PAP-436

EFFECTS OF SALINITY GRADIENTS ON DEFLECTION OF ACOUSTIC WAVE IN THE SACRAMENTO-SAN JOAQUIN DELTA

BY

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PAP-436

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Memorandum

Denver, Colorado

TO : Memorandum Files

DATE: January 19, 1981

FROM : Henry T. Falvey, Technical Specialist

SUBJECT: Effects of Salinity Gradients on Deflection of Acoustic Wave in the Sacramento-San Joaquin Delta

BACKGROUND

Previous memorandums dated February 20, 1980, and September 12, 1980, investigated the effects of salinity in the entire river cross section and the combined effects of temperature and salinity at a piling on the deflection of the acoustic wave. The gradients and the deflections were assumed to occur in a vertical plane only. These studies showed that multiple reflections would occur off the water surface or off the riverbed when making measurements across the entire river section. Since these paths are so divergent from the assumed path, an estimate of the probable error in the net flow cannot be made. To mitigate the multiple reflections, it would be necessary to shorten the acoustic path to about 400 m instead of the present 1130-m length.

The purpose of this study is to investigate the effect of salinity gradients in the horizontal plane. In addition, the magnitude of the uncertainty in determining the net flow is estimated for a 400-m path length considering only the effects of variations in the mean velocity correlation coefficient C. This coefficient varies with both river stage and with the curvature of the acoustic path.

ANALYSIS

Salinity Effects on Horizontal Curvature of Acoustic Path

Only those gradients which are perpendicular to the acoustic path cause a deflection of the path. Therefore, it is necessary to make an assumption about the horizontal gradient in the river. Two reasonable assumptions are either the density is constant at points equidistant from the bank or the density is constant at each cross section of the river, figure 1. Fortunately, either one of these assumptions will produce the same definition of gradient perpendicular to an acoustic path which is inclined at a 45° angle with the river centerline.

For the computations, it was assumed that the soundings of velocity and salinity were made at points located 32.6 m apart on a line perpendicular to the river centerline. The radius of curvature was computed using the equation:

$$R(m) = -(1471.1 + 0.57\ \Delta S)\ \frac{(1.414 \times 32.6)}{(1.13 \times \Delta S)} \qquad (1)$$

Estimate of Error Due to Variation of Mean Velocity Correlation Coefficient

The measured discharge can be considered as though it consists of three components: a net flow or trend value, a tidal flow or cyclical value, and an error or irregular value. The purpose of this section is to obtain an estimate for the magnitude of the uncertainty in determining the net flow as a result of errors introduced by refraction of the acoustic path.

It can be assumed that the acoustic velocity meter indicates the true mean line velocity to an error of less than 1 percent. Then, the only error in determining the mean flow velocity is that due to errors in determining the mean velocity correlation coefficient. The mean velocity correlation coefficient, C, is defined as

$$C = \frac{\overline{V}}{V} \qquad (2)$$

where: $\overline{V}$ = Q/A for entire cross section
Q = Total flow through the cross section
A = Area of cross section
V = Average line velocity on acoustic path

Two sources of error exist in the determination of C. These are variations of C due to tidal phase and variation of C with depth. In this latter case, errors are introduced when the acoustic path deviates from a straight line. Smith 1/ showed that the random error in C due to tidal variations is $S_C = 2.6$ percent.

The effect of the variation of C with depth was studied by assuming a linear variation of C with depth. Between the water surface and the 7 m depth, the data presented by Smith fitted a curve of the form

$$C = 0.924 + 0.0135\ y \qquad (3)$$

where y = depth, measured from the water surface in meters

1/ Smith, W., Feasibility Study of the Use of the Acoustic Velocity Meter for Measurement of Net Outflow From the Sacramento-San Joaquin Delta in California, Geological Survey Water-Supply Paper No. 1877, 1969, 54 pp.

The coefficient of determination for the linear regression was 0.98. A value of 1.0 indicates a perfect fit.

To combine the effect of the two factors which contribute to the error in C, it is necessary to assume that they are independent. The results of the September 12, 1980 memorandum demonstrate that the radius of curvature is essentially independent from the tidal cycle. For instance, if they were dependent then the cross correlation would have had a large value at periods which corresponded with a lunar day. Since no large amplitude periodicity was revealed in the correlation (fig. 9 of the September 12 memorandum), it can be concluded that the two factors are independent.

If the path length is 400 m and the radius of curvature is 5 km, then the deflection of the acoustic path from a straight line is 4 m. With transducers located at a 5-m depth, the maximum variation in the C value is 5.7 percent. Assuming sinusoidal deviations from the straight line path results in a root mean square value of the error of

$$S_A = \frac{1}{\sqrt{2}} \times 5.7 = 4.0$$

If the errors in the individual flow measurements were randomly distributed, then the uncertainty in the net flow could be estimated by conventional statistical methods. Unfortunately, if the time interval between the data points is not large enough, the magnitude and sign of the error is dependent upon the previous values.

Smith discussed the question of how many instantaneous discharge values could be legitimately used from a large array of data to compute the mean discharge. He concluded that only one reading an hour could be considerd as statistically independent for the standard deviation of C with tidal stage.

The September 12 memorandum demonstrated a persistence of the radii of curvature for periods up to 2 days. 2/ Therefore, readings taken at intervals of less than 2 days cannot be considered as randomly independent. If averages are determined over periods shorter than 2 days then a systematic error in the determination of the net flow will result. The uncertainty S_N in the net flow rate can be estimated from

$$S_N = \left(\frac{Sc}{\sqrt{N}}\right) + S_A \quad \frac{\sum_{1}^{N} |Q|}{N}$$

where: S_A = The maximum value of the error of the acoustic component.
N = Number of hours over which the mean is computed

2/ The time scale in the figures of the memorandum is in days and the frequency is in cycles per day. Thus the 2 hour persistance mentioned on page 11 should have been 2 days.

The numerical value of the equation is

$$S_N = \left(\frac{0.026}{\sqrt{N}} + 0.040\right)\frac{\left(\sum_1^N |Q|\right)}{N} \qquad (5)$$

When the period exceeds 2 days, then the error due to the acoustic bending effects can be considered as random. In this case the appropriate equation is:

$$S_N = \frac{\left(\sqrt{\frac{S_C^2}{N} + \frac{S_A^2}{M}}\right)\left(\sum_1^N |Q|\right)}{N} \qquad (6)$$

where S_A = The rms value of the error of the acoustic component
M = Number of days in multiples of 2.

The numerical value of the equation

$$S_N = \frac{\sqrt{\frac{6.76 \times 10^{-4}}{N} + \frac{1.6 \times 10^{-3}}{M}}\left(\sum_1^N |Q|\right)}{N} \qquad (7)$$

RESULTS

Horizontal Curvature of Acoustic Path

The mean radius of curvature in the horizontal plane is about 100 km, figure 2. Upstream curvatures are as likely to occur as downstream curvatures. Translated into absolute values, the deflection of the acoustic ray from a 1130-m straight line path is less than 0.16 m. Therefore, for all practical purposes the acoustic ray path can be considered as a straight line in the horizontal plane.

Errors Due to Variation of Mean Velocity Correlation Coefficient

The following table of probable errors was computed using equations 5 and 7.

Table 1. - Probable errors in net outflow computation based on variations in mean velocity corelation coefficient

Average Discharge (ft^3/s)			Probable error in net outflow (ft^3/s)		
Ebb flow	Flood flow	Net outflow	S_{24}	S_{96}	S_{336}
150,000	-148,000	2,000	± 6750.	± 2120.	± 440.
150,000	-147,000	3,000	± 6730.	± 2110.	± 440.
150,000	-146,000	4,000	± 6710.	± 2100.	± 440.
150,000	-145,000	5,000	± 6680.	± 2100.	± 440.

$$S_{24} = \left(\frac{0.026}{\sqrt{24}} + 0.040\right) \frac{\left(Q_{EBB} + \left|Q_{FLOOD}\right|\right)}{2}$$

$$S_{96} = \left(\frac{6.76 \times 10^{-4}}{96} + \frac{1.6 \times 10^{-3}}{2}\right)^{1/2} \frac{\left(Q_{EBB} + \left|Q_{FLOOD}\right|\right)/2}{2}$$

$$S_{336} = \left(\frac{6.76 \times 10^{-4}}{336} + \frac{1.6 \times 10^{-3}}{7}\right)^{1/2} \frac{\left(Q_{EBB} + \left|Q_{FLOOD}\right|\right)/2}{7}$$

CONCLUSIONS

1. Gradients either in the stream direction or parallel with the river banks do not significantly deflect the acoustic ray from a horizontal path.

2. Errors introduced by bending of the acoustic path over a length of 1130 m are too large to estimate.

3. Errors caused by bending of the acoustic path over a length of 400 m are very large. This is due to the systematic nature of the error over periods of less than 2 days.

4. The probable error in determining the net outflow decreases as the averaging time increases if the net outflow remains constant.

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Memorandum

TO : Memorandum Files

Denver, Colorado
DATE: February 20, 1980

FROM : Henry T. Falvey, Technical Specialist

SUBJECT: Effects of Salinity Gradients on Deflection of Acoustic Wave in the Sacramento-San Joaquin Delta

BACKGROUND

Sound and light obey the same laws of physics when traveling through a nonuniform density medium. The deflection of a sound or light path from a straight line can be predicted from Snell's law of refraction. Based on Snell's law it can be shown that the sound path travels a circular arc in the presence of a linear density gradient 1/, 2/. The radius of curvature of the circular arc, R (m), is given by:

$$R = -1450\left(3.63\ \frac{dT}{dy} + 1.13\ \frac{dS}{dy}\right)^{-1} \qquad (1)$$

Where T = Temperature (°C)
y = Depth measured downward from the water surface (M)
S = Salinity (g/kg)

This equation shows that the deflection of the ray path is affected more by temperature than by salinity gradients.

Stable salinity gradients always result in positive values for the gradient. These gradients produce upward curvatures of the ray paths. On the other hand, a stable temperature gradient produces a downward curvature.

1/ Urick, R. J., Principles of Underwater Sound for Engineers, McGraw Hill Book Company, 1967.
2/ Cole, J. A., The Deflection of an Acoustic Beam by Temperature and Salinity Gradients, Support Paper, Water Research Centre, Henley Road, Medmenham, PO Box 16, Marlow Bucks SL7 2HD, England, March 1979.

The bending of the sound path results in an increase in the travel distance for the sound ray to pass between two points a distance L apart. The percent increase in the travel length due to the curved path is given by:

$$\frac{X-L}{L} = \left[\frac{2R}{L} \sin^{-1}\left(\frac{L}{2R}\right) -1\right] 100 \qquad (2)$$

Where X = True path length
L = Chord length between points
R = Radius of curvature of sound path

As well as traveling a longer distance, density gradients also cause the ray to be deflected from a straight line path. The amount of deflection, D, is given by:

$$D = R\left(1 - \sqrt{1 - \frac{1}{4}\left(\frac{L}{R}\right)^2}\right) \qquad (3)$$

A longer sonic path and the deflection from a straight path can potentially affect the accuracy of an acoustic velocity meter. This memorandum investigates the magnitude of these effects at the Chipps Island Channel in the Sacramento-San Joaquin Delta.

ANALYSIS

Data on salinity as a function of depth were obtained from Mr. Stuard Hoffard, Geological Survey, Menlo Park Subdistrict Office, California, to analyze. These data were measured during the period September 11-27, 1954, in the Chipps Island Channel. A computer program was written to determine a histogram of the radii of curvature of the data, appendix I. By varying the parameters in the program, it was possible to obtain histograms for both the flood and slack tide periods. In addition, histograms as a function of depth were also determined. These latter histograms represent 10-foot-deep segments of the water prism.

The program output was written so that the numerical results appear on the left side of the page and a rough plot of the histogram appears on the right side, figures 1-9.

The results are biased somewhat toward the larger values of radii of curvature because the distance between the last depth and the river bottom was not known. In the computations, this interval was assumed to be equal to 10 feet. Actually, this distance is less than 10 feet. The equation used to determine the radius of curvature is:

$$R(m) = -1450 \left(\frac{1.13\ \Delta S}{10 \times 0.305}\right)^{-1} = \frac{-3911}{\Delta S} \qquad (4)$$

Where ΔS = Difference between salinity readings at adjacent 10-foot depths

A positive value for R indicates downward curvature of the acoustic ray, whereas, negative values indicate upward curvature of the rays.

The maximum acoustic path length at Chipps Island is about 1130 m. Since a radius of curvature of the acoustic path of 1×10^6 m represents only a 15-cm deflection, equation 3, all radii equal to or greater than 1×10^6 m were assumed to be the same as a direct path.

RESULTS

All Data

The histogram indicated a concentration of the radii of curvature in the range 1×10^4 to 5×10^4 m. These acoustic rays have an upward curvature. Only 10 percent of the rays could be considered as being on the direct path.

0- to 10-foot Depth

In the top 10 feet, over 30 percent of the radii curvature lie in the 1×10^4-to 5×10^4-m range, figure 2. Another 30 percent of the data have a radius of curvature less than 1×10^4 m.

10- to 20-foot Depth

Nearly 50 percent of the radii curvature lie in the 1×10^4-to 5×10^4-m range, figure 3. Only 5 percent of the rays follow a direct path.

20- to 30-foot Depth

At this depth 40 percent of the radii of curvature lie in the 1×10^4-to 5×10^4-m range, figure 4. The histogram is somewhat biased toward larger radii of curvature.

30- to 40-foot Depth

Although over 30 percent of the radii of curvature are in the 1×10^4 to 5×10^4 range, the histogram is strongly biased toward larger values of the radii of curvature, figure 5. Over 40 percent of the data have a radius of curvature greater than 1×10^4 m.

40- to 50-foot Depth

At this depth range, the radii of curvature are centered around the 1×10^5 to 5×10^5 range. Over 20 percent of the rays follow the direct path, figure 6.

50- to 60-foot Depth

Over 40 percent of the rays follow a direct path. It should be noted that 25 percent of the rays have a downward curvature, figure 7.

Ebb and Flood Tides

These two tides were analyzed by using only that data which were greater than a 3-foot or less than a 4-foot elevation. These data show a clustering around the 1×10^4-to 5×10^4-m radii of curvature range, figure 8.

High and Low Slack Water

These two conditions were analyzed by using only that data which were greater than 5-foot or less than a 2-foot elevation. These data show a clustering around the 1×10^4 to 5×10^4 radii with a slight bias toward the larger values, figure 9.

EFFECT OF RAY PATH CURVATURE

Deviation from Horizontal Path

Using a horizontal path length, 1127 m, and a radius of curvature of 5×10^4 m results in a deflection from the horizontal of 3.18 m, figure 10a. This path is the shortest one connecting the transducers on opposite ends of the measuring section. The next shortest ray is one which reflects off the water surface.

With a radius of curvature of 1×10^4 m, the shortest ray is one which reflects off the water surface one time, figure 10b. For a hydrophone set located 5.70 m below the water surface, the ray passes about 1.5 m below the horizontal before rising to reflect off the water surface. In this case, the total deflection is about 7.2 m vertically. The next shorter path has two reflections off the water surface. This ray traverses about 8.0 m vertically as it passes from one hydrophone to the other at the 5.7-m depth.

Using the curves of Smith 3/, the value of mean velocity correlation coefficient C will vary between 0.94 to 0.96 for a 1×10^4 radius of curvature and 1.02 to 1.04 for a 5×10^4 radius of curvature. The mean velocity correlation coefficient is defined as:

$$C = \frac{\overline{V}}{V_p} \qquad (5)$$

Where $\overline{V}$ = Q/A for the entire cross section
V_p = Line velocity over the selected acoustic path
Q = Total discharge
A = Total cross sectional flow area

Therefore, if the salinity and temperature gradients are not measured simultaneously with the acoustic velocity measurements, errors of ±5 percent in the total discharge may result as the shortest sound path is deflected either above or below the horizontal path.

Change in Path Length

The sound from a hydrophone occurs as a short burst of pulses at a specific frequency. One effect of rays following two separate paths is noticeable in the modulation of the received signal.

With a radius of curvature of 5×10^4 m, the two rays traveling on the shortest paths reach the receiving hydrophone with a 27-μ s delay, figure 10a. This delay would tend to eliminate the second pulse of a 20 kHz (50-μ s period) signal since the second pulse would be about 180° out of phase with the initial signal.

With a radius of curvature of 1×10^4 m, the two rays traveling on the shortest paths reach the receiving hydrophone with a 108-μ s delay. This delay would tend to amplify the second pulse since the two rays are approximately in phase.

The rays traveling on the shortest paths for the two radii of curvature experience a significant delay relative to the horizontal path. However, Smith 3/ has shown that these delays do not cause errors if the delay is the same in both travel directions.

3/ Smith, W., Feasibility Study of the Use of the Acoustic Velocity Meter for Measurement of Net Outflow From the Sacramento-San Joaquin Delta in California, Geological Survey Water-Supply Paper 1877, 1969, 54 pp.(see p. 25).

Reflection off Water Surface

At a low enough frequency and a sufficiently small grazing angle, the water surface can act as a nearly perfect reflector of sound. Urick 1/ states that the surface is essentially smooth if:

$$\lambda > 8 H \sin \theta \qquad (6)$$

Where λ = Wave length of acoustic signal
H = Wave height roughness
θ = Angle with which acoustic wave meets water surface

For both the 1×10^4 and the 5×10^4 radii of curvature ray paths, the grazing angle is approximately 1°. The wave length for a 20-kHz signal is 0.07 m with a 1487-m/s acoustic velocity. Substitution of these values into equation 6 shows that the water surface can be considered a smooth surface for wave roughness values less than 0.5 m.

CONCLUSIONS

1. For the majority of the measurements, salinity gradients will cause the acoustic rays to have a significant deflection.

2. The radius of curvature of the ray path will most probably lie between 1×10^4 and 5×10^4 m.

3. With a 1×10^4-m radius of curvature, the shortest ray path will lie almost entirely above the horizontal path. The ray will reflect off the water surface.

4. With a 5×10^4-m radius of curvature, the shortest ray path will lie entirely below the horizontal path.

5. Unless salinity and temperature gradients are measured coincidently with the acoustic velocity measurements, deflections of the acoustic path can introduce an error of ± 5 percent in the determination of the mean discharge.

6. Increases in the acoustic path length due to deflection of the ray will not introduce errors in the discharge determination.

Figure 1

ALL DATA

THE NUMBER OF SECTIONS = 4324

UPWARD CURVATURE OF ACOUSTIC RAY	
LESS THAN -1EXP6	.00
RANGE -5EXP5 TO -1EXP6	.00
RANGE -1EXP5 TO -5EXP5	.15
RANGE -5EXP4 TO -1EXP5	.12
RANGE -1EXP4 TO -5EXP4	.37
RANGE -5EXP3 TO -1EXP4	.11
RANGE -1EXP3 TO -5EXP3	.06
RANGE 1EXP3 TO -1EXP3	.00

DOWNWARD CURVATURE OF ACOUSTIC RAY	
RANGE 5EXP3 TO 1EXP3	.00
RANGE 1EXP4 TO 5EXP3	.00
RANGE 5EXP4 TO 1EXP4	.02
RANGE 1EXP5 TO 5EXP4	.02
RANGE 5EXP5 TO 1EXP5	.06
RANGE 1EXP6 TO 5EXP5	0.00

DIRECT PATH	
GREATER THAN 1EXP6	.10

HISTOGRAM

TOTAL NUMBER OF INCREMENTS = 13248

Figure 2

O TO 10·FT DEPTH SEGMENT

THE NUMBER OF SECTIONS = 4324

UPWARD CURVATURE OF ACOUSTIC RAY		HISTOGRAM
LESS THAN -1EXP6	0.00	
RANGE -5EXP5 TO -1EXP6	0.00	
RANGE -1EXP5 TO -5EXP5	.12	
RANGE -5EXP4 TO -1EXP5	.09	
RANGE -1EXP4 TO -5EXP4	.33	
RANGE -5EXP3 TO -1EXP4	.16	
RANGE -1EXP3 TO -5EXP3	.14	
RANGE 1EXP3 TO -1EXP3	.00	

DOWNWARD CURVATURE OF ACOUSTIC RAY

RANGE 5EXP3 TO 1EXP3	.00
RANGE 1EXP4 TO 5EXP3	.00
RANGE 5EXP4 TO 1EXP4	.02
RANGE 1EXP5 TO 5EXP4	.02
RANGE 5EXP5 TO 1EXP5	.05
RANGE 1EXP6 TO 5EXP5	0.00

DIRECT PATH

GREATER THAN 1EXP6 .07

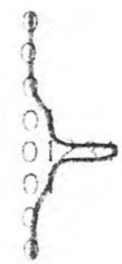
TOTAL NUMBER OF INCREMENTS = 3380

Figure 3

10- TO 20-FT DEPTH SEGMENT

THE NUMBER OF SECTIONS = 4324

UPWARD CURVATURE OF ACOUSTIC RAY		HISTOGRAM
LESS THAN -1EXP6	0.00	
RANGE -5EXP5 TO -1EXP6	.00	
RANGE -1EXP5 TO -5EXP5	.10	
RANGE -5EXP4 TO -1EXP5	.10	
RANGE -1EXP4 TO -5EXP4	.47	
RANGE -5EXP3 TO -1EXP4	.16	
RANGE -1EXP3 TO -5EXP3	.07	
RANGE 1EXP3 TO -1EXP3	0.00	



DOWNWARD CURVATURE OF ACOUSTIC RAY		
RANGE 5EXP3 TO 1EXP3	.00	
RANGE 1EXP4 TO 5EXP3	.00	
RANGE 5EXP4 TO 1EXP4	.01	
RANGE 1EXP5 TO 5EXP4	.01	
RANGE 5EXP5 TO 1EXP5	.03	
RANGE 1EXP6 TO 5EXP5	0.00	

DIRECT PATH

GREATER THAN 1EXP6	.05	

TOTAL NUMBER OF INCREMENTS = 3198

Figure 4

20- TO 30- FT DEPTH SEGMENT

THE NUMBER OF SECTIONS = 4324

UPWARD CURVATURE OF ACOUSTIC RAY	
LESS THAN -1EXP6	0.00
RANGE -5EXP5 TO -1EXP6	0.00
RANGE -1EXP5 TO -5EXP5	.16
RANGE -5EXP4 TO -1EXP5	.13
RANGE -1EXP4 TO -5EXP4	.41
RANGE -5EXP3 TO -1EXP4	.09
RANGE -1EXP3 TO -5EXP3	.02
RANGE 1EXP3 TO -1EXP3	0.00
DOWNWARD CURVATURE OF ACOUSTIC RAY	
RANGE 5EXP3 TO 1EXP3	.00
RANGE 1EXP4 TO 5EXP3	.00
RANGE 5EXP4 TO 1EXP4	.02
RANGE 1EXP5 TO 5EXP4	.02
RANGE 5EXP5 TO 1EXP5	.05
RANGE 1EXP6 TO 5EXP5	0.00
DIRECT PATH	
GREATER THAN 1EXP6	.08

HISTOGRAM

TOTAL NUMBER OF INCREMENTS = 3081

Figure 5

30- TO 40-FT DEPTH SEGMENT

THE NUMBER OF SECTIONS = 4324

HISTOGRAM

UPWARD CURVATURE OF ACOUSTIC RAY

LESS THAN -1EXP6	.00
RANGE -5EXP5 TO -1EXP6	0.00
RANGE -1EXP5 TO -5EXP5	.20
RANGE -5EXP4 TO -1EXP5	.14
RANGE -1EXP4 TO -5EXP4	.32
RANGE -5EXP3 TO -1EXP4	.04
RANGE -1EXP3 TO -5EXP3	.01
RANGE 1EXP3 TO -1EXP3	0.00

DOWNWARD CURVATURE OF ACOUSTIC RAY

RANGE 5EXP3 TO 1EXP3	.00
RANGE 1EXP4 TO 5EXP3	.00
RANGE 5EXP4 TO 1EXP4	.03
RANGE 1EXP5 TO 5EXP4	.03
RANGE 5EXP5 TO 1EXP5	.08
RANGE 1EXP6 TO 5EXP5	0.00

DIRECT PATH

GREATER THAN 1EXP6	.14

TOTAL NUMBER OF INCREMENTS = 2254

Figure 6

40- TO 50-FT DEPTH SEGMENT

THE NUMBER OF SECTIONS = 4324

UPWARD CURVATURE OF ACOUSTIC RAY		HISTOGRAM
LESS THAN -1EXP6	0.00	
RANGE -5EXP5 TO -1EXP6	0.00	
RANGE -1EXP5 TO -5EXP5	.23	
RANGE -5EXP4 TO -1EXP5	.13	
RANGE -1EXP4 TO -5EXP4	.17	
RANGE -5EXP3 TO -1EXP4	.01	
RANGE -1EXP3 TO -5EXP3	.00	
RANGE 1EXP3 TO -1EXP3	.00	

DOWNWARD CURVATURE OF ACOUSTIC RAY	
RANGE 5EXP3 TO 1EXP3	0.00
RANGE 1EXP4 TO 5EXP3	0.00
RANGE 5EXP4 TO 1EXP4	.06
RANGE 1EXP5 TO 5EXP4	.04
RANGE 5EXP5 TO 1EXP5	.13
RANGE 1EXP6 TO 5EXP5	0.00

DIRECT PATH

GREATER THAN 1EXP6 .23

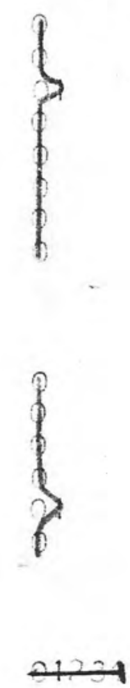
TOTAL NUMBER OF INCREMENTS = 1227

Figure 7

50- TO 60-FT DEPTH SEGMENT

THE NUMBER OF SECTIONS = 4324

UPWARD CURVATURE OF ACOUSTIC RAY		HISTOGRAM
LESS THAN -1EXP6	0.00	
RANGE -5EXP5 TO -1EXP6	0.00	
RANGE -1EXP5 TO -5EXP5	.16	
RANGE -5EXP4 TO -1EXP5	.09	
RANGE -1EXP4 TO -5EXP4	.09	
RANGE -5EXP3 TO -1EXP4	0.00	
RANGE -1EXP3 TO -5EXP3	0.00	
RANGE 1EXP3 TO -1EXP3	0.00	
DOWNWARD CURVATURE OF ACOUSTIC RAY		
RANGE 5EXP3 TO 1EXP3	.02	
RANGE 1EXP4 TO 5EXP3	.01	
RANGE 5EXP4 TO 1EXP4	.01	
RANGE 1EXP5 TO 5EXP4	.02	
RANGE 5EXP5 TO 1EXP5	.19	
RANGE 1EXP6 TO 5EXP5	0.00	
DIRECT PATH		
GREATER THAN 1EXP6	.42	



TOTAL NUMBER OF INCREMENTS = 108

Figure 8

EBB & FLOOD TIDES

THE NUMBER OF SECTIONS = 4324

UPWARD CURVATURE OF ACOUSTIC RAY

HISTOGRAM

LESS THAN -1EXP6	.00
RANGE -5EXP5 TO -1EXP6	.00
RANGE -1EXP5 TO -5EXP5	.13
RANGE -5EXP4 TO -1EXP5	.10
RANGE -1EXP4 TO -5EXP4	.40
RANGE -5EXP3 TO -1EXP4	.16
RANGE -1EXP3 TO -5EXP3	.07
RANGE 1EXP3 TO -1EXP3	0.00

DOWNWARD CURVATURE OF ACOUSTIC RAY

RANGE 5EXP3 TO 1EXP3	.00
RANGE 1EXP4 TO 5EXP3	.00
RANGE 5EXP4 TO 1EXP4	.01
RANGE 1EXP5 TO 5EXP4	.01
RANGE 5EXP5 TO 1EXP5	.05
RANGE 1EXP6 TO 5EXP5	0.00

DIRECT PATH

GREATER THAN 1EXP6	.08

TOTAL NUMBER OF INCREMENTS = 3491

Figure 9

HIGH & LOW SLACK WATER

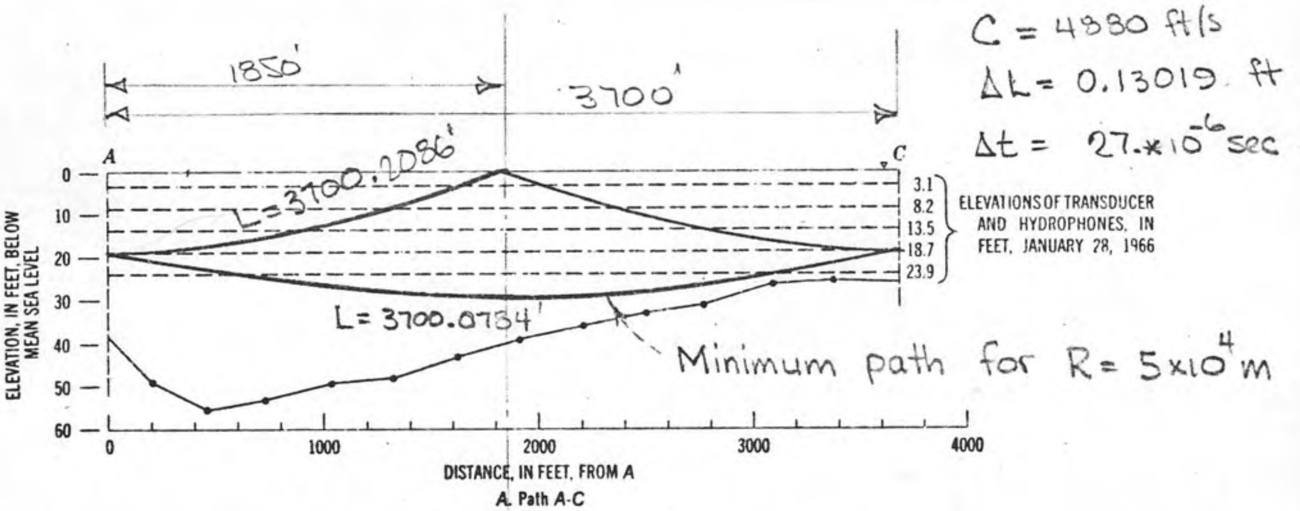
THE NUMBER OF SECTIONS = 4324

UPWARD CURVATURE OF ACOUSTIC RAY	
LESS THAN -1EXP6	0.00
RANGE -5EXP5 TO -1EXP6	0.00
RANGE -1EXP5 TO -5EXP5	.16
RANGE -5EXP4 TO -1EXP5	.13
RANGE -1EXP4 TO -5EXP4	.33
RANGE -5EXP3 TO -1EXP4	.07
RANGE -1EXP3 TO -5EXP3	.07
RANGE 1EXP3 TO -1EXP3	.00
DOWNWARD CURVATURE OF ACOUSTIC RAY	
RANGE 5EXP3 TO 1EXP3	.00
RANGE 1EXP4 TO 5EXP3	.00
RANGE 5EXP4 TO 1EXP4	.03
RANGE 1EXP5 TO 5EXP4	.03
RANGE 5EXP5 TO 1EXP5	.07
RANGE 1EXP6 TO 5EXP5	0.00
DIRECT PATH	
GREATER THAN 1EXP6	.11

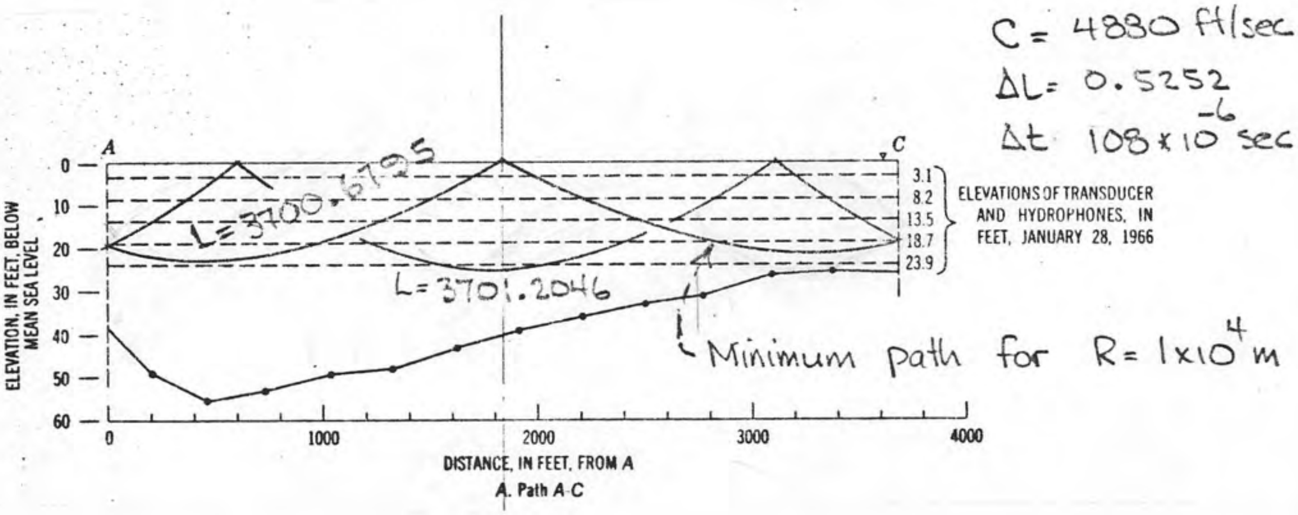
HISTOGRAM

TOTAL NUMBER OF INCREMENTS = 4543

Figure 10



a. $R = 5 \times 10^4$ m



b. $R = 1 \times 10^4$ m

APPENDIX I

Computer Program to Determine the Radius of Curvature of an Acoustic Ray Due to Salinity Gradients

```
      PROGRAM HFSAC(HFSFD1,HFSFD,HFSFD3,OUTPUT,TAPE3=HFSFD,
     +TAPE1=HFSFD1,TAPE2=HFSFD3,TAPE5=OUTPUT)
C
C     PROGRAM TO DETERMINE A HISTOGRAM OF THE ACOUSTIC RADIUS OF
C     CURVATURE FOR DATA FROM THE SACRAMENTO-SAN JOAQINE DELTA
C     STUDY.
C
C
      DIMENSION N(15),S(7),RN(15)
      DATA N/15*0/
      NUM= 10H0123456789
      NR= 1
C
C     DO LOOP TO READ IN DATA
C
      DO 12 I=1,5000
        GO TO (1,3,5)NR
    1   READ(1,6)D,(S(J),J=1,7)
        IF(EOF(1))2,7
    2   NR= 2
    3   READ(2,6)D,(S(J),J=1,7)
        IF(EOF(2))4,7
    4   NR= 3
    5   READ(3,6)D,(S(J),J=1,7)
    6   FORMAT(12X,F4.1,4X,7F8.0)
        IF(EOF(3))13,7
C
C       DO LOOP TO REDUCE READINGS TO G/KG AND TO ELIMINATE
C       THE ZEROS BETWEEN THE LAST DATA POINT AND THE BED
C
C   7   IF(D.LT.(5.).AND.D.GT.(2.))GO TO 12
C   7   IF(D.GT.(4.).OR.D.LT.(3.))GO TO 12
    7   DO 8 K=1,7
          S(K)= S(K)/1000.
          IF(ABS(S(K)).LE.0.001)GO TO 9
    8   CONTINUE
        GO TO 10
    9   IF(S(1).LE.0.001)GO TO 12
        SSAV= S(7)/1000.
        IF(S(6).LE.0.001)S(7)= 0.
        S(K)= SSAV
C
C       DO LOOP TO COMPUTE THE RADIUS OF CURVATURE OF THE ACOUSTIC
C       PATH.  TEMPERATURE GRADIENTS AND DEPTH GRADIENT EFFECTS ARE
C       NEGLECTED.  THE DISTANCE BETWEEN THE LAST DATA POINT AND
C       THE BED IS ASSUMED TO BE 10 FEET.  THE EQUATION USED HERE
C       HAS BEEN CONVERTED TO METRIC UNITS.
C
   10   DO 11 J=2,K
          IF(S(J).LE.0.001)GO TO 12
          DELTS= S(J)-S(J-1)
          IF(ABS(DELTS).LE.1.E-10)DELTS= -1.E-05
          R= -3911./DELTS
```

```
C
C        COUNTING OF DATA IN APPROPRIATE RANGES
C
         IF(R.LE.(-1.E+06))N(1)= N(1)+1
         IF(R.LE.(-5.E+05).AND.R.GT.(-1.E+06))N(2)= N(2)+1
         IF(R.LE.(-1.E+05).AND.R.GT.(-5.E+05))N(3)= N(3)+1
         IF(R.LE.(-5.E+04).AND.R.GT.(-1.E+05))N(4)= N(4)+1
         IF(R.LE.(-1.E+04).AND.R.GT.(-5.E+04))N(5)= N(5)+1
         IF(R.LE.(-5.E+03).AND.R.GT.(-1.E+04))N(6)= N(6)+1
         IF(R.LE.(-1.E+03).AND.R.GT.(-5.E+03))N(7)= N(7)+1
         IF(R.LE.(+1.E+03).AND.R.GT.(-1.E+03))N(8)= N(8)+1
         IF(R.LE.(+5.E+03).AND.R.GT.(+1.E+03))N(9)= N(9)+1
         IF(R.LE.(+1.E+04).AND.R.GT.(+5.E+03))N(10)= N(10)+1
         IF(R.LE.(+5.E+04).AND.R.GT.(+1.E+04))N(11)= N(11)+1
         IF(R.LE.(+1.E+05).AND.R.GT.(+5.E+04))N(12)= N(12)+1
         IF(R.LE.(+5.E+05).AND.R.GT.(+1.E+05))N(13)= N(13)+1
         IF(R.LE.(+1.E+06).AND.R.GT.(+5.E+05))N(14)= N(14)+1
         IF(R.GT.(+1.E+06))N(15)= N(15)+1
   11   CONTINUE
   12 CONTINUE
C
C     DO LOOP TO MAKE HISTOGRAM DIMENSIONLESS
C
   13 NSUM= N(1)+N(2)+N(3)+N(4)+N(5)+N(6)+N(7)+N(8)+N(9)+
     +N(10)+N(11)+N(12)+N(13)+N(14)+N(15)
      IF(NSUM.EQ.0)NSUM= 1
      DO 14 M=1,15
        RN(M)= FLOAT(N(M))/FLOAT(NSUM)
        N(M)= IFIX(10.*RN(M))+1
   14 CONTINUE
C
C     OUTPUT OF DATA
C
      WRITE(5,15)I,(RN(M),N(M),NUM,M=1,15),NSUM
   15 FORMAT(1H1,10X,25HTHE NUMBER OF SECTIONS = ,I4//
     +         9X,32HUPWARD CURVATURE OF ACOUSTIC RAY ,7X,9HHISTOGRAM //
     +         10X,16HLESS THAN -1EXP6 ,6X,F8.2,T50,A= /
     +         10X,22HRANGE -5EXP5 TO -1EXP6 ,F8.2,T50,A= /
     +         10X,22HRANGE -1EXP5 TO -5EXP5 ,F8.2,T50,A= /
     +         10X,22HRANGE -5EXP4 TO -1EXP5 ,F8.2,T50,A= /
     +         10X,22HRANGE -1EXP4 TO -5EXP4 ,F8.2,T50,A= /
     +         10X,22HRANGE -5EXP3 TO -1EXP4 ,F8.2,T50,A= /
     +         10X,22HRANGE -1EXP3 TO -5EXP3 ,F8.2,T50,A= /
     +         10X,22HRANGE  1EXP3 TO -1EXP3 ,F8.2,T50,A= //
     +         8X,34HDOWNWARD CURVATURE OF ACOUSTIC RAY //
     +         10X,22HRANGE  5EXP3 TO  1EXP3 ,F8.2,T50,A= /
     +         10X,22HRANGE  1EXP4 TO  5EXP3 ,F8.2,T50,A= /
     +         10X,22HRANGE  5EXP4 TO  1EXP4 ,F8.2,T50,A= /
     +         10X,22HRANGE  1EXP5 TO  5EXP4 ,F8.2,T50,A= /
     +         10X,22HRANGE  5EXP5 TO  1EXP5 ,F8.2,T50,A= /
     +         10X,22HRANGE  1EXP6 TO  5EXP5 ,F8.2,T50,A= //
     +         19X,11HDIRECT PATH//
     +         10X,18HGREATER THAN 1EXP6 ,4X,F8.2,T50,A=//
     +         11X,29HTOTAL NUMBER OF INCREMENTS = , I5///)
      CALL EXIT
      END
```

OPTIONAL FORM NO. 10
JULY 1973 EDITION
GSA FPMR (41 CFR) 101-11.6

UNITED STATES GOVERNMENT

Memorandum

TO : Memorandum Files

Denver, Colorado
DATE: September 12, 1980

FROM : Henry T. Falvey, Technical Specialist

SUBJECT: Effects of Salinity and Temperature Gradients on Deflection of Acoustic Wave in the Sacramento-San Joaquin Delta

BACKGROUND

An analysis made February 20, 1980, of salinity gradients showed that significant errors in the instantaneous line velocity measurement were possible. The present study investigates the combined effect of salinity and temperature gradients on the accuracy of the acoustic velocity meter.

The effect of salinity is to increase the fluid density. This results in the sound velocity increasing as the salinity increases. Increasing the water temperature decreases its density. By analogy with the salinity, it would be expected that the sonic velocity should decrease. However, within limits the increased molecular activity of the higher temperature water evidently causes the sonic velocity to increase as the water temperature increases. The maximum sonic velocity occurs at a water temperature of about 49 °C. Above this temperature, the sonic velocity decreases (fig. 1). Various equations have been proposed to predict the sonic velocity in water. For sea water, Wilson (1960) proposed the equation (neglecting higher than second order terms)

$$V_S = 1449.22 + 4.623T - 0.0546T^2 + 1.391(S - 35) + 0.016h \qquad (1)$$

where T = temperature, degres Celsius
S = salinity, parts per thousand
h = depth, meters

This equation underpredicts the sonic velocity for pure water. Cole (1979) proposed the following equation, which is a good approximation for temperatures around 10 °C,

$$V_S = 1415.5 + 1.135 + 3.627T + 0.018h \qquad (2)$$

where T = temperature, degrees Celsius
S = salinity, parts per thousand
h = depth, meters

A better approximation for mean temperature in the 20 °C range is

$$V_S = 1421.9 + 2.458T + 1.13S + 0.018h \qquad (3)$$

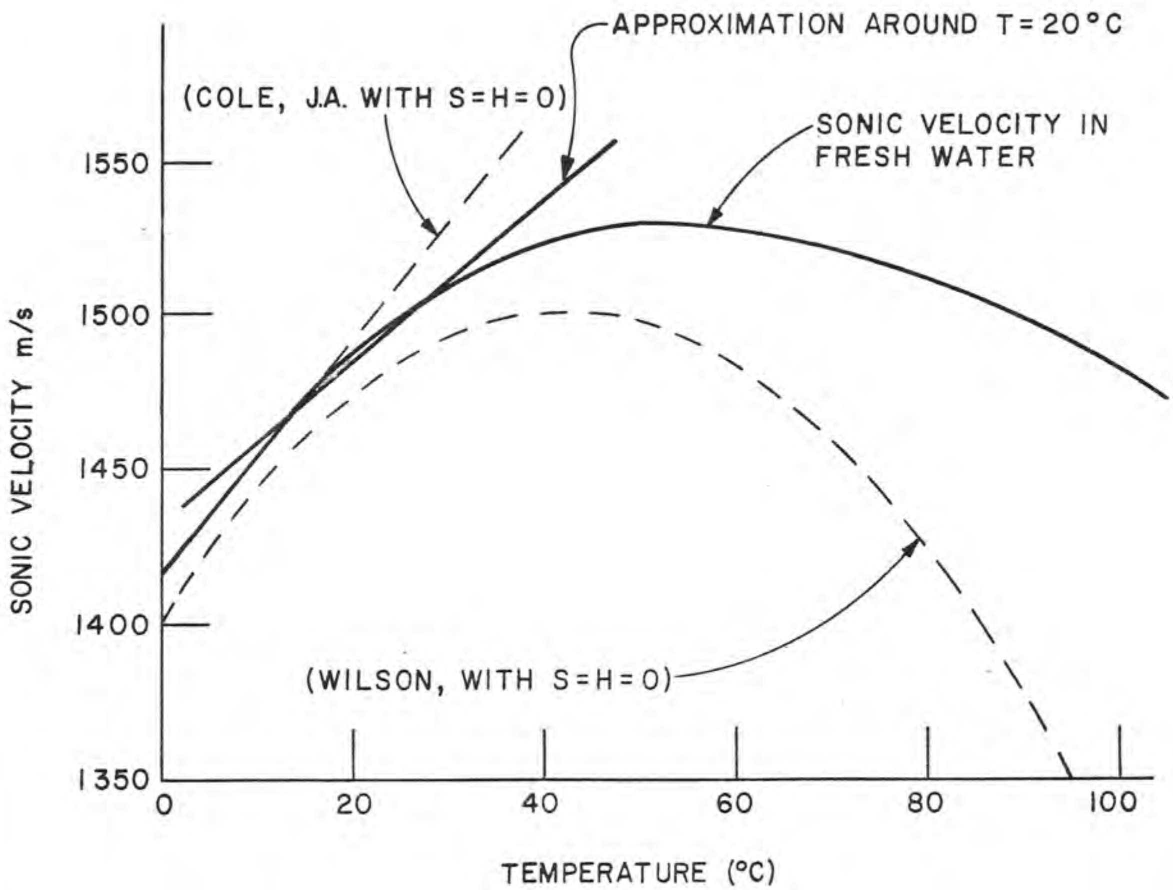


Figure 1. - Sonic velocity in fresh water.

The use of this latter equation results the following equation for the radius of curvature of the ray path in the presence of a linear gradient;

$$R = -\frac{1421.9 + 2.458T + 1.13S + 0.018h}{2.458\frac{dT}{dy} + 1.13\frac{dS}{dy} + 0.018} \qquad (4)$$

With T = 20 °C, S = 0, h = 0, equation 4 can be approximated by

$$R = -\frac{1470}{2.458\frac{dT}{dy} + 1.13\frac{dS}{dy} + 0.018} \qquad (5)$$

Equation 4 was used in this study to estimate the curvature of the ray paths.

ANALYSIS

The data on salinity and temperature in the Sacramento River were obtained from a piling which had been instrumented by the Corps of Engineers. The piling is located about 400 m downstream from the proposed measuring site at Chipps Island. Temperatures and salinities were measured at three elevations on the piling. The measuring points were 0.9, 3.0, and 5.2 m from the bottom of the piling which was placed at a 7.2-m mean depth. Although the measurements were made every half hour, only the hourly data were analyzed.

The measurements began on the 159th Julian day in 1979 (June 8) and continued until the 273rd day (September 30). Several gaps were noted in the data, (fig. 2). The longest of these was a 23-day record which was missing from August 30 to September 22. The next biggest gap was a 13-day record from June 20 to July 4.

The record from the upper temperature gage during the period July 4 to July 18 appears to be incorrect. The temperature gradients for this period are approximately 5 times larger than the gradients for the remainder of the record. Since the period July 4 to July 18 appeared to be anomalous it was deleted from the record (see fig. 5A).

The goal of this study was to investigate the combined effects of salinity and temperature. However, before the results of measurements from the piling could be extrapolated to the entire river cross section, it was necessary to verify that the piling measurements were representative of the cross section. This verification was accomplished by comparing the piling and river histograms using only the salinity data. Some differences in the two histograms were expected since the piling data extended over a 4-month period, whereas, the river data corresponded with only the last month of the piling data series. Thus, seasonal effects could be present in the piling data. For this verification, the 2.0 to 6.3 m depth range from the piling data was compared to the 3.0 to 6.1 m depth range of the river data, figure 3. Statistical errors due to unequal numbers of data samples were minimal since the size of the piling and river data samples were approximately equal; 2,955 increments for the piling data and 3,198 increments for the river data.

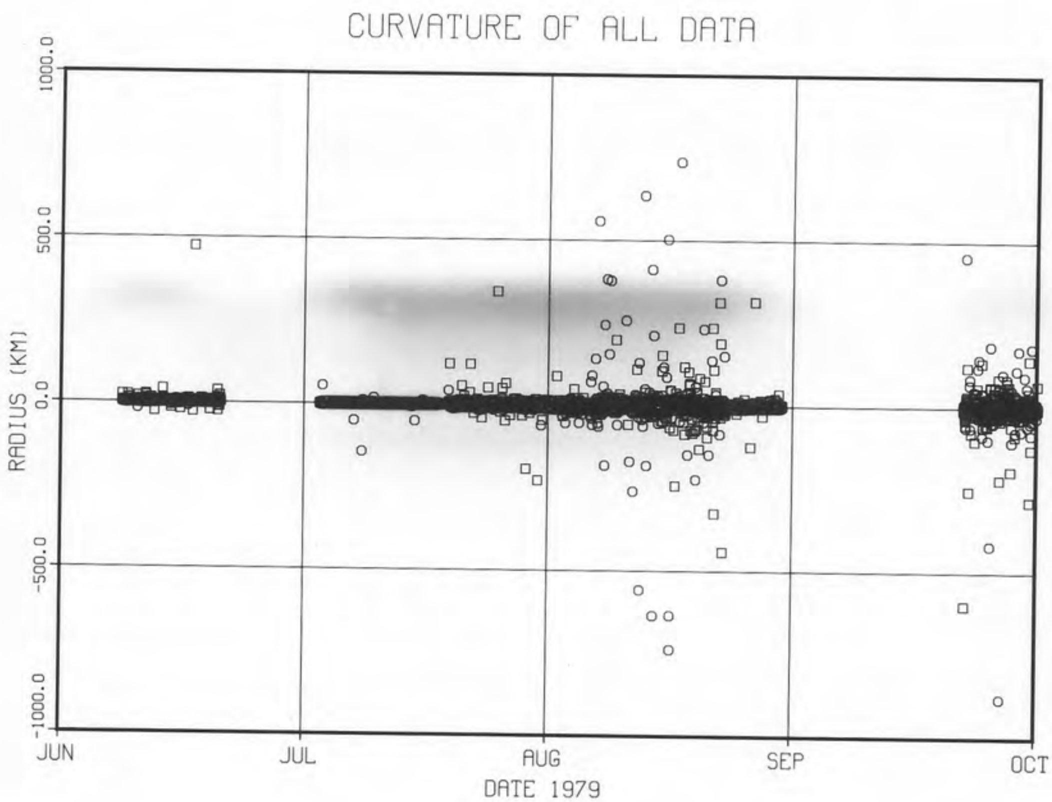


Figure 2. - Radii of curvature of acoustic paths.

Seasonal, tidal, and daily variations in the radii of curvature was investigated by calculating an autocorrelation of the data. One-hour steps were used to reveal daily variations over a period which had a continuous record of about 35 days. Because of gaps in the rest of the data it was not possible to extend the analysis to monthly variations. The reason for this analysis was to reveal whether or not the acoustic ray would consistantly bend upward, or downward, over a preiod of several hours or more.

RESULTS

Salinity Histograms of River and Piling Data

The predominant feature of the river histogram was a significant peak which corresponded to an upward radius of curvature of 2.5 by 10^4 m, figure 3A. This peak was also present in the pilng data, figure 3B.

A significant difference in the two histograms is the larger number of downward curving rays from the piling data. This indicates that an unstable salinity gradient (salinity decreasing with depth) is more likely to develop near the riverbank than in the mainstream.

This comparison was not as good as could be desired. Therefore, generalizing the conclusions reached from the piling data to the entire river should be done with some caution.

Combined Effects of Salinity and Temperature

Although the values of the radii of curvature scatter to very large magnitudes, figure 2, the majority of the values are contained within ± 50 km, figure 4. An examination of the radii of curvature obtained from the top and middle transducers on the pile show a pronounced tendancy for downward curving ray (positive values). Between the middle and bottom transducers, the ray curvature is more or less evenly distributed between upward and downward curving paths, figure 5.

A histogram of all the curvatures shows that the mean radius of the upward curving ray is about 4 km and that of the downward curving ray is 2.5 km, figure 6. Twice as many downward as upward curving rays occur. This implies that temperature effects were more significant than salinity during the entire test period. This effect is undoubtedly seasonal. An indication of the seasonal nature of the downward curving paths can be seen from the radii versus time plots, figure 5. At the end of September, the upward and downward curving rays are about evenly distributed. However, in June the preponderance of the rays have a downward or positive curvature.

Probable Acoustic Paths

An upward curving path having a radius of curvature of 5 km and starting at a 4-m depth will experience several reflections off the water surface, figure 7. With this radius of curvature and a grazing angle at the water surface of 2.6°, near perfect reflections of the signal will occur for crest to trough wave heights less than 0.4 m.

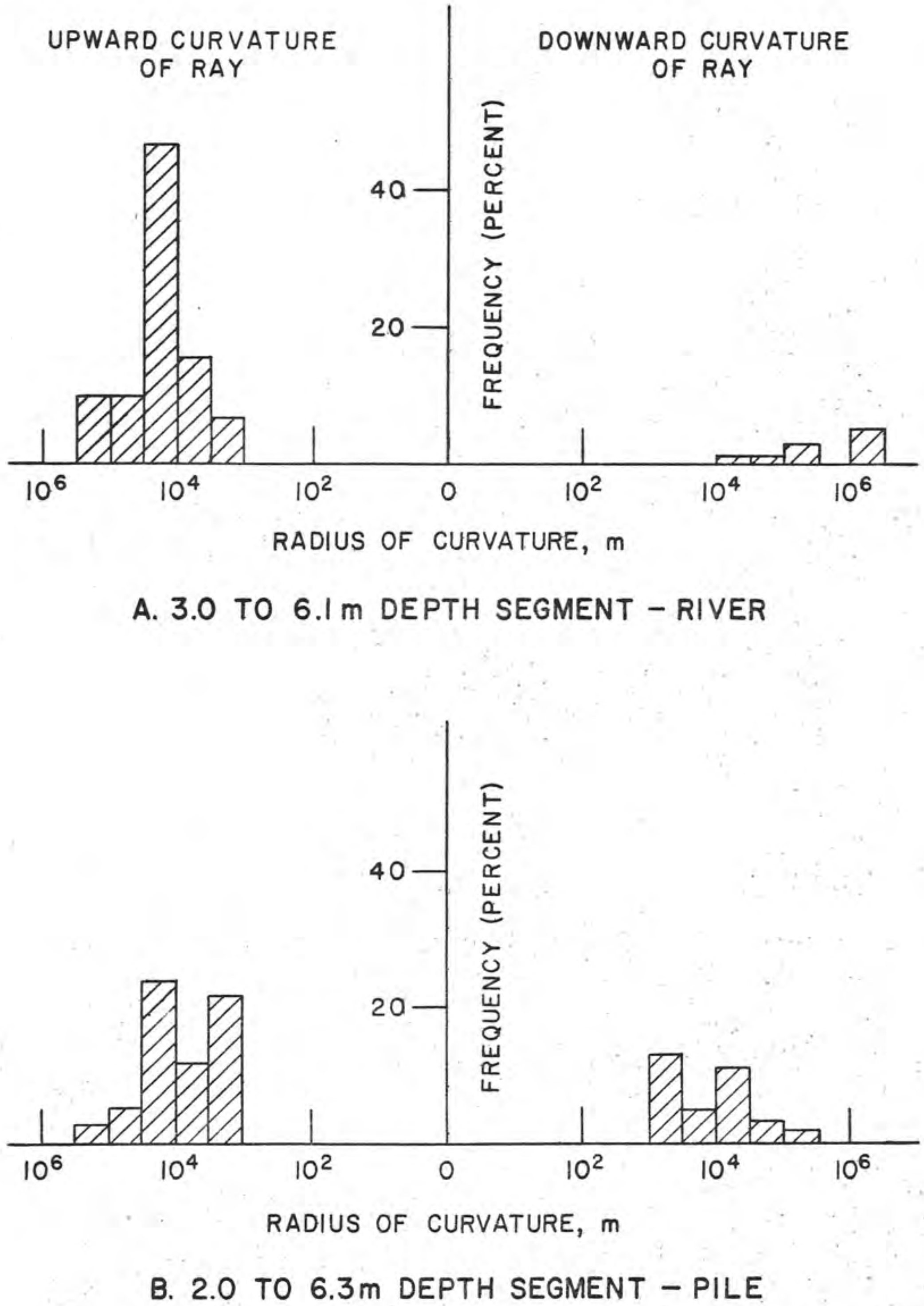


Figure 3. - Histogram considering only salinity effects.

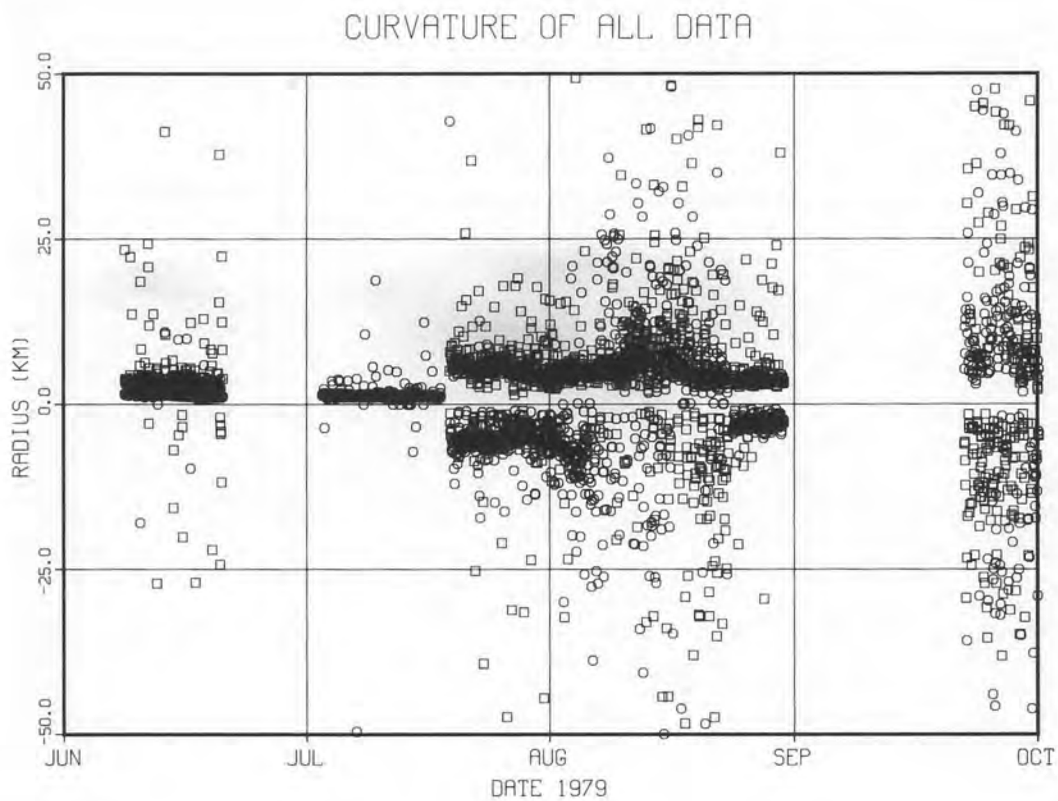
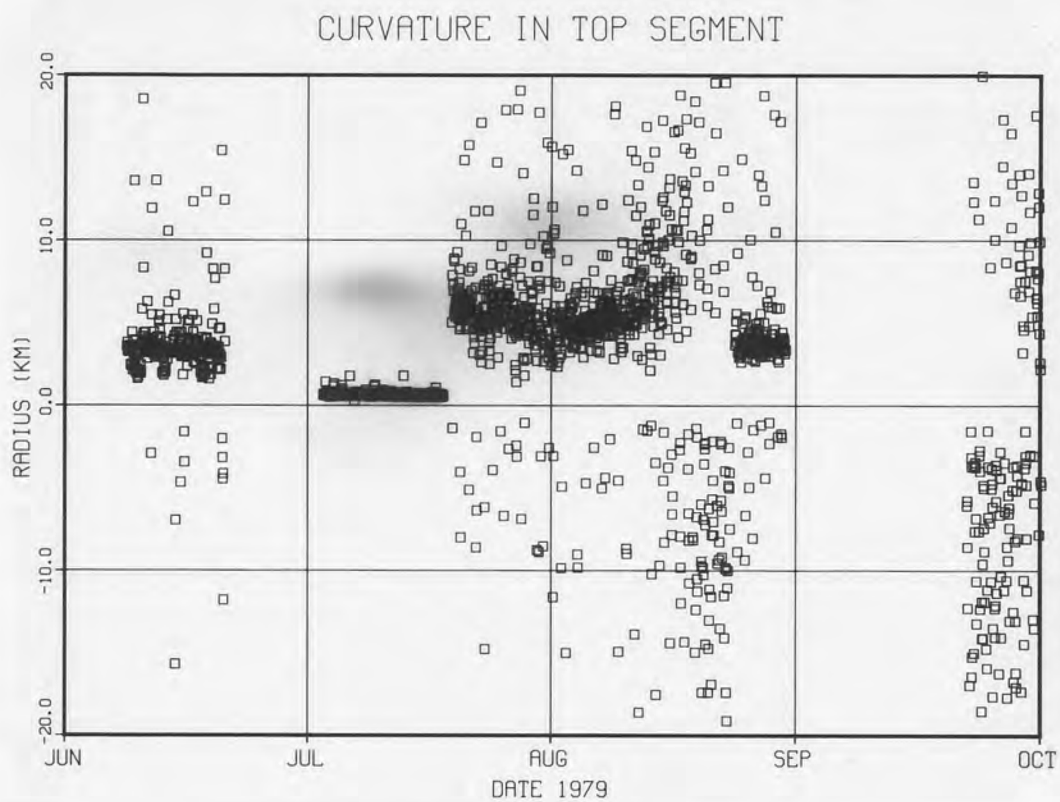


Figure 4. - Radii of curvature of acoustic paths.



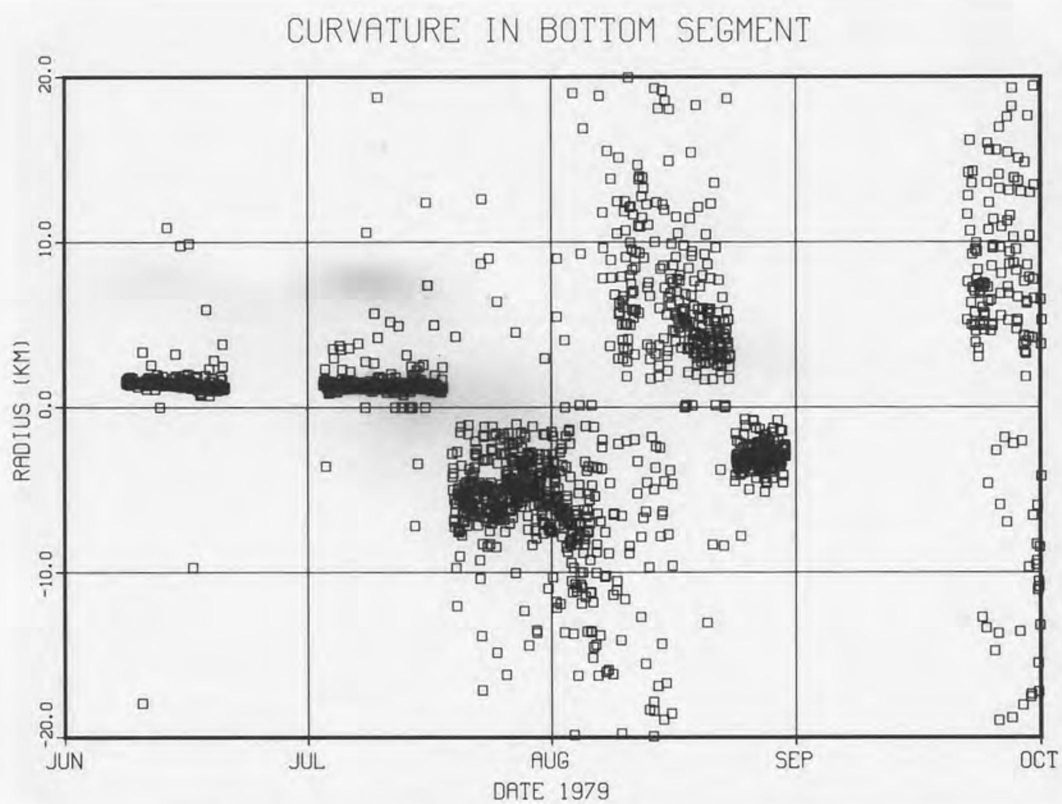


Figure 5. - Curvature of acoustic path.

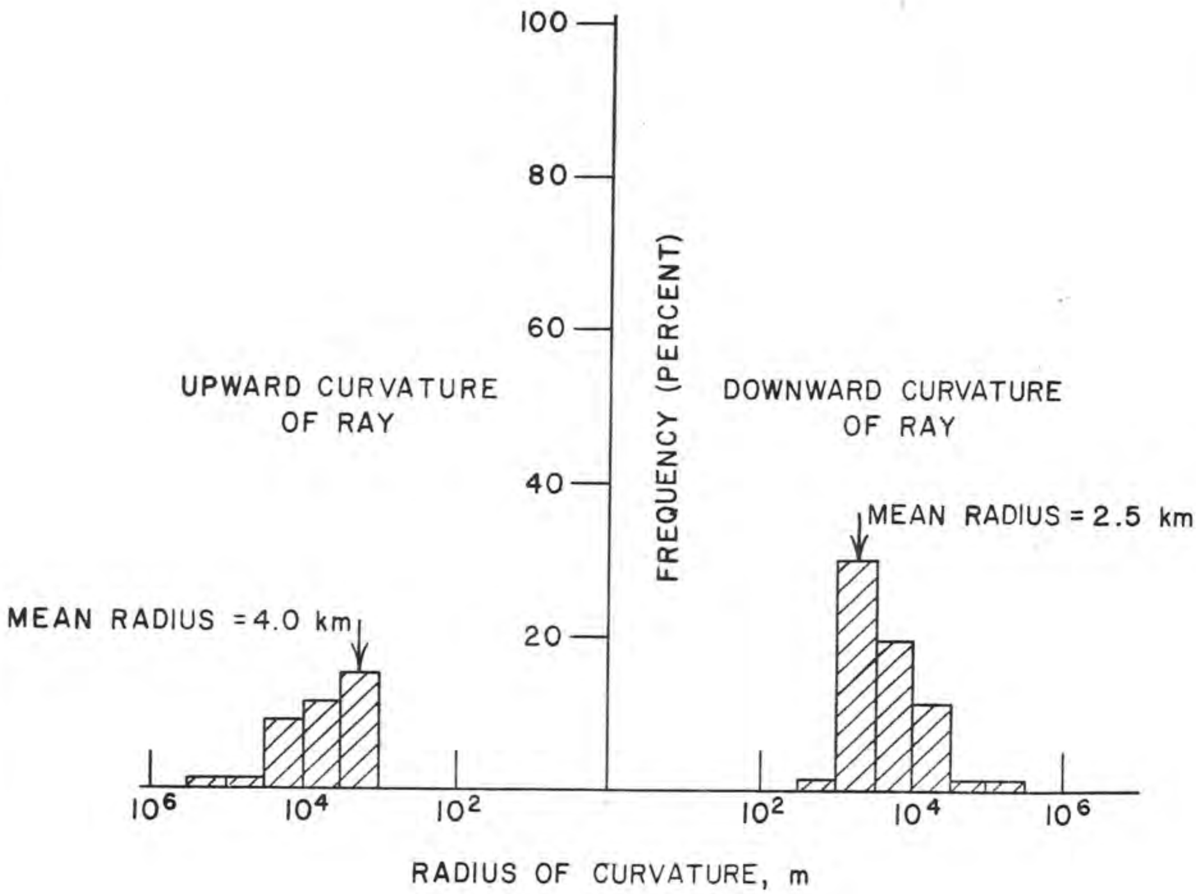
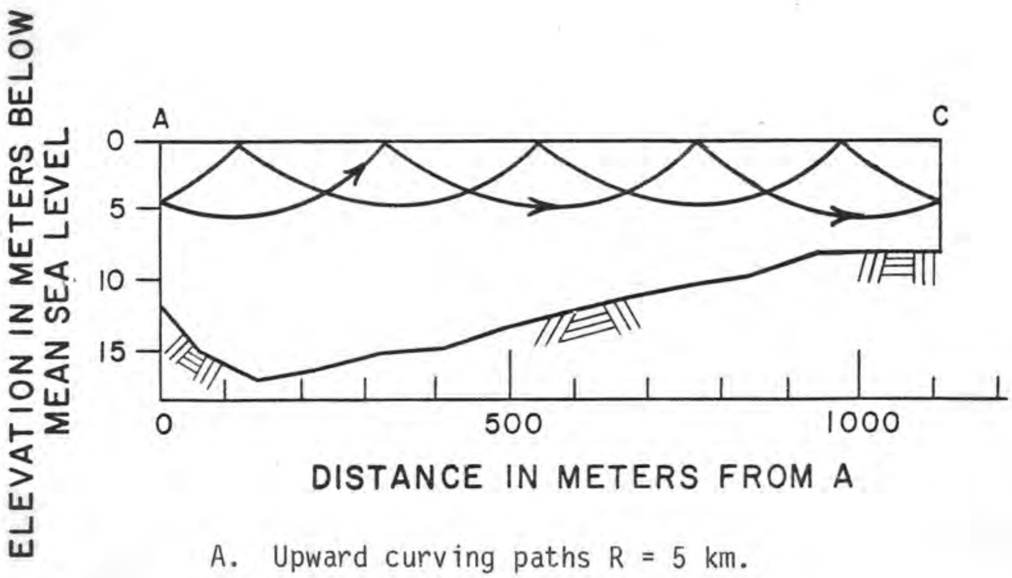
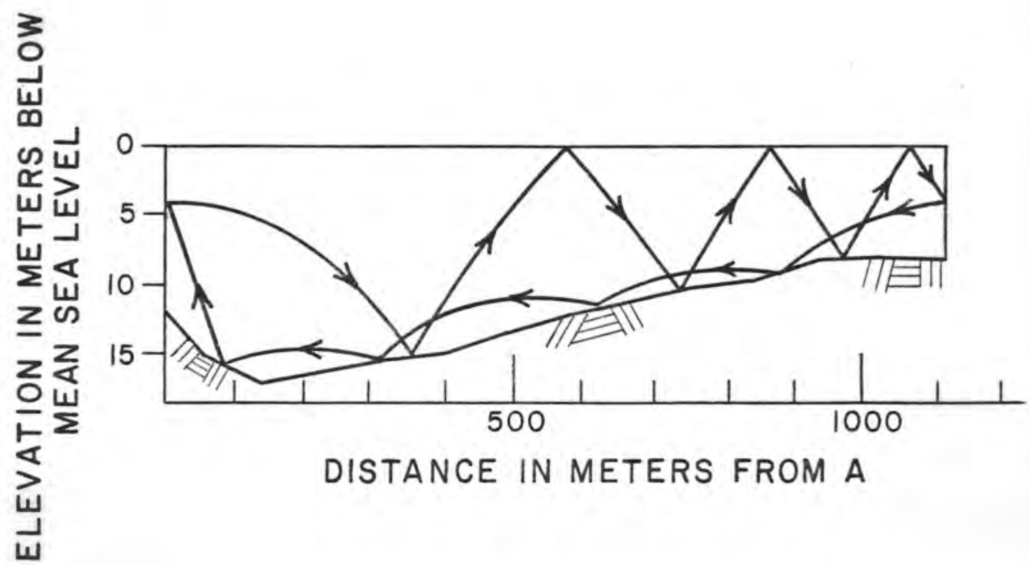


Figure 6. - Combined effect of temperature and salinity.



A. Upward curving paths R = 5 km.



B. Downward curving paths R = 5 km.

Figure 7

A downward curving path with a radius of curvature of 5 km and starting at a 4-m depth will experience several reflections off the riverbed. The number of reflections and the path taken is a function of the direction of the signal, figure 7. For instance, signals going from A to C will tend to reflect alternatively off the water surface and the riverbed. Whereas, signals going from C to A will tend to remain close to the riverbed. The angle that the ray makes with the bed at the point of reflection accounts for the difference in the ray paths. Significant attenuation of the signal during periods having downward curvatures can be expected.

Temporal Variations in Radii of Curvature

Due to tidal cycles and the diurnal variation a temporal correlation in the data was expected. To analyze this an autocorrelation of the data was performed. This type of analysis requires data spaced at equal time increments. The longest continuous data record was from July 19 to August 23. For each time increment the radius of curvature was computed using the top and bottom set of transducers on the pile. If data from one of the transducers were missing, the previous radius of curvature was used to fill in the missing data.

The histograms indicated very few radii of curvature greater than 50 km. These points appear as anomalies on a radius versus time plot. Therefore, to obtain better values for analysis, all radii with values greater than 50 km were replaced with an average of the previous and succeeding data point values (fig. 8).

The autocorrelation of the radii shows that there is very little persistence in the values for times longer than 2 hours, figure 9. In other words, there is no long term systematic variation in the curvatures. If the radius is positive over a 2 hour period, it is likely to be negative over the next, etc.

The spectrum of the autocorrelation function can be used to reveal cyclical variations in the curvatures, figure 10. The frequency scale is in cycles per day. The accuracy of these cycles is somewhat poor because the data record length is short. However, the spectrum indicates peaks at cycles which have periods of 2 days, daily, as well as, 12, 8, 6, and 5 hours. The large amplitude at low frequencies indicates that seasonal periods may be significant.

METHODS TO REDUCE ERRORS

Shorten path length

One method of eliminating multiple reflected rays is to shorten the path length. The relative deflection of the path is given by

$$D/L = R/L\ (1 - \sqrt{1 - 1/4(L/R)^2}) \qquad (6)$$

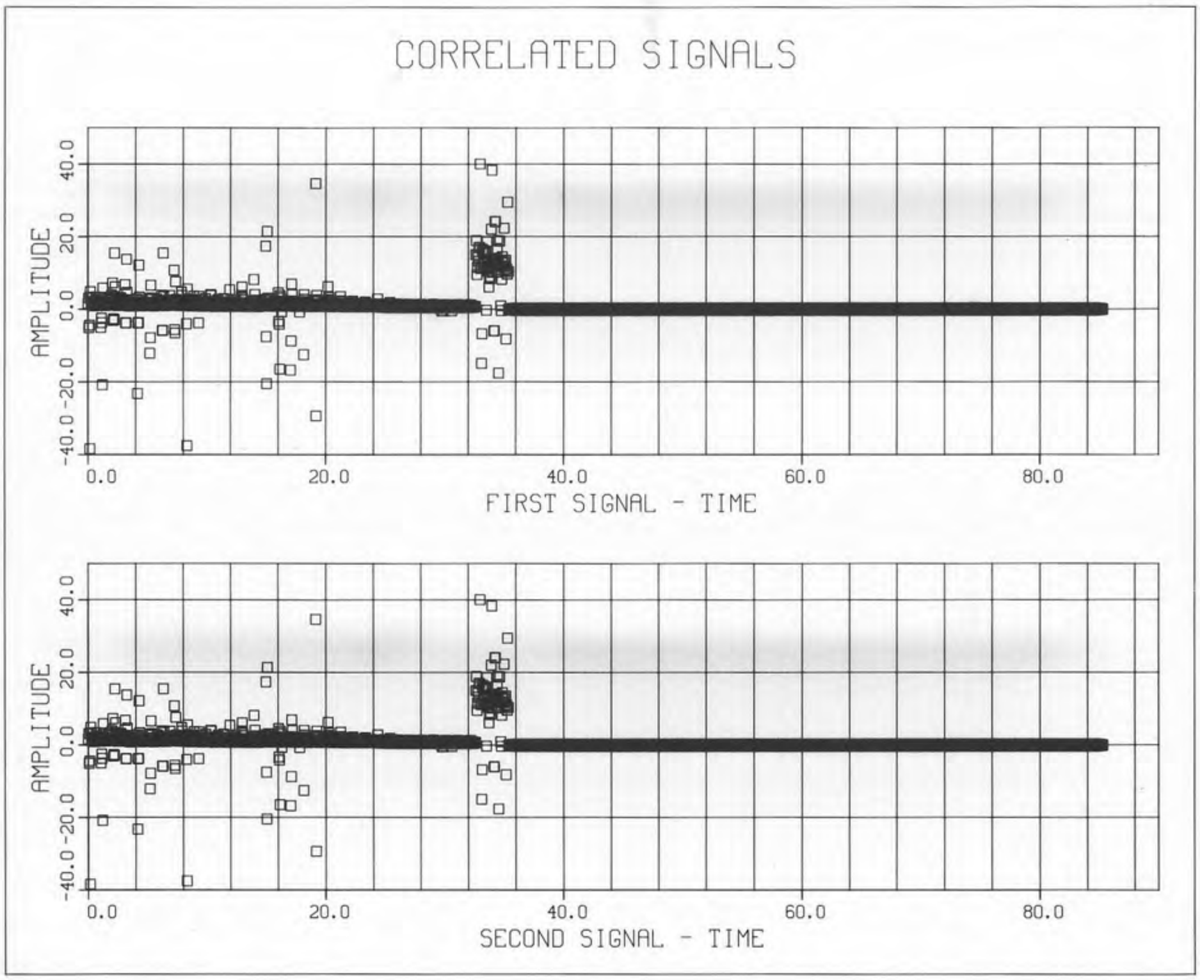


Figure 8. - Correlated signal.

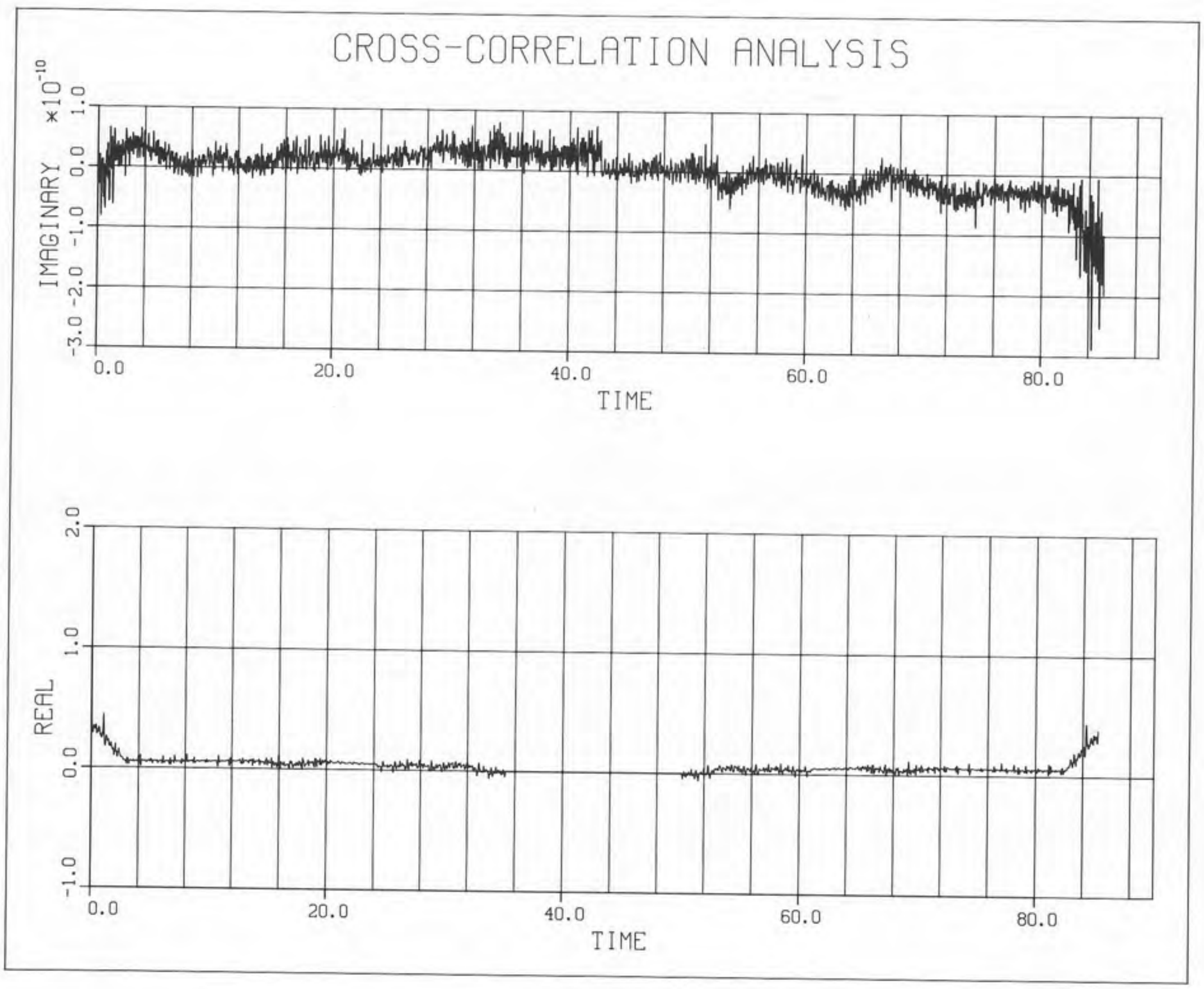


Figure 9. - Cross correlation.

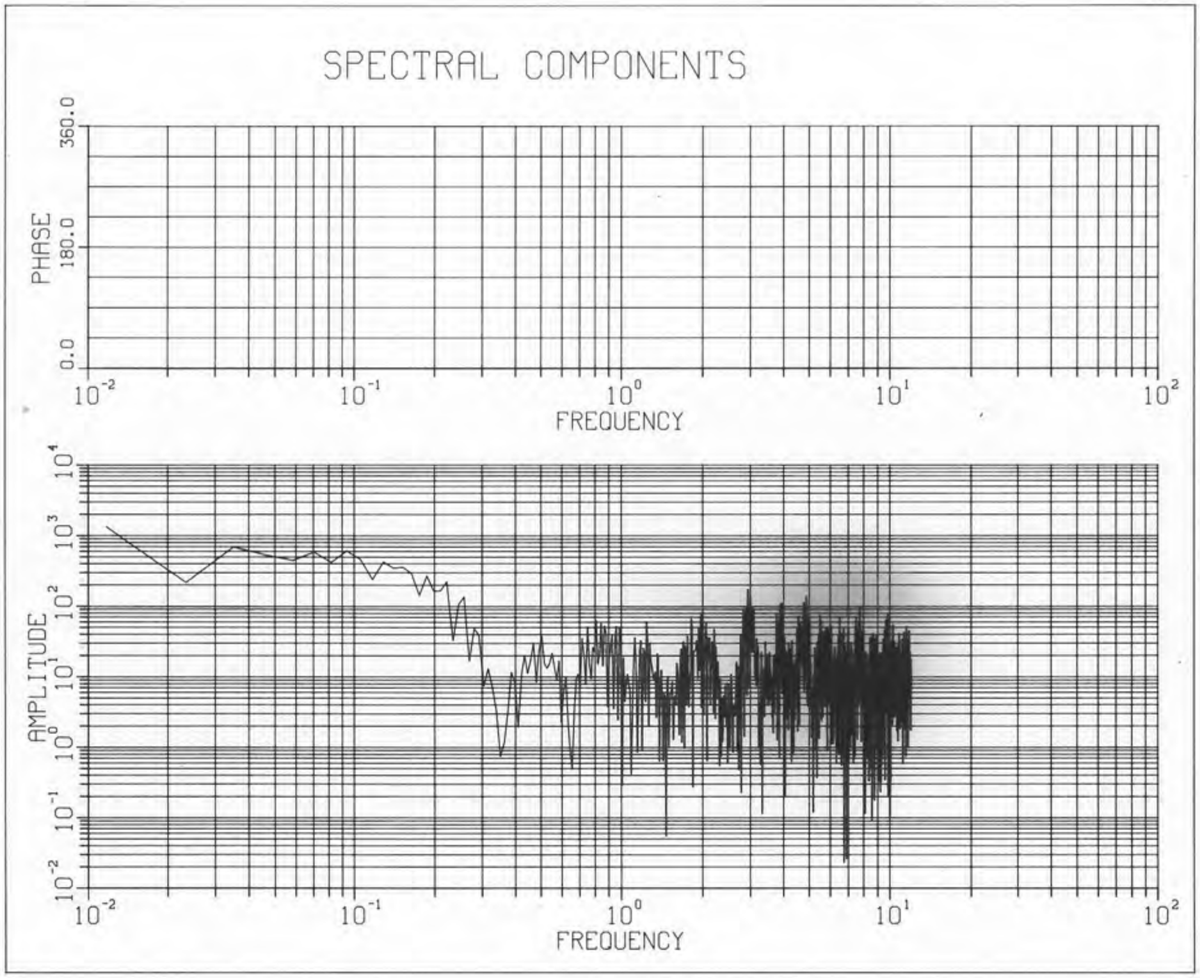


Figure 10. - Autospectrum.

where D = deflection of ray
L = path length
R = radius of curvature of path

$$D/L = \frac{1}{8} \cdot \frac{L}{R} \tag{7}$$

when L/R is small. Thus to keep $D/L < 0.01$, L/R must be less than 0.08.

For example, with R = 5 km, the required path length must be less than 400 m for relative deflections of about 1 percent.

Measure Path Curvature

If the sign of the curvature of the ray path were known, then a relatively good estimate of the C value could be made for a given set of transducers. This C value would then be used to correct the instantaneous mean line velocity. The determination of the sign of the curvature could be made with two thermisters and two conductivity probes mounted at one of the transducer stations. Sufficient computer logic would have to be available to calculate the sign of

$$2.46 \frac{\Delta T}{\Delta Y} + 1.13 \frac{\Delta S}{\Delta Y}. \tag{8}$$

If this expression is positive, the ray has an upward curvature. Otherwise, the curvature is downward.

A study of the variation of C with depth would have to be conducted for depths exceeding 6.7 m. Data obtained during the 1954 current measurement determination of discharge could probably be used to calculate reasonable values of C with the multiple reflections.

Improve Signal Detection Technique

The present method for determining when the pulse has arrived at the receiving transducer is to measure the amplitude of the signal. If the amplitude exceeds some threshold level, a trigger pulse is sent to a timer indicating arrival of the signal.

Due to the multiple reflections off the bed, the first few waves received often have a very low amplitude. Smith (1) showed that a delay will not cause significant errors if the delay is equal in both wave travel directions. However, if the trigger pulse is actuated by different cycles of the received signal, the error could be appreciable.

One solution to the problem is to cross correlate a sine wave with the received signal. The frequency of the sine wave should be equal to the sending frequency of the tranducers. If the received signal output is set to give zero output for no signal, then the output of the correlator will be zero until a signal begins to be received. When the signal is received, an amplified version of the signal will appear on the output of the correlator. Details of this procedure are discussed by Lee (2). Use of this technique will reduce the probability that the trigger pulse is actuated by the incorrect cycle of the received signal. This will not, however, reduce errors due to the bending of the acoustic path.

CONCLUSIONS

1. Temperature and salinity cause significant deflections of the acoustic rays at the proposed measurement section near Chipps Island.

2. About twice as many rays have a downward curvature as those with an upward curvature. This indicates a high probability for multiple reflections off the channel bed.

3. There does not appear to be a temporal correlation of the radii of curvature during the period July 19 to August 23.

4. Errors due to bending of the acoustic ray can be reduced by shortening the acoustic path length to 400 m, by measuring the sign of the curvature in the field, or by employing signal detection techniques to identify the first ray to traverse the measuring section.

REFERENCES

1. Smith, W., "Feasibility of the Use of the Acoustic Velocity Meter for Measurement of Net Outflow From the Sacramento-San Joaquin Delta in California," Geological Survey Water-Supply Paper 1877, 1969.

2. Lee, Y. W., Statistical Theory of Communications, John Wiley and Sons, 5th printing, 1966.