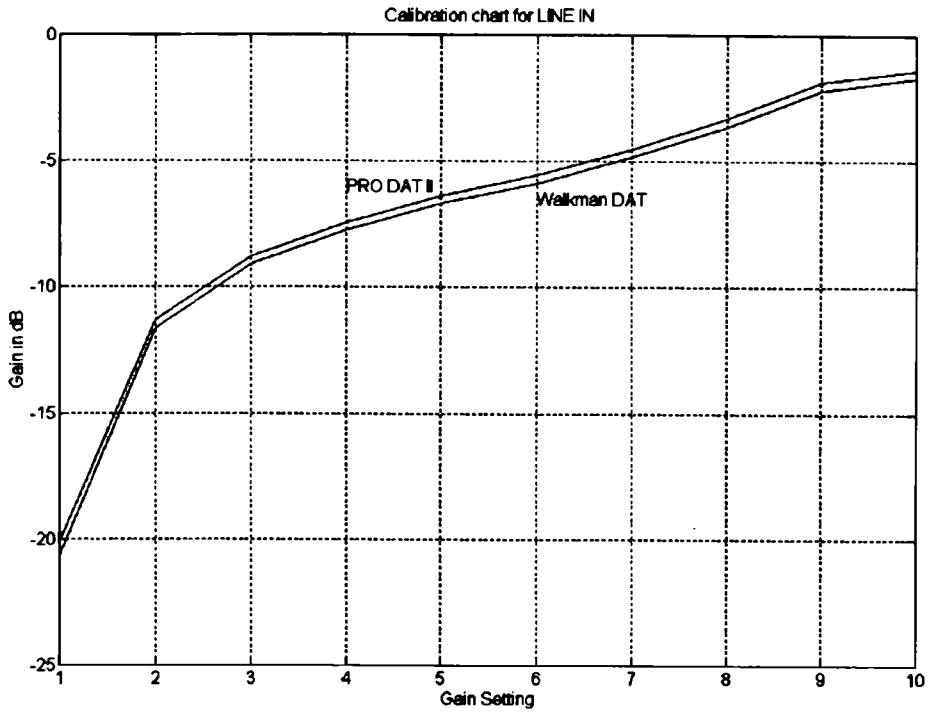
Appendix E

DAT Calibration Data

All of the data collected was recorded on a PRO DAT II TCD-D10 machine. Calibration of both this machine and a Walkman DAT TCD-D7 was performed. A 1kHz sine wave of varing amplitude was recorded on the PRO DAT at different gains and for different input sources. These were then played back on the two machines and the gain introduced was calculated. The PRO DAT has three different input settings, LINE IN, MIC no attenuation and MIC with 20dB attenuation.

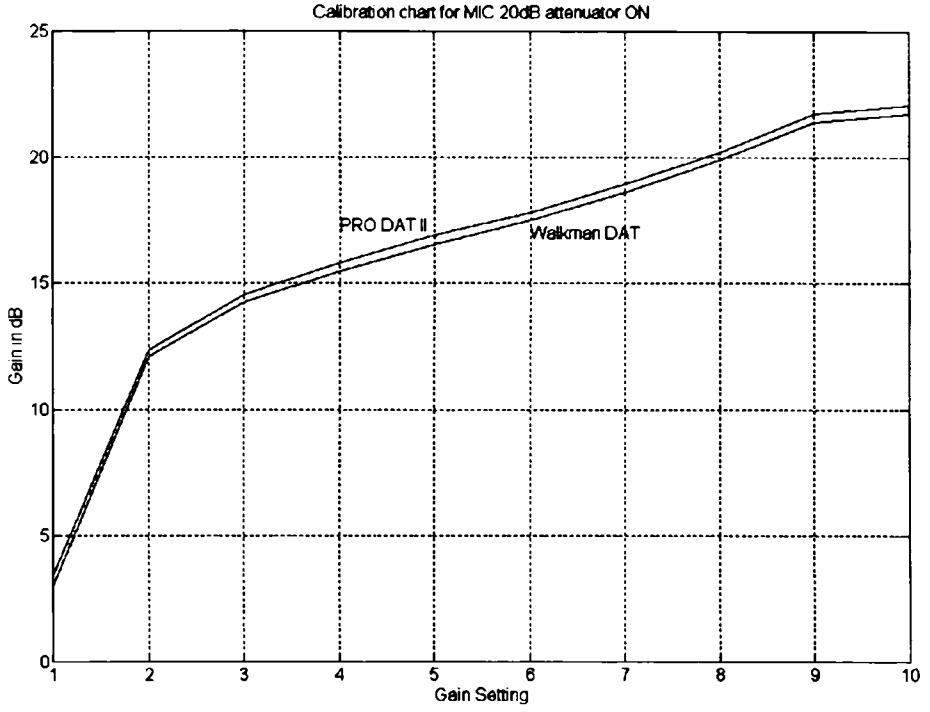
Input signal: 500mV peak 1kHz sine wave
Input to: LINE IN

	PRO DAT II TCD-D10			Walkman DAT TCD-D7		
Gain	RMS	PEAK	dB	RMS	PEAK	dB
10	0.257	0.363	-1.39	0.238	0.337	-1.71
9	0.229	0.324	-1.88	0.212	0.3	-2.22
8	0.165	0.233	-3.32	0.153	0.216	-3.65
7	0.125	0.177	-4.51	0.116	0.164	-4.84
6	0.098	0.139	-5.56	0.091	0.129	-5.88
5	0.0814	0.115	-6.38	0.0758	0.107	-6.70
4	0.0636	0.090	-7.45	0.0592	0.0837	-7.76
3	0.047	0.066	-8.79	0.0437	0.0618	-9.08
2	0.026	0.037	-11.31	0.0242	0.0342	-11.65
1	0.00345	0.0049	-20.09	0.0031	0.0043	-20.66


Calibration chart for LINE IN
0
-5
-10
-15
-20
-25
Gain in dB
PRO DAT II
Walkman DAT
1
2
3
4
5
6
7
8
9
10
Gain Setting

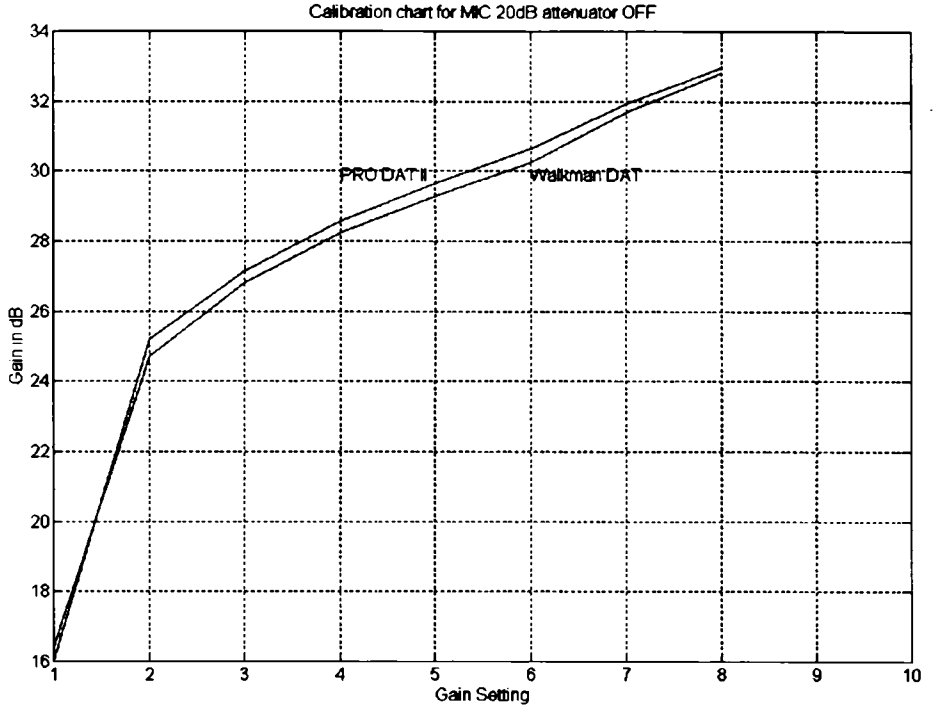
Input signal: 5mV peak 1kHz sine wave
Input to: MIC 20dB attenuator ON

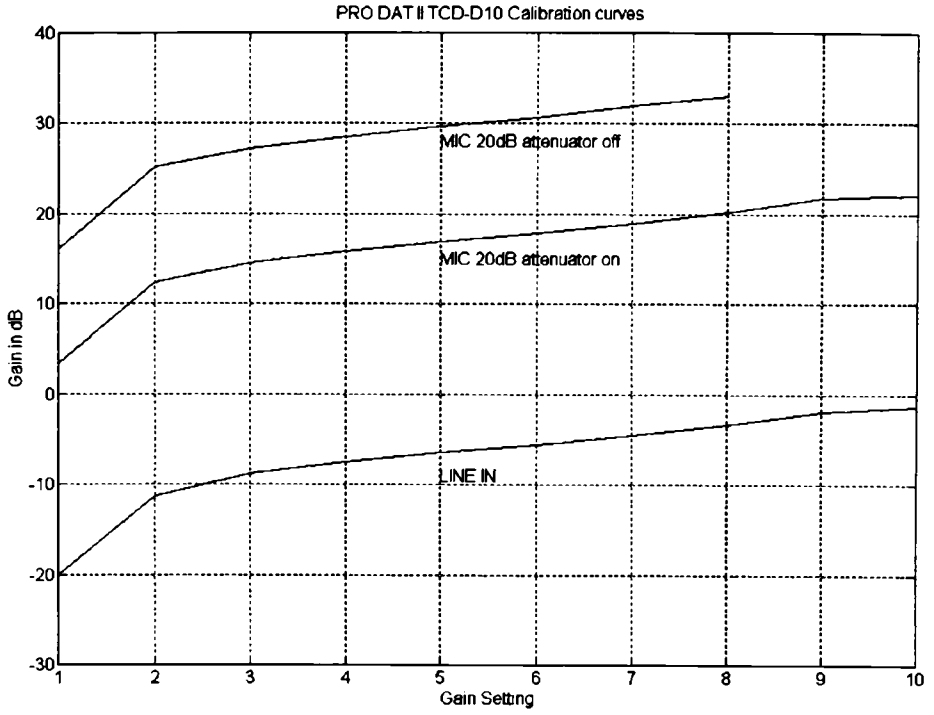
	PRO DAT II TCD-D10			Walkman DAT TCD-D7		
Gain	RMS	PEAK	dB	RMS	PEAK	dB
10	0.569	0.805	22.07	0.529	0.748	21.75
9	0.529	0.748	21.75	0.491	0.694	21.42
8	0.374	0.529	20.24	0.348	0.492	19.93
7	0.278	0.393	18.95	0.258	0.365	18.63
6	0.214	0.303	17.82	0.199	0.281	17.5
5	0.173	0.245	16.9	0.16	0.226	16.55
4	0.135	0.191	15.82	0.125	0.177	15.49
3	0.101	0.143	14.56	0.094	0.133	14.25
2	0.061	0.086	12.36	0.057	0.081	12.1
1	0.008	0.011	3.42	0.007	0.01	3.01

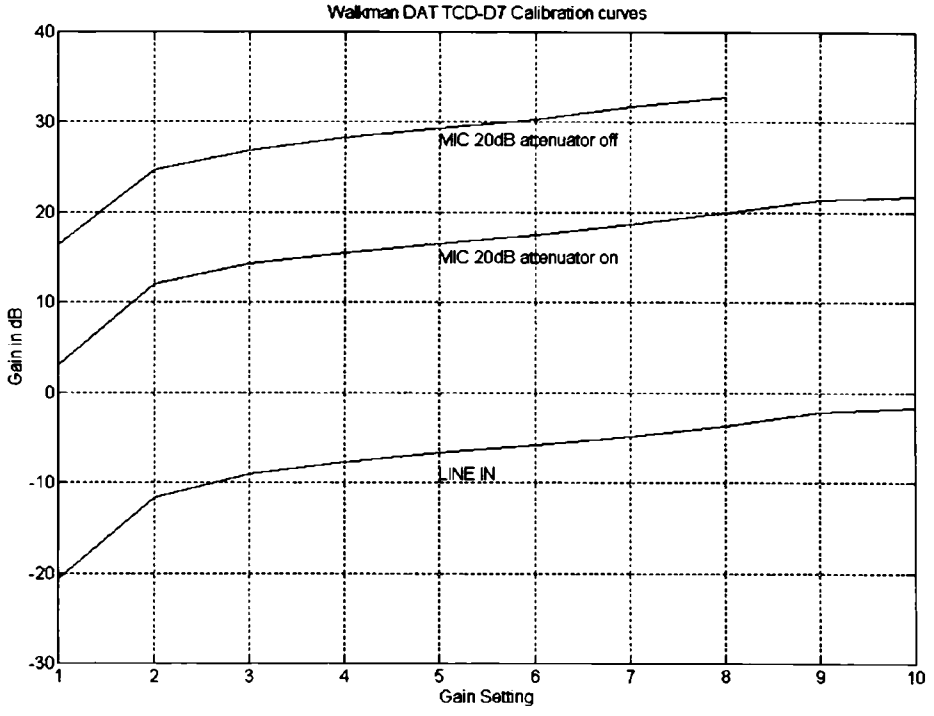


Input signal: 1mV peak 1kHz sine wave
Input to: MIC 20dB attenuator OFF

	PRO DAT II TCD-D10			Walkman DAT TCD-D7		
Gain	RMS	PEAK	dB	RMS	PEAK	dB
8	1.4	1.98	32.97	1.35	1.91	32.81
7	1.1	1.56	31.93	1.05	1.48	31.70
6	0.82	1.16	30.64	0.75	1.06	30.25
5	0.65	0.92	29.64	0.6	0.849	29.29
4	0.51	0.72	28.57	0.47	0.665	28.23
3	0.37	0.52	27.16	0.34	0.48	26.81
2	0.23	0.33	25.19	0.21	0.296	24.71
1	0.031	0.04	16.02	0.031	0.044	16.43




PRO DAT II TCD-D10 Calibration curves
MIC 20dB attenuator off
MIC 20dB attenuator on
LINE IN
Gain in dB
Gain Setting
40
30
20
10
0
-10
-20
-30
1
2
3
4
5
6
7
8
9
10


Walkman DAT TCD-D7 Calibration curves
MIC 20dB attenuator off
MIC 20dB attenuator on
LINE IN
Gain in dB
Gain Setting
40
30
20
10
0
-10
-20
-30
1
2
3
4
5
6
7
8
9
10

Appendix F

The position of point W, must conform to the following expressions,

$$(x - L)^2 + y^2 = (a + d)^2 \tag{F.1}$$

$$(x - L - s)^2 + y^2 = a^2 \tag{F.2}$$

L, s and d are known or can be calculated. x and y are the unknowns, therefore by eliminating a an expression relating x and y can be found,

Rearranging equation (F.2) for a we obtain,

$$a = \sqrt{(x - L - s)^2 + y^2} \tag{F.3}$$

Expansion of equation (F.1) yields,

$$a^2 + 2ad + d^2 = (x - L)^2 + y^2 \tag{F.4}$$

Substituting for a from equation (F.3) into equation (F.4) gives

$$(x - L - s)^2 + y^2 + 2d\sqrt{(x - L - s)^2 + y^2} + d^2 = (x - L)^2 + y^2 \tag{F.5}$$

Collecting the expressions with y on the left gives,

$$\sqrt{(x-L-s)^2+y^2} = \frac{(x-L)^2-(x-L-s)^2-d^2}{2d}$$

Squaring both sides and subtracting $(x\text{-}L\text{-}s)^2$ from both sides gives,

$$y^2 = \left(\frac{(x-L)^2-(x-L-s)^2-d^2}{2d}\right)^2 - (x-L-s)^2,$$

Which can be simplified to,

$$y = \sqrt{\left(\frac{(x-L)^2-(x-L-s)^2-d^2}{2d}\right)^2 - (x-L-s)^2} \qquad \text{(F.6)}$$

Appendix G

The Order Cetacea

The common and scientific names of the order cetacea are given below.

Suborder Mysticeti: The Baleen whales

Family Balaenidae: The Right whales

Bowhead whale, Balaena mysticetus
Northern Right whale, *Eubalaena glacialis*
Southern Right whale, *Eubalaena australis*
Pygmy Right whale, *Caperea mmarginata*

Family Balaenopteridae: The Rorqual whales

Blue whale, *Balaenoptera musculus*
Fin whale, *Balaenoptera physalus*
Sei whale, *Balaenoptera borealis*
Bryde's whale, *Balaenoptera edeni*
Minke whale, *Balaenoptera acutorostrata*
Humpback whale, *Megaptera novaeangliae*

Family Eschrichtiidae: The Gray whale

Gray whale, *Eschrichtius robustus*

Suborder Odontoceti: The toothed whales, Dolphins and porpoises

Family Physeteridae: The Sperm, Pygmy Sperm, and Dwarf Sperm Whales

Sperm whale, *Physeter macrocephalus*
Pygmy Sperm whale, *Kogia breviceps*
Dwarf Sperm whale, *Kogia simus*

Family Monodontidae: The Narwhal and White whale

Narwhal, *Monodon monoceros*
White whale or Beluga, *Delphinapterus leucas*

Family Ziphiidae: The Beaked whales

Baird's Beaked whale, *Berardius bairdii*
Arnoux's Beaked whale, *Berardius arnuxii*
Northern Bottlenose whale, *Hyperoodon ampullatus*
Southern Bottlenose whale, *Hyperoodon planifrons*
Cuvier's Beaked whale, *Ziphius cavirostris*
Tasman Beaked whale, *Tasmacetus shepherdi*

Genus Mesoplodin: The Mesoplodonts

Blainville's Beacked whale, *Mesoplodon densirostris*
Sowerby's Beaked whale, *Mesoplodon bidens*
Gervais' Beaked whale, *Mesoplodon europaeus*
True's Beaked whale, *Mesoplodon mirus*
Strap-toothed whale, *Mesoplodon layardii*
Gray's Beaked whale, *Mesoplodon grayi*
Andrew's Beaked whale, *Mesoplodon bowdoini*
Longman's Beaked whale, *Mesoplodon pacificus*
Hector's Beaked whale, *Mesoplodon hectori*
Ginkgo-toothed Beaked whale, *Mesoplodon ginkgodens*
Stejneger's Beaked whale, *Mesoplodon stejnegeri*

Hubb's Beaked whale, *Mesoplodon carlhubbsi*

Family Delphinidae: The Oceanic dolphins

Irrawaddy dolphin, Orcaella brevirostris
Melo-headed whale, *Peponocephala electra*
Pygmy Killer whale, *Feresa attenuata*
False Killer whale, *Pseudorca crassidens*
Killer whale, *Orcinus orca*
Long-finned Pilot whale, *Globicephala melaena*
Short-finned Pilot whale, *Globicephala mmacrorhynchus*
Rough-toothed dolphin, *Steno bredanensis*
Tucuxi, *Sotalia fluviatilis*
Indo-Pacific Hump-backed dolphin, *Sousa chinensis*
Atlantic Hump-backed dolphin, *Sousa teuszii*
White-beaked dolphin, *Lagenorhynchus albirostris*
Atlantic White-sided dolphin, *Lagenorhynchus acutus*
Dusky dolphin, *Lagenorhynchus obscurus*
Pacific White-sided dolphin, *Lagenorhynchus obliquidens*
Hourglass dolphin, *Lagenorhynchuscruciger*
Peale's dolphin, *Lagenorhynchusaustralis*
Fraser's dolphin, *Lagenorhynchus hosei*
Common dolphin, *Delphinus delphis*
Bottlenose dolphin, *Tursiops truncatus*
Risso's dolphin, *Grampus griseus*
Spotted dolphins, *Stennella spp., including Stenella attenuata, Stenella dubia, Stenella frontalis, and Stenella plagiodon*
Striped dolphin, *Stenella coeruleoalba*
Long-snouted Spinner dolphin, *Stenella longirostris*
Short-snouted Spinner or Clymene dolphin, *Stenella clymene*
Southern Right whale dolphin, *Lissodelphis peronii*
Northern Right whale dolphin, *Lissodelphis borealis*
Heaviside's dolphin, *Cephalorhynchus heavisidii*
Hector's dolphin, *Cephalorhynchus hectori*
Black dolphin, *Cephalorhynchus eutropria*
Commerson's dolphin, *Cepalorhynchus commersonii*

Family Phocoenidae: The True porpoises

Harbor porpoise, *Phocoena phocoena*
Burmeister's porpoise, *Phocoena spinipinnis*
Cochito, *Phocoena sinus*
Spectacled porpoise, *Phocoena dioptrica*
Dall's porpoise, *Phocoena dalli*
Finless porpoise, *Neophocaena phocaenoides*

Family Platanistidae: The River dolphins and the Franciscana

Indud susu, *Platanista minor*
Ganges susu, *Platanista gangetica*
Boutu, *Inia geoffrensis*
Beiji, *Lipotes vexillifer*
Franciscana, *Pontoporia blainvillei*

Appendix H

Wave File Format

Byte Number	HEX	ASCII	Description
1	52	R	
2	49	I	
3	46	F	
4	46	F	
5,6,7,8			size of the remainder of the file in bytes
9	57	W	
10	41	A	
11	56	V	
12	59	E	
13	66	f	
14	6D	m	
15	74	t	
16	20		
17,18,19,20	10		size of the format structure
21,22	1		format tag (WAVE_FORMAT_PCM)
23,24			Number of channels (1=mono, 2=stereo)
25,26,27,28			samples per second
29,30,31,32			bytes per second
33,34			block align
35,36			bits per sample (8 or 16)
37	64	d	
38	61	a	
39	74	t	
40	61	a	
41,42,43,44			size of the data block following

Arrangement of the bytes in the following data block

byte number	45	46	47	48	49	50	51
8 bit mono	left	left	left	left	left	left	left
8 bit stereo	left	right	left	right	left	right	left
16 bit mono	high left	low left	high left	low left	high left	low left	high left
16 bit stereo	high left	low left	high right	low right	high left	low left	high right

Appendix I

Specgram assembly code for ADSP 21020

```
{_____________________________________________________________
SPECGRAM.ASM      This program is the top-level of the spectral routines.
_____________________________________________________________}
#include  "constant.h"

{_____________________External Variables and Routines_____________________}
.EXTERN spectral;     {Routine that runs spectral demo}

.SEGMENT/DM         iocard;
.PORT  iocard;
.ENDSEG;

.SEGMENT/PM         pm_sram;
.ENDSEG;

.SEGMENT/DM         dm_sram;

{variables for DAC output service routine}

.VAR   adacbuf[PNTS/2+1+2];                 {Buffer for DAC A}{two extra bins }
.VAR   bdacbuf[PNTS/2+1+2];                 {Buffer for DAC B}{ are dummies  }

{variables for the hip interface routine}

.VAR   inleft[PNTS];                        {audio left channel input buffer}
.VAR   inright[PNTS];                       {audio right channel input buffer}
.VAR   outleft[2*PNTS];                     {audio left channel output buffer}
.VAR   outright[2*PNTS];                    {audio right channel output buffer}
.VAR   inbufptr;                            {tracks pntr to inbuffer for intffir}
.VAR   aadc_dat;                            {ADC A current data in}
.VAR   badc_dat;                            {ADC B current data in}

{variables for the cursor routine}

.VAR curbuffer;
.VAR nextbuffer;
.VAR curbin;
.VAR orgvalue;
.VAR xtable[16]=    -16, -8, -4, -4, -2, -1,  0,  1,
                          2,  2,  4,  4,  4,  8,  8, 16;

.GLOBAL adacbuf;
.GLOBAL bdacbuf;
.GLOBAL inleft;
.GLOBAL inright;
.GLOBAL inbufptr;
.GLOBAL outleft;
.GLOBAL outright;
.GLOBAL aadc_dat;                           {ADC A current data in}
.GLOBAL badc_dat;                           {ADC B current data in}
.GLOBAL curbuffer;
.GLOBAL nextbuffer;
.GLOBAL curbin;
.GLOBAL orgvalue;
.ENDSEG;

{These are the 2111 hip port addresses}

.SEGMENT/DM         hip_regs;
.PORT  hdr0;                                {in left audio}
.PORT  hdr1;                                {in right audio}
.PORT  hdr2;                                {out left audio}
.PORT  hdr3;                                {out right audio}
.PORT  control_0;                           { AD1849 input source, and gain }
.PORT  control_1;                           { AD1849 sample rate }
.ENDSEG;
```

```
{Addrs for the AD7769 8-bit ADC/DAC}

.SEGMENT/DM        adc_a;
.PORT  adc_a;
.ENDSEG;

.SEGMENT/DM        adc_b;
.PORT  adc_b;
.ENDSEG;

.SEGMENT/DM        dac_a;
.PORT  dac_a;
.ENDSEG;

.SEGMENT/DM        dac_b;
.PORT  dac_b;
.ENDSEG;

{_____reset service routine_____}

.SEGMENT/PM        rst_svc;                    { program starts at the reset vector }
        PMWAIT=0x0021;                         {pgsz=0,pmwtstates=0,intrn.wtstates only}
        DMWAIT=0xa421;                         {pgsz=0,dmwtstates=0,intrn.wtstates only}
                                               {except DM bank2 has 2 waitstates}

        bit set mode2 0x10;                    {cache init workaround}
        nop;
        read cache 0;
        bit clr mode2 0x10;

        jump start;

.ENDSEG;

{_____DAC output service routine_____}
.SEGMENT/PM        tmzh_svc;
        jump dac_rnt (db);
          bit set mode1 SRRFHISRD1H;           {set alt DAG 4-7, R(8-15) registers}
          bit clr mode1 BR0;                   {make sure we are not bit reversing    }
.ENDSEG;

{_____Control word service routine_____}
.SEGMENT/PM        irq1_svc;
        jump settings;
.ENDSEG;

{_____2111 hip service routine_____}
.SEGMENT/PM        irq3_svc;
        jump hip_rnt (db);
          bit set mode1 SRRFLISRD1L;           {set alternate DAG 0-3, R(0-7) registers}
          bit clr mode1 BR0;                   {make sure we are not bit reversing    }
.ENDSEG;

{_____Interrupt button service routine_____}
.SEGMENT/PM        irq2_svc;

        bit tst ustat2 2;                      { test if AD1849 setup mode is enabled }
        if not tf jump skip_setup;             { for AD1849 setup }
        bit set ustat2 1;                      { for AD1849 setup }
skip_setup:                                    { label for AD1849 setup }

        bit set ustat1 IRQED;                  {flag irq2 pressed}
        if not flag0_in rti;
        rti (db);
          bit set ustat1 FLIRQ;                {also flag if flag0 at same time}
          nop;
.ENDSEG;
```

```
.SEGMENT/PM         pm_sram;
start:
          imask  =IRQ3I|IRQ2I|TMZHI;        {unmask irq3,irq2,timer.high}
          tperiod =DACPER;                  {period of DAC output}
          tcount  =tperiod;
          mode1  =ALUSAT;                   {enable ALU saturation}
          mode2  =0x0007002f;               {edge-sen. interrupts,
                                              enable timer, flag1-3 out}
  {perform init for dac_rnt}
          bit set mode1 SRD1H|SRRFH;        {set alternate DAG 4-7, R(8-15) registers}
          nop;
            b4=dac_a;
            b5=dac_b;
            b6=adacbuf;                     {set up buffers}
            b7=bdacbuf;
            l4=0x0;
            l5=l4;
            l6=PNTS/2+1+2;                  {two extra bins as dummies}
            l7=PNTS/2+1+2;                  {two extra bins as dummies}
            m7=1;
          bit clr mode1 SRD1H|SRRFH;        {back to regular DAG 4-7, R(8-15) registers}
          nop;

  {perform init for hip_rnt}
          bit set mode1 SRD1L|SRRFL;        {set alternate DAG 0-3, R(0-7) registers}
          nop;                              {set up buffers}
            b0=inleft;
            b1=inright;
            b2=outleft;
            b3=outright;
            l0=PNTS;
            l1=l0;
            l2=2*PNTS;
            l3=l2;
            m0=1;
            m2=0;
            r2=PNTS/2;
            r3=PNTS;
          bit clr mode1 SRD1L|SRRFL;        {back to regular DAG 0-3, R(0-7) registers}
          nop;

          do demos until forever;
            ustat1=0x00000000;              {clears status of routines}
            do wait1 until not flag0_in;    {wait for flag0 to be depressed}
                    bit set astat FLG1;     {signal no demo}
                    bit set astat FLG2;
wait1:     bit set astat FLG3;
            do wait2 until flag0_in;        {waits for flag0 to start demos}
                    lcntr=0x5f5e10;
                    do (pc,1) until lce;
                      if flag0_in jump wait2 (la);
                    bit tgl astat FLG1|FLG2|FLG3;
wait2:     if flag0_in jump espl (la);

espl:
            call setup;
            IRPTL=0x0;                      {clear out interrupts}
            bit set mode1 IRPTEN;           {enable interrupts}

            bit clr astat FLG2;
            bit clr astat FLG3;
            call spectral;

            nop;
            nop;
demos:    bit clr mode1 IRPTEN;             {disable interrupts}
```

```
{_____DAC output routine_____
Dag alternate reg defs:
  b4: addr of DAC A
  b5: addr of DAC B
  b6: addr of adacbuf
  b7: addr of bdacbuf
  i6: pointer to adacbuf
  i7: pointer to bdacbuf
  m7: 1

USTAT1 bits:
  4:  DAC A output enable
  5:  DAC B output enable

_____}

dac_rnt:
  {if pntr at start of buf, we need to make decisions}
          r10=i6;
          r11=l6;
          r11=r11-1,    r12=b6;
          r10=r10-r12,  r8=dm(i6,m7);          {read data from buffers and upd pntrs}
          comp(r10,r11), r9=dm(i7,m7);
          if eq jump zero;                     {at second dummy, output zeros}
          r11=r11-r10+CI-1;                    {CI=0}
          if eq jump trigger;                  {at first dummy, do the osc. trigger}

outdac: bit tst ustat1 ENDAA;                  {only write to DACs if enabled in USTAT1}
          if tf dm(i4,0)=r8;                   {write to DAC A}
          r8=lshift r8 by -24;
          dm(iocard)=r8;                       {output to interface card}
          bit tst ustat1 ENDAB;
          if tf dm(i5,0)=r9;                   {write to DAC B}
          pop sts;                             {workaround int stack pop anamoly}
          push sts;
          rti;                                 {This also switches contexts since MODE1 pop}


zero:  tcount= TDLYLEN;                        {for delay after trigger}
          jump outdac (db);
            r8=0x00000000;                     {zero dac}
            r9=0x00000000;

trigger:                                       {since we finished forw. scan, }
          bit tst ustat1 LADC;
          if not tf jump do_b (db);
            bit tgl ustat1 LADC;
            r13=dm(adc_a);

do_a:  jump trgcon (db);
            dm(aadc_dat)=r13;                  {store new data}
            dm(adc_b)=r13;                     {start ADC B conversion}

do_b:  call cursor (db);                       {do a call to the cursor routine now}
            dm(badc_dat)=r13;                  {store new data}
            dm(adc_a)=r13;                     {start ADC A conversion}

trgcon: tcount= TRIGLEN;                       {for longer trigger}
          jump outdac (db);
            r8=0xff000000;                     {pound DAC for trigger}
            r9=0xff000000;
```

```
{_____2111 hip service routine_____
This routine gets data from and puts data to the ADSP-2111. More specifically
it:
        1) grabs left/right audio data from the HDR0 and HDR1 on the 2111
        2) grabs 2111 status information from HDR4
        3) puts left/right proc. audio data into HDR2 and HDR3

Defined alternate DAG registers are:
  b0,i0:   buffer and pointer to inleft
  b1,i1:   buffer and pointer to inright
  b2,i2:   buffer and pointer to outleft
  b3,i3:   buffer and pointer to outright
  m0:      1
  m2:      0

Defined alternate RF registers are:
  r2:      half point of in buffers
  r3:      half point of out buffers

USTAT1 bits:
  0,1:  left, right output enable
  2,3:  left, right input enable

  16:   output buffer half filled flag
  17:   output buffer filled flag
  18:   input buffer half filled flag
  19:   input buffer filled flag

_____________________________________________________________________}
hip_rnt:
        bit clr ustat1 0x0f0000;            {clear buffer flags}

  {get data from hip}
        r0=dm(hdr0);
        r1=dm(hdr1);
        dm(i0,m2)=0x0;                      {initialize to zero first}
        dm(i1,m2)=0x0;
        bit tst ustat1 ENIAL;               {if input enabled, write in the data}
        if tf dm(i0,0)=r0;
        bit tst ustat1 ENIAR;
        if tf dm(i1,0)=r1;
        modify(i0,1);                       {always update both pointers}
        modify(i1,1);
        dm(inbufptr)=i0;

  {set flags}
        r0=i0;
        r4=b0;
        r0=r0-r4;                           {find offset}
        if ne jump (pc,2);
        bit set ustat1 INBF;                {zero offset =>flag buffer filled}
        comp(r0,r2);
        if ne jump (pc,2);
        bit set ustat1 INBH;                {flag half buffer offset}

  {put data to the hip}
        r0=dm(i2,m0);
        r1=dm(i3,m0);
        bit tst ustat1 ENOAL;               {if output enabled, write out to hip}
        if not tf jump (pc,2);
          dm(hdr2)=r0;
        bit tst ustat1 ENOAR;
        if not tf jump (pc,2);
          dm(hdr3)=r1;

  {set flags}
        r0=i2;
        r5=b2;
        r0=r0-r5;                           {find offset}
        if ne jump (pc,2);
          bit set ustat1 OUTBF;             {zero offset =>flag buffer filled}
        comp(r0,r3);
        if ne jump (pc,2);
          bit set ustat1 OUTBH;             {flag half buffer offset}

        pop sts;
```

```
        push sts;

        rti;
        nop;
        nop;


{_____Change Setup for the AD1849_____}

setup:
        r0=0x000d0000;                  { modulo 16 }
        dm(control_1)=r0;               { output sample rate to 2111 hip }
        r0=0x5b000000;
        dm(control_0)=r0;               { write to 2111 hip }
        rts;

{_____Change settings of sound port_____}
settings:
        r0=dm(iocard);
        r0=lshift r0 by 16;
        r1=0x000F0000;
        r0=r0 AND r1;
        dm(control_1)=r0;

        r1=lshift r1 by -1;
        r0=r1;
        r1=0x38000000;
        r0=r1 AND r1;
        r0=lshift r0 by -3;
        r0=r0 OR r1;
        r1=0x7F000000;
        r0=r0 AND r1;
        dm(control_0)=r0;
        rti;

.ENDSEG;
```

Spectral Routine

```
{_____________________________________________________________________
SPECTRAL.ASM
   This program converts data in *inleft* and *inright* to floating point format,
 does Blackman-Harris windowing on it and then feeds it to rfft2.asm.
After the RFFT, it computes the magnitude, scales the data and places it in *adacbuf*
and *bdacbuf* for display on an oscilloscope or transfer to the PC.
This entire sequence of events is triggered by the input buffer full flag in USTAT1.
_____________________________________________________________________}
#include   "constant.h"

.EXTERN rfft2, logb2;
.GLOBAL spectral;
.GLOBAL win_dat, log_mag;

.SEGMENT/PM         pm_sram;
.EXTERN imfft;

.VAR   window[PNTS/2+1]= "bhwin.dat";

.ENDSEG;

.SEGMENT/DM         dm_sram;
.EXTERN inright;
.EXTERN inleft;
.EXTERN real;
.EXTERN refft;
.EXTERN adacbuf;
.EXTERN bdacbuf;
.EXTERN badc_dat;

.VAR   tmpright[PNTS];                    {temporary in audio right buffer}
.GLOBAL tmpright;
.ENDSEG;

.SEGMENT/PM         pm_sram;
spectral:
          ustat1=CNFG_SPEC;               {Enable left audio in and  DAC A out}

again:  bit clr astat BTF;
          do nothing until forever;       {Wait until in audio buffer is full}
            bit tst ustat1 INBF;          {Test if in audio buffer is full}
            if tf jump go (la);
            bit tst ustat1 INBH;
nothing:   if tf jump go (la);

go:    bit set astat FLG1;                {Turn on analog usage meter}

          bit tst ustat1 IRQED;           {check if irq2}
          if not tf jump (pc,3);
           bit tgl ustat1 UM1;            {toggle user mode bit 1}
           bit clr ustat1 IRQED;

          b0=inleft;                      {in audio data}
          l0=PNTS;
          b1=inright;
          l1=PNTS;

          bit tst ustat1 INBH;
          if not tf jump bfull;
           nop;
           nop;
           i0=inleft+PNTS/2;
           i1=inright+PNTS/2;

bfull:  b4=real;                          {processing buffers}
          l4=PNTS;
          b5=tmpright;
          l5=l4;

          m1=1;

   {Move data to processing buffers, do fixed to float conversion}
```

```
            r15=FSCL;

            r0=dm(i0,m1);
            r1=dm(i1,m1);

            lcntr=PNTS, do fconv until lce;
              f4=float r0 by r15, r0=dm(i0,m1);
              f5=float r1 by r15, r1=dm(i1,m1);
              dm(i4,m1)=f4;
fconv:      dm(i5,m1)=f5;

  {perform Blackman-Harris windowing on left audio data in *real*}
            b0=real;                              {src pointer to *real*}
            l0=PNTS;
            i4=real+PNTS-1;                       {src  backward pointer to *real*}
            l4=0;
            call win_dat;

  {perform the FFT of the left audio data}
            call rfft2;

  {if FLAG0, do not update display}
            if flag0_in jump skip_adac;

  {do 2*log2 on FFT data and put it in adacbuf}
            b1=adacbuf;                           {destination buffer}
            l1=PNTS/2+1;
            bit tst ustat1 UM1;
            if not tf call log_mag;
            bit tst ustat1 UM1;
            if tf call lin_mag;

skip_adac:
  {check if we need to compute data for right channel}
            bit tst ustat1 ENDAB;
            if not tf jump clean_up;              {if not, go to end of routine}

  {do the right channel, window the data and put it into *real*}
            b0=tmpright;                          {src pointer to *tmpright*}
            l0=PNTS;
            i4=tmpright+PNTS-1;                   {src pntr to end of *tmpright*}
            l4=0;
            call win_dat;

  {perform the FFT of the right audio data}
            call rfft2;

  {if FLAG0, do not update display}
            if flag0_in jump clean_up;

  {do 2*log2 on FFT data and put it in bdacbuf}
            b1=bdacbuf;                           {destination buffer}
            l1=PNTS/2+1;
            bit tst ustat1 UM1;
            if not tf call log_mag;
            bit tst ustat1 UM1;
            if tf call lin_mag;

clean_up:   {check if we should continue.}
            bit clr astat FLG1;                   {Turn off analog usage meter}
            nop;
            bit tst ustat1 FLIRQ;                 {Is it O.K. for next?}
            if not tf jump again;                 {  nope, continue}

            rts;                                  {if FLAG0+IRQ2 then finished}
```

```
{_____________________________________________________________________
WIN_DAT
  This routine windows the data pointed to by i0 (forward) and i4 (backward)
and stores it in *real*.  The windowing data table is *window*.
_____________________________________________________________________}
win_dat:
  {perform Blackman-Harris windowing and store it in *real*}
        b2=real;                                {dest pointer to *real*}
        l2=l0;
        i6=real+PNTS-1;                         {dest backward pointer to *real*}
        l6=0;
        i8=window+PNTS/2;                       {backward window pointer}
        l8=l6;

        m7=-1;
        m8=-1;

        {Do first point}
                        f1=dm(i0,m1), f0=pm(i8,m8);
        f8=f0*f1;
                        dm(i2,m1)=f8;

                        f1=dm(i0,m1);
                        f2=dm(i4,m7),  f0=pm(i8,m8);

        {Do the rest, including the midpoint}
        lcntr=PNTS/2, do l_win until lce;
          f8=f0*f1,  f1=dm(i0,m1);
          f9=f0*f2,  f2=dm(i4,m7),  f0=pm(i8,m8);
                        dm(i2,m1)=f8;
l_win:          dm(i6,m7)=f9;
        rts;
        nop;
        nop;

{_____________________________________________________________________
LOG_MAG
  This routine computes 2*log2(magnitude(FFT))*scaling to display and
certain dynamic range on the scope and puts it in the buffer pointed to by
 b1/i1 for dac output.
_____________________________________________________________________}
log_mag:
        b0=refft;
        l0=PNTS/2+1;
        l3=0;                                   {this is for the logb2 routine}

        b8=imfft;
        l8=PNTS/2+1;

        m1=1;
        m8=1;

        f14=LGOFF;                              {log offset}
        f15=256.0*3.01/DRNG;                    {coeff. for dynamic range}
        m15=SCLIP;                              {display clipping value}
                                                        f4=dm(i0,m1),  f5=pm(i8,m8);
          f4=f4*f4;                             {square real}

        lcntr=PNTS/2+1, do lmloop until lce;
          f5=f5*f5;                             {square imag}
          f0=f4+f5;
          if EQ jump (pc,4);
          call logb2;

          f0=f0+f14;
          if LT f0=f15-f15;                     {if result is negitive, zero it}
          f11=f0*f15, r6=m15;
          r12=fix f11,          f4=dm(i0,m1),  f5=pm(i8,m8);
          r12=clip r12 by r6;
          r13=lshift r12 by 24;                 {puts data into dac field}
lmloop:  f4=f4*f4,              dm(i1,m1)=r13;

        rts;
        nop;
        nop;
```

```
{_____________________________________________________________________
LIN_MAG
  This routine computes (magnitude(FFT))*scaling to display and
certain dynamic range on the scope and puts it in the buffer pointed to by
 b1/i1 for dac output. Scaling is determined by ADC B
_____________________________________________________________________}
lin_mag:
          b0=refft;
          l0=PNTS/2+1;
          l3=0;                                   {this is for the logb2 routine}

          b8=imfft;
          l8=PNTS/2+1;

          m1=1;
          m8=1;

          r2=SCLIP;

          r13=0xff;                               {figure out joystick scaling}
          r14=JOYSCL+24;
          r15=dm(badc_dat);
          r15=lshift r15 by -24;
          r15=r13-r15;
          f15=float r15 by r14;
                                                        f4=dm(i0,m1),  f5=pm(i8,m8);
            f4=f4*f4;                             {square real}

          lcntr=PNTS/2+1, do linloop until lce;
            f5=f5*f5;                             {square imag}
            f0=f4+f5;
            f11=f0*f15;
            r12=fix f11,        f4=dm(i0,m1),  f5=pm(i8,m8);
            r12=pass r12;
            if lt r12=r2;
            r12=clip r12 by r2;
            r13=lshift r12 by 24;                 {puts data into dac field}
linloop:  f4=f4*f4,                 dm(i1,m1)=r13;

          rts;
          nop;
          nop;

.ENDSEG;
```

Fast Fourier Transform Routine

```
{_____________________________________________________________
RFFT2.ASM      ADSP-21020 Radix-2 DIT Real FFT

Does a radix-2 FFT of length 32 or greater on input data x(n). This is
accomplished by doing a N/2 (HN) complex FFT of y(n), where Re[y(n)] = x(2n) and
Im[y(n)] = x(2n+1) for n=0,1,...,N-1. This is followed by some calculation to
derive X(k) from Y(k). This method has been refered to as "Packing". Input data
is NOT destroyed during the course of this routine.

    N      real normal-ordered input in DM.
    N/2+1  real part of fft stored in DM,
    N/2+1  imag part of fft stored in PM.
    Two N/4 long Cosine tables stored in PM,
    Two N/4 long Sine tables in DM.

Note that only (N/2+1) elements are necessary to define the real FFT spectra
because of its Hermitian (complex conjugate) symmetry.

Calling Information:
  pm(cosine[N/4])   - cos(2pi*n/HN) table from RFFT2TBL program
  pm(h_cosine[N/4]) - 0.5*cos(pi*n/HN) table from RFFT2TBL program
  dm(sine[N/4)      - sin(2pi*n/HN) table from RFFT2TBL program
  dm(h_sine[N/4)    - 0.5*sin(pi*n/HN) table from RFFT2TBL program
  dm(real[N])       - real input array, bitreved to working array

  (Note: Because the bit reversed address mode is used with the array
  real, it must start at addresses that are integer multiples of the length
  (N) of the transform, (i.e. 0,N,2N,3N,...). This is accomplished by
  specifing the segment starting at that addresses in the architecture file
  and placing the variable alone in its own segment. This address must
  also be reflected in the preprocessor variables IRE and IREP1 in bit
  reversed format.)

Results:
  dm(refft[N/2+1])  - real working array and output
  pm(imfft[N/2+1])  - imaginary working array and output

Benchmarks: Radix-2, real

                    time (ms)
  FFT Length  cycles  20MHz   25MHZ
  ----------  ------  ------  ------
      64        636    .032    .026
     128       1226    .061    .049
     256       2504    .125    .100
     512       5286    .264    .211
    1024      11331    .566    .453
    2048      24418   1.22     .977
    4096      52608   2.63    2.10
    8192     113054   5.65    4.52

  First 2 Stages   - 8 cycles per 4 butterflies
  Middle Stages    - 4 cycles per butterfly
  2nd to Last Stage - 9 cycles per 2 butterflies
  Last FFT Stage   - 5 cycles per butterfly group
  Conversion Stage - 6 cycles per 2 elements (N/2 elements total)

Memory Usage:
  pm code = 187 words, pm data = N+1 words, dm data = 2*N+1 words
_____________________________________________________________}

{ Include for symbolic definition of system register bits }
#include "constant.h"
```

```
{_______These constants are independent of the number of points_____________}
#define BFLY8       4                          {Offset between bf branches in a group of 8}

.SEGMENT/DM         dm_sram;
.VAR   sine[HN/2] = "ts.dat";                  { imag twiddle factors, from RFFT2TBL }
.VAR   h_sine[HN/2]= "ths.dat";                { end comp. sin coeff. from RFFT2TBL}
.GLOBAL sine;
.GLOBAL h_sine;
.ENDSEG;

.SEGMENT/DM         dm_algn0;                  { Segment Addr. = integer multiple of N }
.VAR   real[N];                                { input real array }
.GLOBAL real;
.ENDSEG;

.SEGMENT/DM         dm_algn1;                  { Segment Addr. = integer multiple of N }
.VAR   refft[HN+1];                            { real part of fft}
.GLOBAL refft;                                 { Set on N boundry cause used by irfft2}
.ENDSEG;

.SEGMENT/PM         pm_sram;
.VAR   cosine[HN/2]= "tc.dat";                 { real twiddle factors, from RFFT2TBL }
.VAR   h_cosine[HN/2]= "thc.dat";              { end comp. cos coeff. from RFFT2TBL}
.VAR   imfft[HN+1];                            { imag result }
.GLOBAL cosine;
.GLOBAL h_cosine;
.GLOBAL imfft;
.ENDSEG;

.GLOBAL rfft2;

.SEGMENT/PM         pm_sram;
{_____________________________begin FFT_____________________________________}
rfft2:
    bit set MODE1 BR0;                         { enable bit reverse of i0 }

{Do bitrev and packing within first two stages}
    b0=IREP1;                                  { Points to beginning of odd indices to be read in }
                                               { bit reversed order }
    l0=0;
    m0=BRMODIFY;

    b8=imfft;
    l8=HN;
    m8=1;

  {Store bit-reversed odd indices in pm and consider them imaginary}
    f0=dm(i0,m0);
    LCNTR=HN-1, DO (PC,1) UNTIL LCE;
      f0=dm(i0,m0), pm(i8,m8)=f0;
    pm(i8,m8)=f0;

{Now bitrev even indices within first two stages}
    b0=IRE;                                    { Points to input real array to be read in }
                                               { bit reversed order }
    b2=refft;
    l2=HN;
    m1=1;                                      { This loop increments forward +1}

    i8=imfft;
    b10=imfft;
    l10=HN;

  {Do the first two stages (actually a radix-4 FFT stage)}

                    f0=dm(i0,m0),  f1=pm(i8,m8);
                    f2=dm(i0,m0),  f3=pm(i8,m8);
        f0=f0+f2,   f2=f0-f2,   f4=dm(i0,m0),  f5=pm(i8,m8);
        f1=f1+f3,   f3=f1-f3,   f6=dm(i0,m0),  f7=pm(i8,m8);
        f4=f6+f4,   f6=f6-f4;
        f5=f5+f7,   f7=f5-f7;
        f8=f0+f4,   f9=f0-f4;
        f10=f1+f5,  f11=f1-f5;

LCNTR=HN/4,   do FSTAGE until LCE;  { do N/4 simple radix-4 butterflies }
        f12=f2+f7,  f13=f2-f7,  f0=dm(i0,m0),  f1=pm(i8,m8);
```

```
        f14=f3+f6,    f15=f3-f6,    f2=dm(i0,m0),  f3=pm(i8,m8);
        f0=f0+f2,     f2=f0-f2,     f4=dm(i0,m0),  f5=pm(i8,m8);
        f1=f1+f3,     f3=f1-f3,     f6=dm(i0,m0),  f7=pm(i8,m8);
        f4=f6+f4,     f6=f6-f4,     dm(i2,m1)=f8,  pm(i10,m8)=f10;
        f5=f5+f7,     f7=f5-f7,     dm(i2,m1)=f12, pm(i10,m8)=f14;
        f8=f0+f4,     f9=f0-f4,     dm(i2,m1)=f9,  pm(i10,m8)=f11;
FSTAGE: f10=f1+f5,    f11=f1-f5,    dm(i2,m1)=f13, pm(i10,m8)=f15;


  {middle stages loop }

    bit clr MODE1 BR0;                          {finished with bitreversal}

    b0=refft;
    l0=HN;
    b1=sine;
    l1=@sine;

    b9=cosine;
    l9=@cosine;
    b10=imfft;
    l10=HN;
    b11=imfft;
    l11=HN;

    m0=-BFLY8;
    m1=-HN/8;
    m2=-BFLY8-1;
    m9=-HN/8;
    m11=-1;

    r2=2;
    r3=-BFLY8;                                  {initializes m0,10 - incr for butterf branches }
    r5=BFLY8;                                   {counts # butterflies per a group             }
    r9=(-2*BFLY8)-1;                            {initializes m12 - wrap around to next grp + 1 }
    r10=-2*BFLY8;                               {initializes m8 - incr between groups          }
    r13=-BFLY8-1;                               {initializes m2,13 - wrap to bgn of 1st group  }
    r15=HN/8;                                   {# OF GROUPS IN THIRD STAGE}

    f1=dm(i1,m1),  f7=pm(i9,m9);                {set pointers to tables to 1st coeff.  }

LCNTR=STAGES-5, do end_stage until LCE;         {# OF STAGES TO BE HANDLED = LOG2(HN)-4}
    m8=r10;
    m10=r3;
    m12=r9;
    i0=refft+HN-1;
    i2=refft+HN-1;
    i8=imfft+HN-1;
    i10=imfft+HN-1;
    i11=imfft+HN-1;
    r15=r15-r2,   m13=r13;                      {CALCULATE # OF CORE }
                                                {BFLIES/GROUP IN THIS STAGE}

                  f0=dm(i1,m1),  f7=pm(i8,m8);
f12=f0*f7,            f6=dm(i0,m0),  f1=pm(i9,m9);
f8=f1*f6,                    modify(i11,m10);
f11=f1*f7,                   f7=pm(i8,m8);
f14=f0*f6, f12=f8+f12,       f8=dm(i0,m0);
f12=f0*f7, f13=f8+f12, f10=f8-f12,  f6=dm(i0,m0);

{Each iteration does another set of bttrflys in each group}

LCNTR=r5,  do end_group until LCE;              {# OF BUTTERFLIES/GROUP IN THIS STAGE}

{core butterfly loop}

LCNTR=r15, do end_bfly until LCE;               {Do a butterfly in each group - 2}
  f8=f1*f6,  f14=f11-f14,          dm(i2,m0)=f10, f9=pm(i11,m8);
  f11=f1*f7, f3=f9+f14,    f9=f9-f14,    dm(i2,m0)=f13, f7=pm(i8,m8);
  f14=f0*f6, f12=f8+f12,           f8=dm(i0,m0),  pm(i10,m10)=f9;
end_bfly:
  f12=f0*f7, f13=f8+f12,   f10=f8-f12,   f6=dm(i0,m0),  pm(i10,m10)=f3;

{finish up last bttrfly and set up for next stage}
```

```
f8=f1*f6,          f14=f11-f14,   dm(i2,m0)=f10, f9=pm(i11,m8);
f11=f1*f7, f4=f9+f14, f9=f9-f14,    dm(i2,m0)=f13, f14=pm(i8,m11);
f14=f0*f6, f12=f8+f12,           f8=dm(i0,m2),  pm(i10,m10)=f9;
      f13=f8+f12, f10=f8-f12,   f0=dm(i1,m1),  f7=pm(i8,m8); {dm:sin}
            f14=f11-f14,  dm(i2,m0)=f10, f9=pm(i11,m12);
 {start on next butterfly in each group}
f12=f0*f7, f3=f9+f14, f9=f9-f14,    f6=dm(i0,m0),  f1=pm(i9,m9); {pm:cos}
f8=f1*f6,                  dm(i2,m2)=f13, pm(i10,m10)=f4;
f11=f1*f7,                       pm(i10,m10)=f9;
f14=f0*f6, f12=f8+f12,           f8=dm(i0,m0),  f7=pm(i8,m8);
end_group:
f12=f0*f7, f13=f8+f12, f10=f8-f12,   f6=dm(i0,m0),  pm(i10,m13)=f3;


      r4=r15+r2,      i1=b1;                    {PREPARE R4 FOR #OF BFLIES CALC}
      r15=ashift r4 by -1;                      {# OF BFLIES/GRP IN NEXT STAGE}
      r4=-r15,        i9=b9;
      m1=r4;                                    {update inc for sin & cos }
      m9=r4;
      r5=ashift r5 by 1, f1=dm(i1,m1);          {update # bttrfly in a grp}
      r3=-r5;                                   {  inc for bttrfly branch}
      r13=r3-1,       m0=r3;                    {  wrap to 1st grp     }
      r10=ashift r3 by 1, f7=pm(i9,m9);         {  inc between grps    }
end_stage: r9=r10-1,      m2=r13;               {  wrap to grp +1      }

{_________ next to last stage_________}
    m1=-2;                                      {modifier to sine table pntr   }
    m8=r10;                                     {incr between groups           }
    m9=-2;                                      {modifier to cosine table pntr }
    m10=r3;                                     {incr between bttrfly branches }
    m12=r9;                                     {wrap around to next grp + 1   }
    m13=r13;                                    {wrap to bgn of 1st group      }

    i0=refft+HN-1;
    i1=sine+(HN/2)-2;                           {pntr to 1st sine coeff        }
    i2=refft+HN-1;
    i8=imfft+HN-1;
    i9=cosine+(HN/2)-2;                         {pntr to 1st cosine coeff      }
    i10=imfft+HN-1;
    i11=imfft+HN-1;
                    f0=dm(i1,m1),  f7=pm(i8,m8);
f12=f0*f7,              f6=dm(i0,m0),  f1=pm(i9,m9);
f8=f1*f6,                       modify(i11,m10);
f11=f1*f7,                       f7=pm(i8,m12);
f14=f0*f6, f12=f8+f12,          f8=dm(i0,m0);
f12=f0*f7, f13=f8+f12, f10=f8-f12,   f6=dm(i0,m0);

{Do the HN/4 butterflies in the two groups of this stage}

LCNTR=HN/4, do end_group2 until LCE;
  f8=f1*f6,          f14=f11-f14,   dm(i2,m0)=f10, f9=pm(i11,m8);
  f11=f1*f7, f3=f9+f14,   f9=f9-f14,    dm(i2,m0)=f13, f1=pm(i9,m9);
  f14=f0*f6, f12=f8+f12,           f8=dm(i0,m2),  pm(i10,m10)=f9;
        f13=f8+f12,   f10=f8-f12,   f0=dm(i1,m1),  f7=pm(i8,m8);
  f12=f0*f7,          f14=f11-f14,   f6=dm(i0,m0),  f9=pm(i11,m12);

  f8=f1*f6,  f3=f9+f14,   f9=f9-f14,    dm(i2,m0)=f10, pm(i10,m10)=f3;
  f11=f1*f7,                  dm(i2,m2)=f13, pm(i10,m10)=f9;
  f14=f0*f6, f12=f8+f12,           f8=dm(i0,m0),  f7=pm(i8,m12);
end_group2:
  f12=f0*f7, f13=f8+f12,    f10=f8-f12,    f6=dm(i0,m0),  pm(i10,m13)=f3;


{  The last stage    }

    m0=-HN/2;
    m2=-HN/2-1;
    m10=m0;
    m13=m2;
    i0=refft+HN-1;
    i1=sine+(HN/2)-1;                           {pntr to 1st sine coeff        }
    i2=refft+HN-1;
    i8=imfft+HN-1;
    i9=cosine+(HN/2)-1;                         {pntr to 1st cosine coeff      }
    i10=imfft+HN-1;
    i11=imfft+HN-1;
```

```
    m1=-1;                                          {modifiers to coeff tables    }
    m9=-1;

{start first bttrfly}
                        f0=dm(i1,m1),  f7=pm(i8,m11);
f12=f0*f7,                  f6=dm(i0,m0),  f1=pm(i9,m9);
f8=f1*f6,                           modify(i11,m10);
f11=f1*f7;
f14=f0*f6, f12=f8+f12,          f8=dm(i0,m2),  f9=pm(i11,m11);

{do HN/2 bttrflys in the last stage}

LCNTR=HN/2, do last_stage until LCE;
        f13=f8+f12,   f10=f8-f12,   f0=dm(i1,m1),  f7=pm(i8,m11);
  f12=f0*f7, f14=f11-f14,           f6=dm(i0,m0),  f1=pm(i9,m9);
  f8=f1*f6,  f3=f9+f14,   f15=f9-f14,   dm(i2,m0)=f10, f9=pm(i11,m11);
  f11=f1*f7,                    dm(i2,m2)=f13, pm(i10,m10)=f15;
last_stage:
  f14=f0*f6, f12=f8+f12,            f8=dm(i0,m2),  pm(i10,m13)=f3;


{compute the N point FFT of real from the packed N/2 transform}

i0=refft;       { real src pntr forward}
b1=h_sine+1;    { real sine pntr}
i2=refft+HN-1;  { real src pntr backward}
i3=refft;       { real dest pntr forward}
i4=refft+HN;    { real dest pntr backward}
l4=0;

i8=imfft;       { imag src pntr forward}
b9=h_cosine+1;  { imag cosine pntr}
i10=imfft+HN-1; { imag src pntr backward}
i11=i8;         { imag dest pntr forward}
i12=imfft+HN;   { imag dest pntr backward}
l12=0;

m0 = 1;
m8 = 1;
f2 = 0.5;       { this register is used to div by 2}
f15= 0.0;

{do first pair, U(0)+jV(0) & U(HN)+jV(HN)}
                        f12=dm(i0,m0),  f9 =pm(i8,m8);
        f11=f12+f9, f3=f12-f9,  f12=dm(i0,m0),  f9 =pm(i8,m8);
        f10=PASS f15,       f8 =dm(i2,m1),  f13=pm(i10,m9);
                        dm(i3,m0)=f11;

{do the rest in pairs (n,HN-n) except the mid-point}

        f4=f8+f12,  f5=f8-f12,  f0 =dm(i1,m0),  f1 =pm(i9,m8);

LCNTR = (HN/2)-1, DO trans UNTIL LCE;
    f8=f0*f5,  f6=f9+f13, f7=f9-f13;
    f12=f1*f6, f10=f10+f15,f15=f10-f15,  dm(i4,m1)=f3,  f13=pm(i10,m9);
    f11=f2*f4, f14=f8+f12,          f12=dm(i0,m0), pm(i11,m8)=f10;
    f10=f1*f5, f11=f11+f14,f3=f11-f14,  f8 =dm(i2,m1), pm(i12,m9)=f15;
    f14=f0*f6, f4=f8+f12, f5=f8-f12,  f0 =dm(i1,m0), f1 =pm(i9,m8);
trans: f15=f2*f7, f10=f10-f14,          dm(i3,m0)=f11, f9 =pm(i8,m8);

{finish up and do the mid-point}
        f10=f10+f15,f15=f10-f15,  dm(i4,m1)=f3;
        f14=-f9,                    pm(i11,m8)=f10;
  rts (db); {finished}
                                pm(i12,m9)=f15;
                        dm(i3,m0)=f8,  pm(i11,m8)=f14;

{_____________________________________________________________________}
.ENDSEG;
```

'C' source code for data transfer and display program.

```
#include <dos.h>
#include <stdio.h>
#include <stdlib.h>
#include <conio.h>
#include <graphics.h>

#define   IOCARD                0x300
#define   IRQ5                  0x0D
#define   VECT5                 0x5
#define   ENABLE_IRQ5           0xDF
#define   EOI                   0x20
#define   ADDR_8259             0x20
#define   ADDR_8259_MASK 0x21

#ifdef __cplusplus
        #define __CPPARGS ...
#else
        #define __CPPARGS
#endif

/*************************************************************************/
/* Global variable declarations                                          */
/*************************************************************************/
char string[10];
int samplex[16];
int sampley[16];
int data [520];
int x_pos=1;
int dsp_settings=0xCD;
int cnt;

/*************************************************************************/
/* Function prototype headers                                            */
/*************************************************************************/
void interrupt collect(unsigned bp, unsigned di, unsigned si,
                                        unsigned ds, unsigned es, unsigned dx,
                                        unsigned cx, unsigned bx, unsigned ax);
void interrupt send(__CPPARGS);
void install(void interrupt (*faddr) (),int inum);
void interrupt (*old_int)(__CPPARGS); /* interrupt function pointer */

/*************************************************************************/
/* Data collection interrupt routine                                     */
/*************************************************************************/
void interrupt collect(unsigned bp, unsigned di, unsigned si,
                                        unsigned ds, unsigned es, unsigned dx,
                                        unsigned cx, unsigned bx, unsigned ax)
{
        disable();
        data[x_pos]=inportb(IOCARD);
        if (data[x_pos]==255)
        {
                x_pos=0;
        }
        else
        {
                x_pos++;
                if (x_pos>519)
                {
                        x_pos=0;
                }
        }
        outportb(ADDR_8259,EOI);
        enable();
}


/*************************************************************************/
/* Data transmit interrupt routine                                       */
/*************************************************************************/
```

```
void interrupt send(__CPPARGS)
{
        int mic,in_gain;
        int sample=13;
        int c;
        samplex[0]=100;
        samplex[1]=100;
        samplex[2]=100;
        samplex[3]=100;
        samplex[4]=100;
        samplex[5]=100;
        samplex[6]=100;
        samplex[7]=100;
        samplex[8]=300;
        samplex[9]=300;
        samplex[10]=300;
        samplex[11]=300;
        samplex[12]=300;
        samplex[13]=300;
        samplex[14]=300;
        samplex[15]=300;

        sampley[0]=220;
        sampley[1]=230;
        sampley[2]=240;
        sampley[3]=250;
        sampley[4]=260;
        sampley[5]=270;
        sampley[6]=280;
        sampley[7]=290;
        sampley[8]=220;
        sampley[9]=230;
        sampley[10]=240;
        sampley[11]=250;
        sampley[12]=260;
        sampley[13]=270;
        sampley[14]=280;
        sampley[15]=290;
        disable();
        clearviewport();
        setcolor(WHITE);
        rectangle(120,90,370,160);
        outtextxy(130,100,"Sound Port Current Settings");
        outtextxy(130,120,"Input source");
        if (dsp_settings & 0x80)
        {
                outtextxy(330,120,"Mic");
                mic=1;
        }
        else
        {
                outtextxy(330,120,"Line");
                mic=0;
        }
        in_gain=dsp_settings&0x70;
        in_gain=in_gain>>4;
        itoa(in_gain,string,10);
        outtextxy(130,130,"Input gain");
        outtextxy(330,130,string);
        sample=dsp_settings&0xF;
        itoa(sample,string,10);
        outtextxy(130,140,"Sample rate");
        outtextxy(330,140,string);

        outtextxy(100,200,"Sample rate selection");
        outtextxy(samplex[0],sampley[0],"0 - 8kHz");
        outtextxy(samplex[1],sampley[1],"1 - 16kHz");
        outtextxy(samplex[2],sampley[2],"2 - 27.42857kHz");
        outtextxy(samplex[3],sampley[3],"3 - 32kHz");
        outtextxy(samplex[4],sampley[4],"4 - Unused");
        outtextxy(samplex[5],sampley[5],"5 - Unused");
        outtextxy(samplex[6],sampley[6],"6 - 48kHz");
        outtextxy(samplex[7],sampley[7],"7 - 9.6kHz");
        outtextxy(samplex[8],sampley[8]," 8 - 5.5125kHz");
        outtextxy(samplex[9],sampley[9]," 9 - 11.025kHz");
        outtextxy(samplex[10],sampley[10],"10 - 18.9kHz");
```

```
outtextxy(samplex[11],sampley[11],"11 - 22.05kHz");
outtextxy(samplex[12],sampley[12],"12 - 37.8kHz");
outtextxy(samplex[13],sampley[13],"13 - 44.1kHz");
outtextxy(samplex[14],sampley[14],"14 - 33.075kHz");
outtextxy(samplex[15],sampley[15],"15 - 6.616kHz");
outtextxy(samplex[sample]-10,sampley[sample],"*");

do
{
        c=getch();
        if (c==109)
        {
                setcolor(BLACK);
                if (mic==1)
                {
                        outtextxy(330,120,"Mic");
                        mic=0;
                        setcolor(WHITE);
                        outtextxy(330,120,"Line");

                }
                else
                {
                        outtextxy(330,120,"Line");
                        mic=1;
                        setcolor(WHITE);
                        outtextxy(330,120,"Mic");
                }
                dsp_settings=dsp_settings&0x7F; /*clear bits*/
                mic=mic<<7;
                dsp_settings=dsp_settings|mic; /*set to new values*/
                mic=mic>>7;
                outportb(IOCARD,dsp_settings);

        }

        if (c==105) /*  "i"  */
        {
                setcolor(BLACK);
                itoa(in_gain,string,10);
                outtextxy(330,130,string);
                in_gain++;
                if (in_gain==8)
                {
                        in_gain=0;
                }
                itoa(in_gain,string,10);
                setcolor(WHITE);
                outtextxy(330,130,string);
                in_gain=in_gain<<4;
                dsp_settings=dsp_settings&0x8F; /*clear bits*/
                dsp_settings=dsp_settings|in_gain; /*set to new values*/
                in_gain=in_gain>>4;
                outportb(IOCARD,dsp_settings);

        }
        if (c==32) /*  " "  */
        {
                setcolor(BLACK);
                outtextxy(samplex[sample]-10,sampley[sample],"*");
                itoa(sample,string,10);
                outtextxy(330,140,string);

                sample++;
                if (sample==16)
                {
                        sample=0;
                }
                setcolor(WHITE);
                outtextxy(samplex[sample]-10,sampley[sample],"*");
                itoa(sample,string,10);
                outtextxy(330,140,string);
                dsp_settings=dsp_settings&0xF0;
                dsp_settings=dsp_settings|sample;
                outportb(IOCARD,dsp_settings);
        }
```

```
                if (c==88 || c==120)
                {
                        cnt=13;
                }
        }while(c!=13);
        clearviewport();
        enable();
}

/*****************************************************************************/
/* Install interrupt routine in interrupt table                              */
/*****************************************************************************/
void install(void interrupt (*faddr) (),int inum)
{
        setvect(inum,faddr);
}

/*****************************************************************************/
/* Main program for display                                                  */
/*****************************************************************************/

void main(void)
{
        int x=0, cursor=0;
        int new_mask;
        int old_mask;
        int total;
//      unsigned long x;
        char cnt;
        int max_x;
        int pos_x;

        /* select a driver and mode that supports the use */
        /* of the setrgbpalette function.          */
        int gdriver = VGA, gmode = VGAHI, errorcode;
        struct palettetype pal;
        int i, ht, y, xmax;

        /* initialize graphics and local variables */
        initgraph(&gdriver, &gmode, "c:/borlandc/bgi");

        /* read result of initialization */
        errorcode = graphresult();
        if (errorcode != grOk)  /* an error occurred */
        {
                printf("Graphics error: %s\n", grapherrormsg(errorcode));
                printf("Press any key to halt:");
                getch();
                exit(1); /* terminate with an error code */
        }

        /* grab a copy of the palette */
        getpalette(&pal);

        /* create gray scale */
        for (i=0; i<pal.size; i++)
                setrgbpalette(pal.colors[i], i*4, i*4 , i*4);

        /* display the gray scale */
        ht = getmaxy() / 16;
        xmax = getmaxx();
        y = 0;
        for (i=0; i<pal.size; i++)
        {
                setfillstyle(SOLID_FILL, 16-i);
                bar(0, y, xmax, y+ht);
                y += ht;
        }

        setviewport(0,0,600,480,1);

        /* get old interrupt vector */
        old_int=getvect(IRQ5);
```

```
        old_mask=inportb(ADDR_8259_MASK);
        new_mask=old_mask & ENABLE_IRQ5;
        outportb(ADDR_8259_MASK,new_mask);

        install(collect,IRQ5);
        setvect(VECT5,send);

        do{
                if (x_pos==0)
                {
                        cursor++;
                        if (cursor==600)
                        {
                                cursor=0;
                                setcolor(WHITE);
                                outtextxy(560,6,"20kHz");
                                outtextxy(560,122,"15kHz");
                                outtextxy(560,238,"10kHz");
                                outtextxy(570,354,"5kHz");
                        }
                        max_x=0;
                        pos_x=0;
                        setcolor(BLACK);
                        line(cursor+1,0,cursor+1,480);
//                      rectangle(600,480-(total/500),610,480);
//                      total=0;
                        for (x=0;x<513;x++)
                        {

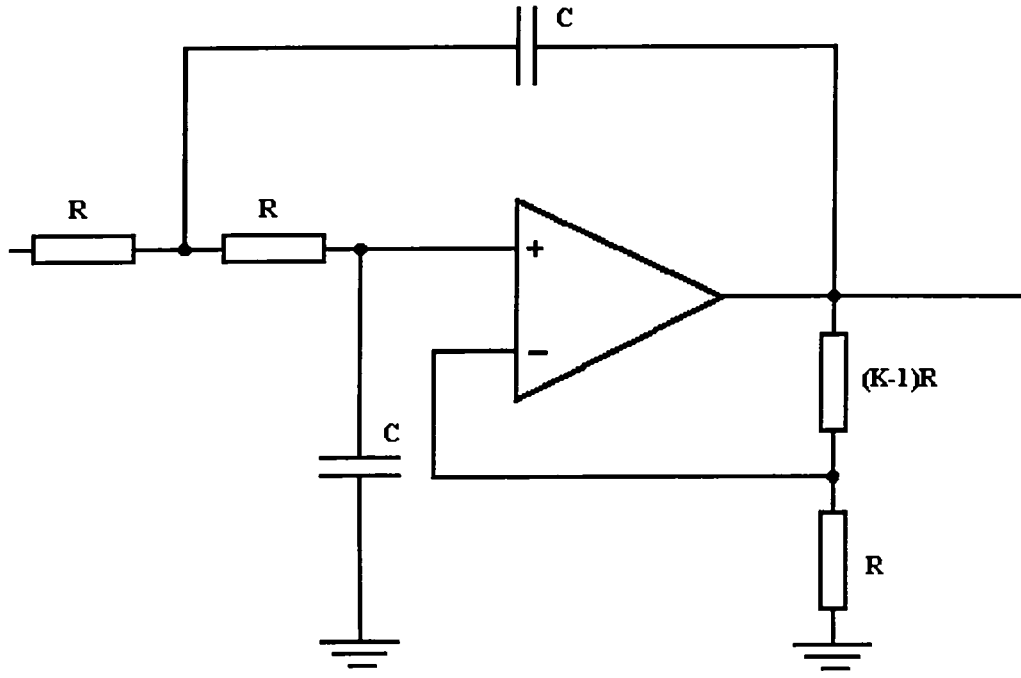
                                if (max_x<data[x])
                                {
                                        data[464]=200;
                                        data[348]=200;
                                        data[232]=200;
                                        data[116]=200;
                                        putpixel(cursor,480-x,data[x]/16);
                                }
//                              setcolor(WHITE);
//                              total=total+data[x];
                        }
//                      rectangle(600,480-(total/500),610,480);
                }
        }while (cnt!=13);


}
```

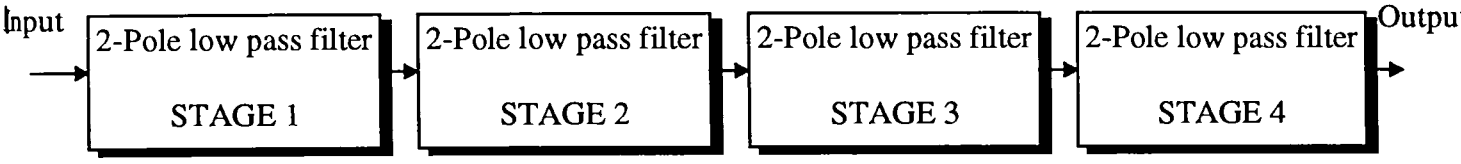
Appendix J

8-Pole Low Pass Bessel Filter

Circuit Diagram For One Stage (2-Poles)



Complete Filter



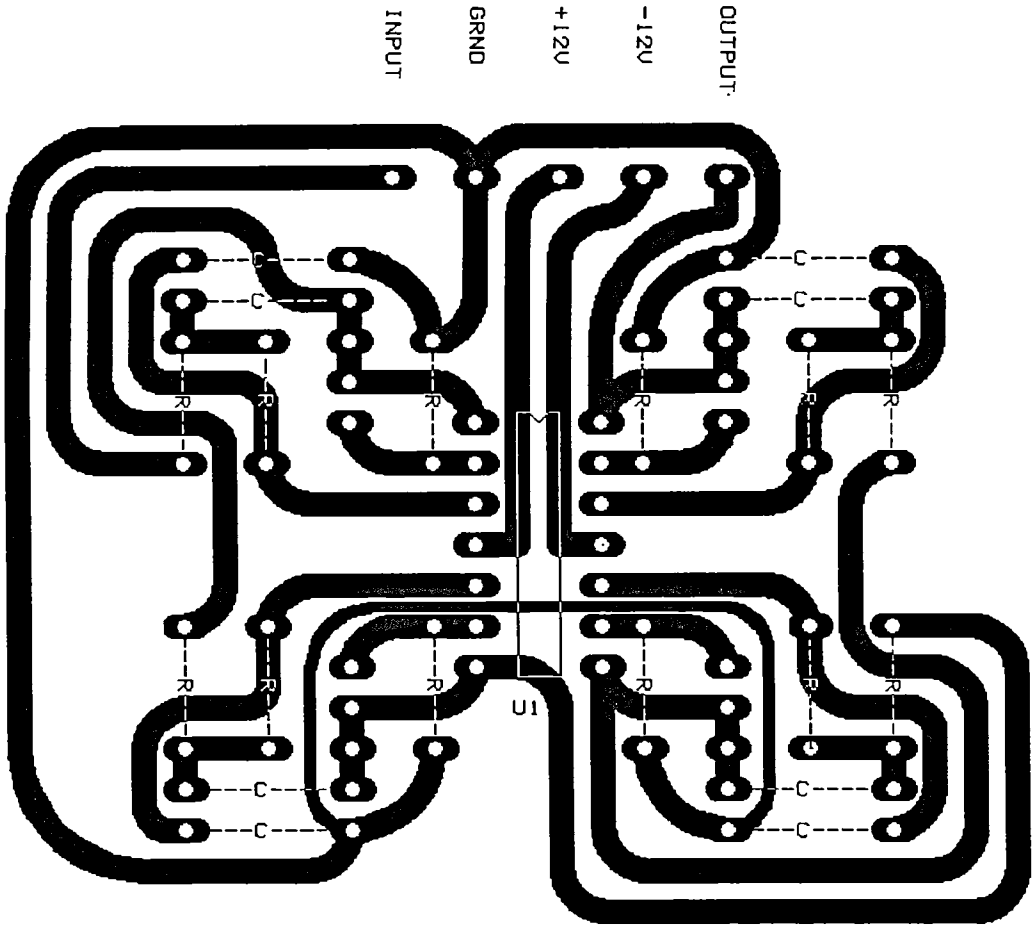
Design Equation

$$RC = \frac{1}{2\pi f_n f_c}$$

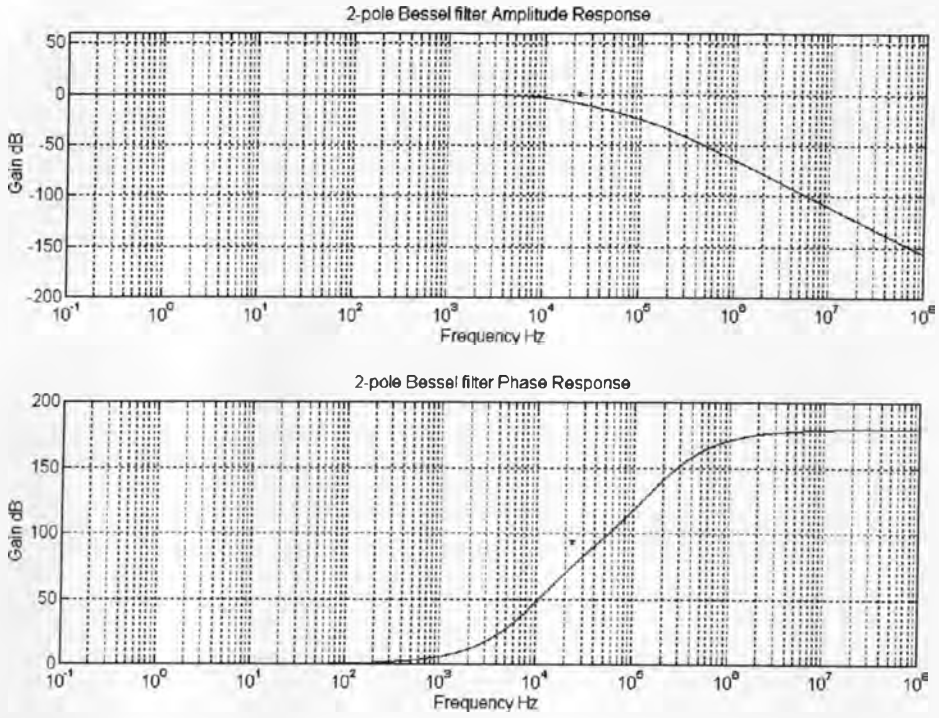
Component Selection

Stage	f_n	K	R	(K-1)×R	C
1	1.781	1.024	27k	640	150pF
2	1.835	1.213	12k	2.5k	330pF
3	1.956	1.593	11k	6.5k	330pF
4	2.192	2.184	10k	11.8k	330pF

PCB Schematic



Amplitude and Phase Response of One Stage



Amplitude and Phase Response of Complete Filter

