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PERFORMANCE OF AN ACOUSTIC SONDE DESIGN

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ABSTRACT

The potential of multi-frequency acoustic technology for quantifying fish and plankton is widely recognized. At a U.S. GLOBEC workshop in 1991, one of the considered problems was measuring macrozooplankton and micronekton. It was concluded that in order to survey animals in the size range 0.5-5 cm, it would be expedient to use at least three and perhaps as many as 8-10 frequencies in the range 38-420 kHz. Here, a specific design is evaluated: ten more or less standard, approximately logarithmically spaced frequencies are chosen. Each frequency represents the resonant condition of a circular piston transducer with 10-deg beamwidth. The performance of this system is assessed through the maximum detection range of single targets, assuming transmission near the cavitation limit but consistent with dynamic strength and heat generation in ceramic elements, isotropic ambient noise, and detection threshold of 20 dB. Target strength is treated as a parameter, with investigated values from -130 to -50 dB. Performance assessment for a volumetric distribution of scatterers is similarly treated.

RESUME: PERFORMANCE D'UN PROJET DE SONDE ACOUSTIQUE

Les potentialités de la technologie acoustique pour quantifier le poisson et le plancton sont considérées largement. Au groupe de travail U.S. GLOBEC en 1991, l'un des problèmes abordés fut la mesure sur du macrozooplancton et du micronecton. La conclusion fut que pour évaluer des organismes d'une taille comprise entre 0.5 et 5 cm, il serait souhaitable d'utiliser au moins trois ou peut-être 8-10 fréquences dans la gamme 38-420 kHz. Dans cette note, un projet spécifique est évalué: dix fréquences plus ou moins standard, réparties approximativement de manière logarithmique, sont choisies. Chaque fréquence représente les conditions de résonnance d'un transducteur-piston circulaire avec 8° de faisceau d'emission. Les performances de ce système sont calculées pour la portée maximum de détection de cibles uniques, avec une hypothèse de transmission proche des limites de cavitation, le niveau de bruit isotropique ambiant et un seuil de détection de 20 dB. L'index de réflexion est traité comme un paramètre avec des valeurs variant de -130 à -50 dB. La méthode de calcul des performances pour une distribution volumétrique de diffuseurs est décrite.

INTRODUCTION

The potential for acoustics in measuring biological scatterers is well known. It may enable zooplankton and fish to be measured in situ, non-invasively and remotely, and often rapidly and synoptically too. Use of frequency diversity is especially powerful, as for detecting the presence of an air bladder or for discriminating size (Holliday 1980).

This potential has been recognized in the Global Ocean Ecosystem Dynamics (GLOBEC) program, where multiple-frequency acoustic methods have been considered in detail on at least several occasions. At a U.S. GLOBEC workshop in April 1991, acoustics was considered for measurement of three broad classes of scatterers: fish, macrozooplankton and micronekton, and small zooplankton (U.S. GLOBEC 1991). At an International GLOBEC workshop in April 1993, acoustics was again considered, but for general use on all scatterer classes (International GLOBEC 1993).

Requirements that associated acoustic systems be capable of performing size discrimination and density determination impose conditions on the range and number of acoustic frequencies. An excellent precedent for this exists in the example of the Multifrequency Acoustic Profiling System (MAPS), which aims to cover the size range 0.1-10 mm: the frequency range is 100 kHz - 10 MHz, which is spanned by 21 discrete frequencies, with logarithmic spacing (Holliday et al. 1989).

The object class of scatterers here is that of the macrozooplankton and micronekton considered in the mentioned U.S. GLOBEC workshop. The defined size range is 0.5-5 cm. It was recommended at the workshop that the frequency range 38-420 kHz be used and that this be spanned by at least three and perhaps as many as 8-10 frequencies, including some conventional frequencies for comparisons with historical data.

In this paper, the performance of a particular system design is examined, with three distinct aims: to make available numbers for assessing performance, to illustrate the manner of performing computations, and to serve as a guide for specifying acoustic measurement systems, as for quantifying animals in different size ranges than that considered here. The sonar equation is the basic tool of analysis (Urick 1983).

TRANSDUCER DESIGN AND CHARACTERISTICS

The frequency range is given as 38-420 kHz. Based on the reasoning underlying MAPS (Holliday et al. 1989) and discussions within the GLOBEC program, this range is chosen to be spanned by ten frequencies. While it is desirable a priori to span this by discrete frequencies with logarithmic spacing, the requirement that some of the frequencies be conventional supports the following choice: 38, 50, 70, 100, 120, 150, 200, 250, 330, and 420 kHz. The ratio of successive frequencies is thus 1.32, 1.4, 1.43, 1.2, 1.25, 1.33, 1.25, 1.32, and 1.27, respectively.

The transducer geometry is based on that of the planar circle, with diameter determined by the requirement that the beamwidth be 10 deg between opposite half-power or -3-dB levels. The transducer type is thus that of the planar circular piston, which is moreover assumed to operate in a condition of resonance and to be perfectly baffled. This idealization is quite reasonable for ordinary performance evaluations, because of the narrowness of the acoustic beam and ease, and indeed necessity, of baffling the associated transducer.

For the general beamwidth $\Delta\theta$, the transducer radius a is given by the approximate equation,

$$ka \sin\frac{\Delta\theta}{2} = 1.615 \quad , \tag{1}$$

where k is the wavenumber. For design purposes, the sound speed is assumed to apply for sea water of temperature $5^{o}C$, salinity 35 ppt, pH 7.7, and depth 3 m, namely 1470.7 m/s (Mackenzie 1981). Computed diameters 2a are presented in Table 1.

Given $\Delta\theta$, hence ka, the directivity index DI and equivalent beam angle Ψ, or integrated beam factor (Clay and Medwin 1977), are immediately determined. By definition (Urick 1983),

$$DI = 10 \log \frac{4\pi}{\int b \, d\Omega} \quad , \tag{2}$$

and

$$\Psi = 10 \log \psi = 10 \log \int b^2 d\Omega \quad , \tag{3}$$

where b denotes the one-way beam pattern. Because of baffling, b or b^2 is effectively integrated over the half space of 2π sr about the axis. In the narrow-beam approximation assumed here, DI=20 log (ka)=25.4 dB, $\psi=5.78(ka)^{-2}$ =0.0168 sr, and Ψ=-17.7 dB.

Each transducer is assumed to be driven as near to the cavitation limit as is feasible, recognizing limitations due to dynamic strength and heat generation, which may cause depolarization in ceramic transducer elements (Woodward et al. 1993). This is a function of transducer frequency, pulse duration, depth, and gas content of water medium, among other factors. For definiteness, the nominal design figures used by SIMRAD according to H. Bodholt are assumed. The figures for the acoustic intensity I_{ac} listed in Table 1 apply to sea water at 3 m depth.

The acoustic power is thus

$$P_{ac} = \pi a^2 I_{ac} \quad . \tag{4}$$

The required electrical power is $P_{el}=P_{ac}/\eta$, where η is the transducer efficiency, typically 50-60% for modern ceramic devices. If P_{ac} is expressed in terms of watts, then the source level is

$$SL = 10 \log P_{ac} + DI_T + 170.8 \quad , \qquad (5)$$

where DI_T specifies the transmitting directivity index, with value 25.4 dB. The units of SL are dB re 1 μPa at 1 m. These and other parameters are given in Table 1.

Table 1. Design diameter 2a of circular piston transducers with half-beamwidth 5 deg, and other assumed or derived parameters: acoustic intensity I_{ac}, acoustic power P_{ac}, source level SL, absorption coefficient α, noise spectral level SPL, and noise band level NL for each of two sea states (ss). Parameters independent of frequency are the directivity index DI=25.4 dB, equivalent beam angle ψ=0.0168 sr or Ψ=-17.7 dB, and detection threshold DT=20 dB.

f (kHz)	2a (mm)	I_{ac} (W/cm^2)	P_{ac} (W)	SL	α (dB/km)	SFL (dB re 1 Hz)		NL (dB)	
						ss=0	ss=6	ss=0	ss=6
38	228.3	3.1	1269	227.2	10.7	22.4	58.2	44.5	80.3
50	173.5	5.0	1182	226.9	15.3	23.2	60.2	42.5	79.5
70	123.9	10.0	1206	227.0	21.6	25.3	63.7	40.1	78.6
100	86.7	10.0	591	223.9	28.5	28.1	68.1	37.8	77.8
120	72.3	10.0	410	222.3	32.2	29.6	70.4	36.9	77.7
150	57.8	10.0	263	220.4	37.2	31.6	73.3	36.2	77.9
200	43.4	10.0	148	217.9	45.6	34.0	77.0	36.2	79.2
250	34.7	10.0	95	215.9	55.1	36.0	80.0	37.1	81.0
330	26.3	10.0	54	213.5	73.6	38.4	83.6	38.8	84.0
420	20.7	10.0	34	211.4	100.0	40.5	86.7	40.6	86.9

SONAR MODEL

A convenient measure of performance is the maximum range of detection for a single animal of given target strength TS or an aggregation of like animals distributed throughout the sampling volume with mean volume backscattering strength S_v. If the target is to be discriminated from isotropic background noise, with band level NL, then the detection range is determined by solving the active sonar equation in one of two forms:

$$SL - 2\,TL + TS - (NL - DI_R) = DT \quad , \qquad (6)$$

and

$$SL - 2\,TL + S_v + 10 \log V - (NL - DI_R) = DT \quad , \qquad (7)$$

where TL denotes the transmission loss, DI_R is the receiving directivity index, and DT is the detection threshold. The several parts of the equations are now elaborated.

Transmission loss For two-way propagation,

$$TL = 40 \log r + 2\alpha r \quad , \tag{8}$$

where r is the target range, and α is the absorption coefficient. Here, α is determined by the equation due to Francois and Garrison (1982), with values shown in Table 1.

Scattering strengths For a given scatterer type and size, both TS and S_V are generally functions of frequency (Greenlaw 1977, Holliday and Pieper 1980, Wiebe et al. 1990). For the object size range 0.5-5 cm and frequencies 38-420 kHz, the variation in TS and S_V may be tens of decibels, or orders of magnitude in the intensity domain, which is to be exploited in acoustic sizing, for example. The scattering strengths are thus treated as parameters in the computations.

Sampling volume The acoustic sampling volume is a rather complicated function of scatterer properties and system characteristics, including detection threshold (Foote 1991). For simplicity, the usual nominal sampling volume is assumed, namely

$$V = r^2 \frac{c\tau}{2} \psi \quad , \tag{9}$$

where τ is the pulse duration, assumed to be 0.1 ms in the computations.

Noise band level Three sources of noise are considered: the ambient environment as characterized by sea state, thermal noise, and electronic noise in the receiver. The noise spectral level SPL due to the first source is given by the Knudsen curves (Bartberger 1965):

$$SPL_{amb} = 46 + 30 \log (n_{ss}+1) - 17 \log (f/1000) \quad , \tag{10}$$

where n_{ss} denotes the sea state, and f is the frequency in Hertz. The thermal noise spectral level is (Mellen 1952):

$$SPL_{th} = -15 + 20 \log (f/1000) \quad . \tag{11}$$

The receiver noise is assumed to be equivalent to the thermal noise level. The combined spectral noise level due to the three sources is thus

$$SPL = 10 \log [10^{(SPL_{amb}/10)} + 2 \cdot 10^{(SPL_{th}/10)}] \quad . \tag{12}$$

The band level is just

$$NL = SPL + 10 \log \Delta f \quad , \tag{13}$$

where Δf denotes the receiver bandwidth in Hertz. Here, the receiver bandwidth is assumed to be 10% of the transmit frequency, or $\Delta f = f/10$. Values of SPL and NL are given in Table 1 for each of sea states 0 and 6.

Receiving directivity index The receiving directivity index is assumed to be equivalent to the transmitting directivity index, i.e., $DI_R = DI_T$, which is a simple consequence of reciprocity.

Detection threshold The detection threshold DT specifies the signal-to-noise ratio required for detection. Here DT=20 dB, which choice attempts to ensure unambiguous detection. This is especially important for size discrimination.

RESULTS AND DISCUSSION

The various components of equations (6) and (7) are specified, if by parameter values. The only unknown is the range r, although implicit. Solution of the respective equation is straightforward, and results are presented in Table 2 and in Figures 1 and 2. The detection range generally exceeds the Rayleigh distance, namely a^2/λ where λ is the acoustic wavelength, requiring no further qualification of the numbers.

The results indeed show the expected dependences on range, frequency, and scattering strength. What may be particularly useful are the magnitudes, for example, detailed specification of maximum detection range for a given frequency and target strength or volume backscattering strength.

Clearly, the detection range for a given scattering strength at lower frequencies is substantially greater than at higher frequencies, which is largely a consequence of the increasing rate of absorption with frequency, but which is also affected by the frequency dependence of the noise level. The scattering strength of a target of particular species and size, as already mentioned, will vary with frequency. For solid scatterers without gas inclusions, the scattering strength generally increases rapidly with frequency from the Rayleigh regime, where the wavelength is large compared to typical scattering dimensions, to the geometric scattering regime, with wavelength small compared to the same dimensions. Scatterers with gas inclusions may show a much more complicated behavior, owing to the special phenomenon of resonance. This may account for a peak in the scattering response at quite low frequencies.

Given a specific scatterer frequency dependence, the tables and figures may be used to assess the performance of the acoustic system design. If this can be reduced to a likely maximum detection range apropos of the simultaneous use of all frequencies in the same volume, then rates of detection, hence duration of sampling exercises, may be planned with respect to distribution fields as described by mean density and measures of patchiness.

The investigated range of scattering strengths, [-130,-50] dB, is quite large, which reflects the physical range in scattering from rather large gas-bladdered organisms to small gelatinous zooplankton. The present

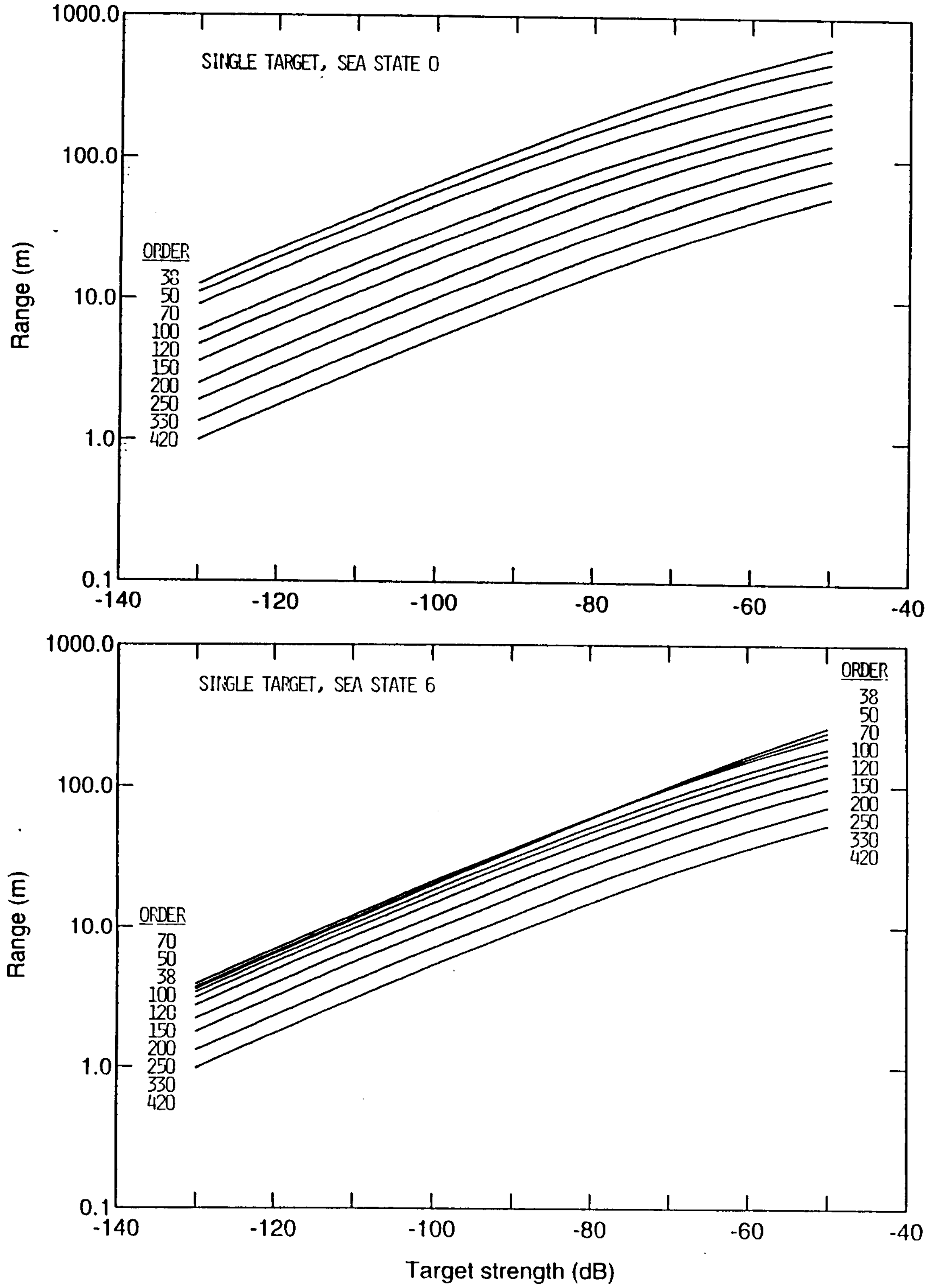

Figure 1. Maximum detection ranges of single targets for the described system design, assuming detection threshold of 20 dB.

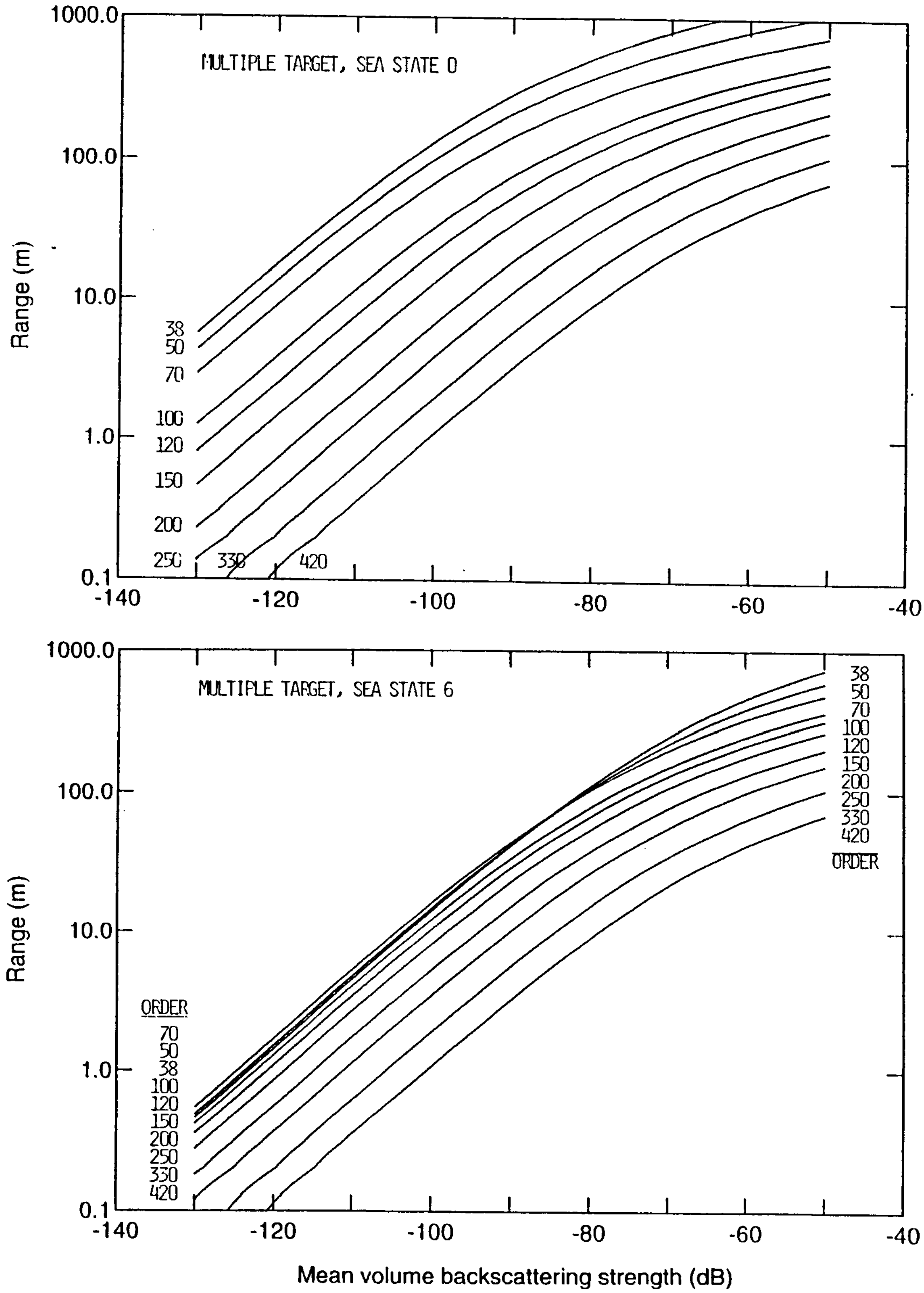

Figure 2. Maximum detection ranges of multiple targets for the described system design, assuming detection threshold of 20 dB.

Table 2. Maximum detection ranges for single and multiple targets.

f (kHz)	TS or S_V (dB)	Single target ss=0	Single target ss=6	Multiple target ss=0	Multiple target ss=6
38	-120	22.2	6.3	17.6	1.4
38	-110	38.8	11.2	51.3	4.5
38	-100	66.6	19.7	132.7	13.9
38	-90	112.0	34.5	286.9	41.1
38	-80	182.6	59.5	516.1	109.9
38	-70	285.9	100.5	803.7	247.5
38	-60	427.3	165.1	1129.9	461.8
50	-120	19.3	6.5	13.4	1.5
50	-110	33.5	11.5	38.8	4.7
50	-100	57.2	20.1	99.3	14.5
50	-90	95.2	34.8	211.7	41.7
50	-80	152.9	59.3	376.0	105.4
50	-70	235.3	98.5	580.3	221.6
50	-60	345.1	157.8	812.4	389.1
70	-120	15.8	6.9	9.0	1.7
70	-110	27.2	12.0	26.2	5.3
70	-100	46.2	21.0	67.6	15.9
70	-90	76.3	35.9	145.2	43.7
70	-80	121.3	60.1	259.8	102.8
70	-70	184.3	97.4	403.0	200.3
70	-60	267.0	151.5	566.2	330.9
100	-120	10.3	6.0	3.9	1.3
100	-110	17.9	10.5	11.7	4.0
100	-100	30.5	18.2	32.4	12.1
100	-90	50.8	31.0	76.6	33.2
100	-80	81.6	51.5	149.7	78.2
100	-70	125.6	82.6	248.1	152.1
100	-60	184.2	127.0	364.6	251.1
120	-120	8.3	5.5	2.5	1.1
120	-110	14.4	9.6	7.6	3.4
120	-100	24.6	16.7	21.7	10.3
120	-90	41.1	28.4	54.1	28.4
120	-80	66.6	47.1	111.6	67.2
120	-70	103.3	75.4	193.0	131.8
120	-60	152.8	115.6	292.3	218.7
150	-120	6.3	4.8	1.4	0.9
150	-110	11.0	8.5	4.5	2.7
150	-100	18.8	14.7	13.1	8.0
150	-90	31.7	25.0	34.5	22.5
150	-80	51.7	41.4	76.3	54.1
150	-70	81.1	66.2	139.9	107.9
150	-60	121.4	101.3	221.0	181.6
200	-120	4.4	3.9	0.7	0.6
200	-110	7.7	6.8	2.2	1.7
200	-100	13.3	11.8	6.7	5.3
200	-90	22.5	20.1	18.6	15.0
200	-80	37.1	33.4	44.8	37.5
200	-70	58.9	53.4	89.0	77.7
200	-60	89.3	81.8	149.3	134.9
250	-120	3.3	3.1	0.4	0.4
250	-110	5.8	5.5	1.3	1.1
250	-100	10.1	9.5	3.9	3.5
250	-90	17.2	16.3	11.2	10.1
250	-80	28.5	27.0	28.5	26.0
250	-70	45.5	43.3	60.3	56.1
250	-60	69.5	66.5	106.4	100.7
330	-120	2.4	2.3	0.2	0.2
330	-110	4.1	4.0	0.6	0.6
330	-100	7.2	7.0	2.0	1.9
330	-90	12.2	12.0	5.9	5.6
330	-80	20.3	19.9	15.7	15.1
330	-70	32.6	31.9	35.5	34.4
330	-60	50.0	49.1	66.4	64.9
420	-120	1.8	1.7	0.1	0.1
420	-110	3.1	3.0	0.4	0.3
420	-100	5.3	5.3	1.1	1.1
420	-90	9.0	9.0	3.3	3.2
420	-80	15.0	14.9	9.1	8.9
420	-70	24.1	23.9	21.6	21.3
420	-60	36.9	36.6	42.3	41.9

method may be used to determine the detection capabilities of the particular design, as well as that of other designs involving other beamwidths, frequencies, and other characteristics too.

Use of data collected with an acoustic sonde as described here has not been treated for being well known. The method of multi-frequency size discrimination is described, for example, by Holliday et al. (1989). Measurement of absolute density by the echo integration and echo counting methods is described by, among others, MacLennan (1990).

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