SHALLOW-WATER ASW SONAR DESIGN

S.W. Marshall

Lockheed Missiles and Space Co., 1725 Jeff Davis Highway, Arlington, Va.

1. Introduction

The utility of passive ASW sonars, particularly in shallow water where noise is high, is diminishing. To be effective, active sonars in shallow water must overcome reverberation and noise *and* must deal with generally poor and certainly highly variable propagation. This is done best by reducing the fraction of source energy which encounters the surface and the bottom (i.e., a vertically directive source), reducing the reverberation in the receiver to only that arising from the immediate vicinity of the target (i.e., a horizontally directive receiver), and placing source(s) and receiver(s) and selecting waveforms to exploit local anomalies in propagation and reverberation. Unlike deep water, in shallow water the ocean *must* be considered as a part of the system. The purpose of this paper is to discuss the relationships of the ocean with other system components, with numerical examples.

1.1 Definition of Shallow Water

There are two general criteria for "acoustically shallow water":

- Water depth is less than a few wavelengths.
- Sound speed at the surface is greater than at the bottom.

The first criterion relates to lower frequencies where guided wave propagation is influenced by the physical properties of the bottom. The second criterion is important at all frequencies but moreso at higher frequencies where propagation is ray-like and downward refraction repeatedly directs acoustic energy toward the bottom. If either criterion is satisfied, the water is shallow; if both are satisfied, the water is *really* "shallow". In both cases, the more strongly the criteria are met, the "shallower" the water is and the less likely that systems designed for deep water operation will operate satisfactorily. We will assume that a water depth H = 50 to 400 m typifies "shallow water."

1.2 Background

Horizontal acoustic propagation in shallow water is not intrinsically poor, and may be very good owing to upward refraction within the bottom. But bottom encounters are frequent, and penetration of the bottom by the acoustic wave results in viscoelastic loss and in scattering by inhomogeneities. The loss may be low for very hard bottoms and scattering may be low for very smooth and homogeneous bottoms. Generally however, bottoms are either lossy or rough (or both) so that straightforward propagation is frustrated. In addition, the wide variety of geoacoustic bottom properties leads to large differences whenever bottom interaction is strong. Consequently, ASW systems designed to work in deep water perform badly in shallow water and predictions of their performance are equally erratic. Reference to **Figure 1** underscores the strong role that sound speed plays in shallow water, magnifying the importance of the bottom and sub-bottom properties.

Reverberation tends to be higher in shallow water than in deep water, resulting from scattering directly off a rough bottom, from inhomogeneities in the bottom sediments, and from rough features of the basement. Hard bottoms tend to be rough with pockets of sediment filling cavities. Sedimentary bottoms are smoother but have internal inhomogeneities derived from tectonic processes. Ocean currents whose velocity has high spatial variability determine both the bottom composition and roughness in many shallow water areas. Tidal currents and river runoff can result in large variability in ocean sound speed, resulting in even larger variability in ocean acoustic processes in shallow water. The net geological and oceanographic influences on shallow water acoustic propagation result in uniqueness associated with every shallow water area, often over distances of tens of kilometers and times of only a few hours. Clearly, it is desirable to limit unwanted scattering of source energy from the boundaries and the water volume and to further limit the resulting reverberation as seen by the receiver(s).

Below we discuss the factors crucial to active ASW sonars suited to shallow water operation and develop the rules for their design.

2. Propagation and optimum frequencies.

It is convenient to examine the shallow water propagation process as that which endures *after* attenuation processes have taken their toll. A large body of experimental data shows that in shallow water there is a preferred frequency band for propagation between 100 and 1000 Hz, depending on the local conditions. **Jensen (1983)** quantitatively explained these results on the basis of losses in the water column at low frequencies from bottom penetration and losses from boundary scattering at high frequencies, as indicated in the widely referenced experimental and simulated propagation data shown in **Figure 2 (a)**. There is a strong preference for propagation at about 250 Hz for this ocean case.

In the absence of resonant scattering, volume attenuation is well known to be derived from molecular absorption, increasing with the square of frequency. Resonant scattering can arise from molecular resonances (notably boron at about 1000 Hz) and infrequently from swim bladders of migratory fish (typically at frequencies greater than about 500 Hz). Scattering at the wind-driven water surface increases sharply with frequency and wind speed, particularly for speeds greater than about 7 m/sec where waves are breaking. This gives rise to surface-induced attenuation. In addition, there is a bottom-induced attenuation, resulting from three causes:

- Scattering at the rough interface (here, roughness and its lateral extent is scaled to wavelength)
- Mode conversion into shear waves in the bottom and followed by severe viscoelastic loss
- Penetration into the bottom followed by scattering by inhomogeneities there.

Regarding mode conversion, **Vidmar (1980a)** and **Jensen (1983)** articulate the major role that shear plays in permitting an often very lossy event at the boundary for the water-propagated wave, enhancing transfer of acoustic energy into the bottom at low frequencies (< 200 Hz) where the wavelength is so large that most bottoms appear smooth. Moreover, as **Vidmar (1980a,b)** predicted and **Hughes (1990)** showed, a thin sediment above the basement can lead to a strongly frequency-dependent coupling into the basement. Following the notion of **Kuperman (1977)** by gauging propagation by considering attenuation, we see typical results of all the attenuation mechanisms in **Figure 2 (b)**, with the *total* attenuation dominated by bottom at low frequencies, the wind at mid-frequencies, and the water volume itself at high frequencies. It is easy to see that a change in the environment driven by any or all of the primary drivers of attenuation -- water depth, sound speed profile, wind, and bottom properties -- can have a dramatic effect on propagation and concomitant sonar performance.

If reverberation is not limiting, ambient noise must be considered. Ambient noise in shallow water (particularly near land) tends to be high because of coastal shipping, other man-made causes, and surf-generated noise. Therefore, optimum sonar frequencies in shallow water may not be as low as reverberation considerations alone would indicate.

Besides acoustic levels, one must consider spatial and temporal coherence of propagation as it relates to signals, reverberant energy, and ambient noise. A matched filter (i.e., replica correlator) can time-compress signal energy only to the extent that the phase and amplitude of the signal are preserved. Irregularities in the boundaries will reduce temporal coherence, thus diminishing the effectiveness of the matched filter in time-compressing the signal to overcome noise or reverberation.

Maintaining high spatial coherence is required both to maintain signal gain and to prevent sidelobe leakage from high-level interference (noise or reverberation). As the aperture of a receiver is increased, loss of spatial coherence increases, effectively limiting the array gain. We can expect that each shallow water area of interest will behave differently, with respect to both temporal and spatial coherence, so that both receivers and signal waveforms should be selected based on local measurements. A thorough analysis of the effects of the environment on coherent processing is contained in **Carey (1987)**.

Analysis of propagation based on attenuation underscores the ocean's own optimization process for propagation. The shallow water waveguide is frequency-selective. Propagation is modal, with the number of modes supported by a given shallow water region depending on both the physical properties of the region and the frequency of propagation; as the frequency is lowered, eventually the number of propagating modes goes to one and then zero. This is equivalent to the view that steep rays undergo many bottom interactions stripping off all rays except those near the horizontal. **Smith (1983)** has summarized this in the expression for the grazing angle β of the first mode

$$\sin \beta_1 = c/2fH = \lambda/2H, \qquad (1)$$

where c is the speed of sound in the water, f is the frequency, and H is the total water depth. Grazing angles of the higher order modes satisfy

$$\sin \beta_n = n \sin \beta_1, \qquad (2)$$

so that it is highly desirable to confine excitation to the first mode, equivalent to eliminating energy at steep angles.

If we choose $\lambda = H/10$ (which corresponds to very low frequencies for deeper water) to reduce loss and scattering within the bottom, then $\beta_1 = 3$ degrees, $\beta_2 = 6$ degrees, and $\beta_3 = 9$ degrees. If we then take $L = H/2$ as a practical maximum vertical source aperture, the source beamwidth will be

$$\varphi = \lambda / L \text{ (rad)} = 1/5 \text{ rad} = 12 \text{ degrees}. \qquad (3)$$

Now, as Smith shows, the mode functions for modes 1 and 3 are large near the mid-depth of the acoustic channel, whereas the mode function for mode 2 is small. Thus, when $L = H/2$, mode 1 (with $\beta_1 = 3$ degrees, well inside the source beam pattern) will be well-excited; mode 2 will be poorly excited if the source is located near the middle of the channel;. and, modes 3 and higher will be poorly excited because their grazing angles are outside the source beampattern.

For deeper water (e.g., 400 meters), the conditions above lead to either very low frequencies (e.g., 38 Hz) or excitation of higher order modes, i.e., multipaths. For $H = 50$ m, excitation for modes 1 and 3 would indicate an optimum frequency of 300 Hz, based on propagation alone. If other system considerations lead to a choice of higher frequencies, the higher modes will be excited, but the energy in higher order modes will be stripped in the shallow water channel as a natural consequence of its propagation. To stick to cases of practical interest, we will consider frequencies less than 1000 Hz.

RULE 1. SOURCE VERTICAL BEAMWIDTH SHOULD BE SMALL, AND THE SOURCE SHOULD BE LOCATED AT MID-DEPTH.

3. Reverberation

Scattering from a boundary or from the water volume leads in turn to reverberation, an acoustic measurable at a receiver. We will focus attention on the boundary processes, since volume scattering at low frequencies is highly variable, unpredictable, and rarely limits sonar performance.

From conservation of energy, reverberation from the bottom and sub-bottom tends to follow propagation. I.e., there is a frequency band specific to each shallow water area where reverberation will be least. Ducted propagation (a low-frequency, wave propagation view) for both signal echo and reverberation follows the duct's horizontal direction (a high-frequency, ray propagation view). A vertically directive receiver has little opportunity to suppress reverberation. Rather, a horizontally directive receiver can best discriminate against reverberation via suppression of reverberation from non-target azimuths. Fortunately, horizontal arrays are easily adapted to deployment and use in shallow areas.

A horizontal array is effective in discriminating against reverberation to the extent that it restricts the area of the bottom and surface within a beam. It must reduce the bottom reverberation level in the target beam to less than the level of the target echo. Recent test results [e.g., **Ogden (1992a)**] have confirmed that at low frequencies considered here, propagation energy loss from source-to-target-to-receiver is virtually the same as that from source-to-reverberation cell-to-receiver. Then, detectability of a target echo above the reverberation background is given simply by **[Urick (1975)]**

$$\mathrm{TS} \geq \mathrm{SS} + 10 \log A + \mathrm{DT}, \qquad (4)$$

where TS is the submarine target strength, SS is the surface/bottom scattering strength, A is the area within the pulse ensonifying the boundary surfaces, and DT is the detection threshold. The scattering area A, the resolution cell of the sonar, is shown in **Figure 3a** and is given by

$$A = 2R\Delta\,\theta\ \ (c\Delta t/2). \qquad (5)$$

Pulse spreading Δt is governed by propagation. In deep ducts in the deep ocean, Δt may be measured in seconds. In shallow water and for relatively short ranges, it has been found to be of the order of 100 to 300 msec.

Following eq (3), the azimuthal resolution of a horizontal array of length L is

$$\Delta\,\theta = \lambda/L\ \ (\mathrm{rad}), \qquad (6)$$

so that

$$A = R\ c\ \Delta t\ \lambda/L. \qquad (7)$$

This equation can be used in conjunction with eq (4) to determine the ability of a system to reject reverberation given the target, the range, and the other environmental parameters, shown in **Figure 3b**.

3.1 Bottom reverberation

The bottom scattering strength SS is a function of bottom composition, roughness, slope, and frequency. Moreover, it is a very difficult measurement to make in the ocean, particularly at low frequencies and low grazing angles. Low-frequency bottom scattering strength data have been reported by **Merklinger (1968), Urick (1970), Blanc (1978), Ivakin (1985), Thiele (1992), Reilly (1992), and Steele (1992).** In shallow water, mode stripping effectively limits propagation (and thus bottom scattering) to only small angles. Thus, we can project data taken in different areas onto a common frequency axis. Results are shown in **Figure 4**. The data indicate that there tend to be five bottom types as far as bottom reverberation is concerned. Relevant bottom properties and features of the data are summarized in Table 1.

Description		Speed, m/sec	Attenuation dB/m/kHz	Density g/cm3	Bottom Scattering	Reference*
Sand	p	1750	0.26	2.06	Low, $100 \leq f \leq 400$ Hz	Hughes, Steele
	s	170	13.0			
Clay/sand	p	1600-1900	.01-.02	1.6-1.9	High; no freq. dependence	Matthews, Thiele, Kibblewhite
	s	300-600	30-60			
Sand/rock	p	1750	0.26	2.06	Low, except for very thin sediments	Hughes, Hamilton
	s	170	13.0	2.06		
Rock	p	5500	.01	2.6	Low, but roughness leads to clutter	Hughes
	s	2400	.06			
Limestone/chalk	p	2200	.02	2.16	Moderate	Matthews, Reilly
	s	1578	.07			

*Citations are for geoacoustics or bottom scattering strength or both.

Table 1. Geoacoustic properties and their effect on bottom scattering

Data in **Figure 4** indicate that, for $100 \leq f \leq 400$ Hz, SS $\leq$ -55 dB, except for clay over sand, limestone/chalk, or sand over very thin sediments, where SS is considerably higher in some cases. But, a warning against generalization for shallow water sonars may be seen in the data and simulated results for three areas taken from **Hughes (1990)**, shown in **Figure 5**. TL at ranges of 13 km for water depths of 70, 106, and 150 m is dramatically different for bottoms of sand, chalk, and thin sand over rock, respectively. Note that the measured data fail to follow the mode prescriptions indicated by the theoretical predictions.

3.2 Surface reverberation

Surface scattering has long been represented by the empirical curves of **Chapman (1962)**, as a function of wind and frequency. Unfortunately, wind and sea state (jointly responsible for surface reverberation) are partially correlated. Sea state depends on fetch and wind duration, both of which in the generation of very long wavelength waves must be very long. Consequently, we would expect that deviations from the Chapman-Harris curves are substantial in some cases. Recent measurements confirm these deviations, leading to a revision of the Chapman-Harris model, the Ogden-Erskine model (**Ogden (1992b)**). Representative data are shown in **Figure 6** for 70 and 930 Hz; also shown are the two models, (CH and OE).

Near the sea surface, when the wind speed exceeds about 7 m/sec and waves are breaking, bubble clouds form and persist down to depths of tens of meters in extreme cases (**Henyey (1992)**). As shown by **Carey (1989)**, the consequence of these bubbles is a reduction in sound speed to less than 1200 m/sec. By Snell's Law and at frequencies higher than about 500 Hz where this very low speed layer is a few wavelengths thick, refraction is strongly upward into the sea surface, so that propagation suffers *and* reverberation increases. (Note also that this condition makes precise measurements of surface-related propagation and scattering very difficult if not impossible.)

We recognize that wind-wave spectra are different in shallow water than in deep water, with speed and fetch the principle factors. Nonetheless, we adopt deep water data for the purposes of estimating system performance in shallow water. **Figure 6** shows some of these data, and we conclude that, except for high wind speeds and frequencies above a few hundred hertz, $SS \leq -55$ dB is a representative value for most conditions of interest.

3.3 Clutter, false targets, and noise.

Reverberation suppression and noise avoidance are *independent*. Reverberation has two substantially different components: A continuous component following the direct blast and decaying exponentially with time; and, discrete components arising from extraordinarily favorable opportunities for scattering from boundary and occasionally volume anomalies. The continuous and exponentially decaying reverberation from a randomly rough surface is uncorrelated and simply raises the background level to mask signal echoes. A system may still yield useful target echoes even when reverberation-limited; operationally it would be best to reduce source level particularly in areas of very good propagation where clutter from the previous ping could interfere with target detection. In shallow water this reverberation decays faster than in deep water, since propagation at longer range is poorer.

Clutter associated with echoes from objects large compared to the ensonifying wavelength may appear target-like, whether geological or man-made. Clutter tends to be worse where propagation is good, since it is easier for smaller irregularities to be distinguished. This may be particularly true at lower frequencies where propagation into and out of the bottom is good. Although there are more man-made objects in shallow water than in deep water, wrecks have few large air cavities so that low-frequency echoes from wrecks and other man-made objects should be very small compared to those from a submarine. We conclude that clutter and false targets should be similar though more numerous to those in deep water -- of little consequence in smooth areas and difficult to deal with in rough areas. It should be stressed that the total reverberation and (target-like) clutter a system must deal with increases with range. Thus, the system must have requisite horizontal directivity to reduce reverberation as in eq (4) by reducing A, the area within a system resolution cell.

Ambient noise may be overcome by filtering in frequency, time, and space. In passive sonars, frequency-filtering has focused on narrowband processing, time-averaging has been used to smooth fluctuations in (signal+noise)-to-noise, and beamforming has been used to reject noise from directions other than that containing the target. In active sonars, the filtering process still entails beamforming, but time-frequency processing involves a filter matched to the source waveform together with a smoothing normalizer. The effects of noise as seen by a matched filter processor are likely to be quite different from those of a narrowband processor, but the incidence of noise spikes (appearing as false targets) and their intensity will be reduced by horizontal directivity. Array gain (AG) is the observed gain of a receiver to reject noise and may be divided into separate components for signal and noise (**Urick (1975)**):

$$AG = ASG - ANG. \qquad (8)$$

Horizontal directivity may be achieved by a horizontal line receiver array (or by another shape having horizontal aperture). If a line array of n equispaced elements experiences isotropic uncorrelated noise, then ANG = 10 log n. With no loss in signal coherence, we have

$$AG = 20 \log n - 10 \log n = 10 \log n. \qquad (9)$$

Just as in passive sonars, azimuthal anisotropy of noise may be exploited operationally. Measurements by **Wagstaff (1983)** and others have indicated that spatial anisotropy of ambient noise is most prominent on slopes, since long-range propagation from adjacent deep-water areas admits noise from distant noise sources but is limited in shallow water. This is exemplified in **Figure 7**, showing median values of horizontal noise. But, azimuthal anisotropy in high shipping areas is large (as high as 33 dB over a change in azimuth of only 20 degrees), may extend up in frequency to a few hundred hertz, and changes rapidly as the ships move (**Marshall (1975)**). Since a line array receiver is sums the power from a steered beam and its "mirror" beam, it is essential that the true noise field be properly accounted for when orienting it. Alternatively, a planar array with a minimum variation of azimuthal beam response may be used.

Thus, horizontal directivity is highly desirable for suppressing *both* noise and reverberation.

RULE 2. HORIZONTAL DIRECTIVITY PROPORTIONAL TO MAXIMUM RANGE MAY BE USED TO REDUCE THE REVERBERATION LEVEL BELOW THE ECHO LEVEL FROM A *MINIMUM* STRENGTH TARGET FOR A GIVEN OPERATIONAL CONCEPT AND TO SUPPRESS HIGH NOISE INTERFERENCES.

4. Discussion

4.1 Bistatics, multistatics, and target strength.

Cox (1989) has presented a thorough introduction to the bistatic problem with a focus on bistatic geometry and the sonar equation. Concepts employing multiple receivers are more likely to view the target at favorable aspects than a single bistatic receiver, and Cox's analysis pertains. For multistatic system concepts using a horizontally directive receiver and where source-to-target range R_1 > target-to-receiver range R_2, the resolution cell A is smaller and the reverberation is proportionately reduced, yielding a "multistatic advantage." In addition, the stripping of the higher order modes by the shallow water channel (and the concomitant reverberation) will have already occurred prior to ensonification of the target. As in the monostatic case, in locations where reverberation is azimuthally anisotropic, line array receiver(s) will have preferred orientations. It would appear that the operational success of shallow water active sonars would depend critically on how well reverberation can be suppressed for each local environment through control of the geometry of the source(s) and receiver(s).

Suppression of the direct blast is particularly important in a bistatic geometry, either by sidelobe control or by adaptive beamforming (ABF), since the target echo occurs close behind the direct blast. The larger the bistatic angle, the closer in time is the echo.

At the frequencies of interest, the target strength is a high at favorable aspect angles, broadside in a monostatic geometry or near specular in a bistatic geometry, where $\theta_{TS} = \theta_{TR}$. It is reduced by 10-15 dB lower at aspect angles far from specular. Consequently, operational concepts either should have spatial diversity (i.e., many receivers) or must rely on "glints" at favorable aspects.

As in deep water, multistatic receivers offer both a certain immunity from countermeasures and the opportunity to mix system components to match the need. For example, area coverage may be tactically optimized by relatively long-range propagation from a high-level source to target followed by shorter range target-to-receiver propagation, exploiting the multistatic advantage. In CST-5, bistatic receivers between the source and the shallow-water target exploited the multistatic advantage to obtain good target echoes. In this case, the acoustic path included bottom-bounce from source to target and target to receiver, reducing signal coherence and increasing reverberant clutter potential.

4.2 Bottom slope.

Bottom slopes are less than 1 degree on continental shelves and up to 9 degrees on slopes leading down to benthic depths. *A slope of only 1 degree can radically alter propagation conditions* described by eq (1) and (2) over ranges of tens of kilometers. Consider a geometry where propagation occurs up a slope of angle γ but skewed at an angle χ, as shown in **Figure 8**. As the water gets shallower, bottom interaction increases; if the slope is constant, then the bottom interaction increases with range R. Both appear like attenuation factors, $\alpha(\gamma)$. For a given frequency,

$$TL' = TL + \alpha(\gamma)\, R \cos \chi, \text{ and} \qquad (10)$$

$$SS' = SS + \alpha(\gamma)\, R \cos \chi. \qquad (11)$$

Though the effect on TL is to degrade upslope propagation, the effect limiting system performance is likely that on SS', even for very small gamma. Now, if downslope TL' and SS' are reduced downslope as much as they are increased upslope, there will be a concomitant gain for downslope receivers. Note that an upslope/downslope reverberation measurement can determine alpha R. Systems implications are:

- Exploitation of gain for a receiver looking downslope;
- Preference for receiver type and orientation which can discriminate upslope from downslope arrivals (line array oriented downslope or difar with upslope null).

These advantages are exemplified by signal-to-reverberation ratio predictions of **Orchard (1992)**, shown in **Figure 9**. Here, the water depth increases from 100m to 200m up the page. The source and receiver are separated by 20 km with the source upslope from the receiver. The rows are labeled by source depths of 12.5, 30, and 50 m, and the columns are for omni sources and 4-element vertical arrays spaced at $\lambda/2$ and $3\,\lambda/4$, respectively. Results for other cases are also shown in this paper, but somewhat less signal excess. When array orientation is added to the list of environmentally-driven variables, it becomes clear that sonar performance depends critically on how well the system is matched to the environment.

4.3 Waveforms and processing.

Transmit waveforms fall into two categories: Doppler-sensitive and doppler-insensitive. The former may take the form of CW pulses, overlapped and/or frequency-dispersed, or may have noise-like character. They suffer from the disadvantage of being computationally intensive and are not robust against slow-moving targets and/or high-speed source/receiver platforms (introducing sidelobe-induced false targets in attempts at own-ship doppler nullification). The latter (usually hyperbolic FM) have more general utility as detection waveforms, with subsequent classification and tracking enhanced by doppler sensitivity.

Signal processing in shallow water is exacerbated by extreme multipath (or, multimodal) propagation resulting in inexact pulse compression via matched filtering. Each shallow water area will behave differently, so that waveforms should be selected based on measurements there. Robustness is enhanced through use of relatively short pulses, but having sufficient bandwidth Δf to resolve features less than one submarine length S,

$$\Delta f > c/2S. \qquad (12)$$

However, inasmuch as most acoustic projectors are peak-power-limited, pulse lengths are often increased to obtain greater energy source level.

Source bandwidth can enhance system performance, even for doppler-insensitive waveforms by providing:

- Reduced likelihood of signal dropouts resulting from propagation anomalies
- Better clutter discrimination arising from robust temporal echo classification clues
- Resistance to noise jammers (which would also have to have large bandwidth)
- But, target highlights from high resolution, eq (12), can lead to temporal spreading of the signal and lower levels with respect to the background.

The value of bandwidth in shallow water environments is likely to be greater than in deep water, which must be investigated.

Individual waveforms can be repeated to form a wavetrain for post-detection integration and/or M-of-N processing, depending on allowable false alarm rate and clutter. In addition, with sufficient flexibility of operation, we can tailor the wavetrain (frequency, bandwidth, pulse type(s), pulse repetition interval) and processor settings (threshold, normalizer windows, M-of-N, neural net parameters) *after* the noise and clutter properties of a given shallow water area have been measured.

Processing can have results strongly coupled to a particular environment. For example, **Gauss (1992)** noted that the number of features at lower frequencies was greater than at higher frequencies simply because of thresholding. Such an outcome typifies the strong coupling of the environment with active sonar performance at low frequencies.

We may choose to employ waveforms specifically for classification. These waveforms can be interspersed with detection waveforms, e.g., CW waveforms to measure doppler of suspected echoes arising from HFM pings, or employed separately once detection has been achieved.

Alternatively, we may elect to use a swept-frequency source (SFS) in which the vertical launch angle is encoded by frequency [see **Sullivan (1992)**]. Reverberation suppression may be enhanced with SFS, since eigenrays connecting the source with a non-boundary scatterer will have different frequency structure than eigenrays scattered from the boundary. The price for using SFS is either source complexity or a dedicated waveform (thus removing a degree of freedom of the overall system), or both.

We consider briefly the value of adaptive beamforming (ABF). In active sonars, particularly where source and receiver(s) are fixed, cells of high reverberation may have high bearing rate. They can be dynamically suppressed. That is, the ABF weights for suppression can be time-dependent for each receiver, based on reverberation measurements. Thus, ABF has the potential for substantially improving shallow-water sonar performance.

4.4 Receive array design and grooming

Most types of active source transducers have a limited bandwidth (rarely more than 1/2 octave) over which they operate free of phase distortion and without output power loss. Consequently, the receiver configuration may be optimized for a much narrower band than typically employed in passive systems. As discussed by **Urick (1975)** a good candidate is a line array with elements spaced at slightly less than that needed for the minimum wavelength of interest, $d = \lambda_{min}/2$, and shaded in order to suppress sidelobes. As noted above, use of line arrays must take into account azimuthal anisotropy of signal and noise determinants (bathymetry, sound speed, noise sources, bottom properties). If the array must operate equally in all steer directions, then a horizontal planar hydrophone configuration is desirable. Finally, if the array must have a wide receive band, then placement of the hydrophones must be chosen to provide the desired reponse, by "nesting" of equispaced segments or by tapering of the spacing.

Sidelobes of poorly formed beams can contain more power than the main lobe of interest, particularly when integrated over all azimuths and when the background noise or reverberation is highly anisotropic. The array *must* be groomed for good sidelobe rejection, for either adaptive or non-adaptive beamforming. The higher the resolution, the more important is the suppression of sidelobes. ABF can be used to minimize power in beams only to the extent that the array has independent elements. It cannot make up for a poorly groomed array, particularly if the noise or reverberation field is relatively azimuthally isotropic. For sources and receivers on fast platforms, own-ship doppler nullification generates false contacts unless sidelobe suppression is extraordinarily good. (This fact favors slow or fixed acoustic elements if doppler-sensitive waveforms are used.) Because sidelobe levels are so critical to array operation, it is desirable that dynamic sidelobe suppression be designed into the system concept. Over time, Wagstaff (cf. **Wagstaff (1983)**) has developed diagnostic techniques for grooming an array on line and has shown the value of grooming to detection success. These techniques are based on finding deviations from behaved beam noise statistics and have demonstrated their robustness. Fixed arrays have the advantage over mobile arrays that, except for component failure, array grooming need not be dynamic. Nonetheless, care must be paid to ensure that the array is *really* performing as assumed.

4.5 Energy source level.

Typically, in a shallow water waveguide where the bottom is reflective and has low loss, TL for ranges less than about 20 to 50 km is *less than TL in deep water;* TL = 80 to 90 dB at a range of 50 km is not uncommon at lower frequencies. For many coastal areas, we might expect omnidirectional noise power spectrum levels = 83 dB at low frequencies, and a well-groomed, high-gain horizontal array whose $ANG \leq 10 \log n$ should successfully isolate individual high noise sources. We must allow for system losses L for pulse spreading, coherence loss, and other losses not under the operator's control (usually omitted!). Then an energy source level adequate to overcome noise (ignoring reverberation) is

$$ESL = TL_1 + TL_2 + AN - AG - TS + DT + L. \qquad (13)$$

5. Concept Development

We now apply the two rules (source vertical directivity and receiver horizontal directivity) and the principles discussed above to see what achievable concepts make operational sense. We will choose two representative examples rather than a complete set of system concepts and operating environments: A low-gain receiver used in favorable target aspects; and, a medium-gain receiver used in non-optimum target aspects, both receivers being near to the target and thus short range. We assume a favorable bistatic geometry with $R_1 > R_2$. Two examples are summarized in Table 2.

Quantity, dB	Low-Gain Receiver	Medium-Gain Receiver
Against reverberation:		
SS	55	55
TS	22	12
DT	13	13
10 log A (from eq 4)	67	57
R_2, km	20	20
$\Delta\,\theta$, deg (from eq 6)	Difar (N/A)	10
And against noise		
TL_1	87	87
TL_2	80	80
AN	83	83
AG (from eq 9)	3	13
L	5	5
ESL (from eq 13)	230	230

Table 2. Example System Concepts

An ESL of 230 dB would require pings lasting tens of seconds during which the source-target-receiver geometry must support at least partially coherent processing. In such a case, detections to ranges of 50 to 100 km in favorable environments and geometries could be achieved. It should be noted that, for reverberation-limited environments, there is no advantage in operating with a higher source level than that just barely required to satisfy eq (13).

Here, AG was simply traded for TS. Both assume a high-power vertically directive source and that bottom reverberation is not inordinately high. As indicated above, the latter may be obtained via proper exploitation of the local environment. From the foregoing, it appears that the types, operating frequencies, and depths of today's active sonars are inappropriate for shallow water ASW.

6. Summary.

The ocean is an integral part of the sonar system and the controllable parts of the system must be adapted to the local ocean. The central issue for active sonar in shallow water is rejection of reverberant clutter, rather than poor propagation as sometimes supposed. The source should have vertical directivity and the receiver should have horizontal directivity with good sidelobe rejection. The processor must recognize and reject non-target echoes. Intentionally limiting sonar ranges has the marked advantages of clutter rejection and improved reliability.

The effectiveness of the matched filter processor in time-compression is determined by the phase and amplitude fidelity of signals, reverberation, and noise. Since some coherence is lost in boundary interactions, the waveforms should be selected based on measurements in the various shallow water areas, and optimum waveforms (and frequencies) will vary widely. Selection of suitable transmit wavetrains as well as all signal processing parameters depends on knowing how the clutter *as seen by the processor* responds to those settings. Likewise, exploitation of distinct properties of representative shallow-water environments, e.g., selective mode-stripping of reverberation and clutter in thick-sediment areas, must be considered in system design.

Recent shallow water results are encouraging, in both detection and echo clarity. Since all shallow water environments are acoustically unique, many geographical areas must be investigated: Measurement of target-like echoes and clutter density as a function of the environment itself (bottom slope, viscoelastic profile), wavetrain, and processor settings.

There is an intrinsic advantage in multistatic concepts having $R_1 >> R_2$ for two reasons: Lower reverberation in the vicinity of the target (from stripping of the higher order modes) and higher resolution at the receiver (and thus better reverberation suppression), both relative to monostatic concepts employing the same sources and receivers. This advantage may be further increased by proper placement and orientation of receivers with respect to the local bottom slope.

Fixed or slowly moving source(s) and receiver(s) will have greater operational robustness than fast moving ones because of reduced chance for spurious false targets, particularly if doppler-sensitive waveforms are used.

Acknowledgments

I thank particularly Fred Erskine, Pete Ogden, Steve Wolf, and Chuck Bohman for review of this paper and help with the figures, Harry Cox and Peter Cable for stimulating the thought that all is not lost in shallow water ASW, and the many referenced and unreferenced investigators in the Critical Sea Test program and other recent measurement programs for their thoughtful analysis of data which taken together confirm points in this paper.

References

[1] Jensen F.B.and Kuperman, W.A., Optimum frequency of propagation in shallow water environments. *Journal of the Acoustical Society of America* **73**, 1983: 813-819.

[2] Vidmar, P.J., The effect of sediment rigidity on bottom reflection loss in a typical deep sea sediment. *Journal of the Acoustical Society of America* **68**, 1980a: 634-638.

[3] Vidmar, P.J., Ray path analysis of sediment shear wave effects on bottom reflection loss. *Journal of the Acoustical Society of America* **68**, 1980b: 639-648.

[4] Hughes, S.J., Ellis, D.D., Chapman, D.M.F., and Staal, P.R., Low-frequency acoustic propagation loss in shallow water over hard-rock seabeds covered by a thin layer of elastic solid sediment. *Journal of the Acoustical Society of America* **88**, 1990: 283-297.

[5] Kuperman, W.A., and Ingenito, F., Attenuation of coherent sound in shallow water. *Journal of the Acoustical Society of America* **61**, 1977: 1178-1187.

[6] Carey, W.M., and Moseley, W.B., Space time processing, environmental-acoustic effects. Naval Underwater Systems Center technical report 8077, 1987.

[7] Smith, P.W., Low-frequency rolloff in the response of shallow water channels.*Journal of the Acoustical Society of America* **79**, 1986: 71-75.
[8] Ogden, P.M., and Erskine, F.T., Low frequency bottom and surface scattering measurements using SUS charges in the Ionian Sea during CST-5. NRL contribution, 1992a.
[9] Urick, R.J., Sound Propagation in the Sea, McGraw-Hill Book Co., New York p. 219 1975.
[10] Merklinger, W.M., Bottom reverberation measured with explosive charges fired deep in the ocean. *Journal of the Acoustical Society of America* **44**, 1968: 508-513.
[11] Urick, R.J., Reverberation-derived scattering strength of the shallow sea bed. *Journal of the Acoustical Society of America* **48**, 1970: 392-397.
[12] Blanc, S., Novarini,, J.C., and Nunez, A.L., Bottom reverberation measurements at low grazing angles in the NE Atlantic and Mediterranean Sea. *Journal of the Acoustical Society of America* **64**, 1978: 1342-1346.
[13] Ivakin, A.N. and Lysanov, Yu.P., Backscattering of sound from an inhomogeneous bottom at small grazing angles. *Soviet Physics Acoustics* **31**, 1985: 236-237.
[14] Thiele, R. and Tielburger, D., Broadband omnidirectional reverberation measurements in shallow water with explosives. FWG-1992-1. Kiel, FRG, Forschungsanstalt der Bundeswehr fur Wasserschall und Geophysik, 1992.
[15] Reilly, S.M., and Sundvik, M.T., CST-5 Direct-path, active waveform bottom reverberation analysis. TRACOR report T 92-95-1013-U, 1992.
[16] Steele, M.J., System performance results. Presented at NRL conference on low frequency acoustics, 14-15 December 1992.
[17] Matthews, J.E., Geoacoustic models for the Straits of Sicily and Sardinia. Naval Ocean Research and Development Activity Technical Note 99, 1982: 71.
[18] Kibblewhite, A.C., Attenuation of sound in marine sediments: A review with emphasis on new low frequency data. *Journal of the Acoustical Society of America* **86**, 1989: 713-738.
[19] Hamilton, E.L., Shear-wave velocity versus depth in marine sediments: a review. *Geophysics* **41**, 1976: 985-996.
[20] Chapman, R.P. and Harris, J.H., Surface backscattering strengths measured with explosive sound sources. *Journal of the Acoustical Society of America* **34**, 1962: 1592-1597.
[21] Ogden, P.M., and Erskine, F.T., An empirical prediction algorithm for low-frequency acoustic surface scattering strengths. NRL report FR/5160-92-9377. 1992b.
[22] Henyey, F.S., Ballard, J., Ewart, T.E., Farmer, D.M., and Hill, S., Effects of surface-wave forward scattering on near-surface acoustic fields. *Journal of the Acoustical Society of America* **92**, 1992: 2480A.
[23] Carey, W.M., Browning, D.G., and Fitzgerald, J.W., Low-frequency noise: Wave turbulence interaction and bubble cloud oscillations. *Journal of the Acoustical Society of America* **85**, 1989: S152 (A).
[24] Cox, H. Fundamentals of bistatic active sonars. BBN technical memorandum W1068. 1988.
[25] Orchard, B.J., Fromm, D.M., and Wolf, S.N., Unpublished.
[26] Gauss, R.C., Soukup, R.J., and Fialkowski, J.M., Low-frequency direct path surface/near-surface scattering using intermediate-length narrow-band and broadband waveforms. *Journal of the Acoustical Society of America* **92**, 1992: 2478A.
[27] Sullivan, S.F. U.S. Patent 5150336, Frequency dispersive transmitting array, 1992.
[28] Wagstaff, R.A., and Marshall, S.W., Unpublished.
[29] Marshall, S.W., Unpublished.

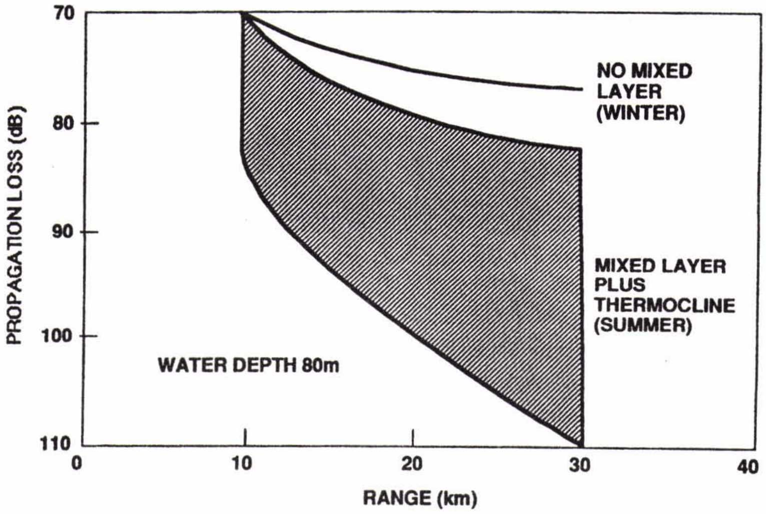
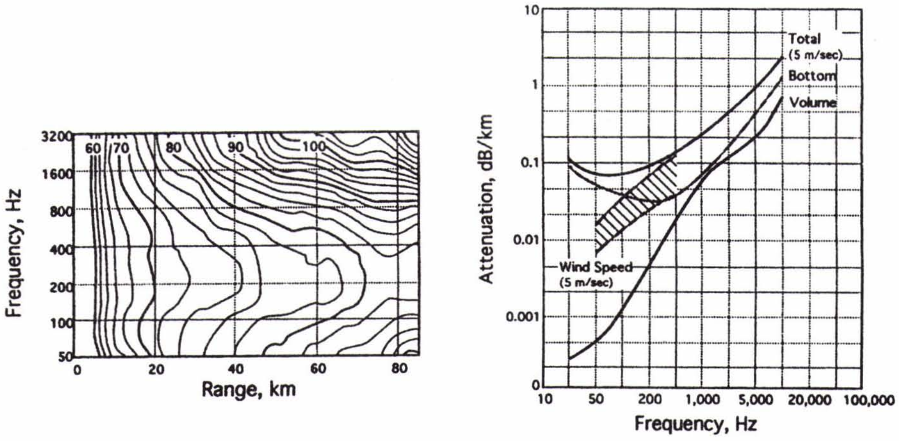


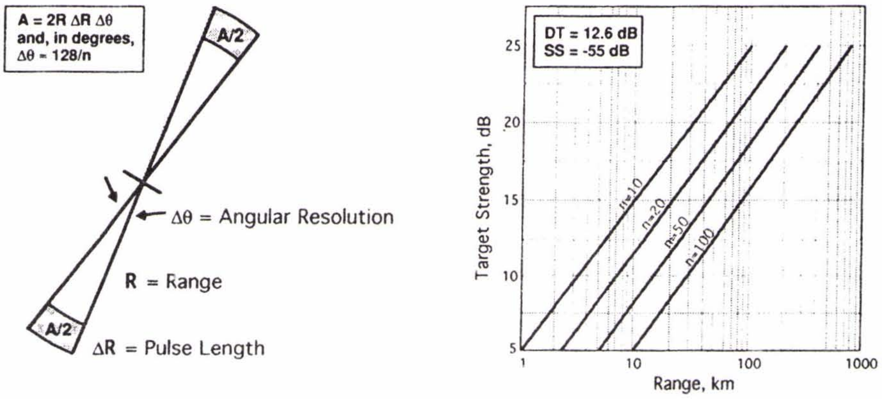
Figure 1: Effect of Sound Speed Profile in Shallow Water (typical)



(a) Propagation loss (dB) in 125 m water

(b) Total attenuation composed of volume, surface, and bottom attenuation (typical)

Figure 2: Optimum Frequency of Propagation in Shallow Water



(a) Spatial Resolution (Broadside)

(b) Performance (reverberation limited)

Figure 3: Active Sonar Performance for a Horizontal Line Array, Parameterized for n-Elements Spaced at Half-Wavelength Intervals

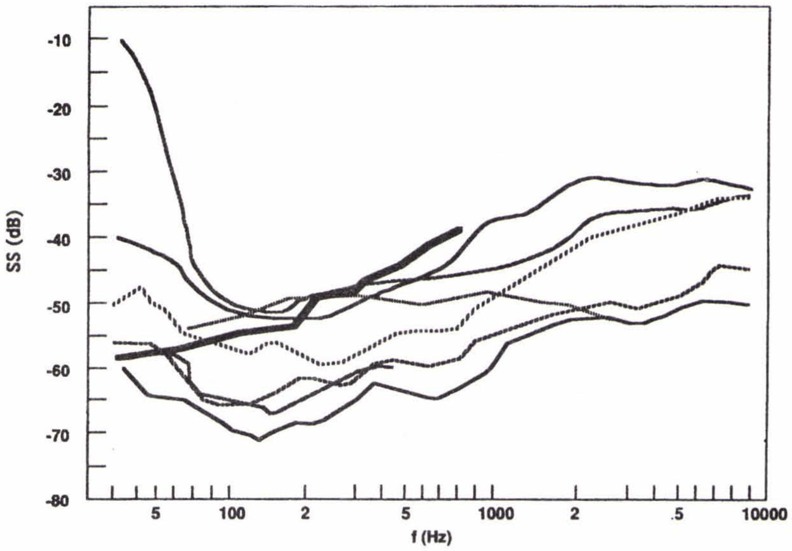
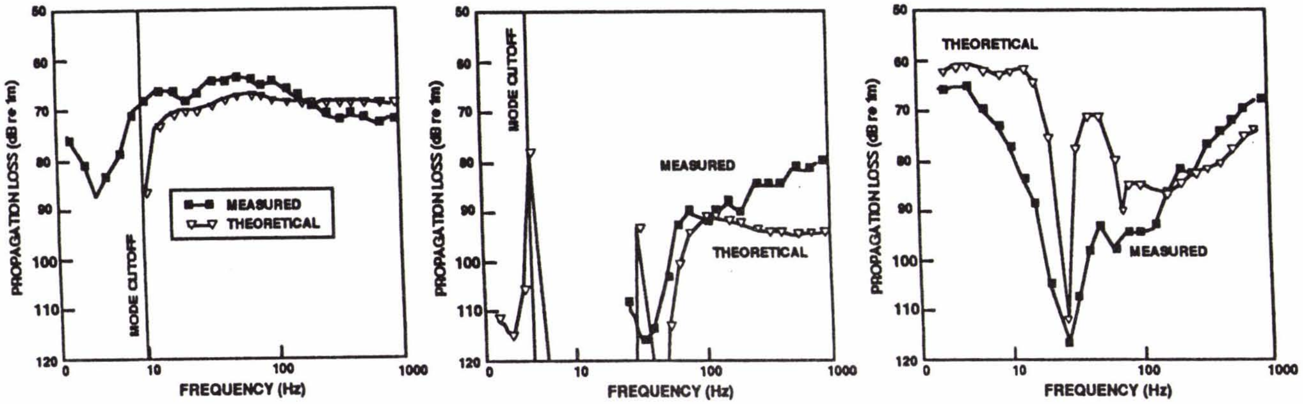


Figure 4: Range-averaged SS on sand bottom for different positions in the North Sea and Gulf of Mexico



(a.) Propagation loss over a thick bank of sand and single layer unconsolidated sediments. Source-to-receiver range is 12.7 km; water depth is 70 m.

(b.) Propagation loss over a thick layer of chalk single layer consolidated sediments. Source-to-receiver range is 13.0 km; water depth is 106 m.

(c.) Propagation loss over 1.75m sand layer on rock. Source-to-receiver range is 13.0 km; water depth is 150 m.

Figure 5 : Propagation in Three Geoacoustically Different Shallow Water Areas

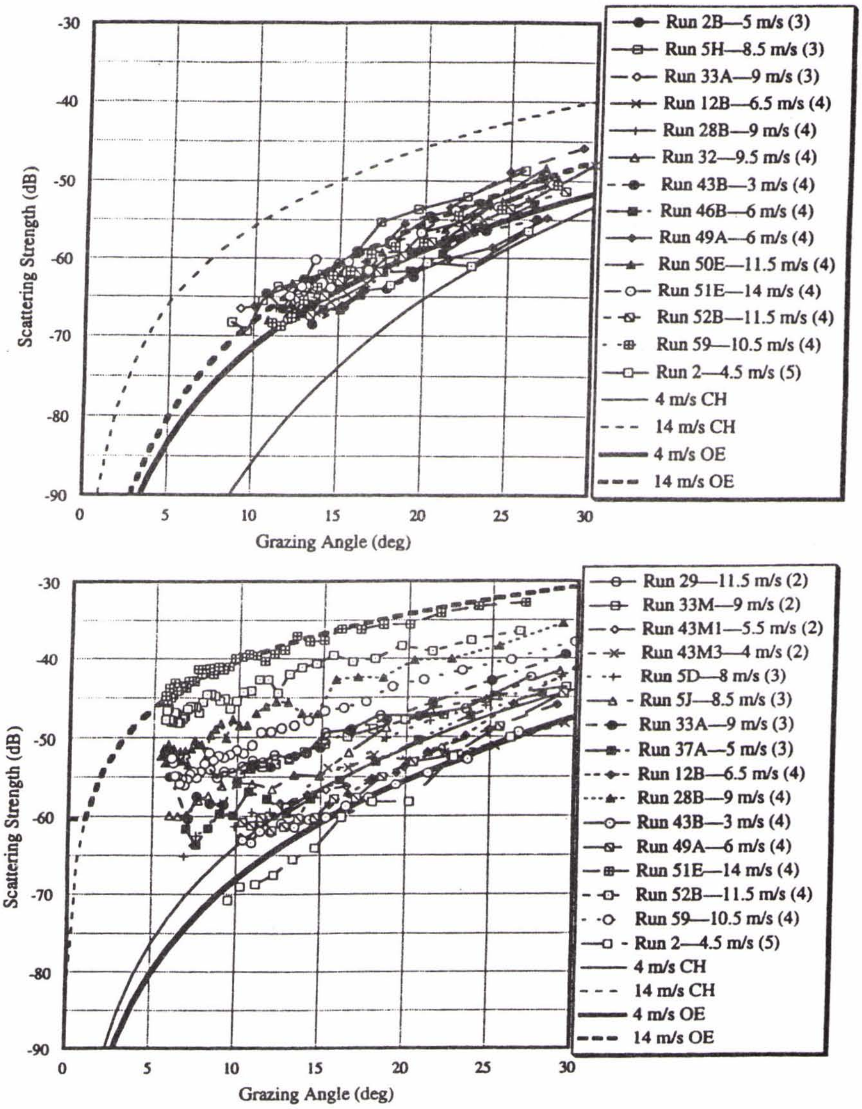


Figure 6: Surface backscattering at (a) 70 Hz and (b) 930 Hz. Shown are data from Critical Sea Tests (CST) and Chapman-Harris and Ogden-Erskine models.

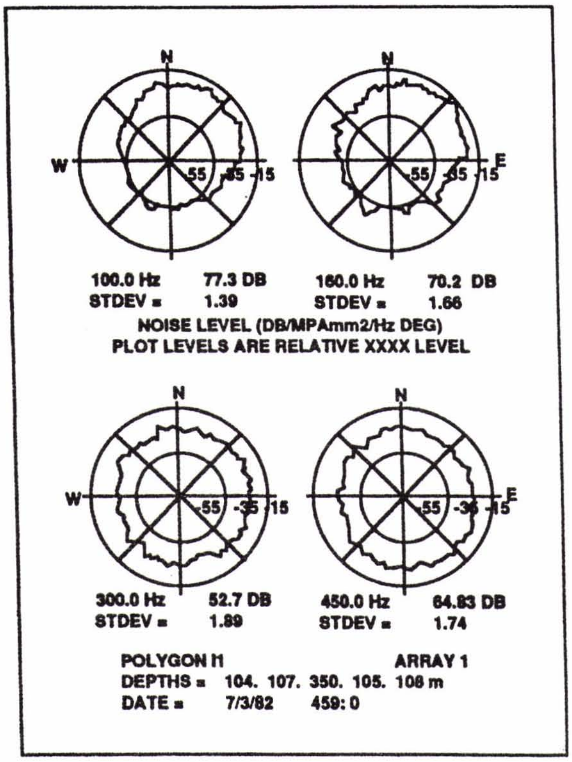


Figure 7: Horizontal noise directionality for slope water (typical)

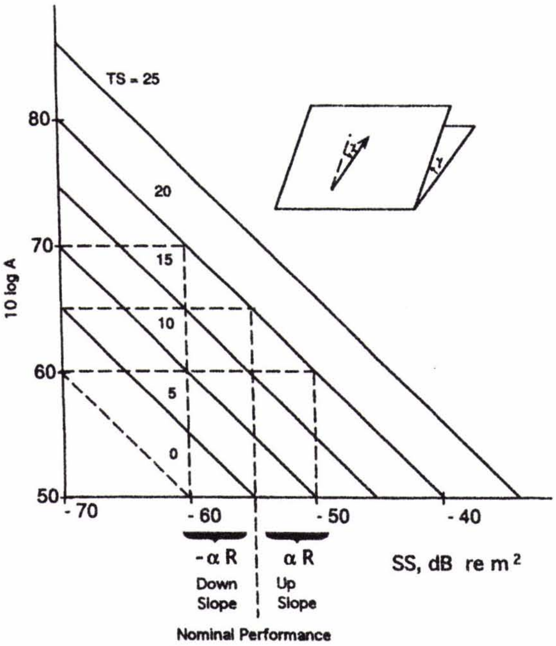


Figure 8: Effect of Bottom Slope (γ) on Reverberation

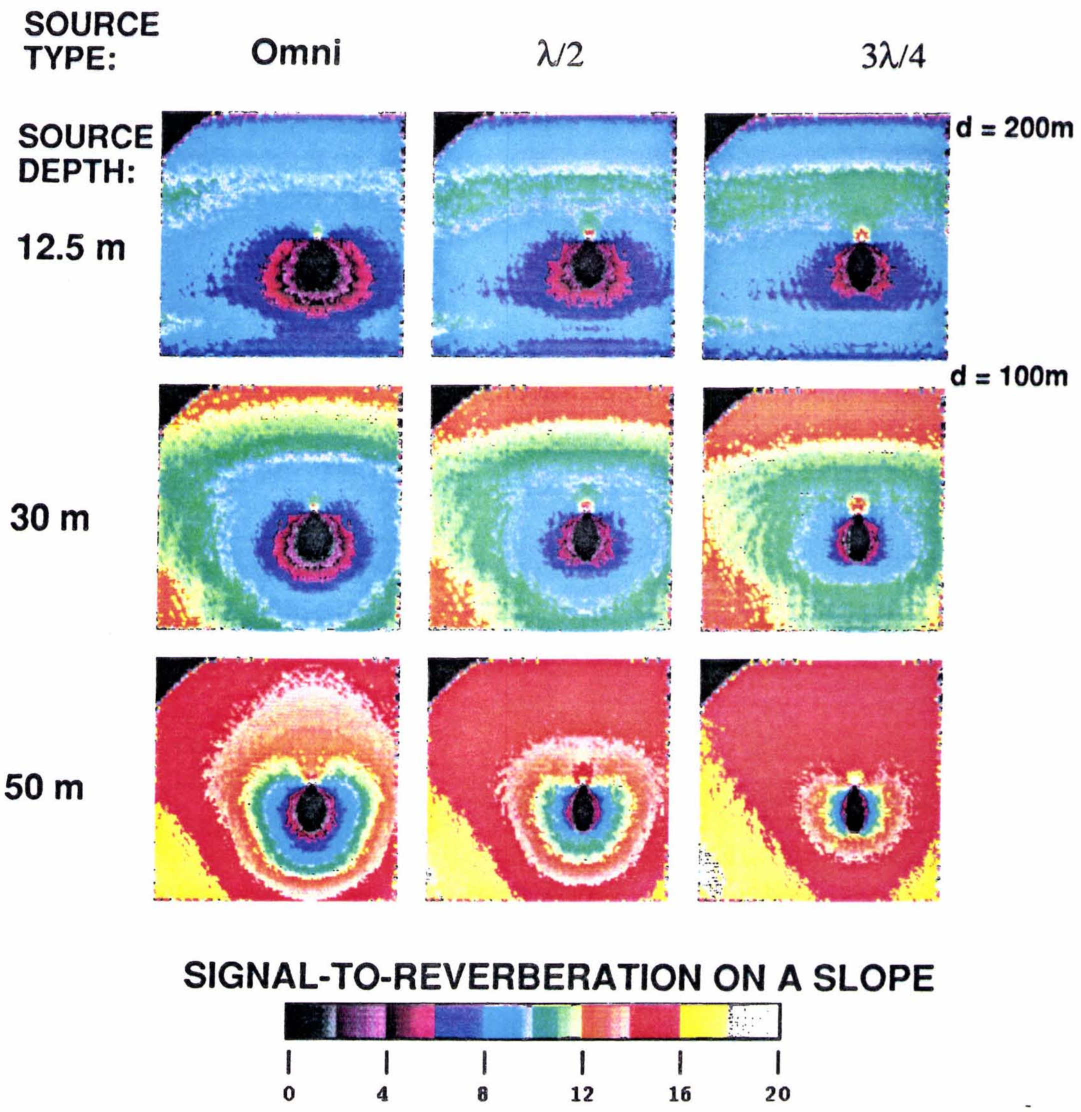


Figure 9: Signal-to-reverberation for slope-mounted source and receiver separated by 20 km. Water depth increases from 100 m to 200 m up the page.