NRL Report 6113

Microacoustic System Analysis by the Measurement of Free-Field Sound Speed

W. G. NEUBAUER AND L. R. DRAGONETTE

Propagation Branch
Sound Division

August 3, 1964

U.S. NAVAL RESEARCH LABORATORY
Washington, D.C.

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An analysis of the microacoustic system was undertaken by means of the measurement of free-field sound speed in water. The water was contained in a 10 × 5 × 5 ft cypress tank. A pulse was transmitted from a fixed source to a receiver which was positioned at two different distances along a radius of the source. The distance difference of approximately one meter and the travel time over this distance were accurately measured. Sound-speed measurements were taken at 41 temperatures over a range from 16.8 to 23.10°C. A 290-degree spherical cap was used as the fixed source. The movable receiver was a disk transducer whose active element radius was 0.16λ at the source resonant frequency of approximately 200 kc. Measurements were also obtained by using 0.63-cm radius disks as source and receiver with the same results.

The experimental measurements led to the detection of a large error which exists in the remote determination of large distances using a cathetometer mounted horizontally. This error was eliminated and evaluated by moving along an accurately calibrated bar, allowing distance to be measured directly. Subsequently, a new system was designed which will allow the remote determination of distances accurate to within ±0.001 cm.

It was found that the ambient temperature at a given depth in the tank remained constant to within ±0.01°C for a time sufficient to make the required measurements and that vertical temperature gradients were not present to a significant degree. The electronic system was found to be consistent and dependable.

After a careful scrutiny and consideration of all the factors which could possibly influence the present measurement of sound velocity, the free-field value of velocity was determined to be at least 0.2 to 0.6 m/sec lower than confined field values measured by others.

INTRODUCTION

In the course of free-field measurements of the acoustic scattering and reflection by finite bodies in water, it was felt that the measurement of a fundamental quantity would unearth systematic errors in the placement-and-location equipment, electronics, and the measurement of ambient conditions. Toward this end the measurement of the free-field sound speed was undertaken since the means of making time, distance, and temperature measurement were already available in the laboratory. In the experiment a pulse was transmitted from a fixed source to a receiver which was positioned at two different distances along the same radius of the source. Sound speed was determined by measuring the time difference which was related to the distance difference.

APPARATUS

The water medium was contained in the same 10 × 5 × 5 ft cypress tank previously described (1). A diagram of the electronic apparatus is shown in Fig. 1. The 100-kc Laboratory-Standard-Frequency was multiplied first by five and then by twenty, causing these frequencies to be synchronized. The resultant 10-Mc signal was scaled down by a factor of 10^5 and triggered a pulse generator each 10 msec. The pulse generator produced a 0.4-μsec pulse which, after amplification and series tuning, was applied to the acoustic source. The acoustic signal was received and amplified and displayed on one trace of a four-trace oscilloscope. The other three traces displayed the 100-kc, 500-kc, and 10-Mc signals, all synchronized with respect to the acoustic signal. The pulse generator jitter was unnoticeable. The composite signal displayed on the oscilloscope is shown in Fig. 2.

The mechanical placement and optical location equipment previously described (1) was basically unchanged in the first sound speed measurements attempted. A large error was detected in measuring large distances when a cathetometer was used which was mounted horizontally along the edge of the tank. The error arose from the very slight angle between the cathetometer bar and a horizontal line, caused by the bending of the bar due

NRL Problem S01-04; Project RF 001-03-45-5252. This is an interim report on the problem; work is continuing. Manuscript submitted April 20, 1964.

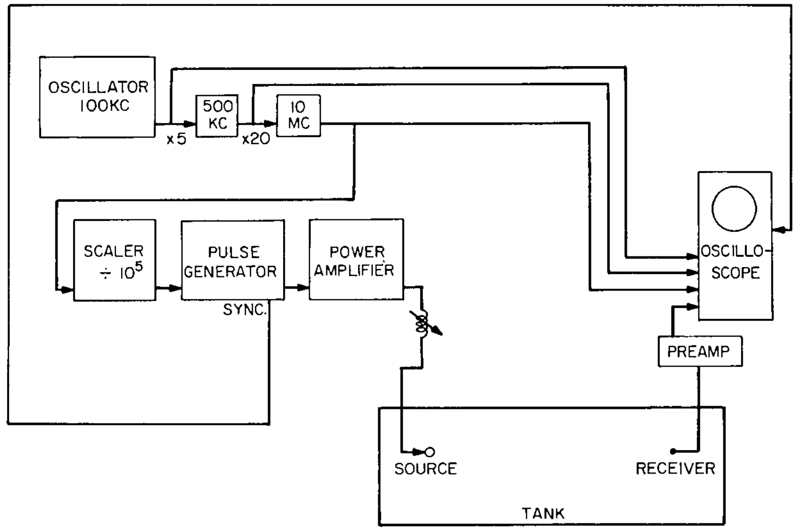


Fig. 1 — Diagram of electronic apparatus used for the measurement of sound speed. (The oscilloscope used was a Tektromix 545-A with a type M, four-trace preamplifier.)

to its own weight when supported at both ends. This sag was only 0.050 cm at the center. This caused no significant inaccuracy in the calibration of the scale on the bar, but when the telescope was used, the optical lever between the bar and the point being viewed exaggerated the effect of the sag. The difficulty amounted to the inability of the telescope to view points in a vertical plane at a given position on the bar or even to view in two planes parallel to each other. The distance-measurement error was in excess of 1 millimeter in measuring a length of 1 meter in the center of the tank. This error was avoided by eliminating optical viewing in the tank and, instead, moving through a distance measured along the accurate bar directly. This latter method allowed an evaluation of the error introduced by the optical system. The cathetometer vernier was rigidly fixed to a 3/4-in. rod which held the acoustic receiver, and the calibrated cathetometer bar was placed on a framework which held it just above the water surface. At each position of the receiver for which a signal-propagation time was read on the oscilloscope, the rod holding the receiver was set vertical with a coincidence level of 1-second angular sensitivity. The level was rigidly fixed to the rail at a position very close to the position at which the rod holding the receiver was clamped to the rail.

EXPERIMENTAL PROCEDURE

The source was located in a fixed position 63 cm below the water surface with the closest wall of the tank 25 cm away. In order to avoid interference at the receiver due to the simultaneous arrival of the directly transmitted signal and one reflected from the nearest wall, *i.e.*, in order to achieve a free wave, the distance r between source and receiver for a 20-μsec received pulse length is controlled by the inequality*

$$r \geqslant \frac{2\mathbf{d}^2}{ct_p} - \frac{ct_p}{2} = 415 \text{ cm},$$

where $\mathbf{d}$ is the distance to the nearest wall parallel to the direct transmission path, c is the sound speed, and t_p is the pulse length. The rail holding the receiver was clamped and leveled at a position along the measuring bar, thus establishing a distance d_s between source and receiver. At each setting of the receiver the temperature was read with a thermometer which will be described later.

A time position with respect to the 10-Mc signal was read on the oscilloscope and identified relative to the 500-kc and 100-kc signals (see Fig. 2).

*This formula is described in Ref. 2.

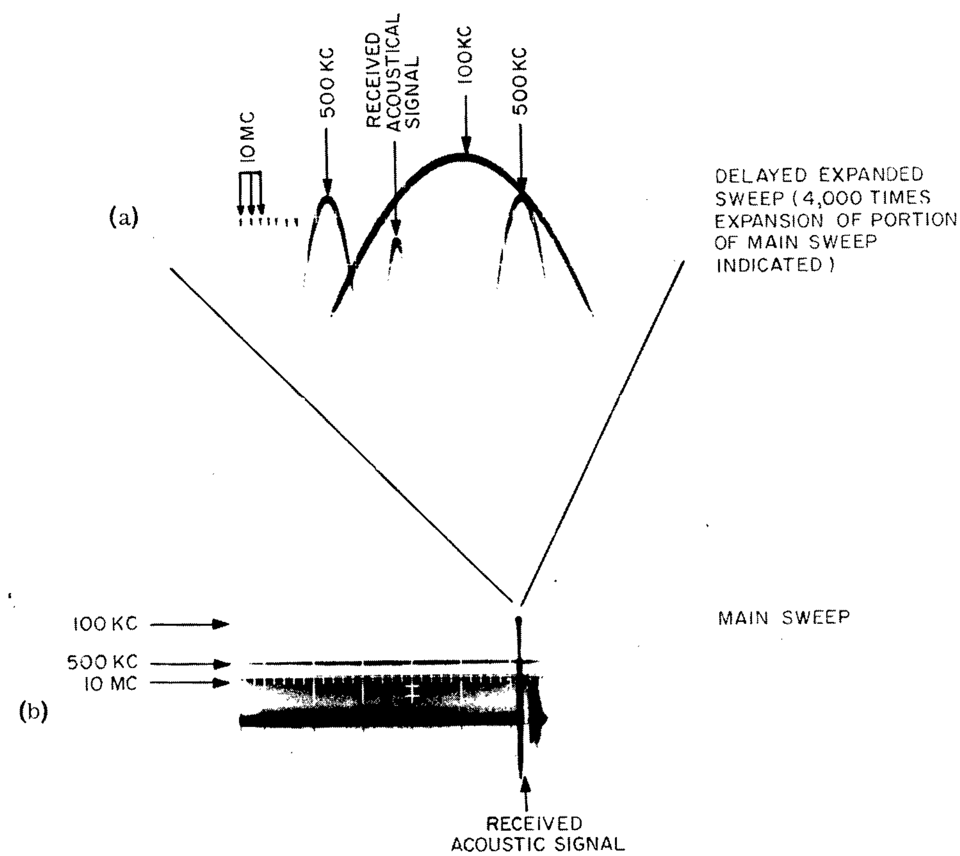


Fig. 2 – Four-trace oscillograph of 100-kc, 500-kc, and 10-Mc signals and the first peak of the acoustic signal; (a) delayed sweep, and (b) main sweep. (It was necessary to darken with ink some of the 10-Mc/sec peaks to indicate their existence in (a), since they did not survive the photographic reproduction.)

The time position of the signal was determined at the center of the cathode ray tube in order to minimize parallax errors in reading. At each time determination a photograph of the oscilloscope face was taken. Figure 2(a) shows an expanded portion of the entire sweep obtained by the use of a delayed sweep. The main sweep (Fig. 2(b)) was synchronized with the pulse which was applied to the source. The rail holding the receiver was then moved to the other end of the calibrated bar without touching the bar, and another distance d_ℓ was then established in the same way as was d_s. To ensure that the bar had not been accidentally moved while the receiver was being moved, a graduation of the measuring bar was viewed through a fixed telescope. To ensure that the receiver-carrying rail moved along the tank and was maintained parallel at both distances d_s and d_l, the distances of the ends of the rail were measured with respect to a fixed rail.

The delayed sweep on the oscilloscope was then moved with respect to the main sweep on which both signal positions were displayed at different times. The cycles of 100 kc by which the delay was increased, or through which the delayed sweep moved along the main sweep, were counted and the acoustic signal was located with reference to the three displayed frequencies. The time interval Δt thus established is related to the differential distance $d_l - d_s = \Delta d$ or acoustic signal path. Sound speed is thus determined since $c = \Delta d/\Delta t$.

DISCUSSION

In order to use the measurement of sound speed as a quantitative measure of the ability of the given system to accurately measure a physical quantity, and thus to allow the evaluation of the system, it is necessary to consider briefly just what physical quantity it is which is being measured. Since a transient acoustic signal is used, an exact analysis of the measurement would necessitate the application of a Fourier transform to find the frequency components of the pulse and thus allow evaluation of the measurement in terms of a precise mathematical representation. On the basis of pulse similarities (which will be discussed) and the use of a difference method, the results will be interpreted in terms of a steady-state solution.

A conceptual idealization of scalar wave propagation in an infinite homogeneous medium is one of a spherical wave which is produced by a true point, or simple source. The elementary solution to the scalar wave equation expressed in terms of the velocity potential φ or pressure for the out ward going radial wave in this geometry is

$$\varphi = \frac{A}{r} e^{ik(ct-r)}.$$

Here r is the radial distance from a field point to the source center, A is the amplitude, the wave number k is $2\pi/\lambda$, c is the sound speed, and t is time. In this simple case of a source emitting continuous waves of a constant frequency there is no difficulty in defining the wavelength λ as the distance interval between two successive peaks, axis crossings, or wavefronts, or in defining sound speed as the distance per unit time with which the wavefront, or any other identifiable characteristic of the radial vibration of the source, propagates radially outward from the source.

These rudimentary concepts of sound speed, wavelength, and the concept of a simple source and field point are relatable to quantities which are measured in a real physical situation to the degree to which limitations imposed by their rigorous definition can be overcome. A simple source at a desired frequency may be approximated by a vibrating body whose dimensions are small compared with a wavelength. Sources small compared with a wavelength are difficult to manufacture for use at frequencies which are sufficiently high to satisfy free-field conditions in a laboratory. A degree of success may be achieved essentially by driving an equipotential surface by the use of a radially vibrating finite-radius sphere.

The practical requirements involved in the sampling of the acoustic field can impose serious limitations on experimental results. Imposition of the least geometrical limitation, that is, making a receiving element as small compared to the wavelength as possible, results in the practical limitation of reduced sensitivity, thus placing the signal in the electronic noise of the receiving system electronics. A compromise which tends to optimize a representative sampling of the acoustic pressure at a point can be achieved by making the sensitive element and receiver structure at least smaller than a wavelength, preferably less than $\lambda/4$, and small in cross section so that the wavefront curvature may be regarded as negligible over the area of the receiver element at a significant nearest approach to the spherical source.

Free-field or free-wave conditions at a field point were satisfied to a desired degree by using short pulses, causing a time separation of the reception, at a field point, of the pulse from the source and all reflections, and by using a pulse repetition rate long enough so that all reflections in the tank, are below the noise level of the receiver system electronics at the time the source is pulsed again.

In the foregoing, relative terms such as "negligible" and "significant" have been used to describe the practical achievement of a theoretical ideal. Unfortunately, quantitative criteria which would allow direct relationships and resultant errors in the use of fundamental equations to describe an achieved result are elusive, and one resorts to a subjective judgment. The use of a pulse excitation of a resonant source and the resultant determination of sound speed in the case of this experiment requires such a judgment. The experimental evidence which influenced the formation of the judgment will be given.

The radial pressure pattern of a 290-degree spherical cap acoustic source, which was an approximation to a 1/4-in.-radius sphere, is shown in Fig. 3. Over the central part of the axial lobe a close approximation to a constant pressure and phase is achieved at a constant distance from the source center. The fact that the radial pressure pattern differs from true sphericity creates a difficulty in that there is now a "near-field" region, as previously measured (2), whereas a true point source has no near field. This near-field region has been measured as extending no further than 5 cm. Beyond this radius the pressure has been

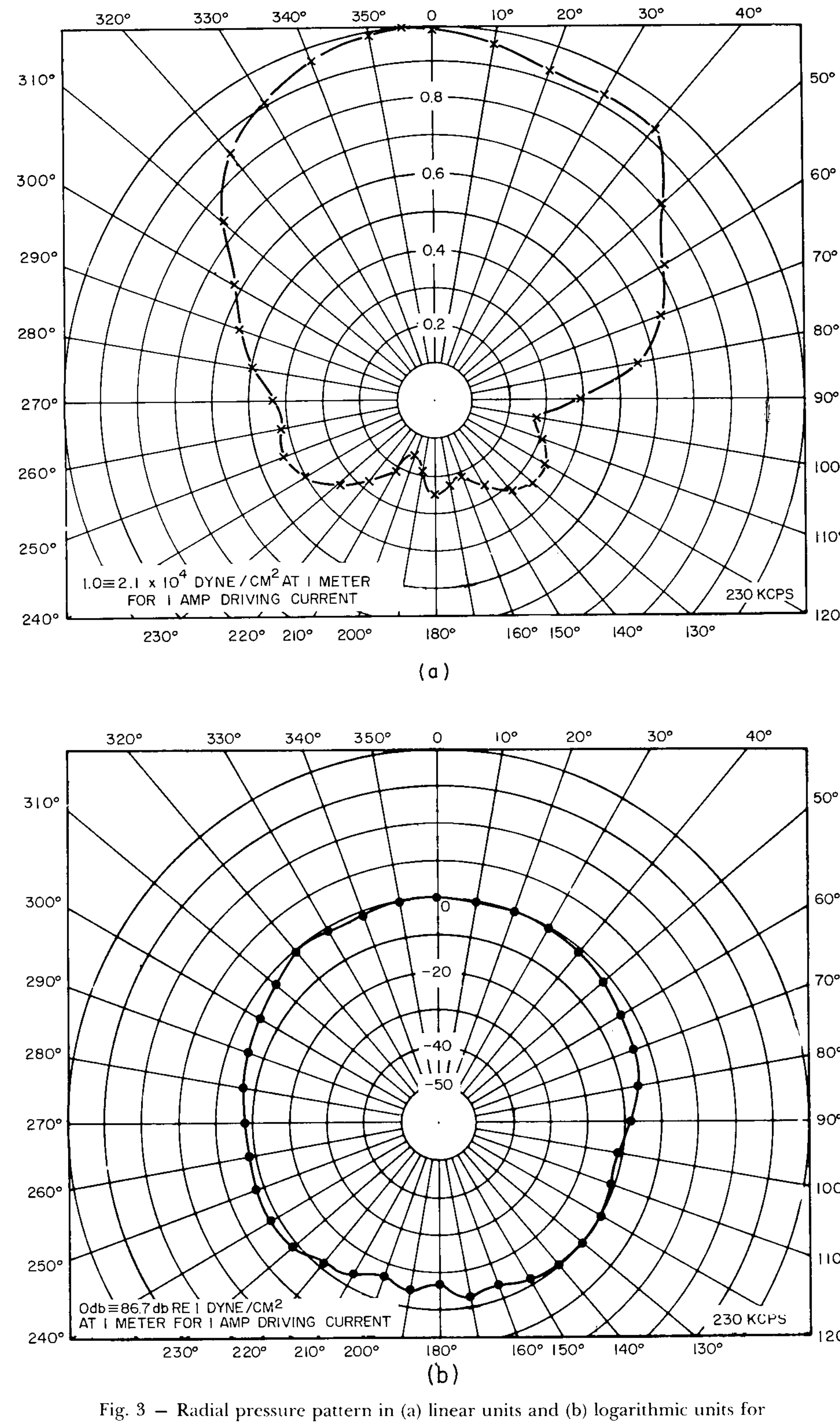


Fig. 3 – Radial pressure pattern in (a) linear units and (b) logarithmic units for 290-degree spherical cap acoustic source resonant at 230 kc

measured as decreasing with the inverse of the radial distance to within ±2 percent.

The acoustic probe* has a radial pressure pattern, measured for reception, as shown in Fig. 4, which approaches the spherical pattern characteristic of a true probe. In these measurements the angle subtended at the source by the largest sensing part of the probe at its nearest approach to the source was 0.46 degree. For the greatest distance between source and receiver, an angle of 0.03 degree was subtended by the probe. The active disk element radius is approximately 0.16λ, whereas the probe housing is approximately 0.25λ, at the source resonant frequency of approximately 200 kc.

The initial part of the received acoustic pulse is shown in Fig. 5 as it was received at the two distances d_s and d_l. Within the experimenter's ability to locate in time any characteristic part of this pulse, *e.g.*, the initial axis departure or the first or second peak, the two pulses are indistinguishable from each other. Therefore, the resultant determination of sound speed is no further in error than that error which is the result of the time measurement itself. If there were an inaccuracy of pulse location in time, say the location of the first axis departure, which is the most difficult determination to make, it would be due to the finite curvature of the wavefront at the receiver during the onset of the pulse on the sensitive element. This would cause a slower rise time at the very initial departure from zero of the received signal. In such a case an observer would have made a time determination which was later on the sweep than it should have been, and a Δt associated with the Δd determination would have been too small, resulting in a velocity derived from the experimental values which would have been too large. That is, the true sound speed would have been below that determined experimentally. A noise limitation would have resulted in an error of the location of the axis departure, but during these measurements noise was not significant, *i.e.*, the effect on time location was less than the accuracy of the time reading.

Pulse shape comparisons were carried out with different received pulse shapes, as well as with different distances, with identical results. These pulse shape comparisons were carried out with 0.63-cm-radius transducer disks, and again the results were the same even though such a disk has approximately a 25-degree central lobe of the radial pressure pattern. Figure 6 shows the pulses which were compared using these larger disks.

*The details of the probe construction are given in Ref. 1.

What has been measured, then, to within the experimental accuracy, can be concluded to be the speed of sound emitted by a true spherical source and detected with a true probe at a frequency assumed to be represented by $f = c\lambda$, where f may be any frequency within the relatively small bandwidth involved in the resonance of the source. The resonant frequency of the spherical cap source is nominally 200 kc; for the disk source it is nominally 1 Mc. The previous assumption regarding frequency, and thus wavelength, is in a sense superfluous since, for the frequencies involved in these measurements, the acoustic medium is considered to be nondispersive, *i.e.*, c is a single function of f and λ, at least to the degree of the accuracy of these experiments.

RESULTS

Figure 7 is a plot of sound speed measurements made with the acoustic sources and receivers described. Also shown are the results of measurements made in two other independent investigations. The present measured values, which appear in Table 1, were carried out by three experimenters independently. As to the question of whether this sound speed is what is normally called phase, signal, or group velocity: it is all three, to within the accuracy of the experimental results.

The results obtained also represent the plane wave sound speed since the elementary plane wave solution to the one-dimensional wave equation is

$$\varphi = A' e^{ik(ct-x)},$$

which is the same solution as the spherical wave case if we disregard the amplitude A' and allow the distance to the source x to be sufficiently large so that the spherical divergence and wavefront curvature is essentially zero over the receiver sensing area. Again, comparison of the pulse shapes on Fig. 5 and Fig. 6 verifies this conclusion. Actually in the experiments which were carried out, the limitations resulting from the rigid definitions of conditions of the simple solutions were sufficiently overcome to result not only in a spherical wave but also in a plane wave. The plane wave could not be as good an approximation as the spherical wave, but the difference was indistinguishable at the distances used and within the accuracy of the measured values.

MEASUREMENT ACCURACY

In order to determine the total maximum error due to the uncertainties in the measurement of the independent variables, the total differential of $c(\Delta d,\Delta t,\theta)$ was computed.

Errors in the Measurement of Path Difference Δd

The maximum error in c due to a 0.001-cm error in the measurement of Δd is 0.015 m/sec. The following factors relating to distance were considered.

1. Bar calibration: The distance between any two divisions on the calibrated bar scale is certified to be accurate to ± 0.0015 cm at 20°C.

2. Bar-material coefficient of thermal expansion: A correction to Δd was made based on a thermal expansion coefficient of 16.4×10^{-6} m/m/°C for the bar temperature which was read to ± 0.5°C. This temperature uncertainty resulted in a maximum uncertainty to the corrected Δd of ± 0.0008 cm.

3. Scale and vernier reading error (parallax): The experimenter's ability to arrive at a unique reading of position on the scale at any position on the scale was accurate to within 0.0010 cm. Since two such readings were involved in a determination of Δd, the total uncertainty caused by scale reading in a value of Δd was ± 0.0020 cm.

4. Source and receiver alignment: Calculations were made for a possible maximum difference in source and receiver alignment when the source and receiver centers were never outside of a 0.20-cm-radius cylinder whose axis was parallel to the measuring bar. This caused a maximum error in Δd of $+0.0008$ cm.

5. Error due to leveling accuracy: The coincidence level has a sensitivity of ± 1 second of arc. The receiver was at the end of a lever arm less than 67 cm below the scale. Therefore the limited ability to achieve absolute level at each distance position caused an error in Δd no greater than ± 0.0003 cm.

6. Error caused by a lack of parallelism at all reading positions: As previously mentioned, the distances between the ends of the rail holding the receiver and a fixed rail across the tank were measured at each distance position in order always to maintain the movable rail parallel to its initial position. This parallelism was established to within 0.08 cm. The resultant difference in motion along the bar of the vernier and receiver was ± 0.0031 cm.

7. Scale length change due to bar bowing: As previously mentioned, the calibrated bar deflects due to its own weight when supported only at both ends, as was done in its supporting structure. This downward deflection was measured to be no greater than 0.050 cm at its center. The resulting error in Δd was computed to be -0.00001 cm, causing a negligible error in c.

The total maximum error in Δd as a result of these seven factors was $+0.0075$ cm and -0.0067 cm, causing a maximum error in c of $+0.113$ m/sec and -0.101 m/sec.

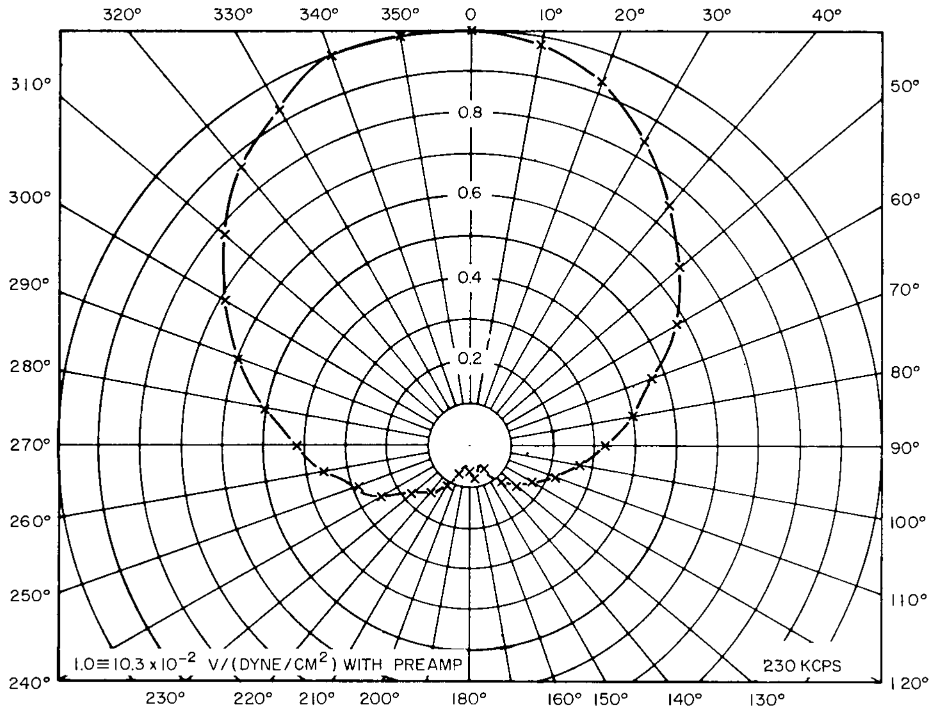
Errors in the Measurement of Time Difference Δt

The maximum error in c due to a 0.01-μsec error in Δt is 0.022 m/sec. The following factors relating to time were considered.

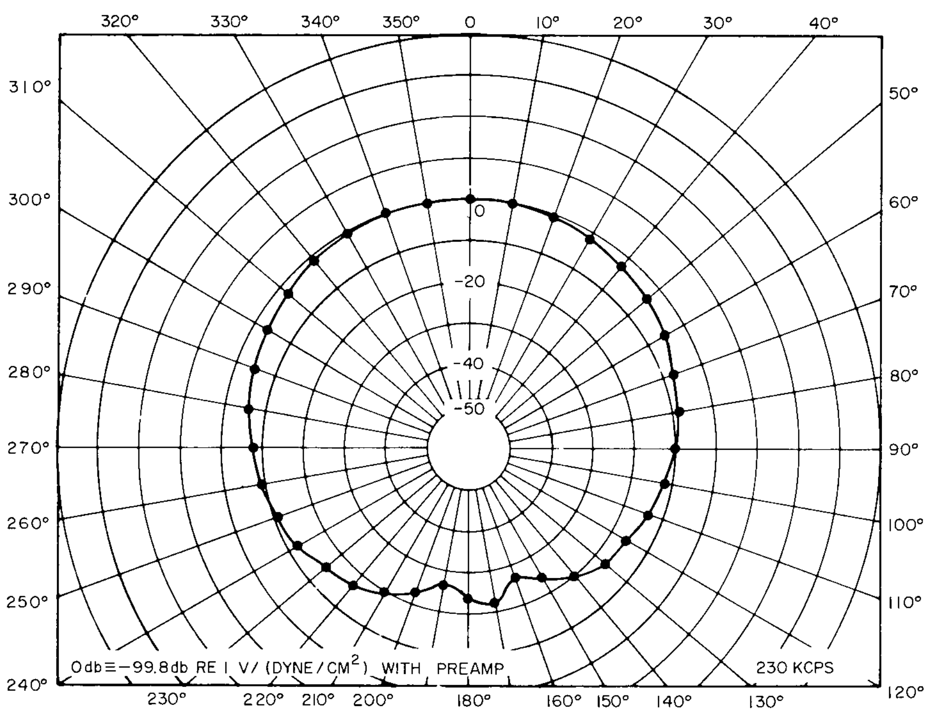
1. Accuracy and stability of time base: The Laboratory-Standard-Frequency of 100 kc was known to be accurate and constant to better than one part in 10^9. Uncertainty of any time difference measured using this reference is negligible.

2. Time reading error: The experimenter could determine the position of the received acoustic signal at each distance position to the nearest peak or axis crossing of the 10-Mc signal (see Fig. 2). In measuring Δt two such determinations were necessary, and therefore the maximum error in Δt was ± 0.025 μsec.

The total maximum error in c as a result of the above error in time reading was ± 0.055 m/sec.



(a)



(b)

Fig. 4 — Radial pressure pattern in (a) linear units and (b) logarithmic units for acoustic probe with 0.08-cm-radius disk sensing element

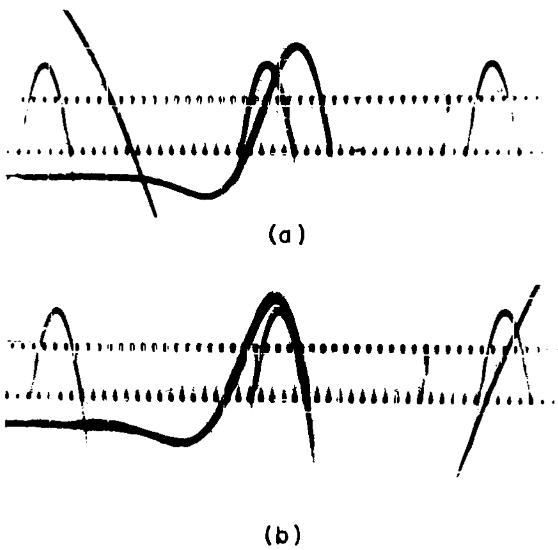


Fig. 5 — Initial portion of acoustical pulse received at the distances (a) d_s and (b) d_t using the spherical cap source and probe

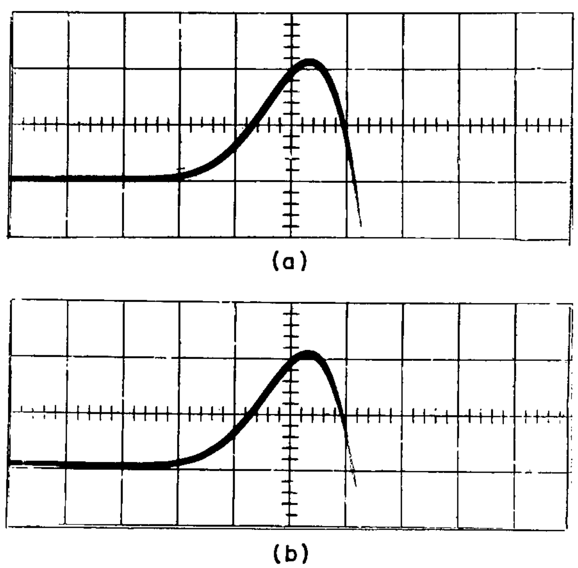


Fig. 6 — Initial portion of the acoustical pulse received, using 0.63-cm-radius disk source and receiver, at the distance (a) d_s and (b) d_t.

Errors in the Measurement of Temperature θ

The maximum error in c due to a 0.01°C error in the temperature θ is 0.0328 m/sec. The partial derivative of c with respect to θ was taken as 3.28 m/sec/°C from the report of Greenspan and Tschiegg (3). The thermometer was always read with the entire thermometer in the transmission path before and after each pair of distance readings. Also, readings were taken with the bulb toward the receiver and toward the source. Sound speed determinations were not made when a horizontal gradient as great as 0.01°C was noticed. The thermometer was a 24-in. bomb-type fuel calorimeter graduated each 0.01°C between 18°C and 28°C. The temperature in the transmission path was determined to an accuracy of ±0.01°C. Absolute accuracy was determined by comparison with a National Bureau of Standards calibrated secondary standard thermometer, which was similar to the one used. An uncertainty of ±0.01°C in the temperature measurement resulted in a sound speed measurement that was uncertain, at the measured temperature, by ±0.033 m/sec.

Water Purity

Greenspan and Tschiegg (3) report that "Several measurements made on local tap water give results about 30 ppm higher than for distilled water." Thus, since the 1800-gallon water tank used in the present measurements was filled with tap water in the same city in which the difference was measured, an error in c of −0.045 m/sec was assumed. The experimental results presented here do not represent a single body of water since the temperature was changed by adding hot or cold water from the tap.

The maximum total error in c as a result of the sum of the errors associated with all of the independent variables was +0.20 m/sec and −0.23 m/sec.

It should be stated that the measurement of the independent variables was done with equipment which was on hand and used in other acoustic field measurements not directly involving sound speed, and are therefore not those instruments which could measure these parameters most accurately. These results therefore do not represent maximum accuracy for this type of free-field measurement. The ultimate accuracy, allowing the foregoing interpretation of sound speed, would probably be reached when pulse shape difference are observed as time resolution is improved.

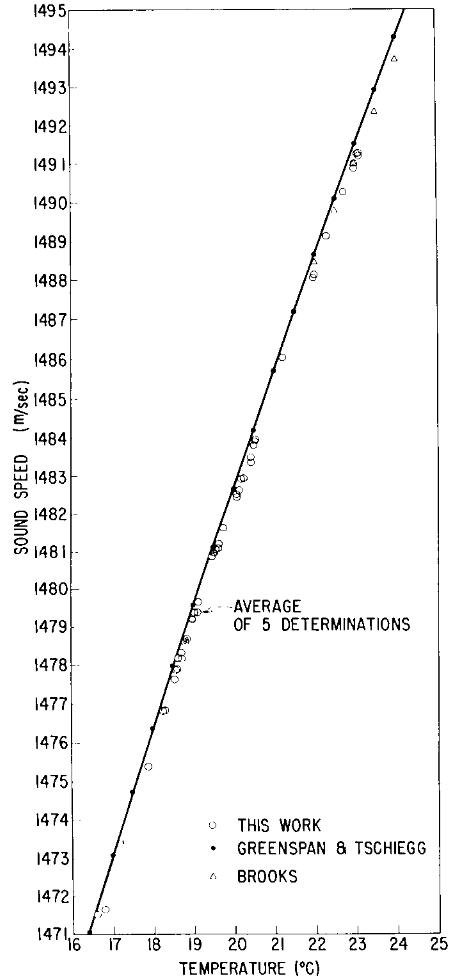


Table 1
Sound Speed Versus Temperature

θ (°C)	c(m/sec)	θ (°C)	c(m/sec)
16.6[a]	1471.51	19.64	1481.19
16.8[a]	1471.65	19.75	1481.61
17.9[a]	1475.38	20.06	1482.51
18.26	1476.81	20.07	1482.44
18.31	1476.82	20.12	1482.63
18.55	1477.61	20.18	1482.92
18.59	1477.86	20.24	1482.94
18.62	1477.88	20.42	1483.35
18.64	1478.16	20.42	1483.48
18.72	1478.15	20.51	1483.81
18.72	1478.31	20.55	1483.95
18.81	1478.58	20.56	1483.95
18.81	1478.57	21.22	1486.02
18.85	1478.65	21.97	1488.04
18.85	1478.67	22.01	1488.11
19.01	1479.22	22.30	1489.11
19.04	1479.36	22.72	1490.25
19.11	1479.47	22.98	1490.86
19.14	1479.64	22.99	1490.99
19.47	1480.85	23.07	1491.24
19.51	1480.98	23.09	1491.19
19.57	1481.04	23.09	1491.26
19.63	1481.07		

[a] These temperature measurements were below the range of the calibrated thermometer which was described. These temperatures are known to within only ±0.1°C.

Fig. 7 — Sound speed vs temperature

COMPARISON WITH OTHER MEASUREMENTS

Free-field measurements reported by Brooks (4) are shown on the plot in Fig. 7. Although the temperature ranges of Brooks' measurements and the measurements given here are different, those points common to both ranges show good agreement. The results of Greenspan and Tschiegg (3) are also shown in Fig. 7. The measurements described in the present report indicate that the free-field sound speed is between 0.2 and 0.6 m/sec lower than the confined field measurements of Greenspan and Tschiegg.

Other confined field values of sound speed have been reported by both Del Grosso (5) and Wilson (6) and are higher than those of Greenspan and Tschiegg in the range of temperature of these measurements. There has been no evidence found in the course of this work to indicate that the use of pulses is invalid, as they were used in this experiment, for the determination of phase velocity in a free field. Every reasonable effort has been made to uncover possible systematic effects which would explain the difference between these results and the confined field measurements and none have been found.

SUMMARY

The present measurement of sound speed has resulted in the identification of a large systematic error in distance measurement in the tank. The previously reported method (1), employing a cathetometer with its telescope to remotely determine distances between points in the water body, caused this error. When the optical determination of distances was eliminated, a sound speed was determined which will be used in the future study of reflected and scattered acoustic fields.

Instrumentation is under construction which will again allow the remote determination of positions along two dimensions since the current method of moving directly along an accurate measuring bar is not readily adaptable to two normal degrees of freedom. In the new system an alignment telescope is mounted on a carriage which moves along a granite straight edge on top of a granite surface plate. A right-angle eyepiece and a pentaprism mounted on the front of the telescope will allow viewing in vertical planes to the accuracy required, which is at least 0.001 cm. With a second telescope and surface plate on an adjacent edge of the tank, any position in the center square meter, at any level in the tank, can be located to the nearest 0.001 cm in a rectangular coordinate system.

It was found that temperature is easily determined to the nearest 0.01°C and remains stable for a sufficiently long period so that acoustic measurement can be carried out in a temperature field uniform to that extent. The movement of devices through the water caused no measurable disturbances in the temperature structure of the tank. The temperature structure in the water body was found to be free of gradients to a surprising degree in both the horizontal and vertical dimensions. By the combined use of water from the tap at a desired temperature and control of the laboratory ambient air temperature, the water temperature could be varied between 18 and 23°C. The electronic system was found to be dependable and consistent with the requirements of future reflection and scattering experiments to be performed at this Laboratory.

The free-field value of sound speed obtained was between 0.2 and 0.6 m/sec below the confined field sound speed values measured by others.

ACKNOWLEDGMENT

The authors wish to express their appreciation to A. J. Rudgers for his contribution to this work.

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