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HYDROPHONE LOCATION

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HYDROPHONE LOCATION

BY

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FEBRUARY, 1959



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A B S T R A C T

TWO METHODS OF LOCATING A BOTTOM HYDROPHONE IN DEEP WATER OFF BERMUDA BY UNDERWATER ACOUSTIC METHODS ARE DESCRIBED. THE FIRST METHOD UTILIZED AN EXPLOSIVE RANGING TECHNIQUE, THE SECOND METHOD UTILIZED A PRECISION ECHO SOUNDER TO LOCATE POSITIONS WITH EQUAL TRAVEL TIMES TO THE HYDROPHONE. HYDROPHONE POSITION ACCURACIES OBTAINED WERE 15-20 FEET FOR A LOCATION IN 456 FATHOMS (2736 FEET) OF WATER. THIS POSITION ACCURACY WAS LIMITED BY THE ACCURACY WITH WHICH THE SURFACE SOUND SOURCE COULD BE LOCATED RATHER THAN BY UNDERWATER ACOUSTICS.

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INTRODUCTION

THIS STUDY HAS ADDRESSED ITSELF TO THE PROBLEM OF DETERMINING THE POSITION OF A HYDROPHONE THAT IS CONNECTED TO SHORE BY CABLE AND DETERMINING THE OBTAINABLE POSITION ACCURACY.

WHEN A HYDROPHONE IS INSTALLED THE EXACT LOCATION OF THE SHIP LOWERING THE HYDROPHONE WILL NOT DETERMINE THE FINAL HYDROPHONE POSITION WITHIN CLOSE LIMITS. THE CONTINUAL DRIFT OF THE CABLE SHIP WITH WIND AND SURFACE CURRENTS CAUSES A WIRE ANGLE IN THE LOWERING CABLE. MOREOVER, THE SURFACE WIRE ANGLE IS NOT INDICATIVE OF THE WIRE ANGLE AT DEPTH WHERE UNKNOWN CURRENTS MAY EXIST. IN WATER OVER A FEW HUNDRED FATHOMS THE DECREASE IN CABLE TENSION AS THE HYDROPHONE REACHES BOTTOM IS DIFFICULT TO DETECT ON A ROLLING SHIP AND IN ANY CASE IS ONLY INDICATIVE OF THE TIME THE PHONE FIRST TOUCHED BOTTOM RATHER THAN ITS POSITION. THIS IS PARTICULARLY TRUE WHEN LIGHT HYDROPHONE ASSEMBLIES ARE LOWERED TO BOTTOM WITH A HEAVY SIGNAL CABLE THAT IS STEEL ARMORED FOR PROTECTION IN SHALLOW WATER CLOSE TO SHORE. A HYDROPHONE POSITION BASED ON THE SURFACE WIRE ANGLE OF THE LOWERING CABLE AND THE POSITION OF THE CABLE SHIP MAY BE IN ERROR BY 10% OF THE WATER DEPTH.

IN THIS STUDY TWO METHODS OF HYDROPHONE LOCATION HAVE BEEN ATTEMPTED AND REPORTED. IN METHOD I (EXPLOSIVE RANGING) A PHOTOGRAPHIC RECORDING OSCILLOGRAPH MEASURED THE UNDERWATER ACOUSTIC TRAVEL TIME TO A HYDROPHONE OF THE SIGNAL FROM ACCURATELY LOCATED SURFACE EXPLOSIONS. TWO SERIES OF SHOTS PLUS HYDROGRAPHIC DATA FOR DETERMINING THE ACOUSTIC VELOCITY-DEPTH PROFILE ARE REQUIRED BY THIS METHOD. ONE SERIES OF SHOTS DIRECTLY OVER THE HYDROPHONE IS USED TO DETERMINE THE HYDROPHONE DEPTH. A SECOND SERIES OF SHOTS FIRED AT A HORIZONTAL DISTANCE OF ONE OR TWO TIMES THE HYDROPHONE DEPTH IS USED TO ESTABLISH THE HYDROPHONE POSITION USING EACH MEASURED ACOUSTIC TRAVEL TIME TO COMPUTE A LINE OF POSITION.

METHOD 2 (EQUAL TRAVEL TIMES) USED A PRECISION DEPTH RECORDER TO CONTINUOUSLY RECORD, ESSENTIALLY AS AN ECHO SOUNDER TRACE, THE TRAVEL TIME BETWEEN THE BOAT'S ECHO SOUNDER AND THE HYDROPHONE. IN THIS METHOD THE BOAT MUST BE ACCURATELY AND CONTINUOUSLY TRACKED. POSITIONS ALONG THE SOUNDING BOAT TRACKS WITH ARBITRARY BUT EQUAL TRAVEL TIMES ON THE PDR RECORD, ARE THEN USED AS THE BASIS FOR HYDROPHONE LOCATION.

BOTH METHODS REQUIRE A SHIP-SHORE RADIO LINK. BOTH METHODS ASSUME THERE IS NO HORIZONTAL VARIATION IN THE

VELOCITY DEPTH PROFILE AND THAT THE RAY OF THE SOUND WAVE WHOSE TRAVEL TIME IS MEASURED IS THE RAY WITH A SOURCE ANGLE SUCH THAT THE SOUND TAKES A MINIMUM TIME TO REACH THE HYDROPHONE. INFORMATION ON THE HYDROPHONE DEPTH AND THE ACOUSTIC VELOCITY DEPTH PROFILE FOR THE AREA ARE NOT REQUIRED IN METHOD 2.

THESE TECHNIQUES WERE TESTED USING THE EQUIPMENT AND FACILITIES AT HAND AT COLUMBIA UNIVERSITY GEOPHYSICAL FIELD STATION (NAVY SOFAR STATION) ST. DAVIDS, BERMUDA. THERE HAS BEEN IN OPERATION AT THIS STATION FOR NINE YEARS A 25 CPS VERTICAL GEOPHONE, IN A SUITABLE PRESSURE CASE, AS A BOTTOM HYDROPHONE. THIS HYDROPHONE IS LOCATED ABOUT 4 MILES OFF THE EASTERN TIP OF BERMUDA IN A DEPTH OF OVER 400 FATHOMS. THIS IS CONNECTED BY SUBMARINE CABLE TO THE STATION ON KINDLEY AFB AND THENCE VIA LAND LINE TO THE BERMUDA-COLUMBIA SEISMOGRAPH STATION AT ST. GEORGE'S, WHERE CONTINUOUS SIGNAL RECORDINGS ARE MADE ON A SEISMOGRAPH DRUM RECORDER. A COPY OF THE CALIBRATION CURVE OF THIS PHONE AFTER MILNE AND HERSEY (1958) IS SHOWN IN FIGURE I.

THE STATION'S T-BOAT WAS USED AS A FIRING VESSEL DURING METHOD 1, AND AS A SOUNDING VESSEL DURING METHOD 2. THIS BOAT IS A STUBBY 65 FOOTER DEVELOPED BY THE ARMY FOR COASTAL FREIGHT AND PASSENGER WORK.

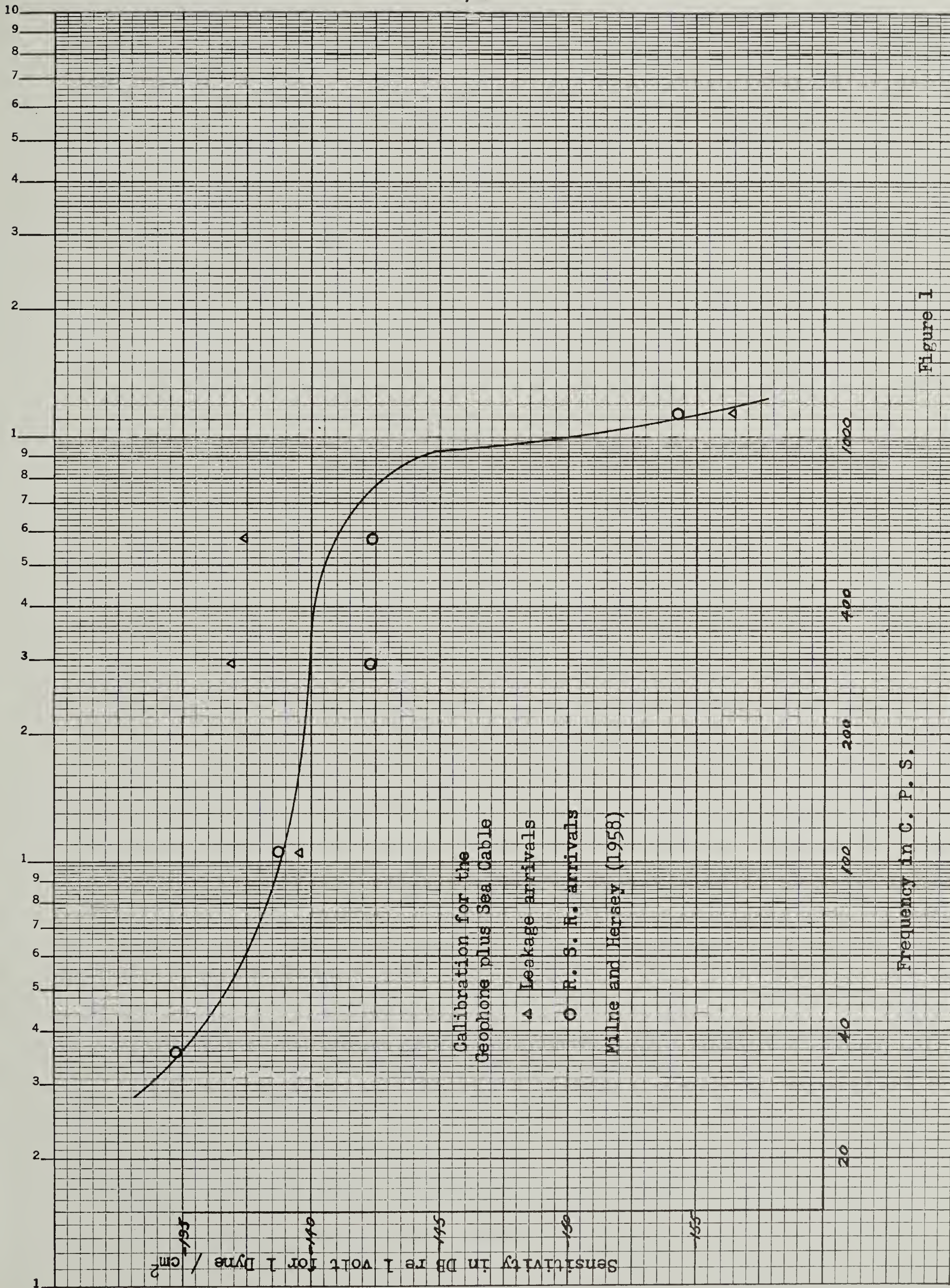


Figure 1

POSITIONING

BOTH THESE METHODS REQUIRE A TECHNIQUE FOR DETERMINING ACCURATE POSITIONS OF EITHER PLUMES OF WATER FROM THE EXPLOSION OR THE T-BOAT ECHO SOUNDER TRANSDUCER IN THE HYDROPHONE OFFSHORE.

THE BEST METHOD OF DOING THIS INEXPENSIVELY IS BY OPTICAL TRIANGULATION FROM THE SHORE. AFTER EXPERIMENTATION IT WAS DECIDED THAT AZIMUTH INSTRUMENTS, WAR DEPARTMENT (1941) SHOULD BE USED. THESE WERE DESIGNED FOR COAST ARTILLERY FIRE CONTROL USE. ALTHOUGH HEAVY, THEY WERE RUGGED AND, WHEN MOUNTED ON A FIRM SUPPORT, TAKE ROUGHER HANDLING THAN THE USUAL OPTICAL SURVEY INSTRUMENT. THEY READ DIRECTLY TO 0.01° (WITH ESTIMATES OF 0.001°) FACILITATING ACCURATE VOICE RADIO TRANSMISSION OF DATA. THE AZIMUTH INSTRUMENTS USED WERE TESTED FOR ACCURACY AGAINST A 11° TEST ANGLE MEASURED WITH A WILD T-2 THEODOLITE TO SECOND ORDER ACCURACY (A GEODETIC SURVEY TERM HERE REFERRING TO A MEASUREMENT WITH A PROBABLE ERROR OF LESS THAN 3" - ADAMS (1942). THIS TEST ANGLE WAS BETWEEN TWO SHARPLY DEFINED BUILDING EDGES AT A RANGE OF ABOUT TWO MILES. THIS ANGLE WAS THEN MEASURED BY EACH AZIMUTH INSTRUMENT IN EACH 10° SEGMENT OF THE AZIMUTH SCALE OF THE INSTRUMENT. THE AZIMUTH INSTRUMENTS WERE FOUND ACCURATE TO

0.01° ON THE ENTIRE 360° SCALE AND IN THE AZIMUTH SEGMENTS USED FOR THIS WORK TO 0.005°. IN ADDITION TO RUGGEDNESS, ONE OF THE AZIMUTH INSTRUMENT'S ADVANTAGES LIES IN THE CONTINUOUS SLOW MOTION AZIMUTH CRANK THAT MAY BE OPERATED IN EITHER DIRECTION. THIS IS A GREAT CONVENIENCE SINCE IT IS IMPOSSIBLE TO RUN OUT OF TANGENT SCREW, AS IN A NORMAL TRANSIT OR THEODOLITE, MAKING CONTINUOUS TRACKING POSSIBLE AND OBVIATES MISSING OBSERVATIONS.

THE AZIMUTH INSTRUMENTS WERE LOCATED IN MOUNT HILL B.E. STATION AND PAYNTER'S HILL B.E. STATION FOR THE OFFSHORE POSITION WORK. THESE ARE THE OLD "BASE END" STATIONS OF THE BERMUDA COASTAL DEFENSE FIRE CONTROL SYSTEM. THEY ARE CONCRETE TOWERS DESIGNED FOR USE WITH AZIMUTH INSTRUMENTS, AND ARE LOCATED ON PROMINENT HILLS WITH GOOD VISIBILITY. THE AZIMUTH INSTRUMENT MOUNTING POSTS IN THESE TOWERS WERE TRIANGULATED IN USING THE WILD T-2 THEODOLITE FROM THREE SECOND ORDER STATIONS PREVIOUSLY ESTABLISHED ON THE BERMUDA SPECIAL LAMBERT PLANE COORDINATE PROJECTION BY THE COAST AND GEODETIC SURVEY (1942). SIX REPETITIONS OF EACH ANGLE DIRECT AND REVERSE WERE MEASURED. TRIANGLE CLOSURE WAS LESS THAN 3 SECONDS FOR EACH TRIANGLE AND THE AZIMUTH INSTRUMENT STATIONS ARE CONSIDERED SECOND ORDER. THIS

PROVIDED A BASE LINE OF 6115.90 YARDS WITH AN AZIMUTH OF 58.369° (SEE FIGURE 2) FOR THE OFFSHORE POSITIONING WORK. THIS LINE MAY BE CONSIDERED ACCURATE TO ONE PART IN 10,000 AND TO 3 SECONDS IN ARC FOLLOWING THE STANDARDS OF ADAMS (1942). THESE BASE END STATIONS ARE CONNECTED BY FIELD TELEPHONE (EE9I) AND USN/TCS RADIOS HAVE BEEN PERMANENTLY INSTALLED AT EACH TOWER.

THE AZIMUTH LINES FROM THESE STATIONS CROSSED OVER THE GEOPHONE AT AN ANGLE OF ABOUT 24° WHICH IS FAR FROM THE IDEAL. HOWEVER, USING THE REASONABLE FIGURE OF $\pm .005^{\circ}$ ACCURACY AND TAKING INTO ACCOUNT THE INACCURACY OF THE BASE, THE LONG AXIS OF THE FIGURE OF ERROR IS ABOUT 10 YARDS AT ABOUT $100^{\circ}T$ AND 2 YARDS ON THE SHORT AXIS. THIS WAS DETERMINED ANALYTICALLY BY CALCULATING THE ERROR CAUSED BY TRANSLATION OF ONE LINE TO ALLOW FOR THE INACCURACY OF THE BASE AND A ROTATION OF BOTH BEARING LINES $\pm .005^{\circ}$ AT THE APPROXIMATE DISTANCE. IF THE POSITION OF THE EXPLOSION IS ASSUMED TO BE AT THE CENTER OF THE PARALLELOGRAM THE MAXIMUM DISTANCE THAT THE FIX MIGHT BE IN ERROR IS THE LENGTH OF THE LINE FROM THE CENTER TO THE CORNER OF THE PARALLELOGRAM.

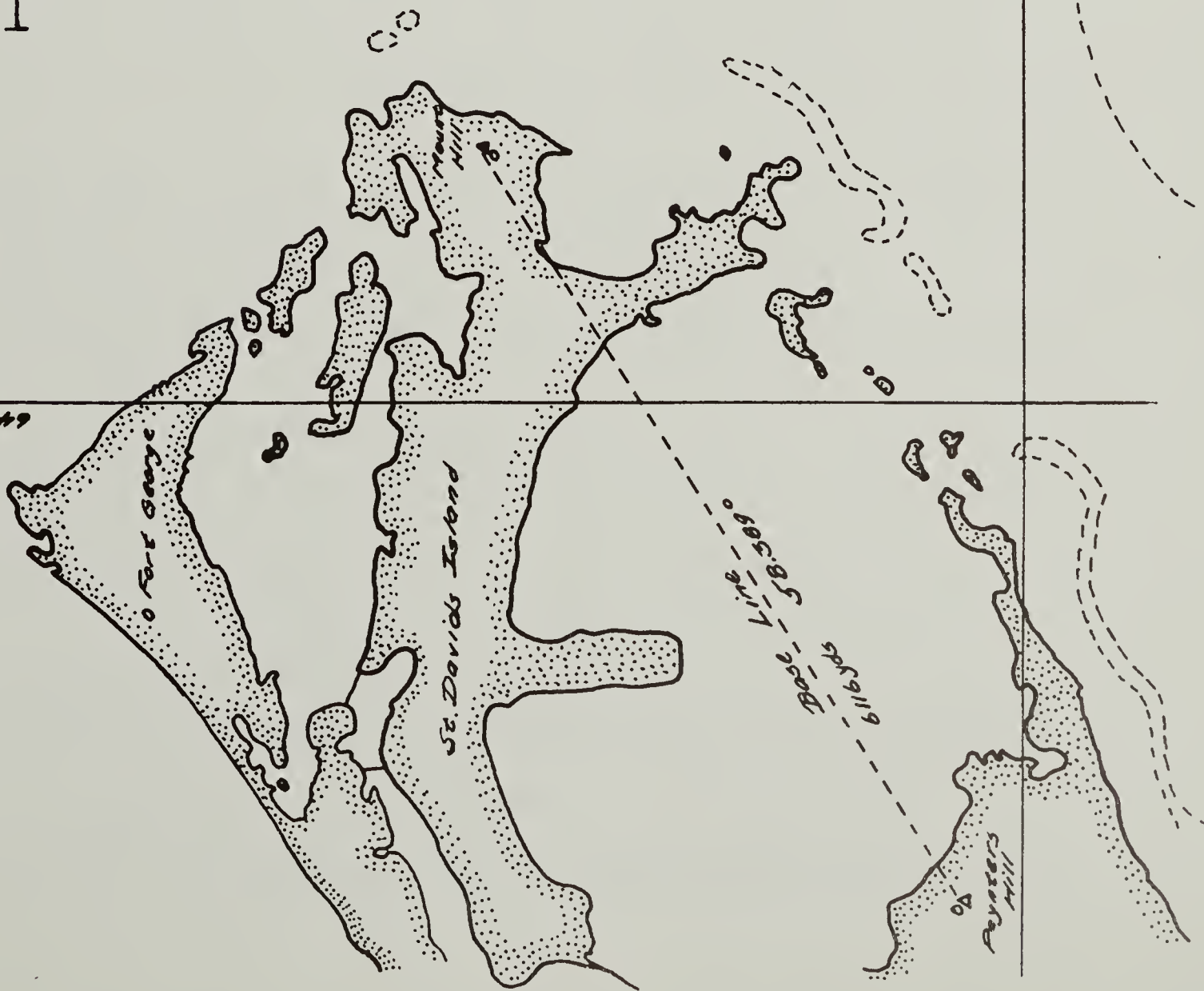
Base Line

- Existing 2nd order stations
- △ New 2nd order stations

1 mile

M. 5E. 0. 49

M. 04. 49



△ Geophone

fig. 2

Error Parallelogram near Geophone

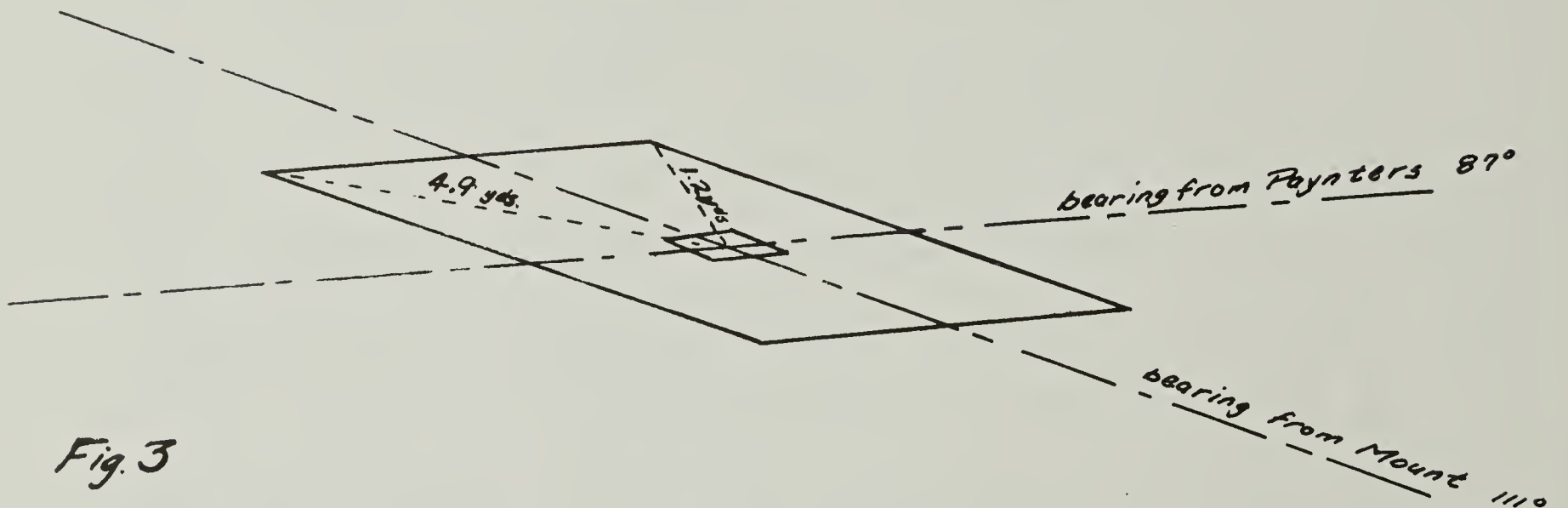


Fig. 3

IN FIGURE 3 THE CENTER PARALLELOGRAM IS THE ERROR DUE TO THE MAXIMUM ERROR IN LOCATION OF THE AZIMUTH INSTRUMENT OBSERVATIONS STATIONS. THE LARGER PARALLELOGRAM IS THE SUMMATION OF THIS ERROR AND THE $.005^{\circ}$ ERROR IN THE LINE OF BEARING. LOCATING EXPLOSION PLUMES IN METHOD 1 WHERE BACK SIGHTS WERE TAKEN AFTER EVERY SHOT AND ANGLES WERE ESTIMATED TO $.001^{\circ}$, THIS ERROR PARALLELOGRAM IS VALID. DURING THE CONTINUOUS T-BOAT TRACKING OF METHOD 2, READINGS WERE MADE TO THE NEAREST $.01^{\circ}$ AND A SAFE ASSUMPTION OF THE ACCURACY OF THE AZIMUTHS

IS $\pm .01^{\circ}$. THE RESULTING LONG AXIS OF THE FIGURE OF ERROR IS 18 YARDS AND THE SHORT AXIS 5 YARDS.

THE GEOGRAPHY OF THE SITUATION AT BERMUDA WOULD HAVE ALLOWED A BETTER FIGURE OF ERROR BY ONLY ABOUT 10% FOR THE PARTICULAR AREA IN WHICH THE GEOPHONE IS LOCATED. THE CHOICE OF STATIONS WERE ALSO INFLUENCED BY PRACTICAL ASPECTS SUCH AS AVAILABILITY OF ELECTRIC POWER, PHYSICAL SECURITY AND FUTURE USE. AT OTHER SITES THE TRACKING STATIONS MIGHT BE CHOSEN TO GIVE A MORE NEARLY SQUARE FIGURE OF ERROR, AND THUS CONSIDERABLY INCREASE THE POSITION ACCURACY OBTAINABLE.

FOR INSTANCE, USING $\pm .01^{\circ}$ AZIMUTH ACCURACY AND WITH RANGES COMPARABLE TO THE GEOPHONE DISTANCE FROM SHORE THE ACCURACIES ALONG THE LONG AXIS VARY AS SHOWN BELOW:

ANGLE OF CROSS	ACCURACY
24°	\pm 9 YARDS
45°	\pm 5.2 YARDS
60°	\pm 4.0 YARDS
90°	\pm 2.9 YARDS

THEORY OF METHOD I (EXPLOSIVE RANGING)

IF THE TRAVEL TIME OF AN OMNI-DIRECTION TRANSIENT ACOUSTIC SIGNAL FROM ITS ORIGIN AT THE SURFACE OF THE SEA, WITH AN ASSUMED ACOUSTIC VELOCITY-DEPTH PROFILE,

TO A HYDROPHONE AT A KNOWN DEPTH IS MEASURED, THE HORIZONTAL DISTANCE BETWEEN THE SOURCE AND THE HYDROPHONE MAY BE CALCULATED. EACH CALCULATED DISTANCE WILL BE THE RADIUS OF A CIRCLE OF POSITION CENTERED AT THE SOURCE LOCATION. IF THE POSITION OF SEVERAL SOURCES ARE OBSERVED AND PLOTTED AND THEIR CIRCLES OF POSITION DRAWN, THE LOCATION OF THE HYDROPHONE WILL BE AT THE INTERSECTION OF THE CIRCLES.

IF THE ASSUMPTION IS MADE THAT THE VELOCITY OF THE SHOCK WAVE FROM THE EXPLOSION CAUSED BY A SMALL CHARGE OF TNT ($\frac{1}{2}$ POUND BLOCK) RAPIDLY APPROACHES ACOUSTIC VALUES, THESE MAY BE USED TO GENERATE THE ACOUSTIC SIGNAL. THE PLUME FROM SUCH AN EXPLOSION ON THE SURFACE IS EASILY OBSERVABLE AND POSITIONED.

THE EQUATION FOR THE TRAVEL TIME IN ANY LAYER WITH A CONSTANT GRADIENT IS WRITTEN BY EWING AND WORZEL (1948)

$$t = \frac{1}{g_i} \int_{\theta_i}^{\theta_{i+1}} \frac{d\theta}{\cos \theta} \quad (I)$$

AND

$$g_i = \frac{dc}{dy}$$

WHERE

- t - TRAVEL TIME
- g_i - VELOCITY DEPTH GRADIENT
- c - VELOCITY OF SOUND
- y - LAYER DEPTH
- θ_i - ANGLE OF RAY ENTERING THE LAYER WITH THE HORIZONTAL
- θ_{i+1} - ANGLE OF RAY LEAVING THE LAYER WITH THE HORIZONTAL

IF THE VELOCITY DEPTH CURVE MAY BE APPROXIMATED BY A STRAIGHT LINE THE VELOCITY DEPTH GRADIENT IS CONSTANT AND THE RAY PATH IS A CIRCULAR ARC, THE VELOCITY DEPTH GRADIENT BECOMES:

$$g_i = \frac{c_i - c_{i+1}}{\Delta y}$$

FROM SNELL'S LAW THE RAY ANGLES HAVE THE FOLLOWING RELATIONSHIP:

$$\frac{c_i}{\cos \theta_i} = \frac{c_{i+1}}{\cos \theta_{i+1}}$$

EQUATION (I) MAY BE INTEGRATED INTO ANY OF THE SEVERAL FORMS LISTED IN TABLE I. A CONVENIENT FORM IS,

$$t = \pm \frac{1}{g_i} \left[\tanh^{-1} \sin \theta \right]_{\theta_i}^{\theta_{i+1}}$$

IF TABLES OF ANTI-CUDERMANNIANS ARE AVAILABLE SUCH AS IN LUFBURROW (1955) THE FOLLOWING MAY BE USED,

$$t = \pm \frac{1}{g_i} \left[Gd^{-1} \theta \right]_{\theta_i}^{\theta_{i+1}}$$

FROM THE GEOMETRY IT MAY BE SHOWN THAT THE HORIZONTAL DISTANCE (X) COVERED BY A RAY IN A LAYER OF THICKNESS (Y) WITH CONSTANT VELOCITY GRADIENT MAY BE EXPRESSED AS,

$$X = y \cot \left(\frac{\theta_{i+1} + \theta_i}{2} \right) \quad (2)$$

THE VELOCITY-DEPTH CURVE IS DIVIDED IN LAYERS IN SUCH A WAY THAT EACH SEGMENT CLOSELY APPROXIMATES A STRAIGHT LINE. THE LOWER LIMIT OF THE LOWEST LAYER IS THE DEPTH OF THE HYDROPHONE. USING ANY GIVEN SOURCE

TRAVEL TIME VS HORIZONTAL DISTANCE
456 FM GEOPHONE FEBRUARY 1957
AT VARIOUS SOURCE ANGLES

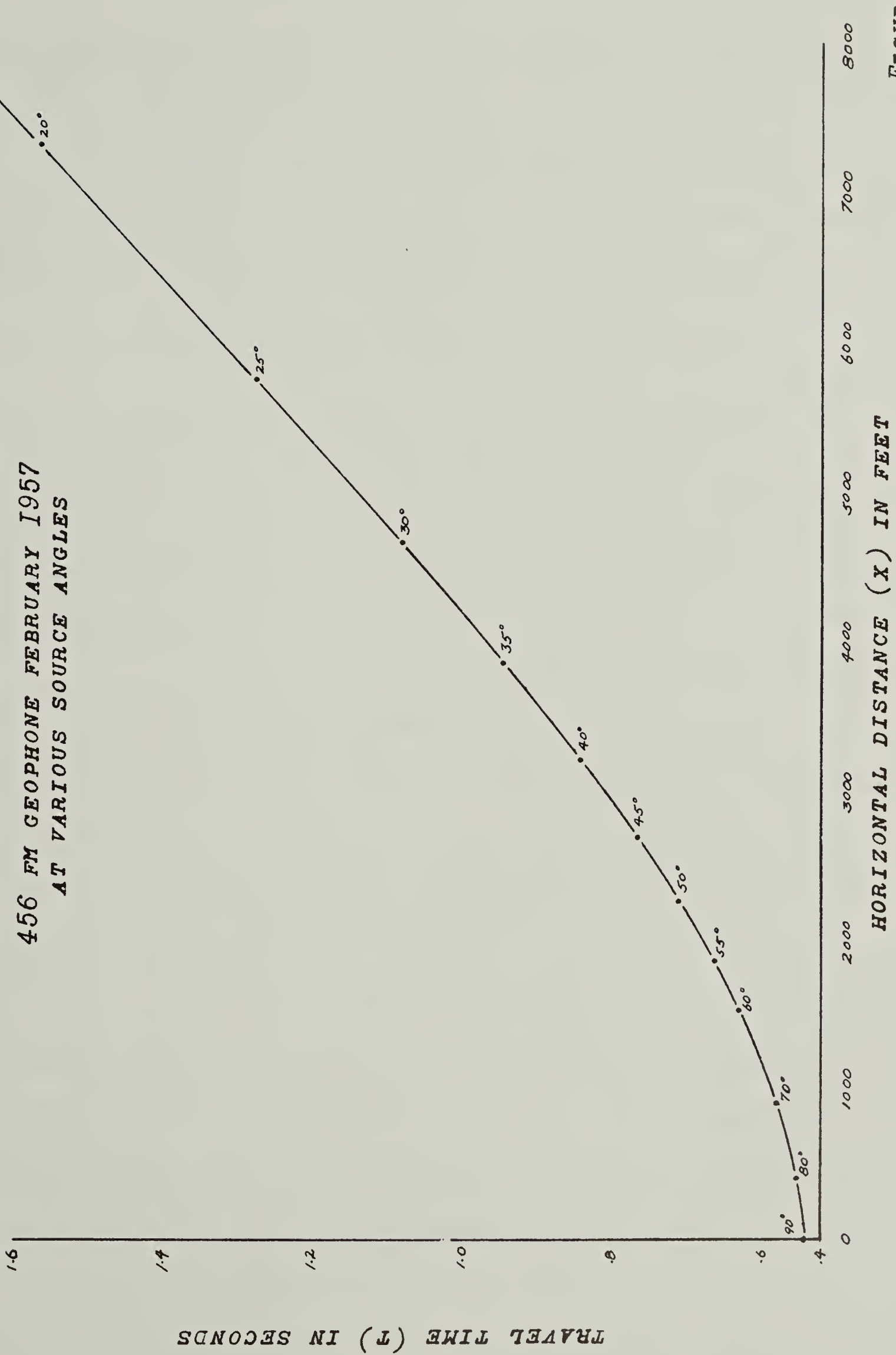


FIGURE 4

ANGLE (θ_i) THE VALUES OF TRAVEL TIME AND HORIZONTAL DISTANCE OF THIS RAY MAY BE CALCULATED BY EQUATIONS (1) AND (2) FOR EACH LAYER AND THEIR VALUES ADDED. DOING THIS FOR RAYS WITH CONVENIENTLY SELECTED SOURCE ANGLES (ABOUT EVERY 5°) WILL ALLOW A MORE ACCURATE AND LARGER SCALE CURVE THAN THAT SHOWN IN FIGURE 4, TO BE PLOTTED.

A HORIZONTAL DISTANCE MAY BE TAKEN FROM SUCH A GRAPH FOR THE TRAVEL TIMES OF EACH SHOT. USING THE SHOT'S POSITION AS THE CENTER AND THIS DISTANCE AS A RADIUS A CIRCLE OF POSITION MAY BE DRAWN ON A LARGE SIZE, SMALL SCALE PLOT.

THE ROUGH LOCATION FORMED BY THE INTERSECTION OF SEVERAL CIRCLES OF POSITION MAY BE REFINED BY A TECHNIQUE SIMILAR TO THAT USED IN A MARINE CELESTIAL FIX. FROM THIS ROUGH LOCATION AN ASSUMED HYDROPHONE POSITION IS TAKEN. SHOT LOCATIONS ARE CALCULATED INTO LAMBERT COORDINATES FROM THE TRIANGULATION DATA. A DISTANCE AND BEARING TO THE ASSUMED POSITION FROM EACH SHOT IS CALCULATED. THIS DISTANCE FROM THE SHOT TO THE ASSUMED HYDROPHONE POSITION IS COMPARED WITH THE DISTANCE TAKEN FROM THE "TRAVEL TIME-HORIZONTAL DISTANCE CURVE" FOR THE

SHOT'S OBSERVED TRAVEL TIME. THE DIFFERENCE IS CALLED AN "INTERCEPT". THIS IS LAID OFF ON A LARGE SCALE PLOT SUCH AS FIGURE 10 ALONG THE BEARING LINE AND IN THE PROPER DIRECTION FROM THE ASSUMED POSITION. AT THIS POINT A "LINE OF POSITION" IS DRAWN AT RIGHT ANGLES TO THE BEARING LINE. THIS LINE IS ACTUALLY A SMALL SEGMENT OF HYDROPHONE CIRCLE OF POSITION AS DEFINED BY THE MEASURED TRAVEL TIME. IF THE ASSUMED POSITION IS FAR AWAY FROM THE INTERSECTION OF LINES A NEW AND MORE ACCURATE ASSUMED POSITION SHOULD BE CHOSEN AND THE PROBLEM REWORKED.

ACOUSTIC RANGING FOR DISTANCES OF A FEW MILES IN THE OCEAN IS QUITE PRECISE. ERRORS IN SHOT POSITION, OR COMPUTATIONS, ARE IMMEDIATELY OBVIOUS. ERRORS IN HYDRO-PHONE DEPTH OR ASSUMED VELOCITY-DEPTH PROFILE BECOME OBVIOUS IF SHOTS FROM OPPOSITE AZIMUTHS ARE AVAILABLE.

INSTRUMENTATION METHOD I (EXPLOSIVE RANGING)

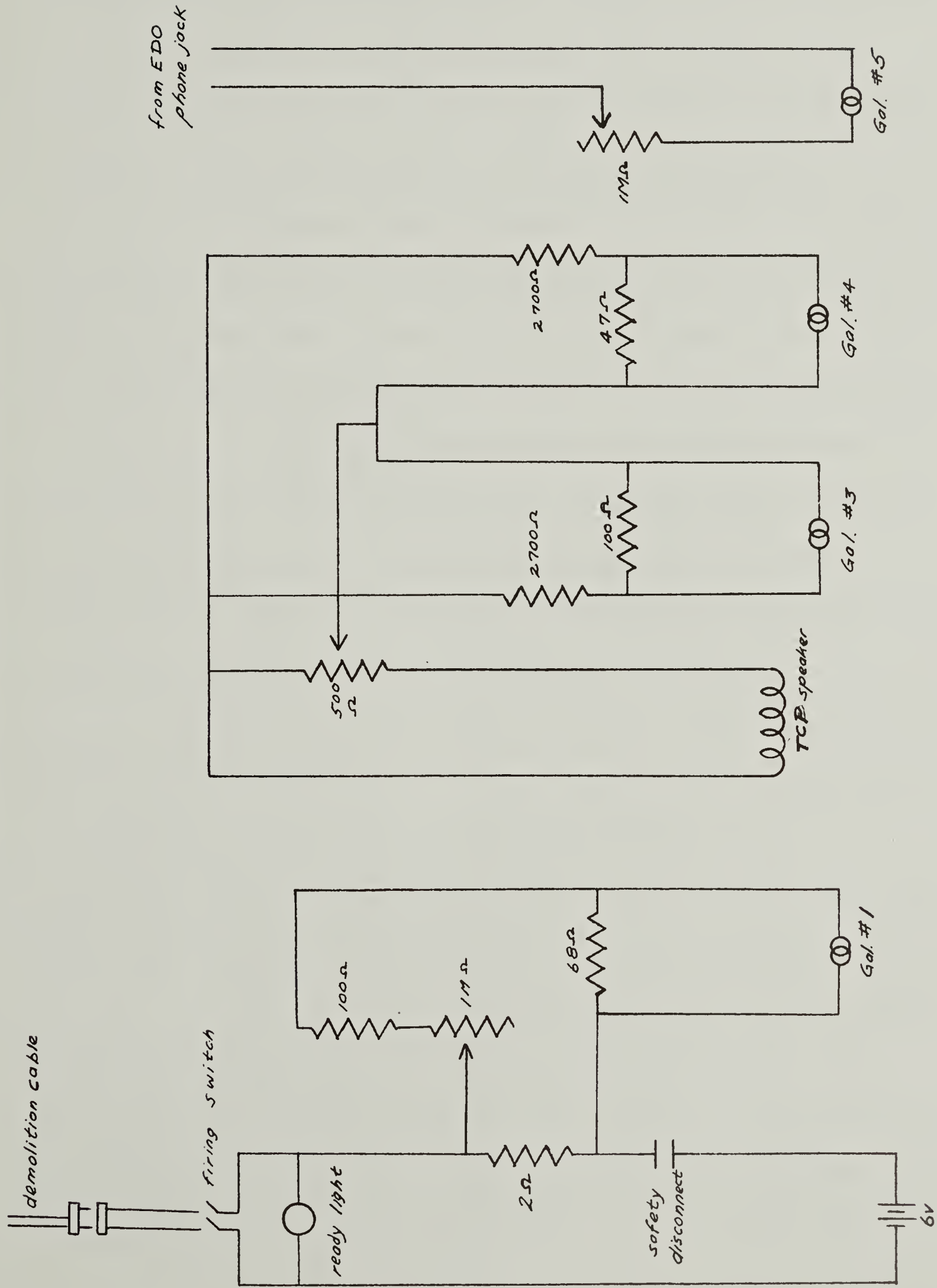
SINCE A MILLISECOND TRAVEL TIME IS EQUIVALENT TO ABOUT 5 FEET IN DISTANCE, IT WAS NECESSARY TO RECORD SHOT TRAVEL TIMES IN SUCH A WAY THAT TIMES COULD BE ESTIMATED TO MILLISECONDS. TO DO THIS A CENTURY GEO-PHYSICAL CORP. MODEL 3 OSCILLOGRAPH WAS USED. THIS

RECORDED THE REQUIRED SIGNALS WITH GALVANOMETER TRACES ON PHOTOGRAPHIC PAPER MOVING WITH SPEEDS UP TO ABOUT 3 FEET/SECOND. TIMING LINES CONTROLLED BY A TEMPERATURE COMPENSATED TIMING FORK WERE SUPERIMPOSED EVERY .01 SECONDS. THIS GIVES ABOUT ONE THIRD OF AN INCH BETWEEN .01 SECOND LINES AND MILLISECONDS COULD BE EASILY ESTIMATED. THE ACCURACY OF THE TIMING LINES WAS FREQUENTLY CHECKED AGAINST TIME SIGNALS FROM WWV.

FOR SEVERAL REASONS IT WAS DECIDED TO MAKE THE TRAVEL TIME OSCILLOGRAPH RECORDINGS ABOARD THE SHOT FIRING T-BOAT. PREVIOUS EXPERIENCE HAD INDICATED THAT TELEMETERING THE SHOT BREAK WAS DIFFICULT WHEN MILLI-SECOND ACCURACY WAS REQUIRED. FURTHERMORE IT IS ADVANTAGEOUS TO HAVE A RECORD OF THE EXPLOSIVE SIGNAL IN THE WATER AS RECEIVED BY A HYDROPHONE ON THE FIRING SHIP TO INSURE THAT THE FIRING RECORDING CIRCUIT IS OPERATING PROPERLY. RECORDING ABOARD THE T-BOAT THEREFORE REQUIRED A SINGLE RADIO CHANNEL RATHER THAN TWO.

THE TELEMETERED GEOPHONE SIGNAL AS RECEIVED ABOARD THE T-BOAT DROVE TWO OSCILLOGRAPH GALVANOMETERS, BOTH FLAT TO 300 CPS, THROUGH DIFFERENT ATTENUATING RESISTORS, AS SHOWN IN FIGURE 5, TO INSURE A READABLE RECORD AT LARGE AND SMALL SIGNAL AMPLITUDES. ON LATER SHOTS A RECTIFIED GEOPHONE SIGNAL WAS ADDED AND RECORDED WITH

SIMPLIFIED OSCILLOGRAPH SCHEMATIC



THESE GEOPHONE TRACES IN ORDER TO CLARIFY THE ARRIVAL INSTANT IN CASES WHERE THE BACKGROUND NOISE WAS HIGH.

THE CHARGES USED WERE MARK 4 DEMOLITION CHARGES (HALF POUND BLOCKS OF TNT WITH A TETRYL BOOSTER) TOWED WITH 130 FEET OF DEMOLITION CABLE BEHIND THE T-BOAT AT SPEEDS THAT CAUSED THEM TO RIDE NEAR THE SURFACE SO THAT THERE WAS NO BUBBLE PULSE. THEY WERE FIRED ELECTRICALLY WITH A 6 VOLT BATTERY. THE DIRECT ACOUSTIC SIGNAL FROM THE SHOT WAS RECEIVED BY THE T-BOAT'S AN/UQN-IB (EDO) ECHO SOUNDER AND RECORDED ON GALVANOMETER 5. THIS SIGNAL APPROXIMATELY .026 SECONDS AFTER DETONATION ENABLED ANY GROSS VARIATION IN THE RECORDED SHOT BREAK CIRCUIT TO BE OBSERVED. THIS ECHO SOUNDER OUTPUT GALVANOMETER ALSO RECORDED THE BOTTOM REFLECTION OF THE SHOT AS RECEIVED THROUGH THE EDO ELECTRONICS.

NOT SHOWN IN THE SCHEMATIC, BUT ALSO RECORDED ON THE OSCILLOGRAPH WERE TIME TICKS FROM A BREAK CIRCUIT CLOCK TO INSURE THAT ANY INTERMITTENT FAILURE IN THE TIMING LINE WOULD BE DETECTED.

THE OSCILLOGRAPH RECORDED SHOT DETONATION SIGNAL WAS BASED ON THE BREAK IN THE ELECTRICAL CONTINUITY OF THE DETONATOR BRIDGE WIRE WHEN IT WAS BLOWN APART BY THE DETONATION. A 2 OHM RESISTOR IN SERIES WITH THE

10 OHM DEMOLITION CABLE LIMITED THE CURRENT THROUGH THE BLASTING CAP TO 0.5 AMPERES. THIS INSURED THAT THE BRIDGE WIRE INSIDE THE CAP DID NOT BURN APART BEFORE THE CAP EXPLODED. FOR A LARGE FIRING CURRENT THE BRIDGE WIRE MIGHT BURN OUT BEFORE THE IGNITED PRIMING CHARGE HAD IGNITED THE BASE CHARGE CAUSING ITS DETONATION. UNDER THIS CONDITION THE ACTUAL TIME OF THE DETONATION MIGHT HAVE APPRECIABLY LAGGED THE TIME THAT THE RECORDED BRIDGE WIRE BREAK INDICATED DETONATION.

FIGURES 6 AND 7 ARE PICTURES OF THE OSCILLOGRAPH RECORD AT FIRING TIME SHOWING THE CLOSING OF THE FIRING SWITCH, THE SHOT BREAK AND THE ARRIVAL OF THE DIRECT SIGNAL AT THE EDO. FIGURES 8 AND 9 SHOW THE ARRIVAL OF THE ACOUSTIC SIGNAL AT THE GEOPHONE.

GEOPHONE DEPTH, METHOD I (EXPLOSIVE RANGING)

FROM DISTANT SHOTS A ROUGH GEOPHONE POSITION WAS OBTAINED. ATTEMPTS WERE THEN MADE TO PUT A SHOT DIRECTLY OVER THE PHONE. IN THIS THE T-BOAT WAS CONTROLLED FROM MOUNT HILL, COACHED ON VARIOUS LINES OF BEARINGS WHILE TOWING A CHARGE. SHORTLY BEFORE THE FIRING POINT WAS REACHED AS DETERMINED BY CROSS BEARINGS FROM PAYNTER'S HILL A FIRING ORDER WAS GIVEN. AFTER SOME 32 SHOTS WERE PLACED IN THE NEAR VICINITY OF

Firing Switch Closed

2 Mer. #9

2 Mech #9

Shot Break

Gal #1

Gal #3

Gal #4

Gal #5

12

90

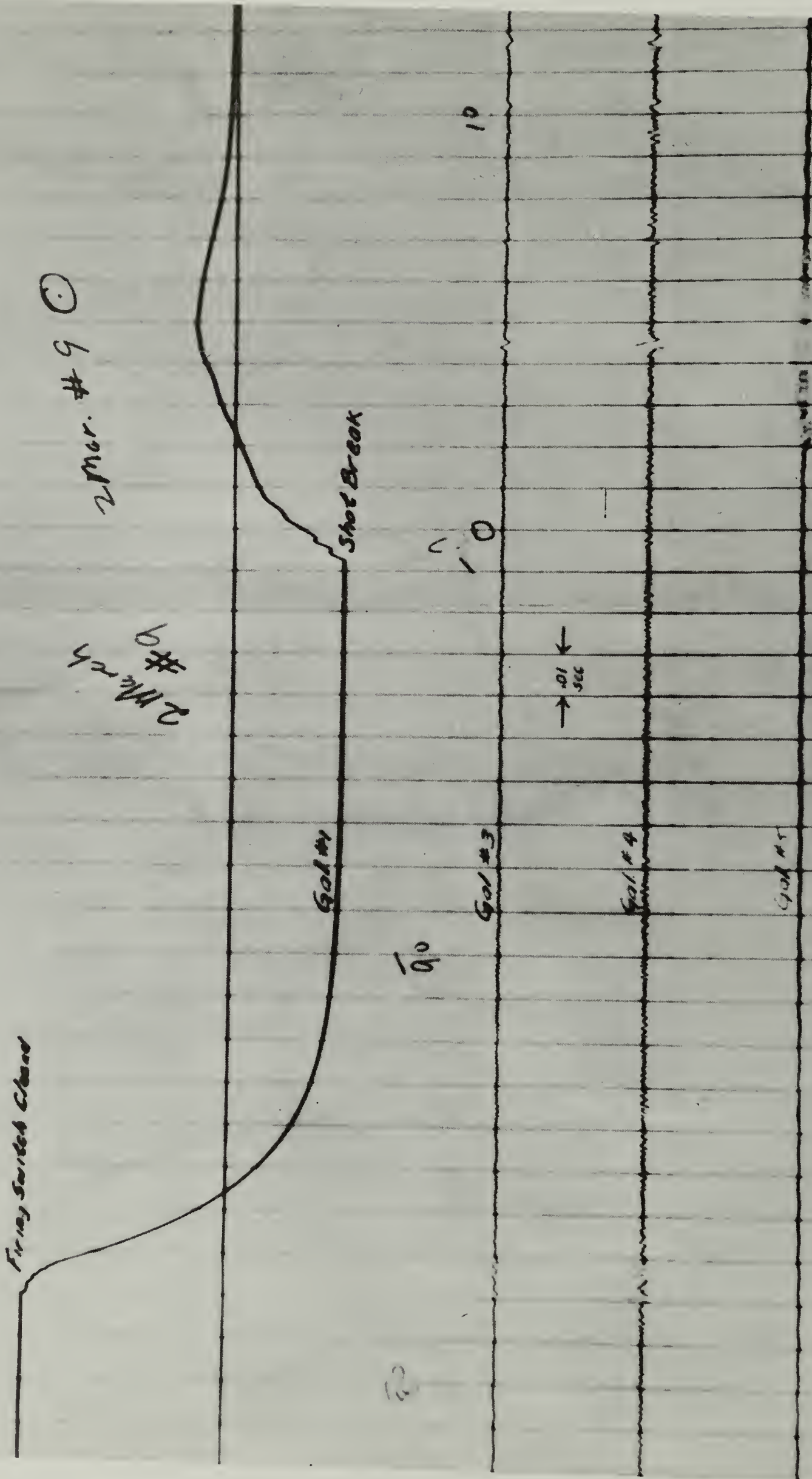
10

10

0.01 sec

Direct arrival
at EDO rec

Fig. 6



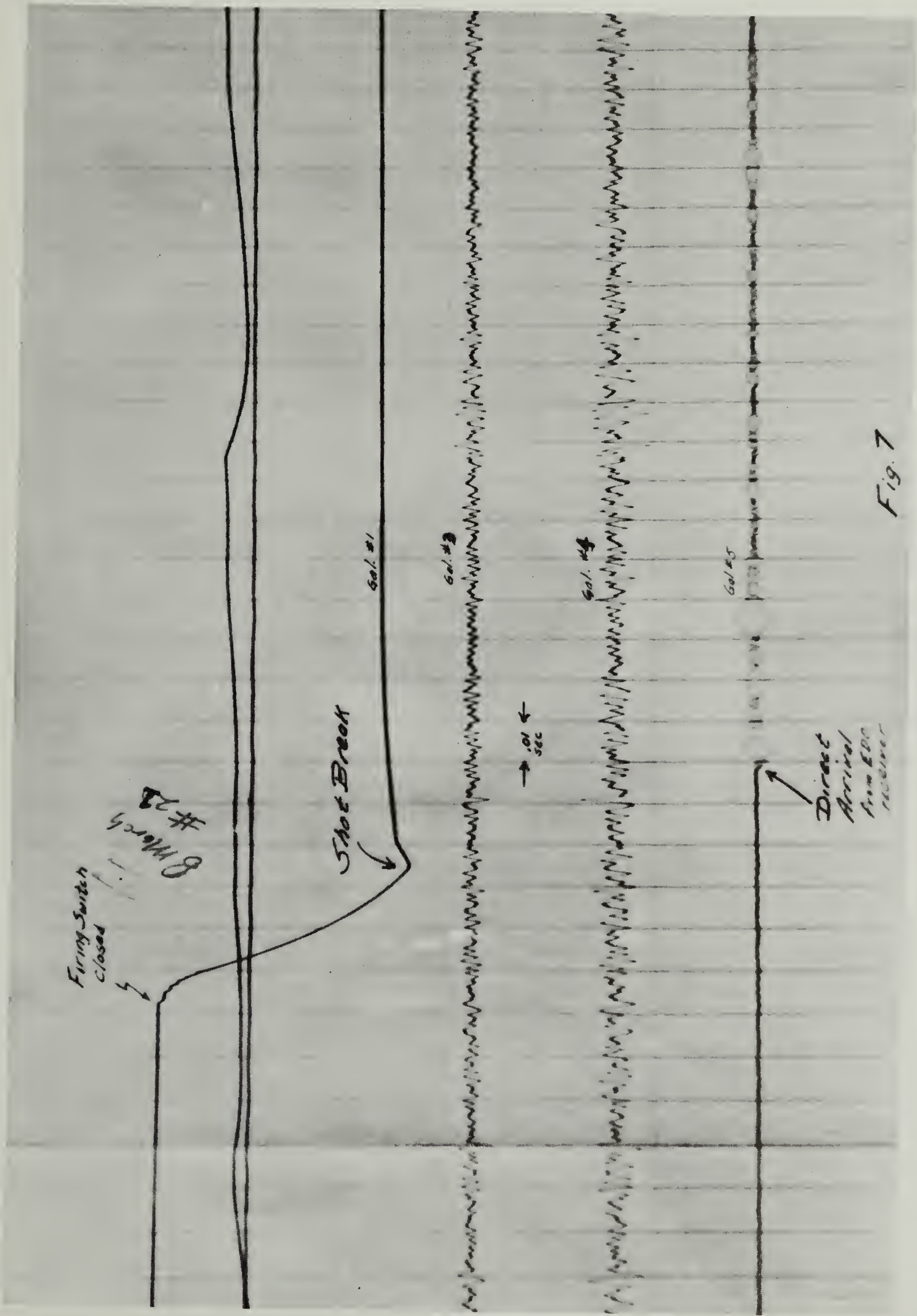


Fig. 7

09

Gal #1

↑ break circuit clock

60

70

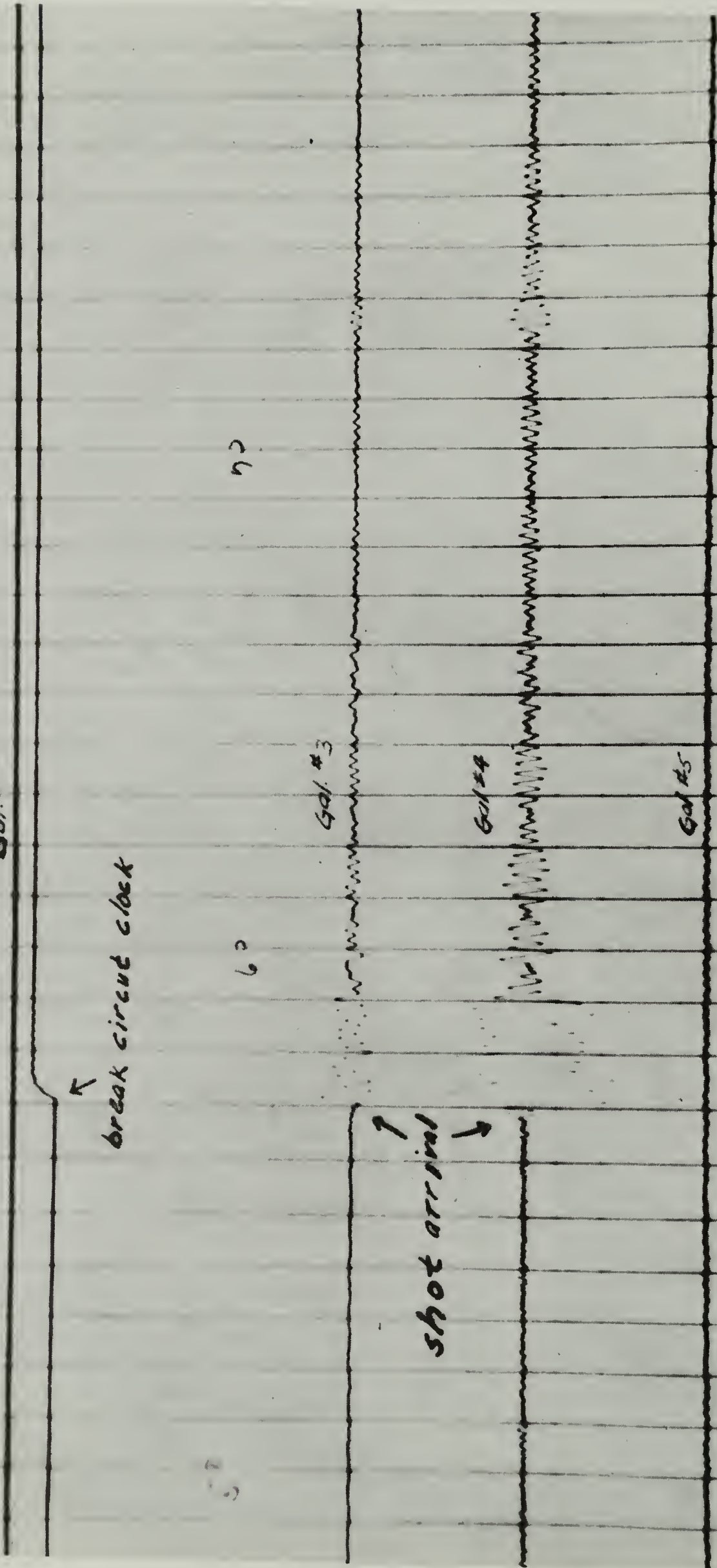
Gal #3

Gal #4

Gal #5

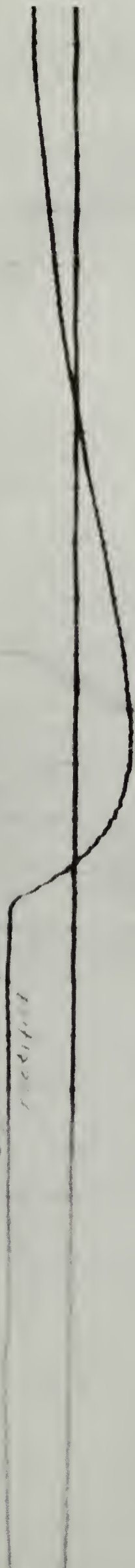
↑ shot arrival ↓

Fig. 8



1000
T-300-57

Signal from No. 4
modified



→ .01
sec ←

Gal #1

Gal #3

shot arrival

Gal #4

Gal #5

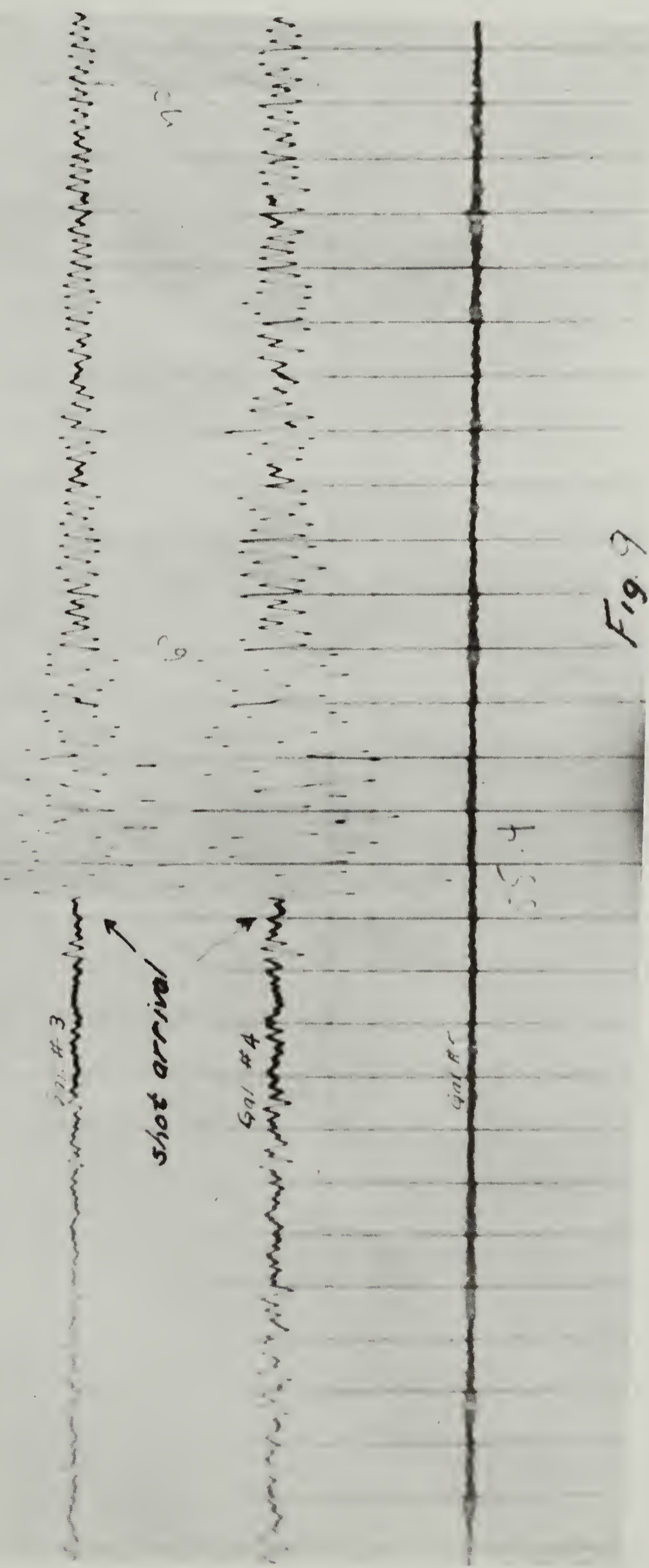


Fig. 9

THE PHONE A MINIMUM TRAVEL TIME OF 0.547 SECONDS WAS OBTAINED.

THE EQUATION FOR THE SPECIAL CASE OF VERTICAL TRAVEL TIME IS GIVEN BY LUFBURROW (1955) AS:

$$t = \frac{\Delta y}{c_i} \left[1 - \frac{1}{2} \frac{\Delta c}{c_i} + \frac{1}{3} \left(\frac{\Delta c}{c_i} \right)^2 - \dots \right] \quad (3)$$

LUFBURROW (1955) ALSO PROVIDES A GRAPH WITH THE ARGUMENTS Δc AND c_i WHICH YIELDS AN APPROXIMATION FOR THE SERIES TO AT LEAST FIVE PLACE ACCURACY.

USING EQUATION (3) TO DETERMINE t FOR THE TOP LAYER (TWO LAYERS WERE ASSUMED IN THIS WORK) AND THE DIFFERENCE BETWEEN THIS AND 0.547 SECONDS IN THE EQUATION THE Δy OF THE BOTTOM LAYER (WHICH ENDS AT THE GEOPHONE) IS CALCULATED. THIS WAS ADDED TO THE DEPTH OF THE TOP LAYER AND THE DEPTH OF THE GEOPHONE DETERMINED TO BE 456 FATHOMS. THIS SHOT #9 WITH A 0.547 SECONDS TRAVEL TIME, LATER PROVED TO BE 53 FEET SOUTHWEST OF THE GEOPHONE AND THE ACTUAL GEOPHONE DEPTH WAS CALCULATED TO BE 455.9 FATHOMS ASSUMING THE 53 FOOT SHOT DISPLACEMENT.

USING THIS DEPTH AND THE TRAVEL TIME OF THE REFLECTED ECHO FROM THE NEAREST TOPOGRAPHY AS RECEIVED

BY THE EDO THE MAXIMUM POSSIBLE SLOPE OF THE BOTTOM IN THIS VICINITY IS CALCULATED TO BE ABOUT 14.5° .

THIS IS IN GENERAL AGREEMENT WITH BATHYMETRIC DATA TAKEN IN THE GENERAL AREA (SEE FIGURE 14).

PLOT OF TRAVEL TIME METHOD I (EXPLOSIVE RANGING)

FROM BT'S TAKEN ON THE FIRING DAYS AND DATA FROM FUGLISTER (1947) A VELOCITY-DEPTH CURVE WAS PLOTTED. THIS COULD BE APPROXIMATED BY TWO STRAIGHT LINES, ONE NEARLY ISOTHERMAL TO 300 FATHOMS, THE OTHER A SHARP NEGATIVE GRADIENT BETWEEN 300 AND 900 FATHOMS.

IN THIS WORK THE SPEED OF SOUND WAS CALCULATED FROM THE FOLLOWING FORMULA DEVELOPED BY KUWAHARA (1939)

$$C = 4422 + 11.25T - 0.045T^2 + 0.0182D + 4.3 (\text{SAL} - 34) \quad (4)$$

THIS GIVES VALUES BETWEEN THOSE OF MATTHEWS (1939) AND DEL GROSSO (1952). IN GENERAL THE POOR ACCURACY IN LOCATING THE SHOT POSITIONS AS COMPARED TO THE SHORT ACOUSTIC RANGES USED, MAKE IT IMPOSSIBLE TO USE THIS EXPERIMENT TO DECIDE BETWEEN THESE VELOCITY DETERMINATIONS.

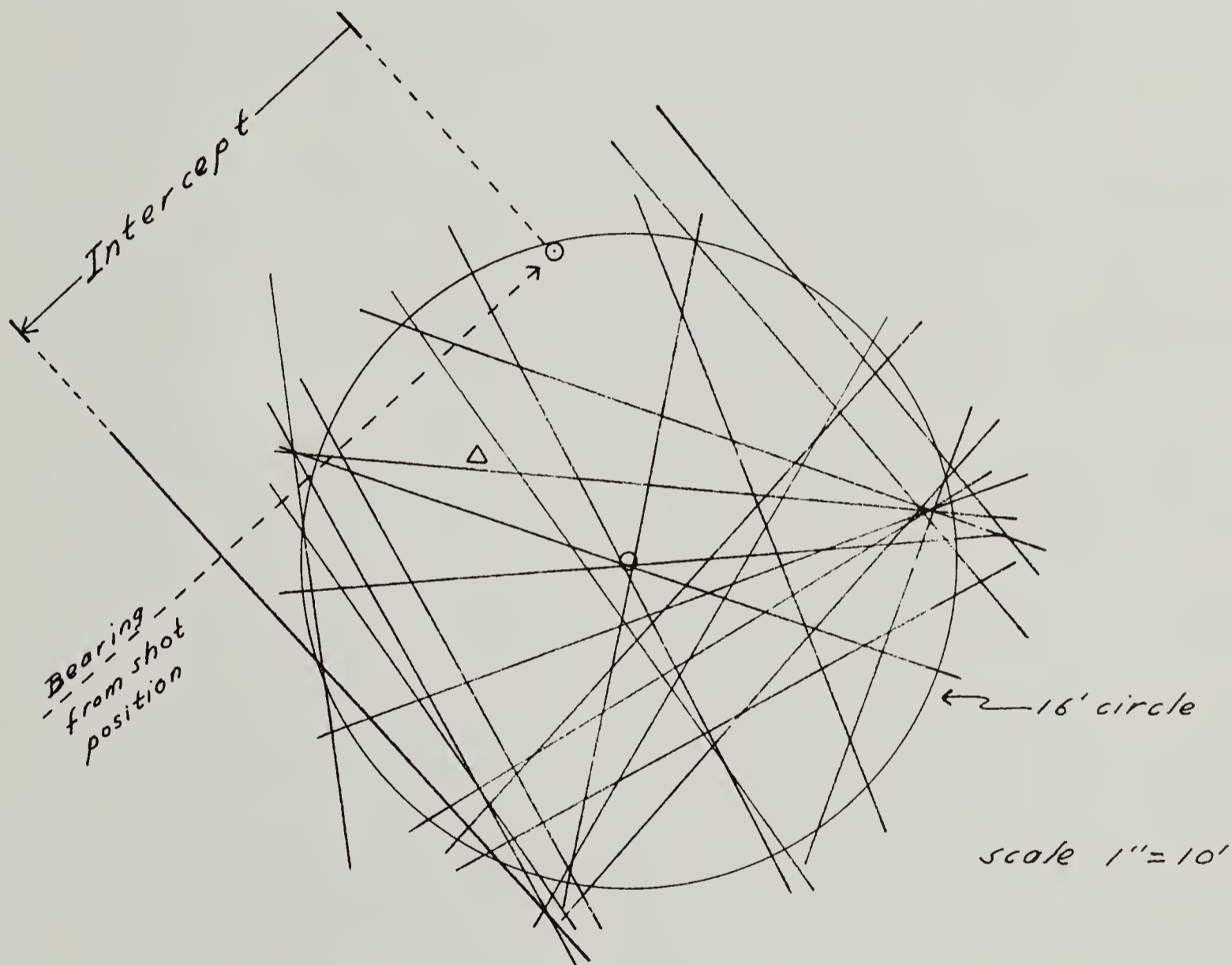
WITH THIS DATA THE ACCURATE, LARGE SCALE, TRAVEL TIME-HORIZONTAL DISTANCE CURVE WAS PLOTTED IN THE PREVIOUSLY DESCRIBED MANNER. FOLLOWING THE TECHNIQUE

OUTLINED ABOVE AND USING THE RANGE DATA FROM THE DISTANT SHOTS, INTERCEPTS WERE CALCULATED FOR THE ASSUMED POSITION. THE PLOT OF THESE IS SHOWN IN FIGURE 10. ALL OF THESE LINES FALL WITHIN 16 FEET OF THE ESTIMATED CENTER OF THE FIGURE FORMED WHICH IS THE POSITION TAKEN FOR THE LOCATION OF THE GEOPHONE. THIS SPREAD IS WITHIN THE ESTIMATED SHOT LOCATION ACCURACY.

THEORY OF METHOD 2 (EQUAL TRAVEL TIMES)

IN THIS METHOD THE OUTGOING PINGS FROM THE T-BOATS ECHO SOUNDER WERE RECEIVED BY THE HYDROPHONE, AMPLIFIED ASHORE AND RADIOED BACK TO THE T-BOAT WHERE THEY WERE RECORDED ON THE PRECISION DEPTH RECORDER. THIS PROVIDED AN ACCURATE AND CONTINUOUS RECORD OF THE TRAVEL TIME FROM ECHO SOUNDER TO HYDROPHONE. IN THE VICINITY OF THE HYDROPHONE THE HYPERBOLIC RECORDER TRACE INDICATED THE POINT OF CLOSEST APPROACH. DURING THESE RUNS THE BOAT WAS CONTINUALLY TRACKED WITH THE AZIMUTH INSTRUMENTS ASHORE. FROM THE T-BOAT TRACKS AND THE ECHO SOUNDER DATA THE HYDROPHONE POSITION MAY BE PLOTTED BY ANY OF SEVERAL METHODS. THE BEST OF THESE IS TO PICK ANY TWO CONVENIENT POINTS OF EQUAL TRAVEL TIME AND PLOT THESE ON THE CHART. THE PERPENDICULAR BISECTOR OF THE

Lines of Position from Explosions



- assumed position 6864 yards east, 2624 yards south of Mount Hill
- estimated center of figure
- △ position from "equal travel times" method

Intercept shown is for shot bearing 238° from assumed position

Fig. 10

LINE JOINING THESE TWO POINTS IS A LINE OF POSITION OF THE HYDROPHONE. A SERIES OF THESE LOCATES THE PHONE.

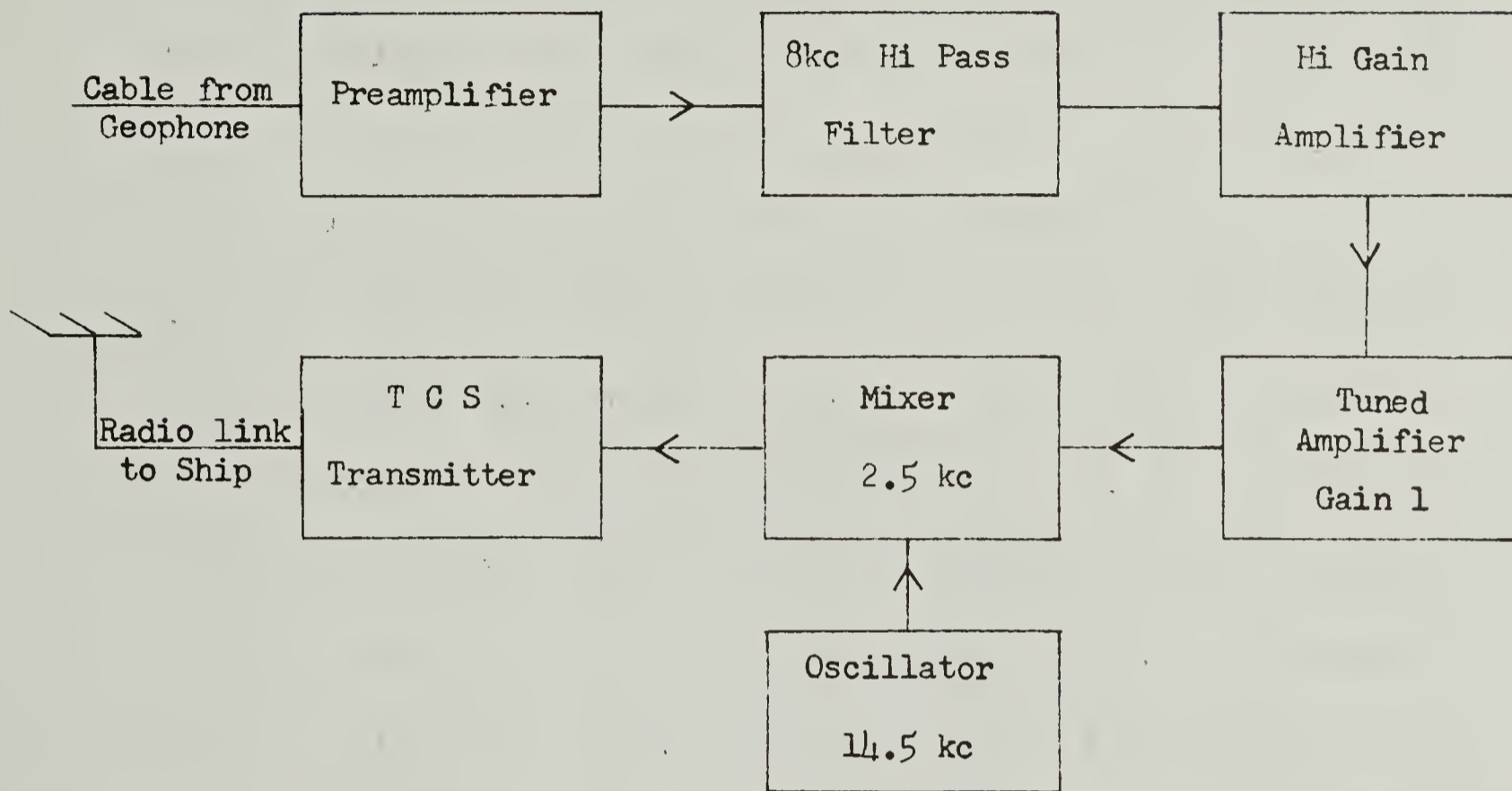
INSTRUMENTATION METHOD 2 (EQUAL TRAVEL TIMES)

THE GEOPHONE, IT'S AMPLIFIERS, AND THE USN/TCS TO USN/TCP RADIO LINK ARE ALL INSENSITIVE TO THE 12 KC OPERATING FREQUENCY OF THE ECHO SOUNDER INSTALLED ON THE T-BOAT. THIS REQUIRED SPECIAL FILTERS AND AMPLIFIERS TO PICK OUT THE LOW AMPLITUDE 12 KC SIGNAL FROM THE NOISE. BEFORE BEING RADIOED TO THE T-BOAT THIS SIGNAL WAS MIXED WITH 14.5 KC'S AND THE 2.5 KC'S DIFFERENCE FREQUENCY USED TO MODULATE THE TCS TRANSMITTER. THIS ARRANGEMENT IS SHOWN IN FIGURE II.

ON BOARD THE T-BOAT THE ECHO SOUNDER OUTGOING PING WAS TRIGGERED BY, AND THE TELEMETERED SIGNALS RECORDED ON A PRECISION DEPTH RECORDER, LUSKIN ET AL (1954). THIS DRUM RECORDER WAS THE ORIGINAL LAMONT GEOLOGICAL OBSERVATORY PRECISION DEPTH RECORDER. IT IS A DRUM WITH A VERY ACCURATE ROTATION RATE ORIGINALLY DEVELOPED FOR FACSIMILE PICTURE TRANSMISSION WORK WHERE IT IS DESIRABLE TO CONSERVE FREQUENCY BANDWIDTH BY NOT REQUIRING A SYNC SIGNAL BETWEEN TRANSMITTER AND RECEIVER. THE DRUM ROTATION IS CONTROLLED BY A TEMPERATURE COMPENSATED TUNING FORK. THE DRUM ROTATED AT 120 RPM. THE

TELEMETERING ARRANGEMENT

SHORE STATION



SHIPBOARD

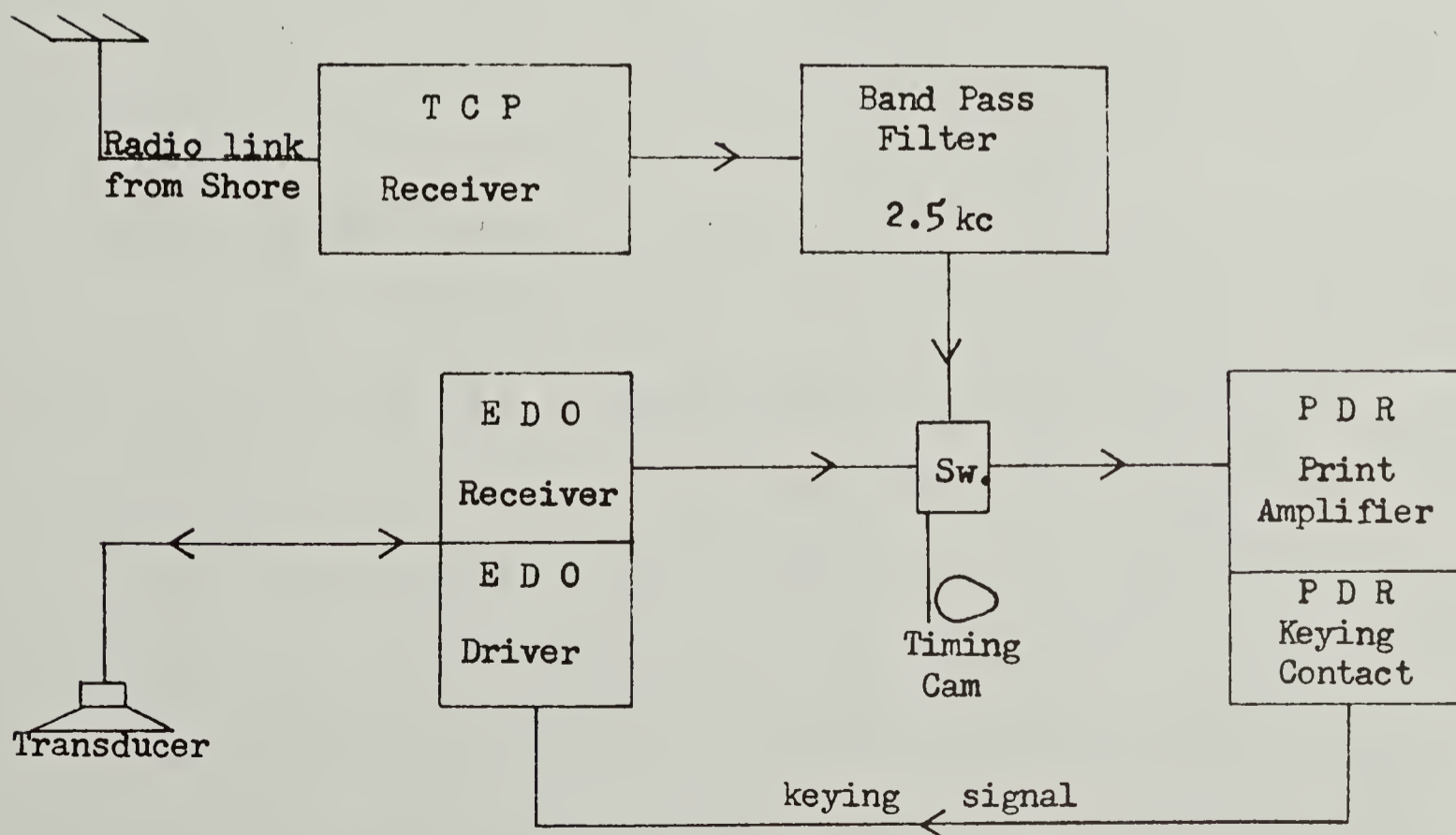


FIGURE II

CIRCUMFERENCE IS 18.75 INCHES MAKING IT POSSIBLE TO MEASURE TRAVEL TIMES TO .001 SECONDS. THE STYLUS WAS TRANSLATED ALONG THE 10" LENGTH OF THE DRUM IN 20 MINUTES BY A SMALL AC MOTOR FROM THE REGULAR SHIPS AC SUPPLY.

AS ORIGINALLY ATTEMPTED BOTH RADIOED GEOPHONE SIGNAL AND THE 12 KC BOTTOM ECHOES WERE RECORDED ON THE RECORDING DRUM. FOR THE GEOPHONE DEPTH THIS PROVED IMPRACTICABLE SINCE THE DIRECT TRAVEL TIME WAS NEARLY ONE DRUM ROTATION WHILE THE BOTTOM ECHO WAS APPROXIMATELY TWO ROTATIONS CAUSING THE TWO SIGNALS TO SUPERIMPOSE AND BECOME DIFFICULT TO READ. ATTEMPTS WERE MADE TO DIFFERENTIATE BETWEEN THESE TWO SIGNALS BY INTERMITTENTLY TURNING ONE OR BOTH OFF AS SHOWN IN FIGURE 12. HERE THE BOTTOM ECHO IS ON ONLY 3/5THS OF THE TIME. EVENTUALLY, HOWEVER, TO GET AN OPTIMUM RECORD IT WAS NECESSARY TO RECORD ONLY THE TELEMETERED SIGNAL FROM THE GEOPHONE. THIS IS SHOWN IN FIGURE 13.

THE DIRECTIVITY OF THE EDO ECHO SOUNDER TRANSDUCER AND THE RESPONSE OF THE VERTICAL GEOPHONE BOTH FAVOR A VERTICAL TRANSMISSION PATH. THUS THE DISTANCE FROM THE GEOPHONE AT WHICH THE ECHO SOUNDER SIGNAL COULD BE RECEIVED WAS LIMITED. SIGNALS COULD BE RECEIVED AT A POSITION ABOUT 34° OFF THE VERTICAL BUT WERE NOT IN FACT

Geophone signal recorded
continuously, bottom can
recorded 3/5 of the time.
T boat speed 4.7 knots

Geophone
Signal
←

Fig. 12

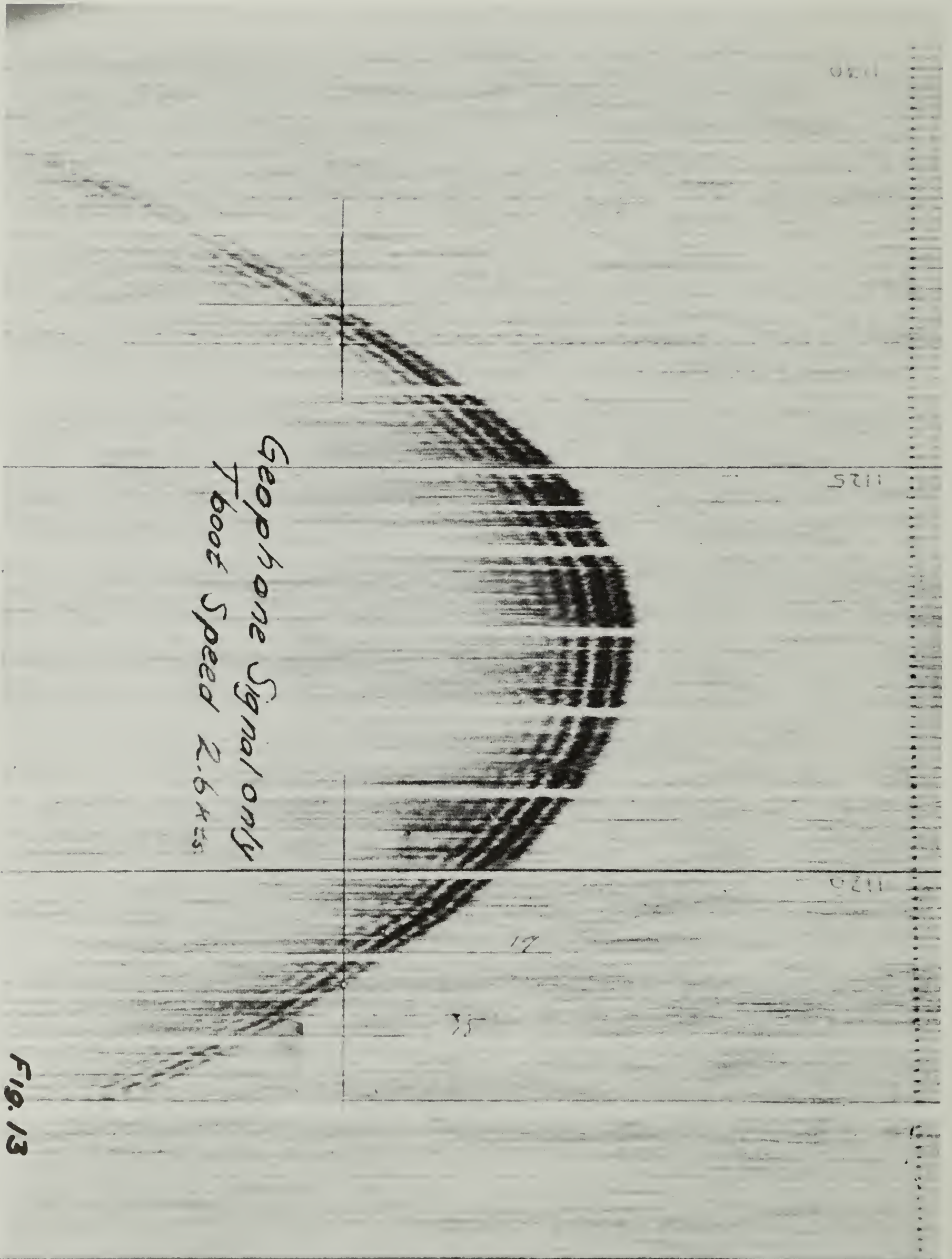


Fig. 13

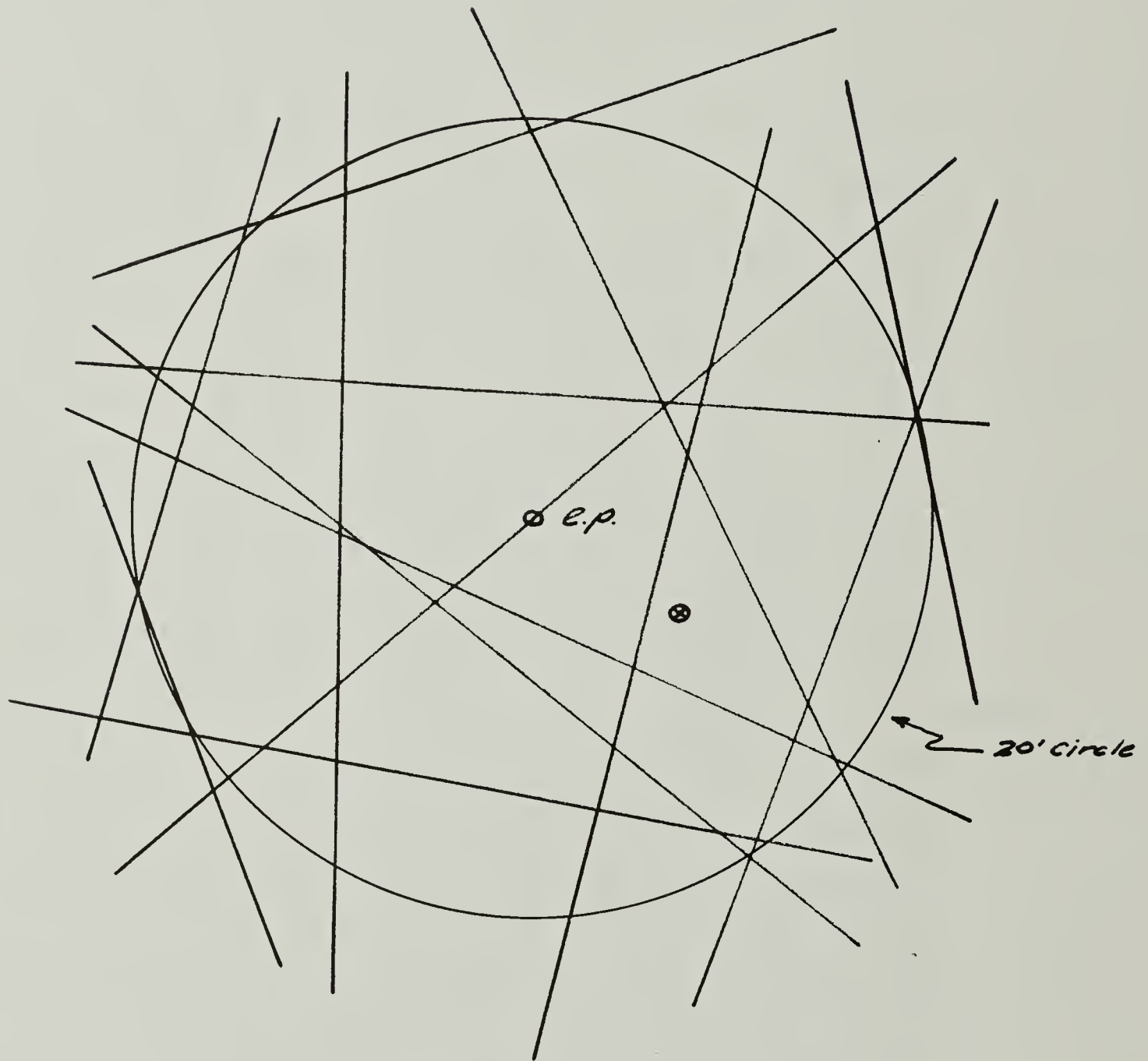
STRONG ENOUGH TO BE USED UNTIL THE BOAT HAD REACHED A POSITION ABOUT 26° FROM THE VERTICAL. THIS GAVE A RELATIVELY SHORT USEFUL DISTANCE FOR DETERMINING COMPARATIVE TRAVEL TIMES. FOR INSTANCE, RUN No.4 ON 30TH. AUGUST (FIGURE I3) WHICH PASSED WITHIN 80 FEET OF THE POSITION DIRECTLY OVER THE PHONE HAD A DISCERNIBLE TRACE FOR ABOUT 1200 YARDS BUT ONLY 900 YARDS WERE USEABLE. THIS MEANT THAT THE BASE OF THE PERPENDICULAR BISECTOR WAS RELATIVELY SHORT, AND THE BISECTOR AZIMUTH HAS RELATIVELY LARGE ERRORS FOR SMALL SHIP POSITIONING ERRORS. IT SHOULD BE NOTED THAT THIS SOURCE OF ERROR COULD BE MINIMIZED IN THE CASE OF AN OMNIDIRECTIONAL RECEIVING HYDROPHONE AND A BROAD REPETITIVE SOUND SOURCE SUCH AS A SPARK OR GAS SOURCE.

WHEN FIGURE I2 WAS MADE, THE T-BOAT WAS MAKING 4.7 KNOTS. IN FIGURE I3 THE BOAT WAS FURTHER SLOWED TO 2.6 KNOTS AND STEADIED ON COURSE, BY HAVING IT DRAG A 26 FOOT PERSONNEL PARACHUTE AS A SEA ANCHOR. THIS RECORD WAS USED TO PLOT THE GEOPHONE POSITION.

POSITION PLOT METHOD 2 (EQUAL TRAVEL TIMES)

THE PLOT OF THE POSITION LINES USING THE ABOVE DATA IS SHOWN IN FIGURE I5. THESE LINES FALL WITHIN A

Lines of Position from Echo Sounder "Pings"



e.p. - estimated center of figure

⊗ - position from explosions method

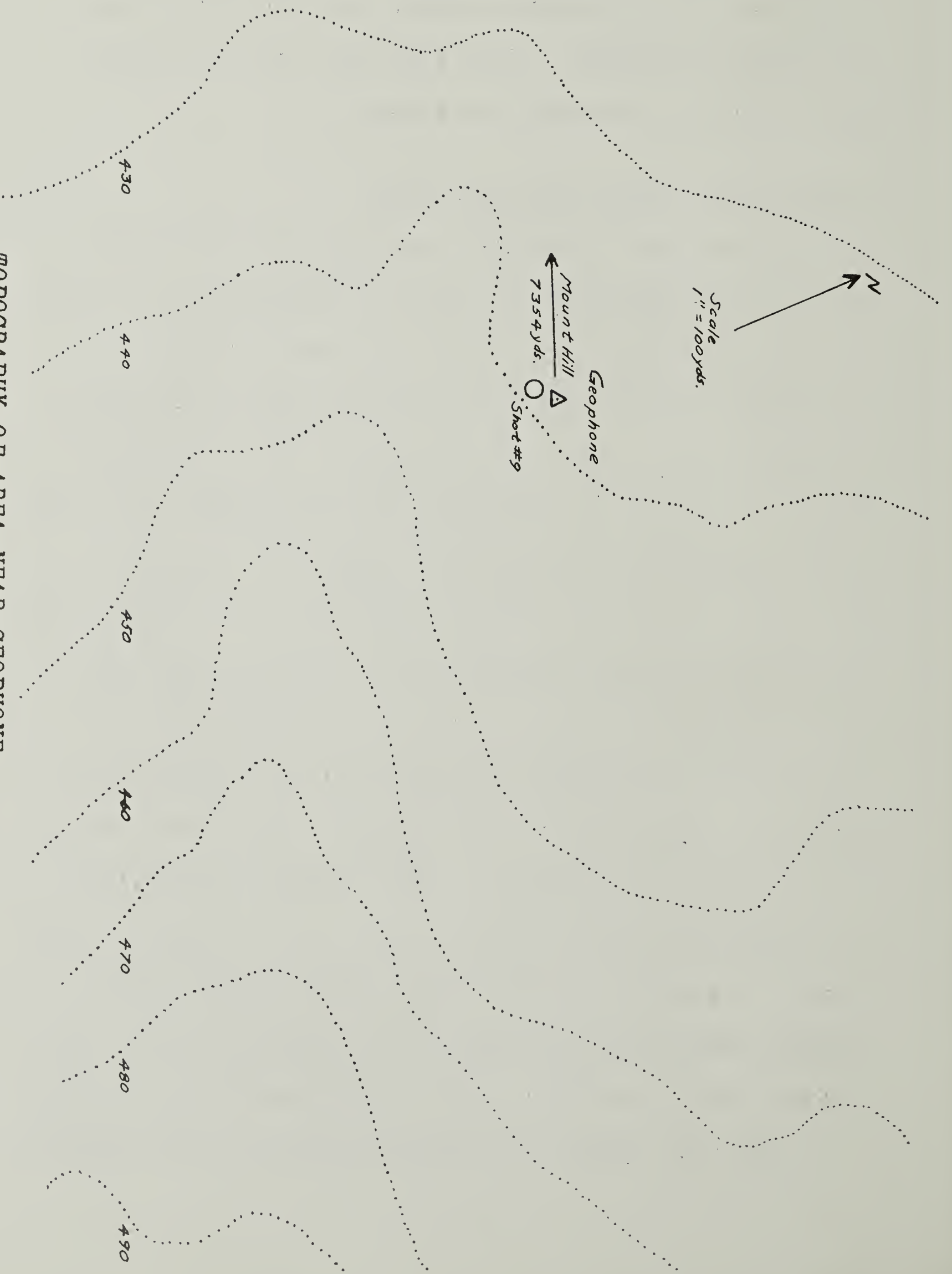
scale 1" = 10'

fig. 15

20 FOOT CIRCLE THE CENTER OF WHICH IS TAKEN AS THE GEOPHONE POSITION AND IS WITHIN THE ESTIMATED SHIP POSITION'S ACCURACY. THIS POSITION IS 9 FEET FROM THE POSITION DETERMINED BY METHOD I.

TOPOGRAPHIC SURVEY GEOPHONE AREA.

A DETAILED TOPOGRAPHIC SURVEY WAS MADE OF THE AREA IN THE IMMEDIATE VICINITY OF THE GEOPHONE. THIS CENTRAL PORTION OF THE SURVEY IS SHOWN IN FIGURE I4. THE GEOPHONE RESTS ON THE NORTHERN SLOPE OF A SMALL RAVINE WHICH IS PART OF A COMPLEX, GULLIED MOUNTAIN-SIDE. THE DEPTHS IN FATHOMS ARE UNCORRECTED FOR SLOPE. DUE TO THE WIDTH OF THE BEAM OF THE ECHO SOUNDER, THE RECORDED "DEPTH" IS ACTUALLY THE DISTANCE BETWEEN THE TRANSDUCER AND THE NEAREST BOTTOM RATHER THAN THE DISTANCE TO THE BOTTOM VERTICALLY BENEATH THE SHIP. THE DEPTHS RECORDED IN THE VICINITY OF THE GEOPHONE AND SHOT #9 ARE ABOUT 439 FATHOMS. IT IS DIFFICULT TO APPLY SLOPE CORRECTIONS TO THIS COMPLEX TOPOGRAPHY, BUT USING THE TRAVEL TIME OF THE BOTTOM REFLECTION OF SHOT #9 HALVED, AND WITH THIS, LUFBURROW'S (1955) METHOD, THE SLANT DISTANCE TO THE NEAREST BOTTOM CALCULATES TO 441 FATHOMS WHICH IS IN GENERAL AGREEMENT. THE TRUE DEPTH, THE DISTANCE FROM THE GEOPHONE TO



TOPOGRAPHY OF AREA NEAR GEOPHONE
SOUNDINGS IN FATHOMS UNCORRECTED

FIGURE 14

THE SURFACE ALONG THE VERTICAL IS 456 FATHOMS AS GIVEN ABOVE.

PRECISION OF METHODS

THE WEAK POINT OF BOTH METHODS LIES IN THE POSITIONING ACCURACY OF THE SOUND SOURCE. IN METHOD 1 IT IS NECESSARY TO GET THE INSTRUMENT TRAINED ON THE EXPLOSION PLUME QUICKLY. THIS COULD BE IMPROVED BY USE OF A PHOTO-THEODOLITE BUT AT AN INCREASED COST AND DIFFICULTY OF INSTRUMENTATION. IN METHOD 2 THERE ARE TWO POSITIONING PROBLEMS. CONTINUOUS TRACKING EVEN BY THE MOST EXPERIENCED CREWS IS INHERENTLY LESS ACCURATE THAN OCCASIONAL FIXES WITH THE OPPORTUNITY FOR BACK SIGHTS AND INSTRUMENT CHECKS AFTER EACH FIX. THE SECOND TROUBLE IN THIS SECOND METHOD IS THAT ONE OF THE TWO POINTS OF EQUAL TRAVEL TIME USUALLY DOES NOT FALL ON A FIX MARK AND ITS POSITION MUST BE INTERPOLATED BETWEEN TWO ADJACENT MARKS. WITH A SMALL LIGHT BOAT, SUCH AS THE 65 FT T-BOAT, WHICH IS NOT EASILY KEPT STEADY ON COURSE, DEVIATION FROM A STRAIGHT LINE BETWEEN FIXES CAN BECOME LARGE EVEN WITH FIXES AT A 15 SECOND INTERVAL. IT WAS TO DECREASE THE DISTANCES BETWEEN FIXES AND STEADY THE BOAT ON COURSE THAT WE SLOWED THE T-BOAT BY ADDING A SEA ANCHOR ASTERN. WITH

A LARGER AND STEADIER SHIP THIS EFFECT WOULD NOT BE NOTICEABLE.

WITH THE ASSUMPTION THAT THERE ARE NO HORIZONTAL DIFFERENCES IN THE VELOCITY-DEPTH STRUCTURE NO ERRORS IN THE HYDROPHONE LOCATION ARE INTRODUCED BY ERRORS IN MEASURING THE SOUND VELOCITY IN METHOD 2, SINCE THIS METHOD USES COMPARATIVE TRAVEL TIMES RATHER THAN ABSOLUTE TRAVEL TIMES. IT IS OF COURSE AN ADVANTAGE NOT TO BE CONCERNED WITH SOUND VELOCITY DATA AT ALL IN THIS METHOD. SOUND VELOCITY ERRORS WHICH DO EFFECT METHOD 1 SHOULD BE SMALL ASSUMING REASONABLE ERRORS IN THE MEASUREMENT OF THE PARAMETERS INVOLVED. THE VARIATIONS IN THE METHODS IN CALCULATION OF SOUND VELOCITY WITH THESE PARAMETERS ALSO LEAD TO VERY SMALL ERRORS, I.E. 5 FT PER SECOND VARIATION IN THE HORIZONTAL VELOCITY. WITH TRAVEL TIMES OF LESS THAN 1.5 SECOND THIS ERROR IS SMALL RELATIVE TO THE SOUND SOURCE POSITIONING ERROR. IN FACT THE INCREASED SOUND SOURCE POSITION ACCURACY OBTAINED IN METHOD 1, WITH THE TECHNIQUES USED IN THIS WORK PROBABLY MORE THAN OFFSET ANY ERRORS INTRODUCED BY THE ASSUMED VELOCITY-DEPTH PROFILE. THE TECHNIQUE OF MEASURING TRAVEL TIMES IN THESE METHODS ARE OF THE SAME ORDER OF ACCURACY AND BOTH ARE ACCURATE TO ABOUT A MILLISECOND WHICH AGAIN IS SMALL RELATIVE TO

THE POSITIONING ERRORS.

CONCLUSION

DUE PRIMARILY TO THE BETTER POSITIONING ACCURACY EXPLOSIVE RANGING IS SLIGHTLY MORE ACCURATE THAN THE EQUAL TRAVEL TIME METHOD OF LOCATING A HYDROPHONE. HOWEVER, EXPLOSIVE RANGING REQUIRES MORE TIME, MORE COMPUTATIONS AND MORE ELABORATE INSTRUMENTATION. EQUAL TRAVEL TIME METHOD IS SIMPLER REQUIRING ONLY A RADIO LINK AND TRACKING EQUIPMENT. THIS METHOD MAY BE MORE EASILY ADAPTED TO SHIPS WITHOUT ELABORATE OSCILLOGRAPH INSTRUMENTATION. IT IS THE PREFERRED METHOD IN AREAS LACKING THE ACOUSTIC VELOCITY-DEPTH PROFILE DATA REQUIRED FOR DETERMINING THE HYDROPHONE DEPTH.

TABLE I

VARIOUS FORMS OF INTEGRATION OF EQUATION (I)

$$\begin{aligned} \int_{\theta_i}^{\theta_{i+1}} \frac{d\theta}{\cos \theta} &= \operatorname{sech}^{-1} \cos \theta \\ &= \operatorname{cosh}^{-1} \sec \theta \\ &= \frac{1}{2} \ln \frac{1 + \sin \theta}{1 - \sin \theta} \\ &= \operatorname{tanh}^{-1} \sin \theta \\ &= \ln \frac{1 + \sin \theta}{\cos \theta} = \ln (\sec \theta + \tan \theta) \\ &= \ln \tan \left(\frac{\pi}{4} + \frac{\theta}{2} \right) \\ &= \sinh^{-1} \tan \theta \\ &= \operatorname{ctnh}^{-1} \csc \theta \\ &= \operatorname{csch}^{-1} \operatorname{ctn} \theta \\ &= 2 \operatorname{tanh}^{-1} \tan \frac{\theta}{2} \\ &= \operatorname{gd}^{-1} \theta \end{aligned}$$

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