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WOODS HOLE OCEANOGRAPHIC INSTITUTION

Woods Hole, Massachusetts

LONG RANGE SOUND TRANSMISSION

Interim Report No. 1

March 1, 1944 — January 20, 1945

by

Maurice Ewing

and

J. Lamar Worzel

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with the cooperation of
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FOREWORD

Contract NObs - 2083, Formerly OEM sr - 31

Task No. 1. Study the basic phenomena involved in the propagation of underwater sound, including the transmission, reflection and scattering of sonic and supersonic sound.

Problem 1B. Study the transmission of low-frequency sound at the greatest possible ranges, especially the transmission of explosive sound in sound channels.

TABLE OF CONTENTS

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LIST OF FIGURES

[redacted]

LIST OF FIGURES (cont'd)

LIST OF PLATES

ABSTRACT

Experiments are described to demonstrate a new method of sonic signalling at extremely long ranges in the oceans, utilizing the natural sound channel. Signals were made by causing a four pound charge of TNT to explode at about 4000 feet depth. These signals have the following qualities:

(a) Extremely long range transmission (probably 10,000 miles).

(b) Signal is positively identifiable.

(c) Abrupt termination of the signal allows the arrival time to be read with an accuracy better than 1/20th second. This permits location of source to better than a mile, if the signal is received at three suitably located stations.

(d) The signal duration is related in such a way to the distance that the distance may be estimated to 30 miles in 1000 from reception at a single station.

The limitations are:

(a) It is required that the great circle path which the sound follows between source and receiver lie entirely in deep water (probably at least 1000 fathoms).

(b) Sound travels in water at a speed of roughly 1 mile per second so that the interval between the origin of the signal and its reception becomes sufficiently great to be a handicap for some uses, particularly with aircraft.

The signals were received to distances up to 900 miles. Two receiving arrangements have been used, a hydrophone hung 4000 feet over the side of a ship which was hove to, and a shore connected hydrophone which lay on bottom 4000 feet deep. Extrapolation of the results indicate a range of at least 10,000 miles from this size charge. Recommendation is made

to utilize a network of monitoring stations to locate planes, ships, and life rafts in distress on the open oceans. Three or more stations receiving a signal could locate the source better than one mile.

> NOTE: In recent work not included in this report a half pound bomb was heard with abundant signal strength at over 800 miles, and a four pound bomb was heard up to 2300 miles. Detonators have been heard to 75 miles.

INTRODUCTION

This work involves reception of sound from an explosion, at distances up to 1000 miles, where both the source and the receiver are at a depth of about 4000 feet. From a typical shot 40 to 100 separate sound arrivals have been identified to the extent that the path over which each has travelled is definitely known. This identification has been made on the basis of accurate travel time measurements, and comparison of the measured times with those computed from ray diagrams based on the known velocity distribution in the oceans.

In the oceans in deep water, the temperature generally decreases fairly rapidly with increasing depth to a little above zero centigrade at around 700 fathoms. It then decreases slowly from there to bottom. The sound velocity decreases in a similar fashion to a minimum at around 700 fathoms, but then increases from that depth to bottom achieving a higher velocity at the bottom than at the surface. The increase in velocity below 700 fathoms is caused by the pressure effect. The velocity decrease above 700 fathoms is more pronounced near the tropics where the surface temperature is high and less pronounced near the poles where the surface temperature is low.

If a non-directional sound source is placed at the depth of minimum velocity, hereafter called the axis of the sound channel, the sounds which start at angles above the horizontal are bent downwards due to sound refraction. Those which start at angles below the horizontal are bent upwards. For a typical location, if the initial angle lies between 12° above the horizontal and 15° below, the sound recurves and returns to the axis. Thus, a sound starting with an inclination of less than 12° will cross and recross the axis indefinitely until it is absorbed, scattered, or intercepted by some obstacle. Sounds travelling in this manner are channelled: hence, the name sound channel is given to this type of velocity structure. The abbreviation SC will hereafter be used to indicate these sounds.

These sound channel sounds have been heard at far greater distances than any other man-made sounds. These long ranges depend primarily on two factors: (1) the absorption coefficient is very small for low frequency sound, and (2) the existing relation between sound velocity and depth in the ocean greatly impairs transmission between a source and receiver located at a great distance from each other near the surface because it necessitates a large number of reflections from the bottom, but this velocity-depth relation greatly improves long range transmission between a source and receiver located at the axis of the sound channel because it eliminates all reflections and confines a large fraction of the total sound energy to the sound channel. It is fruitless to attempt an off hand theoretical prediction of the relation between peak sound pressure and range for sound channel sounds from explosion sources, but it is obvious that (neglecting absorption and diffraction) the total energy per unit area will vary as the inverse first power of the distance out to distances at which the convergence of the great circle paths though the sound source becomes significant.

Sounds starting with an inclination of between 12° and 15° refract back to the axis from below, but must reflect from the surface before returning to the axis from above. These sounds have been called refracted and surface reflected sounds, hereafter abbreviated RSR. Sounds starting with an inclination greater than 15° can only travel by alternate reflection at the surface and the bottom, hereafter called reflected sounds.

In a sound channel, sounds may travel by many paths between a source and a receiver separated by a large distance. Of all these, the first sound to arrive starts with the maximum angle, travels the longest actual path, and makes the smallest number of axial crossings. The second sound to arrive makes one more axial crossing, the third two more, and so on. Finally the last sound to arrive travels along the axis, which is the shortest sound path between the source and receiver. The time separation between subsequent arrivals becomes less and less as the number of axial crossings increases causing a final accumulation of arrivals.

In accordance with the foregoing considerations, it was found that the sounds arriving at the receiver commence at a low intensity and with long intervals between them. Gradually the interval shortens, and the sounds become louder until they blend into one loud sound which ceases abruptly. The lead of the first sound over the last sound amounts to about 1.2 seconds per 100 miles, or about 1 second per 100 seconds of water travel. A fairly good estimate of the distance between the sound source and the receiver can be made from the duration of the sound channel signal.

The RSR sounds exhibit the same sort of pattern of time intervals as the earlier sound channel arrivals. Although they cease abruptly, there is no accumulation at the end as in the sound channel. They begin shortly after the first and terminate shortly before the last sound channel sounds. So far it has not been possible to identify them completely and separate them from the sound channel sounds.

The reflected sounds show a marked difference. They arrive at intervals which are short at first and grow longer with each arrival. The earliest sounds are the loudest, and the sounds grow progressively weaker with each arrival. The earliest reflections sometimes come in before the sound channel sounds have terminated, but carry on after the sound channel. They fall of with increasing distance much more rapidly than the other sounds because of the losses at each reflection, and become negligible at distances over 200 miles. These reflected sounds are received equally well on both the deep hydrophone and on an auxiliary shoal one, whereas the sound channel sounds are much stronger on the deep hydrophone.

In July 1943, Dr. M. Ewing of Woods Hole Oceanographic Institution wrote a memorandum proposing this long range transmission as a system of communications. This was sent to the Bureau of Ships, and rejected on the basis of security, difficulty of establishing a new coding system, and possible jamming either intentionally or by ordinary operations. In January 1944, the Underwater Sound Design Section of the Bureau of Ships approved tests of the long range transmission by the Woods Hole Oceanographic Institution and the U. S. Navy Underwater Sound Laboratory to determine the attenuation of low frequency sounds, the USS SALUDA and the SC 665 being assigned for the experiments. The services of Mr. Gale White, and some of the necessary equipment were lent by the Naval Ordnance Laboratory. The operational arrangements were made by the U. S. Navy Underwater Sound Laboratory, and the rest of the equipment was assembled at Woods Hole. The ships arrived at the station ready to work on March 22, 1944. Operations were begun, but had to cease when the weather became too bad in the area occupied at the time by the SC 665.

Some tests on equipment and sound transmissions from shallow charges at distances up to 30 miles were obtained from charges set off by the SC 1292 which was escorting the SALUDA. This work has been reported in a separate report called "Deep Water Sound Transmissions from Shallow Explosions" by J. L. Worzel and M. Ewing.

It was then arranged for the DE 51 to fire charges for the SALUDA to record. These tests were begun April 2, 1944 and were concluded April 5, 1944. One-half pound shots at 50 feet depths and four pound charges at 4000 feet depths were fired at 100 mile intervals to ranges of 900 miles. Some depth charges at 300 feet depth and grenades near the surface were also fired.

These shots were received and recorded by means of a shallow and a deep hydrophone. The shallow hydrophone was a standard C-21 Brush hydrophone which was lowered 80 feet below the surface. The deep hydrophone was made by attaching a standard C-21 hydrophone completely filled with castor oil to a pressure case which contained a preamplifier. This was lowered on a 4000 foot length of demolition cable and reached a depth of about 3500 feet. The sounds received by the shallow hydrophone were recorded on three traces of a Shell Oil Company oscillograph. One trace recorded the amplified signal directly and was most sensitive to 900 cycles/second. The other two recorded the amplified-rectified signal at different gains and were most sensitive to frequencies around 3000 cycles/second. Sounds received by the deep hydrophone were recorded on five traces of the same oscillograph. Two of these recorded the amplified signal directly at different gains and were most sensitive to frequencies around 100 cycles/second. Another recorded the amplified signal directly and was most sensitive to frequencies around 500 cycles/second. The other two recorded the amplified-rectified signal at different gains and were most sensitive to frequencies around 8000 cycles/second. All of these systems were calibrated by introducing a known signal voltage of suitable frequency into the hydrophone lead. The amplifying system of the deep hydrophone was calibrated but there is no data available on the pressure effect on the hydrophone. For the purpose of this report the pressure and temperature effects on the hydrophone are ignored. Any effect of this sort would only change the absolute values of the sound pressures for the deep hydrophone and not the relative values.

The maximum range possible for the DE 51 under her orders was 900 miles. The extreme limit for audibility of signals was not reached as the signal was still well above the noise level of the deep hydrophone. Multiple reflections were received by both the deep and shallow hydrophones to distances of 200 miles. The sound channel sounds bore out the theory almost in detail. The end of the sound channel transmission was so sharp that it was not possible for even the most unskilled observer to miss it.

Having thus conclusively obtained long range sound channel transmission with the hydrophone suspended from a ship and far from bottom, it was desirable to see if comparable results could be obtained with the hydrophone lying on bottom in the correct depth and connected by cable to a receiving station on an island. For this purpose, a station was established at Eleuthera Island in the Bahamas in October, 1944. This site was picked because of the proximity of deep water to shore. The Bureau of Ships assigned Lt. E. L. Newhouse as project officer and arranged for the communications and necessary vessels to carry on the work. The New London Underwater Sound Laboratories and Woods Hole Oceanographic Institution provided the technical personnel and equipment.

Great difficulty was encountered in laying a cable out to the 700 fathom curve because of the weather, the surf, and coral heads. A working installation was finally completed on January 9, 1945 and shots to distances of about 450 miles were recorded with the installation until it failed on January 29, 1945, during the early stages of a transatlantic operation. The failure was almost certainly attributable to the cable chafing through on the coral. Other cable installations have been made and successful records made at greater distances, but they will be discussed in a later report.

The shots were fired by the USCGC VALOR, which had previously charted the area in which the hydrophone was laid and assisted in laying the hydrophone. Besides the deep shots, many half pound demolition blocks were fired near the surface at the same positions. Some additional shallow shots were fired in between these positions. Until February 10, 1945, when the Woods Hole detonator was designed, this project was always handicapped by a scarcity of deep bombs. The hydrophone used on this installation was an AX 58 C, modified at

New London to withstand the pressure. Instead of a preamplifier at the hydrophone, a matching transformer was included.

The cable output was fed to a special cathode follower amplifier where the signal was split. One part was amplified and fed to a speaker for audio-monitoring. The other part was amplified and fed to a bank of six amplifiers tuned for different frequencies. These latter signals were recorded on a photographic recording coil oscillograph. The tuned amplifiers were peaked at 10, 32, 140, 550, 1500, and 5000 cycles/second and had a band width of about two octaves. The output of the latter three was rectified before recording.

The recordings made at the Eleuthera station again bore out the sound channel theory almost in detail, and no serious ill effects were noted due to the hydrophone lying on bottom.

Three types of deep bombs have been used for this work. All of them were made in pressure proof cases which were filled with about four pounds of cast TNT. The difference was in the type of fusing. The ones for the SALUDA cruise were fused by a Bourdon tube closing an electrical contact at the correct depth firing the cap from self contained batteries. An external switch was used as a safety precaution. One of the types used for the Eleuthera shots was a modified version of the above. This used an external sea cell for both battery and safety switch. Both of these bombs were stop-gaps which required special personnel for handling. The first of our bombs to be designed according to Navy standards of safety* was named "Rockwell"type for the inventor.

*"Hydrostatically Detonated Exploders" by G. O. Rockwell, OSRD no 6.1 sr1128 1937, March 6, 1945.

It consisted of a sylphon bellows which moved an electric detonator into firing position for the arming operation at half the firing depth. At the firing depth two diaphragms ruptured flooding a chamber which contained a sea cell. This acted as both battery and switch to fire the electric detonator.

HYDROGRAPHIC DATA

The courses travelled by the ships for these experiments and the positions at which deep shots were fired are shown in Figure 1. The positions which have numbers beside them are positions at which there are deep hydrographic data available for the approximate time of year when these experiments were done. Figure 2 shows a composite plot of the velocity depth curves at all these stations. The data for these curves were taken in 1932 and 1933. There is no more modern data available. The mean curve is that curve which seems to the authors a fair average of all of these velocity depth measurements. Later when sound channel durations are discussed, it will be seen that the part of the curve between 0 and 400 fathoms should have been further divided at 250 fathoms. Figure 3 shows the mean velocity-depth curve alone. Actually the point of minimum velocity should be on a smooth curve instead of on the instersection of two straight lines. This change would not alter any of the results. Figure 4 shows the yearly variation of the isotherms at approximately the same position as a function of the time of year. The data for these illustrations were taken within the area surrounded by the dotted line in Figure 1 during the years 1937, 1938, and 1939.

From all these stations it may be seen that the velocity depth relation does not shift significantly either with the time of year or position in that part of the Atlantic Ocean in which the work covered in this report was done.

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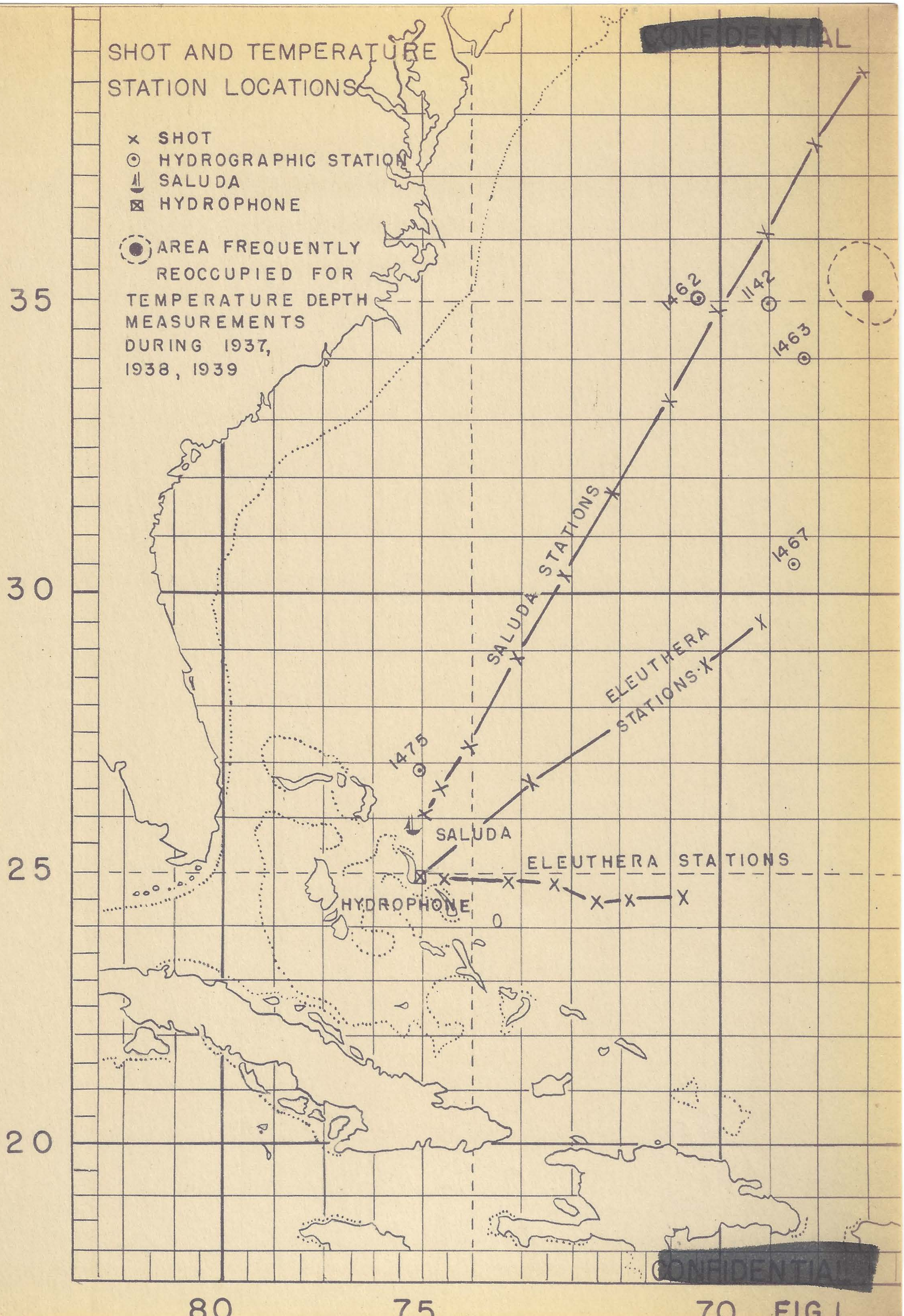
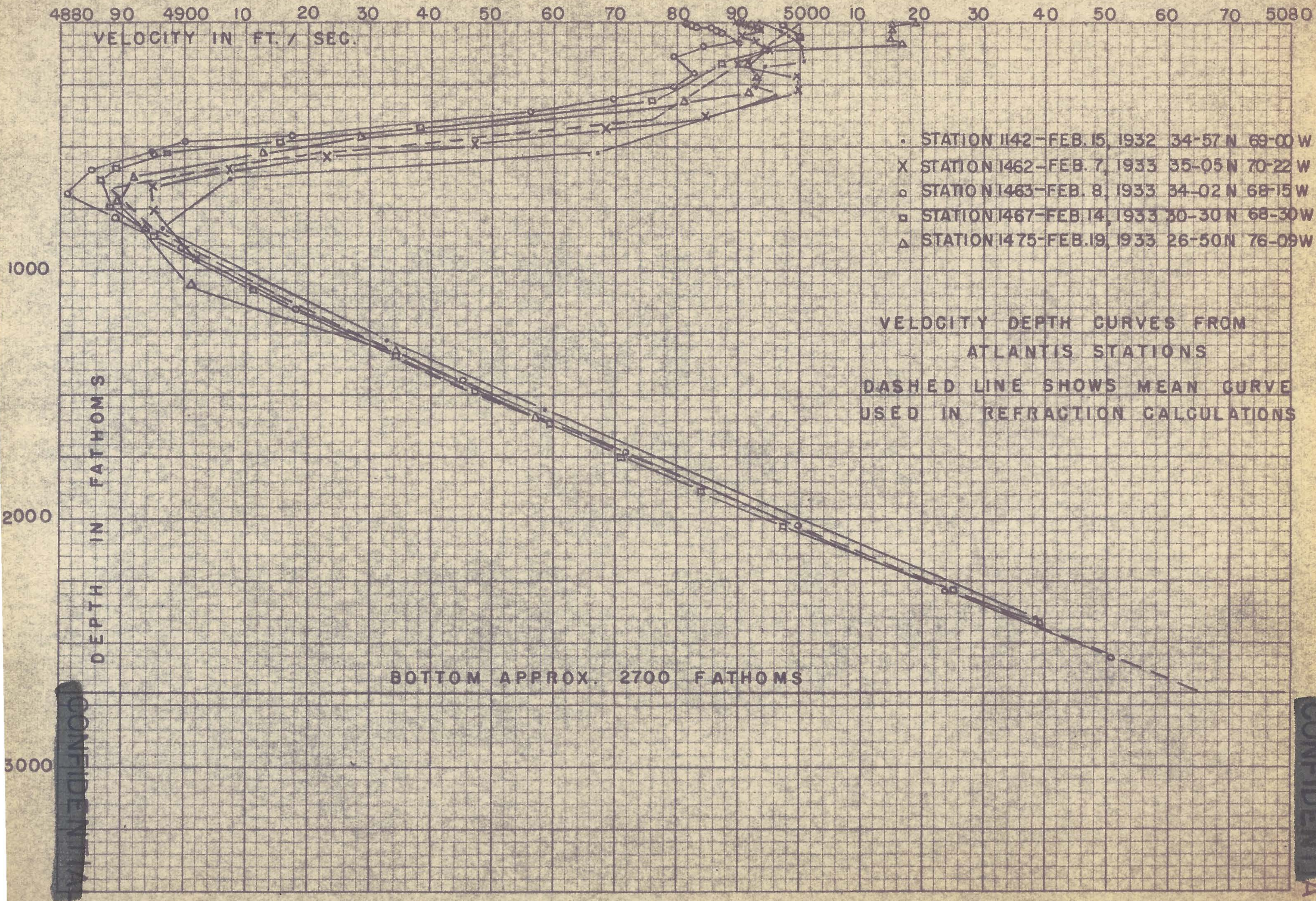


FIG. I.

[redacted]

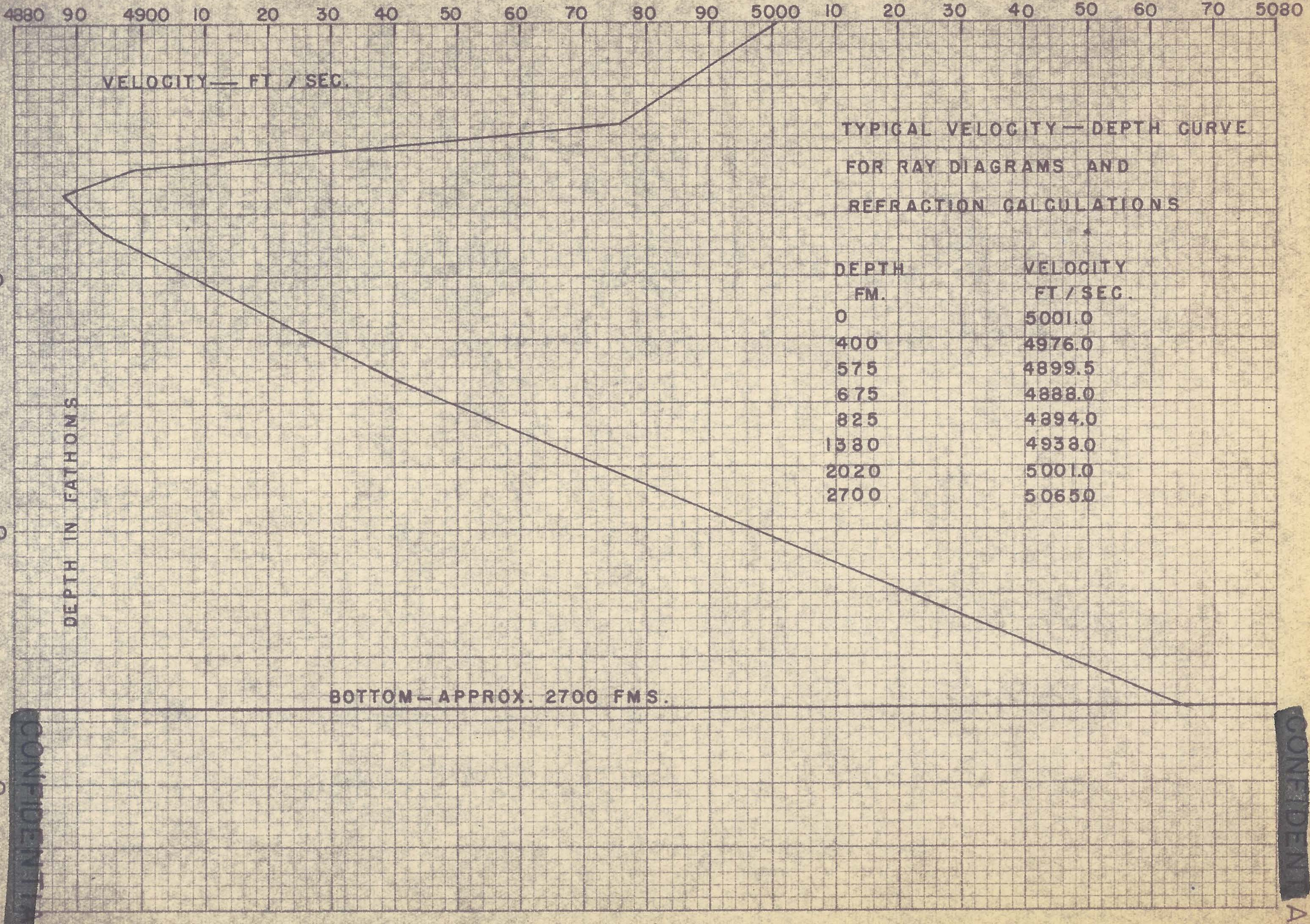
[redacted]



[redacted]

FIG. 2.

[redacted]



DEPTH FM.	VELOCITY FT / SEC.
0	5001.0
400	4976.0
575	4899.5
675	4888.0
825	4894.0
1380	4938.0
2020	5001.0
2700	5065.0

[redacted]

FIG. 3.

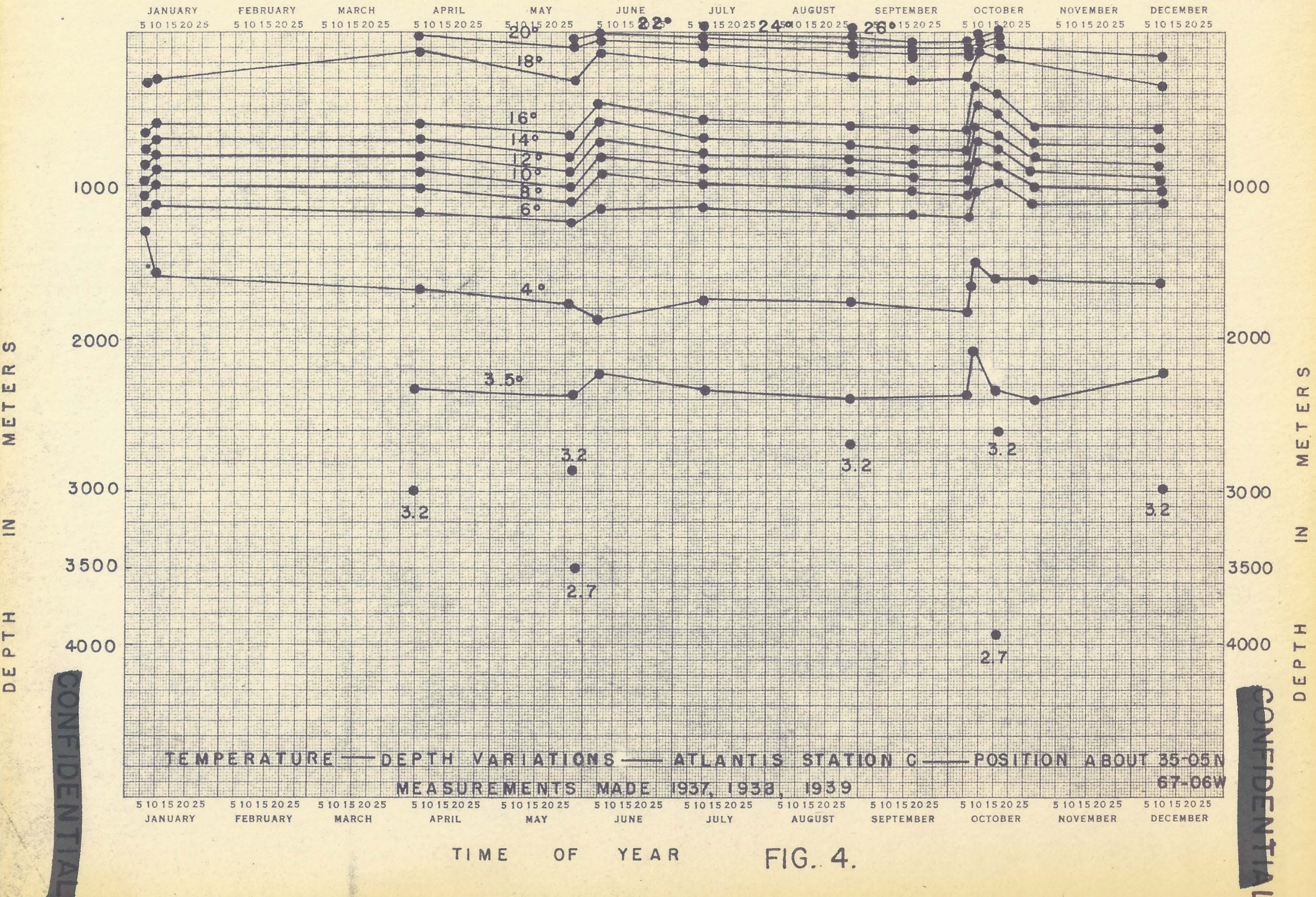

JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
5 10 15 20 25
20°
22°
24°
26°
18°
16°
14°
12°
10°
8°
6°
4°
3.5°
3.2
2.7
1000
2000
3000
3500
4000
DEPTH IN METERS
TEMPERATURE — DEPTH VARIATIONS — ATLANTIS STATION C — POSITION ABOUT 35-05N 67-06W
MEASUREMENTS MADE 1937, 1938, 1939
TIME OF YEAR
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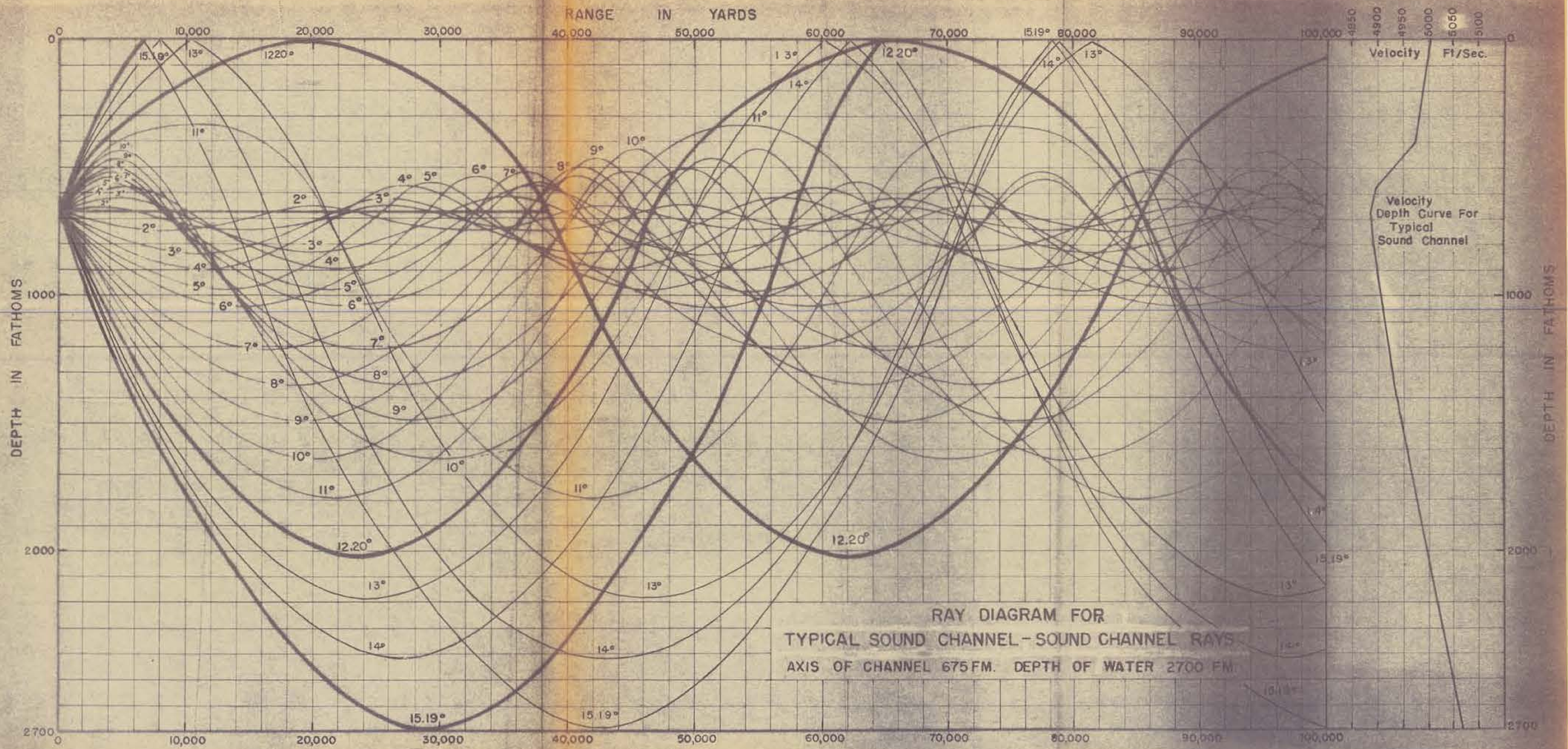
FIG. 4.

From the mean velocity depth curve rays were calculated for a non-directional sound originating at the sound channel axis. This was done for every degree above and below the horizontal from 2° to 11°. The rays which graze the surface and bottom and the rays between 13° and 15° were also calculated. These are all shown in Figure 5 and they illustrate the SC and RSR rays. Rays for the reflected sounds were not included because they overlap the others and confused the diagram, but they may be found plotted to the same scale in Figure 6. The mean velocity depth curve is reproduced for convenience on the right hand side of Figures 5 and 6.



RAY DIAGRAM FOR TYPICAL SOUND CHANNEL - SOUND CHANNEL RAYS

AXIS OF CHANNEL 675 FM. DEPTH OF WATER 2700 FM

FIGURE 5.

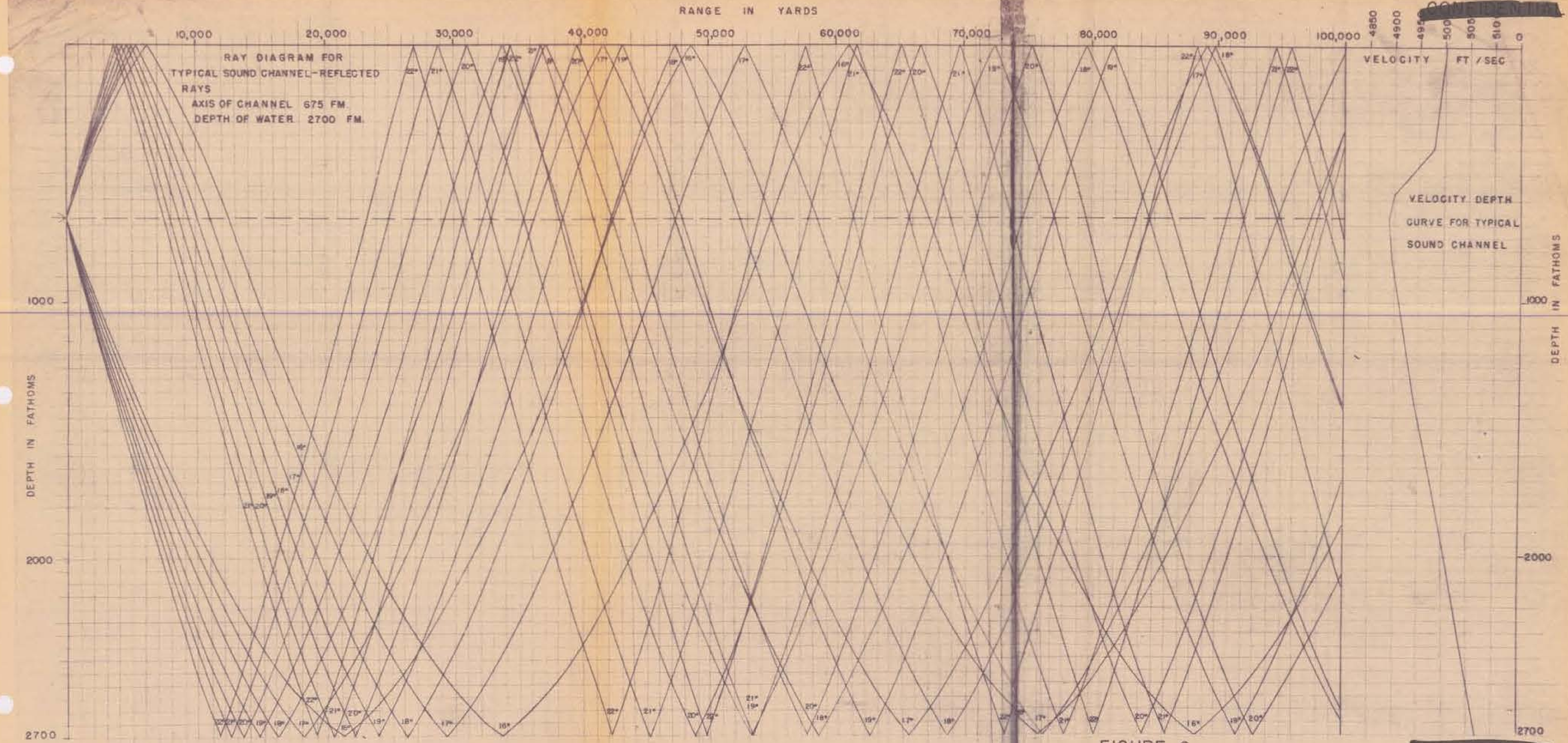

RANGE IN YARDS
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
90,000
100,000
RAY DIAGRAM FOR
TYPICAL SOUND CHANNEL-REFLECTED
RAYS
AXIS OF CHANNEL 675 FM.
DEPTH OF WATER 2700 FM.
VELOCITY FT / SEC
4850
4900
VELOCITY DEPTH
CURVE FOR TYPICAL
SOUND CHANNEL
DEPTH IN FATHOMS
1000
2000
2700

FIGURE 6.

TRAVEL TIMES

In order to discuss sound rays which travel in relation to a sound channel, it is desirable to define the following terms: Top - that portion of a sound ray which travels above the axis of the sound channel from the point where it leaves the axis to the point where it returns. Bottom - that portion of a sound ray which travels below the axis of the sound channel from the point where it leaves the axis to that where it returns. Cycle - one top plus one bottom. It will be noted that all these definitions can be used for SC, RSR, and Reflected rays.

From the theories of geometrical acoustics, the ray paths and travel times were calculated. Methods for calculating the ray paths have been published in Sound Transmission in Sea Water prepared by the Woods Hole Oceanographic Institution for the National Defense Research Committee, February 1, 1941. The theory and derivation of the method for calculating the travel time along a ray path is given in Seismic Propogation Paths, by Maurice Ewing and L. Don Leet, American Institute of Mining and Metallurgical Engineers Technical Publication No. 267, 1930. For convenience the derivation is carried out in Appendix A, using the standard symbols for ray diagram calculations.

Figure 7 is a graph of the range versus the axial angle, and Figure 8 is a graph of the travel time versus the axial angle for a top, a bottom, and a cycle. Figure 9 is a graph of the mean horizontal velocity versus the axial angle. These have been calculated from the mean velocity depth curve of Figure 3.

[redacted]

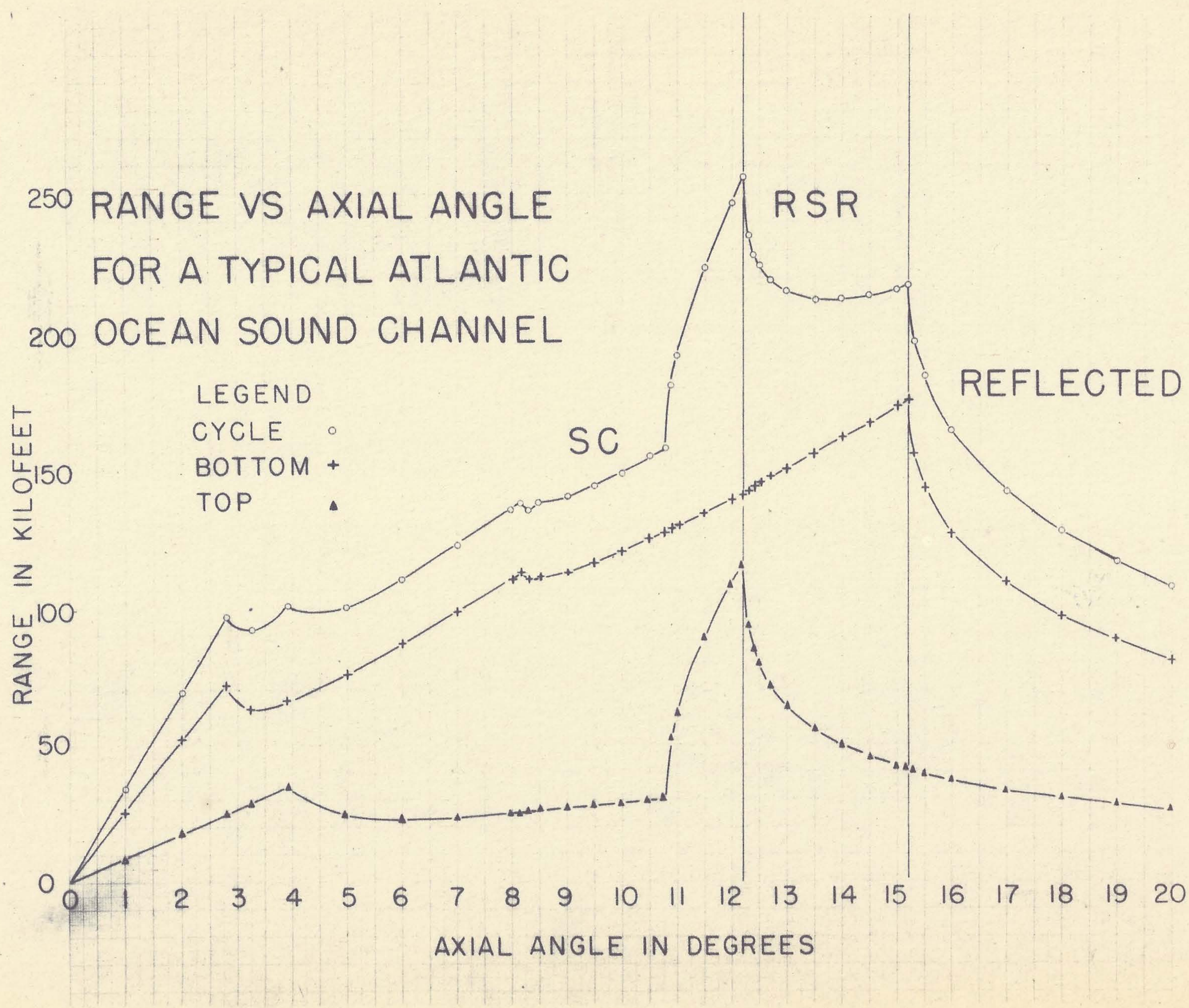


FIG. 7.

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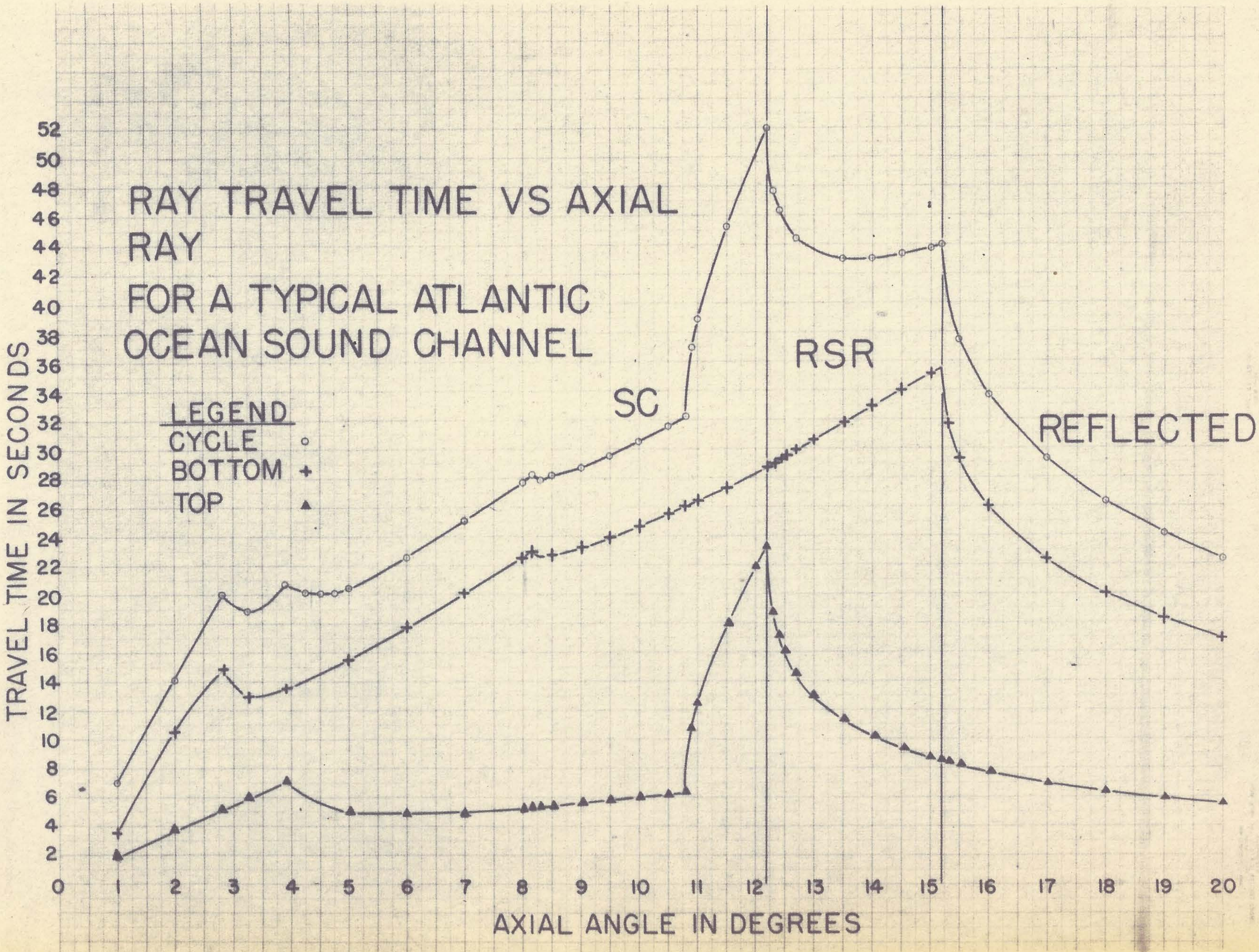

FIG. 8.

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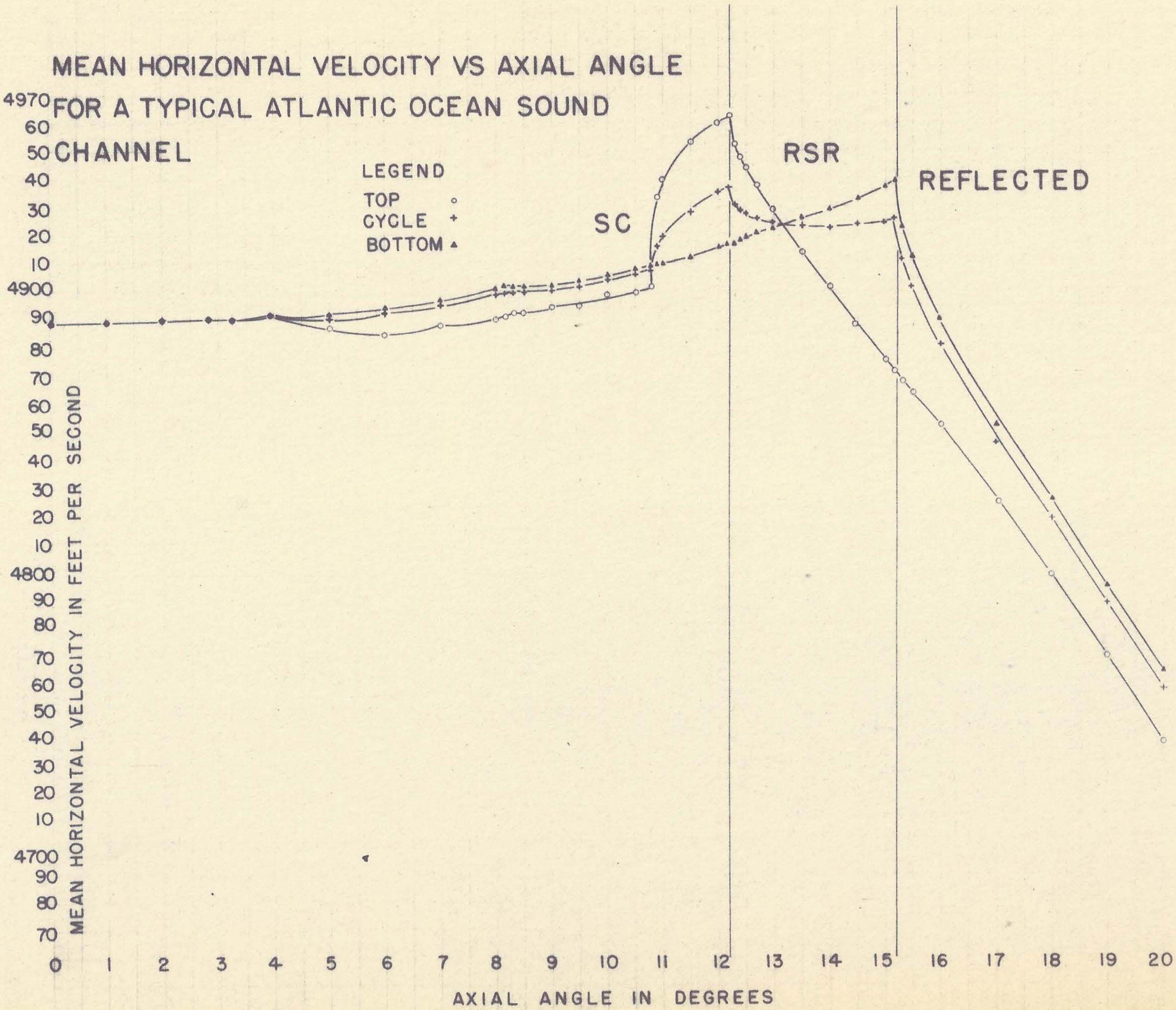

FIG. 9.

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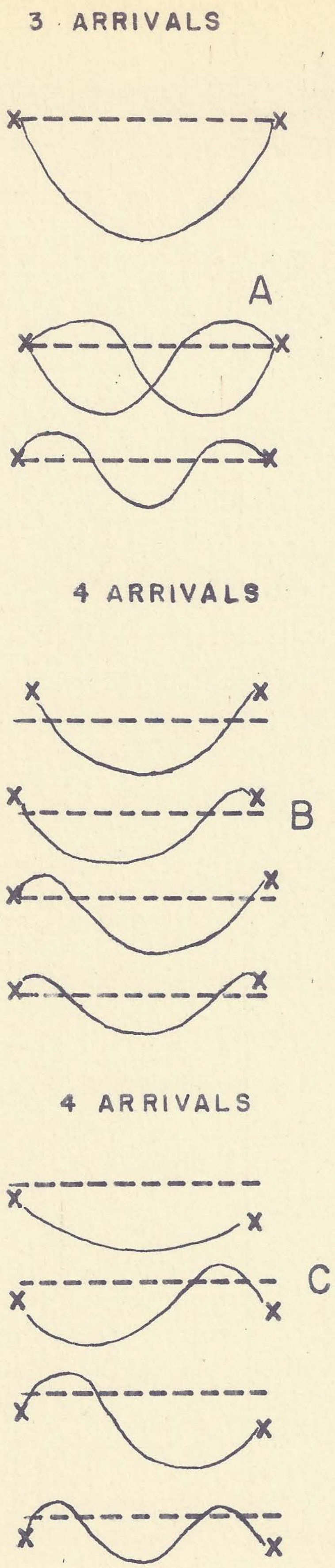
Utilizing these graphs, the ray paths and the corresponding travel times between two points on a sound channel axis can easily be determined. There are two rays with the same axial angle, which make the same number of complete cycles between a source and a receiver at the same depth (see Figure 10A). These rays travel at the same speed and arrive at the same time so that they are inseparable. However, if the source and receiver are at different depths, these two paths differ in axial angle, speed, and arrival time so that they become separated into two arrivals (see Figure 10B - 10E). At a fixed separation on the sound channel axis there are two rays which make the least number of complete cycles between the source and receiver. These rays are determined by dividing the distance of separation by the range of the limiting sound channel ray, approsimately 42 miles. The whole number just larger than this resultant is the least number of complete cycles possible. The maximum number of complete cycles is practically unlimited.

In addition to the paths composed of complete cycles, there are paths consisting of one more or one less top than bottom. It can be seen from Figures 7 and 8 that the time of travel for either of these paths will be nearly the same as that for the paths composed of the corresponding number of complete cycles, because the time and distance for a top are much smaller than for a bottom with the same axial angle.

From the above description it may be seen that the rays within the sound channel arrive at a receiver on the axis in groups of three arrivals from a non-directional source on the



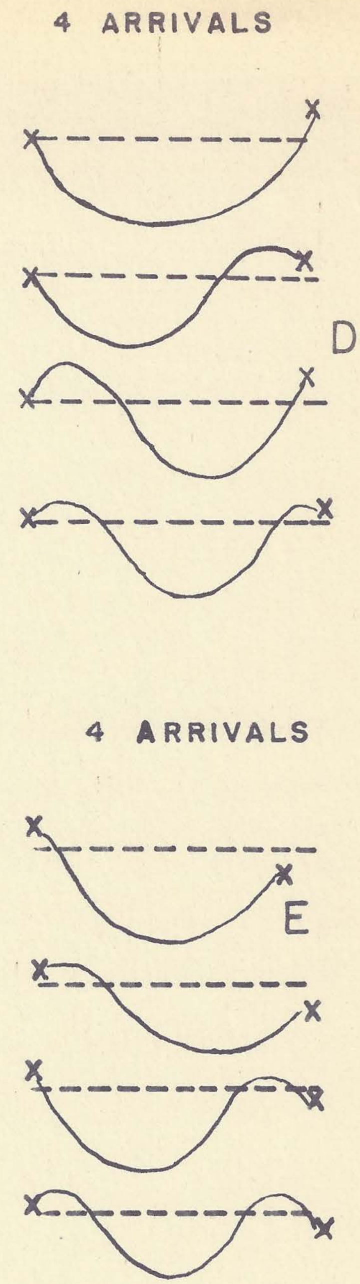


FIG. 10 —— SCHEMATIC DIAGRAM OF RAY PATHS HAVING SIMILAR TRAVEL TIMES WITH VARIOUS RELATIONS OF SOURCE & RECEIVER TO THE SOUND CHANNEL AXIS. THESE DIAGRAMS ARE FOR THE BASIC RAY PATH OF ONE CYCLE. X STANDS FOR POSITION OF SOURCE OR RECEIVER, ---- STANDS FOR SOUND CHANNEL AXIS.

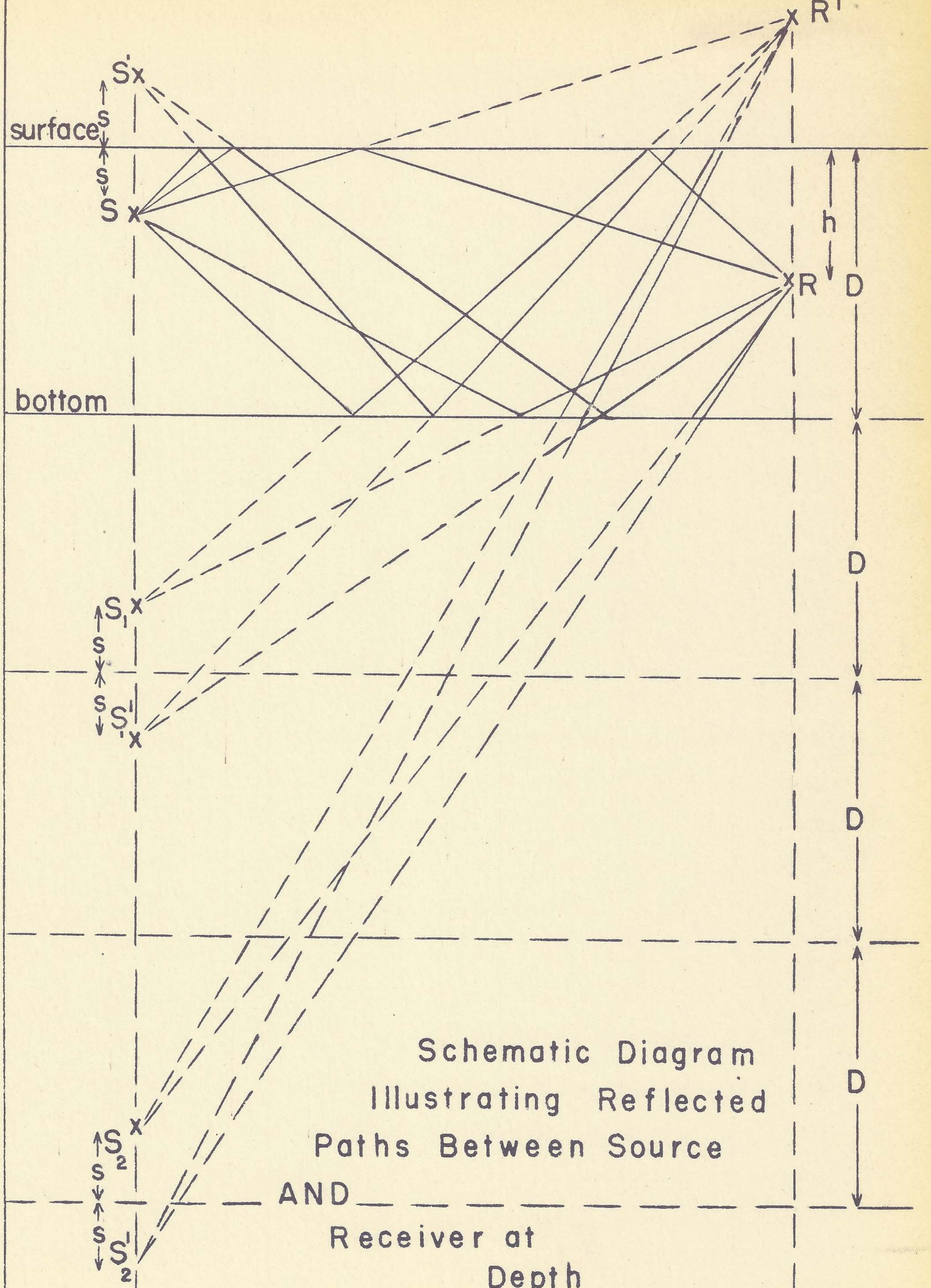
FIG. 10.

axis, and that this becomes a fourfold arrival, if the sound and receiver are at different depths. It is also clear that sounds leaving the axis at the greatest inclination arrive first. The RSR rays arrive in threefold or fourfold groups likewise, but their arrival time is best visualized from Figure 8.

In general the reflected sound shows a group of four arrival for each possible number of cycles. Figure 11 illustrates the paths for the case of one cycle, and it is obvious that the same situation would exist for any greater number of cycles.

If the hydrophone depth, h, and the depth of the source, s, are equal, two of the paths are of equal length and travel time, so only three arrivals can be detected. If either s or h is practically zero, only two arrivals can be observed. If both are practically zero, only one arrival can be observed.

The rays for reflected sound are actually curved, and it can be seen from Figure 5 that the longest distance which can be covered by one cycle is about 36 miles. The smallest number of cycles for reflected sound in any case is found by dividing the distance to be travelled by 36 miles. It may be seen from Figure 11 that the spread in time within each fourfold group of arrivals becomes greater as the number of cycles increases, appraoching as a limit the time required to travel the distance $2(s+h)$. The time difference between successive groups of four also increases with the number of cycles, approaching as a limit the time required to travel the distance 2D.



Schematic Diagram
Illustrating Reflected
Paths Between Source
AND
Receiver at
Depth

FIG. 11.

From this discussion it can be seen that reflected sounds arrive as a set of signals decreasing in intensity and tempo, as contrasted to the sound channel sounds in which both intensity and tempo increase.

The most convenient procedure for comparing the various arrival times calculated from ray diagrams with those actually observed was to construct curves showing the difference in travel time between the axial ray and each of the other rays over the total range of distance involved. This procedure is desirable because the sound arriving along the axial ray is the most conspicuous feature of the actual records, and the ray diagram calculation for it is very simple. Figures 12, 13, and 14 show this time difference or "lead" for the SC, RSR, and reflected rays respectively. All lines on Figure 12 should pass through the origin, but the lower part of each line has been omitted to avoid congestion on the drawing. The curves in Figure 13 are really continuations of those in Figure 12, and those in Figure 14 are continuations of those in Figure 13, but they are shown on separate sheets to avoid confusion. In Figure 14, the lines which extend below the axis represent reflected signals which arrive after the last of the sound channel transmission. There is no theoretical limit to the amount of lag, but usually only three or four reflections can be read after the arrival of the last sound channel sound. Up to the present time, no reflected sounds have been detected beyond 200 miles, and they are even less pronounced at the Eleuthera station than they were on the SALUDA.

[redacted]

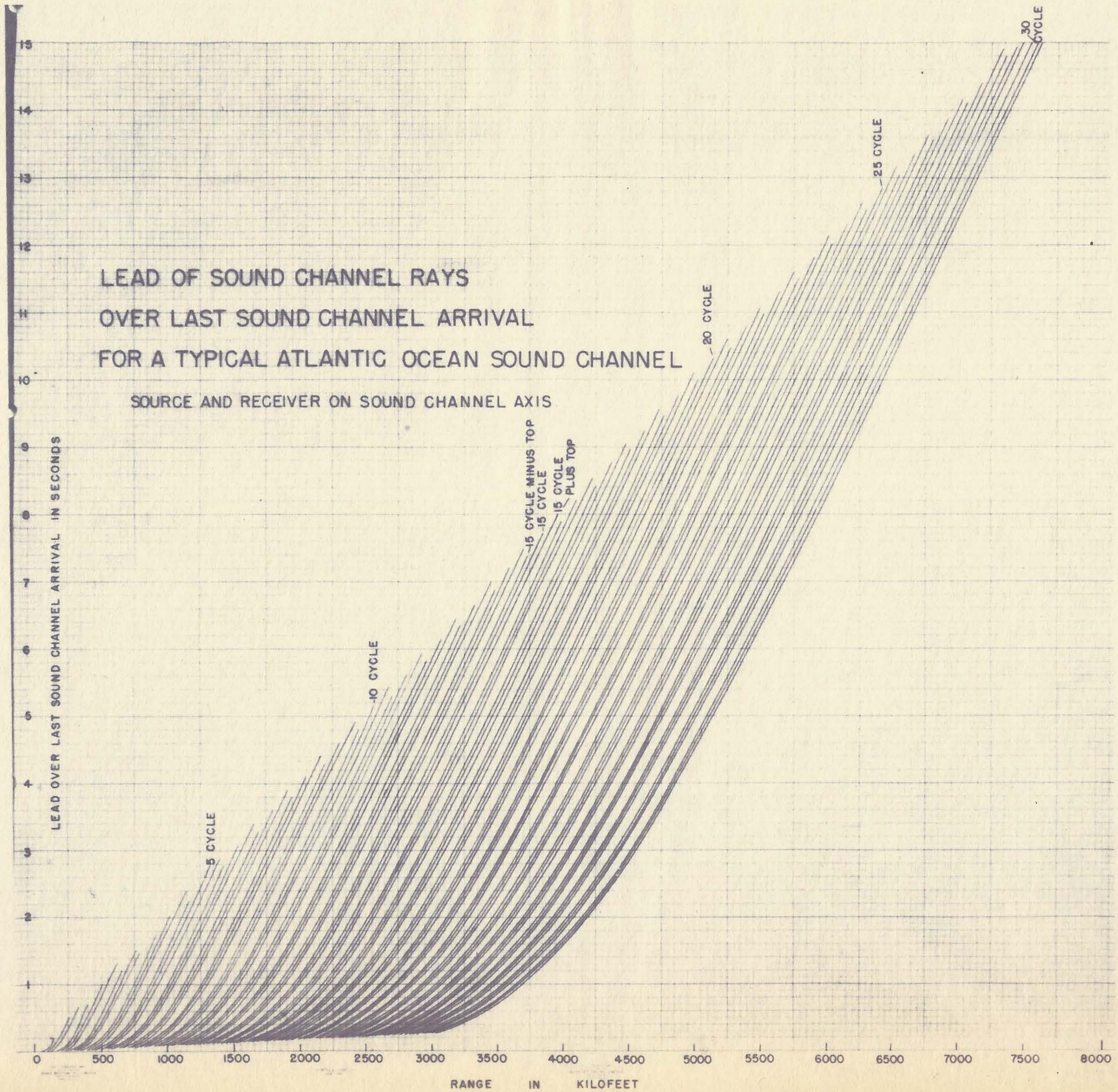


FIG. 12.

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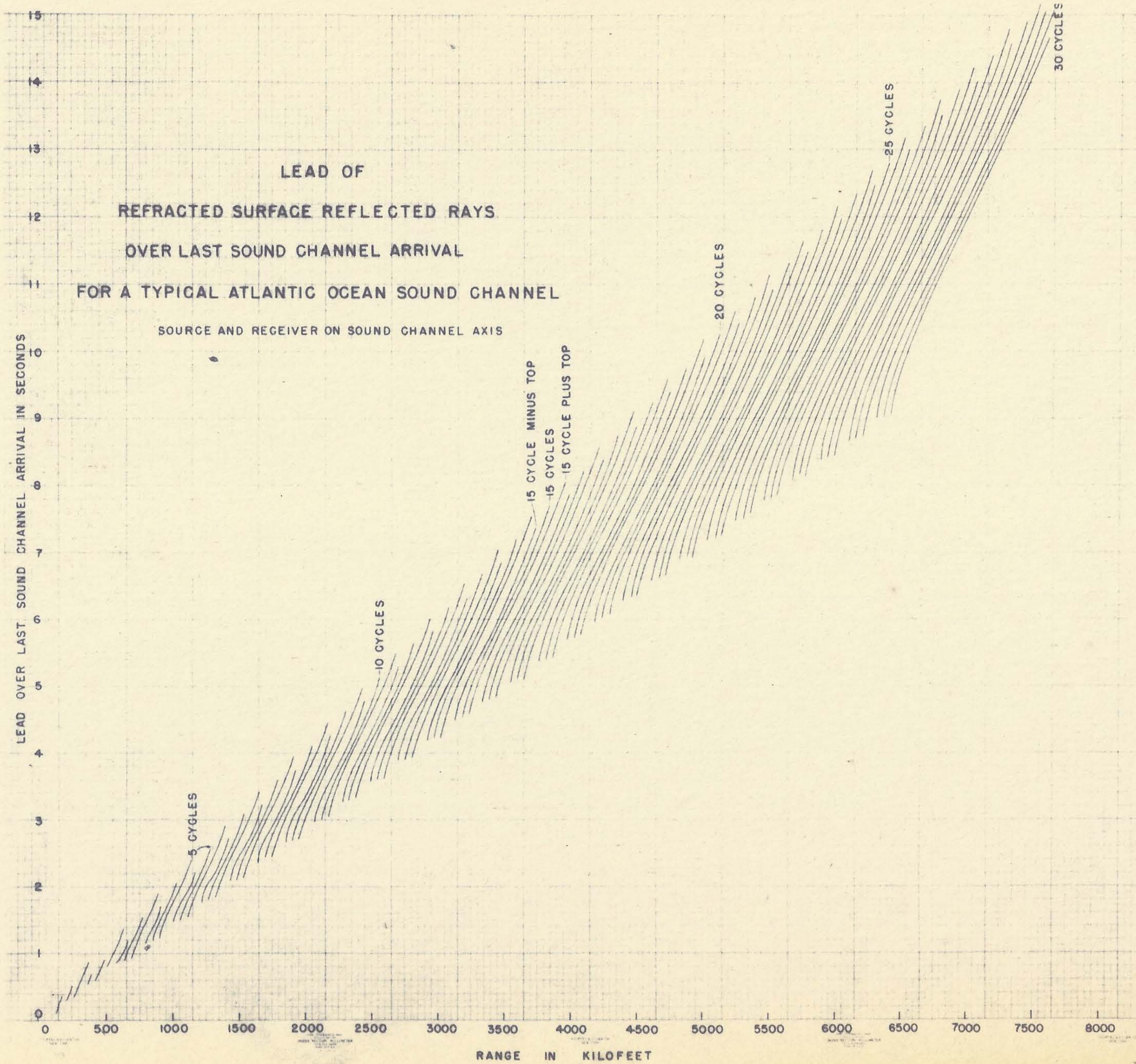

FIG. 13.

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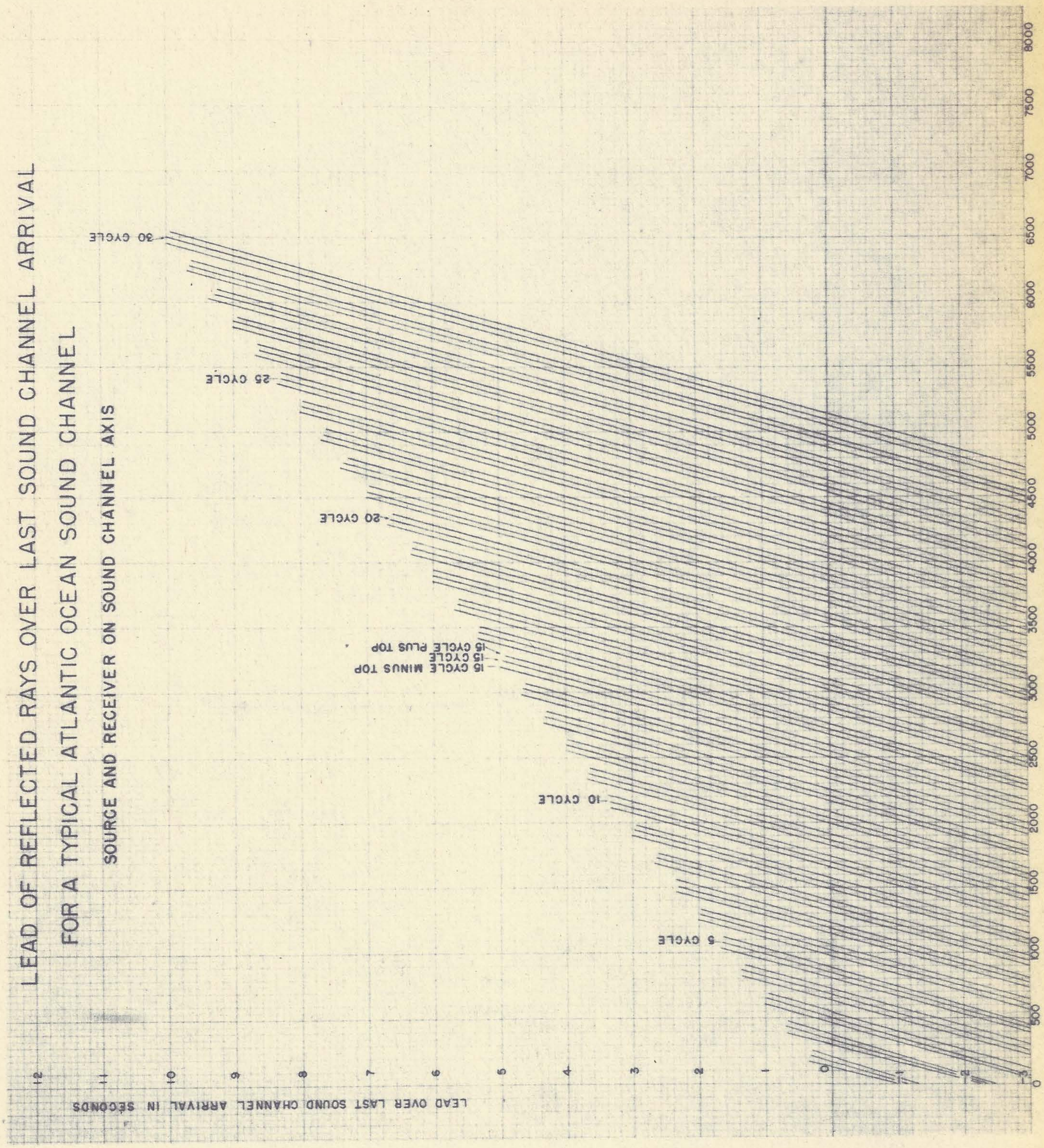
LEAD OF REFLECTED RAYS OVER LAST SOUND CHANNEL ARRIVAL
FOR A TYPICAL ATLANTIC OCEAN SOUND CHANNEL
SOURCE AND RECEIVER ON SOUND CHANNEL AXIS
30 CYCLE
25 CYCLE
20 CYCLE
15 CYCLE PLUS TOP
15 CYCLE
15 CYCLE MINUS TOP
10 CYCLE
5 CYCLE
LEAD OVER LAST SOUND CHANNEL ARRIVAL IN SECONDS
RANGE IN KILOFEET

FIG. 14.

Using these graphs, one can read off the time lead of any ray over the last sound channel arrival at any desired separation between the source and receiver on the sound channel axis. These arrival times, determined by theoretical consideration from the mean velocity depth curve, were plotted alongside the records from the SALUDA cruise and from Eleuthera. Some of these records and plots are reproduced in Plates 1, 2, 3, and 4. The first and most important thing to notice is the extremely good agreement of the over all duration of the sound channel. The next thing to notice is the fourfold arrivals on the SALUDA records. The hydrophone was known to be only about 3600 feet deep from an analysis of the multiple reflections from cap shots fired from the SALUDA. Thus, fourfold arrivals would be expected. The grouping of the arrivals at the Eleuthera Island station is not so clear. This is probably due to the reverberation caused by the sound striking the sloping bottom on which the hydrophone lay.

On the SALUDA records, the agreement between the predicted group arrivals and the observed arrivals is fair. It is believed that the disagreement is partially caused by a certain amount of idealization of the time lead curves of Figures 12, 13, and 14, to simplify the drafting, and partially by the variation of the actual velocity depth section from the mean curve over the distance covered by the sounds.

A list of shots and data read from the records for the deep shots may be found in Appendix B. The observed sound channel signal durations are plotted by two different methods in Figures 15 and 16. The over all sound channel duration of

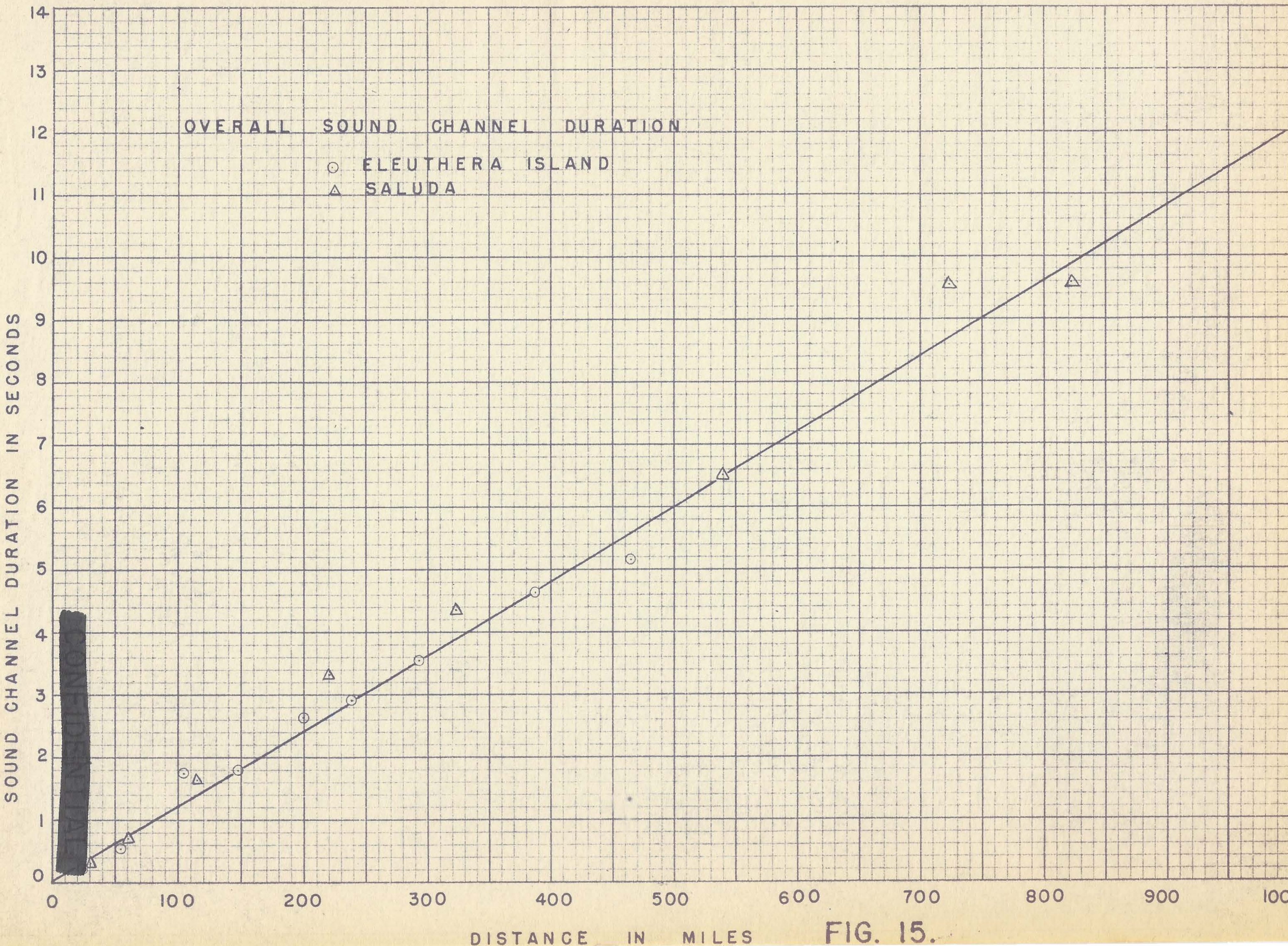

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FIG. 15.

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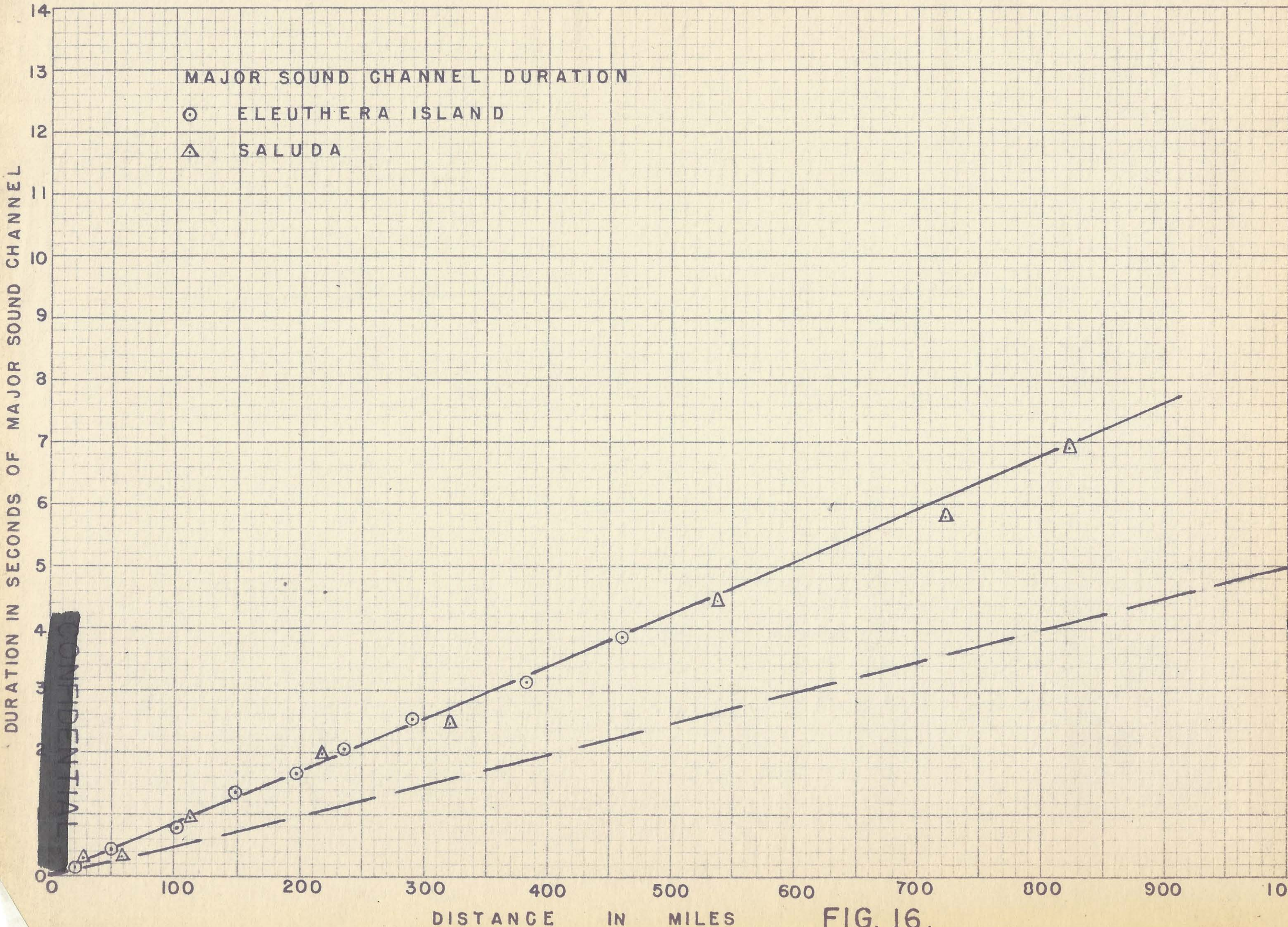

[redacted]

FIG. 16.

Figure 15 is measured from the time of the first detectable sound channel sound to the last. The curve of Figure 15 is the over all sound channel duration, calculated from the mean velocity depth curve (see Figure 3). The major sound channel duration of Figure 16 is measured from the time of the large increase of intensity, which occurs shortly after the first sound channel sound (see Plates 1, 2, 3, 4), to the last sound channel sound. The low intensity of the earlier signals is caused by the refraction effects which they experience in the region near the surface. Since this region varies most with geographical and time changes, the over all sound channel duration would be expected to be a less reliable indication of the range than the major sound channel duration. The dashed curve of Figure 16 represents the duration of the sound rays which travel below 400 fathoms. The solid line is the best line to fit the observed points. The observations would have checked the calculations better if the mean velocity depth curve had been further divided above 400 fathoms to make a better average of the observed velocity depth curve.

At distances less than 100 miles, at the Eleuthera Island station, there were some earlier low intensity sound arrival which were ignored in these plots. These were clearly not related to the sound channel sounds, although it is not yet known by what path they travelled.

A fair estimate of the range to a shot can be obtained to ±50 miles from Figure 15, or to ±30 miles from Figure 16.

A determination of the axial velocity was attempted for all of these shots. Most of the velocities fall between 4900 and 5000 ft/sec. In other words, the variation was about 2%.

Probably the distance between source and receiver is not known better than 2% because the firing ship could only tell her position by celestial navigation and dead reckoning in both experiments. More precise methods of determining range are needed if the axial velocity is to be accurately determined.

CALIBRATION AND FREQUENCY RESPONSE

The frequency response curves for the SALUDA cruise are given in Figure 17 for the shoal channel and in Figure 18 for the deep channel. Figure 19 is a plot of the frequency-response curves for the Eleuthera installation. The reduction of the recorded signals to the sound pressures was done by standard methods, as explained in Explosive Sounds in Shallow Water, by Maurice Ewing and J. Lamar Worzel, October 11, 1944, for the SALUDA channel. The hydrophone response curve is not yet known for the Eleuthera installations, so only relative pressures could be determined.

[redacted]

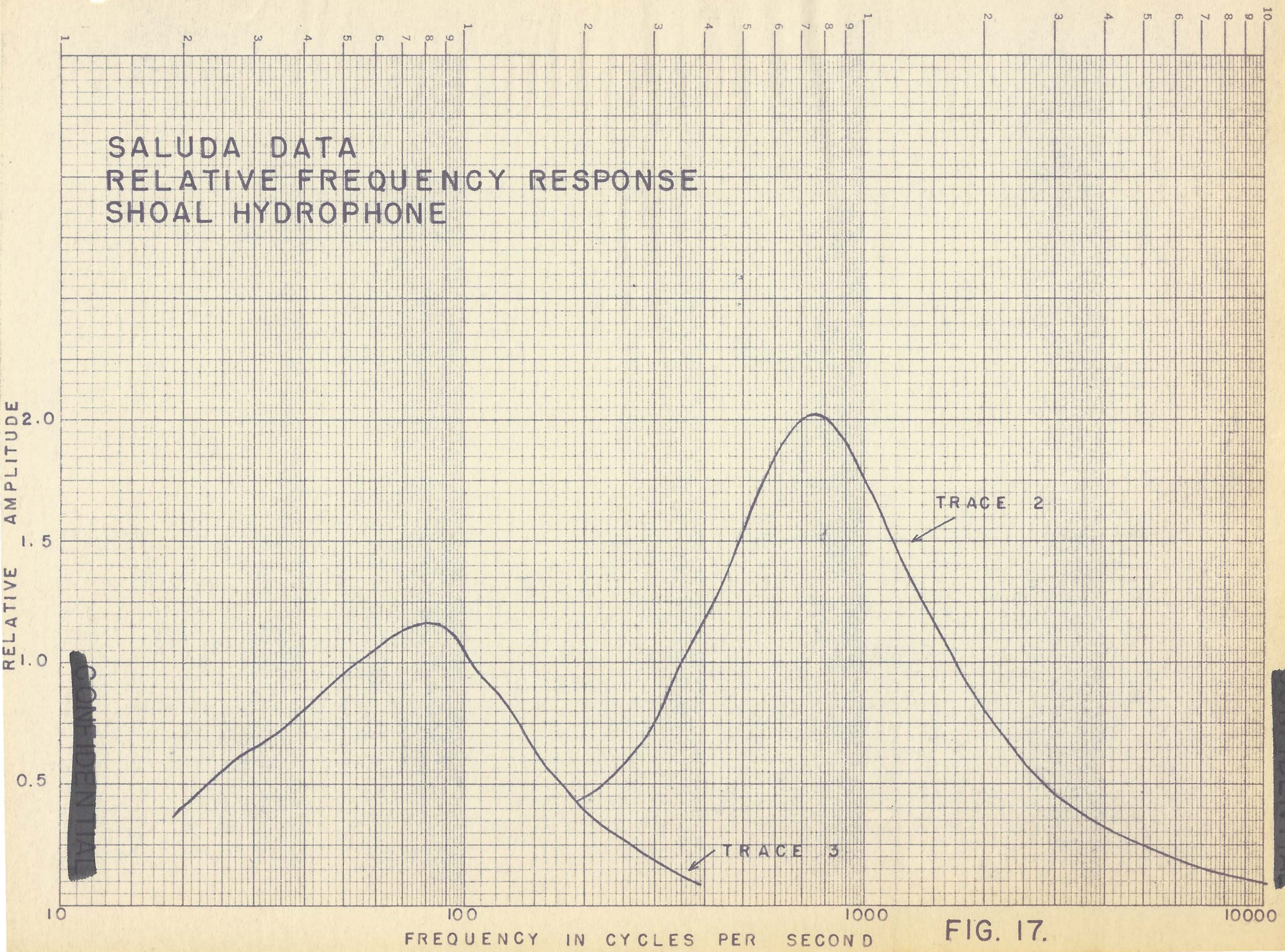

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FIG. 17.

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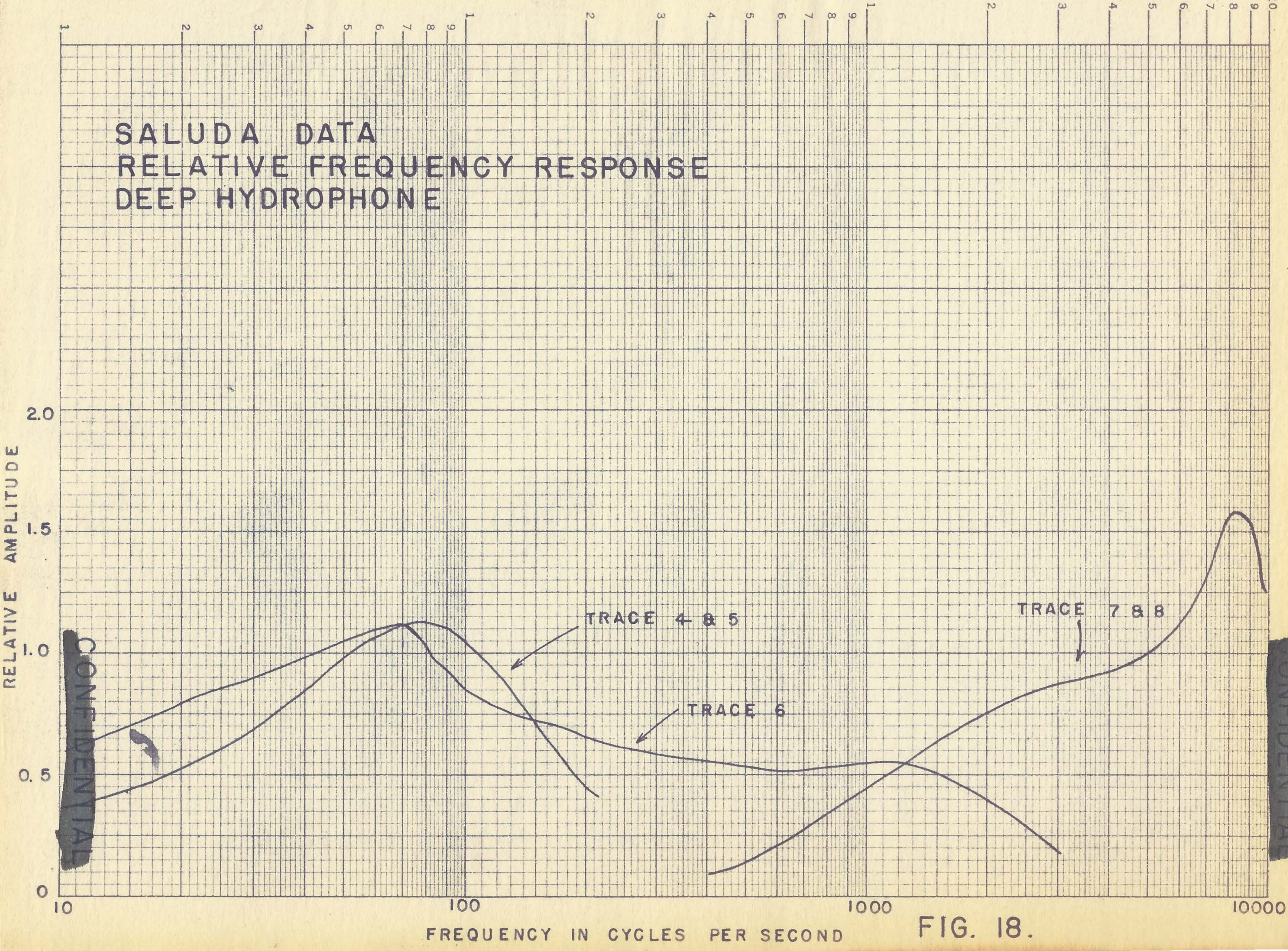

FIG. 18.

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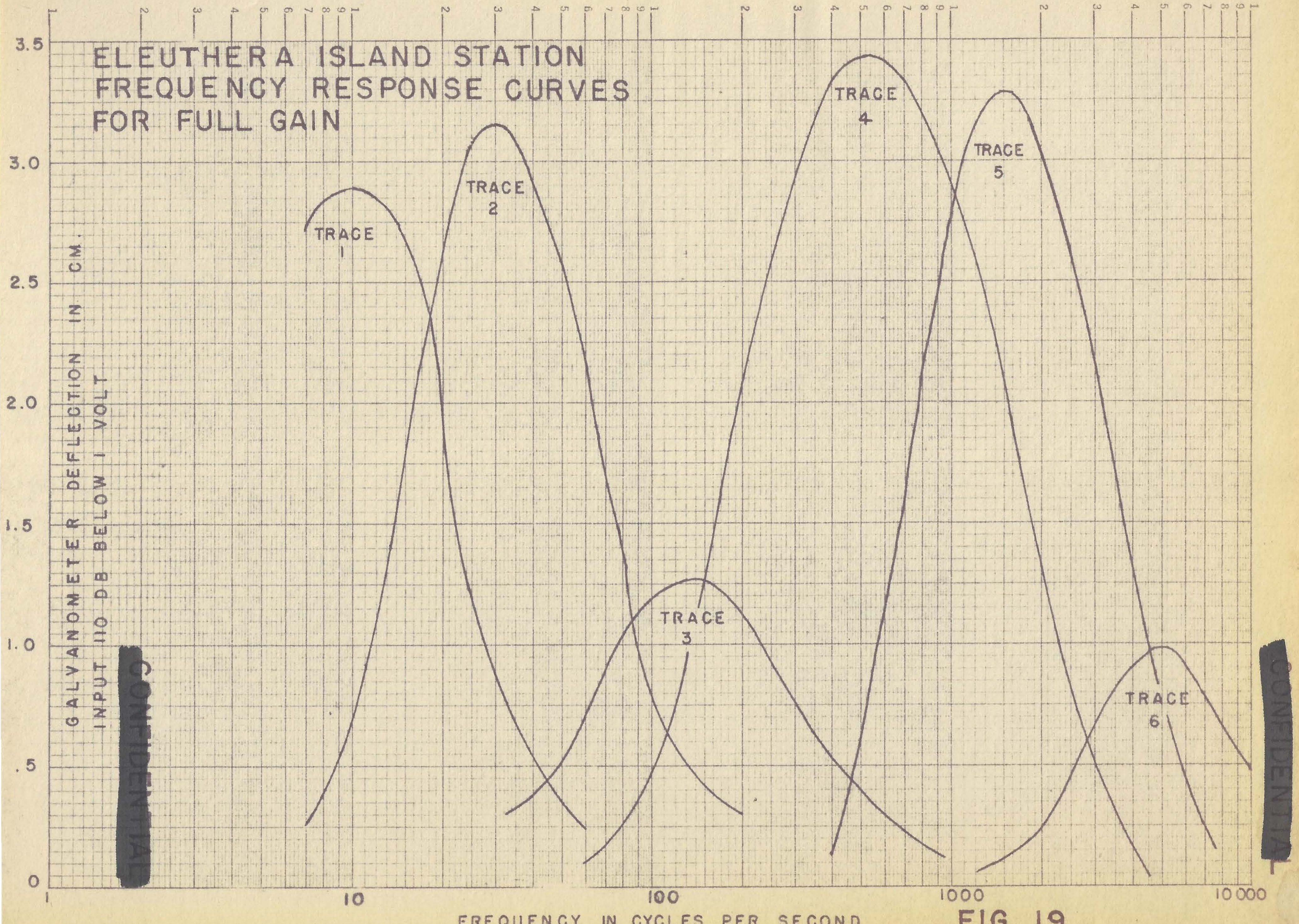

[redacted]

[redacted]

FIG. 19.

PEAK INTENSITIES

Maximum sound intensity occurs near the end of the sound channel transmission. The amplitudes of these signals were read and the pressures corresponding to them were calculated for the SALUDA records. Relative maximum pressures only were read for the Eleuthera Island records because the calibration is in doubt. A noise level was also determined for each trace for both stations. Plots of the logarithm of the maximum pressure versus the logarithm of the travel time (which is equivalent to distance) are given in Figures 20, 21, and 22 for the SALUDA data. Logarithm of the relative maximum pressure versus the logarithm of the travel time is plotted in Figures 23, 24, 25, and 26 for the Eleuthera Island data. The noise level is indicated at the bottom of each graph. The noise level for each trace was determined by increasing the gain until the background noise was readable in that trace. The numerical value of sound pressure given in these graphs is the pressure of a single frequency sound, of frequency selected for the peak sensitivity for the trace in question, which would produce a deflection equal to that produced by the explosion sound.

A resumé of the results obtained in these graphs is given in Table I with remarks about the quality of the determination.

From these results, the most apparent observation is that the point at which the maximum pressure approaches the noise level for low frequencies is of the order of 30,000 seconds or about 25,000 miles. At 10,000 miles then, the end

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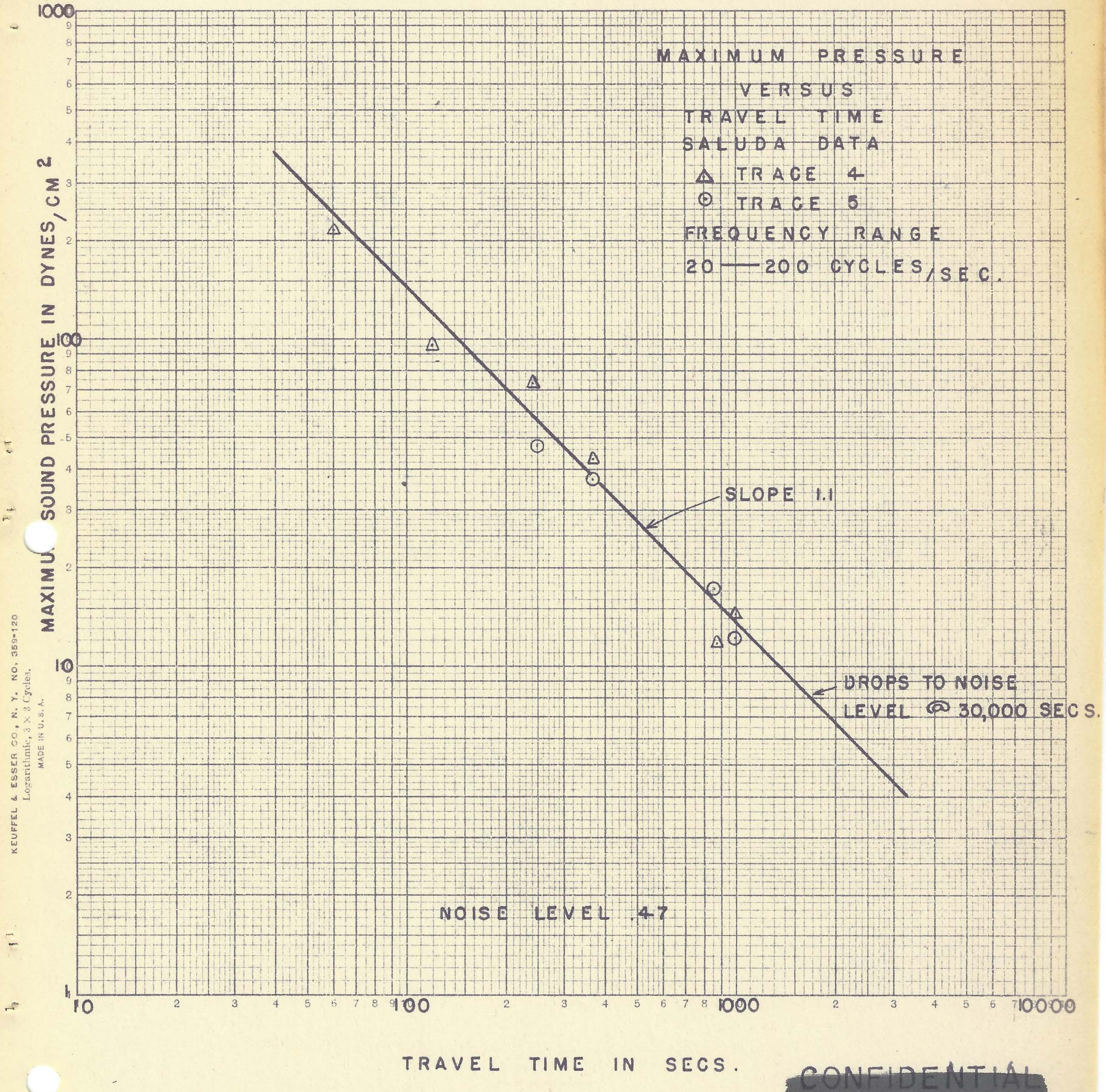

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FIG. 20.

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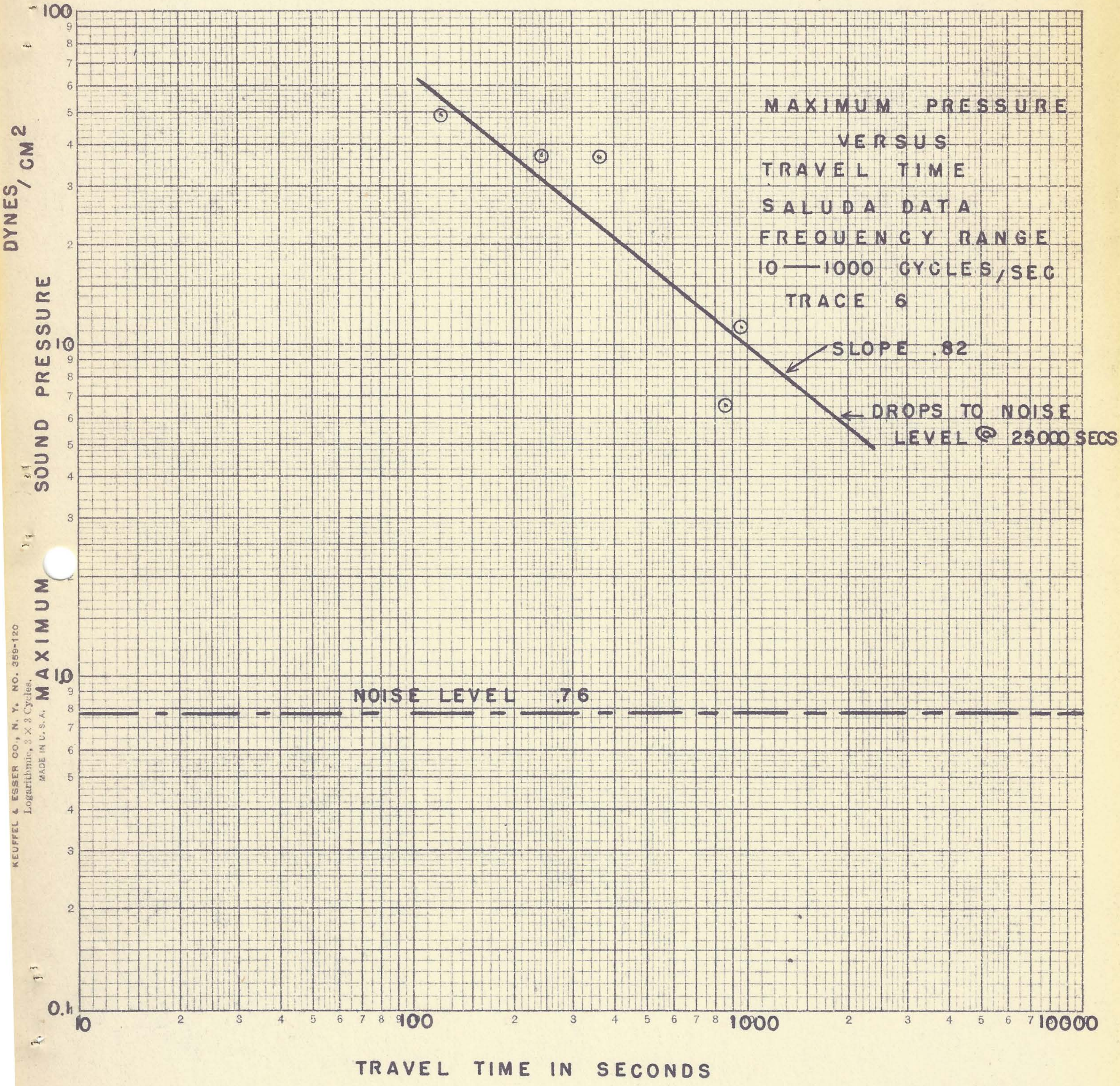

FIG. 21.

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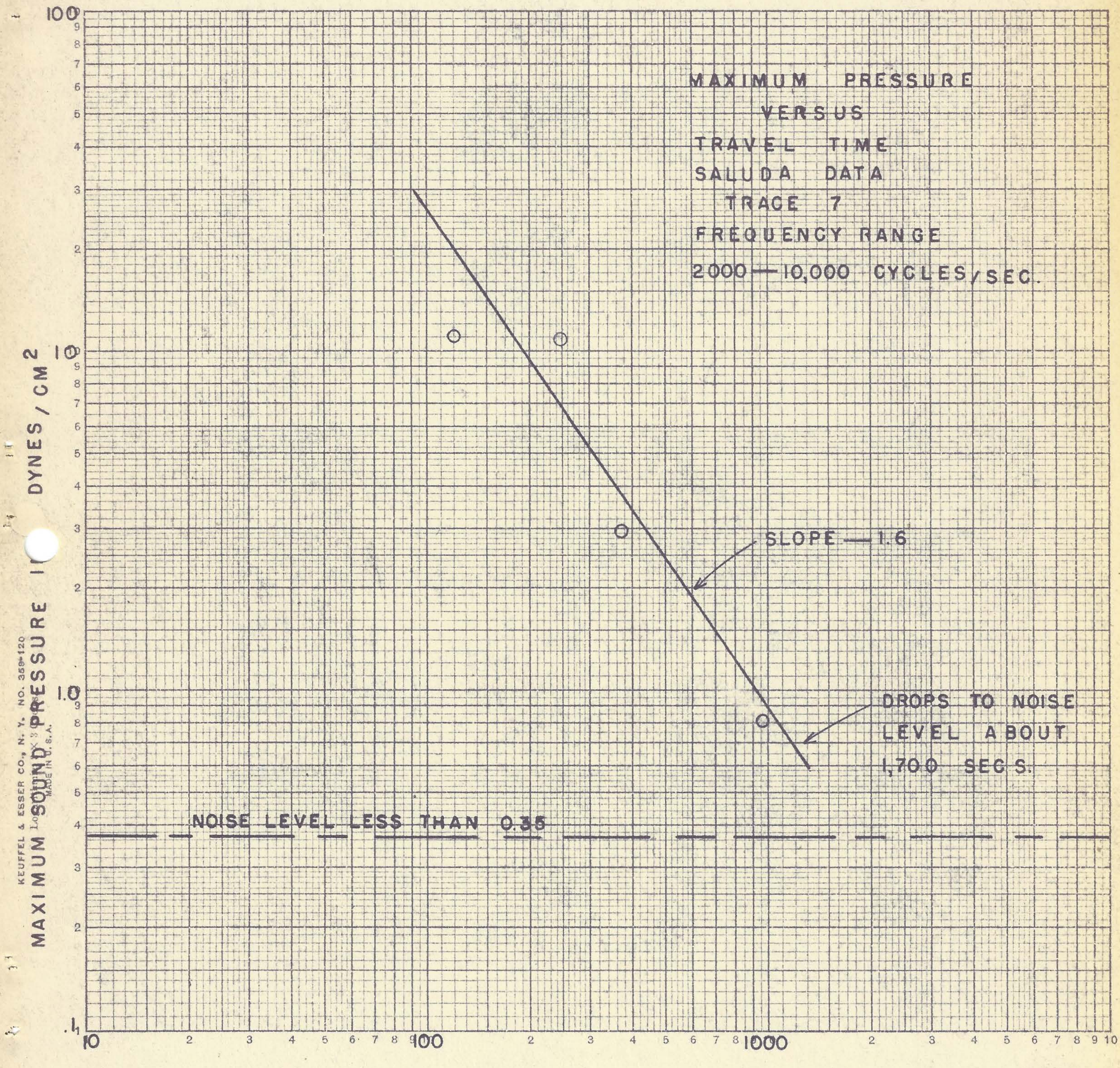
MAXIMUM PRESSURE
VERSUS
TRAVEL TIME
SALUDA DATA
TRACE 7
FREQUENCY RANGE
2000 — 10,000 CYCLES/SEC.
SLOPE — 1.6
DROPS TO NOISE
LEVEL ABOUT
1,700 SECS.
NOISE LEVEL LESS THAN 0.35
MAXIMUM SOUND PRESSURE IN DYNES / CM²
TRAVEL TIME IN SECONDS
KEUFFEL & ESSER CO., N. Y. NO. 359-120
MADE IN U.S.A.

FIG. 22.

[redacted]

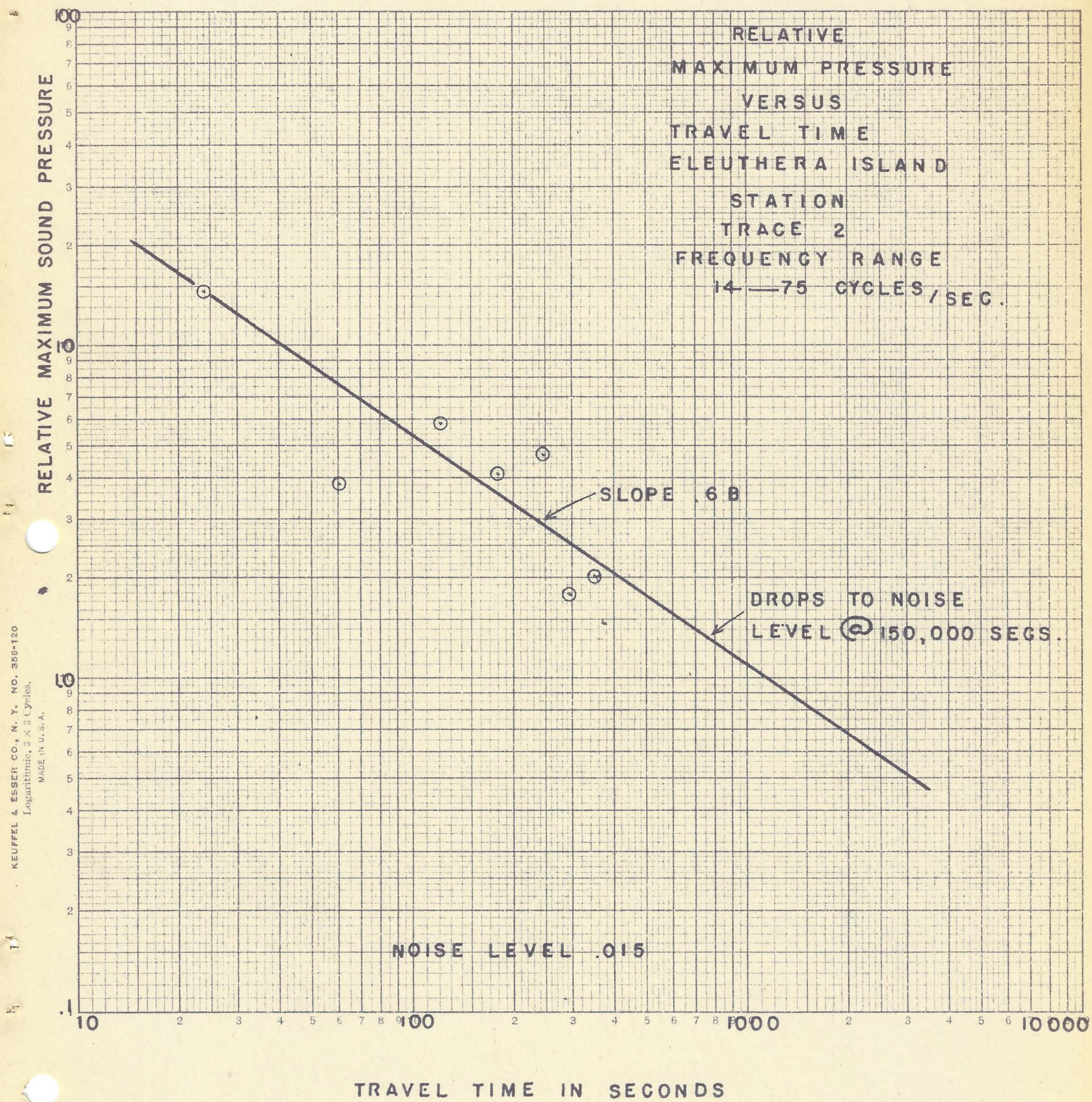

FIG. 23.

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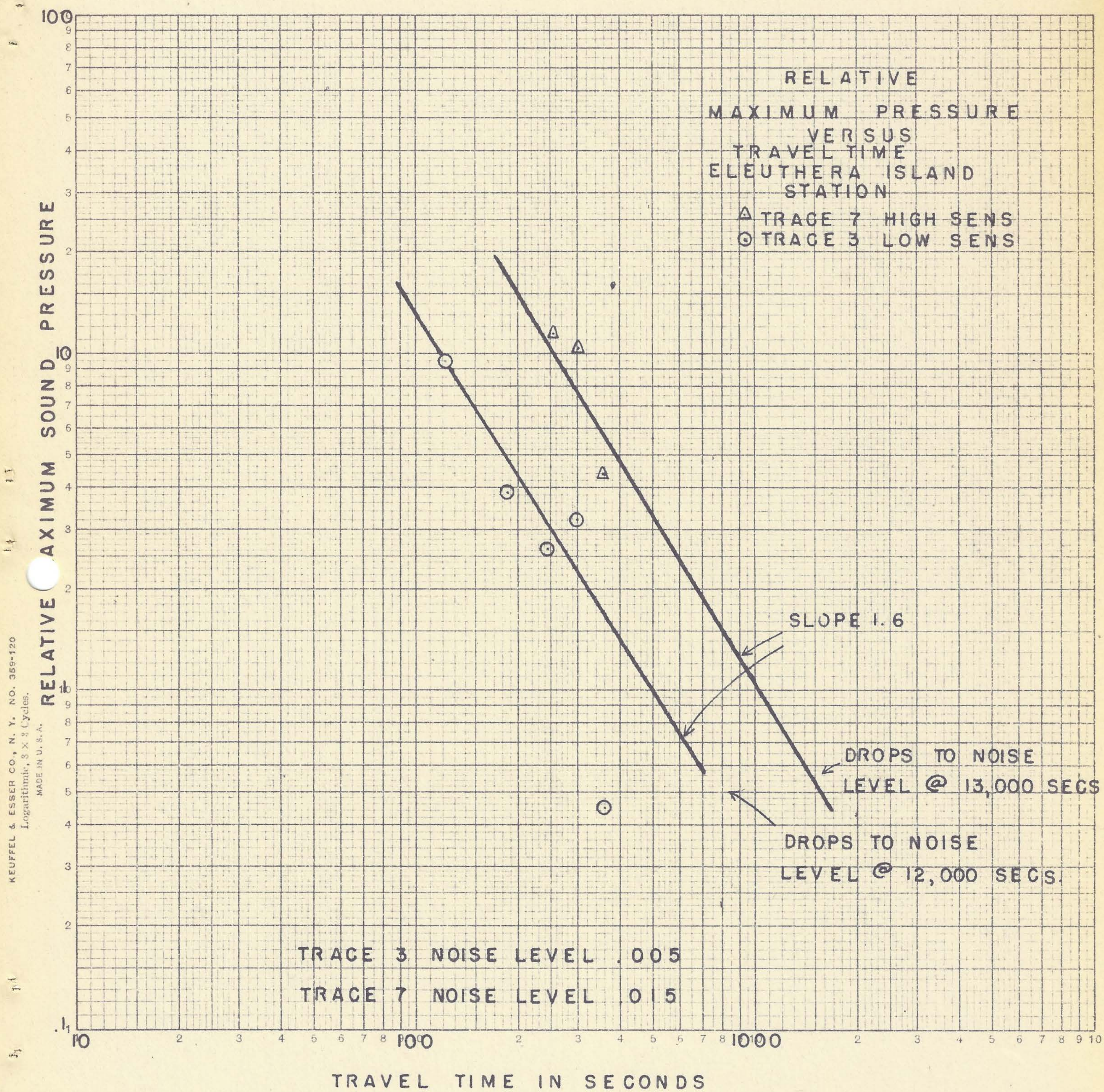

FIG. 24.

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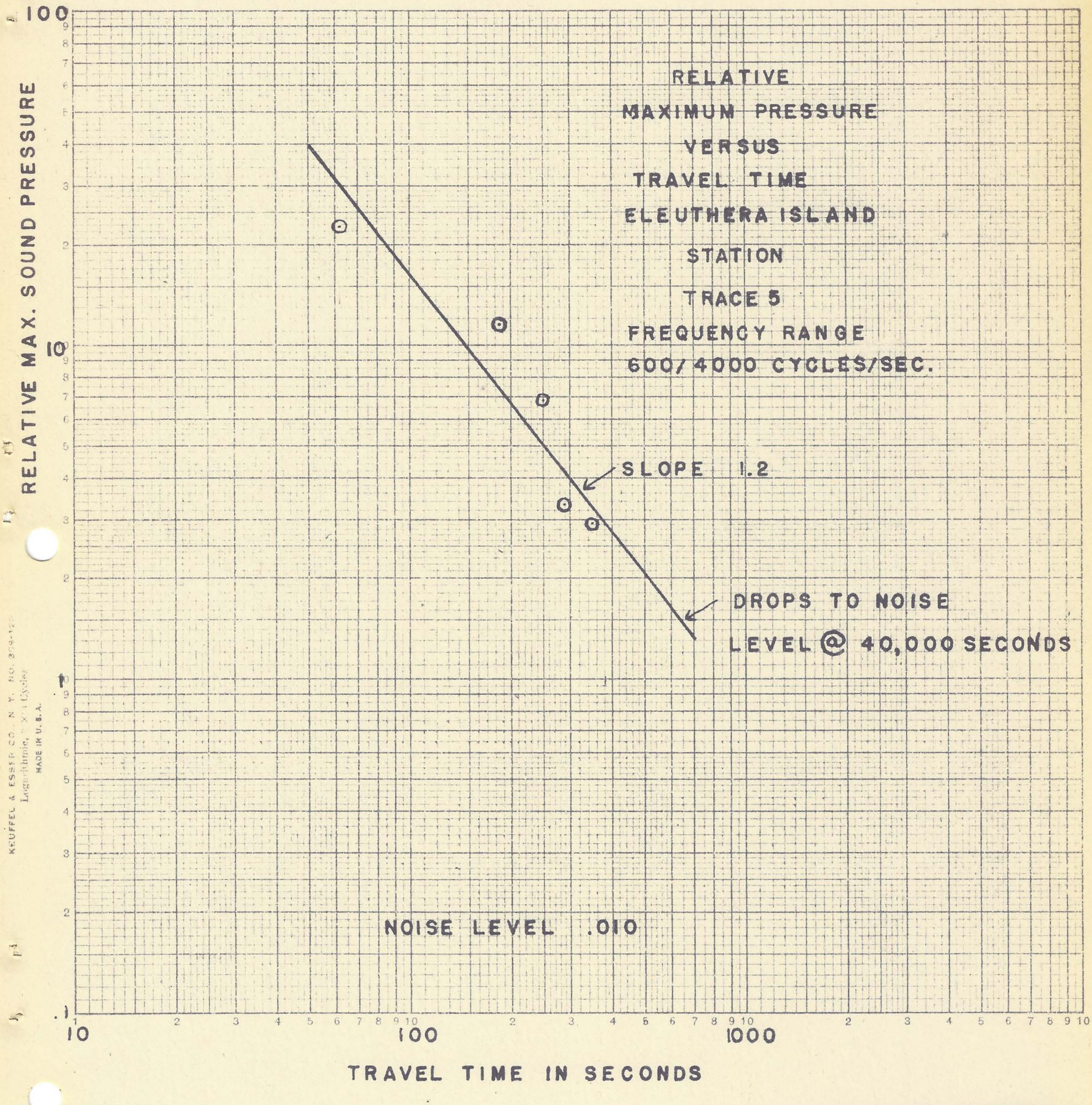

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FIG. 25.

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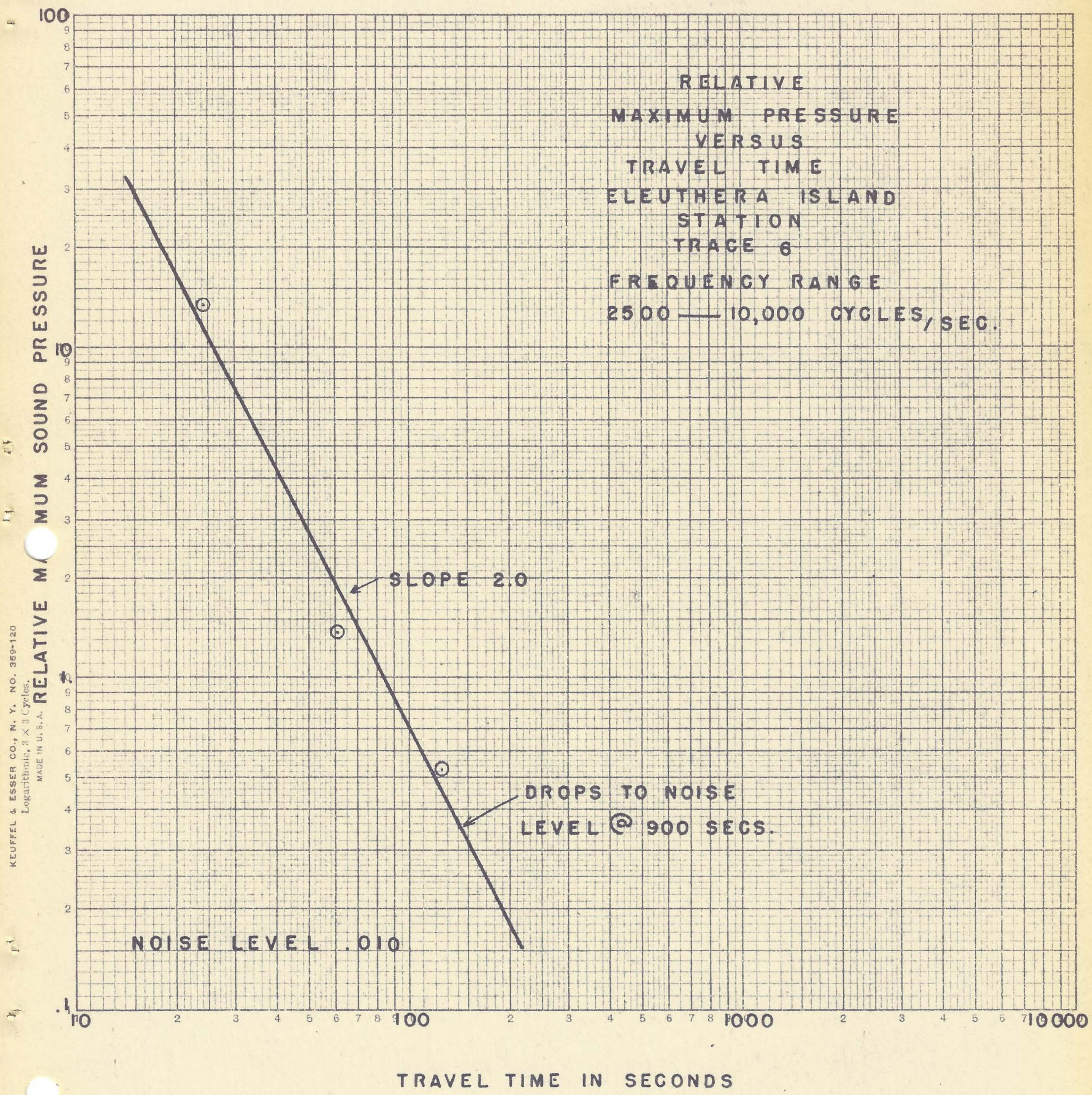

FIG. 26.

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of the signal would be quite readable. This also indicates that the maximum pressure varies according to some power between the inverse first and the inverse second power of the distance.

In the absence of absorption or other loss of energy from the sound channel, the peak pressure would be expected to vary as the inverse first power of the distance because geometrical spreading occurs only in the horizontal dimension, and the duration of the signal is proportional to the distance.

TABLE I

Trace	Frequency Range cycles/sec	Slope	Distance at Which Peak Pressure would Reach Noise Level-seconds	Quality of Data
SALUDA data:				
4 & 5	20 - 200	-1.1	30,000	Very Good
6	10 - 1,000	-0.82	25,000	Poor
7	2,000 - 10,000	-1.6	1,700	Fair
ELEUTHERA ISLAND data:				
2	14 - 75	-0.68	150,000	Poor
3 & 7	55 - 350	-1.6	12,000	Poor
5	600 - 4,000	-1.2	40,000	Good
6	2,500 - 10,000	-2.0	900	Fair

SOUND ENERGIES

The total sound channel energy per unit area arriving at the receiver was measured by integrating by the trapezoid rule the square of the signal amplitude at every time line on the record. The time lines occured every 1/100 second on the SALUDA records and every 4/100 second on the Eleuthera Island records. For each trace, the energy was calculated by the formula $E = \int \frac{p^2}{\rho C} \, dt$ as though the received signal consisted of a single frequency equal to that at which the trace in question has maximum sensitivity. The calibrations were not known for the Eleuthera Island data, so the measured values were merely corrected to a common gain.

The total sound energy arriving at a vertical section of unit width through the sound channel should vary as the inverse first power of the distance, due to the geometric spreading. On the average, the value of the total energy measured at the axis on this section should be proportional to the energy arriving at the section. Hence, the equation for the energy per unit area is:

$$E = \frac{E_0}{CT} e^{-C \alpha T} \qquad (1)$$

where E is the energy per unit area received, E_0 is the energy per unit area at unit distance from the source, C is the velocity of sound in sea water, T is the travel time of the sound, and α is the absorption coefficient of the water. Eliminating the effect of the geometric spreading and taking logarithms of this equation we get:

$$\log ET = \log \frac{E_0}{C} - C \alpha T \qquad (2)$$

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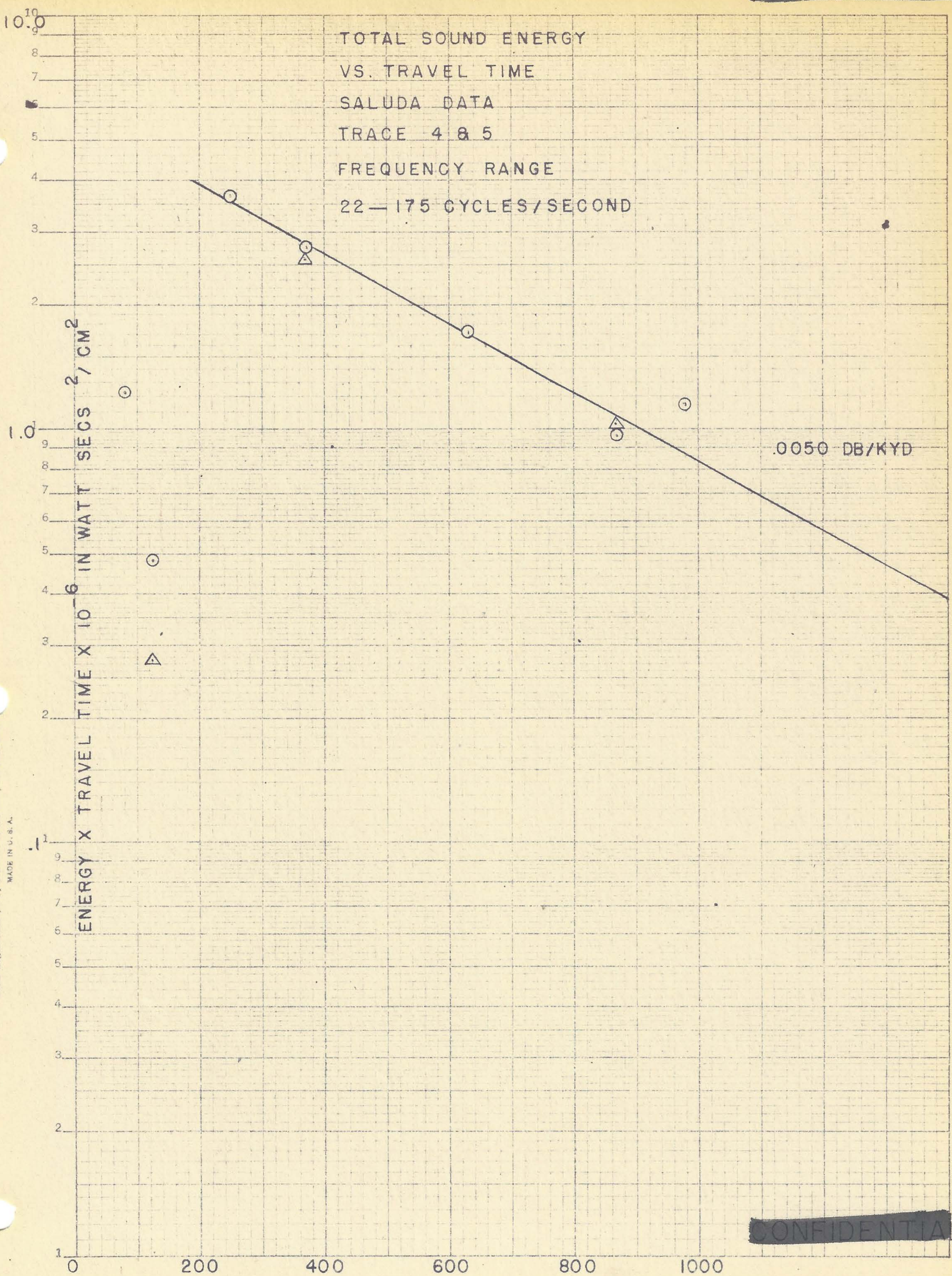

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FIG. 27.

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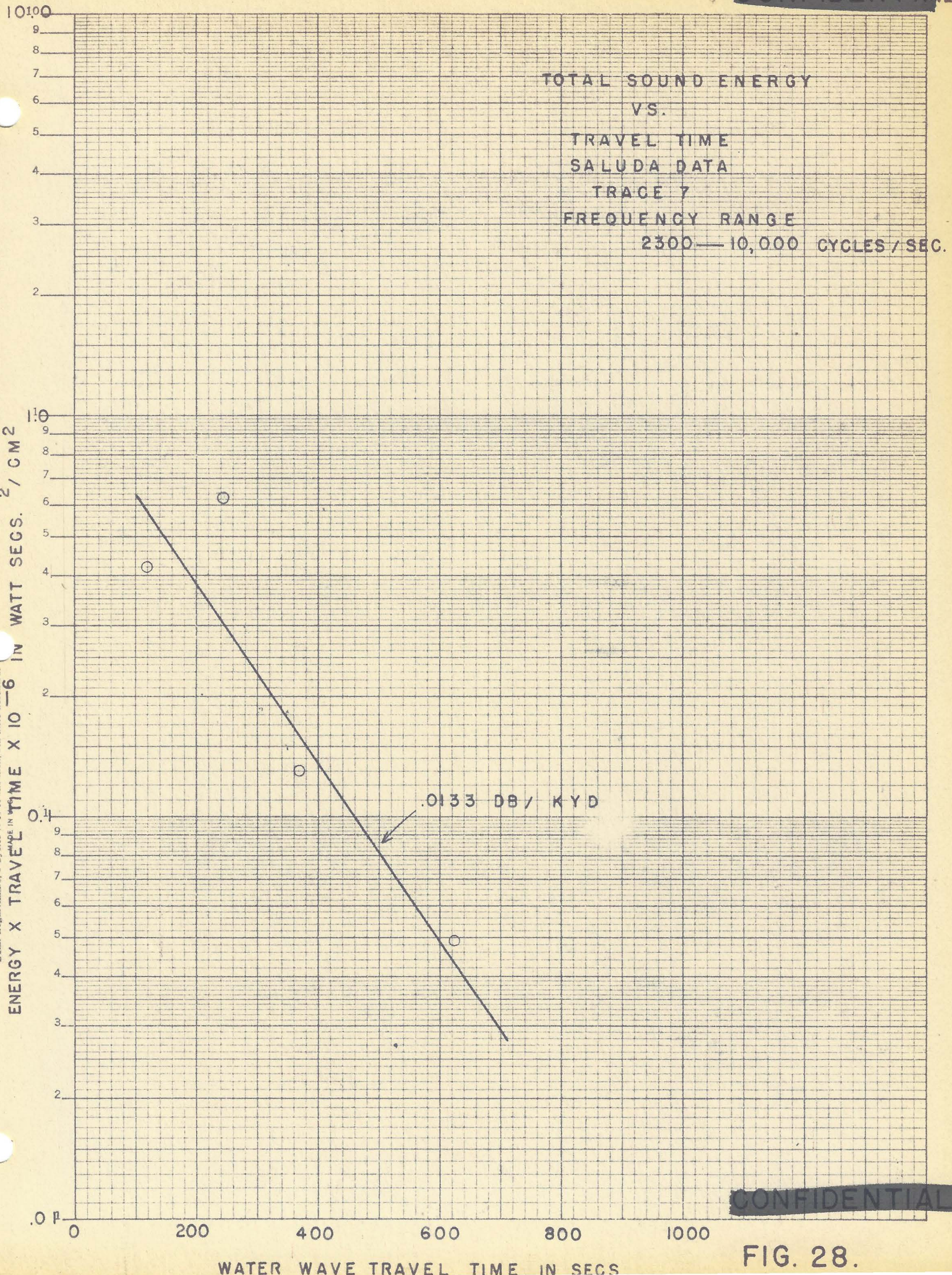

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FIG. 28.

For the SALUDA data the log ET was plotted against the travel time in Figures 27 and 28. The slope of the line determined by these points determines the absorption coefficient of the water. For the Eleuthera Island data this equation was rearranged as follows:

$$\log \frac{ET}{E_o} = \log \frac{1}{C} - C \alpha T \qquad (3)$$

The log $\frac{ET}{E_o}$ was plotted against the travel time in Figures 29, 30, 31, and 32. Again the slope of the line determines the absorption coefficient of the water. A resume of the results is given in Table II below with appropriate remarks about the quality of the determination.

TABLE II

Trace	Frequency Range cycles/sec	Absorption db/kyd	Quality of Observation
SALUDA data:			
4 & 5	22-175	.0050	good
7	2300-10,000	.0133	poor
ELEUTHERA ISLAND data:			
2	14-75	.0252	fair
3	56-350	.0427	fair
5	600-4000	.0352	fair
7	56-350	.0498	fair

The points for the close shots do not agree very well with the other points. This is probably due to the fact that the sound field has not had sufficient time to distribute itself so that a measurement at one point is sufficiently related to the sound energy arriving at a vertical section.

The absorption loss lies between .005 and .05 db/Kyd. for sounds below 10,000 cycles/second. More frequent shots

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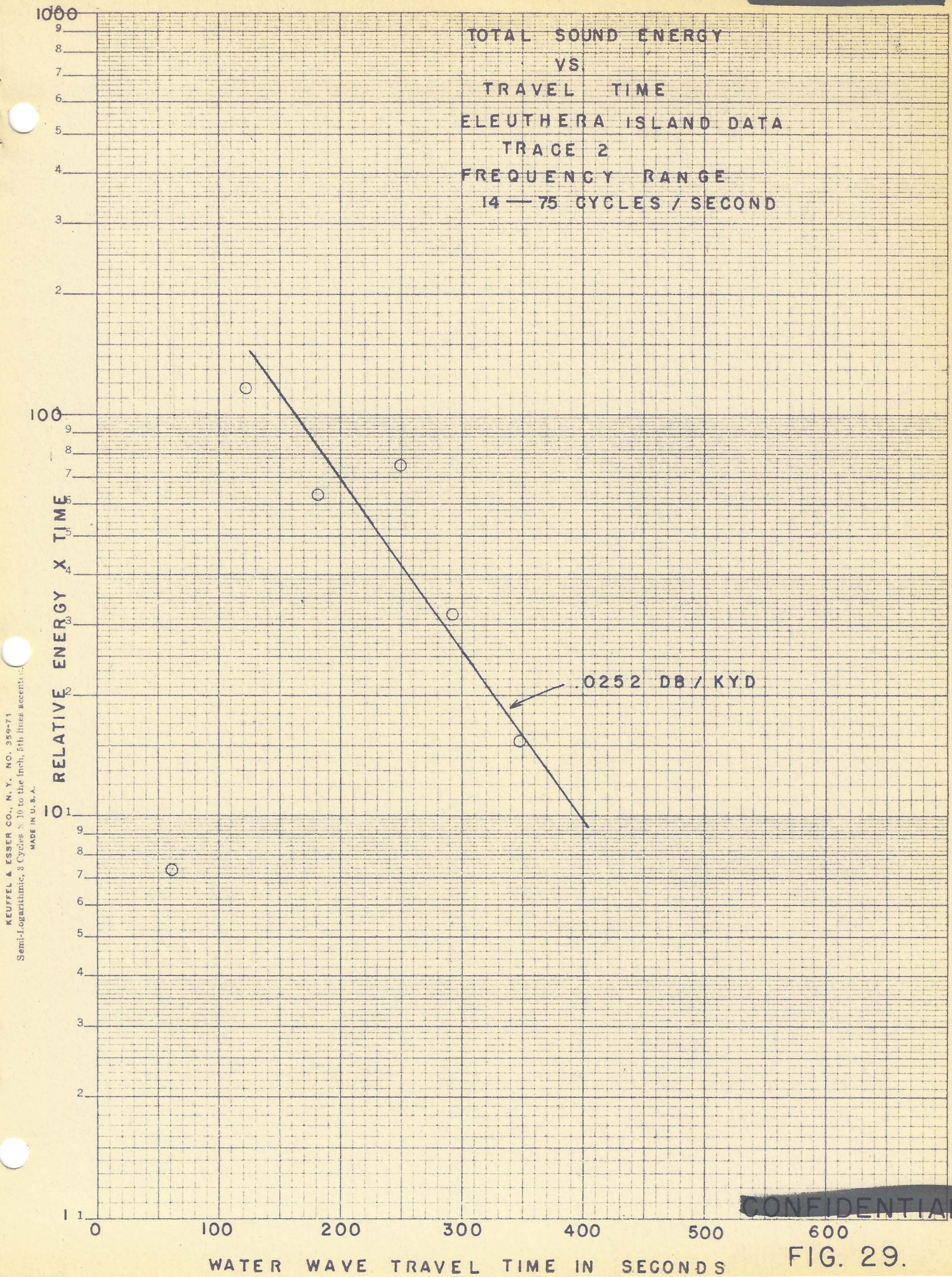

FIG. 29.

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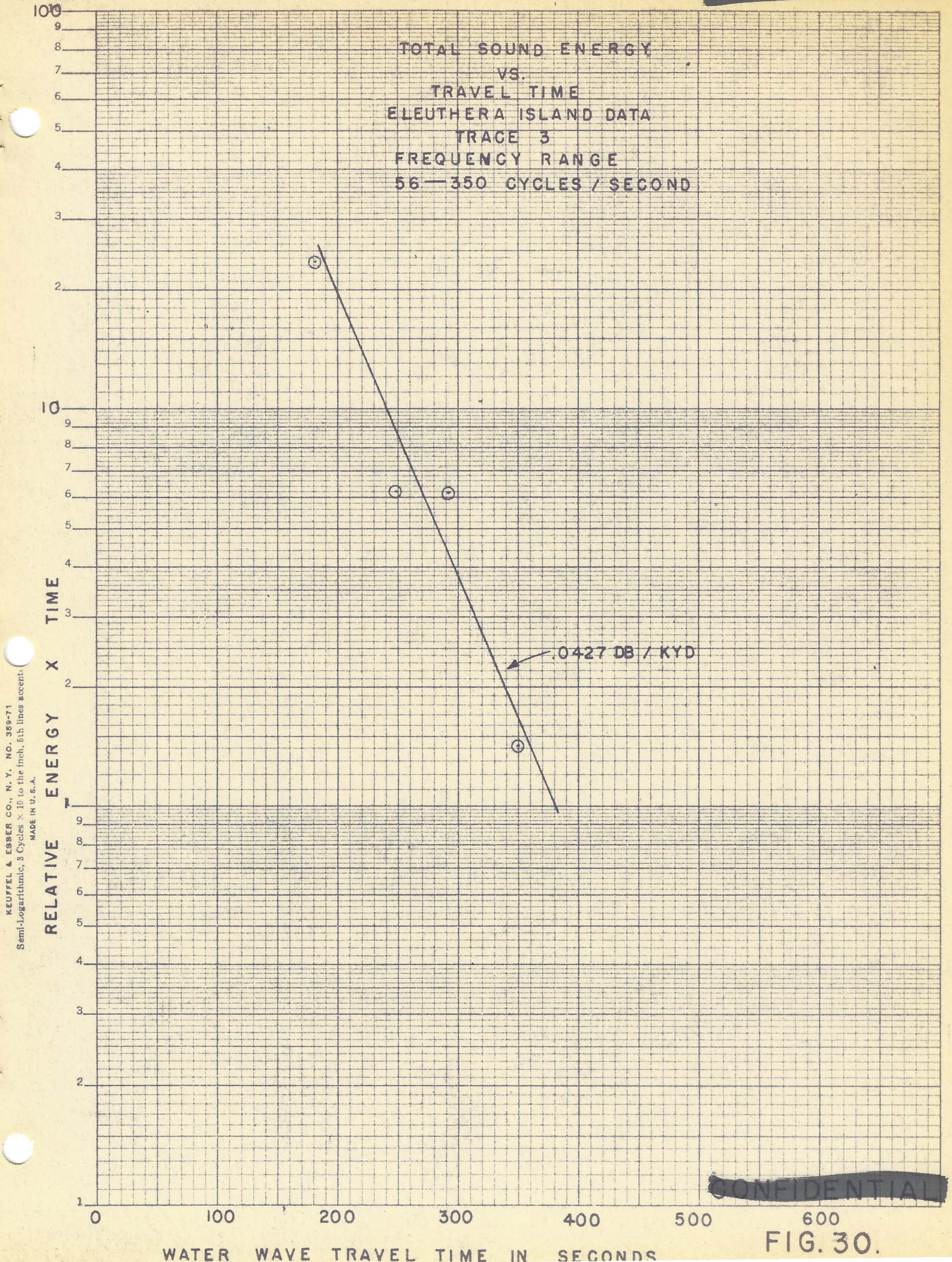

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FIG. 30.

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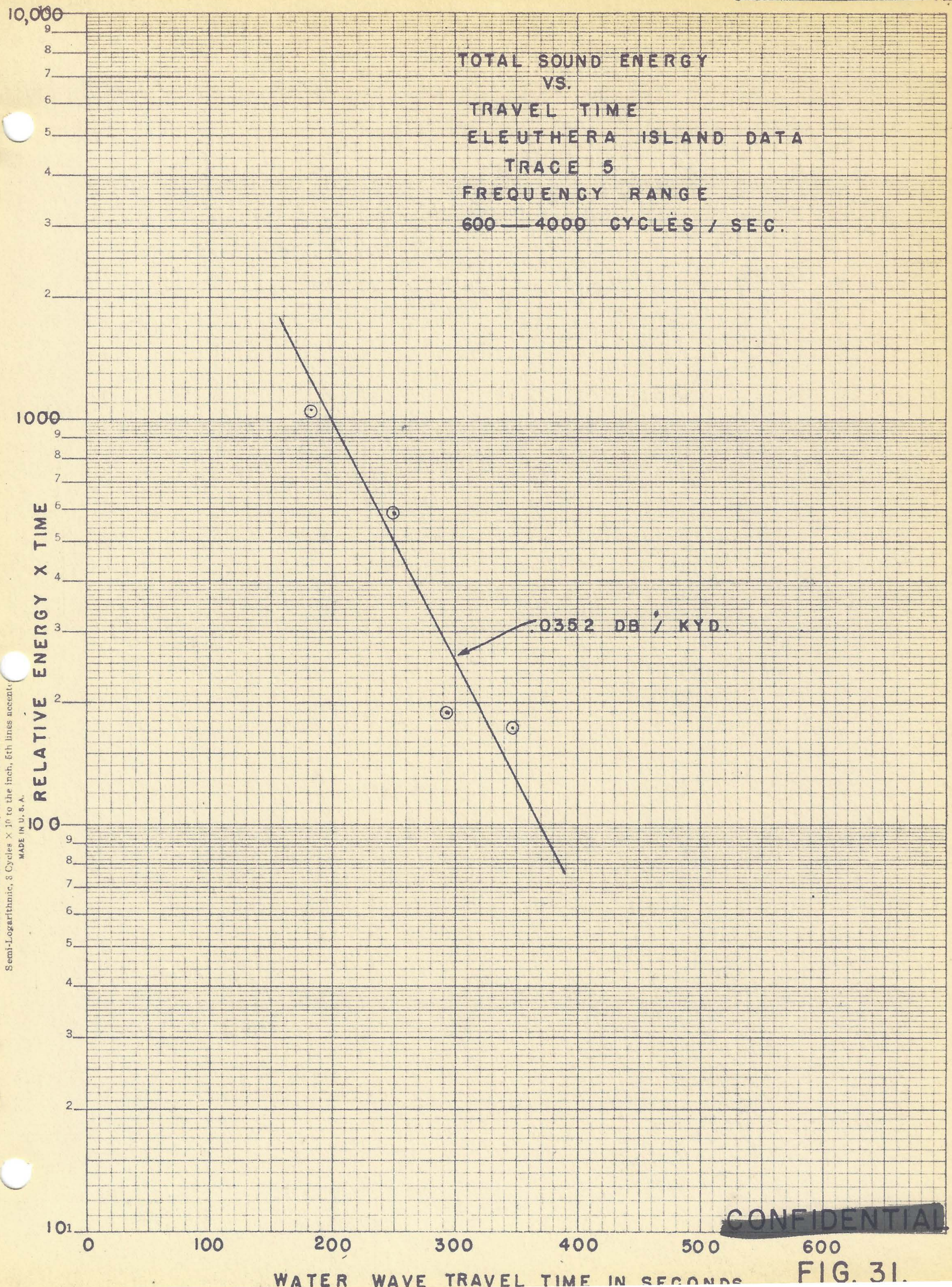

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FIG. 31.

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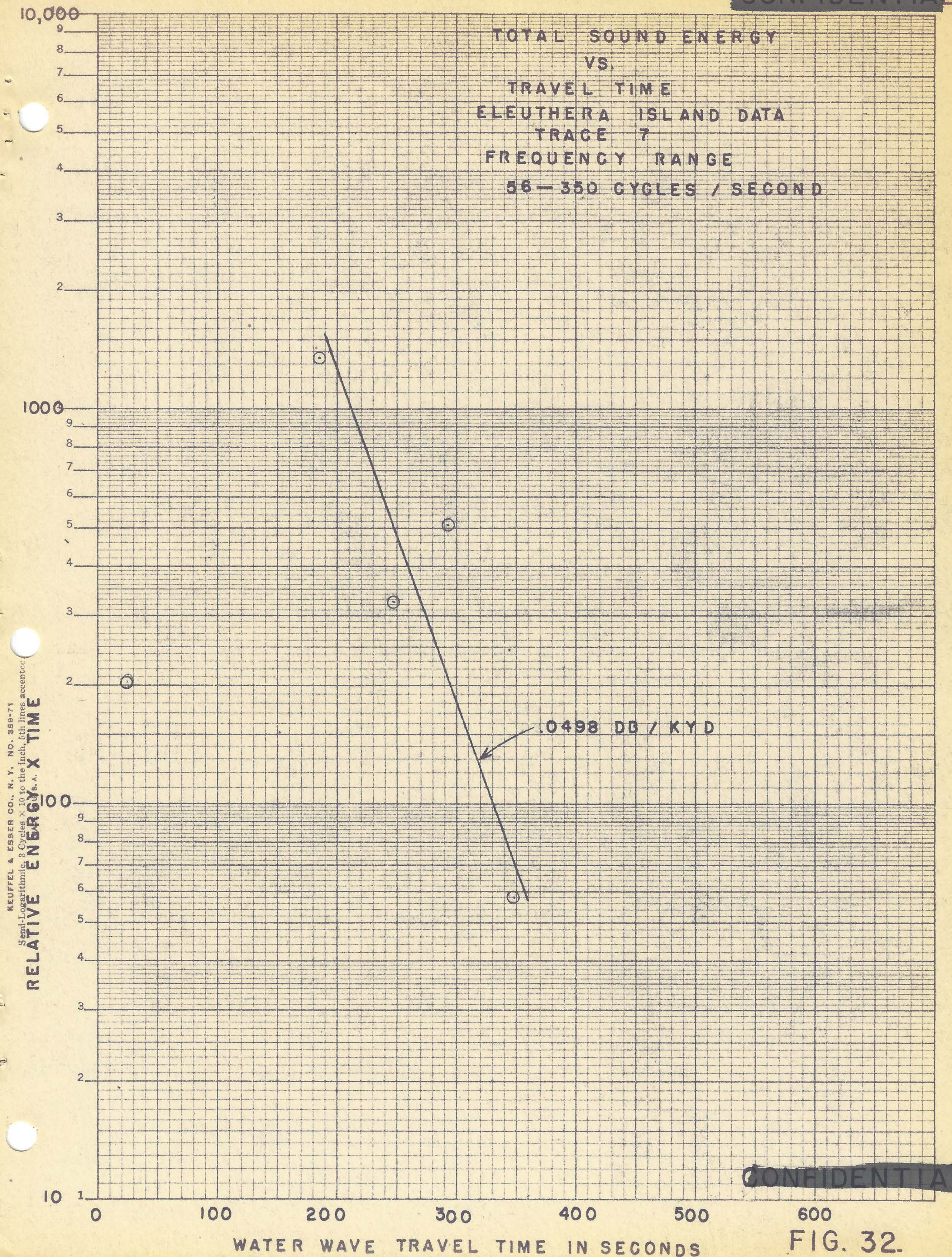

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FIG. 32.

and sharper filters are needed to obtain better determinations. This range of values for the absorption coefficient is lower than the commonly accepted values.

CONCLUSIONS

Signals from a four pound bomb fired at a depth of about 4000 feet have been detected to ranges up to about 900 miles in the Atlantic Ocean. In recent work not included in this report a half pound bomb was heard with abundant signal strength at over 800 miles and four pound bombs have been heard over 2300 miles. These signals have been detected by a hydrophone suspended by an electric cable 3600 feet deep from a ship hove to in the open ocean, and by a hydrophone lying on bottom at a depth of about 4000 feet connected to shore with electric cable. An extrapolation of the data indicates that ranges up to 10,000 miles are possible with this size charge. Analysis of the sound energies indicate an absorption loss between .005 and .05 db/Kyd. for sounds below 10 KC.

The long ranges achieved are made possible by the natural sound channel which exists in the oceans. The sound channel exists because of the decrease of the sound velocity caused by the rapid decrease of the temperature in the first 700 fathoms, and the increase of sound velocity caused by the increase in pressure below that depth. The sound channel axis, or depth of minimum velocity, occurs at about 700 fathoms in the Atlantic Ocean. There is a similar sound channel in all the deep oceans of the world except possibly in the polar regions.

The sounds travelling in the sound channel are refracted back forth across the axis and can travel to any distance without contacting either the surface or the bottom of the ocean. The maximum departure of a ray from the axis, and the mean horizontal velocity of the sound increase as the axial angle increases. Rays with small axial angles remain very near to the axis and the sounds which travel along these rays are the last to arrive at a given receiver. Rays with larger axial angles sweep through greater vertical distances as they cross and recross the axis. The sound channel sounds received at a distance have the distinctive character of commencing with long intervals between arrivals which become shorter and shorter with each subsequent arrival. The sound channel sounds terminate abruptly, dropping from peak intensity to zero in less than 1/20th second. The character is further enhanced by a gradual increase of intensity from the beginning to the end. The duration of the sound channel signal can be used to estimate the distance between the source and the receiver to 30 miles in 1000 miles. The experimental results fully confirm the refraction theory. Sounds travelling in this manner are restricted to deep water and to great circle courses. Thus an island or shoal area would stop the sound travelling on a great circle course through it.

Three or more monitoring stations could locate the position at which a charge was fired to better than one mile by determining the difference in time of arrival of the sound channel termination at the various stations. From the sound channel terminations two monitoring stations would locate a line of position passing through the firing point. By estimating the distance to the firing point by the sound channel duration two points on the line of position would be determined, one of which would be reasonably close to the firing point. Ordinarily, for island receiving stations, one of these positions could be ruled out as being in the shadow of the island itself. If a single station were made with two hydrophones located at least 10 miles apart the range to the firing point could be determined to ± 30 miles, and the bearing to ± 1/2°. If a radio signal were sent which indicated the firing instant of a deep charge, the range to a receiving point could be determined to a better than a mile.

Plate 5 shows a hypothetical three station location system in the Pacific Ocean. One station is located at Midway Island, one at Amchitka Island, and one at Saipan. Each family of curves relates to a pair of stations, and each curve contains all points having a constant difference in distance from the two stations. This difference in distance in miles is written on each curve. From the differences in termination arrival time the difference in distance may be directly determined. This gives three lines of position whose intersection is a fix on the firing point. Such a system could be used to locate a ship, plane, life raft, or submerged submarine in the area between the stations. Another possible use for this method would be to check the flight of robot devices, such as rockets, over the deep ocean, either to chart their progress in flight, or so that a correction could be made to the last part of their flight. Sound travels 1000 miles in 20 minutes, so that there is an appreciable lag between the signal transmission and its reception at long ranges. This time lag is in some cases a disadvantage for air navigation.

A fuse known as the Woods Hole detonator costing in the vicinity of one dollar has been developed very recently for firing charges at the necessary depth. This fuse merely takes the place of a blasting cap or electric detonator in an ordinary charge. A half pound demolition block and one of these fuses could be included in life raft equipment. If a person on a life raft wished to signal for help and at the same time give his position, he would merely place the fuse in the demolition block and throw the whole thing overboard. A half pound block will give a signal about half as strong as a four pound charge. Planes and ships could carry larger charges which would cost no more than $10.00 apiece. If a charge were carried attached to a plane with its fuse in place, when the plane sank a signal would be sent automatically. These charges can also be made to be thrown from a plane in the air, or expelled from the signal ejector tube of a submarine. They could be used to measure the course and landing point of robot devices such as rockets. A multiple shot bomb is being developed at the U.S. Navy Underwater Sound Laboratory for use in transmitting coded signals.

The necessary equipment to received the signal could be inexpensive, quick to assemble, and light. One system which could be used would consist of a hydrophone, connecting cable, amplifier, sound level recorder, and break circuit chronometer, if the installations were near existing housing, radio, and power facilities.

One feature which is being investigated is possible influence of charge size on signal frequency as caused by the period of bubble oscillation. If this effect exists it is important as an auxiliary means of signally and as a guide to selection of best frequency characteristics of the receiving equipment. An effort is being made to obtain data on the sharpness of the shadow zone of an island and on the transmission past the Mid-Atlantic Ridge. The extent to which sound channel sounds climb onto a continental shelf is not known, nor have the effects of the Gulf Stream and of polar waters been determined. At Eleuthera, where the hydrophone lies on a steeply sloping bottom, there is a reverberation-type sound which arrives after the sound channel termination, but easily distinguished from it, which was absent at the deep water SALUDA station. This is being investigated together with the many interesting phenomena introduced by reflections from a steeply sloping bottom. Thus, there are many interesting issues still to be decided, but there is no room for reasonable doubt about the main features of sound channel transmission.

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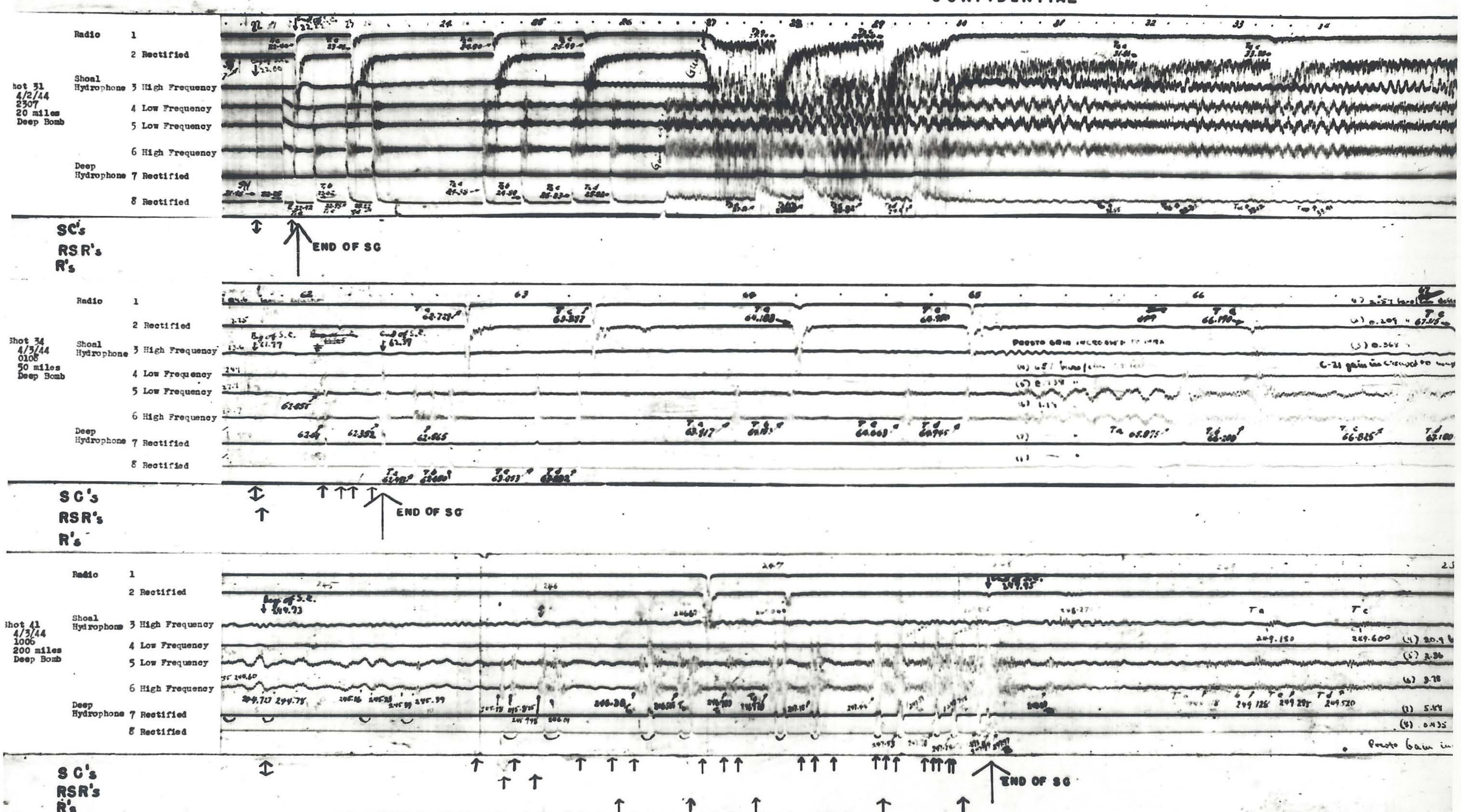

RECORDS TAKEN AT SEA FROM USS SALUDA

↥ FIRST OBSERVED S C ARRIVAL

LAT. 25° 45'
LONG. 76° 26'
PLATE I

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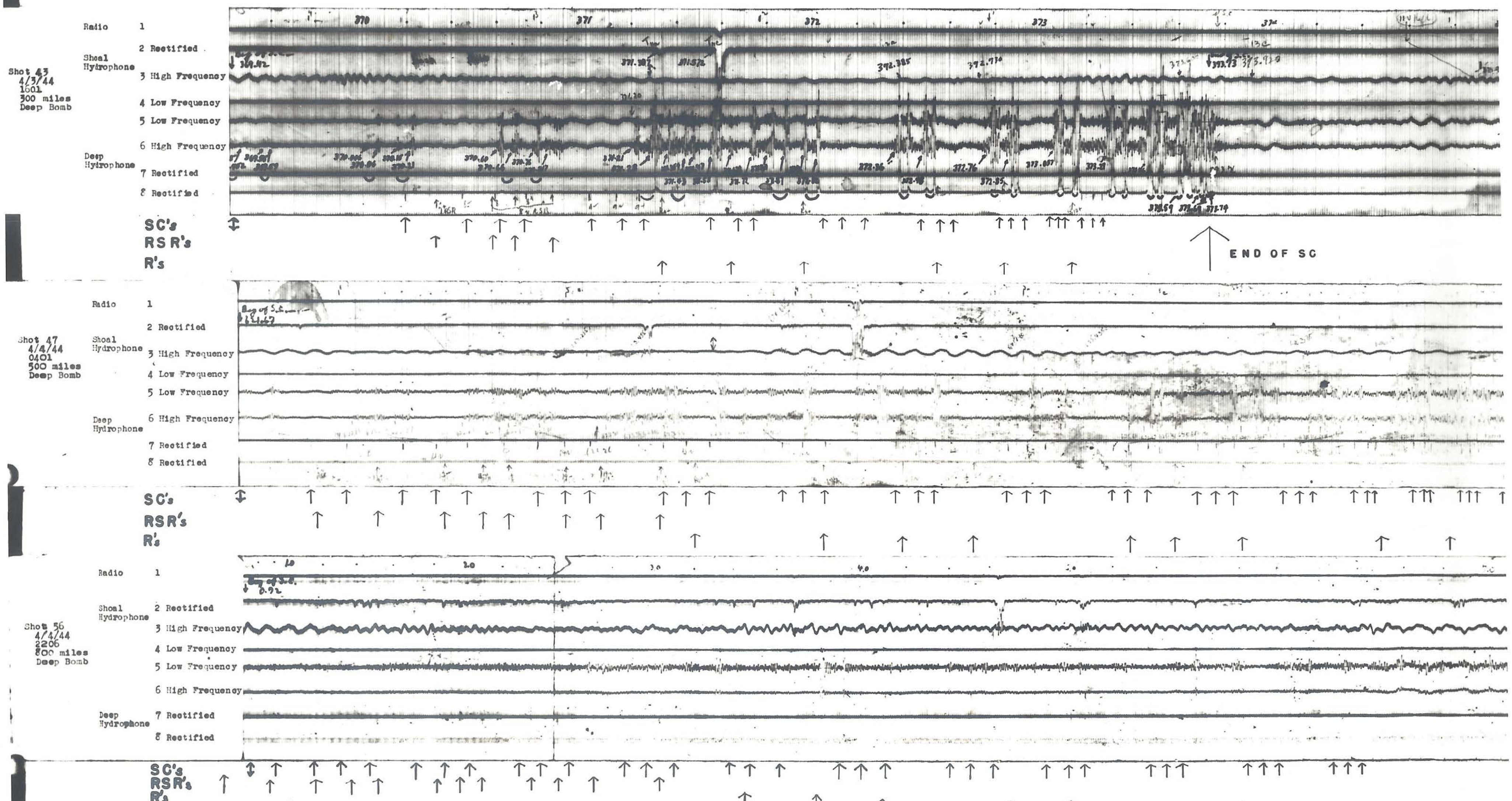

↕ FIRST OBSERVED SC ARRIVAL

RECORDS TAKEN AT SEA FROM USS SALUDA

LAT. 25° 45'
LONG. 76° 26'

PLATE II

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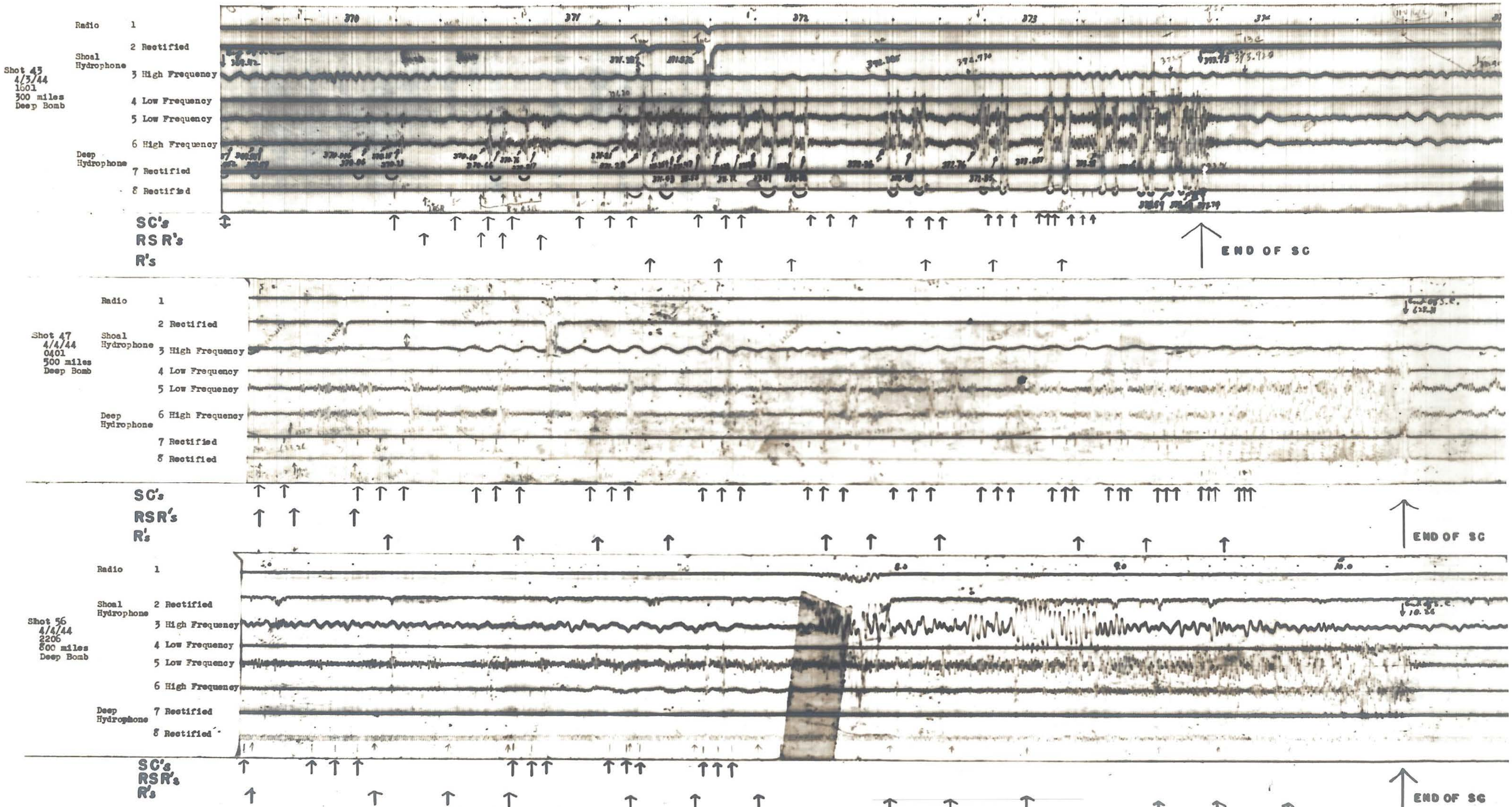

RECORDS TAKEN AT SEA FROM USS SALUDA

↕ FIRST OBSERVED SC ARRIVAL

LAT. 25° 46'
LONG. 76° 26'

PLATE III

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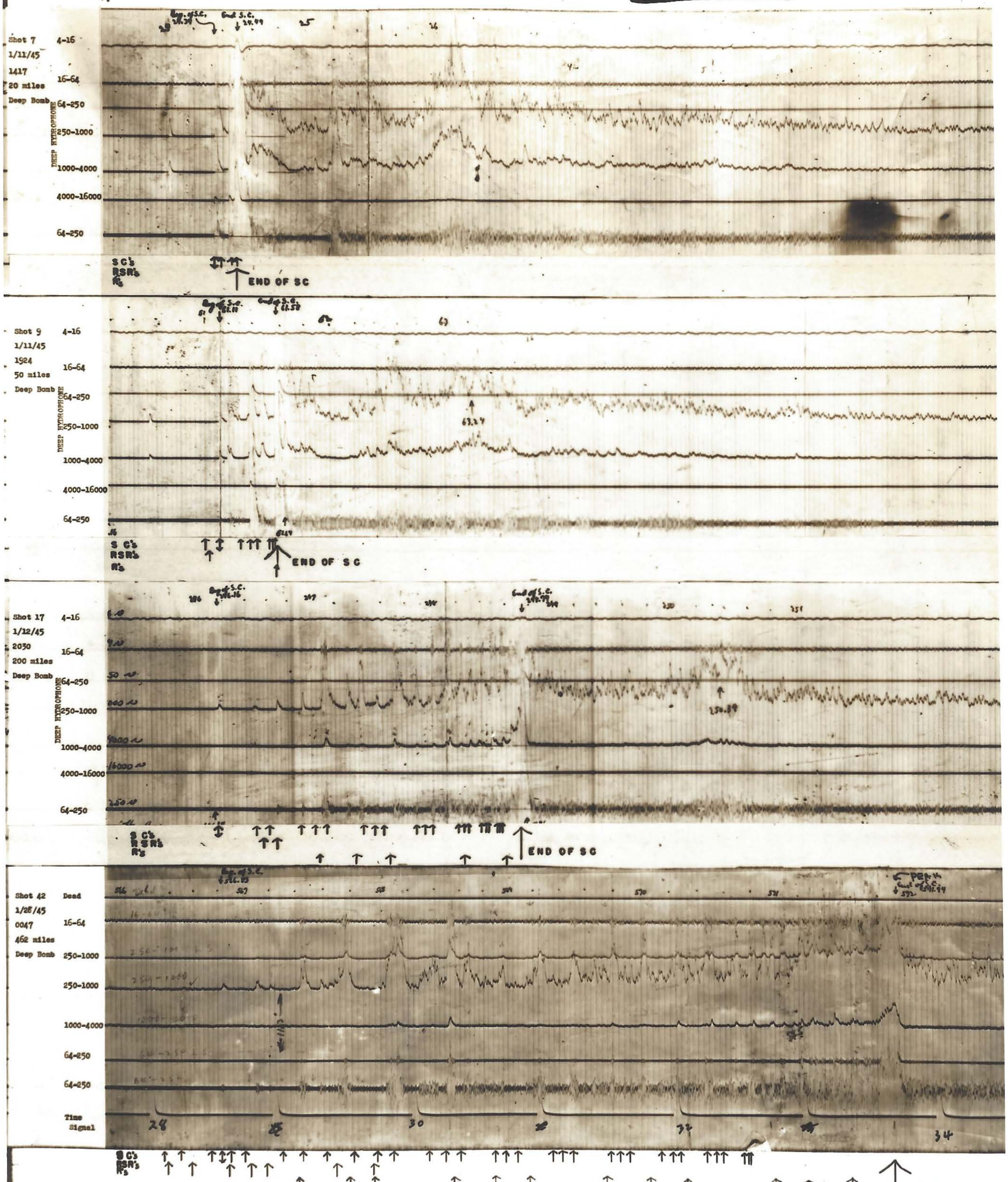

FIRST OBSERVED SC

RECORDS FROM ELEUTHERA ISLANDS STATION
PLATE IV

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[redacted]

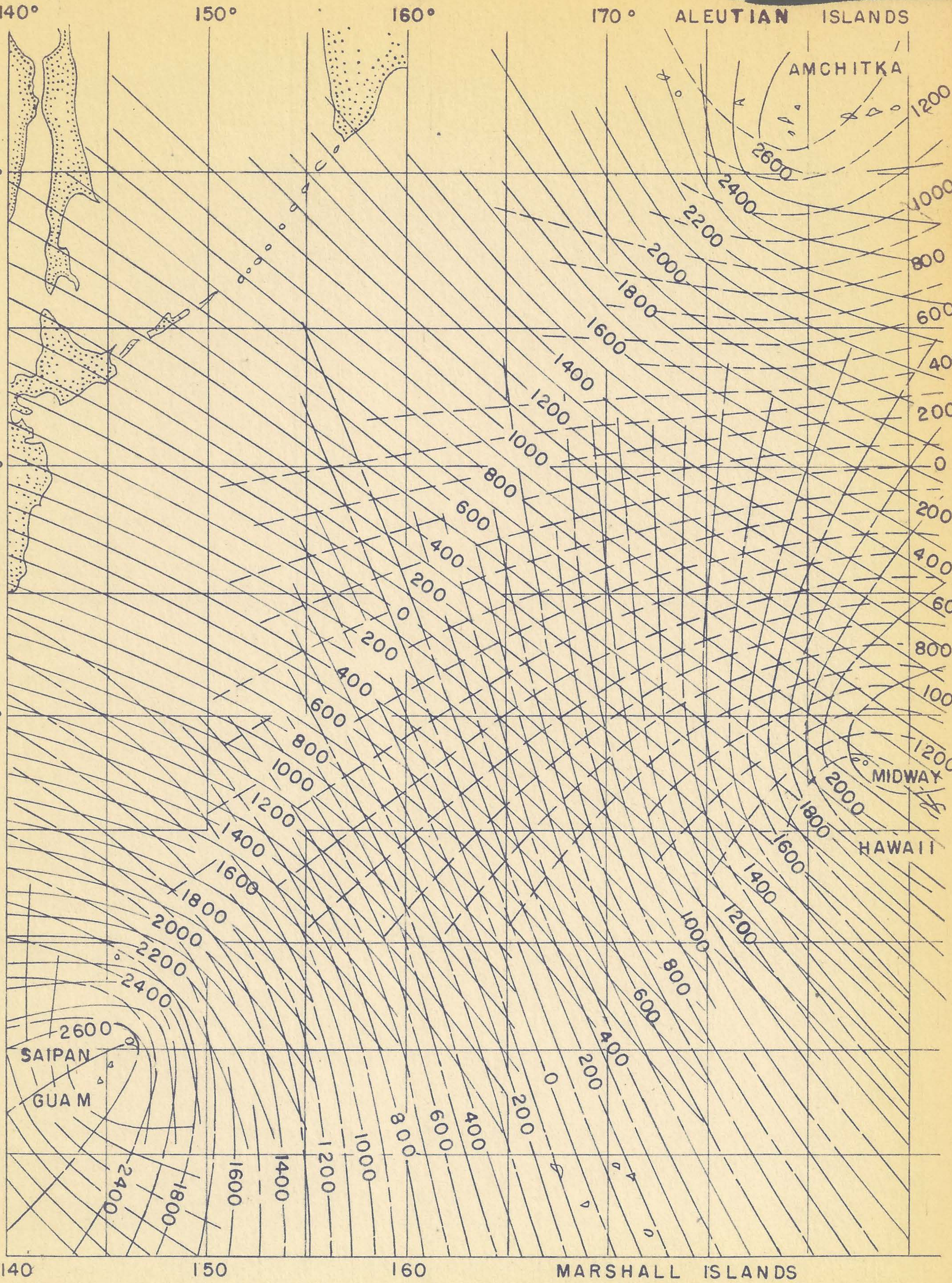

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PLATE V

APPENDIX A

Calculation of Travel Time Along A Sound Ray

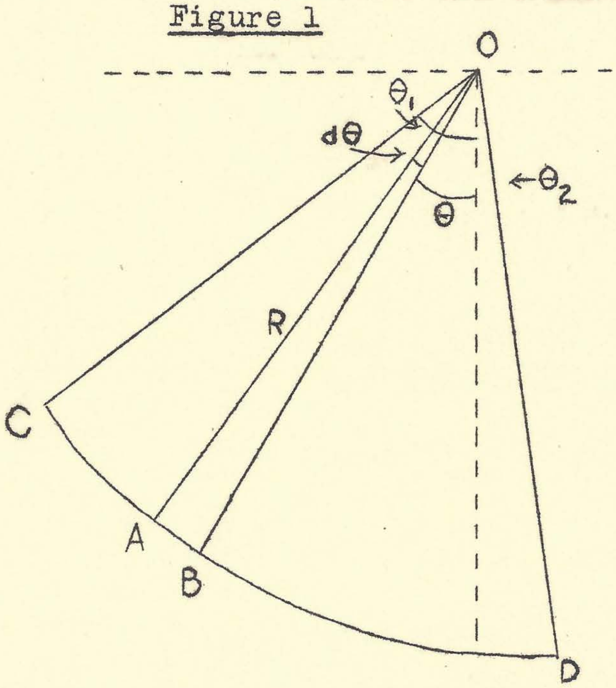
In a medium in which the velocity of sound is a linear function of depth, the ray paths are circular arcs with centers lying in the plane at which the velocity of sound would be zero if the linear rate of change remained constant.

With standard ray path notation consider Figure 1. The element of path AB = $Rd\theta$ is at a distance $R\cos\theta$ below O in a medium of velocity gradient g. The velocity of the sound travelling the element AB is then $gR\cos\theta$. The time required* for the sound to travel from C to D is

$$T = \frac{1}{g}\int_{\theta_1}^{\theta_2} \frac{d\theta}{\cos\theta} = \pm\left[\frac{1}{2g}\log\frac{1+\sin\theta}{1-\sin\theta}\right]_{\theta_1}^{\theta_2} = \pm\frac{1}{g}\left[Gd^{-1}\theta\right]_{\theta_1}^{\theta_2}$$

Tables of anti-Gudermannian ($Gd^{-1}\theta$) may be found in "Theorie der Potenzial order Cyklisch-Hyperbolischen Functionen" by Dr. C. Gudermann, Berlin 1833, G. Reimer, Publisher. Table I.

Figure 1



*See Dwight, "Tables of Integrals and Other Mathematical Data" Formulas 442.10, 640.

[redacted]

SHOT LIST

Shot No.	Date	Queen Time	Lat. N.	Long. W.	Distance miles	Axial Travel Time (sec.)	Axial Velocity ft/sec. **	1st SC Arrival Time. (sec.)	Major SC Arrival Time (sec.)	Overall SC Duration (sec).	Major SC Duration (sec).
SALUDA Data Receiving Position: 25°45'N.-76°20'W.											
31	4/2/44	1908	26-01	76-00	25?	22.22	----	22.00	22.00	.22	.22
34	4/2/44	2108	26-31.5	75-40	56.5	62.37	5438	61.77	62.07	.60	.30
37	4/3/44	0006	27-18	75-09	111	122.95	5454	121.37	121.96	1.58	.99
41	4/3/44	0606	28-51.2	74-07.8	219.5	247.95	5365	244.73	245.95	3.22	2.00
43	4/3/44	1206	30-18	73.09.5	320	373.73	5195	369.42	371.28	4.31	2.45
47	4/3/44	2906	33-22.5	71-04	538	628.11	5201	621.67	623.68	6.44	4.43
50	4/4/44	0606	34-52.7	70-01	638	No Record	----	----	----	----	----
52	4/4/44	1207	36-05.2	69-08.7	721	862	5081	852.60	856.18	9.40	5.82
56	4/4/44	1823	37-31.8	68-06.5	821	10.26*	----	.72	3.30	9.54	6.96
59	4/5/44	0024	38-48.3	67-09	910	10.94*	----	.00	------	10.94	----
Eleuthera Island Data Receiving Position: 24°56.2'N.-76°06.45'W.											
7	1/11/45	1417	24-56.0	75-44.0	20.3	24.49*	----	24.34	24.34	.15	.15
9	1/11/45	1924	24-53.8	75-10.0	51.2	61.58*	----	61.11	61.18	.47	.40
11	1/12/45	0340	24-50.2	74-16.0	100.2	122.51*	----	120.78	121.71	1.73	.80
14	1/12/45	1334	24-40.4	73-23.4	148.4	182.84	4913	181.10	181.46	1.74	1.38
17	1/12/45	2030	24-28.8	72-29.0	199.5	248.74	4845	246.16	247.08	2.58	1.66
19	1/13/45	0935	24-33.9	71-45.3	237	291.00	4925	288.16	288.94	2.84	2.06
22	1/13/45	2105	24-35.0	70-46.7	290	349.66	5031	346.18	347.16	3.48	2.50
36	1/25/45	1855	26-42.0	73-53.1	160.5	198	4909	------	------	----	----
40	1/27/45	0720	28-48.7	70-24.6	385	469''	4983	470.34	471.76	4.58	3.16
42	1/28/45	0955	29-31.2	69-10.5	462	566.5''	4951	566.83	568.04	5.11	3.90

* No travel time measured.

'' Travel times not known when records marked. These travel times are correct. For duration calculations 474.92 and 571.94 were used respectively.

** These velocities are calculated from the axial travel time plus .8 seconds. This allows for the time the sound takes to travel from a depth of 4000 feet to the surface.

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