9
Analysis of the Acoustic Data

9.1. Introduction

During the May 1996 trial, recordings of the received sound signals were made. These recordings were independently analysed by three institutes. The objective of these analyses was to identify the presence of marine mammals in Kyparissiakos Gulf during the time period 12-15 May, 1996.

If biological signatures were found, the process of elimination was to be used to reveal “unclassified biologic signals”, since no acoustic signatures are known for Ziphius. The analysis indicated that marine mammal activity occurred during the SWAC trials mentioned above. Some of the signatures were identified as sperm whales that were at ranges of greater than 3 km. Other, unknown odontocetes were detected at unknown ranges. Families of recurring transients of unknown origin occurred throughout the trial, as well as many isolated transient sounds that did not support further analysis. However, due to limited time available, not all detections were analyzed. The summary reports of the investigators follows.

9.2. Passive Processing and Analysis of Acoustic Data - (Information supplied by Dr. D. Abraham, W. Zimmer, SACLANTCEN and Dr. G. Pavan, University of Pavia, Italy)

A passive acoustic analysis of data recorded during the SWAC 4 sea-trial in Kyparissiakos Gulf during May, 1996 was performed with the specific objectives of detecting, localizing, and classifying marine mammal sounds. Detection and localization (bearing only) was performed using a passive sonar system in ‘playback mode’ and then by an automatic detection algorithm for specific runs or run segments. Detections associated over time and bearing were labeled ‘events’, formulated into time series, and submitted to Prof. G. Pavan of the University of Pavia for classification. Many of these events were classified as sperm whale or ‘generic’ dolphin acoustic emissions (the bandwidth of the 'listening part' of the equipment was limited to the frequency band 750-1500 Hz). Not all detected sounds were analyzed owing to limited time and resources.

Acoustics has been proved to give an important chance in understanding the behaviour of marine animals and, in particular, of marine mammals. For several species, acoustic methods outperform all other study methods in species identification, population size assessment and movement monitoring.

The sound library of University of Pavia holds more than 150 h of recordings belonging to Sperm whales (*Physeter macrocephalus* L.) - the most represented species with more than 71% of the total, Striped dolphins (*Stenella coeruleoalba* (Meyen)), Bottlenose dolphins (*Tursiops truncatus* (Montagu)), Risso's dolphins (*Grampus griseus* (G.Cuvier)), Long-finned pilot whales (*Globicephala melas* (Traill)) and Common dolphins (*Delphinus delphis* L.).

The library also include cuts of recordings of Rough toothed dolphins (*Steno bredanensis*) (Watkins *et al*., 1987) and of Fin whales (*Balaenoptera physalus*) made by W.A.Watkins (SOUND database, WHOI, USA; Watkins *et al*. 1992).

Cuvier’s beaked whales (*Ziphius cavirostris*) are quite timid and elusive animals, and it is often difficult to approach them; they are deep divers and are frequently reported in Greek waters over bottom depths greater than 1000 m (Montesi, personal communication). Unfortunately, sound recordings are not available.

The detection, localization, and classification objectives could have been met by either passive listening or active ranging. The latter is desirable because it provides range and bearing information as opposed to bearing-only information from passive listening, Annex H presents results of active acoustic analyses in which no mammals were identified. However, the difficulties in detection, clutter rejection, and classification in active ranging systems forced the use of passive techniques for this situation. Data were available from two towed arrays representing a total of four different apertures (128 sensors at 375 Hz, 750 Hz, and 1500 Hz, and 32 sensors at 4166 Hz). The best trade-off between bandwidth and directivity index (DI, the amount of gain against isotropic noise provided by beamforming an array of sensors) over the usable bands of each of the array apertures resulted in choosing the frequency band 750-1500 Hz from the 128 element 1500 Hz array.

The bandpass filtered and beamformed data were displayed on a passive sonar system, with audio and spectral analysis available for a single beam. All of the acoustic trial data collected during 12-15 May, 1996 (36 h of data) were analyzed in this manner.

9.2.1. Replay analyis

Several types of transients were observed during the replay analysis of the acoustic analysis. They were categorized with the following descriptions and the frequency of their occurrence was logged during the replay analysis. The classification of sperm whale clicks and codas was provided by G. Pavan, University of Pavia.

9.2.1.1. Click Trains

The *click trains* are characterized as follows

- *Click trains* are not consistent with ship introduced noise

- Usually they have a long duration (order of minutes) with short interruptions (10-20 s). Usually they have stable repetition rate (0.6-1.5 clicks/s), but speeding up and slowing down of the repetition rate is observed, speeding up usually before interruptions.
- Usually the interference pattern indicates two pulse arrivals within 166 ms; good candidates are direct and surface reflected path.
- *Click trains* are observed on most of the analyzed runs, with varying intensity and occurrence.

Figure 9.2.1.1. shows the time series of a *click train* and Fig. 9.2.1.2. shows the arrival structure of a single click.

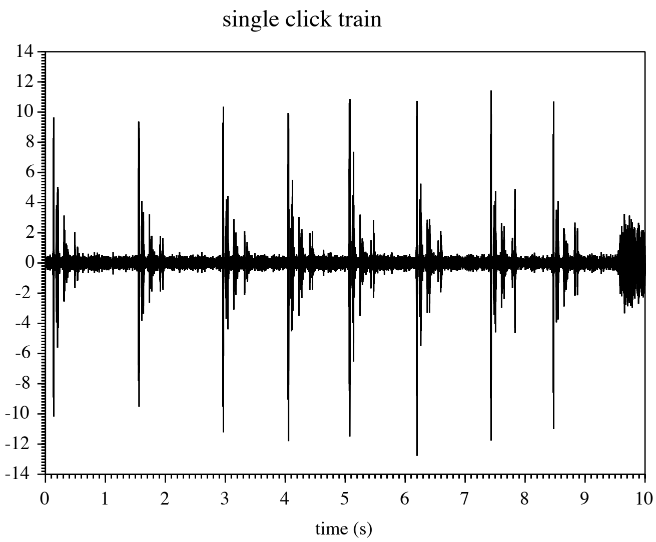

Figure 9.2.1.1. *Single Click Train*

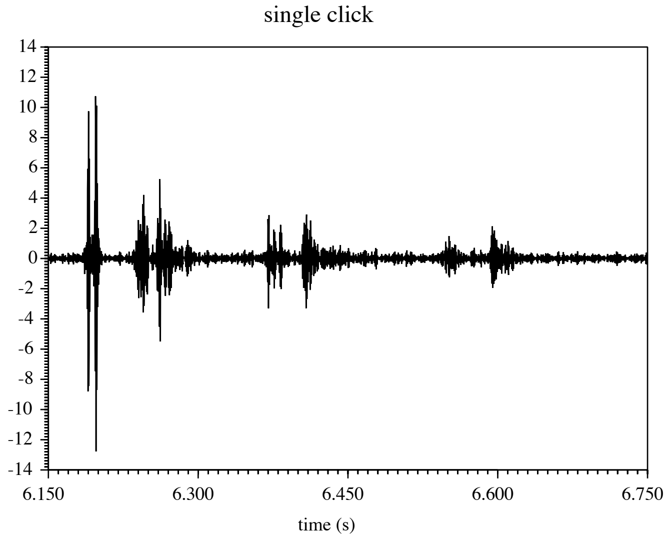

Figure 9.2.1.2. *Single Click Train*

9.2.1.2. Click Bursts

Click bursts are characterized as follows

- High occurrence of *click bursts* is observed at the end of run 11 (RV *Alliance* position: N 37° 29’ E 21° 15’) which also coincides with RV *Alliance* coordinates of run 9 at 0700Z
- Click rates are of the order of 10 clicks/s
- Duration of single burst is of the order of 2 – 4 s
- Intensity is usually decreasing during burst
- Spectrum indicates varying click frequency as function of time

Figure 9.2.1.3 shows the time series of a sequence of two click bursts.

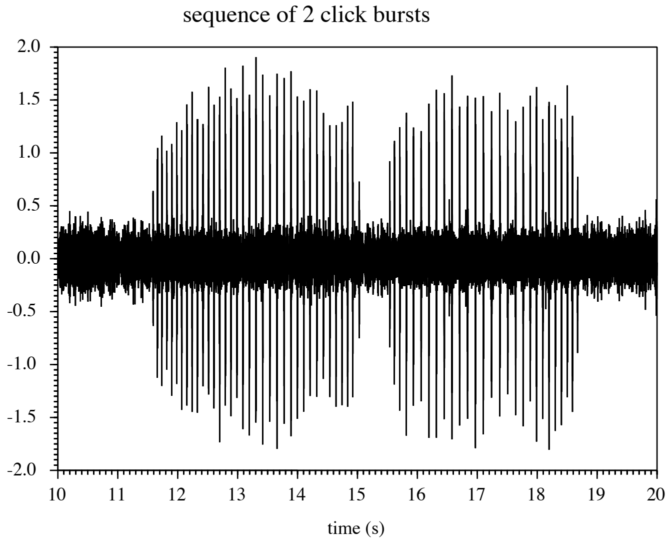

Figure 9.2.1.3 *Sequence of two Click bursts*

9.2.1.3. Codas

Codas are typical click sequences of sperm whales when communicating among themselves. The 3+1 *Codas* found correspond to the typical pattern found in the Mediterranean (G. Pavan, personal communication). The *Codas* sequence found, was followed in time by 2 distinct *click trains* (angular separation ca. 1deg). Figure 9.2.1.4. shows the time series of a sequence of sperm whale Codas.

9.2.1.4. Click Codes

Click codes are similar to *Codas*, but with different pattern (e.g.: 1+2+2+1). There are indications that up to 3 sequences are transmitted at a time. When observed, *click codes* show up in large quantities and spread out in arrival angle indicating a large number of sources. Figure 9.2.1.5 shows two *click codes* during 10 s of data.

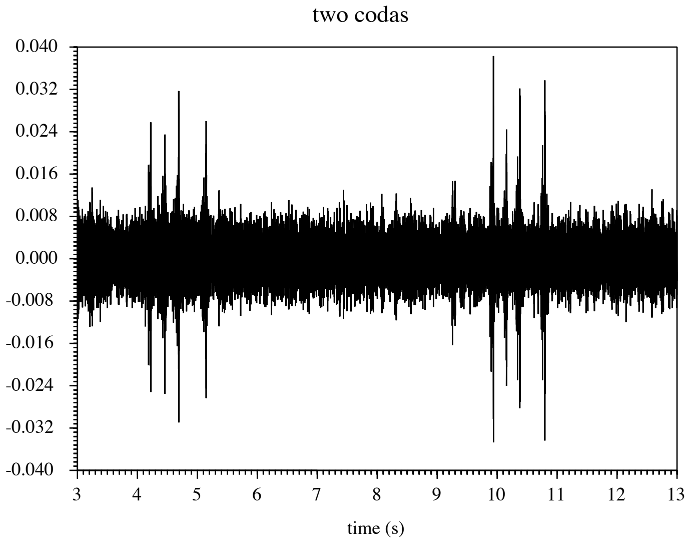

Figure 9.2.1.4 *Sequence of Sperm Whale Codas (3+1)*

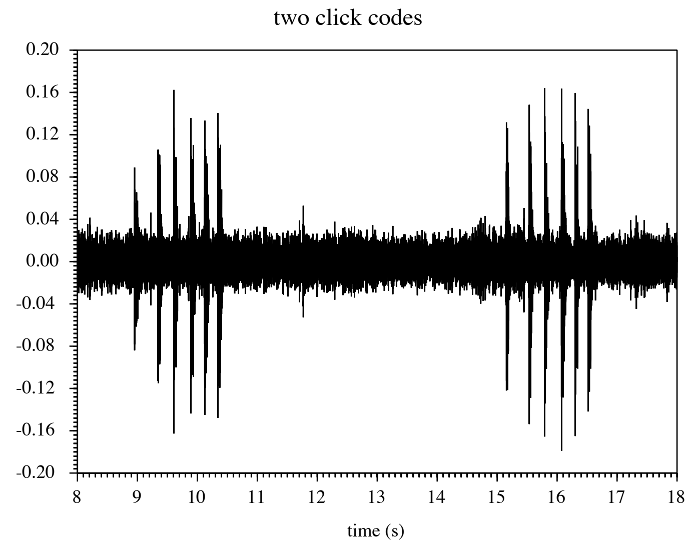

Figure 9.2.1.5 *Sequence of Click Codes*

9.2.1.5. Isolated Clicks

Isolated clicks have been recorded and heard, but not yet been investigated.

9.2.1.6. Summary of passive Analysis

Passive analysis of 36 h of data over a 4 day period can be summarized as follows:

- One or more *click trains* are observed for all runs analyzed. Intensity varies from strong to very weak. In one occasion *Codas* have classified Mediterranean sperm whales.
- Most *click bursts* are observed during the runs 9, 11,12, 16 and 17.
- In particular at the end of run 11 numerous click bursts of varying intensity in various angles have been observed (RV *Alliance* position: N 37° 29' E 21° 15').
- Weak *click bursts* have been heard from rear end-fire at beginning of run 11.
- *Click trains* and *click burst* can be heard on third day.
- Sudden onset of strong *click trains* can be observed frequently.
- Most *click trains* and *click bursts* are clearly audible.
- Large numbers of *click codes* were observed during run 14 and at the end of run 20.

9.2.2. Acoustic Classification of Transient Signals

Sample cuts from runs 9, 11, and 14 were sent to the University of Pavia for identification of transient sounds of probable biological origin. The cuts we received for analysis were extracted from raw passive sonar data by selecting a bearing at a time, according to the level of the received signals.

The characteristics of the recordings appear to be not suitable for classifying marine mammal sounds as the bandwidth is limited to the range 750-1500 Hz (LF passive). A very limited range compared with the frequency extension of marine mammal vocalizations which may span from 10 Hz to 25 kHz, if considering social communication signals, and up to 200 kHz if echolocation signals of dolphins are concerned.

Though, the temporal patterning of series of wide band transients was retained and the identification of the source was thus possible.

Recordings were examined aurally and with the support of different sound analysis packages. Due to the limited bandwidth, spectrograms had only relative utility and the analyses were mostly done on the envelope of the recordings to evaluate the temporal patterning of the transients. As the recordings were extracted by single bearings, we can't assess the number of the sources.

9.2.2.1. Analysis results

Transients were classified into the following categories:

a) long series of clicks, lasting up to several minutes, with short gaps and click rates ranging from 0.5 to 2.4 clicks/sec.
b) bursts of clicks, lasting from 0.8 to 11.8 s, with click rates ranging from 6.4 to 15 clicks/sec.
c) short stereotyped patterned series of 4 to 6 clicks,
d) isolated clicks and very weak series of clicks,
e) other sounds, including traces of whistles.

In the cuts we analyzed mostly categories (a), (b), and (c) were found; according to their temporal patterning we determined they belong to sperm whales (Pavan, unpublished data; Whitehead *et al*., 1989; Goold *et al*., 1995). Observations were:

- *RUN 9* - Long series of clicks dominate this run.

- *RUN 11* - Among long series of clicks, already determined as belonging to sperm whales, several bursts of clicks have been found. As these bursts have relative stable characteristics, it is likely they belong to sperm whales.

- *RUN 14* - In this run, among long series of clicks, several patterned series of clicks were recorded as well. Some of them matched the pattern 3+1 which is typical of sperm whales of the Mediterranean Sea (Pavan & Borsani, 1997; Pavan *et al*., 1998). Other patterns found in the recordings have never been recorded before in the Mediterranean Sea.

As we received and analyzed only few samples extracted by single bearings, we were not able to assess the number of the animals. Though, the real-time display of the sonar (passive detections, replay mode), which shows amplitude *versus* time *versus* bearing, revealed the presence of several sperm whales vocalizing at different bearings.

Categories (d) and (e) cannot be assigned to any species in particular; some sounds belonging to them may be emitted by (unidentifiable) delphinids or to still sperm whales.

9.2.3. Automatic Detection Processing

Based on the replay analysis, two time segments were selected for further analysis by an automatic detection algorithm. These segments consisted of all of the first run (run 9) and the first hour of run 11. The automatic detection algorithm essentially compared the data with a long-term average, looking for substantial differences. Output from the algorithm is the start and stop time and estimated signal energy of each detection as well as the estimated background noise power level at the time of the detection. These data may be combined to display detection results over long periods of time (in the configuration used, the passive sonar system showed one minute of data in a rolling time display), as seen in Figure 9.2.3.1. where the signal energy-to-noise power ratio (ENR) of all detections in 6 s intervals is displayed in a gray-scale, overlaid on estimates of the background noise power levels (color scale) for all beams for the first 20 min of run 9.

Just forward of broadside to the array (beam 60) are two click trains; a strong one seen across several beams and a weaker one just forward of the strong one. Such detector outputs were visually tracked and associated into 'events'. Time series 'snippets' were created for each event by choosing the beam containing the largest ENR over 12 s intervals. The snippets were then classified by Pavan as two sperm whale click trains.

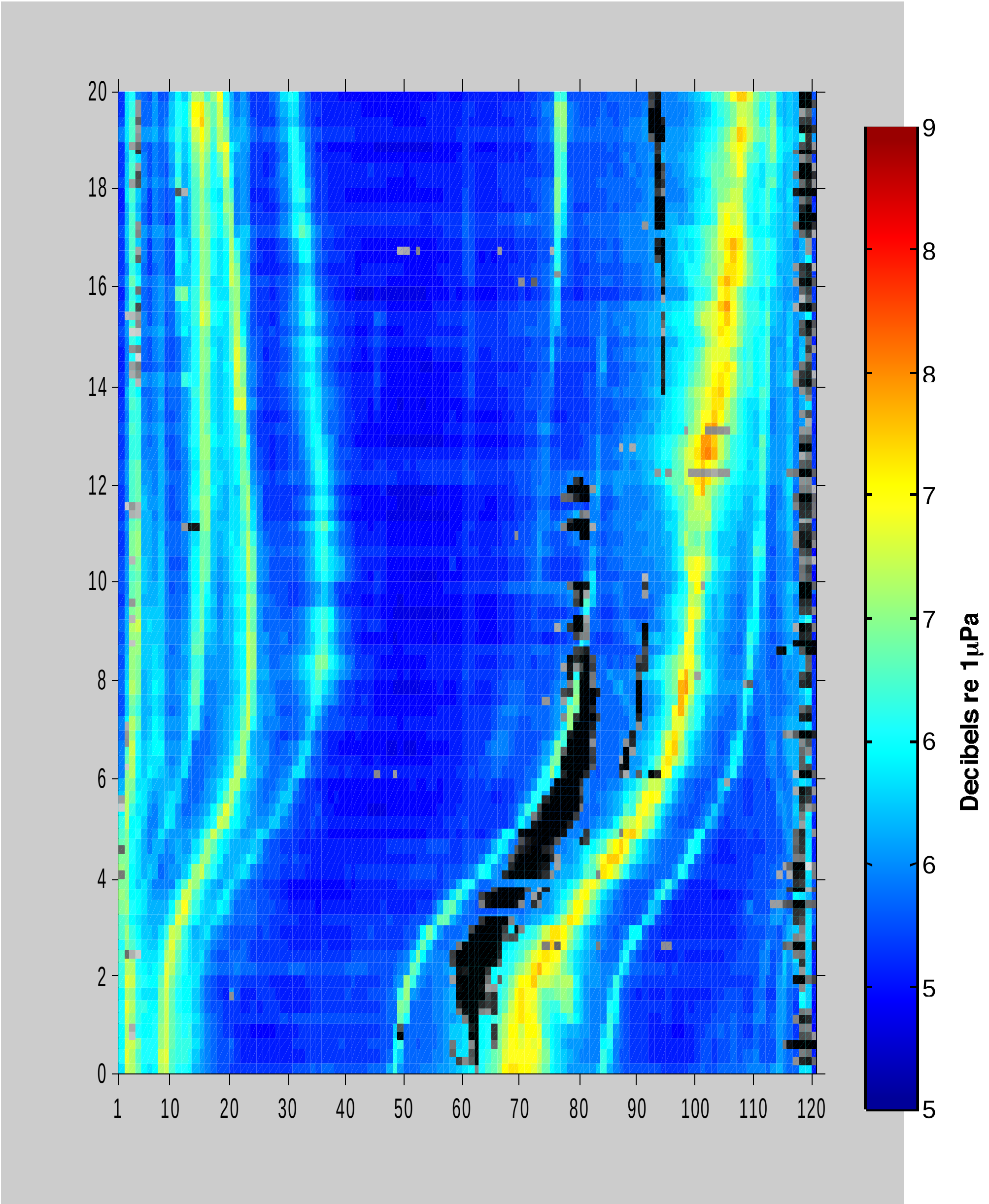

Figure 9.2.3.1 *Raw beam background noise (color scale) with overlaid signal energy-to-noise power ratio (ENR) of detected events (gray scale).*

9.2.4. Localization

Passive listening of acoustic emissions inherently only provides bearing information, and owing to the line array nature of the data acquisition, there exists a cone of ambiguity; that is, the sound arriving at the array sounds the same if it arrives from anywhere on a cone axially aligned with the towed line array. All of the runs analyzed were such that the tow ship (RV *Alliance*) was on a constant bearing. Thus, triangulating detections observed over extended periods of time still results in an ambiguity to the left or right side of the array. However, during the first 10 min of run 9, the array was still completing a turn the tow-ship had made prior to commencing the run. From the array heading information (which is quite noisy) it was then possible to localize the two sperm whale click trains in those minutes as being west of the tow-ship track as seen in Fig. 9.2.4.1. Preliminary ranging of the first *click train* observed (beginning of run 9) indicate a source in proximity to an off-shore 1000 m sea-mount @ N 37° 32' E 21° 7'. Taking this sea-mount as reference points the distances to the track of run 9 vary as follows

- 14.5 km, start of run 9
- 11.2 km, closest point of approach
- 23 km, end

Note that although all of the events shown in this figure have been classified as sperm whale click trains, they may not necessarily be from the same animal.

9.2.5. Conclusion

The analysis of the recordings revealed the presence of sperm whales in the area of the SWAC trials. The identification was possible due to their characteristic broad-band rhythmic vocalizations. No modifications in their vocalizing behaviour, possibly related to the SWAC trials were observed. Further analyses to be carried out by the SACLANTCEN may allow to determine the number of animals present in the area and, possibly, their distance from the SWAC source.

It was neither possible to identify other cetacean species because of the too narrow bandwidth available, nor to determine the presence, or absence, of Cuvier's beaked whales because their species-specific sounds are not known.

9.2.6. Recommendation

Even if a direct cause-effect relationship has not been established, it will be important to improve our knowledge about the acoustics (species specific signals, detectability ranges, hearing abilities, echolocation abilities, reactivity to noise, etc.) and behaviour of marine mammals (diving behaviour, migration routes, feeding, reproductive and nursery areas, etc.) in order to develop procedures to minimize any possible negative effect related with the use of high power sound sources underwater. The development of suitable instruments and procedures for acoustic monitoring and identification of marine mammals will allow to gather new valuable information about their presence and behaviour in the Mediterranean Sea and in other Seas and Oceans.

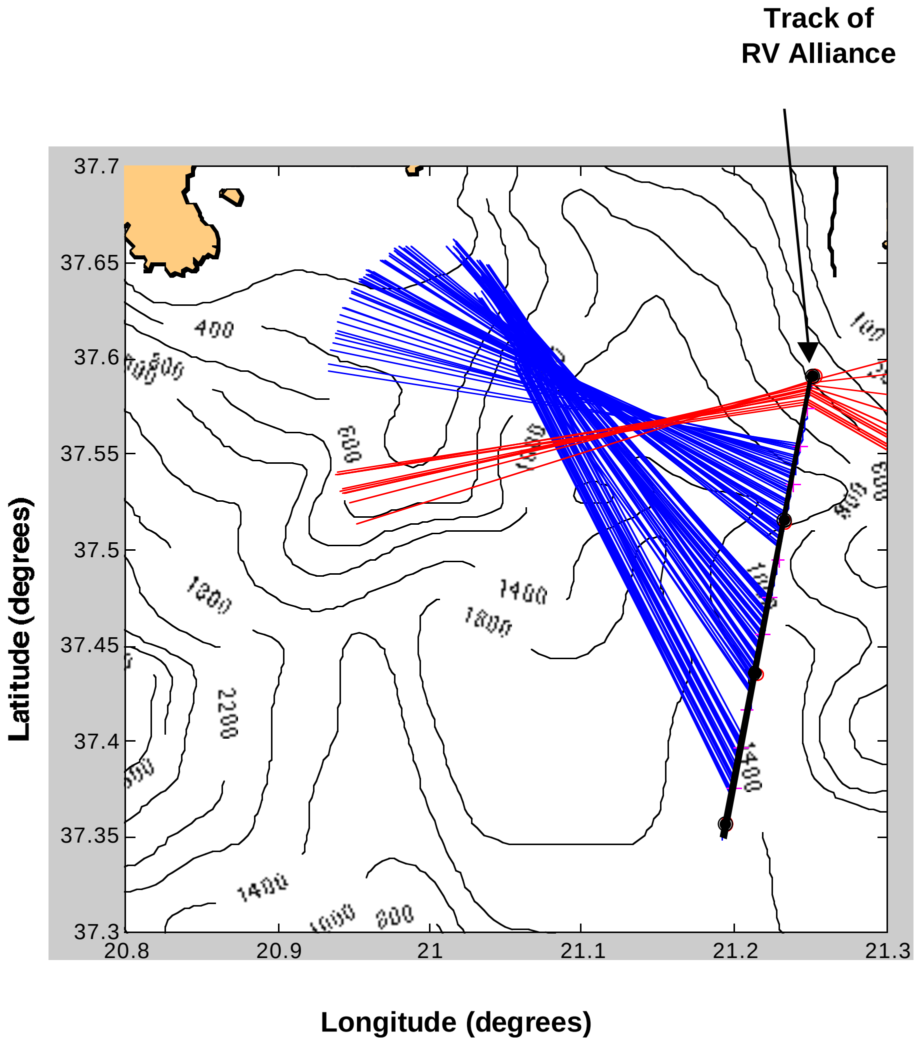

Figure 9.2.4.1. *Bearings only tracking of events 1, 4, 10 and 15 from Run 9, which were all classified as sperm whale emissions. The turning of the array during event 1 (red lines) allows resolution of left/right ambiguity of line array. Each bearing line is 15 nautical miles long.*

9.3. Passive Processing and Analysis of Acoustic Data - Information supplied by M. Van Velzen, G. Hotho, TNO-FEL)

SACLANTCEN provided the Underwater Acoustics Group of TNO-FEL, an institute of the Netherlands Institute of Applied Scientific Research (TNO) acoustic data for independent analysis of recordings made during the SWAC trials. These data were observed using a Transient Detection Demonstrator (TDD).

The purpose of the TDD is to scan passive sonar data for transient signals. Using advanced algorithms the demonstrator automatically detects transient signals from the background and presents the detected transient to the sonar operator both audibly and visually. The demonstrator software has been implemented in a real time fashion and can be used at sea but, can also be used in the laboratory to scan large amounts of raw passive data written to disk. As opposed to the sonar operator, the demonstrator is able to scan all beam directions at the same time. The detected transients are automatically stored to disk, building online a transient data base.

From a scientific point of view the demonstrator can be used to compare the performance of different processing and classification algorithms on passive sonar data containing transient signals. The demonstrator consists of three independently running programs: data generation, processing and display. The data generation program first generates passive background data by reading data from a large file containing real or simulated background data. It then superimposes transient signals, obtained from some data base, onto this background at positions and with signal-to-noise ratios as specified in a parameter file. This data is then processed and searched for transient signals by the processing program. When a transient is detected, the display program is notified and presents this transient to the operator. Using the same parameter file and transient data base, the performance of different processing and classification algorithms can be compared in terms of detection probability versus false alarm probability.

9.3.1. Data analysis

The SWAC active sonar data of run 9 and run 11 were analyzed by the TDD. The objective was to identify Cetacean sounds in the data notwithstanding the limited frequency range available (750 to 1500 Hz). The data consisted of more than 3 h of data:

RUN 9: May 12, 05:30-08:30

RUN 11: May 12, 16:30-16:50

This data was already beam formed by SACLANTCEN and the active part was removed through band pass filtering. As the TDD is designed primarily for the detection of submarine transients we had to tune the parameters used in the algorithms had to be tuned to make the demonstrator suitable for the detection of Cetacean sounds. For this a few examples of Cetacean sounds that were available were used. Due to time constraints only 1 out of each 2 transmissions was analyzed. The data was processed for all 120 beams available and on the original sampling frequency of 6000 Hz. The output of the processor is presented showing the amplitude of the processor output versus beam number and time (Fig. 9.3.1.1.). Then detections were made visually, selecting beams which where obviously different from the back ground. See, for example, beams 80 and 88. In this manner 136 beams where selected and stored to disk. We then listened to the sound corresponding to these beams and selected seven representative examples appropriate for a close inspection by experts.

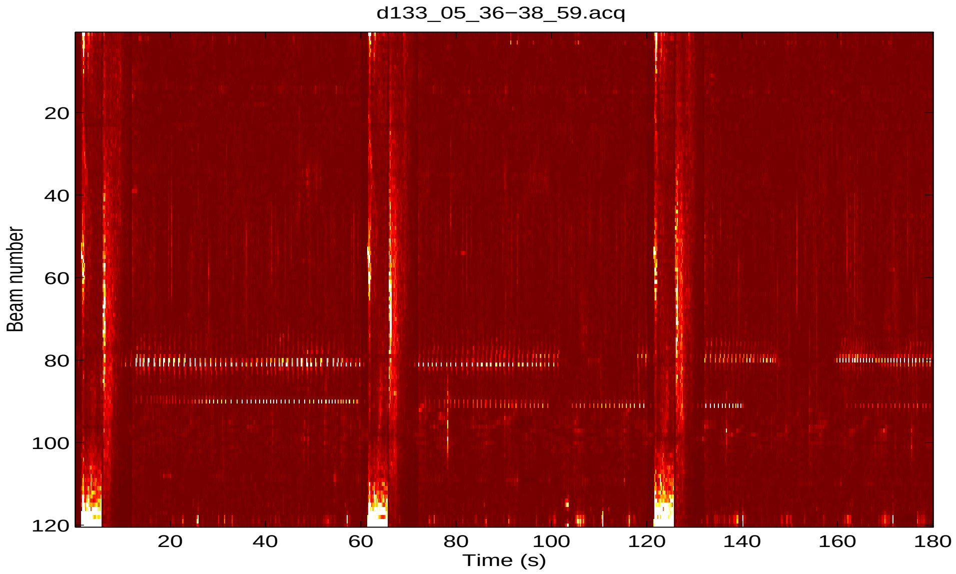

Figure 9.3.1.1. *Examples of detections in three minutes of data*

We presented the selected examples to CODA and the TNO Institute of Applied Physics (TNO-TPD). CODA is an institute of the Royal Netherlands Navy specialized in the analysis of underwater sound. Both institutes have experts on the field of classification of biological sounds and both were able to classify all seven examples. They found, besides three examples of non-biological noises (merchant vessels), examples of Sperm Whales and (small) Toothed Whales.

Table 9.3.1.1. *Classification by experts:*

Dutch navy experts (CODA)	TNO Institute of Applied Physics (TNO-TPD)
May 12, 05:36 (d133_05_36_59.acq) Beam 80, 90: Sperm Whales	May 12, 05:36 (d133_05_36_59.acq) Beam 80, 90: Sperm Whales
May 12, 06:48 (d133_06_48_59.acq) Beam 30: small Toothed Whale	May 12, 06:48 (d133_06_48_59.acq) Beam 30: small Toothed Whale
May 12, 16:48 (d133_16_48_59.acq) Beam 37, 61, 77: Merchant vessels Beam 84: Shrimps + small Toothed Whale	May 12, 16:48 (d133_16_48_59.acq) Beam 37, 61, 77: Non biological Beam 84: Toothed Whale

Later all 136 examples were put on CD-ROM and given to CODA for further analysis. They found in the data: 70 Merchant; 25 ambient noise;19 small odontocetes; 17 medium sized odontocetes; 4 shrimps and one unknown biological sound.

9.3.2. Localization

Having positive classification of Cetacean sounds the next question that arises is whether it is possible to determine the distance and even the depth of the animals. The direction of the animals is known as this follows directly from the beam of detection. Several techniques are available to determine the distance of a passive object.

Target Motion Analysis (TMA) uses the fact that the way in which a passive object will move through the beams of the receiver depends on its velocity and distance to the receiver. Being a function of both velocity and distance one can not, in general, obtain the distance unambiguously from a straight run. This ambiguity is solved by making a tactical move with the receiving ship and observe again how the passive source is moving through the beams. With this extra information, the distance can usually be obtained In both analyzed runs, the towing vessel sailed straight tracks and we found that it was not possible to obtain distances through TMA.

At least an impression of the source distance could be obtained if one would know the source level (SL) of the transmitted sound. As the received level (RL) is known, the sonar equation (RL=SL-PL) might give an indication of distance if the propagation loss (PL) can be calculated and is an unique function of range and depth. However, as this method is presumably highly inaccurate, due to the unknown source level and ambiguity of the propagation loss in range and depth, we did not investigate it any further.

One would also obtain the distance of an animal if some change in the behaviour of that animal could be observed when the transmitted pulse arrives. Since both time of transmission, time of reception and sound velocity are known, one would immediately obtain the distance. This change in behaviour should be observed after each sonar transmission in order to establish a good correlation between animal behaviour and sonar transmissions. No such correlation was found in the data.

Another method to determine both range and depth of a whale is ray tracing. When an animal transmits a (short duration) sound, this signal will arrive at the receiver via different paths through the water. Using a simplified description, sound will arrive via a direct path from source to receiver (d-path), reflected from the surface (s-path), reflected from the bottom (b-path) and reflected from the surface and the bottom (sb-path or bs-path) (Fig. 9.3.1.2.). Since each path has its own length, these multi paths will arrive separated in time. This can be observed in Fig. 9.3.1.3., where one sees the direct, surface, bottom and bottom-surface arrivals, respectively. This configuration of multi path arrivals depends on the depth of the receiver, depth of the transmitter, range of the transmitter, ocean depth and sound velocity profile. We have used a program, developed at TNO-FEL, that searches for the right combination of receiver depth, source depth and source distance that produces the same arrival times as found in the real data. Ocean depth and sound velocity are input to this search. Since the receiver depth is known it can be used to check the validity of the search. We found that for an animal at short distances to the receiver, the method worked well as the multi paths are well separated at short distances. At large distances (larger than 10-15 km) the multipaths are too close together and the method does no longer work as indicated by the incorrectly estimated receiver depth.

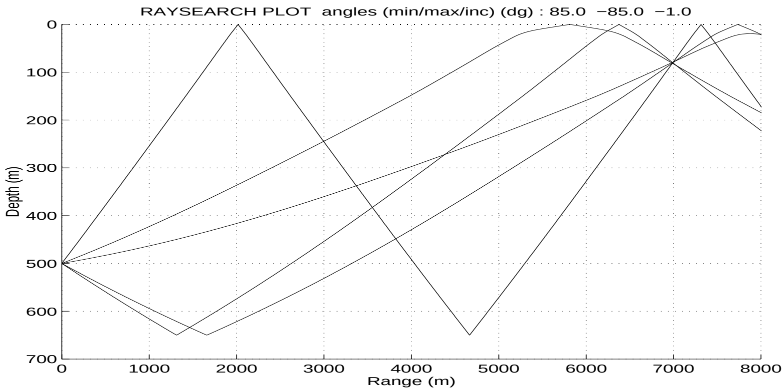

Figure 9.3.1.2 *Ray trace output*

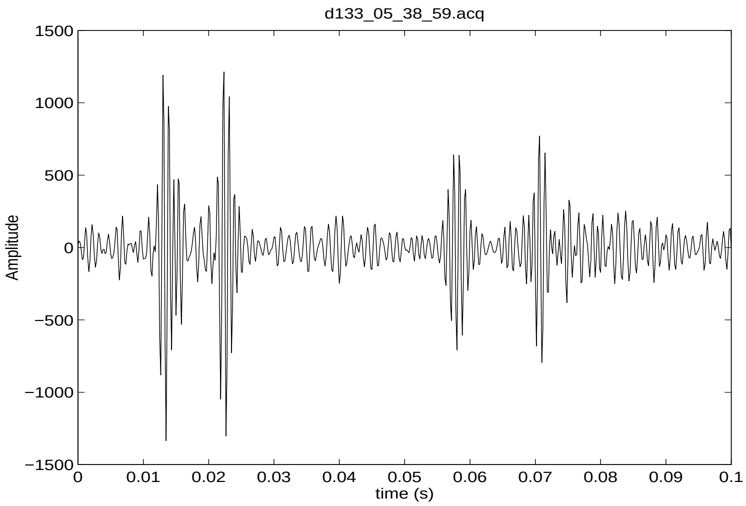

Figure 9.3.1.3 *Example of raw data showing multi-paths*

9.3.3. Summary

We conclude that, despite the limited frequency interval available, Sperm Whales and (small) odontocetes were detected in the SWAC data run 9 and 11. It was shown that for some animals close to the receiver (within 10 km) the distance and depth could be obtained using a technique called ray tracing. A broad band passive sonar in combination with the Transient Detection Demonstrator can be used to detect Cetacean sounds in all directions prior to active sonar transmissions.