A MEASUREMENT SYSTEM TO RECORD THE ULF ELECTRIC FIELDS RELATED TO THE ELASMOBRANCH ELECTROSENSORY SYSTEM

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Abstract: Numerous observations and reports indicate that sharks are often attracted to, or repelled by, the Electromagnetic (EM) Radiation from underwater electrical apparatus and man-made installations resulting in damage to the equipment and possible ecological damage. It is essential that, with the introduction of more and more man-made underwater devices, a study of "normal" electric activity in the oceans is made so this can be compared with possible increased activity from man-made systems. In this paper the development, design and implementation of an underwater electric field recorder that can be towed by a scuba diver is presented. The measurement system uses carbon fibre probes to measure three channels in the frequency range of 0.1 - 10 Hz at 64 samples/sec with a resolution of 24 bits. The input range is ±18 mV/m with a noise floor of less than ±30 μV/m. The system can record for up to one hour and the measurements are downloaded to a computer for analysis.

Key words: Marine electromagnetics, measurement systems, ULF, *Elasmobranch*, sharks, EM radiation, modelling.

1. INTRODUCTION

Numerous observations and reports indicate that sharks are often attracted to, or repelled by electric fields from underwater electrical apparatus and man-made installations [1]. This results in either damage to the apparatus or possible ecological damage as sharks have been reported to leave areas of high unnatural EM activity [2]. Adverse reactions by sharks to strobe flashes, video cameras and protection systems have been reported, as well as an interest in underwater electrical equipment, such as video cameras [1], SONAR arrays and telecommunication equipment [3]. This can cause "distress" to both sharks and humans (when their equipment is "attacked") and could also result in a possible decline of marine resources and tourist activities.

Renewable energy resources in the marine environment, such as offshore wind farms, tidal generators and wave generators [4, 5], could also result in unintentional ecological damage to the habitat of electrosensory fishes. Electric potentials in the marine environment are caused by ocean flow through the earth's magnetic field, non-ocean origins (geomagnetic, atmospheric and ionospheric), man-made (naval, industrial and recreational) and oceanic life [6–9]. To evaluate the possible ecological problems that may be caused by man-made equipment and electrical installations on the elasmobranchii, some idea of the "normal" electric potentials that they are subjected to must be determined.

In this paper the design and construction of a recording system to measure Ultra Low Frequency (ULF) electric potentials in the water is described. Results of the measurements are presented and analysed in terms of both the possible sources and the elasmobranchii' electrosensory system.

2. SOURCES OF ELECTRIC POTENTIALS

2.1 Natural sources

Ridgway *et al.* [6] describes the natural sources as being both internal to the ocean, caused by movement of the sea water through the earth's magnetic field, and external, caused by electromagnetic radiation produced from geomagnetic, atmospheric and ionospheric activity. Electric potentials produced by swells and surface waves, caused by local winds, have frequencies in the range of 50 to 500 mHz. As discussed by Crona *et al.* [8] the background electric fields can be denominated by electromagnetic waves caused by micropulsations in the ionosphere. In shallow-water Schumann resonances, lightning induced random phase standing waves in the ionosphere-earth cavity, have discrete peak frequencies of 8, 14, 20, 26, ... Hz. Spectral analysis from measurements taken by Crona *et al.* [8] off the western shore of Point Loma, San Diego clearly show Schumann resonances and swells in the frequency range 40 mHz to 1.8 Hz. Similar results were obtained by Sanford [9], again off the coast of San Diego.

2.2 Man-made sources

To attempt to quantify or even describe all the man-made electromagnetic sources producing electric potentials in the worlds' oceans is an impossible task. The man-made sources include:

- power-line frequencies as measured by both Crona *et al.* [8] and Sanford [9]

- shipping activity
- marine cathodic protection systems
- offshore drilling rigs
- oil pipelines
- electromagnetic surveying [10]
- telecommunication systems [3]
- naval activity both for submarine communication and warfare systems [11, 12]
- scuba diving equipment and accessories [1].

Much of the work is being conducted at military and commercial levels resulting in few of the publications being available for general access.

3. ELASMOBRANCHII' ELECTROSENSORY SYSTEM

The elasmobranchii electrosensors were first described by Lorenzini in 1687 [13] but their purpose as electrosensors was first reported by Dijkgraaf and Kalmijn in 1962 [14]. Since then a number of researchers have undertaken research programmes to model the electrosensory systems of the elasmobranchii. This includes laboratory and open water experiments [15, 16], Bastian [17] developed a model for the equivalent circuit of the system, Tricas [18] measured the sensitivity and dynamic response and Bodznick *et al.* [19] investigated the filtering of important information from a very noisy environment. The sensitivity the electrosensory system can be less than 1 μV/m [20] with a frequency range of DC to 10 Hz [16].

4. DESIGN OBJECTIVE

The design objective was to develop a system to measure the electric potentials in a recreational scuba diving environment in the sensitivity and frequency range of the elasmobranchii. The goal was to quantify and compare the electric fields produced by divers and the equipment, usually used during recreational dives, and those found without divers present. Ultimately this information could be used to design low emission equipment, thus reducing recreational divers' impact on the marine environment.

Initially a laboratory measurement system was developed, with three dimensional carbon fibre probes and low noise amplifiers to measure voltages in a salt water tank housed within a screened building [1, 21]. Carbon fibre probes were used for both the laboratory and the self contained underwater measurement system in preference to silver/silver chloride (Ag/AgCl) electrodes. Carbon fibre electrodes are more robust, easy to manufacture at a lower cost and perform as well as Ag/AgCl electrodes [22]. The electric fields from an underwater video camera, strobe flash and a dive computer were measured to get an idea of both the voltages and frequencies produced by the equipment. These results were then modelled [23] and used as the basis to design the underwater recording system.

5. LABORATORY MEASUREMENTS

No change in measurements was recorded from the dive computer whereas changes in the measured potentials were obtained from both the strobe flash and the video camera. The measurement system and results are fully described by Zachar and Gibbon [21]. A typical measurement from a strobe flash is shown in Figure 1 and shows a distinct change in the measured potentials when the flash was fired.

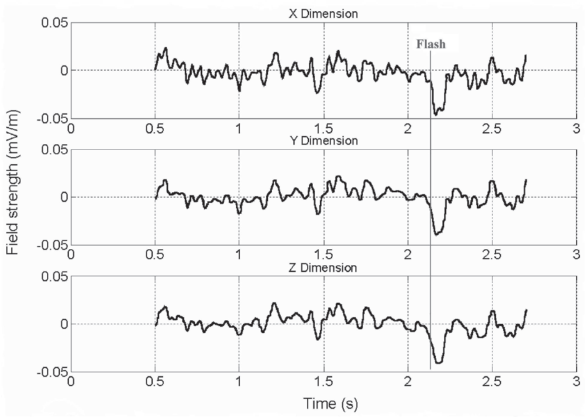
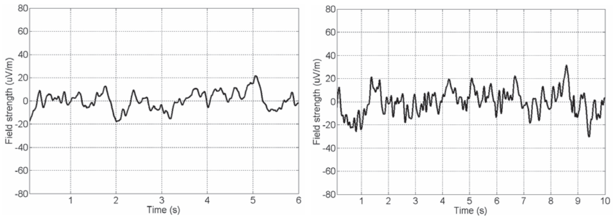
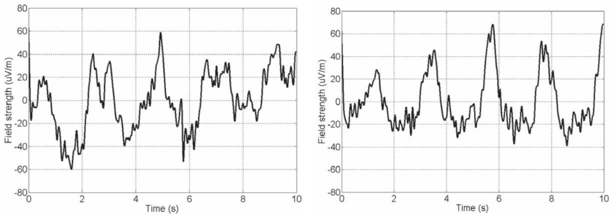


Figure 1: Measurements of a strobe flash discharge

Figure 2 shows voltages measured in the tank with (a) nothing in the water, (b) video camera, switched off (c) video camera, switched on and (d) video camera, in recording mode.



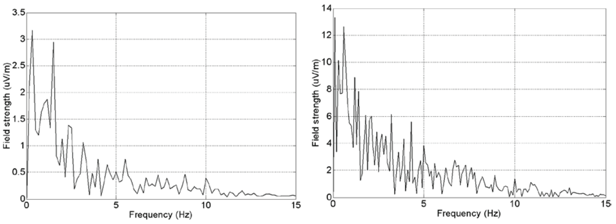
(a) Background Noise (b) Video Off



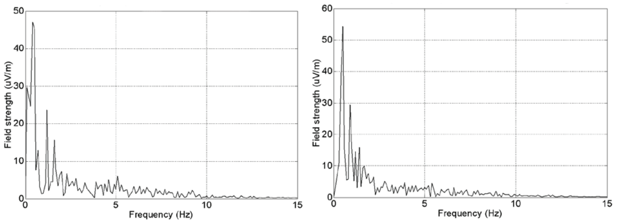
(c) Video On (d) Record On

Figure 2: Amplitude measurements with the Video Camera

Although clear changes can be seen in the time variant signals, more significant changes are apparent in the frequency content of the four recordings, as shown in Figure 3. Please note that the plots have different y-axis scales to enable discussion of the frequency in each mode of operation as follows:



(a) Background Noise (b) Video Off



(c) Video On (d) Record On

Figure 3: Frequency response of measurements with the Video Camera

- The amplitude of signals at frequencies below 1 Hz increase by 17 times when the video camera was placed in the water. This probably due the ionisation caused by the different materials from which the housing is manufactured (stainless steel, powder coated aluminium and various plastics).
- Amplitudes increase at frequencies above 1 Hz when the camera is switched on, most likely due to radiation from the power supply and electronic circuits.
- In the record mode increased amplitude can be seen further up the frequency spectrum as a result of added radiation from the tape drive motors and controlling circuits.

Sharks will, in all probability, be aware of these changes in frequency content due to their adaptive frequency capability [19].

6. SELF-CONTAINED UNDERWATER MEASUREMENT SYSTEM

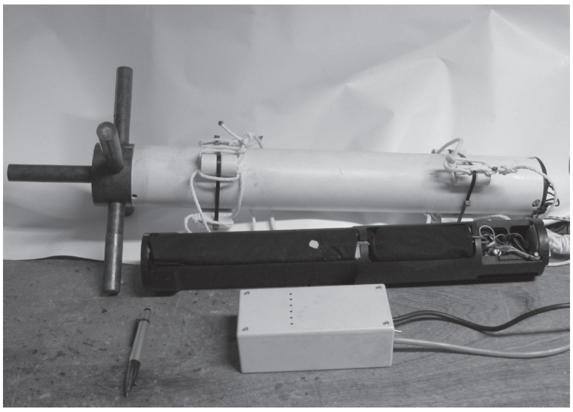


Figure 4: The underwater recording system showing the housing, internal structure and computer interface

A recording system was developed to measure electric field strengths in the ocean (see Figure 4) compact enough to be "towed" by a scuba diver on a recreational dive. The system was based on a modified electrical representation of the sharks' sensory system [1], shown in Figure 5, together with notes on how this was implemented in the recording system. The specifications of the system are given in Table 1. The system uses chopper-stabilised input amplifiers and carbon fibre probes to eliminate input drift due to ionisation in the water. Unity gain chopper-stabilised amplifiers, with a switching frequency of 200 Hz, (TC7650 [24]) were used for the input stage to minimise the input offset voltage and drift, input bias current and input noise voltage. There are no metal fittings on the casing to avoid any interference from cathodic reactions.

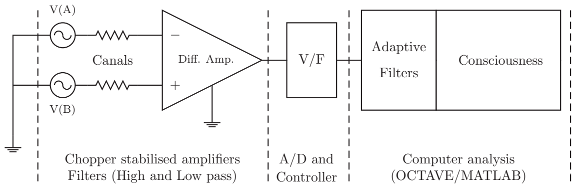


Figure 5: Electrical model of the underwater measurement system

Table 1: **Specifications of the underwater measurement system**

Number of channels	:	3 (x,y and z)
Frequency Response (-3dB)	:	0.1 - 10 Hz
Alias noise	:	-50 dB at 32 Hz
Sample Rate	:	64 samples/sec
Sample size	:	24 bits
Recording time	:	60 minutes
Input range	:	$\pm 18\,\mathrm{mV/m}$
Internal noise	:	$< \pm 30\mu\mathrm{V/m}$
Interface to computer	:	SD card interface

6.1 Results

Measurements were taken off the coast of Port Alfred, Eastern Cape, South Africa. These included five drifts over sand, over sandstone reefs, "deep sea" drifts at 30 m with the sea bottom at 70 m, to measure electric potentials without divers, and 27 dives with a varying number of divers. Two typical recordings are discussed.

Figure 6 shows the electric field measurements and frequency response taken during a drift 5.6 Nautical Miles (NM) off the coast with the recording system hanging from a buoy at 30 m with the sea floor at 70 m. The first 2.5 minutes show electrical activity after the recording system was dropped into the water, probably due to its movement through the water to 30 m and its close proximity to the boat. The spectral power density analysis is calculated relative to the maximum signal recorded and was plotted to -120 db(max) to indicate the noise floor of the recording system.

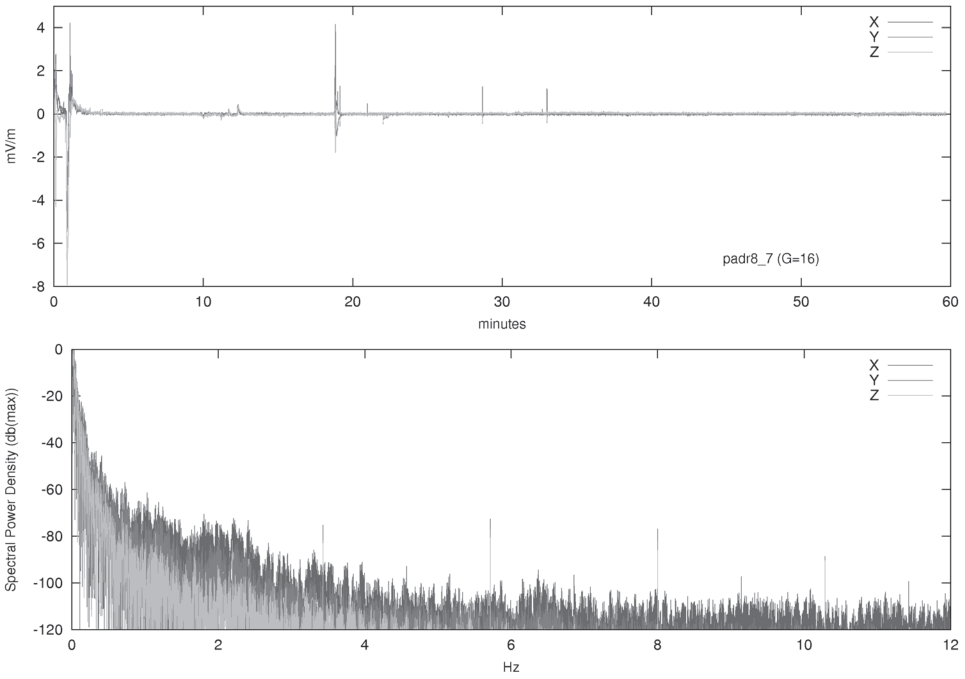


Figure 6: Recordings from an open water drift: depth 30 m, sea bottom at 70 m

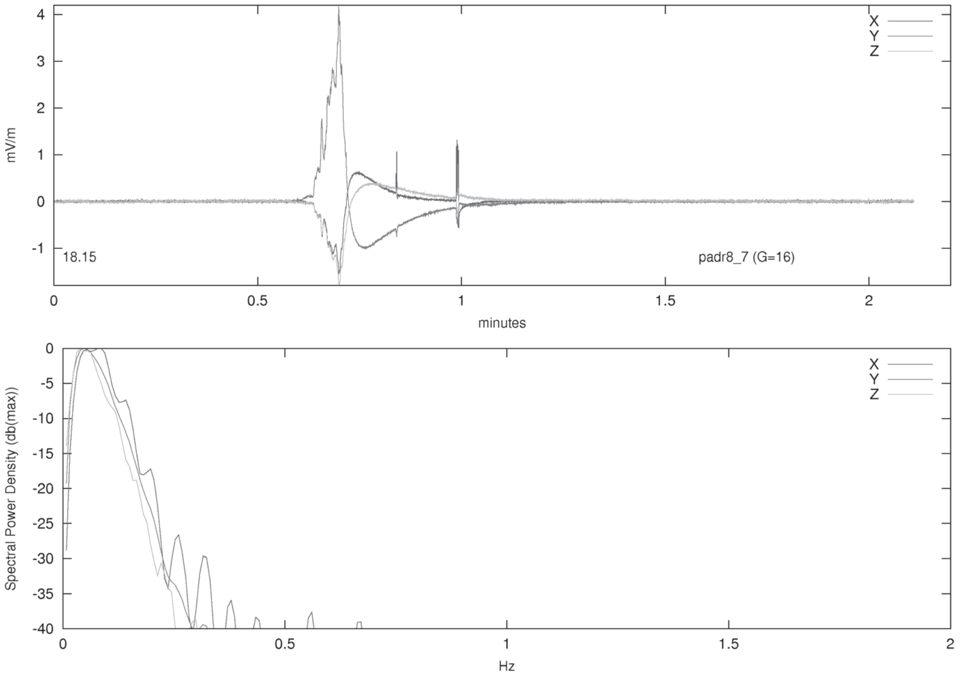


Figure 7: A large pulse measured during the open water drift

Figure 7 shows an expanded section of the large pulse at about 19 minutes. No definite theory is offered for this signal but observations of the buoy changing direction at approximately that time, during the drift, suggest that the measurement system passed through opposing currents with change in water temperature.

Figure 8 shows an expanded section of another pulse, at about 28 minutes, which is typical of measurements taken during most of the drifts and dives recorded off Port Alfred. Interestingly this pulse is almost the same as a pulse recorded by Sanford *et al.* [9] which Sanford suggested could have been caused by a “marine mammal disturbance” although this was not actually observed. These pulses have been recorded during dives where no interaction with marine life was observed and the author

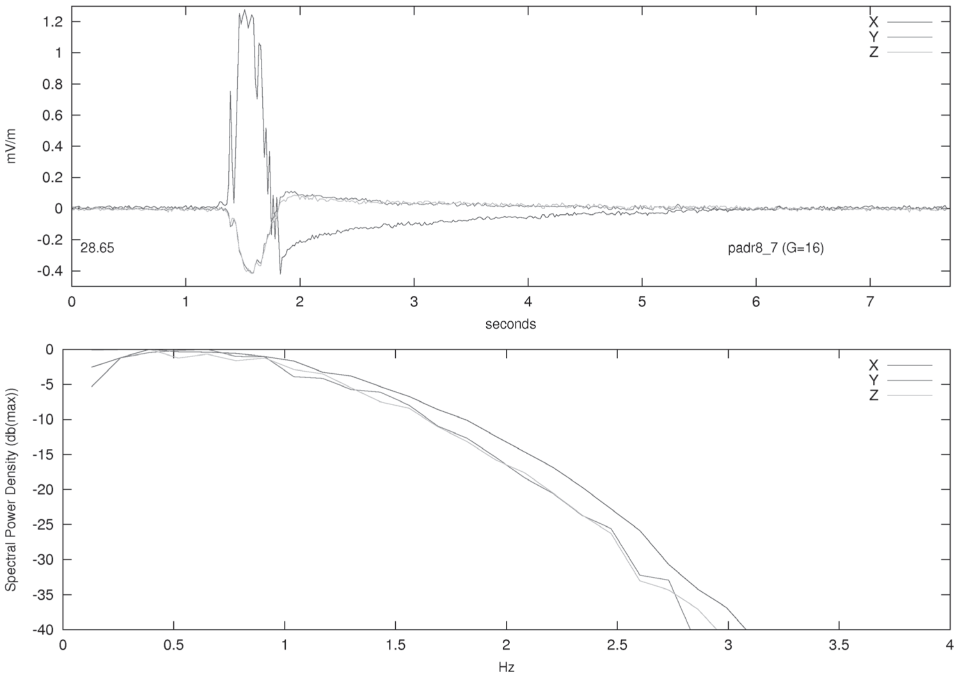


Figure 8: A typical signal measured during an open water drift

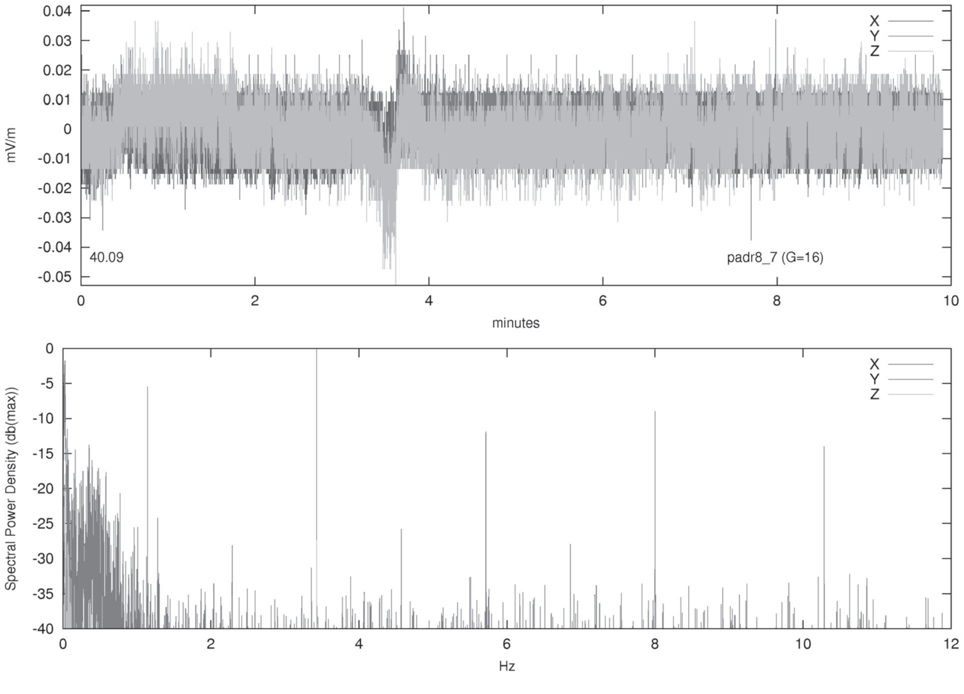


Figure 9: A typical quiet section recorded during open water drift

believes that this maybe related to the system passing through thermoclines or water bodies with dissimilar properties.

Figure 9 shows a “quiet” section during the drift with signals below $50\,\mu\mathrm{V/m}$ being measured with no distinctive signals. The spikes seen at regular intervals from about 0.8 Hz are due the sampling rates of the analogue-to-digital converter and the switching frequency of the chopper-stabilised amplifiers. This noise can be removed, if necessary, during analysis as the peaks are at known frequencies. The low frequency content, below 0.5 Hz, can be explained by the swell and wave action that was present, and is always present, while the measurements were being taken.

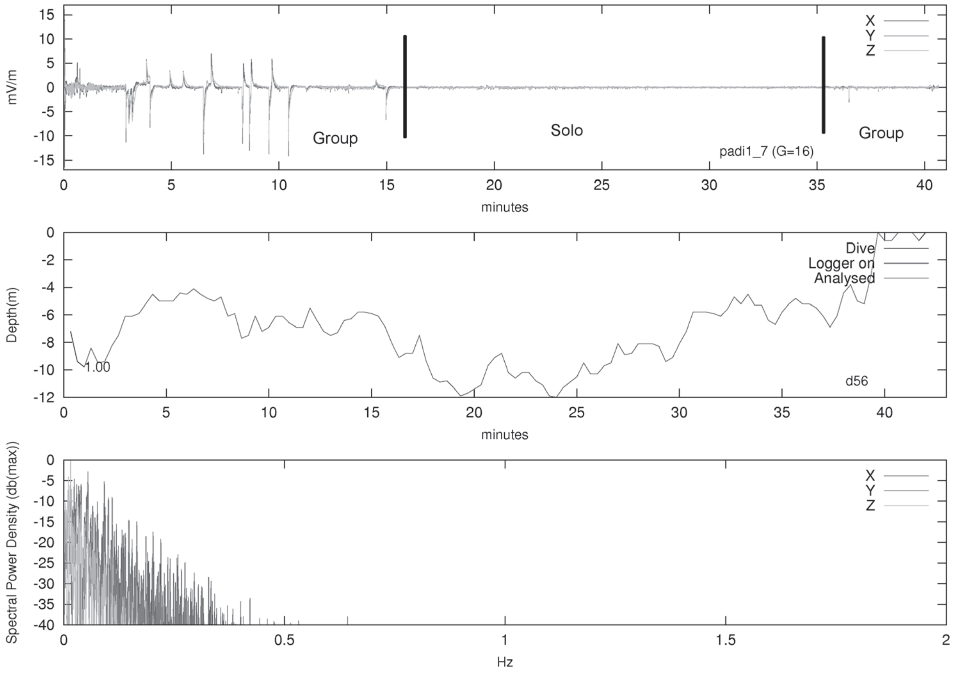


Figure 10: Measurements taken during a dive with up to twelve divers

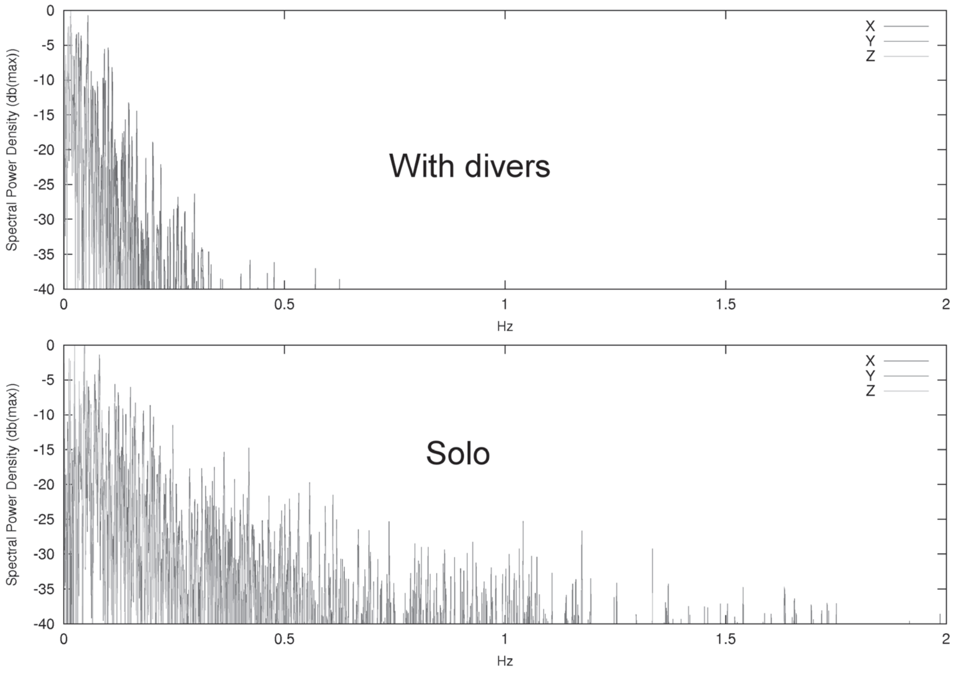


Figure 11: The frequency spectra measured, with and without other drivers near the recording system, during a dive

Figure 10 shows measurements during a dive with a group of 12 divers showing the recorded voltages, the dive profile and the frequency spectrum. Initially the recording system was amongst the divers and at about 15 minutes was moved away from the group and towed at a minimum distance of 5 m from the group. The group was rejoined at 35 minutes for the ascent. From the measurements it appears that groups of divers radiate electric signals into the water at frequencies and amplitudes well within the sharks' sensory range.

In Figure 11 the frequency spectrum of the measurements with and without other divers in the vicinity of the recording system are compared. It should be noted that the scales of the two plots are not comparable as the frequency power density (db(max)) is calculated with the maximum signal in the section being analysed, as with this method it is easier to visualise the frequency spectrum where there are large variations in the voltages being measured. The plots do show, however, that there are more lower frequencies signals produced by a group of divers, in the range DC to 0.5 Hz, as opposed to those produced by a single diver. None of the divers were using any electronic equipment, other than dive computers, and the signals were produced by passive sources such as air cylinders, buoyancy compensators, breathing systems and their bodies.

7. DISCUSSION

One of the problems of analysing the measurements is the separation of far-field events, such as those caused by wave action and ionospheric events, and near-field events, such as diving equipment. The elasmobranchii have adapted to live with the considerable natural electric noise in the sea but do react to near-field disturbances such as camera strobe flashes [1]. One of the solutions is a remote reference system as used by Crona *et al.* [8] where common signals can be removed and only the remaining signals studied. In Crona's case the reference system was placed 1.8 km from the measurement system. This is not a feasible option for a system designed to accompany a diver on many dives at many dive sites. The elasmobranchii also do not have the option of a remote reference and seem to be able to distinguish between near-field and far-field events. It is possible that their "sensor arrays" enable them to ignore far-field events and work by Sisneros [25] and Tricas [26] may provide more information that may be used in the analysis of the measurements.

8. CONCLUSION

The design of, and the results obtained from, an underwater recording system to measure the electric potentials in sea water has been presented. The system has three channels with an input range is ±18 mV/m, a frequency range of 0.1 - 10 Hz at 64 samples/sec, a resolution of 24 bits and a noise floor of less than ±30 μV/m. The system was designed to be "towed" by a diver and record all the electric potentials produced by divers and their equipment during dives one hour. Laboratory results show distinct changes in both the amplitude and the frequency content of the measured potentials from both a strobe flash and a video camera. Measurements in the sea, both drifts and dives, show a surprisingly electrically noisy environment with some unexplained phenomena. The results also show large changes in both the amplitude and the frequency content in the electric potentials when a group of divers is compared to a single diver towing the recording system.

9. ACKNOWLEDGEMENTS

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