LONG-RANGE SOUND TRANSMISSION

BY
MAURICE EWING and J. LAMAR WORZEL
Columbia University, New York, N. Y.

THE GEOLOGICAL SOCIETY OF AMERICA · 1888

October 15, 1948

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 4-lb. charge of TNT to explode at about 4000-foot depth. These signals have the following qualities:

(1) Extremely long-range transmission (probably 10,000 miles).
(2) Signal is positively identifiable.
(3) Abrupt termination of the signal allows the arrival time to be read with an accuracy better than 0.05 second. This permits location of the source to within a mile, if the signal is received at three suitably located stations.
(4) The relation of signal duration to distance is such that the distance may be estimated to 30 miles in 1000 from reception at a single station.

The limitations are:

(1) The great-circle path which the sound follows between source and receiver must lie entirely in deep water (probably at least 1000 fathoms).
(2) Sound travels in water at about 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 of 900 miles. In subsequent work, not included in this report, a ½-lb. bomb was heard with abundant signal strength at over 800 miles, a 4-lb. bomb at 2300 miles, and a 6-lb. bomb at 3100 miles.

Two receiving arrangements have been used, a hydrophone hung 4000 feet deep over the side of a ship which was hove to, and a shore-connected hydrophone lying on bottom 4000 feet deep. Extrapolation of the results indicated a range of at least 10,000 miles from a 4-lb. 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 within 1 mile. An experimental network of listening stations is being installed by the Navy Department in the western Pacific, and this system of signalling has been given the name SOFAR.

Three applications of SOFAR to geological problems have been proposed: (1) position fixing, (2) discovery of shoal areas, and (3) submarine volcano location.

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 by refraction theory from ray diagrams based on the known velocity distribution in the oceans.

In the deep oceans, the temperature generally decreases rapidly with depth to a little above 0° C. at about 700 fathoms in the Atlantic and 500 fathoms in the Pacific. It then decreases slowly to bottom. The sound velocity decreases in a similar fashion to a minimum at around 700 fathoms but 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.

The absorption loss lies between .005 and .05 db/kyd. for sounds below 10,000 cycles per second. More frequent shots and sharper filters are needed to obtain better determinations. This range of values for the absorption coefficient is lower than the commonly accepted values.

TABLE 2.—*Sound-absorption coefficient at different frequencies*

Trace	Frequency range cycles/sec	Absorption db/kyd	Quality of observation
SALUDA DATA:			
4, 5	22– 175	.0050	good
7	2,300–10,000	.0133	poor
ELEUTHERA ISLAND DATA:			
2	14– 75	.0252	fair
3	56– 350	.0427	fair
5	600– 4,000	.0352	fair
7	56– 350	.0498	fair

CONCLUSIONS

Signals from a 4-lb 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 ½-lb bomb was heard with abundant signal strength at over 800 miles, 4-lb bombs at over 2300 miles, and a 6-lb bomb at 3100 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 indicates 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 sound velocity caused by the rapid decrease of 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 and 500 fathoms in the Pacific. There is a similar sound channel in all the deep oceans of the world except in the polar regions.

The sounds travelling in the sound channel are refracted back and forth across the axis and can travel to any distance without contact with the surface or 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 the axis, and the sounds which travel along these rays arrive last at a given receiver. Rays with larger axial angles sweep through greater vertical distances as they cross and recross the axis and are the first to arrive at a receiver. Sound-channel sounds received at a distance have a distinctive character, beginning 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 0.05 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 1 mile, by determining the difference in time of arrival of the sound-channel terminations at the various stations. From the sound-channel terminations two monitoring stations could 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 could 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 $\pm \frac{1}{2}°$. If a radio signal were sent to indicate the firing instant of a deep charge, the range to a receiving point could be determined to within a mile.

Figure 19 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, which is written on each curve. From the difference in termination arrival times the difference in distance may be directly determined. This gives three lines of position whose intersection fixes the location of 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. At present a network of four listening stations is being established in the Pacific by the Navy Department, and the name SOFAR, from the words SOund Fixing And Ranging, has been assigned to the system.

A fuse, known as the Woods Hole detonator, costing about a dollar, has been developed recently for firing charges at the required depth. This fuse is approximately the same size as a blasting cap or electric detonator and will fire by pressure at a given depth. One of these fuses with a $\frac{1}{2}$-lb demolition block constitutes the simplest and cheapest deep-sound source yet devised. It is satisfactory for use without safety devices by specially trained personnel and in cases where extreme weight reduction is necessary. A $\frac{1}{2}$-lb block will give a signal about half as strong as a 4-lb charge.

The necessary receiving equipment can be inexpensive, light, and easy to assemble. One suitable system consists only of a hydrophone, connecting cable, amplifier, sound-level recorder, and break-circuit chronometer, assuming existence of housing, radio, and power facilities.

A feature being investigated is the 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 signalling and as a guide to the 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. In 1945, the USS MUIR dropped about 30 bombs beyond the Ridge. All explosion sounds were received except those from about 10 bombs dropped behind known or suspected shoals. The shadow zone of Bermuda Island has been described in an earlier paper (Ewing, Wollard, Vine, and Worzel, 1946, p. 932). The system clearly provides an acoustical sweep which can be used to scan the ocean for shoals of depth less than 1000 fathoms, at a rate of several thousand square miles per hour. With a network of listening stations, cross bearings on these shoals can locate them with sufficient accuracy for exploration with a fathometer.

The extent to which sound-channel sounds climb onto the continental shelf is not known, nor have the effects of the Gulf Stream or of polar waters been determined. At Eleuthera, where the hydrophone lies on a steeply sloping bottom, a reverberation-type sound arrives after the sound-channel termination but is easily distinguished from it; this was absent at the deep water SALUDA station. This is being investigated, together with other interesting phenomena introduced by reflection from a steeply sloping bottom.

Many sounds heard at Eleuthera are believed to have originated in submarine volcanic activity. The network of listening stations now being installed may locate all areas of volcanic activity over a large part of the Pacific Ocean.

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 A. The element of path $AB =$

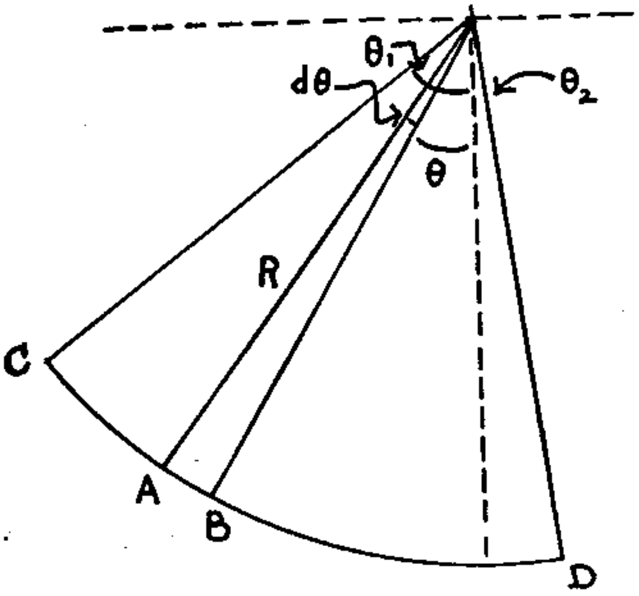
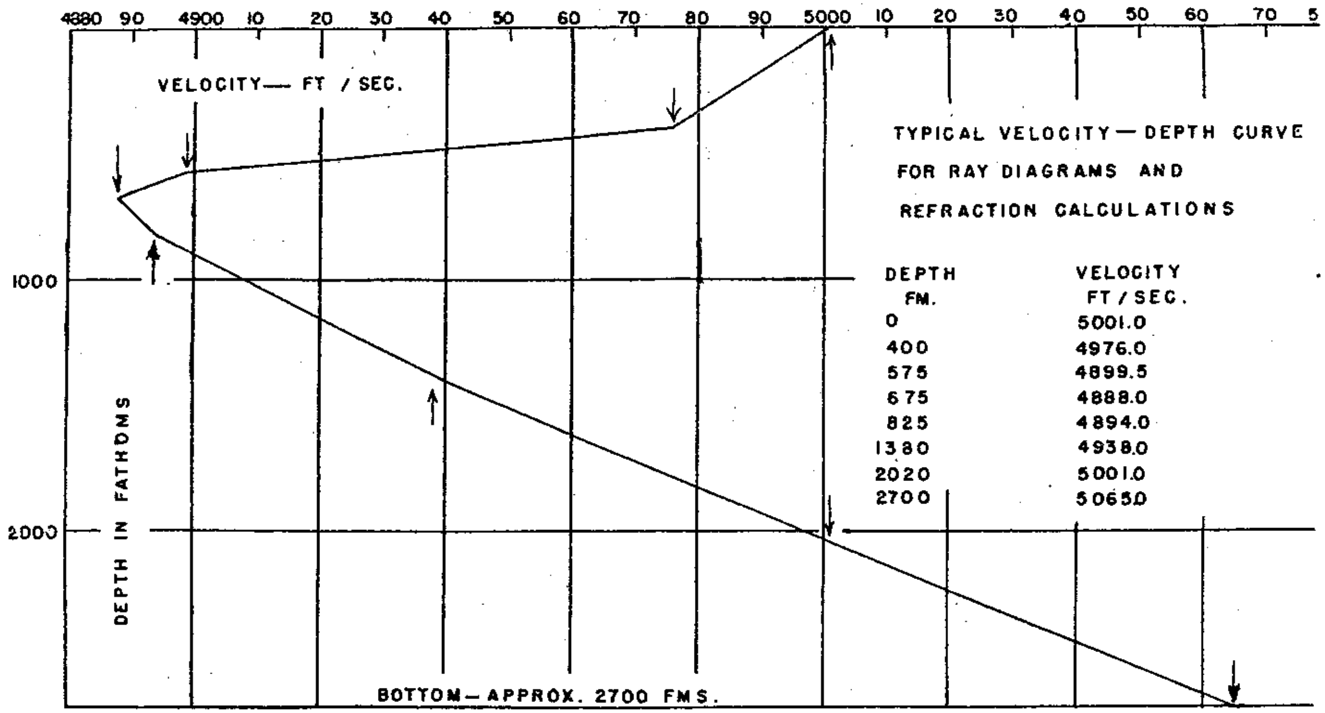


FIGURE A.—*Diagrammatical representation of ray paths*



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

FIGURE 3.—*Mean velocity-depth curve in the Atlantic Ocean*

For ray diagrams and refraction calculations.

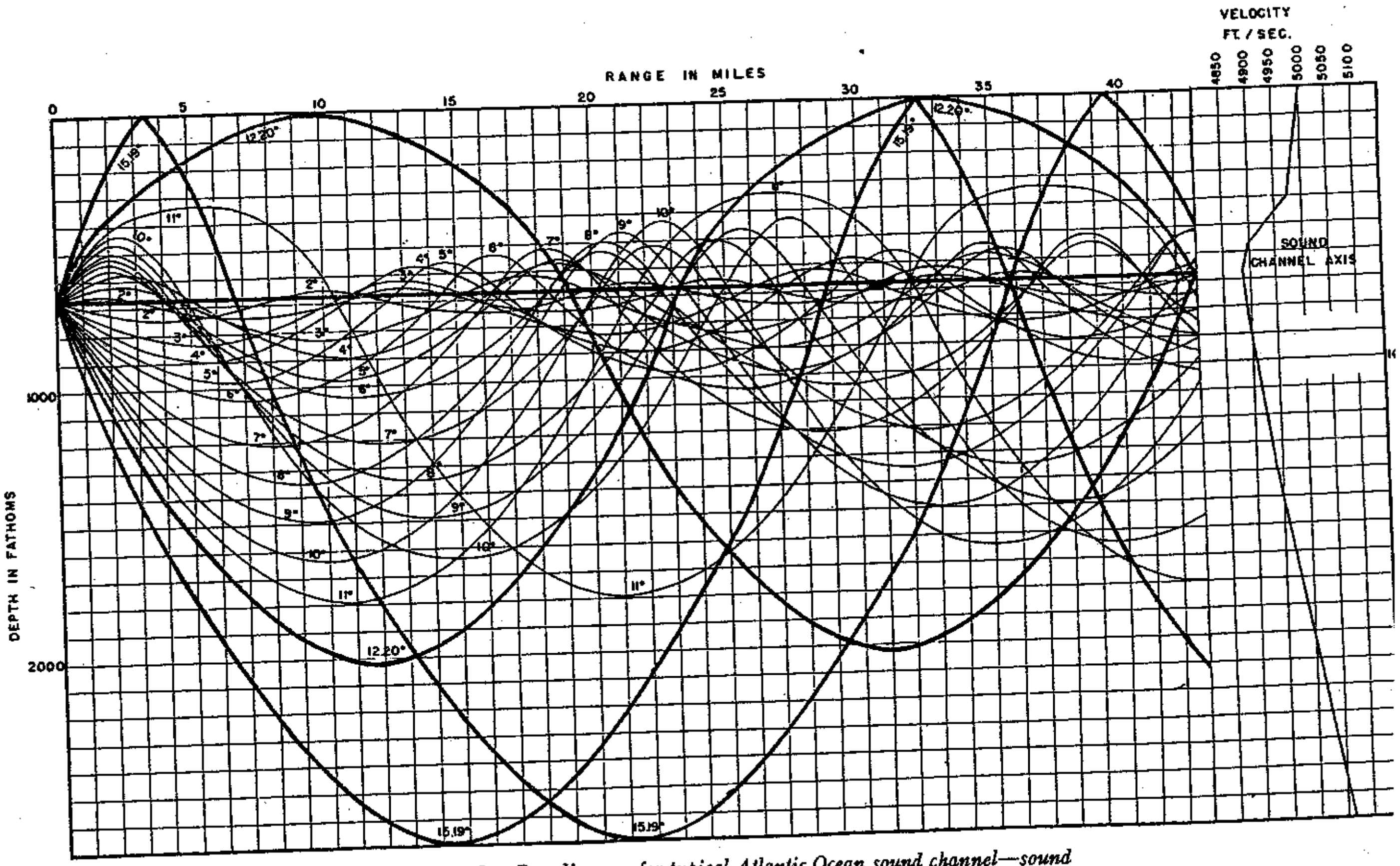


FIGURE 5.—*Ray diagram for typical Atlantic Ocean sound channel—sound channel and refracted surface-reflected rays*

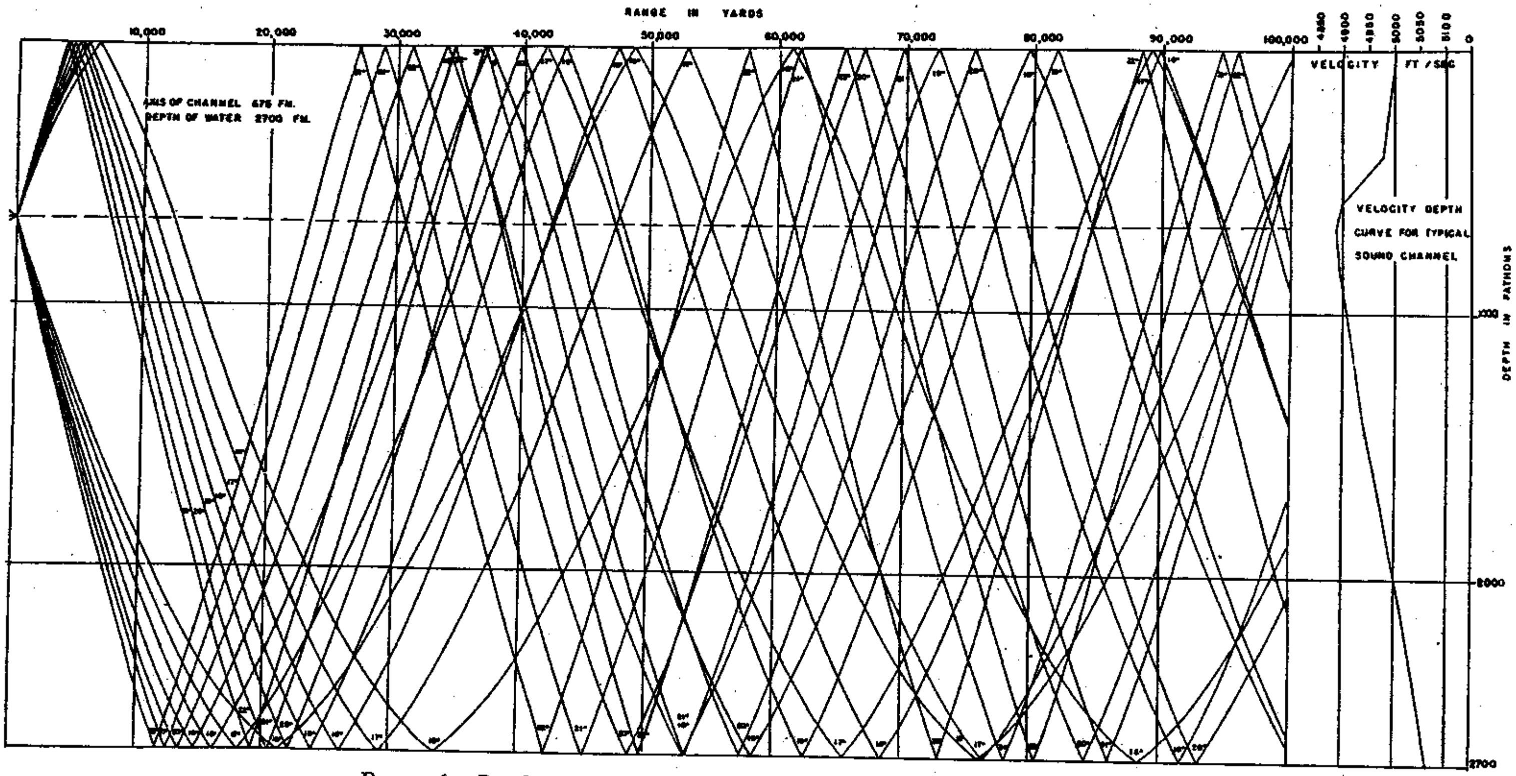


FIGURE 6.—*Ray diagram for typical Atlantic Ocean sound channel—reflected rays*

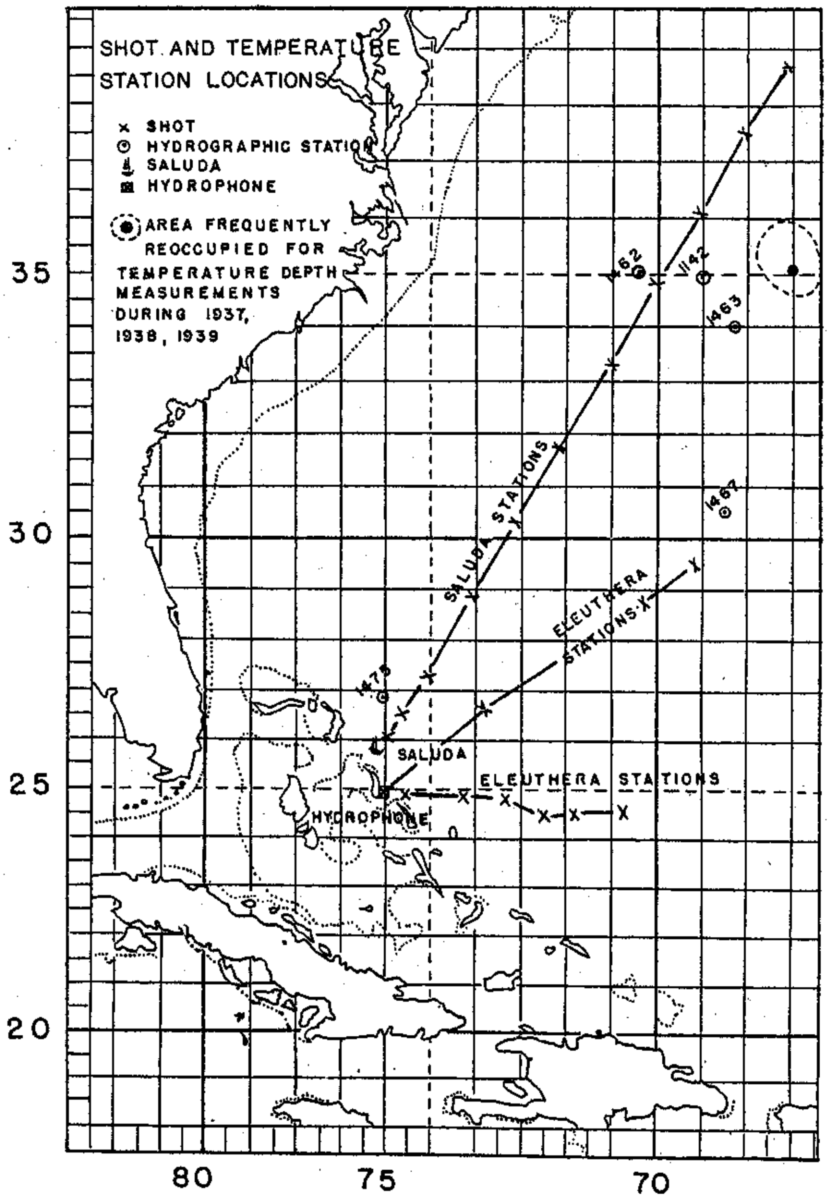


FIGURE 1.—*Shot positions* (SALUDA *and Eleuthera stations) and hydrographic stations* (ATLANTIS)

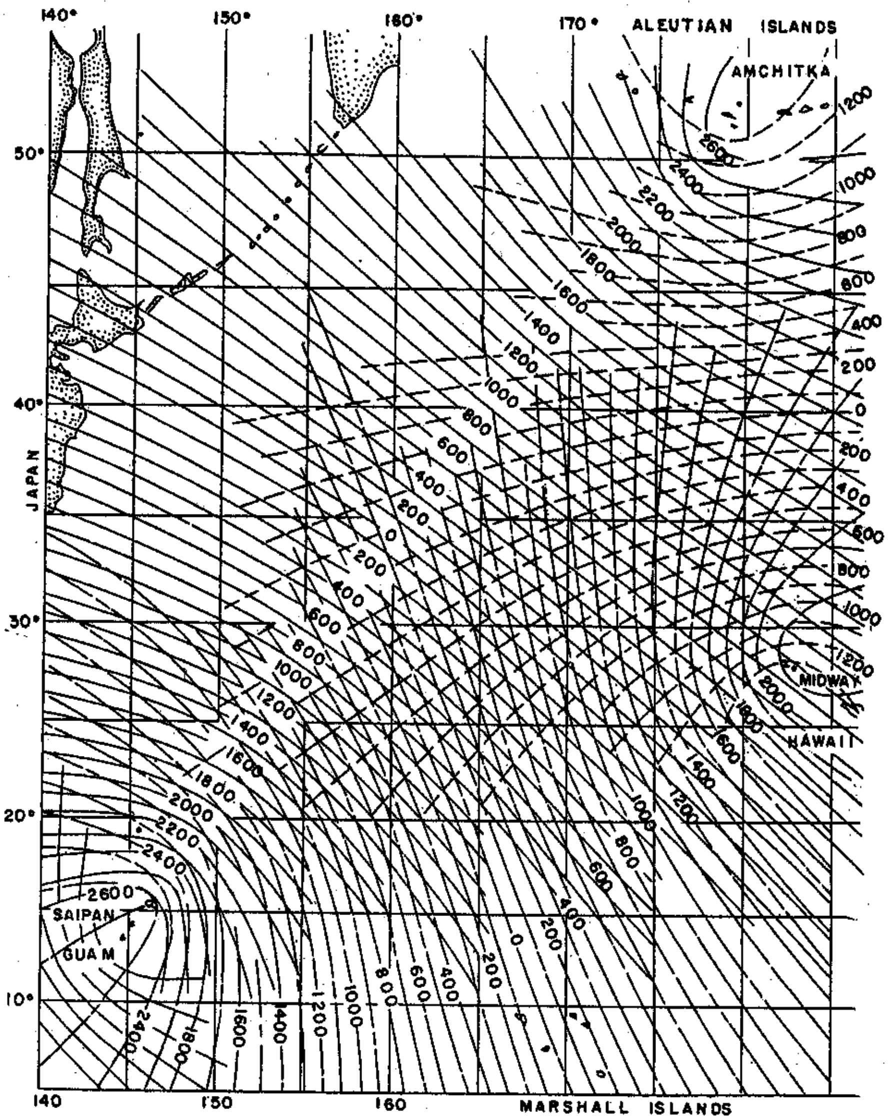


FIGURE 19.—*Three station location system*

In the Pacific Ocean, with curves of equal difference in distance.