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SOFTWARE TOOLS FOR REAL-TIME IPI MEASUREMENTS ON SPERM WHALE SOUNDS

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1. INTRODUCTION

More studies on the social structure and behavioural ecology of sperm whales (*Physeter macrocephalus* L.) have been carried out in the last decade as the latest instruments and techniques allow new insights to their behaviour [9,11,17,18].

It is important to assess the size distribution of sperm whales in the Mediterranean Sea in order to have a better knowledge of their population structure, to understand the population trend in time and to support conservation efforts.
In addition to the traditional observation techniques, it is now possible to remotely assess the body size of sperm whales with simple acoustical methods. Norris & Harvey [13] were the first to make hypothesis on the sound production mechanism in sperm whales. They described the structure of sperm whale clicks as a first intense direct pulse (P1) and a number of reflections (P2, P3, ...Pn) generated in the head of the whale. The inter pulse interval (IPI) seems to be correlated with the size of the spermaceti organ and thus with the overall body size. Several Authors have proved that Inter Pulse Interval (IPI) measurements on pulses P1 and P2 in click recordings of diving sperm whales are useful in assessing the whale's body size [1,5,6,7, 8,10,12,16]. Up to 1996 IPI measurements of the delay among pulses P1 and P2 were mostly carried out visually on waveforms displayed on an oscilloscope. This method required a great effort and limited the number of analysed samples.
Goold [5] developed a computerised semi-automatic cepstrum-based method to measure the IPIs in long sequences of clicks. In the same paper, Goold considered the acoustic transmission properties of the spermaceti oil under different temperature and pressure conditions to accurately assess the spermaceti length [6].

To improve our knowledge on the sperm whales we are carrying out studies in the Mediterranean Sea since 1990. We made a series of IPI measurements on selected recordings from our Cetacean Sound Library [14,15]. We then tried to improve automatic analysis processing to make whale size measurements more reliable and simple.

2. MATERIALS AND METHODS

2.1 Recordings

Recordings were made during research cruises organised by the Centro itself and with the co-operation of other Institutions to study the acoustic behaviour, distribution and biology of cetaceans in the Mediterranean Sea.
Digital (DAT) recordings made in six research cruises (July 1991 - Aeolian Islands; June 1994, September 1994, June 1995 - North Tyrrhenian Sea and Ligurian Sea; September 1996 - Ligurian Sea; June 1997 - South Tyrrhenian Sea and Ionian Sea) were selected to provide samples for the present study. We selected recordings of 7 whales (5 of which successfully photo-identified) and we analysed click sequences starting from the beginning of their dives.

Goold's research [5] is based on recordings made in restrictive conditions (only the first 6 minutes of recordings after fluking up were analysed).
Our analysis was extended, whenever possible, to more consecutive whole dives to evaluate IPI stability with time. All the recordings we processed were made with towed arrays and a CASIO DA2 DAT recorder. Towed array used in 1991 was provided by Tethys Research Institute. In the following cruises a towed array designed by ALENIA specifically designed on our requirements was used [14]. With the ALENIA instrumentation we were able to monitor the operating depth of the array by means of a display. The speed was that to maintain the hydrophone at a depth of at least 25 meters in order to increase the delay of surface echoes. Recordings used for the present study were characterised by having surface echoes clearly identifiable from direct clicks (delays greater than 8 msec) (Fig. 1).

2.2 Analysis procedure
To measure extensively IPI, we developed a program based on our custom real-time PC based Digital Signal Processing Workstation [14]. This software, optimised for this special purpose, shows real-time spectrogram (spectrum Vs time) and cepstrogram (cepstrum Vs time) simultaneously. Recordings were digitised by an Audiologic Duetto sound board and no equalisation was performed.
The optimisation of analysis parameters (Sampling rate 22050, FFT size 512, Window size 512, Window shape Hanning, overlap 75% or 87.5%), allows the real-time display of delays ranging from 0 to 10 ms.

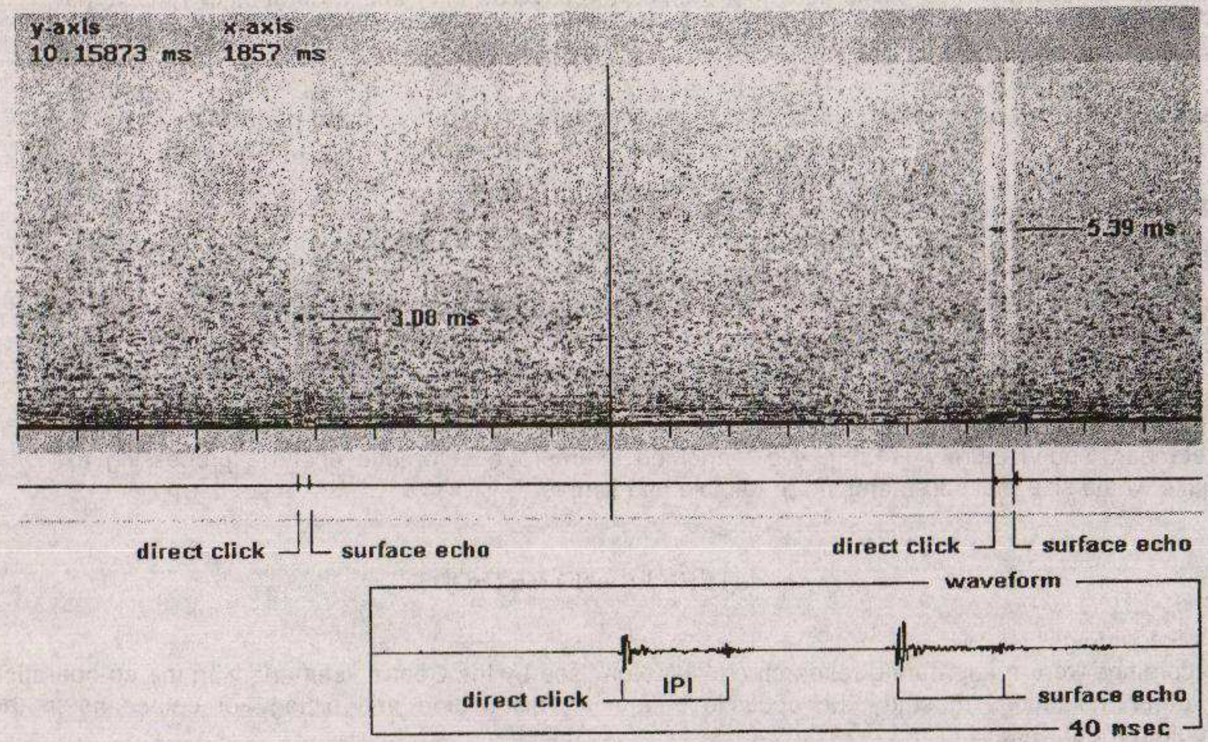

Figure 1 *- Cepstrogram of two whales of different sizes (left: SW0996B; rigth: SW0996A): the value on the y axis of the darker dots corresponds to their IPI's. Clicks from both whales have strong and well spaced surface reflected echoes. The waveform below shows that well spaced echoes don't interfere with IPI measurement.*

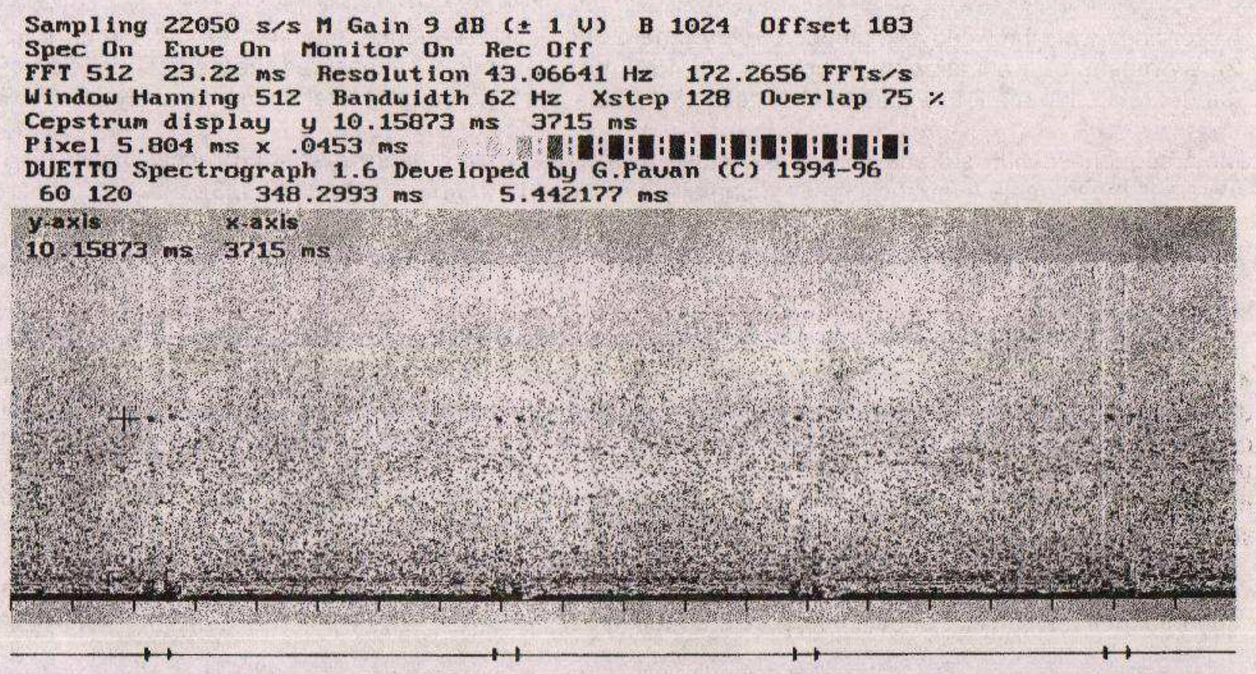

Figure 2 - Actual display of the real-time cepstrogram of a click sequence. The whale is SW0694: the cursor is located at 5.44 msec. Well spaced surface echoes are clearly visible in the envelope trace below, IPIs can here be measured as well.

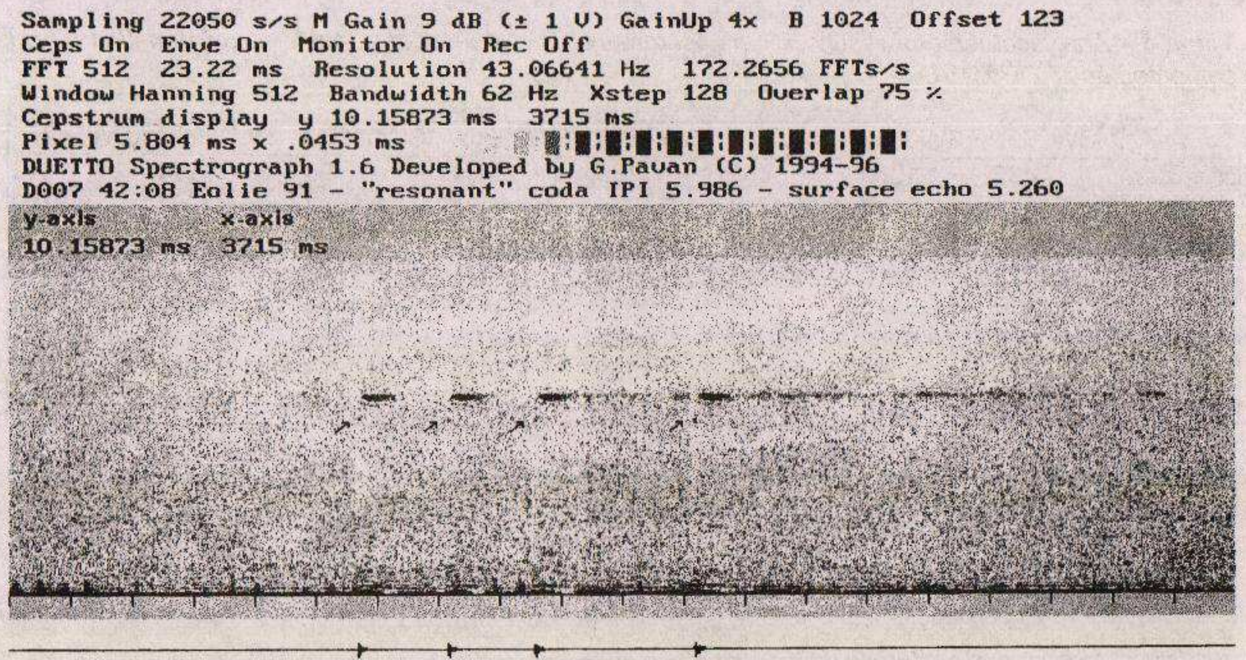

Figure 3 - Coda emitted by whale SW0791: clicks are composed by a well defined series of pulses: their IPI is 5.986 msec; surface echoes at 5.260 msec are barely visible (arrows).

Recordings were browsed and stopped every time a good click sequence appeared on the screen (Fig. 2). By means of a cursor with an accuracy of 45.3 microseconds we measured the vertical position of the dot related to the P1 - P2 interval of each click. Data were stored for a later statistical analysis.

Most sequences with surface echoes too close to the direct clicks were discarded; occasionally, IPIs were still measurable even if clicks were partially overlapped by surface echoes (Fig, 3).

3. RESULTS

3.1 Acoustic measurements

The IPI measurements on the selected click sequences produced the results shown in table 1 and figure 4. By comparing flukes, we discovered that one of the 5 photo identified whales was recorded twice, in June 1995 and in September 1996 (SW0695, SW0996A). This gave us the opportunity to evaluate the growth of the whale (work in progress).
Whenever possible the analysis on sighted and tracked whales was extended to more than 6 minutes and to the consecutive dives. Our results were consistent throughout whole dives and never showed the scattering of IPI values previously reported, even though we confirmed IPIs varied according to the variation of spermaceti properties with the progression of the dive [5]. Therefor spot measurements on short sequences of clicks should be considered reliable.

Codas' IPI emitted by whales SW0791 (Fig. 2), SW0694, SW0996C were measured. These values exactly matched IPIs measured in the click series.
For each whale, IPI measurements were randomly verified, and always confirmed, by visual inspection of waveforms.

***Table 1** - Analytical table of results. IPI measurements in milliseconds. Coefficient of Variation (CV) is computed as STDEV/AVG.*

	SW0791	SW0694	SW0994	SW0695	SW0996A	SW0996B	SW0996C	SW0697A
N	435	1080	600	756	334	90	274	473
AVG	5.9975	5.4092	4.9783	5.1715	5.3894	3.0698	5.1551	6.3102
MIN	5.8500	5.3061	4.8979	4.8072	5.1247	2.5396	5.0340	6.2131
MAX	6.1224	5.5328	5.0793	5.3062	5.4421	3.2653	5.4421	6.4399
STDEV	0.0372	0.0370	0.0418	0.0681	0.0415	0.1424	0.0580	0.0408
CV	0.0062	0.0068	0.0084	0.0132	0.0077	0.0464	0.0112	0.0065
MEDIAN	5.9864	5.3968	4.9886	5.1700	5.3968	3.0839	5.1700	6.3038
MODE	5.9864	5.3968	4.9886	5.1700	5.3968	3.0839	5.1247	6.3038

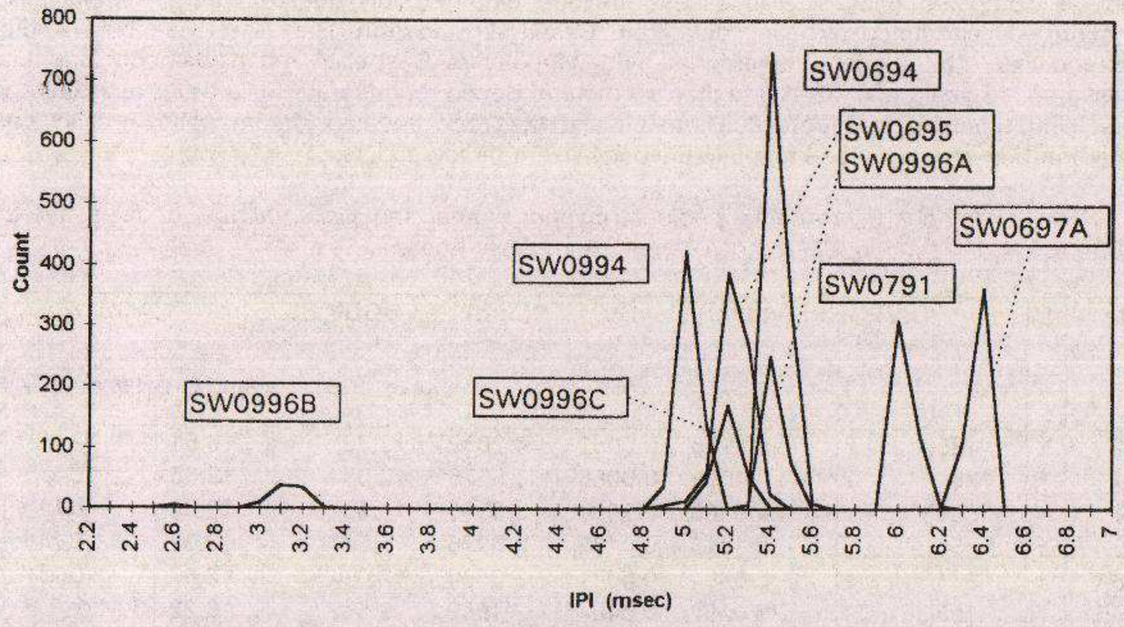

Figure 4 *- Distribution of IPI measurements (100 microseconds intervals).*

3.2 Size computation

IPI measurements are directly related to the spermaceti length (SL). To calculate the body size of a whale we use Clarke's equation [4] that relates body size to spermaceti length assuming that the speed of sound in spermaceti is 1430 m/sec, as suggested by Goold [5,6]:

$$\text{Total Length} = 9.75-0.521*SL+0.068*SL^2+0.057*SL^3$$

$$\text{where } SL = IPI*1430/2000$$

We also used the equation proposed by Gordon [8] which correlates measured IPIs to photographical estimates of body lengths:

$$\text{Total length} = 4.833+1453*IPI-0.001*IPI^2$$

The results are summarised in table 2.

We applied both Clark's and Gordon's equations and we noted that both equations are not suitable for small whales (less than 10 m in size). This could depend on the lack of knowledge of the relationship between the spermaceti organ and the total body size in young animals.

There is a small variability of IPIs within clicks from a single individual and IPIs seem to be reliable indicators of body sizes even if only spot measurements are available.

Further research on correlating IPIs to reliable estimates of length is needed in order to model a more accurate equation that relates IPI measurements to the body length.

3.3 Age determination

We used the computed body size to assess the age, and possibly the sex, of the whales. Age determination was attempted by using data from Berzin [2] and from Best et al. [3]; both Authors correlated the size with the age as determined by dentine layers. Best et al. report data only for whales ageing less than 13 years and sized less than 10 meters; Berzin reports data for a wider range of ages and sizes. Unfortunately, their data don't match and thus age and sex determination results quite inaccurate. Further work is needed to relate the body size with age and sex.

Table 2 *- From left to right: whale name, photo-id, number of analysed clicks, number of dives, average IPI and Coefficient of Variation, Spermaceti Length, Body Size, Age and Sex.*

Whale	ID	N	DIVES	IPI (msec)	CV	SL (m)	BODY SIZE (m)		AGE SEX
							Clarke 1978	Gordon 1991	Berzin 1971
SW0791	Y	435	2	5.9975	0.0062	4.2882	13.26	13.51	12 M
SW0694	Y	1080	2	5.4092	0.0068	3.8676	12.05	12.66	10 M
SW0994	Y	600	2	4.9783	0.0084	3.5595	11.33	12.04	8 M
SW0695	Y	756	2	5.1715	0.0132	3.6976	11.63	12.32	9 M
SW0996A	Y	334	2	5.3894	0.0077	3.8534	12.01	12.63	10 M
SW0996B	N	90	1	3.0698	0.0464	2.1949	9.54	9.28	5 M or 7 F
SW0996C	N	274	3	5.1551	0.0112	3.6859	11.61	12.30	9 M
SW0697A	Y	473	4	6.3102	0.0065	4.5118	14.02	13.96	12.5 M

4. DISCUSSION

This method has in the short time occurrence of surface reflected echoes its greatest limit. The reliability of the automatic IPI measure is low when the transmission path, depending on the position of the clicking animal, the operating depth of the towed hydrophone and the oceanographic conditions, produces a strong short delay echo. In these conditions the echo is very close to, or partially overlaps, the direct click masking its internal pulses. In this situation a fine calibration of the analysis parameters and a visual inspection of waveform is strictly needed.

The extensive application of automatic IPI measurements on far or unsighted whales will probably need a different configuration of the detection and analysis instruments and a better understanding of the influence of long and complex travelling paths on the internal structure of clicks. The use of deep hydrophones will probably help to solve this problem.

We also have to understand the influence of the relative position and orientation of the clicking whale related to the hydrophone: sometimes we found series of strong clicks with well spaced surface echoes but the cepstrogram was unable to show their IPIs, probably because of a very high amplitude ratio among P1 and P2.

On the other hand, when recordings suit our criteria, the method resulted very fine and able to display low level clicks that are otherwise difficult to see on the spectrogram. The real-time approach resulted very helpful in browsing long recordings and in discriminating and counting different whales clicking at the same time.

Concerning size estimation, further work comparing IPIs with reliable estimates of body length from other methods is needed in order to derive a reliable model for body size and age determination.

5. CONCLUSION

Several Authors demonstrated the reliability of IPI measurements. With our work we developed a fast analysis method and demonstrated the stability of IPIs in consecutive dives. Since the accurate application of the method may give new important information, the setting of a wide acoustic monitoring network based on both towed arrays and fixed arrays of hydrophones will provide valuable insight into the structure of the Mediterranean population of sperm whales along with new behavioural data, and therefor help in setting up and tuning conservation strategies.

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