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Calibration of broadband sonar systems using multiple standard targets

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A seven-octave active sonar system spanning the nominal frequency range 25-3200 kHz was deployed in Norwegian waters for the purpose of measuring the acoustic scattering characteristics of a range of marine organisms. This system transmitted linear frequency-modulated (LFM) signals in order to achieve good range resolution and to obtain spectral information on resolved targets. Total system performance was variously measured *in situ* and *ex situ*, depending on the particular octave band, using standard-target spheres. This enabled the frequency response of the entire system to be determined and the sidelobe level of the matched-filter receiver to be reduced. The effects of the deep nulls encountered in the backscattered spectrum of target spheres were partially reduced by using a string of up to six spheres of different sizes and material properties. Typical results will be presented showing that such calibration procedures are sensitive to the relative alignment of the sonar-target and to sound-speed profile changes over the length of the string.

1 Introduction

A biological-classification active sonar system was developed under EU RTD contract MAS3-CT95-0031 for the purpose of measuring the acoustic scattering characteristics of a range of marine organisms. This operated using seven-octave bands spanning the nominal frequency range 25-3200 kHz. This system transmitted linear frequency-modulated (LFM) signals in order to achieve good range resolution and noise-limited range performance [1]. When a single target could be separated from surrounding scatterers, spectral information could also be obtained on resolved targets.

Good range-sidelobe performance of an active sonar system dictates the application of bilateral amplitude-windowing of the transmission and correlator coefficients [1, 2]. This frequency-dependent shading must also include the transfer function of the system electronics and transducers. Total system performance was variously measured *in situ* and *ex situ*, depending on the particular octave band, using standard-target spheres. This enabled the frequency response of the entire system to be determined and the range-sidelobe level of the matched-filter receiver to be improved relative to an uncompensated system. Standard-target spheres have the advantage of being aspect-angle independent with respect to backscattering, but the disadvantage of including deep nulls in the backscattered target strength frequency spectrum. The effects of the deep nulls encountered in the backscattered spectrum of target spheres were partially reduced by using a string of up to six spheres of different sizes and material properties.

2 Sonar system

The seven-octave sonar system deployed is shown in Fig. 1. The majority of the electronic sub-systems were housed within a pressure vessel that could be deployed at variable depths via means of a deck winch. The system was most frequently deployed in a vertical looking mode, with the seven transducers insonifying a similar volume. A string of calibration spheres were also normally deployed below the transducers in order to allow depth-dependent *in situ* calibration of the total system [3]. The selection of sonar parameters and data recording operations was performed on a standard workstation located onboard the host vessel.

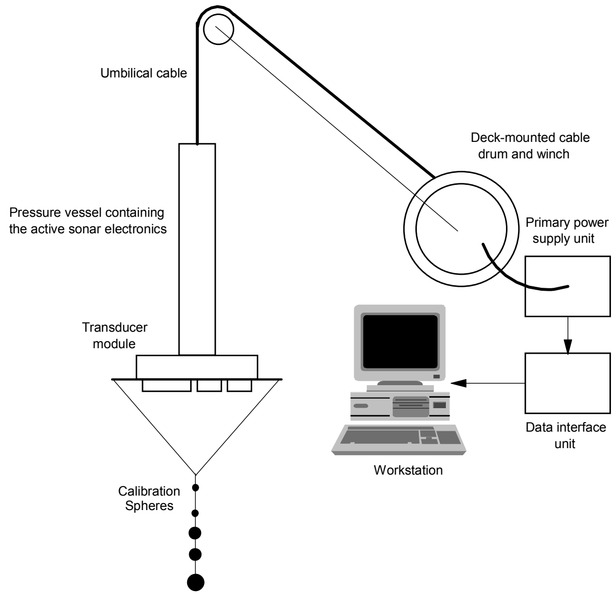

Fig.1. Seven-octave sonar system

3 Standard-target Calibration

The *in situ* calibration of scientific echo sounders has traditionally been undertaken using the standard-target method [3]. Although the method was first developed and applied to narrowband systems [4], the method has also been used for broadband systems [5, 6]. In the standard-target method [3], a special target is placed at a known position in the transducer beam, and the resulting echo is related to the transmit signal by means of the acoustic properties of the target, which are known *a priori*.

The echo signal from the standard-target must be spatially and temporally resolved from all other significant scatterers. Consider the case shown in Fig. 1. where a string of standard-targets is deployed approximately within the main lobe of the transducer response. If the standard-targets are separated by a distance d and insonified by a pulsed sinusoid of duration τ, then a conventional range-resolution argument would imply that $\tau \leq 2d/c$. where c is the velocity of propagation, about 1500 m/s. Were a matched filter to be used within the receiver, then the receiver output extends over a temporal region equivalent to twice the transmission pulse duration [2] and the requirement for the transmission pulse duration becomes $\tau \leq d/c$. Given the time-frequency relationship implied by the Fourier Transform, the finest frequency resolution of any frequency-dependent calibration becomes $\Delta f = c/d$. This relationship holds for any form of transmission pulse and states that a good frequency resolution of an *in situ* calibration operation can only be obtained if the standard-target is well separated from any adjacent scatterers.

The standard-target introduces deep nulls in the backscattered target strength as can be visualized using the thought-experiment illustrated in Fig. 2.

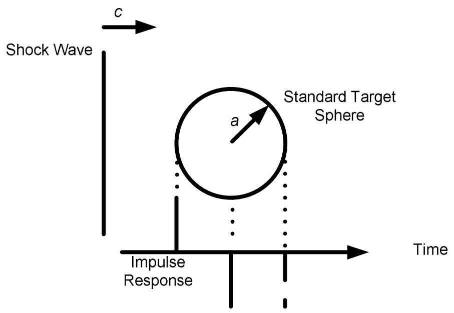

Fig. 2. First two impulses of backscattered signal

Consider a shock wave (impulse) impinging on a sphere of radius a. To a first approximation, using the image-pulse theory developed by Freedman [7-10], the first two artefacts of the backscattered impulse response will consist of two impulses of opposing sign separated by a time duration $2a/c$. If the magnitude of these two impulses is approximately equal then the backscattered frequency response will approximate to

$$X(f) = 1 - \exp\left(j4\pi fa/c\right) \quad (1)$$

where f is the frequency. This frequency response is plotted for a radius value of a = 7.5 mm in Fig. 3 (solid line). As deep nulls occur in the spectrum, it is tempting to include a second sphere of half the radius in order to provide backscattered energy at frequencies corresponding to some of the nulls of the original sphere.

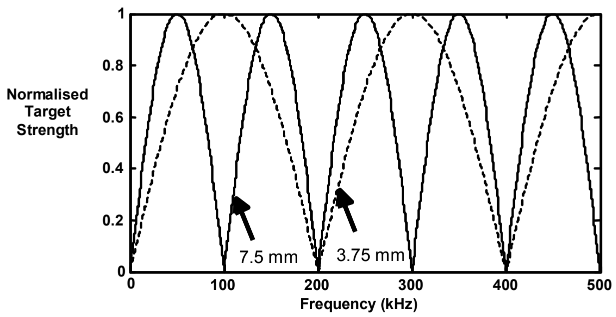

Fig. 3. Corresponding spectrum of backscattered signal for radius values of a = 7.5 mm and a=3.75 mm.

In a practical sonar system, the two standard-target spheres would be resolved and processed separately, the backscattered energy combined incoherently yielding a result similar to that illustrated in Fig. 4.

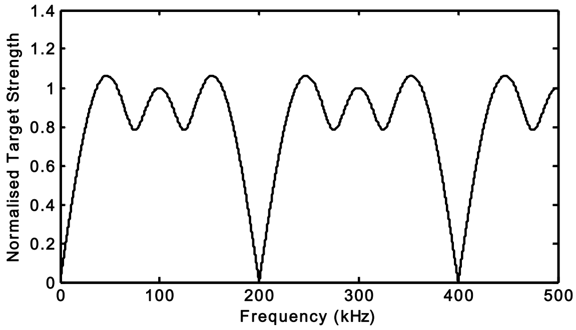

Fig. 4. Combined backscattered energy from two simple approximations to target spheres

It will be noted that nulls still remain, requiring the addition of further calibration spheres. Ripples in the combined backscattered target strength are also present, typically equating to about 1-dB variation in the target strength.

This simple analogy also highlights the critical dependence on the velocity of propagation c, as small variations in this parameter significantly affect the ripple amplitude of the combined backscattered energy, illustrated in Fig. 4. Practical experience of sonar systems deployed within 50 m of the sea surface has highlighted the difference in measured backscattered characteristics from identical spheres comprising part of a calibration string, presumably due to the sound speed profile.

For practical deployment purposes, a more exact calculation of the backscattered target strength was undertaken using the theory of acoustic scattering by homogeneous, solid elastic spheres [11, 12], but with correction of typographical errors as noted in [4], or as a limiting case of scattering by homogeneous elastic shells [13]. These calculations were repeated for a wide variety of sound speed values within the water and the best match was determined using a least-mean-squares approach.

As an example of this process, the following experimental results were obtained by implementing a parametric search across the sound speed of the water using 10 m/s increments and selecting the best match between the measured and predicted results. The results for the third of the sonar system bands (100 kHz to 200 kHz) are presented in Fig.5 for a 30.4 mm-diameter electrical grade copper sphere located at a range of 10 m.

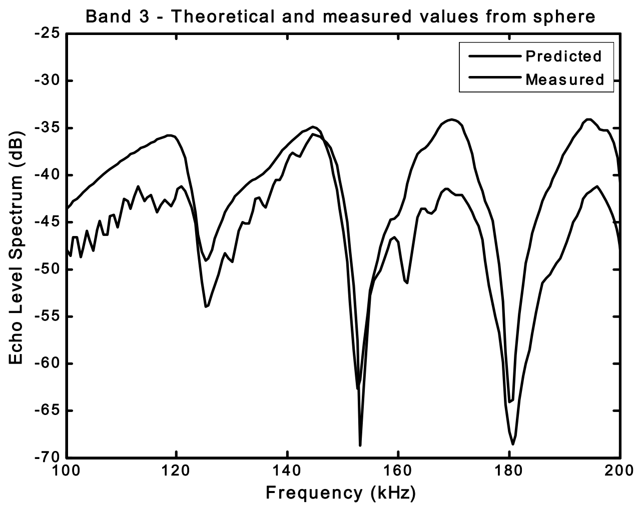

Fig. 5: Experimental and predicted backscattered target strength of a 30.4-mm-diameter Cu sphere at 10 m range

The procedure has correctly aligned the nulls in the frequency spectrum of the modelled standard-target sphere to those of the measured data.

4 Typical results

The sonar system incorporated transducers whose transmit and receive sensitivities had been carefully measured within a laboratory environment [6]. As an example of using these separate laboratory measurements to infer system response, the transmit and receive sensitivities have been combined as illustrated in Fig.6. (longer dashed line). This response differs significantly from the system response measured *in situ* using a standard calibration sphere (solid line). Undoubtedly, at least some of this error is due to the difference in the source impedance of the power amplifier and the input impedance of the receiver amplifier between the laboratory calibration and deployment phases. Assuming that during the laboratory calibration phase, the power amplifier source impedance was zero and that the input impedance of the receive amplifier was infinite, a more realistic prediction can be made of the system response (shorter dashed line). Even this highlights significant inaccuracies at lower frequencies and the conclusion must be made that manufacturer-supplied values of transmit and receive sensitivities of a transducer cannot be readily used to predict overall system performance as the electrical and physical transducer mounting characteristics will differ.

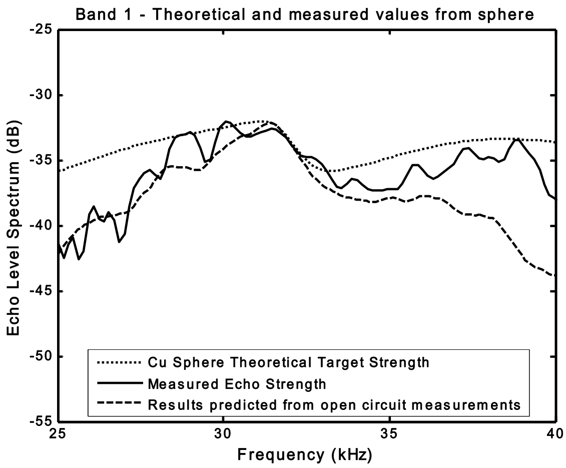

Fig. 6. Comparison of *in situ* and manufacturer-supplied transducer sensitivity performance

The ripples in the measurements made using the standard-target are possibly due to coherent multipath interference from other scatterers (housing artefacts). The *in situ* measurements for this channel of the sonar system (Band 1) notionally covered a frequency range 25 kHz to 40 kHz. A signal was transmitted with a pulse duration of 2 ms. This was used to insonify a 60-mm-diameter electrical grade copper sphere located at a range of 15 m. The experiment collected 60 pings, with the 20% of strongest returns being used for calibration purposes. The maximum amplitude range of these returns was 0.37 dB.

During the calibration process a string of calibration spheres was deployed. This comprised a 30.4-mm-diameter electrical grade copper sphere located at 10 m range, a 60-mm-diameter electrical grade copper sphere located at 15 m range, a 30.05-mm-diameter electrical grade copper sphere located sphere at 20 m range and a 20-mm-diameter tungsten carbide sphere located at 25 m range. In an idealised situation a calibration obtained using one sphere would agree closely with that of another sphere. As illustrated in Fig.7, the nulls in the scattering strength of the spheres introduce significant variations in the individual receiver calibration factors obtained before incoherent energy combination.

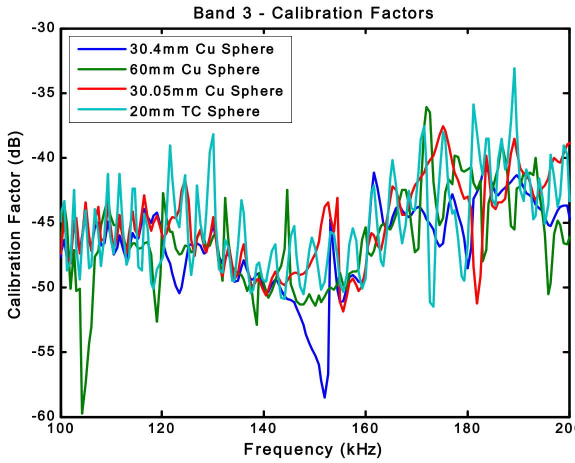

Fig. 7. Required system calibration factors obtained from multiple *in situ* standard-target spheres

5 Standard-target sphere alignment

The standard-target sphere method assumes that the target is accurately located within the bore sight of the transducer, or that the beam pattern of the transducer and the relative spatial location of the target are accurately known. For the purposes of this *in situ* calibration operation, the string of standard-target spheres was positioned to approximately correspond to the main lobe of the transducer. The natural motion of the host vessel was then used to advantage by transmitting a large number of pings and only selecting those with the largest echo strength for further processing – these echoes were assumed to correspond to the case where the standard-target was co-located with the main lobe of the transducer.

Using the main lobe of the transducer as the reference axis, an unknown positional offset bias and independent random variables in the roll and pitch axes, the probability density function of the angular displacement can readily be determined [14, 15]. This must then be transformed using an assumed model for the transducer beam pattern [16] in order to derive the probability density function of the measured echo strength. A suitable threshold can then be applied, such that echo returns exceeding this threshold value may be used as part of the calibration process. The determination of the threshold value will depend on the distribution functions associated with the pitch and roll movements and the threshold is essentially derived using Constant Probability of False Alarm (CFAR) approaches common in both radar and sonar systems [2].

As a typical example, the histogram distribution and cumulative distribution function of several thousand echoes from a standard-target sphere are plotted in Fig. 8. The results were obtained for Band 5 of the sonar system covering a nominal frequency range of 400 kHz to 800 kHz. A transmission pulse duration of 0.1504 ms was used to insonify a 10-mm-diameter tungsten carbide sphere located at a range of 0.3 m. The standard deviation of these returns was 0.2 dB. The threshold was set such that the 20% of strongest returns were used for calibration purposes.

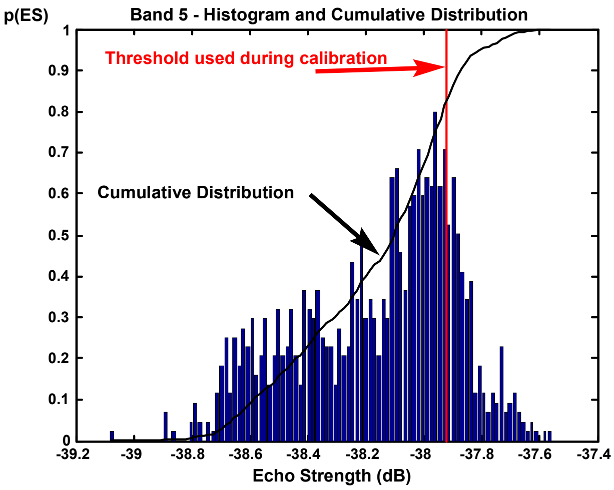

Fig. 8. Histogram and cumulative distribution function of backscattered returns

6 Linear Frequency-Modulated Transmission signals

In a spatially stable laboratory environment it is possible to transmit a stepped-frequency pulsed sinusoidal signal, as good coherence can be assured between adjacent transmissions. In a field environment it is desirable to perform the calibration using a single, or small number, of transmission pulses. For this reason, bilaterally amplitude-weighted Linear Frequency-Modulated (LFM) signals were transmitted [2]. An LFM signal may be described by [1]

$$s(t) = A(t)\exp\left(j\omega t + \frac{jBt^2}{2T} \right) \qquad (2)$$

where B is the bandwidth in radians, and the signal is active in the region $-T/2 \le t \le T/2$. The spectrum of this signal may be determined analytically and is characterised by Fresnel ripples which lead to spectral oscillations typically of the order of 1 dB. In order to improve the range-sidelobe performance of the sonar system, the cross-spectrum calculated within the receiver would assume a symmetrical spectral function based on either a Von Hann, Hamming or Blackman [17] window function. These window functions can be expressed as a summation of N sinusoids

$$|S(\omega)|^2 = \sum_{n=0}^{N-1} K_n \cos\left(\frac{2\pi n}{B} \left[\omega - \omega_0 \right] \right) \text{ for } \omega - \frac{B}{2} \le \omega \le \omega + \frac{B}{2}$$

$$|S(\omega)|^2 = 0 \quad \text{otherwise} \qquad (3)$$

where B is the bandwidth, K_n is an element of the set defining the window function and ω_0 is the centre frequency of the desired spectrum. For an LFM signal, the instantaneous frequency, ω, is linearly related to time t. The bilateral weighting requirement implies that the square root of the window function derived in Eq. (3) is applied to both the transmission waveforms and the receiver filter coefficients. A second positive effect of amplitude-windowing is that it reduces the magnitude of the spectral ripples due to the Fresnel integrations [2].

However, the spectrum of the transmission signal must be calculated as well as the continuous-wave form function of the target sphere obtained using numerical modeling techniques. A weighted-sum multiplication is then calculated to derive the standard-target backscattered target strength that could be expected for a predefined transmission pulse duration.

When used in a calibration mode, the receiver would switch from a correlation-type receiver to that of a conventional Fourier Transform receiver (matched to sinusoids, rather than the LFM signal). This incurs a processing loss of up to twice the bandwidth-time product. Thus for a previously illustrated case where Band 1 was transmitting a 2 ms pulse over the frequency range 25 kHz to 40 kHz, the processing loss could be as high as 18 dB. This implies that any standard-target echo must be at least 18 dB greater that the usual detection threshold value used when operated with a correlation receiver. Assuming that the operator wished to calibrate the sonar system to an accuracy of 0.5 dB, the parameter stated above would lead to the requirement for the signal-to-noise ratio in the water to be at least 37 dB when measured using the correlation receiver. Thus *in situ* calibrations are likely to be carried out with standard-target spheres located at ranges less than one-hundredth of the maximum noise-limited operating range.

7 Conclusion

It is believed that broadband scientific echo sounders transmitting linear frequency-modulated signals may be calibrated *in situ* by using a string of multiple standard-target spheres. Ideally, the dimensions of these spheres should be related by a rational factor and the absolute sizes selected to suit the frequency range of the sonar in use [4]. The natural roll and pitch motions of the host vessel can be used to advantage by reducing the requirement for accurate spatial alignment of the sonar system and standard-target, provided that a large number of transmissions are feasible. All frequency-dependent calibration requirements require that the standard-targets are spatially well separated from any other scatterers. If a frequency-modulated transmission waveform is used, rather than a frequency-stepped sinusoid, a very high signal-to-noise ratio is required and the standard-target must be located at a fraction of the maximum noise-limited operating range.

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References

[1] J. R. Klauder, A. C. Price, S. Darlington and W. J. Albersheim, “The theory and design of chirp radars,” Bell System Tech. J. 39, 745-809 (1960).

[2] C.E. Cook & M. Benfield, "Radar signals, an introduction to theory and application," Academic Press (1967).

[3] K. G. Foote, H. P. Knudsen, G. Vestnes, D. N. MacLennan, and E. J. Simmonds, "Calibration of acoustic instruments for fish density estimation: a practical guide," ICES Coop. Res. Rep. (144), 69 pp (1987).

[4] K. G. Foote, "Optimizing copper spheres for precision calibration of hydroacoustic equipment," J. Acoust. Soc. Am. 71, 742-747 (1982).

[5] S. Vagle, K. G. Foote, M. V. Trevorrow, and D. M. Farmer, "A technique for calibration of monostatic echosounder systems," IEEE J. Oceanic Eng. 21, 298-304 (1996).

[6] K. G. Foote, P. R. Atkins, C. C. Bongiovanni, D. T. I. Francis, P. K. Eriksen, M. Larsen, and T. Mortensen, "Measuring the frequency response function of a seven-octave-bandwidth echo sounder," Proc. Inst. Acoust. 21(1), 88-95 (1999).

[7] A. Freedman, 'The high frequency echo structure of some simple body shapes', Acustica 12(2), 61-70 (1962)

[8] A. Freedman, 'A mechanism of acoustic echo formation', Acoustica, 12(2), 10-21 (1962)

[9] A. D. Dunsiger, 'A study of underwater acoustic target recognition using simple geometric shapes'. PhD thesis, School of Electronics and Electrical Engineering, University of Birmingham, (1968)

[10] A. D. Dunsiger, 'High-frequency acoustic echoes received from simple geometric shapes with possible applications to target recognition,' J. Sound Vib. 13. 323-345 (1970)

[11] J. J. Faran, Jr., "Sound scattering by solid cylinders and spheres," J.Acoust. Soc. Am. 23, 405–418 (1951).

[12] R. Hickling, "Analysis of echoes from a solid elastic sphere in water," J. Acoust. Soc. Am. 34, 1582–1592 (1962).

[13] R. R. Goodman and R. Stern, "Reflection and transmission of sound by elastic spherical shells," J. Acoust. Soc. Am. 34, 338–344 (1962).

[14] S. O. Rice, "Mathematical Analysis of Random Noise" (parts I and II), Bell Systems Tech. J. 23, 282-332 (1944).

[15] S. O. Rice, "Mathematical Analysis of Random Noise"(part III), Bell Systems Tech. J. 24, 46-156 (1945).

[16] D. Stansfield, "Underwater Electroacoustic Transducers," Bath University Press (1991).

[17] F.J. Harris, "On the use of windows for harmonic analysis with the Discrete Fourier Transform," *Proc. IEEE* 66, 51-83 (1978).