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PRELIMINARY EVALUATION OF AN ACTIVE SONAR SYSTEM FOR MEASURING THE FINE STRUCTURE OF THE THERMOCLINE

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TR 71-062

Preliminary Evaluation

of an Active Sonar System

for Measuring the Fine Structure

of the Thermocline

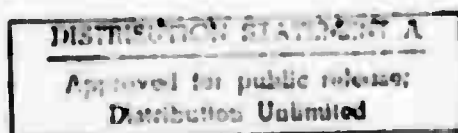Dr. Bernard Harris

Dr. Ross E. Williams

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27

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2

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13. ABSTRACT

    A downward-looking, large-area array, active sonar system has been proposed as a means for monitoring the passage of submerged objects by measuring the backscatter off the altered thermal microstructure. The evaluations here show that the problem is contrast, with the biological backscatter as the limiting factor, so that a large array appears necessary. The degree to which the remnants of the thermocline structure, after passage, would further limit the system are not yet known. As an experimental plan, other unknowns are the desired frequency of operation as well as the required sophistications of the sonar.

11

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Abstract

A downward-looking, large-area array, active sonar system has been proposed as a means for monitoring the passage of submerged objects by measuring the backscatter off the altered thermal micro-structure. The evaluations here show that the problem is contrast, with the biological backscatter as the limiting factor, so that a large array appears necessary. The degree to which the remnants of the thermocline structure, after passage, would further limit the system are not yet known. As an experimental plan, other unknowns are the desired frequency of operation as well as the required sophistications of the sonar.

Summary

A downward-looking, large area array, active sonar system has been proposed as a means for monitoring the passage of a submarine by measuring the backscatter off the altered thermal microstructure. The results of the evaluations here and those in Jason[1] seem to show:

1. The detection problem is not ambient noise but rather that of contrast.

2. If biological backscatter is the limiting factor, then a large array appears necessary. However, the frequency of operation is not evident so that further investigation is required in order to define the array and other system parameters.

3. However, if the backscatter from the thermocline is off sheets of high thermal gradients, range gating may be effective in reducing array requirements.

4. If after passage of the submarine, the thermocline is not completely homogenized, the limitations may not be biological backscatter but the remnants of the thermocline.

5. Detection of the horizontally stratified thermocline before passage and the remnants afterwards may not only require range gating but more sophisticated techniques.

6. The complete system may thus not comprise a large array with a pulse compression sonar but instead resemble a sonic holography system. This may be particularly true if energy changes by themselves are not credible, but actual examination of the thermocline fine structure, before and after passage, is necessary.

The efficacy of these techniques is difficult to comment upon because little is known about the stability and lateral coherence of the thermal microstructure layers in the ocean. More importantly, however, the little that is known has not been fully exploited in terms of synthesizing a system.

1.0 System Analysis

A preliminary evaluation has been made of an active sonar system designed to monitor the passage of a submarine by measuring the backscatter off the fine structure of the thermocline. It is shown that even with a modest array, the effects of ambient noise will be small so that the problem is one of contrast - i. e., the change in backscatter before and after passage of the submarine (Section 3.0).

The evaluation by Jason[1] is based on the volume backscatter due to the gradients of the thermocline being homogenized by the passage so that the remaining backscatter is of biological origin. With this model, the requirement for a large array results from the need to fully exploit the horizontal coherence of the laminar thermal layers and thus obtain sufficient processing gain over the biologically scattered energy.

The efficacy of this suggested technique is difficult to comment upon because of uncertainties in the applicability of the model used for the fine structure of the thermocline, before and after passage. Specifically, before passage,

1. The model is based on a volume backscatter and thus does not show the advantages of range gating. Other models for the thermocline[2,3] show that the principal features are a series of thin laminar-flow sheets of high static stability separated in depth by weakly turbulent layers a few meters thick having only moderate density gradients. The analysis of this model (Section 2.0) shows that the backscatter per layer is

$$R = -84.16 \qquad \lambda > 2\pi L$$

$$= -84 db - 10 \log \frac{2\pi L}{\lambda} \qquad \lambda < 2\pi L$$

in which L is the layer thickness

λ is the sonic wavelength.

Frequency effects result in -91 dB backscatter at 5 KHz and -105 dB at 25 KHz.

2. The estimates from the backscatter model used in Jason[1] are -90 to -100 dB/m. This is not inconsistent, except that in the model used here the backscatter is not per meter but rather the result of a thermal discontinuity less than 10 cm thick.

3. If the biological backscatter is accepted at the values used in Jason

| biological, day | -70 dB/m |
| night | -90 dB/m |

and the sonar range gates to 10 cm, the biological interference level is

| biological, day | -70 | -10 | = | -80 dB/m |
| night | -90 | -10 | = | -100 dB/m |

4. Unless the thermal sheets are less than 10 cm thick, range gating by itself does not appear sufficient for detection. However, range gating does reduce the requirements on the size of the array.

After passage of the submarine:

1. The model for the thermocline is based on a homogenization of the thermal layers leaving only the biological scatters. Other models[4], however, indicate that the mixing is not that all complete.

2. Suppose, for example, after passage a more suitable model is that the thermal sheets are dispersed so that the -100 dB backscatter from discrete sheets is now a volume backscatter.

3. In this case the large array may not be too effective against the backscatter after passage because it comes from extended discontinuities rather than from small biological scatters.

4. Range gating then becomes a necessity to determine that the structure of the backscatter has been distributed.

Indeed it may result that:

1. A large array is needed to reduce biological backscatter.

2. Range gating (pulse compression sonar) is needed to determine that the laminar layer has been disturbed.

3. A holographic data processing procedure is required to further examine the fine structure of the thermocline before and after passage. Perhaps without a procedure such as this, monitoring of energy changes will not be believable.

The preliminary conclusion is that the little that is known about the fine structure of the thermocline has not been fully exploited in designing an acoustic monitoring system.

2.0 Physical Phenomena

The physical phenomena which is to be observed is the fine structure of the thermocline which affects ρC and hence the backscatter of sonic waves. The order of magnitude of this effect will be estimated from two sources, J. D. Woods observations in the Mediterranean [2] and W. W. Denner observations in the Arctic. [3]
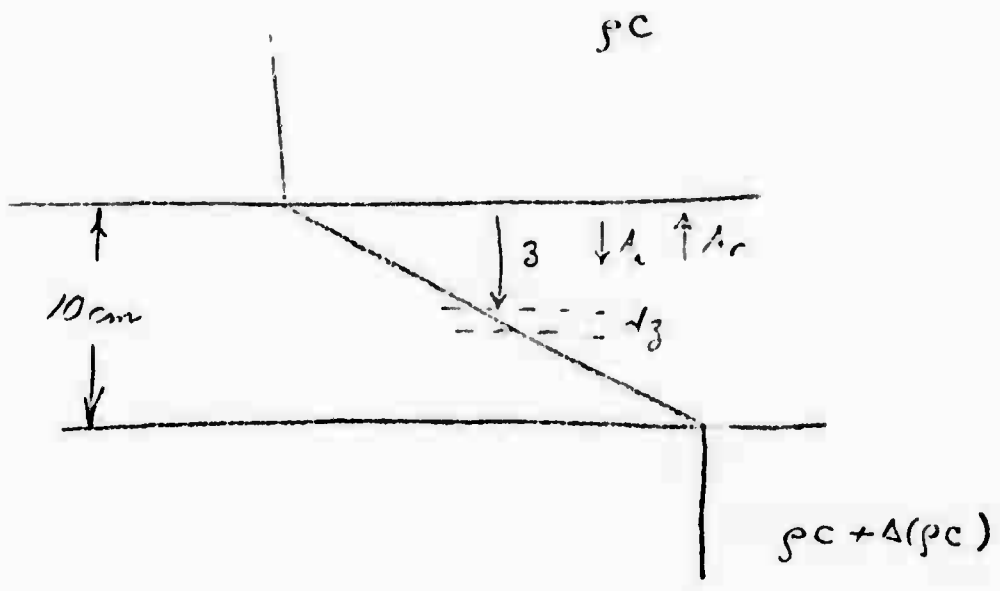
2.1 Mediterranean Data

The principal features of a thermocline, observed by photographs of the tracers, is a series of thin, laminar-flow sheets of high static stability, separated by weakly turbulent layers a few meters thick having only a moderate density gradient.

Temperature	T	= 20° C
Sheet Thickness	z	= 10 cm
Temperature Gradient in Sheet	$\Delta T/\Delta z$	= $1^\circ C/50\,m$
Temperature Step	ΔT	= $-0.2^\circ C$

Both the density and salinity step changes would be desirable. The salinity change will be neglected. The density change is calculated from the temperature change.

$$\Delta \rho = -260 \times 10^{-6} \; \Delta T$$
$$\approx -260 \times 10^{-6} (-0.2)$$
$$\approx 520 \times 10^{-6} \, g/cm^3$$

ρc

$10\,cm$

3

$\downarrow \lambda_e$ $\uparrow \lambda_r$

λ_3

$\rho c + \Delta(\rho c)$

$$\frac{\Delta \rho c}{\rho c} \approx 60 \times 10^{-6}$$

Fig. 1. Model for the Change in ρc with Depth

2.2 Arctic Data

The features observed in the Arctic are sheets of high temperature gradient ranging from a few to a few tens of centimeter thick separated by layers of small gradient a few to a few tens of meters thick.   These data are consistent with the Mediterranean data except there is, in addition to temperature steps, recorded salinity and density step changes.

Temperature	T	$0°C$
Sheet Thickness	z	10 cm
Temperature Step	ΔT	$0.02°C$
Salinity Step	ΔS	10 ppm
Density Step	$\Delta \rho$	$7.0\ \mu\,g/cm^3$

2.3 Model for the Reflectivity

The effect of these step changes is, to a first approximation, representable by a model of the water in which there are layers about 3 meters thick, each layer having a step change in its acoustic velocity.   Wilson's equation[5] may be used to calculate this change[3].

$$C = 1442.2 + 4.623\,T - 0.0546\,T^2 + 1.391\,(S-35)$$

$$\Delta C = 4.623\,\Delta T - 0.1092\,T\Delta T + 1.391\,\Delta S$$

-7-

For the Mediterranean

$$C = 1442.2 + 4.623(20) - 0.0546(20)^2$$

$$= 1442.2 + 92.5 - 21.8$$

$$= 1519.9 \text{ m/sec}$$

$$\Delta C = (-0.2)(4.623 - 0.10)(2(20))$$

$$= (-0.2)(2.443)$$

$$= -0.4886 \text{ m/sec}$$

For the Arctic

$$C = 1442.2 \text{ m/sec}$$

$$\Delta C = 0.02(4.623) + 1.391(0.01)$$

$$= 0.0925 + 0.01391$$

$$= 0.1064 \text{ m/sec}$$

The acoustic reflectivity for a ray at normal incidence is given by

$$\rho = \sqrt{\frac{I_r}{I_i}} = \frac{\rho_2 C_2 - \rho_1 C_1}{\rho_2 C_2 + \rho_1 C_1}$$

$$\approx \frac{\Delta(\rho c)}{2 \rho C}$$

Since

$$\Delta \rho C \approx \rho \Delta C + C \Delta \rho$$

-8-

then

$$R \approx \frac{1}{2} \left(\frac{\Delta c}{c} + \frac{\Delta \rho}{\rho} \right)$$

For the Mediterranean

$$R \approx \frac{1}{2} \left(\frac{-.4886}{1519.7} + \frac{52 \times 10^{-6}}{1} \right)$$

$$\approx \frac{1}{2} \left(-322 + 52.0 \right) 10^{-6}$$

$$\approx 130 \times 10^{-6}$$

For the Arctic

$$R \approx \frac{1}{2} \left(\frac{.10674}{1443.2} + \frac{3.0 \times 10^{-6}}{1} \right)$$

$$\approx \frac{1}{2} \left(72.8 + 7 \right) 10^{-6}$$

$$\approx 20 \times 10^{-6} \qquad \text{should be 40. Due to roll off of decimals.}$$

This is in agreement with Denner [3] who calculated 5×10^{-5} as an approximate value.

While the model is sufficient as a first approximation, it does not contain the effects of acoustic frequency and is thus only accurate if the acoustic wavelength is large compared to the sheet thickness. By large will be meant that the acoustic wavelength is at least eight times the sheet thickness. Hence the wavelength must exceed

$$\lambda \gtrsim 80 \text{ cm}$$

and the frequency must be less than

$$f < \frac{1500 \text{ m/sec}}{0.8 \text{ m}}$$

$$f < 1880 \text{ Hz}.$$

To obtain a more accurate frequency dependent model, the change in ρc across the 10 cm interface will be assumed linear. Moreover, since the reflection coefficient is small, the power loss of the incident ray will be neglected so that the amplitude A_i of the incident ray is constant.

The incremental change in ρc across a distance dz in the interface is

$$d(\rho c) = \frac{\Delta(\rho c)}{L} dz$$

The amplitude of the reflected ray at the point z within the interface is

$$dA_r = \frac{d(\rho c)}{2(\rho c)} A_i \, e^{i \frac{\omega}{v} z_i} dz$$

in which z_i is the extra round trip distance of the reflected ray to the upper edge of the interface.

Then

$$dA_r = \frac{\Delta(\rho c) A_i}{2 \rho c L} \, e^{i \frac{\omega}{v} z_i} dz$$

and

$$dA_r = \frac{R A_i}{L} \, e^{i \frac{\omega}{v} z} dz$$

and

$$A_r = \frac{\langle A_o \rangle}{v_\pi L_f} \left[e^{i\frac{v\pi L}{\lambda}} - 1 \right]$$

In the form

$$A_r = \frac{\langle A_o \rangle}{v\pi L_f} e^{i\frac{v\pi L}{\lambda}} \left[e^{i\frac{v\pi L}{\lambda}} - e^{-i\frac{v\pi L}{\lambda}} \right]$$

the amplitude is easily seen to be

$$|A_r| = \frac{\langle A_o \rangle}{2v\pi L} \sin \frac{v\pi L}{\lambda}$$

Hence the reflection coefficient, including frequency effects is

$$R(f) = R_o \cdot \frac{\sin \frac{2\pi L}{\lambda}}{\frac{2\pi L}{\lambda}}$$

In this frequency dependent model there are resonant effects for back-scatter off a single interface. These resonances may be blurred because the actual edges of the interface are fuzzy. For this reason, the envelope of the $\sin x / x$ function will be used. In addition, to have a single numerical value, the average value of the reflection coefficient for the Mediterranean and Arctic will be used.

$$R = 60 \times 10^{-6} \qquad \lambda > 2\pi L$$

and

$$R = 60 \times 10^{-6} \frac{\lambda}{2\pi L}$$

-11-

3.0 Detection of the Per Layer Backscatter in Ambient Noise

The purpose of this analysis is to show that a sonar having a reasonable range resolution appears capable of detecting the backscatter off the sheets of high thermal gradient. This means that one is dealing with a contrast problem. The presentation, here, is as a working paper, so the details of the evaluation are given.

3.1 Analysis

The system consists of a downward-looking sonar which measures the backscatter off the fine structure of the thermocline. The model for this fine structure is that there are 10 cm thick layers separated by 3 meters such that the amplitude reflection coefficient is *

$$R = 60 \cdot 10^{-6} \qquad \text{for} \qquad \lambda > 2 \cdot L$$

$$R = 60 \cdot 10^{-6} \frac{\lambda}{2 \cdot L} \qquad \text{for} \qquad \lambda < 2 \cdot L$$

in which λ is the sonar wavelength

L is the layer thickness.

The sonar is specified as follows:

Power Output	50 - 100 watts
Array Size	4 x 4 feet, 50 x 50 feet
Frequency	5 - 25 KHz
Directivity Index	35 dB

---

* See Section 2.0. Physical Phenomena.

is the degree to which the ocean will permit coherent processing. The considerations are:

1. The platform moves up and down. At moderate breezes the developed sea has a height $H_{1/3}$ of about 1.12 m and a period down to perhaps 1.6 seconds. The change in sea height is thus

$$\frac{1.12}{4(1.6)} \approx 0.18 \text{ m/sec}$$

The wavelength at the maximum specified sonar frequency of 25 KHz is

$$\lambda = \frac{1500 \text{ m/sec}}{25 \times 10^3} \approx 0.6 \text{ m}$$

Hence, even without decoupling from the ocean, the processing time could be 3.3 seconds.

2. The bandwidth is limited by the thickness of the layer which is 10 cm. If the round-trip time of the reflection through this layer is limited to one fourth the corresponding period, the bandwidth is limited to

$$B = \frac{1500 \text{ m/sec}}{4(0.2 \text{ m})} = 1880 \text{ Hz}$$

3. The maximum time-bandwidth product is thus about

$$BT = 3.3(1880) \approx 6200$$

The processing gain expected of the sonar is about 38 dB.

-13-

whether or not the ocean structure remains
stable enough to support this processing gain.
This would require further examination.

5. In addition to the processing gain, there is a
post detection gain which is an incoherent ad-
dition. If a total of ten seconds is allowed,
the added effect of about 8 samples is 5 log 8
or 5 dB.

Sonar Equation

The basic sonar equation, modified for the extended target of interest
here, is

$$ SE = PG + PD + SL - TL - BL - NL - DT $$

In which

SE is the signal excess
PG is the processing gain
PD is the post-detection gain
SL is the source level
TL is the transmission loss
BL is the backscatter loss
NL is the noise level
DT is the detection threshold.

Source Level

The power output will be taken at the maximum specified 100 watts.
For an omnidirectional radiator this corresponds to

$$ SL = 72.8 + 10 \log 100 $$
$$ = 72.8 \text{ db re } 1 dyne/cm^2 \text{ at 1 meter} $$

-14-

Transmission Loss

The transmission loss depends on whether or not the backscatter is specular. This probably depends, in part, on the wavelength. Since the actual situation is not yet well defined, both will be evaluated. There is also an absorption of the sound energy which is a function of frequency. This is negligible, because at 25 KHz the absorption coefficient is only about 5 dB/kmeter. For a hundred-meter (one way) range, this is only one dB. The situation changes if the frequency of the sonar were higher.

Specular Reflection

The geometry for specular reflection is shown in Fig. 2. The active sonar illuminates the interface layer and the resulting backscatter of the reflected energy illuminates an area A_r in the plane of the sonar array.

$$A_r = \theta (2r)^2$$

in which r is the range

θ is the beamwidth of the array.

If the area of the array is A_a, the fraction of the reflected energy captured by the array is

$$\frac{A_a}{A_r} = \frac{A_a}{\theta(2r)^2}$$

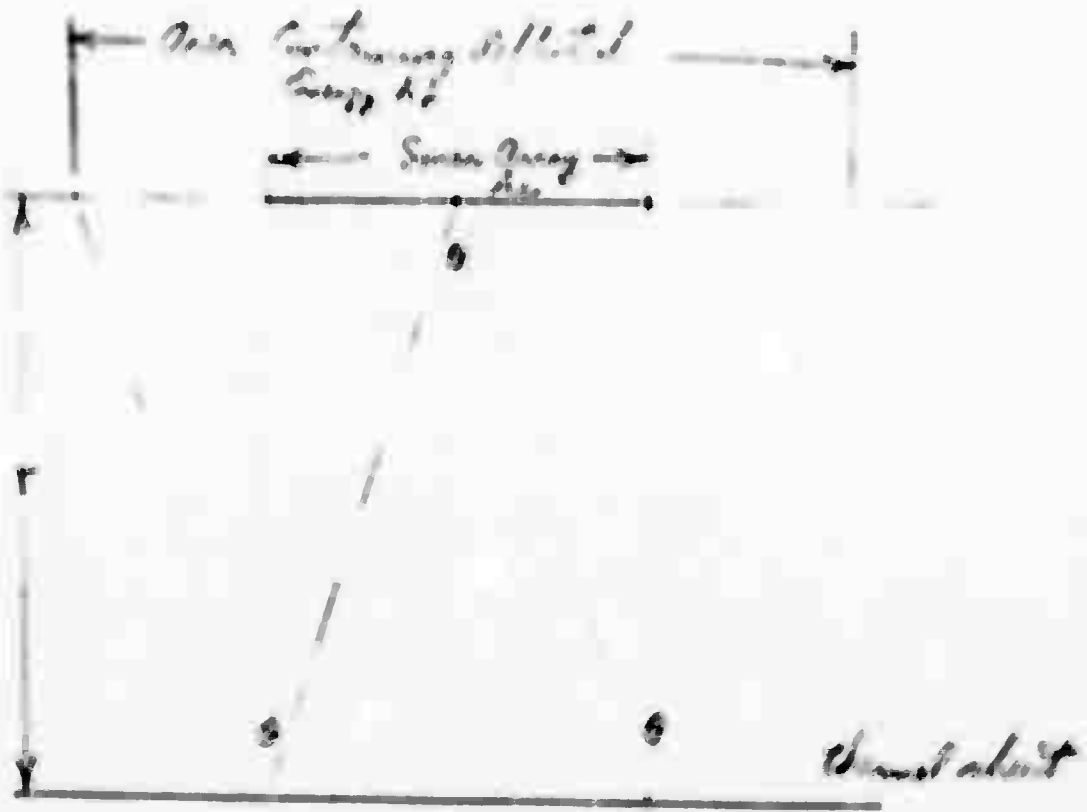Thus

$$TL = -10 \log A_a + 10 \log \theta + 20 \log (2r)$$

Fig. 2.   Model for Specular Reflection

The area of the array is

$$10 \log A_a = 10 \log \pi (0.6m)^2$$
$$= 0.5 \, db \, re \, m^2$$

The beamwidth, θ, can be evaluated from the directivity index, DI, which in turn depends on the array size and frequency

$$DI = 20 \log \frac{\pi D}{\lambda}$$

In which D is the diameter of the array

λ is the wavelength

$$D = 4 ft = 1.2 m$$
$$\lambda = \frac{1500}{25000} = 0.060 \, m \, @ \, 25 \, KHz$$

$$\therefore DI = 20 \log \frac{\pi (1.2)}{.060} = 20 \log 62.8 = 36 \, db \, @ \, 25 \, KHz$$

At 5 KHz, the DI drops by 20 log 5 or 14 dB.

$$\therefore DI = 22.0 \, db \, @ \, 5 \, KHz$$

The beamwidth, θ, is related to the DI by

$$DI = 10 \log \frac{4\pi}{\theta} = 10 \log 4\pi - 10 \log \theta$$
$$\therefore 10 \log \theta = -DI + 10 \log 4\pi$$
$$= -36.0 + 11.0 = -25.0 \, db \, @ \, 25 \, KHz$$
$$10 \log \theta = -22.0 + 11.0 = -11.0 \, db \, @ \, 5 \, KHz$$

-17-

Hence the transmission loss for a range of 200 meters

$$TL = -0.5 - 25.0 + 46.0 = 20.5 \text{ db @ 25 } k\text{c/s}$$

$$= -0.5 - 11.0 + 46.0 = 34.5 \text{ db @ 5 } k\text{c/s}$$

specular reflection

As an upper bound on the useful array size, consider an array with a DI of about 35 db. The beamwidth is then given by

$$DI = 10 \log \frac{4\pi}{\theta}$$

$$\frac{4\pi}{\theta} = 10^{3.5} = 3100$$

The area illuminated by the backscatter at the sea surface based on specular reflection is

$$A_r = \theta (2r)^2$$

$$= \frac{4\pi (2r)^2}{3100}$$

The area of an array of radius r_a is

$$A_a = \pi r_a^2$$

Hence to capture all the backscattered energy

$$r_a^2 = \frac{4(200)^2}{3100} = 51.5 \ m^2$$

$$\therefore r_a = 7.2 \ m$$

or the maximum useful array is 47 feet.

In this case

$$TL = 0.16 \quad \text{for} \quad 47 \text{ ft} \times 47 \text{ ft array}$$
$$DI = 35 \text{ db}.$$

Non-Specular Reflection

Suppose instead of being specular, the backscatter is non-specular and follows Lambert's law. For a DI of 35 dB, the area illuminated at 100 meters has a radius of 3.6 meters. All the angles from points on the illuminated surface to points on the array are thus almost vertical. The $\sin \beta \sin \varphi$ law, for $\beta = \varphi = \frac{\pi}{2}$ is thus unity.

Over a remainder of the hemisphere $\beta = \frac{\pi}{2}$ but at the angle φ the intensity is proportional to $\sin \varphi$.
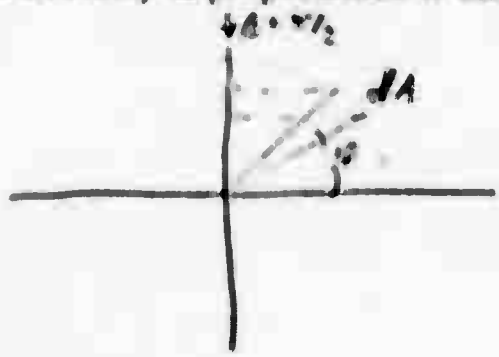
The area on the unity sphere within the ring at the angle φ is

$$dA = 2\pi \cos \varphi \, d\varphi$$

Hence the intensity is $2\pi \sin \varphi \cos \varphi \, d\varphi$ and the total power over the sphere

$$\int_0^{\pi/2} 2\pi \sin \varphi \cos \varphi \, d\varphi = \pi \sin^2 \varphi \Big|_0^{\pi/2} = \pi$$

-19-

The fraction of the transmitted energy received by the array of size A_a is then

$$\frac{A_a}{4\pi r^2} \cdot \frac{1}{\pi}$$

$$\therefore TL = -1 \, \log A_a + 20 \, \log r + 10 \, \log 4\pi^2$$
$$= 55 \, db$$

In the case of non-specular reflection, doubling the diameter of the array improves the TL by only 6 dB.

Backscatter Loss

The backscatter loss comes directly from the reflection coefficient

$$2\pi L = 2\pi (10cm) = 0.628m$$

Hence $\quad \lambda < 2\pi L \quad$ at both 5 and 25 KHz

$\lambda = 0.0600$ m at 25 KHz

$\lambda = 0.300$ m at 5 KHz

$$R = 60 \times 10^{-6} \, \frac{\lambda}{2\pi L}$$

$$= 60 \times 10^{-6} \cdot \frac{(0.060)}{0.628} = 5.7 \times 10^{-6} \, @ \, 25 \, KH_3$$

-20-

$$BL = -20 \log R = -20 \log 5.7 + 120$$

$$\therefore BL = 104.8 \text{ dB at } 25 \text{ KHz}$$

$$BL = 90.8 \text{ dB at } 5 \text{ KHz.}$$

Noise Level

The noise level will be taken for a modest sea state (about 2)

| 5 KHz | NL = -55 dB re 1 dyne/cm^2 |
| 25 KHz | NL = -65 dB |

Detection Threshold

The detection threshold should be somewhat high because the phenomena itself is not deterministic and comparisons have to be made. Instead of the usual 6 dB, a little more margin is essential - say

$$DT = 10 \text{ db}$$

Evaluation of Signal Excess Against Ambient Noise

The Signal Excess can now be evaluated at 5 KHz and 25 KHz for both a small (4 ft x 4 ft) and a large (50 ft x 50 ft) array. The large array is sufficient to collect almost all of the reflected energy, although this evaluation should be refined to check on near-field vs far-field effects.

Array Size	Small				Large	
Reflection	Specular		Non-Specular		Specular	
Frequency	5	25	5	25	5	25
SL	92.3	92.3	92.3	92.3	92.3	92.3
PG	38.0	38.0	38.0	38.0	38.0	38.0
PD	5.0	5.0	5.0	5.0	5.0	5.0
-TL	-34.5	-20.5	-55.0	-55.0	0.0	0.0
-BL	-90.8	-104.8	-90.8	-104.8	-90.8	-104.8
-NL	55.0	65.0	55.0	65.0	55.0	65.0
-DT	-10.0	-10.0	-10.0	-10.0	-10.0	-10.0
SE (dB)	55.0	65.0	34.5	30.5	89.5	85.5

Both 5 KHz and 25 KHz sonar frequencies have been considered as well as models for specular vs non-specular backscatter. In all cases, the Signal Excess is high, showing that the actual problem is contrast.

References

1. Jason 1971, Collected Papers on Wakes in (Micro) stratified Fluids (Preliminary).

2. J. D. Woods, Wave-Induced Shear Instability in the Summer Thermocline. J. Fluid Mech., Vol. 32, Part 4, pp. 791-800; 1968.

3. W. W. Denner, The Layered Microstructure and Acoustic Propagation in the Arctic Ocean (U), U. S. Navy Journal of Underwater Acoustics, Vol. 21, No. 1; January 1971.

4. Denny Ko (Notes from C. Grosch). This evaluation fits the density stratification external to the wake by $\rho_o = \bar{\rho}(1 - \alpha_3)$ and internal to the wake by $\rho_i = \bar{\rho}(1 - \beta_3)$. The results are then compared with more experimental data which shows $\beta/\alpha \approx 0.7$ or the mixing is not very complete. This model could be used to estimate the reflection coefficient after passage.

5. R. J. Urick, Principles of Underwater Sound for Engineers, McGraw-Hill, New York, p. 94; 1967.