# Colossus Revisited:

## A Review and Extension of the Marsh-Schulkin Shallow Water Transmission Loss Model (1962)

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# Colossus Revisited:
## A Review and Extension of the Marsh-Schulkin Shallow Water Transmission Loss Model (1962)

by
M. Schulkin
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## ACKNOWLEDGMENTS

# TABLE OF CONTENTS

## LIST OF FIGURES

# LIST OF TABLES

## ABSTRACT

The Marsh-Schulkin (M-S), or Colossus, model of acoustic transmission loss in shallow water is reviewed in light of new information and techniques that have emerged since its introduction in 1962. The M-S model is a semiempirical model based on extensive measurements taken off the Atlantic Coast. It uses several concepts: (1) refractive cycle, or skip distance, (2) deflection of energy into the bottom at high angles by scattering from the sea surface, and (3) a simplified Rayleigh two-fluid model of the bottom for sand or mud sediments. With a few free parameters, including water depth, about 100,000 measurements from 100 Hz to 10 kHz were fitted within stated error bounds. The model's chief criticisms have been that it could not be adjusted for arbitrary negative sound-speed gradients (it uses the same constant thermocline in all cases), and that it uses empirical bottom loss values. The M-S model yields good predictions when applied properly; it is not to be used for all environments.

The M-S model is compared with Rogers' semiempirical model based on numerical calculations of the normal-mode solutions to the wave equation for propagation in shallow water. (Rogers' model for transmission loss involves a simple range-dependent fit with three coefficients, and allows a convenient sensitivity analysis for the addition or changing of parameters.) Differences in predicted propagation losses are discussed.

The M-S model is also extended for the purpose of treating arbitrary negative and bilinear sound-speed gradients. These extensions use new general expressions for the skip distance, the near-field anomaly, and the reflection coefficients. The reflection coefficients are calculated from the Morse-Mackenzie relations for loss per bounce using the values for bottom-sediment properties reported by E.L. Hamilton. The extended model and Rogers' model are found to give about the same predictions when the same inputs are used.

## I. INTRODUCTION

This document is the first of two reports due under an expanded ONR contract concerning work in shallow-water acoustics. A great deal of research has gone into shallow-water acoustics over the years, especially as it relates to the solution of Navy problems. When the scientific and technical basis of previous work has been hidden for many years in classified reports issued by individual Navy Centers and in the minds of departed personnel whose knowledge has become unavailable, an information and communications gap often develops. This situation gives rise to needless duplication of effort and the loss of much important information gathered in previous expensive and time-consuming measurement programs.

Such is the case for the Colossus II Shallow-Water Acoustics Propagation Studies, the results of which were detailed 25 years ago in a classified document. Project Colossus II was established in 1954 to investigate acoustics in shallow water (100 fathoms or less). A portion of that program was devoted to a study of underwater acoustic transmission loss in the frequency range of 100 to 3000 Hz. A shorter, unclassified report[1] and a letter to the editor of the Journal of the Acoustical Society of America[2] were also prepared.

The letter published in the open literature[2] contained the useful transmission-loss model summarizing almost ten years of theory, analysis, and at-sea measurements. The compact expressions, including an error table, were based on about 100,000 observations of propagation loss — also including the results of a far more extensive semiempirical data base, Project AMOS,[3] which contained, among other results, surface-loss data from 192 acoustic stations occupied mostly in the deep water of the North Atlantic and the Mediterranean during the years 1949 to 1953. The frequency range covered by AMOS was 2-25 kHz.

With time our use of the word "semiempirical" to describe the resultant expressions gave rise to misconceptions and was reduced by others to the word "empirical."[4]

In retrospect, not allowing for arbitrary negative gradients in the water may have been a major drawback of the model. At that time, however, so little was known about bottom properties, and shipboard computer capability was so primitive, that a more detailed predictive model was premature. The emphasis of the model was on predicting bottom loss along with the coupling of surface scattered energy to the bottom.

The original document describing the M-S model[1] contained the following caveat section, called "Other Modes of Propagation," which listed some of the model's limitations:

## "OTHER MODES OF PROPAGATION

The foregoing description applies to the propagation situation which occurs most of the time off the East Coast of the United States. Internal channels were observed so seldom that they were not considered an important situation in our analysis. Presumably, the surface and bottom do not affect this propagation mode which is explicable in terms of spreading and temperature absorption losses. This mode is known to be important in certain localities such as the Scotian Shelf. Very little effect was found with respect to source and receiver depths. [Internal channels have a large depth dependence.]

No attempt was made to carry the analysis below 100 cps. This frequency has a wavelength about a quarter of the water depth of 200 feet, typical of these measurements. Undoubtedly a ray picture does not apply here and normal mode theory is required to explain the observations. Another phenomenon associated with low frequencies which was not treated here was propagation from one point to another by way of the sub-bottom or the seismic mode. The existence of this path has definitely been established, and can be of importance at longer ranges and lower frequencies.

This analysis is not applicable to bottoms with sustained slopes in which a ray picture accounting for progressively changing limiting angles must be employed. The shallow-water analysis applies up to depths of 100 fathoms, which occur at about 100 miles from shore.

In the transition region between shallow water and deep water, it is known that propagation may be described quite well in terms of a detailed ray analysis."

When tested under appropriate situations the model has performed well. It was not meant to be used in isovelocity situations where the Pekeris normal-mode model[5,6] or the Weston ray model[7] apply. Even under strong negative gradients, however, the M-S model was attributed to give the right answer for the wrong reason,[8] i.e, because the average negative gradient which was used for all cases still gave predictions within stated error bounds (see Table V in Section III.D). In this report, the M-S model has been extended to include arbitrary negative and bilinear gradients.

In Section II, we review the M-S model and describe its three main parameters — skip distance, the near-field anomaly correction, and the effective attenuation coefficient. Section III describes the Onboard Prediction Model for Propagation Loss developed by P.H. Rogers of the Naval Research Laboratory (NRL) and compares its results with those of the M-S model. Sections IV and V, respectively, describe how the M-S model can be extended to include arbitrary negative and bilinear gradients and compare the results of the extended model with those of Rogers' model under negative gradient circumstances.

## II. MARSH-SCHULKIN SHALLOW-WATER PROPAGATION-LOSS MODEL

Marsh and Schulkin[1-3] were among the first to show the importance of refractive cycles, or skip distances, for acoustic transmission in both deep and shallow water. In shallow water, propagation at extended range and moderate frequencies is supported by repeated bottom and surface reflections, almost regardless of the thermal conditions. Contact of rays with the rough sea surface causes the scattering of energy at high grazing angles and consequent loss into the bottom. Thus, there is a strong surface-bottom coupling such that the propagation losses are controlled by the number of contacts of rays with both surfaces. The thermal structure of the water affects propagation through its influence on the skip distance and the number of surface and bottom contacts. Determining the skip distance and hence the number of bottom bounces over an acoustic path is important for finding the losses suffered at the bottom. The vehicle used by Marsh-Schulkin for establishing skip distances for both surface and bottom contacts was a bilinear sound-speed profile with a variable depth for the positive-gradient layer.

Along with the concepts of skip distance and bottom loss, the Colossus model, also known as the Marsh-Schulkin (M-S) model, used (1) the AMOS results for a deep-water isothermal surface duct but with the average thermocline appropriate for shallow water, and (2) measurements of the actual propagation loss in shallow water off the East Coast as a function of frequency, separated by bottom type (sand or mud) and by season. Two other mechanisms characteristic of shallow water processes were also included in the M-S model: (1) a "near-field anomaly" correction in the direct radiation zone that included the gain due to multiple bottom and surface bounces, and (2) an energy conservation rule was used to establish the effective shallow-water attenuation coefficient, $a_t$, which includes the additional loss due to the coupling of energy from the the wind-roughened sea surface to the bottom.

The bilinear gradient used in the M-S model is composed of two constant, linear segments drawn toward the surface and toward the bottom from the depth of maximum sound speed (or temperature). The sound ray cycles have one upward radius of curvature (positive sound-speed gradient) for surface bounces and one downward radius of curvature (negative gradient) for bottom bounces. Based on the depth of the surface layer and the water depth, a single effective skip distance is formulated. Multiples of this effective skip distance are used to define a zone of direct ray paths ($20 \log R$, where R = range), a zone of mode stripping ($15 \log R$), and a zone of single-mode control ($10 \log R$). The mode-stripping process was found to be complete at a range equal to $8H$, where $H$ is one effective skip distance.

## A. Propagation Loss Equations

In the M-S model, the propagation loss is thus represented in terms of sea state (wave height), bottom type (or bottom loss, if known), water depth, frequency, and the depth of the positive-gradient layer. The skip distance is used as a reference to define regions where wave-front spreading follows square, three-halves, and first-power laws as a function of range. If the range $R$ between source and receiver is less than or equal to the skip distance $H$, the propagation loss $N$ is

$$N = 20 \log R + aR + 60 - k_L \quad \text{dB}, \tag{1}$$

where $R$ is the range in kiloyards, $a$ is the absorption coefficient in seawater in decibels/kiloyard, and $k_L$ is the near-field anomaly. For intermediate ranges, $H \le R \le 8H$,

$$N = 15 \log R + aR + a_t \left[ \frac{R}{H} - 1 \right] + 5 \log H + 60 - k_L \quad \text{dB}. \tag{2}$$

For long ranges, $R \ge 8H$,

$$N = 10 \log R + aR + a_t \left[ \frac{R}{H} - 1 \right] + 10 \log H + 64.5 - k_L \quad \text{dB}. \tag{3}$$

These equations provide for the gradual transition from spherical spreading in the near field to cylindrical spreading in the far field.

We now discuss the parameters that are used in the model.

## B. Skip Distance

It was stated earlier that the M-S model used the concept of skip distance for acoustic propagation in shallow water. The skip distance is defined in such a way that it represents the *maximum* range at which rays first make contact with either the sea surface or the bottom and thus specifies the near-field region.

In defining skip distance, M-S used a single, negative sound-speed gradient for the layer below the thermocline and a single, positive gradient for the layer above. Both values were based on the average values observed during the Colossus measurements: +0.018 $s^{-1}$ for the upper, isothermal layer and -0.035 $s^{-1}$ for the lower layer. If we divide the range by the skip distance, we get the effective number of bottom contacts that contribute to the propagation loss.

The original M-S skip distance $H$, in kiloyards, is given by

$$H = \left[\frac{L+D}{8}\right]^{1/2} ,$$ (4a)

where $D$ is the depth of the water, in feet, and $L$ is the depth of the mixed, isothermal layer, in feet.

The M-S skip distance, in kilometers, is

$$H = \left[\frac{L+D}{3}\right]^{1/2} ,$$ (4b)

where $L$ and $D$ are in meters.

## C. Near-Field Anomaly

Results of the Colossus measurements showed that at short ranges (i.e., in the near field) propagation was consistently superior to that predicted for inverse square-law spreading. The departure from square-law spreading in the near field can be accounted for by gains due to boundary reflections. The M-S model uses empirical boundary loss values determined from measurements.

Figure 1 is a ray diagram for the direct radiation zone. This diagram can be expected to apply in the region that is essentially free from refraction. It can be seen that there is one direct ray (labeled 1 in the figure) with no boundary contacts, one ray having one more surface contact than bottom contact (labeled 2), one ray having one more bottom contact than surface contact (2'), and thereafter two rays for each order having an
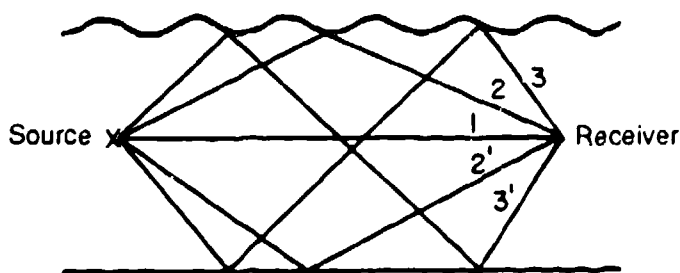


*Figure 1.  First-order ray diagram for direct radiation zone and the determination of near-field anomaly $k_L$.*

equal number of bottom and surface contacts (e.g., 3 and 3'). The set of rays is complete. Accordingly, upper and lower limits on the sound field $\Sigma$ can be calculated assuming incoherent addition of rays:

$$\Sigma = I + 2I(r_s\, r_b + r_s^2\, r_b^2 + \dots\dots + r_s^n\, r_b^n) \tag{5}$$

$$+ I(r_s + r_s^2\, r_b + \dots\dots + r_s^n\, r_b^{n-1})$$

$$+ I(r_b + r_s\, r_b^2 + \dots\dots + r_s^{n-1}\, r_b^n)$$

$$\Sigma = I + I(2r_s\, r_b + r_s + r_b)(1 + r_s\, r_b + r_s^2\, r_b^2 + \dots\dots + r_s^{n-1}\, r_b^{n-1})$$

$$\Sigma = I\left[1 + \frac{(2r_s\, r_b + r_s + r_b)(1 - r_s^n\, r_b^n)}{(1 - r_s\, r_b)}\right] \quad r_s, r_b \leq 1 \,,$$

where

$I$ = intensity of direct ray

$r_s$ = surface reflection coefficient

$r_b$ = bottom reflection coefficient.


The term in brackets, $K_{L,U}$, is called the near-field anomaly.

$$K_{L,U} = 1 + \frac{(2r_s r_b + r_s + r_b)\,(1 - r_s^n r_b^n)}{(1 - r_s r_b)} \quad r_s, r_b \leq 1 \,, \tag{6}$$

where $n$ is the number of bottom and surface contacts that contribute to the field in the near zone, defined as the first skip distance. $n$ is limited by the critical angle. The multiplier has an upper limit,

$$K_U = \left[1 + \frac{(2r_s r_b + r_s + r_b)}{(1 - r_s r_b)}\right], \tag{7}$$

and a lower limit,

$$K_L = \left[1 + (2r_s r_b + r_s + r_b)\right]. \tag{8}$$

The gain, in decibels, due to the near-field anomaly is

$$k_{L,U} = 10 \log K_{L,U} \,. \tag{9}$$

Reflection coefficients $r_s$ and $r_b$ were believed to decrease rather rapidly with increasing grazing angle of incidence. If this were true, $k_L$ might be a better representation than $k_U$ in the direct radiation zone, or near field. The near field is defined as ranges less than or equal to the direct path range, which is taken as equal to the skip distance.

Only $k_L$ was used in the published results, but there is reason to believe that $k_U$ fits the data better under certain conditions (see Table IA).

For reference, we list in Table IB values for $k_L$ and $k_U$ over sand and mud bottoms for sea state 2 conditions and four frequencies.

*Table IA. Median measured minus calculated losses ($k_L, k_U$ compared).[a]*

| Frequency, Hz | Range, kyd | | | | | Near-Field Anomaly |
| | 3 | 9 | 30 | 60 | 90 | |
| --- | --- | --- | --- | --- | --- | --- |
| 112 | -3 | -4 | -5 | -3 | -3 | $k_L$ |
| 446 | -3 | -5 | -4 | -4 | -4 | |
| 1120 | -2 | -1 | -2 | -1 | -7 | |
| 2820 | -1 | 2 | 2 | -6 | -9 | |
| 112 | 0 | 0 | 2 | 0 | 1 | $k_U$ |
| 446 | -1 | 0 | 0 | -3 | -6 | |
| 1120 | -2 | 0 | 5 | 5 | -5 | |

[a] The data set for $k_L$ and $k_U$ were somewhat different by geography and by bottom type. Thus, compatibility of Tables IA and IB is only general.

*Table IB. Near-field anomaly, decibels (sea state 2);*
$$k_L = 10 \log K_L; \quad k_U = 10 \log K_U$$

| Frequency (Hz) | Sand | | Mud | |
| | $k_L$ | $k_U$ | $k_L$ | $k_U$ |
| --- | --- | --- | --- | --- |
| 112 | 6.3 | 11.8 | 6.3 | 11.3 |
| 446 | 6.1 | 10.3 | 5.8 | 9.1 |
| 1120 | 5.0 | 6.7 | 4.5 | 5.8 |
| 2820 | 3.7 | 4.3 | 3.3 | 3.8 |

### D. Effective Attenuation Rate — Surface Scattering and Bottom Coupling

The next consideration to be discussed is $a_t$, the effective shallow-water attenuation coefficient in decibels/skip distance. An energy conservation rule was used to establish this coefficient, which includes the additional loss due to the coupling of energy from the wind-roughened sea surface to the bottom.

M-S postulated that if $r_s$ is the surface reflection coefficient then $(1-r_s)$ is the surface-scattering coefficient, and $a_s = -10 \log r_s$ is the surface loss in decibels/bounce.

Sea surface scattering has three effects on attenuation rate in the channel:

(1) It smooths the depth dependence in the channel.

(2) It modifies the near-field anomaly.

(3) It increases the rate of mode stripping so that the range to single-mode transmission (cylindrical spreading) is shortened considerably to $8H$, where $H$ is skip distance.

Figure 2 is a plot of sea surface loss versus frequency × wave-height product found from analysis of the AMOS data for the various sea states and corresponding wind conditions. The equations in Fig. 2 are based on Ref. 9. Figure 3 shows the same plot in metric units[10] with an analytic expression for wave height.[11]

The surface components $r_s$ and $(1-r_s)$ must undergo different interactions with the bottom if the sea surface is not flat. The simplest expression satisfying this requirement and the Colossus data is

$$r_t = r_s \, r_b + (1-r_s) \, r_b^2 \, ,$$

where $r_t$ is the fraction of energy transmitted down the channel when a bottom event is coupled with each surface reflection, and $r_b$ is the bottom reflection coefficient. The shallow-water attenuation coefficient, in decibels/bounce, would then be

$$a_t = -10 \log r_t \, .$$

The fact that $r_s$ must be multiplied by $r_b$ indicates that near-grazing rays suffer a bottom loss. The fact that the scattered rays must be multiplied by $r_b^2$ means that the angular dependence of the bottom reflection loss is such that, on the average, these steeper rays suffer twice the loss of the near-grazing rays.

The shallow-water attenuation coefficient values for sand and mud bottoms are given as a function of sea state and frequency in Table II.
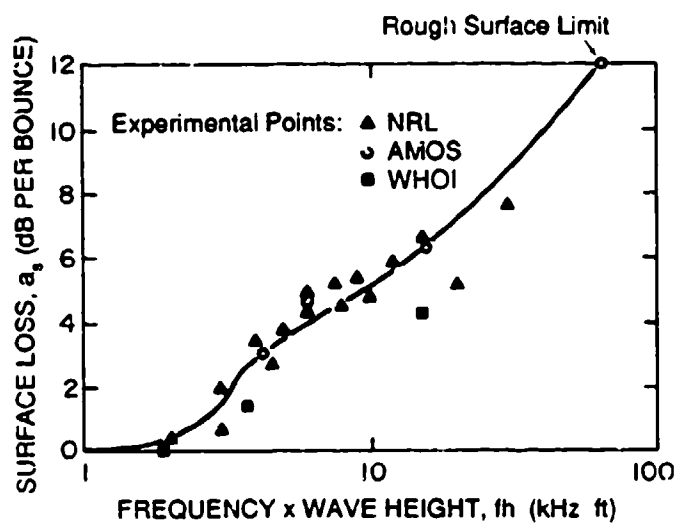
| Sea State | Wave Height (ft) | Wind speed (kn) |
|---|---|---|
| 0 | 0-1 | 1-3 |
| 1 | 1-2 | 4-6 |
| 2 | 2-3 | 7-10 |
| 3 | 3-5 | 11-16 |
| 4 | 5-8 | 17-21 |
| 5 | 8-12 | 22-27 |
| 6 | 12-20 | 28-47 |
| 7 | 20-40 | 48-55 |
| 8 | 40+ | 56+ |

$$a_s = 1.64 \sqrt{fh} \qquad\qquad fh \geq 3.35 \ (\text{kHz ft})$$

$$a_s = 10 \log_{10}\left[1 + \left(\frac{fh}{3.35}\right)^4\right] \qquad fh \leq 3.35 \ (\text{kHz ft}) \qquad \text{Eq. (10)}$$

*Figure 2.   Sea surface loss curve and sea state parameters.*

APL-UW 8508     9
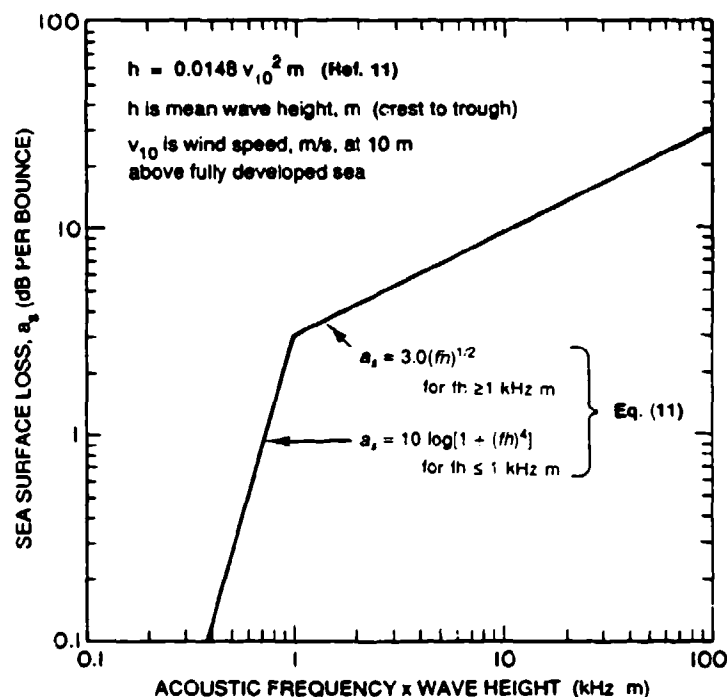
*Figure 3.  The dependence of acoustic loss at the sea surface (Ref. 10) on wind speed.*


*Table II.  Shallow-water attenuation $a_t$ (decibels/bounce).*

| Sea State | 0 | | 1 | | 2 | | 3 | | 4 | | 5 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $f$ (kHz) | Sand | Mud | Sand | Mud | Sand | Mud | Sand | Mud | Sand | Mud | Sand | Mud |
| 0.1 | 1.0 | 1.3 | 1.0 | 1.3 | 1.0 | 1.3 | 1.0 | 1.3 | 1.0 | 1.3 | 1.0 | 1.3 |
| 0.2 | 1.3 | 1.7 | 1.3 | 1.7 | 1.3 | 1.7 | 1.3 | 1.7 | 1.3 | 1.7 | 1.4 | 1.7 |
| 0.4 | 1.6 | 2.2 | 1.6 | 2.2 | 1.6 | 2.2 | 1.6 | 2.2 | 1.7 | 2.4 | 2.2 | 3.0 |
| 0.8 | 1.8 | 2.5 | 1.8 | 2.5 | 1.9 | 2.6 | 2.2 | 3.0 | 2.4 | 3.8 | 2.9 | 4.0 |
| 1.0 | 1.8 | 2.7 | 1.9 | 2.7 | 2.1 | 2.9 | 2.6 | 3.7 | 2.9 | 4.1 | 3.1 | 4.3 |
| 2.0 | 2.0 | 3.0 | 2.4 | 3.5 | 3.1 | 4.4 | 3.3 | 4.7 | 3.5 | 5.0 | 3.7 | 5.2 |
| 4.0 | 2.3 | 3.6 | 3.5 | 5.2 | 3.7 | 5.5 | 3.9 | 5.8 | 4.1 | 6.2 | 4.3 | 6.4 |
| 8.0 | 3.6 | 5.3 | 4.3 | 6.3 | 4.5 | 6.7 | 4.7 | 6.9 | 5.0 | 7.3 | 5.1 | 7.5 |
| 10.0 | 4.0 | 5.9 | 4.5 | 6.8 | 4.8 | 7.2 | 5.0 | 7.5 | 5.2 | 7.8 | 5.3 | 8.0 |

## III. ROGERS' ONBOARD PREDICTION MODEL FOR PROPAGATION LOSS

### A. General

Dr. P.H. Rogers of the Naval Research Laboratory prepared a report[4] that reviewed the information base for shallow-water acoustic-propagation loss, especially in the frequency range 100 to 800 Hz. One of his chief contentions was that so many parameters ("no fewer than 24") were required to determine the shallow-water propagation loss that it was easy to explain measured results but hard to predict them. We quote his complete abstract.

> This report examines the state of the art in the prediction of propagation loss in shallow water as it pertains to onboard performance prediction. The following conclusions are drawn: 1. For simple cases, i.e., homogeneous liquid bottom, linear soundspeed gradient, no surface or bottom roughness, a simple algebraic model, for depth averaged propagation loss works as well as the more complex mode model. (The model is presented in the report.); 2. The uncertainty in bottom parameters, particularly sound velocity and attenuation makes it impossible to set meaningful bounds on propagation loss particularly for negative gradients or slow bottoms. (Useful predictions, however, can probably be made when a positive gradient is present.); 3. Details of the sound-speed profile can cause significant changes in propagation loss, therefore even if bottoms were well characterized, sophisticated computer models would be required to predict propagation loss; 4. Virtually all propagation loss curves can be described to within a fraction of a dB [in the range 5 to 100 km] by the function $PL = B + 15 \log R + AR + CR^2$ with the $C$ coefficient usually zero. Thus, the output field can be described by two or, at most, three free parameters. Since there are no fewer than 24 input parameters it is thus easy to explain observed propagation loss and very difficult to predict it. Moreover, it is doubtful that propagation loss experiments can uniquely define bottom parameters; 5. Certain aspects of the theory remain unverified and/or inadequately treated. These include: (1) surface and bottom roughness, (2) shear in the sediment, (3) substrate roughness, (4) modal coupling, and (5) biological scatterers; 6. Grain size distribution is not an adequate predictor of acoustical properties; hence currently existing sediment charts are of little or no value in performance prediction; and 7. Many input parameters are very poorly known. These include: a. bottom roughness, b. wave height spectrum, c. sediment shear-wave speed, d. sediment shear attenuation, e. shear and sound-speed and attenuation gradients in the sediment, and f. distribution and effective attenuation of biologics. In most cases, the theory is not certain enough to determine the uncertainty in propagation loss caused by uncertainty in these parameters.

We will discuss his conclusions as applicable to the M-S model, but not in his order.

First we would like to add two more inputs to his list (Table III) of "no fewer than 24 inputs" to his Universal (Range Independent) Shallow Water Propagation Loss Model. The overabundance of possibly required inputs is certainly evident from Table III. Our question is, Can we selectively reduce this number to a manageable few which are important for specific categories of problems?

*Table III. Inputs to Universal (Range Independent) Shallow Water Propagation Loss Model*

| | |
|---|---|
| 1. Water depth | |
| 2. Sound speed profile | |
|    A. Temperature | |
|    B. Salinity | Water column |
| 3. Acoustic attenuation in water | |
| 4. Internal waves and tides | |
| 5. Sloping bottom | |
| 6. Density of sediment | |
| 7. Sound speed in sediment | |
| 8. Shear speed in sediment | |
| 9. Acoustic attenuation in sediment | |
| 10. Shear attenuation in sediment | |
| 11. Sound speed gradient in sediment | X number of layers |
| 12. Shear speed gradient in sediment | |
| 13. Attenuation gradient in sediment | |
| 14. Density gradient in sediment | |
| 15. Thickness of sediment layer | |
| 16. Sound speed in basement | |
| 17. Shear speed in basement | |
| 18. Density of basement | Basement |
| 19. Acoustic attenuation in basement | |
| 20. Shear attenuation in basement | |
| 21. Surface roughness | |
| 22. Bottom roughness | |
| 23. Subbottom roughness | Scattering |
| 24. Entrained gas bubbles | |
| 25. Fish and other biological scatterers | |
| 26. Wind vector | |

His report recognizes that "Useful predictions, however, can probably be made when a positive gradient is present." This is precisely the situation depicted by the M-S model.

We note that his model is a semiempirical one based on computed normal-mode solutions. In the report, he covers only profiles in which the sound speed decreases monotonically with depth and the average gradient is $0.2\ \text{s}^{-1}$. In addition, he covers only situations without sea-surface scattering.

Rogers states that virtually all computed (depth averaged) propagation loss curves can be fit to within a fraction of a decibel to the following simple function (for most cases $C = 0$):

$$PL = 15 \log R + AR + B + CR^2 \quad (C \approx 0), \tag{12}$$

where $PL$ is the propagation loss in decibels and $R$ is the range in kilometers (5 to 100 km).

Since only two free empirical algebraic parameters, A and B, are needed to fit his equation between 5 and 100 km, we will relate these free parameters to his theoretical expression and the M-S theoretical base.

Rogers' theoretical model for propagation loss in water with a strictly negative sound-speed profile leads to his Eq. (4) [Eq. (13) here]. (Weston[7] has developed an analogous model for the isovelocity case.)

$$PL = 15 \log R + 5 \log(H\beta) + \frac{\beta R \theta_L^2}{4H} - 7.18 + \alpha_w R \quad \text{dB}, \tag{13}$$

where $15 \log R$ ($R$ is in meters) is the spreading-loss term for the mode-stripping region, $H$ is the water depth in meters, $\beta$ is bottom loss in decibels/radian and comes from the theoretical expression for the Rayleigh reflection coefficient for a two-fluid lossy interface at small grazing angles, and $\alpha_w$ is the absorption coefficient of seawater in decibels/kilometer and is common to all models. $\theta_L$ is the larger of $\theta_g$ or $\theta_c$, where $\theta_g$ is the maximum grazing angle for a skip distance. The definitions of $\theta_g$ and $\theta_c$ follow:

$$\theta_g = \sqrt{(2Hg_N)/C_w}, \tag{14}$$

where $C_w$ is the value of the sound speed (maximum) at the surface of the water and $g_N$ is the magnitude of the negative sound-speed gradient, in meters/second/meter, or seconds$^{-1}$; $\theta_g$ is in radians. $\theta_c$ is the effective plane-wave angle for the lowest propagating mode.

$$\theta_c = \frac{C_w}{2fH}, \tag{15}$$

where $f$ is the frequency in hertz, and $\theta_c$ is in radians.

For most cases of interest, Eller's expression was used by Rogers[4] to obtain the reflection coefficient

$$\beta \approx \frac{0.477 M_0 N_0 k_p}{(1 - N_0^2)^{3/2}} \quad \text{dB/rad}, \tag{16}$$

where

$$N_0 = C_w/C_s \quad \text{and} \quad M_0 = \rho_s/\rho_w$$

$C_w$ = maximum (sea surface) sound speed in the water

$C_s$ = sound speed in the sediment

$\rho_w$ = density of the water

$\rho_s$ = density of the sediment

$k_p$ = sediment attenuation coefficient, decibels/meter/kilohertz.

## B. Frequency Dependence

Rogers claims that for negative sound-speed gradients the effective attenuation coefficient $A$ is independent of frequency over a wide range of frequencies. The assumption in this statement is that $k_p$ is constant over this frequency range, corresponding to the Hamilton loss factor. This assumption has been accepted widely, but not unconditionally or universally. This is an important issue, because the M-S model, which is based on measurement data, shows a distinct frequency dependence due to both sea surface scattering loss and bottom loss. In fact, $k_p$ seems to vary with frequency as a higher power than 1 and may even be as much as 2. Ingenito[12] found $k_p$ to vary as $f^{1.75}$ in the Gulf of Mexico off Panama City. In other work,[13] the measured frequency dependence of the attenuation term has been used as a clue to the nature of the attenuation process controlling the propagation at a particular location and time.

## C. Comparison of Rogers' and M-S Equations

Consider Rogers' empirical Eq. (17) for propagation loss in the mode-stripping region with the very small term $CR^2$ dropped:

$$PL = 15 \log R + AR + B \quad \text{dB}. \tag{17}$$

Rogers estimates $A$ and $B$ by solving the wave equation by normal modes for a specific set of conditions. He then fits the computed points by the least-squares method.

If we write Rogers' solution [Eq. (13)] for propagation loss under strictly negative-gradient conditions and also the M-S Eq. (2) for the mode-stripping region, we find that both equations can be related to $A$ and $B$ of Eq. (17).

Rogers [Eq. (13)]:

$$PL = 15 \log R + 5 \log(H\beta) + \frac{\beta\theta_L^2}{4H} R - 7.18 + \alpha_w R \quad dB$$

M-S [Eq. (2)]:

$$N = 15 \log R + 5 \log H + a_t \left[\frac{R}{H} - 1\right] - k_L + 60 + aR \quad dB$$

$$\text{for } H \le R \le 8H .$$

In these equations, $\alpha_w$ (dB/m) and $a$ (dB/kyd) are the same absorption coefficient. Note also that in Rogers' equation $H$ stands for water depth, while M-S use $H$ for skip distance.

Equation (13) holds from the end of the direct radiation zone to range $R_{10}$, which is where the $10 \log R$ zone begins.

$$R_{10} = \frac{27H^3 f^2}{\beta C^2} . \tag{18}$$

Here, $H$ is the water depth and $\beta$ is given by Eq. (16). Note that $R_{10}$ is now a function of frequency.

The corresponding coefficients in Eqs. (13) and (2) have similar meanings. There is an attenuation-rate term multiplying the range and a constant term representing the reference level at which energy begins to feed into the channel from the direct radiation zone. A major difference concerns the extent of the mode-stripping region. Rogers extends it from 5 km to 100 km instead of using Eq. (18) where bottom losses represented by Eller's expression for $\beta$ may cause it to shorten. The use of $\beta$ is an approximation that holds for small grazing angles only.

The M-S model uses a comparatively short mode-stripping region, $H$ to $8H$, based on measurements off the Atlantic Coast. The limiting value of $8H$ is mainly due to the low-frequency data, which showed relatively large losses at frequencies of about 100 Hz to 500 Hz. These large losses, as well as differences in bottom-type classification, are fundamental to the differences in the values predicted by the M-S and Rogers models. Because sea-surface scattering is small at low frequencies, the larger losses must be due to interaction with the bottom.

The properties of the subbottom also become important at low frequencies.[14] The M-S model assumes that the bottom is homogeneous. The bottom can, however, contain positive sound-speed gradients which can affect propagation drastically by returning energy to the water. For example, the penetration depth into clayey silt at 200 Hz for the

particular case under study can be as much as 23 m; for silt, the penetration depth is 4 m, and for fine sand, 3 m. To depths of 1 to 2 m beneath the seabed surface, the sound-speed gradient is about $+1.0\,s^{-1}$ for silts and clays and about $+15\,s^{-1}$ for fine sand.[15] Substructure layers can also affect energy returned to the water, or the apparent bottom loss. Long bottom paths can feed energy trapped in the bottom back into the shallow-water channel anywhere along the path depending on the lateral inhomogeneities and slopes of sedimentary layers. In South China Sea areas, for example, workers have found the M-S low frequency predictions for the Atlantic Coast give losses that are too high.[16]

Rogers is able to test the sensitivity of his model's predictions to changes in parameters such as bottom roughness or the positive and negative sound-speed gradients in the bottom. He finds that there can be very large changes in the resulting curves of propagation loss vs range. Thus there is an important requirement to measure and know the properties of the bottom in the particular geographic area of interest.

Rogers' overall point is that, for propagation loss in shallow water, there are many parameters that can be used to develop equations for $A$, the attenuation rate, and $B$, the constant term corresponding to contributions by the near-field anomaly. To test these parameters, he chooses to use a theoretical and computational method based on normal-mode solutions to the wave equation. This approach may be appropriate for sensitivity analyses, but any absolute use must be backed by measurements of the parameters that he considers.

The M-S approach was quite specific in developing a semiempirical model based on observed physical data. Although originally designed to handle average sound-speed structures with variability in bottom type, wind speed, and layer depth, the M-S model can now be adapted to specific negative-gradient profiles like those covered by Rogers' model.

On the other hand, normal-mode solutions have been obtained with boundary scattering[17] and can be adapted to Rogers' method. Unless the solutions are tested by a measurement program and error bounds established such as in the M-S model, the model cannot be considered validated. Next we compare the results of the two models and show that they are significantly different.

## D.  Comparison of Predicted Propagation Losses

One of the purposes of the present study is to compare the results of the M-S shallow-water prediction method developed in 1962 with the onboard prediction method devised 20 years later (1981) at NRL[4] using empirical fits of normal-mode solutions by

frequency and bottom type. In Table IV, predictions of propagation loss vs range are listed for Rogers' fine sand and clayey silt at 200 Hz. Alongside are placed the M-S predictions for the Colossus "sand" and "mud." These latter classes are more general, and there is no reason to believe they correspond to the classes for wh·:h Rogers calculated predictions.

*Table IV. Comparison of Rogers' and M-S predictions for propagation loss (decibels) at 200 Hz.*

| Range (km) | Fine Sand Rogers | Sand M-S | Δ | Clayey Silt Rogers | Mud M-S | Δ |
|---|---|---|---|---|---|---|
| 5 | 60 | 69 | +9 | 68 | 69 | +1 |
| 10 | 66 | 74 | +8 | 76 | 75 | -1 |
| 20 | 72 | 81 | +9 | 89 | 82 | -7 |
| 3C | 77 | 86 | +9 | 99 | 88 | -11 |
| 40 | 81 | 90 | +9 | 108 | 93 | -15 |
| 50 | 84 | 94 | +10 | 117 | 97 | -20 |
| 60 | 87 | 97 | +10 | 126 | 101 | -25 |
| 70 | 90 | 100 | +10 | 135 | 104 | -31 |
| 80 | 93 | 103 | +10 | 143 | 108 | -35 |
| 90 | 96 | 105 | +9 | 152 | 111 | -41 |
| 100 | 99 | 108 | +9 | 160 | 115 | -45 |

Table IV shows that, for a fine-sand bottom, the M-S "sand" model predicts a greater loss than Rogers' fine-sand model by about 9 or 10 dB at all ranges. On the other hand, the M-S mud model predicts a smaller loss than Roger's clayey-silt model, with the difference increasing with range. The differences could correspond to differences in classifying the bottom or they could be due to the prediction technique or both. The differences Δ far exceed the M-S probable errors shown in Table V. Where the difference is

*Table V. Probable error of propagation loss (decibels) (semi-interquartile range).*

| Range (kyd) | Frequency (Hz) | | | |
|---|---|---|---|---|
| | 112 | 446 | 1120 | 2820 |
| 3 | 2 | 4 | 4 | 4 |
| 9 | 2 | 4 | 5 | 6 |
| 30 | 4 | 9 | 11 | 11 |
| 60 | 5 | 9 | 11 | 12 |
| 90 | 6 | 9 | 11 | 12 |

constant like that for the sands, it could be due simply to the value used for the bottom reflection coefficient or to an error in the near-field anomaly estimate. Where the differences increase with range as for the muds, they are probably due to the estimate of the attenuation rate. There are nine classes in Hamilton's system, but Rogers does not tabulate prediction fits for other classes of sand and silt.

Table VI compares the environmental and acoustic parameters used by the two models. The most important differences are the skip distance and the reflection loss per bounce. Note that, for the sands, the attenuation rate is about the same in decibels/kilometer because it is equal to the quotient of loss per bounce by skip distance. This is not true for the muds or silts. Both the skip distance and the bottom reflection loss per bounce depend on the magnitude of the negative gradient from the surface to the bottom.

The question to be answered is, Can we extend the M-S model to predict the same propagation loss as Rogers' normal mode procedure if the same shallow-water characteristics are used? We will show that the answer is, yes.

*Table VI. Environmental acoustic parameters for the two models (f = 200 Hz).*

| Parameter | Rogers Model | M-S Model |
|---|---|---|
| *I. Environment* | | |
| Layer depth, m | 0 | 0 |
| Water depth, m | 100 | 100 |
| Negative gradient, $s^{-1}$ | -0.20 | -0.035 |
| Sea state | C | 0 |
| Skip distance, km | 2.45 | 5.86 |
| Skip ray grazing angle, deg | 9.36 | 3.91 |
| *II. Reflection Loss* | | |
| Fine sand: | | |
| dB/bounce | 0.48[b] | 1.3 |
| dB/km[a] | 0.20 | 0.22 |
| $R_{10}$, km | 100 | 47 |
| Clayey silt: | | |
| dB/bounce | 3.46[b] | 1.7 |
| dB/km[a] | 1.41 | 0.29 |
| $R_{10}$, km | 100 | 47 |

[a]Water absorption coefficient must be added to this term. It is $4.63 \times 10^{-3}$ dB/km.

[b]Calculated from Morse-Mackenzie.

## IV.  EXTENSION OF THE M-S MODEL

### A.  Arbitrary Negative Sound-Speed Gradients

The M-S model shown in Table VI uses the same value, -0.035 s$^{-1}$, for all negative gradients. We have developed an extension to the M-S model for handling arbitrary negative gradients like the -0.2 s$^{-1}$ that Rogers uses. Changing the gradient will affect both the reflection loss per bounce and the near-field anomaly and will result in values comparable to Rogers' since the skip distance and grazing angle will also be comparable.

*Near-Field Anomaly*

The general expression for the near-field anomaly $k_{L,U}$ is obtained by combining Eqs. (6) and (9).

$$k_{L,U} = 10 \log K_{L,U} = 10 \log \left[ 1 + \frac{(2\, r_s\, r_b + r_s + r_b)(1 - r_s^n\, r_b^n)}{(1 - r_s\, r_b)} \right] \qquad r_s, r_b \leq 1 \ .$$

The use of $K_{L,U}$ instead of $K_L$ or $K_U$ is one of the keys to the extended M-S model. In particular, we must determine the number $n$ of the surface-reflected bottom-reflected (SRBR) ray system that applies in a particular situation. For a strictly negative sound-speed gradient, we proceed as follows (see Fig. 4).
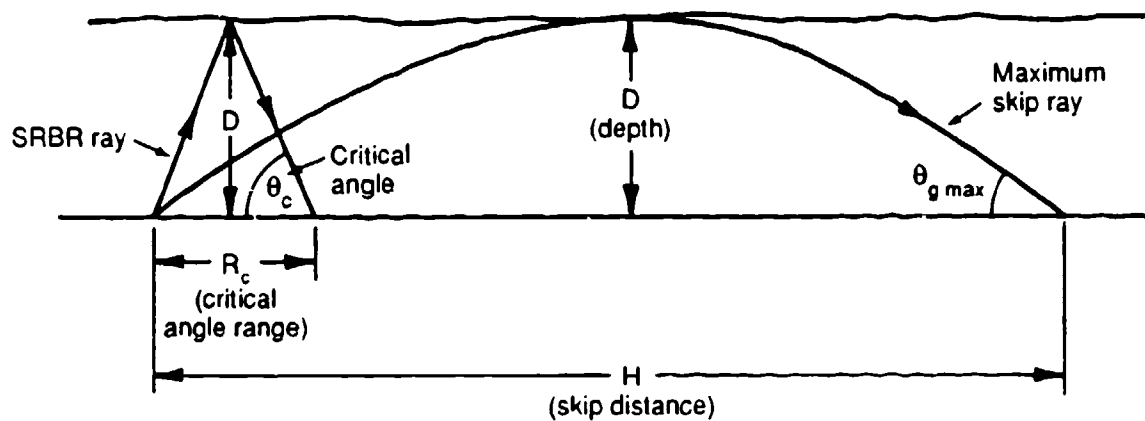


Order $n$ = Integer $(H/R_c)$

*Figure 4.   Determination of number $n$ of SRBR rays in direct radiation zone.*

First we state that the critical angle, i.e., the cutoff angle for accepting energy into the channel, is given by

$$\theta_c = \text{arc cos } N_0 \; ;$$

$N_0 = c_1/c_2$, where $c_1$ is the sound speed in the water at the bottom and $c_2$ is the sound speed in the bottom sediment.

In this situation of negative gradients and low sea states, surface reflection $r_s = 1$. Thus more rays at higher angles up to the critical angle contribute to the field. If $R_c$ is the range between bottom contacts of the ray (not refracted) traveling at the critical angle with the bottom, then, from simple geometry,

$$R_c = 2D \text{ cot } \theta_c \; .$$

The number of bottom-reflected rays that contribute to the near-field anomaly is integer $n = H/R_c$, where $H$ is the skip distance (see Section II.B). In Table VII, we show how to obtain $n$ for water with a depth of 100 m and a negative sound-speed gradient of -0.2 s⁻¹, for two types of bottom sediments — fine sand and clayey silt.

Again, we repeat that the determination of the near-field anomaly is not trivial since the same bottom reflection coefficient $r_b$ must be applicable to all three propagation zones — near, intermediate, and far.

To calculate the extended near-field anomaly, $k_{L,U}$, for the two sediments, we need to know their reflection coefficients, or bottom losses per bounce.

Analysis of the Colossus data yielded the bottom attenuation factors vs frequency for sand and mud shown in Fig. 5; these values are for a sea state 0 and the shallow waters off the East Coast of the United States. Using the Morse-Mackenzie[18] equations for lossy sediments modeled as fluids, we will now study the relation between these empirical values and theoretical values.

*Table VII. Number n of SRBR rays in direct radiation zone.[a]*

| Parameter/Sediment | Fine Sand | Clayey Silt |
|---|---|---|
| Skip distance, m | 2530 | 2530 |
| Critical angle, $\theta_c$, deg. | 29.12 | 9.45 |
| Critical-angle ray range, $R_c$, m | 359 | 1191 |
| Order of ray bounces, $n$ | 7 | 2 |

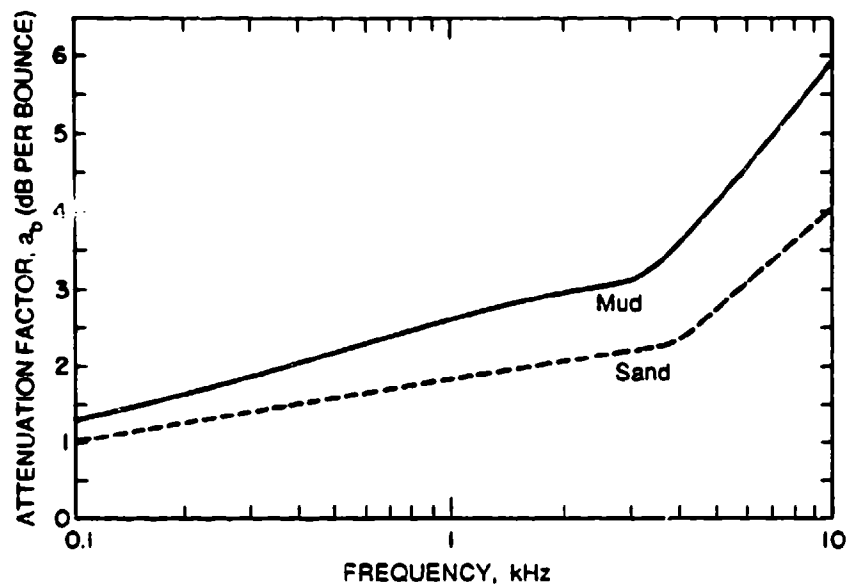[a] Water depth is 100 m and sound speed gradient is -0.2 s⁻¹.

*Figure 5. Bottom attenuation factor for shallow water propagation (0 sea state).*

The Morse-Mackenzie expression for the intensity reflection coefficient in the presence of an absorbing fluid bottom is

$$r_b = \left| \frac{p_r}{p_i} \right|^2 = \frac{(h - \sigma \sin\theta)^2 + g^2}{(h + \sigma \sin\theta)^2 + g^2} . \tag{19}$$

The phase angle $\psi$ between reflected and incident pressures is given by

$$\tan\psi = \frac{2\sigma g \sin\theta}{\sigma^2 \sin^2\theta - (h^2 + g^2)} . \tag{20}$$

In these expressions, $\sigma = \rho_2 c_2 / \rho_1 c_1 \equiv$ the impedance ratio,

$$g = [-B + (A^2 + B^2)^{1/2}]^{1/2} , \tag{21}$$

and

$$h = [B + (A^2 + B^2)^{1/2}]^{1/2} , \tag{22}$$

with

$$A = 0.0183 \, a_B \, v_B \, f^{-1} \tag{23}$$

$$B = 1/2 \left[ 1 - \left[ \frac{\cos\theta}{N_0} \right]^2 - (0.0183 \, a_B \, v_B \, f^{-1})^2 \right] , \tag{24}$$

where

$\theta$ = grazing angle, degrees

$f$ = frequency, hertz

$a_B$ = attenuation in the bottom, decibels/meter

$v_B$ = phase velocity in the bottom, $\cong c_2$

$$N_0 = \frac{c_1}{v_B} .$$

As an example, using the bottom properties for fine sand and clayey silt as defined by Hamilton[19] from Table VIII, we obtain the curves shown in Fig. 6 for bottom loss versus grazing angle at 200 Hz.

*Table VIII. Bottom properties (Hamilton[19]).*

| Parameter | Fine Sand | Clayey Silt | Seawater |
|---|---|---|---|
| Sound speed, m/s | 1749 | 1549 | 1528 |
| Density, g/m$^3$ | 1.941 | 1.488 | 1.027 |
| Hamilton attenuation factor, dB/m/kHz | 0.52 | 0.095 | --- |
| Critical grazing angle, deg | 29.12 | 9.45 | --- |

We have pointed out in discussing the near-field anomaly that $r_b$ turns out to be the reflection coefficient of rays up to the critical angle. This is appropriate for a scattering or reflection process in a channel since this is the cutoff angle for accepting energy into the channel.

E.L. Hamilton[19] has postulated from many measurements that the loss for compressional waves propagating in a specific type of sediment has a fixed attenuation constant, $k_p$, in decibels/meter/kilohertz. If this were true, the Morse-Mackenzie expressions would show that the bottom loss curve is independent of frequency. Figure 5 shows that this last condition is not true for the Colossus data for sand or for mud.
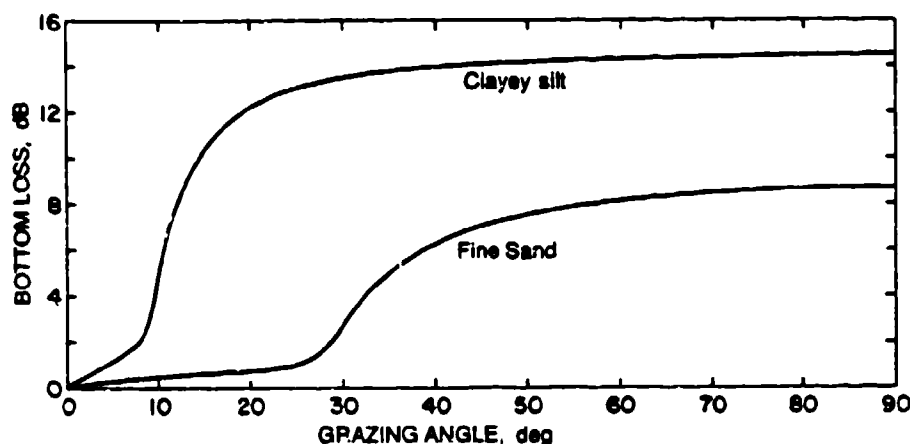
*Figure 6.   Bottom loss (decibels) vs grazing angle (degrees) (Morse-Mackenzie).*

On the other hand, if we take $k_p$ for fine sand and also clayey silt to vary as the first power of frequency up to 1 kHz and calculate the loss per bounce, then the corresponding angle of incidence is approximately the critical angle for each sediment. Above 1 kHz, taking $k_p$ equal to a constant also yields a bottom loss corresponding to the critical angle (see Table IX). This is reasonable, since the critical angle is the cutoff angle for transmission down the channel, and the scattering is quite diffuse. Often, Hamilton's postulate is assumed for convenience, as Rogers does in his model. However, some other workers have also found a behavior similar to that of the Colossus data for the frequency dependence of $k_p$.[12,18,20]

*Table IX.   Empirical bottom loss per bounce (M-S) and corresponding grazing angle.*

| Frequency (kHz) | Sand | | Mud | |
|---|---|---|---|---|
| | $a_b$ (dB/bounce) | $\theta_t^a$ (deg) | $a_b$ (dB/bounce) | $\theta_t^a$ (deg) |
| 0.1 | 1.0 | 29.4 | 1.3 | 9.47 |
| 0.2 | 1.3 | 29.6 | 1.7 | 9.46 |
| 0.4 | 1.6 | 29.5 | 2.2 | 9.40 |
| 0.8 | 1.8 | 29.3 | 2.5 | 9.01 |
| 1.0 | 1.8 | 28.6 | 2.7 | 8.82 |
| 2.0 | 2.0 | 29.0 | 3.0 | 9.06 |
| 4.0 | 2.3 | 29.5 | 3.6 | 9.44 |
| | | Median = 29.3 | | Median = 9.40 |

[a] $\theta_t$ is calculated from Morse-Mackenzie for $k_p \propto f$ when $f \leq 1$ kHz; $k_p$ is constant when $f \geq 1$ kHz (see p. 14 for definition of $k_p$).

## Skip Distance

A new expression for the skip distance can be derived based on the actual gradient in the negative-gradient layer rather than on the average for the Colossus measurements. At this point, we are concentrating on the strictly negative-gradient profile. (The formula for a bilinear gradient is provided in Section IV.B.) For strictly negative sound-speed gradients, there are two useful expressions: (1) maximum skip angle, $\theta_{g\,max}$, and (2) skip distance, $H$.

$$\theta_{g\,max} = \left[\frac{2Dg_N}{c_1}\right]^{1/2} \quad \text{radians}$$

and

$$H = 2\left[\frac{2Dc_m}{g_N}\right]^{1/2},$$

where $D$ is the water depth, $g_N$ is the magnitude of the negative gradient, $c_1$ is the sound speed of the water at the bottom, and $c_m$ is the maximum sound speed (at the surface).

When only negative gradients exist, the sea state must be close to 0, for otherwise near-surface mixing by the wind would begin to form isothermal layers. Under this condition, the sea surface reflection coefficient $r_s$ is 1, and $r_t = r_b$.

As an illustration, we show in Table X the near-field anomaly $k_{L,U}$ for two of Hamilton's sediment classes for shallow water of $g_N = 0.2\ s^{-1}$, $D = 100$ m, $H = 2.45$ km, and $\theta_g = 9.356°$.

Table X. Determination of near-field anomaly for two Hamilton sediment classes at 200 Hz.

| Property/Sediment | Fine Sand | Clayey Silt |
|---|---|---|
| Reflection coefficient, $r_b$, at skip angle | 0.90 | 0.45 |
| Bottom loss, $a_b$, dB/bounce | 0.48 | 3.46 |
| Critical angle, $\theta_c$, deg. | 29.12 | 9.45 |
| Critical cycle range, $R_c$, m | 359 | 1191 |
| Order of ray bounces, $n$ | 7 | 2 |
| Near-field anomaly, $k_{L,U}$, dB | 13.1 | 7.9 |

$g_N = 0.2\ s^{-1}$; $D = 100$ m; $H$ (skip) = 2.45 km; $\theta_g = 9.356°$

At this point, it is useful to discuss the shallow-water propagation-loss measurements of Cole and Podeszwa[21] south of Long Island in 30 fathoms (54.9 m) of water over a sand bottom at 3.5 kHz under strictly negative-gradient conditions. The significance of this experiment is that it was devoted to exploration of the details of the standard M-S model under such conditions. In this case, they found that M-S got the right answer for the wrong reason — that is, use of the average Colossus negative gradient gave a predicted result within the probable error bounds (see Table V), but the Colossus gradient did not correspond to the actual gradient. The M-S model predicted values of 79 dB vs their measured values of 80 dB at 10 kyd, and 92 dB vs 98 dB at 20 kyd; however, Cole and Podeszwa found a skip distance of 1.20 kyd and a mean boundary loss of 1.3 dB/bounce compared with the skip distance of 4.75 kyd and the mean boundary loss of 3.55 dB/bounce predicted by the M-S model. They also found a grazing angle of 11.908° at their skip distance.

To show the versatility of the basic formulation of the M-S propagation-loss equations, we have used the specific environmental parameters found in the Cole-Podeszwa experiment and have calculated predicted propagation loss values to compare with their measured values. We find as they do a skip distance of 1.20 kyd and a skip angle of 11.908° based on ray traces using their typical sound-speed profile. From their values of sand density, sound speed, and a sediment attenuation factor of 0.422 dB/m/kHz at 3.5 kHz, we then calculate a reflection coefficient of 0.75 (or -1.25 dB/bounce). Using the reflection coefficient of 0.75, we calculate $k_{L,U} = 6.28$ dB. Then, using M-S Eqs. (2) and (3), we get a propagation loss at 10 kyd of 80 dB vs their 80 dB, and at 20 kyd we get 96 dB vs their 98 dB.

*Comparing the Extended M-S Model for Arbitrary Negative Gradients with Rogers' Model*

The three propagation-loss zones for the M-S model extended to include arbitrary negative gradients are as follows:

$$N, \text{dB} = 20 \log R + aR + 60 - k_{L,U} \qquad \text{for } R \leq H \qquad (25)$$

$$N, \text{dB} = 15 \log R + aR + a_t \left(\frac{R}{H} - 1\right) + 5 \log H + 60 - k_{L,U} \quad \text{for } H \leq R \leq R_{10} \qquad (26)$$

$$N, \text{dB} = 10 \log R + aR + a_t \left(\frac{R}{H} - 1\right) + 5 \log H + 60 + 5 \log R_{10} - k_{L,U} \qquad (27)$$

$$\text{for } R \geq R_{10},$$

where

$R_{10}$ = range to the start of the far region. $R_{10}$ is obtained from Eq. (18).

$a_t$ = $a_b$ for strictly negative sound-speed gradients from surface to bottom.

We will now use these new expressions to examine the relationships between the extended M-S and Rogers' fits for two different sediments, fine sand and clayey silt.

A problem that we encounter immediately is that Rogers apparently did not use the Morse-Mackenzie expression for the reflection coefficient but rather Eller's expression, Eq. (16). Eller's expression holds only for very small grazing angles. For clayey silt, it yields a reflection loss of 1.99 dB/bounce instead of 3.46 dB/bounce. For fine sand, it yields a reflection loss of 0.58 dB/bounce instead of 0.48 dB/bounce. Using these Eller reflection losses in Eqs. (25), (26), and (27), we obtain the results shown in Table XI. Thus the extended Marsh-Schulkin model will give practically the same results as Rogers' if the same inputs are used.

Table XI. *Comparison of Rogers' and extended M-S predictions for propagation loss (decibels) at 200 Hz.*

| Range (km) | Fine Sand | | $\Delta$ | Clayey Silt | | $\Delta$ |
|---|---|---|---|---|---|---|
| | Rogers | Extended M-S | | Rogers | Extended M-S | |
| 5 | 60 | 60 | 0 | 68 | 66 | -2 |
| 10 | 66 | 66 | 0 | 76 | 75 | -1 |
| 20 | 72 | 73 | +1 | 89 | 87 | -2 |
| 30 | 77 | 78 | +1 | 99 | 98 | -1 |
| 40 | 81 | 82 | +1 | 108 | 108 | 0 |
| 50 | 84 | 86 | +2 | 117 | 117 | 0 |
| 60 | 87 | 89 | +2 | 126 | 126 | 0 |
| 70 | 90 | 93 | +3 | 135 | 135 | 0 |
| 80 | 93 | 96 | +3 | 143 | 143 | 0 |
| 90 | 96 | 99 | +3 | 152 | 152 | 0 |
| 100 | 99 | 102 | +3 | 160 | 160 | 0 |

## B. Bilinear Sound-Speed Gradients

The extension of the M-S propagation-loss model is based on the three-zone spreading-loss system for a bilinear positive-over-negative sound-speed gradient. The original M-S model was a three-zone spreading-loss system derived from measured acoustic data. By using the Hamilton sediment classes for estimating the acoustic properties of the bottom from 100 Hz to 5000 Hz, we obtain the reflection loss per bou::ce

from one of the loss-vs-grazing-angle expressions developed by Morse-Mackenzie,[18] Brekhovskikh,[22] Weston,[7] or Eller.[14] The Schulkin-Marsh surface-scattering loss is also used for a given wind speed or sea state. The water absorption coefficient can be that of Thorp[23] or Francois and Garrison.[24]

The first zone is the direct path zone (20 log R), the extent of which is defined as the skip distance. The skip distance can be obtained by ray tracing or from the formula given below for bilinear gradients:

$$H = (8 \, c_m)^{1/2} \left[ \frac{L}{g_p} + \frac{2(D-L)}{g_N} \right]^{1/2} , \qquad (28)$$

where

$c_m$ = maximum sound speed

$g_p$ = positive gradient

$g_N$ = magnitude of the negative gradient

$H$ = skip distance

$D$ = water depth

$L$ = layer depth.

The near-field anomaly can be taken as $k_U$ or $k_{L,U}$, given by Eq. (9).

The second zone is the mode-stripping zone (15 log R) in which the shallow-water attenuation coefficient, $a_t$, in decibels/bounce, depends on the grazing angle of the bottom skip ray and the sea state/wind speed. The attenuation coefficient multiplied by the number of bounces up to a given range yields the attenuation due to the bottom in the second and third zones.

The third zone is the zone of cylindrical spreading (10 log R) in which there is only one mode of propagation. Instead of using the frequency-independent empirical value of $8H$ as the transition range between zone 2 and zone 3, we use the frequency-dependent $R_{10}$ given in Eq. (18).

## V. ASSESSMENT OF ROGERS' AND M-S MODELS

Rogers' method of fitting two (or more) coefficients to depth-averaged normal-mode solutions of the wave equation for acoustic propagation in shallow water has the advantage of providing a sensitivity analysis for comparing the effects of adding or changing parameters of the model. In addition, the equations furnish convenient parameters which could provide reference solutions for a measurement program.

While the Rogers models are computer-driven, the M-S model is data-driven. The latter model was based on analysis of data gathered during extensive measurements of propagation loss and environmental parameters off the Atlantic Coast, and basically applies to average conditions in this region. To use it anywhere else may furnish preliminary loss estimates but is not strictly justified. The main reason for this is that the loss values at long range were determined mainly by the low-frequency properties of the bottom and subbottom. These are not well known and differ from one location to another. Another limiting factor to its application is that it concentrates on an average positive-gradient layer overlying an average negative-gradient layer when sea surface scattering might be present. When sea state 0 or 1 conditions prevail and a negative gradient is present, it only gives a single answer for all conditions. However, we have shown that the M-S method can be extended to such cases.

Finally, being tied to a measurement data base is an important advantage for the M-S model since error bounds were established for applicable conditions.

## VI. CONCLUSIONS

1. The M-S shallow-water transmission-loss model has been reviewed and extended in the light of 20 years additional work in the field. It appears to be as useful today as it was when first formulated. Based on data gathered during the Colossus program, the model treats surface-scattering loss coupled to the bottom for a water column with a positive-gradient layer overlying a negative-gradient layer for two classes of bottoms, sand and mud.

2. In terms of Hamilton's bottom classes and associated acoustic properties, the Colossus sand is not equivalent to his "fine sand" and the mud is not equivalent to his "clayey silt." Information on subbottom structure and geoacoustic properties is much needed. Hamilton's postulate that sediment attenuation rate is linear in frequency requires more intensive investigation, especially at the lower frequencies.

3. The M-S model performs well at frequencies above 1 kHz. Below 500 Hz, where bottom and subbottom properties are important, there are conflicting reports of its performance. At long ranges and low frequencies, for instance, the Colossus data base for the Atlantic Coast shows a higher loss than that measured in South China Sea areas.

4. Rogers' computational method of fitting normal-mode solutions to two (or three) propagation loss coefficients has some advantages. It may be applied to sensitivity analyses where parameters are changed or added. It also furnishes a convenient way to summarize the effects of treating new phenomena. For example, the Kuperman and Ingenito normal-mode solution to the boundary scattering problem can be conveniently compared with reference models.

5. Rogers' model and the extended M-S model yield close values of propagation loss when the same inputs are used.

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20 ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

The Marsh-Schulkin (M-S), or Colossus, model of acoustic transmission loss in shallow water is reviewed in light of new information and techniques that have emerged since its introduction in 1962. The M-S model is a semiempirical model based on extensive measurements taken off the Atlantic Coast. It uses several concepts: (1) refractive cycle, or skip distance, (2) deflection of energy into the bottom at high angles by scattering from the sea

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surface; and (3) a simplified Rayleigh two-fluid model of the bottom for sand or mud sediments. With a few free parameters, including water depth, about 100,000 measurements from 100 Hz to 10 kHz were fitted within stated error bounds. The model's chief criticisms have been that it could not be adjusted for arbitrary negative sound-speed gradients (it uses the same constant thermocline in all cases), and that it uses empirical bottom loss values. The M-S model yields good predictions when applied properly; it is not to be used for all environments.

The M-S model is compared with Rogers' semiempirical model based on numerical calculations of the normal-mode solutions to the wave equation for propagation in shallow water. (Rogers' model for transmission loss involves a simple range-dependent fit with three coefficients, and allows a convenient sensitivity analysis for the addition or changing of parameters.) Differences in predicted propagation losses are discussed.

The M-S model is also extended for the purpose of treating arbitrary negative and bilinear sound-speed gradients. These extensions use new general expressions for the skip distance, the near-field anomaly, and the reflection coefficients. The reflection coefficients are calculated from the Morse-Mackenzie relations for loss per bounce using the values for bottom-sediment properties reported by E.L. Hamilton. The extended model and Rogers' model are found to give about the same predictions when the same inputs are used.