# Directional Sound Sources for Active Towed Array Sonars

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## Summary

Linear acoustic arrays with high directional resolution and high gain are used in Active Towed Array Sonars(ATAS) to detect submarines. To resolve the directional ambiguity and to improve the signal/reverberation ratio of the towed array directional sources may be used.

Directivity is achieved with a compact arrangement of sources $\lambda/4$ and $\lambda/2$ apart driven with properly phased signals. The directivity of a cardioid can be switched electronically from left to right if the array is driven with + or -90° phase shifted signals.

In reality due to the small spacing and the large dimension of the transducers heavy mutual interaction happens in the nearfield distorting the directivity pattern. The compensation necessary is derived from impedance measurements. The directivity pattern is optimized on-line taking into account the geometry as well as tolerances of the transducers, power amplifiers, transformers, etc. If this is done frequency dependent, a broadband directivity pattern with specified right-/left ratio is achieved.

The total weight of the directional source is rather low, because all individual transducers contributes simultaneously to the produced sound field.

Directional sources were realized for demonstration with two different transducer types. Directivity patterns were optimized. A forward-backward ratio of 12 dB over 130 degrees in the horizontal plane was measured. The sources were used successfully in German ATAS experiments.

# 1 Introduction

Low frequency active sonar (LFAS) systems are under consideration in several nations. A solution for it is an active towed array sonar (ATAS), because it is flexible and gains most from an optimum placement of the sensors in different environmental conditions and expected target depths. There are two basic procedures to overcome the right-/left ambiguity of the linear receiving array . The first is a receiver array with directional characteristic, i.e. a single array with directional hydrophones or a multi line array, at least a twin array. The second is the application of a directional source to transmit one pulse to the left and the next to the right, or to use different frequencies for both directions simultaneously.

In the German ATAS program two demonstrators were built from

- 4 ringshell projectors (RSP) Model 18A0950 from SPARTON (Canada)
- 4 flextensional transducer Model WAB506 from British Aerospace (UK)

working at a center frequency of 950 Hz with a maximum source level of about 206 dB for a single transducer. A source level of about 217 dB was achieved for the complete array. Our experiments were conducted in nearly all cases in reverberation limited conditions, which means that source power level SPL is not critical. A directional source for resolving the left-/right ambiguity was preferred for many reasons, especially it keeps the signal processing in the receiving part of the sonar easy.

# 2 Basic Array Configuration

The basic idea for the array configuration (figure 1, s. next page) is as follows. A pair of ideal transducers separated by a quarter wavelength and driven with signals of 90° phase difference will have the well known cardioidal beam pattern (fig. 2a). To avoid as much as possible the fathometer effect, a second pair of transducers is placed in half wavelength spacing above the other one. This results in a null in the vertical directions (fig. 2b). To solve the right-/left ambiguity a certain difference in source level of at least 10 dB will be needed. From figure 2a the angular range is given as about $\pm 52°(104°)$.

Because the high right-/left ratio in broadside direction is not needed, a phase difference of 110° may be used (figure 3). This results in a sidelobe in backward direction. Still a right-/left ratio of 15 dB is achieved while expanding the sector to $\pm 67°(134°)$.

The above statements are true of course only at a single frequency and for ideal transducers without any interaction.

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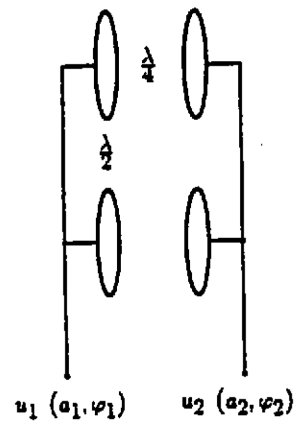
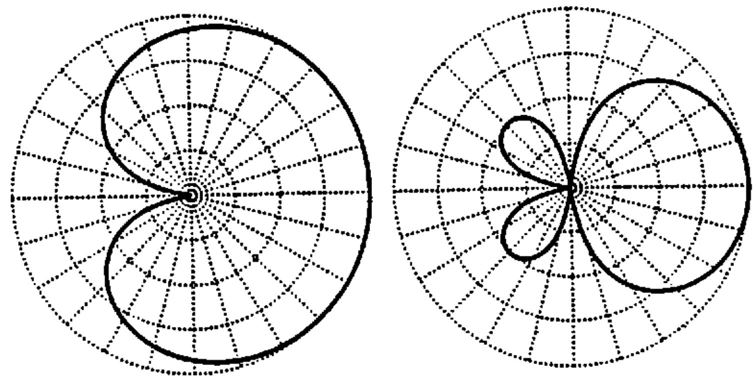



**Figure 1**

Basic configuration of the array. The desired beam pattern is achieved by the transducer spacings and amplitude / phase differences of the signals $u_1$ and $u_2$.

a.



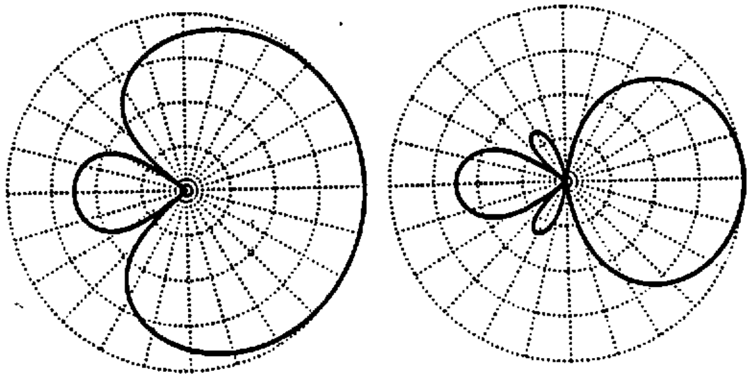
b.

**Figure 2**

a. Beam pattern of a pair of transducers with a quarter wave length spacing and 90° phase difference in the driving signals. This is identical to the horizontal beam pattern of the full array.

b. Vertical beam pattern of the full array (figure 1), i.e. 2 pairs of transducers as in figure 2a in a half wavelength vertical spacing .

a.



b.

**Figure 3**

Horizontal (a) and vertical (b) beam pattern of the full array with 110° phase difference in the driving signals.

Experiments were conducted to measure the impedances of a single and of a pair of transducers at different spacings and frequencies to get information about the interaction of the transducers in close arrangements in the real array . From these experiments we learned that the mutual influence at a spacing of a quarter wavelength is strong but the transducers behaved still well without negative impedances in the frequency range of interest and without cavitation at high levels.

These results encouraged us to build an array of four transducers.

There are two different approaches possible . Configuration I puts the transducers at the corners of a rectangle with $\lambda/4$ and $\lambda/2$ spacing. The second configuration puts the transducers at the corners of a square riding on a top. The diagonal has a length of $\lambda/2$. Thus the cross area of both configuration is $\lambda^2/8$. To reduce interaction which degrades performance and which is less the more the transducers are apart, we would prefer configuration II. The interaction on the impedances however prevents us to get the third signal by a mere polarity change as could be done if no interactions happen. To reduce expenses we therefore settled for configuration I (s.fig.1).

# 3 Directivity Measurements with the Real Array

We did a large number of measurements of directivity patterns by varying the phase and amplitude of the driving signal. These measurements were conducted in calm and deep water of a Norwegian fjord. We found in the frequency band of interest solutions with a right-/left ratio of >10 dB by iterations. Figure 4 presents examples of the results for the Sparton-transducers at the three frequencies 850 Hz, 950 Hz and 1100 Hz.

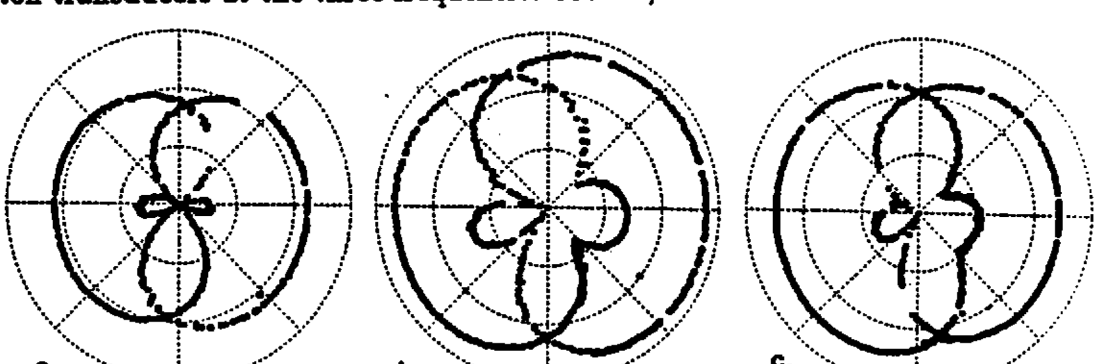
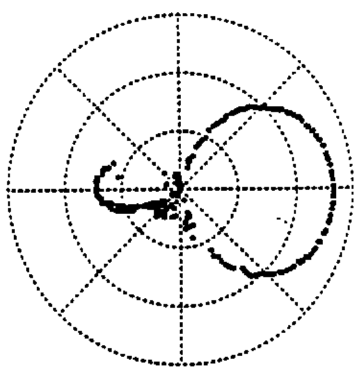



Fig.4: Measured horizontal beam patterns for the frequencies
a: 850 Hz b:950 Hz c:1100 Hz (scale: 10 dB/div)

These depictions show the horizontal pattern for the right and left transmission. Right and left transmission is achieved by just exchanging the driving signals $s_1$ and $s_2$. There are slight differences in the patterns because the individual transducers are not identical in sensitivity and impedance. Our procedure to measure the directivity used two different platforms at some distance to suspend the transmitting array and receiving hydrophones. A magnetic compass was used to determine the orientation of the array. Some deformation of directivity pattern due to declination errors of the compass are obvious.



The vertical pattern of figure 5 corresponds well with the desired one of figure 3b. Less energy will be transmitted towards the sea surface and bottom, thus avoiding the fathometer effect.

Figure 5: Measured vertical beam pattern for the Sparton-array at 950 Hz (scale: 10 dB/div)

The results for the second array with the BAe-transducers were acquired differently. The array was towed along a constant course passing the receiving hydrophone at a close distance. Thus the aspect changed from $+90°$ at infinity to $0°$ at CPA to $-90°$ (s. fig 6).

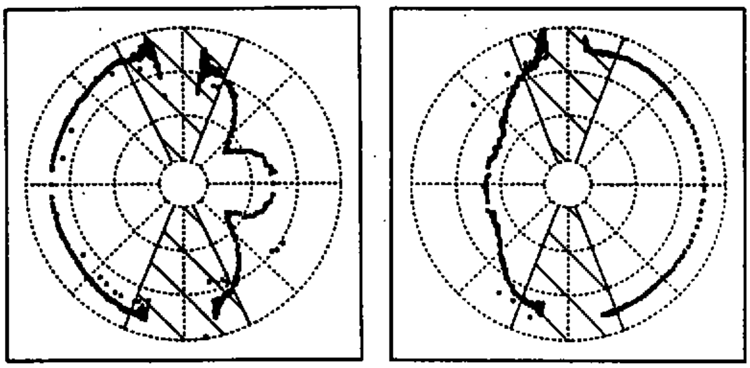


Figure 6: Measured horizontal beam patterns for the BAe-array at 1000 Hz (scale: 10 dB/div)
For large distances corresponding to aspect angles greater than 70° the arrival time difference of the direct signal and the surface reflected signal interfere.

Additionally some measurement points have to be disregarded due to loss of phase synchronization of the driving signals.

# 4 Signal Generation

A pair of signals $s_1$ and $s_2$ fulfilling the phase and amplitude relation as given by measurements has to be presented to the arrays for an operation not only at a single frequency but also with broadband signals. Because signal generation in modern sonar equipment is performed by computer, this is easily done by designing a certain signal $s_1$, transform this signal into the frequency domain by a FFT, perform the complex, i.e. amplitude and phase, weighting corresponding to the needs and do an inverse FFT to get the signal $s_2$ or may even more simple be calculated for signals expressed by analytic functions.

# 5 Directivity Calculations for the Real Array

If we use the most simple equivalence circuit diagram for a single transducer as a combination of an electric capacitor in parallel with a damped resonance circuit, we can calculate the beam pattern from measured voltages and currents with the following formula:

$$P(\alpha) = 20\log\left[\left|I_1 + I_2 \cdot e^{j\varphi_L}\right|\right] + c \quad , \tag{1.1}$$

where $I_n$ is the transducer current, reduced by the current through the electric capacity
$\varphi_L$ is the angle dependant phase conditioned by the travel time
$c$ is a constant

With the driving voltage $U$ and the chosen complex weighting factor $a = \frac{U_1}{U_2} = |a| \cdot e^{-j\varphi_s}$, i.e. the amplitude ratio $|a|$ and the phase difference $\varphi_s$ of the driving voltages, the admittance $Y$, the measured admittance ratio $\frac{Y_2}{Y_1} = |\frac{Y_2}{Y_1}| \cdot e^{j\varphi_W}$, and the resulting transducer internal phase difference $\varphi_w$, the travel time conditioned phase difference

$$\varphi_L = kd \cdot cos\alpha \tag{1.2}$$

and the abbreviation $b = |\frac{Y_2}{aY_1}|$ and

$$\beta = \varphi_L + \varphi_W + \varphi_S \tag{1.3}$$

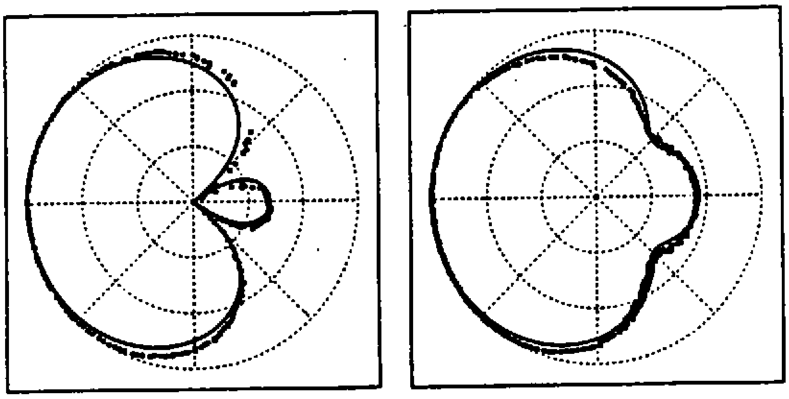
we get from (1.1),(1.2) and (1.3)

$$P(\alpha) = 20\log\left[\left|1 + b \cdot e^{j\beta}\right|\right] + c_1 \quad , \tag{1.4}$$

with

| | |
|---|---|
| the transducer voltage | $U_n$, |
| the reduced conductance and susceptance | $Y_n$, |
| the wavenumber | $k$, |
| the transducer spacing | $d$, |
| the azimuthal angle | $\alpha$, |
| and a constant | $c_1$. |

The calculated curves are overlayed on the measured beam patterns. For two measurements the resulting beam patterns are shown in figure 7 and 8.



| | |
|---|---|
| Figure 7(left) | |
| phase difference: | 95° |
| amplitude ratio: | .66 |
| frequency: | .89Ω |
| Figure 8(right) | |
| phase difference: | 58° |
| amplitude ratio: | 1.03 |
| frequency: | 1.05Ω |
| scale: | 10dB/div |

Figure 7 and 8: Directivity patterns, comparison of measurements and calculations based on impedance measurements

The necessary phase difference and amplitude ratio for the driving signals for the BAe-transducer array were interpolated and incorporated into tables for signal calculations. To take into account the tolerances of the transducers, power amplifiers, transformers, etc. two tables were set up to achieve identical patterns for both directions, right and left individually. A signal added up from 16 CW-signals was used to measure the impedances of the two array halves simultaneously for all frequencies. The impedances were used to calculate the directivity patterns as shown in fig.9.

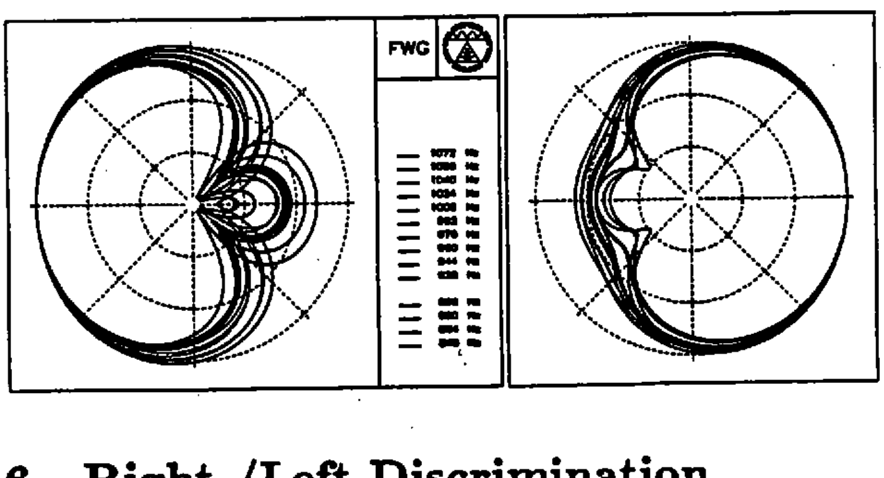



Figure 9: Calculated horizontal beam patterns for the BAe-array (scale: 10 dB/div)

# 6 Right-/Left Discrimination

From (1.4) we see that $P(\alpha)$ is at a minimum if $\beta$ equals $\pi$. The corresponding azimuthal angle $\alpha_N$ follows from (1.2) and (1.3).

$$\varphi_s + \varphi_W = \pi - kd \cdot cos(\pm\alpha_N) \quad . \tag{1.5}$$

With (1.4) and (1.5) and the impedance measurements the angle $\alpha_N$ can be calculated as well as the corresponding level $P_N$. With (1.4) the level ratio for two azimuthal angles $\alpha_i$ and $\alpha_k$ will be

$$RL_{i,k} = 20\log\left[\frac{|1 + b \cdot e^{j\beta(\alpha_i)}|}{|1 + b \cdot e^{j\beta(\alpha_k)}|}\right] \quad .$$

Especially for the main directions $\alpha_i = 0°$ and $\alpha_k = 180°$ we get with (1.2),(1.3) and (1.5) for

$$\beta_{0°} = \pi - kd \cdot cos\alpha_N + kd \cdot cos(0°) = \pi + kd(1 - \cos\alpha_N) \quad \text{and} \tag{1.6}$$

$$\beta_{180°} = \pi - kd \cdot cos\alpha_N + kd \cdot cos(180°) = \pi + kd(-1 - \cos\alpha_N) \quad . \tag{1.7}$$

The source level ratio $RL$ in cross direction as a function of the angle $\alpha_N$ can be calculated with

$$RL = 20\log\left[\frac{\left|1 + b \cdot e^{j(\pi + kd(1-\cos\alpha_N))}\right|}{\left|1 + b \cdot e^{j(\pi + kd(-1-\cos\alpha_N))}\right|}\right] \quad . \tag{1.8}$$

The achievable right-/left ratio according to (1.8) with $b$ equal to 1 is shown in fig. 10.

## 6.1 Sector for a given Right-/Left Ratio

To resolve the right-/left ambiguity we ask for a high right-/left ratio in a given sector. With a given worst case right-/left ratio the question is what sector $\pm\alpha_B$ can be achieved. This can be deducted from (1.4). For the maximum of the sidelobe we reach a phase difference of more than 180° ($\beta = \pi + \Delta\beta$). The phase difference diminishes to 180° at $\alpha_N$ and further decreases to $\beta_B = \pi - \Delta\beta$. Here we achieve the same level as for $\alpha = 0°$ or $\alpha = 180°$ respectively. Therefore we can solve with (1.5), (1.6) and (1.7) for $\beta_B = \pi - kd(\pm 1 - \cos\alpha_N) = \pi + kd(\cos\alpha_B - \cos\alpha_N)$. From this equality follows $\cos\alpha_B - \cos\alpha_N = \mp 1 + \cos\alpha_N$ or $\cos\alpha_\beta = \mp 1 + 2\cos\alpha_N$ and at last $\alpha_B = \cos^{-1}(\mp 1 + 2\cos\alpha_N)$. The interdependence between minimum right-/left ratio and the sector where this ratio is met or surpassed is shown in fig. 11.

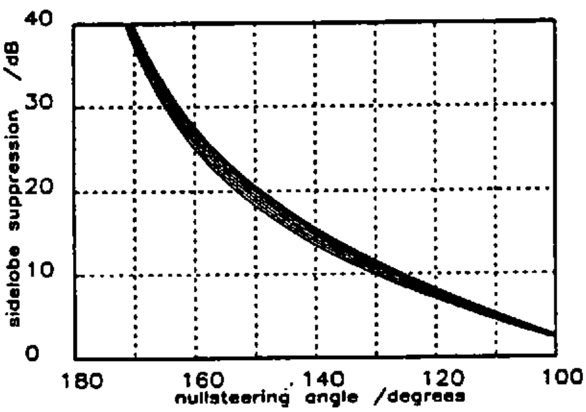



Figure 10

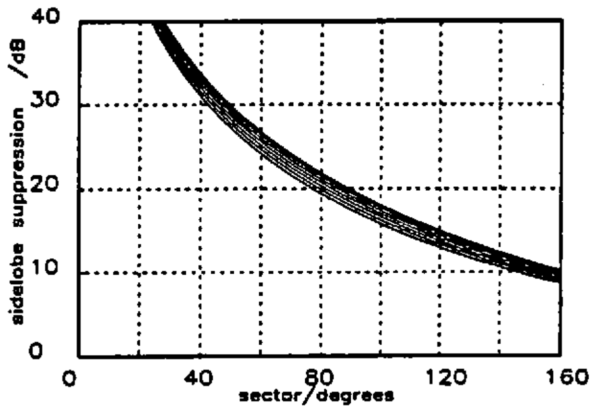



Figure 11

**Sidelobe suppression for an array with $\lambda/4$ spacing for a given nullsteering angle (fig.10, left) and for a given sector (fig.11, right). The upper curve corresponds to the lowest frequency.**

**We see that we can trade the advantage of a high ratio for the disadvantage of a smaller sector and vice versa. A ratio of 20 dB for example is achievable in a sector of $\pm 40°$. The corresponding nulls are found for $\pm 150°$ (s. fig. 10).**

# 7 Optimization of the Directivity Pattern

**Desired operational characteristics tell us where to place the null of the directivity pattern. For general surveillance a frequency independent right-/left ratio may be useful. Another desired pattern could be e.g. to place a broadband null in a certain direction to achieve maximum signal/reverberation ratio, especially under anisotropic reverberation conditions. The different patterns could even be switched from pulse to pulse! To reduce higher mode excitation the BAe-transducers were stacked in line with a minimum spacing of $0.31\lambda$. Some theoretical values for the characteristic numbers of the pattern are found in table 1.**

| | | | $RL/dB$ | | | $\varphi_S + \varphi_W$ | | |
|---|---|---|---|---|---|---|---|---|
| $cos\alpha_N$ | $\alpha_N$ | $\alpha_B$ | $.89\Omega$ | $1.0\Omega$ | $1.1\Omega$ | $.89\Omega$ | $1.0\Omega$ | $1.1\Omega$ |
| 0.90 | 25.8 | 36.9 | 21.1 | 19.8 | 18.2 | 89.4 | 78.8 | 68.1 |
| 0.80 | 36.9 | 53.1 | 15.1 | 14.0 | 12.7 | 99.5 | 90.0 | 80.5 |
| 0.75 | 41.4 | 60.0 | 13.2 | 12.2 | 11.0 | 104.5 | 95.6 | 86.7 |
| 0.70 | 45.6 | 66.4 | 11.7 | 10.7 | 9.6 | 109.5 | 101.3 | 93.0 |
| 0.60 | 53.1 | 78.5 | 9.1 | 8.3 | 7.4 | 119.6 | 112.5 | 105.4 |

**Table 1: Directivity numbers for given values of $cos\alpha_N$ with a transducer spacing of $.31\lambda$.**

From this table the necessary values for $\varphi_s + \varphi_w$ can be selected according to the users needs. From impedance measurements the unknown $\varphi_w$ is determined and $\varphi_s$ is corrected. Likewise $b$ from equ.(1.4) is determined and the amplitude ratio is corrected to yield $b = 1$. From any change of one parameter all others are effected. Therefore the process has to be repeated to get the desired result after some iterations.

The optimal settings for a desired beam pattern can thus be found with a couple of impedance measurements instead of costly beam pattern measurements.

This procedure was used for the BAe-transducer array. Unfortunately one transducer had extremely different specifications from the other ones (-3dB sensitivity), which could not be cured by BAe. Furthermore a gas cushion gradually built up which changed the specifications in a non reproducible way. Therefore the optimized beam pattern could not and did not match the measured beam pattern.

# 8 Conclusion

Small and light weight transducer arrays for a low frequency active towed array sonar have been designed and built with two different projector types. Impedance changes due to nearfield interaction are not detrimental to the transducers nor the amplifiers. The directivity pattern can be designed according to operational needs and the necessary compensation for the nearfield interaction can be deducted from impedance measurements.

As every single transducer contributes to the source level a high ratio of source level to overall ceramic volume keeps the total weight small for the directional source. The weight in air is 400kp for a complete package. The achievable source level of 217 to 218 dB is high enough in case of operating under reverberation limited conditions. This is expected in nearly all areas which are not really deep water. The directional sources were realized as demonstrators and were used successfully in German ATAS experiments.

REFERENCES

[1] E.Helmer, Prediction of the directivity of transducer arrays on the basis of impedance measurements
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