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Memorandum of Project MICHIGAN

A TRINAURAL METHOD FOR SOUND RANGING

Volume I

ARTHUR R. HERCZ

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February 1965

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A TRINAURAL METHOD FOR SOUND RANGING.

Volume I,

⑩

ARTHUR R. HERCZ

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PREFACE

Project MICHIGAN is a continuing, long-range research and development program for advancing the Army's combat-surveillance and target-acquisition capabilities. The research and development effort is oriented towards achieving new and improved techniques which will lead to new or greatly improved combat-surveillance and target-acquisition equipment that will meet the long-range operational requirements of the Army in the field. Sponsored by the U. S. Army Electronics Laboratories, of the U. S. Army Electronics Command, of the U. S. Army Materiel Command, this Project is carried out by a full-time Institute of Science and Technology staff of specialists in physics, engineering, mathematics, and related fields, by members of the teaching faculty, by graduate students, and other research groups and laboratories of The University of Michigan.

The Project's emphasis is on the subjects of imaging radar, MTI radar, infrared-optical imaging and signal correlation techniques, image interpretation, and data transmission beyond-line-of-sight. Project MICHIGAN was established at The University of Michigan in 1953 and has received continuing support from the U. S. Army.

The Project constitutes a major portion of the diversified program of research conducted by the Institute of Science and Technology. The function of the Institute of Science and Technology is to make available to government and industry the resources of The University of Michigan and to broaden the educational opportunities of students in the scientific and engineering disciplines.

Documents issued in this series of Technical Memorandums are published by the Institute of Science and Technology in order to disseminate scientific and engineering information as speedily and as widely as possible. The work reported may be incomplete, but it is considered to be useful, interesting, or suggestive enough to warrant this early publication. Any conclusions are tentative, of course. Also included in this series are reports of work in progress which will later be combined with other materials to form a more comprehensive contribution in the field.

Progress and results described in reports are continually reassessed by Project MICHIGAN. Comments and suggestions from readers are invited.

Robert L. Hess
Director
Project MICHIGAN

ACKNOWLEDGMENT

The author gratefully acknowledges the assistance of Vernon L. Larowe of the Analog Computer Laboratory, who designed the computer program used and prepared the charts from which the nomograms presented here were made.

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A TRINAURAL METHOD FOR SOUND RANGING

ABSTRACT

A more direct manual method for evaluating sound-ranging data by using a series of alignment charts is presented. Arguments are two time intervals from three regularly placed microphones. Range and angle are read off directly and used for a polar plot of the source location. Two such plots use all data available from a complete base and provide mutual confirmation. The method is not only quicker and more economical in manpower and equipment than the conventional method, but slightly more accurate.

1

INTRODUCTION

The current method of artillery sound ranging is virtually the same as that developed in World War I. It uses a regular, straight array of microphones to record the times of arrival of a gun sound at accurately surveyed positions. In evaluating the resulting data each adjacent pair of microphones determines a direction. Because of the approximations of the hyperbolic plotting system used, a preliminary plot is necessary to determine curvature corrections; thereafter a final plot is made.

A simpler, quicker, and more efficient plotting system using the same base can be implemented by computing target locations directly from triads of microphones. Each triad gives a range and a direction to the source.

2

CONVENTIONAL SOUND RANGING

When two microphones are placed at accurately known points on the ground so that they both receive the sound from an impulse source, the elapsed time t between the arrivals of the sound at the two microphones determines a horizontal direction θ in relation to the midpoint between them. More accurately, it determines a hyperbola which passes through the sound source and whose foci are the two microphones (see Figure 1).

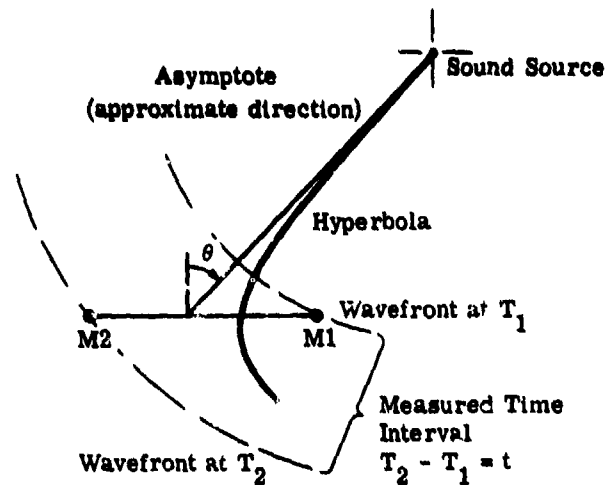


FIGURE 1. DIRECTION FINDING WITH TWO MICROPHONES

When three microphones are used (Figure 2), another pair is added. From this a second hyperbola is determined which also contains the sound source. The intersection of these hyperbolas is the location of the source; hence three microphones are enough to locate a sound source in a horizontal plane.

Corrections for wind and temperature are usually necessary. However, these will not be discussed in detail, since the same corrections are applicable to the conventional and the proposed systems.

In artillery gun location, a base of four to six microphones is normally employed in order to

- avoid erroneous locations
- provide a recognizable pattern on the oscillogram
- increase accuracy
- cover a wider front

A standard sound-ranging base consists of microphones placed accurately on a straight base line at equal intervals (sub-bases) of 1350.4 meters, or 4 sound-seconds (based on a reference

temperature of 50°F). Multiples or sub-multiples of this sub-base are occasionally used. For any sound source, such as an enemy gun, the relative time of arrival T of the sound wavefront at each microphone is recorded [1].

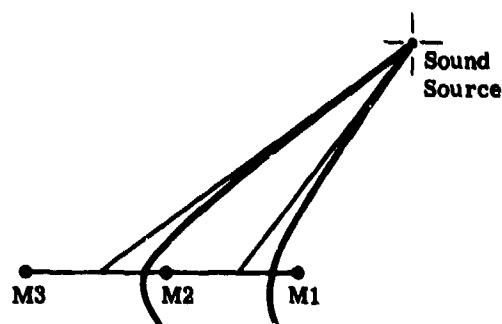


FIGURE 2. POSITION FINDING WITH THREE MICROPHONES—CONVENTIONAL METHOD

The operating procedure for the conventional method of evaluating data is outlined in the left column of Table I. Weather-corrected time intervals are computed for each sub-base. From these a preliminary plot is made by using a special time-angle scale. The plot, called a "cat's cradle," consists of from three to ten intersections of the asymptotes of the time-difference hyperbolas. From the center of the group of intersections the range back to the center of each sub-base is measured. Using this approximate range and its corresponding time difference, another computer applies curvature correction to the previously used time differences. With these corrected time differences a new direction line is plotted for each pair of adjacent microphones, to give the final plot. Since weather conditions and measurement errors usually cause some spread in the group of intersections, the source location is taken to be the average of the individual intersections.

3 TRIAD METHOD

Since, in principle, a sound source can be located by use of three microphones, a more direct plotting method is possible. By using a triad of microphones equally spaced on a straight base line, two independent, measured time intervals can be obtained. From this information the range and direction from the center microphone to the source can be found.

For a complete base of four to six microphones, two such triads can be selected to use all available data. Thus two polar-plotted points are substituted for the two-phase hyperbolic system with its six to ten rays. This should result in a saving of time, men, and equipment, and possibly, as will be shown later, in an increase in accuracy.

The required range and the required angle θ can be found from two measured time intervals t_ℓ and t_s and the equal sub-bases of b meters, or B sound-seconds in length.

In Figure 3 the broken lines represent the wavefront as it passes each microphone. As in the conventional method, the time intervals t are found from the arrival times T at the microphones M , thus:

$$T_2 - T_1 = t_1$$

$$T_3 - T_2 = t_2$$

These are then corrected for weather in the same manner as before. The larger and smaller time intervals will be designated t_ℓ and t_s respectively. If c is the speed of sound, the distance between the first two wavefront positions is ct_s . Similarly, ct_ℓ is the distance from the second position to $M3$. Therefore, the ranges from the source to $M1$ and $M3$ are as shown in Figure 3. Using the cosine law for each triangle gives

$$R_1^2 = (R - ct_s)^2 = R^2 + b^2 - 2Rb \cos (90^\circ - \theta)$$

$$R_2^2 = (R + ct_\ell)^2 = R^2 + b^2 - 2Rb \cos (90^\circ + \theta)$$

These equations can be rewritten:

$$R^2 - 2ct_s R + c^2 t_s^2 = R^2 + b^2 - 2Rb \sin \theta$$

$$R^2 + 2ct_\ell R + c^2 t_\ell^2 = R^2 + b^2 + 2Rb \sin \theta$$

Cancelling R^2 terms, dividing by c^2 , and using the relation $B = b/c$ (where B is the sub-base length in sound-seconds) gives

$$-\frac{2}{c}t_s R + t_s^2 = B^2 - \frac{2}{c}RB \sin \theta$$

$$+\frac{2}{c}t_l R + t_l^2 = B^2 + \frac{2}{c}RB \sin \theta$$

Adding and solving for R gives

$$R = \frac{c}{2} \frac{2B^2 - t_l^2 - t_s^2}{t_l - t_s} \tag{1}$$

Subtracting the last two simultaneous equations and substituting Equation 1 gives

$$\sin \theta = \frac{t_l + t_s}{2B} \left[1 + \frac{(t_l - t_s)^2}{2B^2 - t_l^2 - t_s^2} \right] \tag{2}$$

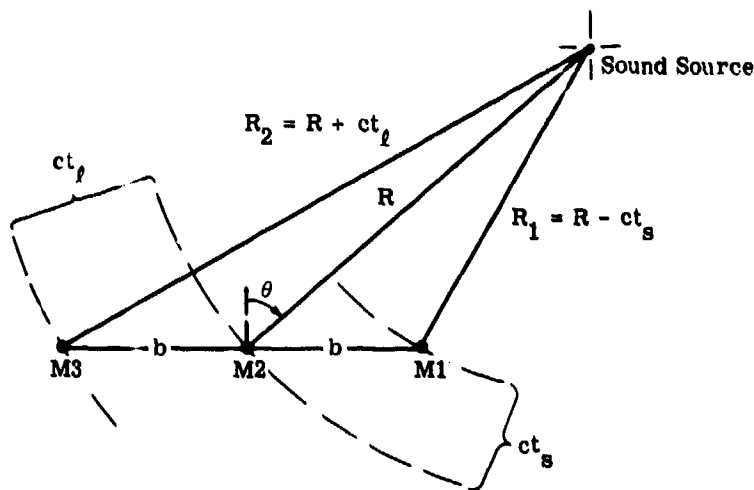


FIGURE 3. POSITION-FINDING WITH THREE MICROPHONES—PROPOSED METHOD

These two equations give the angle and range to the sound source in terms of the sub-base length B , which is a known constant, and the two measured time intervals t_l and t_s . Note that in the right member of Equation 2 the part outside the brackets corresponds to the usual direction equation [1, paragraph 69] if the full span of the triad is taken as a sub-base. This should increase direction accuracy. The fraction within the brackets may be considered equivalent to the correction for curvature. Unlike the hyperbolic system, this system involves no approximation.

These two formulas can provide the basis for a polar-plotting method. However, they are somewhat awkward to solve directly. An electronic computer such as FADAC could be programmed to solve them, but this would be an expensive approach. Attempts to convert these equations directly into nomograms were not successful; therefore an indirect method was used.

By means of an analog computer, each equation was plotted on cartesian coordinates; t_s was used as abscissa, and t_l as ordinate (Figures 4 and 5). In order to achieve the required accuracy of milliseconds for the time arguments and correspondingly closer spacing for the angle and range lines, these plots were expanded. Each numbered square of Figures 4 and 5 was plotted on a 0.75-meter-square sheet to a scale of 1 second = 0.5 meter, and each of these sheets was divided into nine equal square sections.

Within each such limited area all the range and angle lines are essentially straight. Hence they can be transformed directly to nomographic form with the necessary accuracy [2, 3]. Since the entire area of interest is broken down into such small segments, approximately 90 nomograms will be needed. However, some of these would rarely be used under combat conditions. For the sake of economy, only the 33 most frequently used nomograms were produced for use in this report and in field tests; they are presented in the appendix. If the system is adopted, the rest of the set can be produced from the completed analog computations.

Since the range and angle fields are symmetrical about the perpendicular bisector of the base through the center microphone, only half the target area is plotted. By using t_l for larger time interval and t_s for smaller time interval the same charts can be made to apply on either side of the normal reference line. The plot is always made on the side of the smaller time interval. Further, it can be shown that for sub-bases of other lengths the same charts can be used. If in Equation 1 the sub-base and the two time intervals are multiplied by a factor n , the resulting range is multiplied by the same factor; but the angle from Equation 2 is not changed. For example, in changing from a 4- to an 8-second sub-base both time scale and range scale numbers are doubled, but the angle scale is unchanged. Accordingly, the charts have been

drawn up for use with sub-bases of either 4 seconds (numbers left of the scale lines) or 8 seconds (numbers right of the scale lines). When five or more microphones are used on the base, the latter should give greater accuracy.

4

OPERATION OF THE METHOD

4.1. USE OF NOMOGRAMS

To help in selecting the appropriate charts in the appendix (Volume II) quickly, a thumb index is provided. (Trim lines for this are printed on each chart sheet.) The right (upper) number of each tab is the lowest absolute reading of the 8-second time scale. The left (lower) number is the lowest absolute reading of the 4-second time scale. The appropriate tab for t_r , along the right edge, is selected and opened first; then the tab for t_s , along the bottom of the page, is selected and opened. By laying a straightedge through the appropriate readings of the two time scales, the angle and range can be read off directly from the other two scales.

4.2. PLOTTING

A range-deflection protractor is then used to plot the position of the sound source, with the center microphone and a perpendicular to the base used as references. Usually for each base two combinations of three microphones each are selected, to utilize all the available information. Each of these combinations results in a plotted point. Reasonable agreement between the two plots provides a check against inaccuracies and mistakes. If the agreement is acceptable, the midpoint between the two plots is taken to be the location.

5

COMPARISON OF THE METHODS

To provide a basis to discuss the advantages and disadvantages of this system, the chart (Table I) will be used to compare operating procedures of the conventional system with those of the one proposed here. The left column is based on Paragraph 107, FM 6-122, June 1957 [1]. In practice these "assembly line" operations do not take as long as the description of them suggests; however, the method here proposed should simplify them and speed them up.

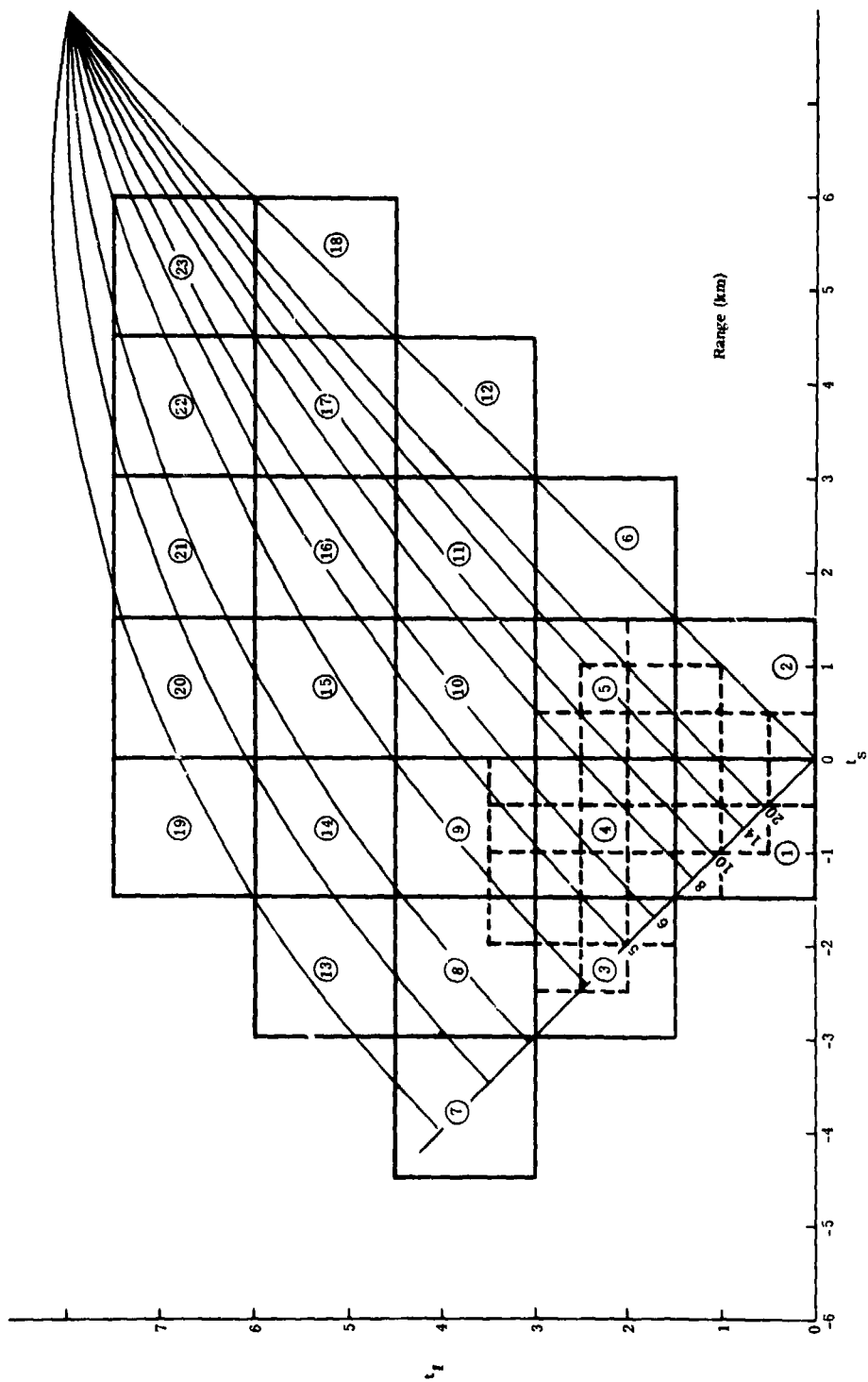


FIGURE 4. CARTESIAN PLOT OF RANGE VS. TIME INTERVALS

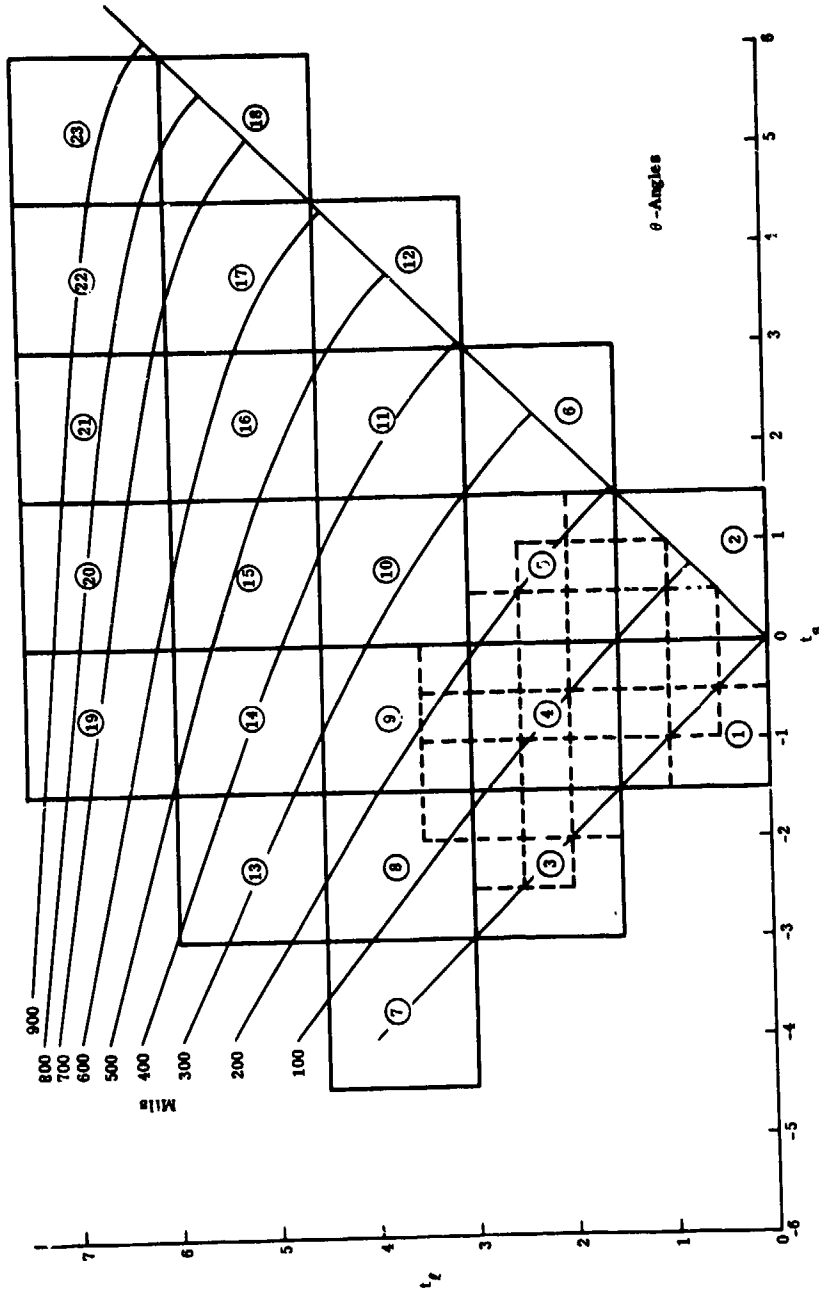


FIGURE 5. CARTESIAN PLOT OF ANGLE VS. TIME INTERVALS

TABLE I. SOUND-RANGING COMMAND POST OPERATIONS

Conventional System	Proposed System
1. Recorder	
a. Records oscillogram	
b. Writes identification and auxiliary data on oscillogram	Same
c. Passes oscillogram to reader	
2. Record reader	
a. Finds pattern of breaks	Same
b. Selects and reads arrival times aloud	
3. Computer No. 1	
a. Records arrival times	Same
b. Computes time intervals for each adjacent pair of microphones (three to five pairs)	Selects two triads. Computes time intervals for each pair (four intervals)
4. Computer No. 2	
a. For each time interval, determines and records temperature correction	
b. Determines and records wind correction	Same
c. Computes weather-corrected time intervals	
5. Plotter No. 1	
a. Plot three to five rays from weather corrected time intervals using special time-angle scale	
b. Estimates center of plot	
c. Measures and records three to five ranges from plot to each mid-point	
6. Computer No. 3	
a. Records ranges	
b. For each time interval (three to five) determines and records curvature correction	For both triads (two) determines and records angle and range
c. Computes corrected time intervals	
7. Plotter No. 2	
a. Makes three to five ray plots from corrected time intervals, using special time scale and overlay	Plots two points directly on map or chart using range-deflection protractor
b. Evaluates polygon of error graphically or by coordinates	Selects mid-point between two plots
c. Reads or computes and records coordinates of location	Reads and records coordinates of location
d. Estimates accuracy	Estimates accuracy

5.1. ADVANTAGES OF THE PROPOSED SYSTEM

(1) The curvature corrections and therefore the preliminary plot (steps 5a, b, c) are eliminated. This saves one man and one set of plotting equipment.

(2) Steps 6a and c are eliminated. For step 6b, in which the standard system requires three to five nomograph readings, the proposed method uses two.

(3) The hyperbolic system produces a rather messy "cat's cradle," which is usually drawn on overlay paper (steps 5a, 5b, and 7a) and which must be laboriously evaluated by a center-of-gravity method (step 7b). In the proposed system two pins are set, as on a firing chart, and an average point between them is selected for a final location. This should save time and cut down mistakes.

(4) Special plotting equipment is replaced by the standard range-deflection protractor.

(5) Fewer pivot points are used, and plotting can be done directly on a tactical map or firing chart rather than on a special gridded plotting board with overlay sheets. This should facilitate evaluation of plot, and set-up time.

(6) The total time of making a location should be reduced.

(7) Because the full width of the triad is used to determine the direction angle, the direction accuracy should be improved. In addition, when double sub-bases are used (five- or six-microphone base), range accuracy should also be improved.

5.2. DISADVANTAGES OF THE PROPOSED SYSTEM

(1) The system is not adaptable to irregular or curved bases.

(2) If a blunder is made in film reading or computing, the form of the plot does not indicate where the mistake may be. This should not be a serious objection.

(3) If one signal should be missing (missing trace) a little practice is necessary in selecting the appropriate triads. In the one special case of a five-microphone base with the third trace missing, the system breaks down. Since that case is rather unusual, and since even with the standard system it provides a poor location at best, this objection should not be serious either.

(4) Some experimenting may be necessary to find the most satisfactory computing form to fit bases of any number of microphones.

6
EXAMPLE

The weather-corrected time differences (first seven lines of Table II) are computed just as for the conventional system, except that alternate rather than successive arrival times are subtracted, so that double sub-bases are used. (Time readings are written from right to left in Table II to conform to the physical positions of the microphones.) For the even and odd sets, respectively, the alignment charts are used to obtain direction and range directly, as follows.

First note that direction is right or left, according to which side the smaller time interval lies on. Next locate the first two digits of the larger time interval on a tab at the right, and turn to that tab. Then, similarly, find the first two digits of the smaller time interval, on a tab at the bottom, and turn to that page (if the signs of the time intervals are alike, use the positive numbers; if they are different, use the negative ones). For the 8-second sub-base, use the upper right index numbers on the tabs. (The lower left ones are for 4-second sub-bases; correspondingly, on the scale lines the right scales are for 8-second sub-bases and the left for 4-second ones.) Lay a straightedge across the two t scales, read off the corresponding angle and range, and enter these in the last two lines of the form in Table II.

TABLE II. COMPUTING FORM
Four-second straight base line.
Metro Message: temperature 75°F; wind azimuth 1080, speed 5 mph.

	$T_6 = 3.709$	$T_5 = 1.959$	$T_4 = 0.757$	$T_3 = 0.338$
Time Readings	$T_4 = 0.757$	$T_3 = 0.338$	$T_2 = 0.790$	$T_1 = 2.138$
	<u>+2.952</u>	<u>+1.621</u>	<u>-0.033</u>	<u>-1.800</u>
Wind Correction	<u>-0.048</u>	<u>-0.048</u>	<u>-0.048</u>	<u>-0.048</u>
	+2.904	+1.573	-0.081	-1.848
Temperature Correction	+0.072	+0.039	-0.002	-0.046
t	<u>+2.976</u>	<u>+1.612</u>	<u>-0.083</u>	<u>-1.894</u>
Pivot		M4	M3	
θ		R200	L20	
Range		6575	5870	

Use a range-deflection protractor to plot each location. Lay off angles so that they pivot on the center microphone (third line from bottom), and measure them from the normal to the base; these points are marked M_3 and M_4 in Figure 6. To make the final location, plot the midpoint between these. In Figure 6 this is shown by the square.

For comparison, Figure 7 shows the conventional kind of plot. Broken lines indicate the preliminary plot and corresponding corrections. Solid rays represent the final cat's cradle, which is evaluated by reading and averaging the coordinates of the ten intersections. Again the final location is indicated by a small square.

This is an unusually large cat's cradle, and correspondingly the two plots in Figure 6 are farther apart than is usual. However, as predicted, the location with the new method is about twice as accurate as that with the conventional one.

REFERENCES

1. Artillery Sound Ranging and Flash Ranging, June 1957, FM 6-122.
2. F. T. Mar's, The Construction of Nomographic Charts, International Textbook Co., 1939.
3. A. S. Levens, Nomography, second edition, New York, Wiley, 1959.

ADDENDUM

Since completion of this report the following additional references were received:

OSRD Report No. 3808
New Analytic Methods of Computing Sound Source Locations
22 April 1944, ATI-62761

OSDR Report No. 3809
Nomographic Method of Computing Sound Source Locations
22 April 1944, ATI-28943

The second of these, in particular, outlines a somewhat similar approach to this same problem. The solution given herein provides simpler computation, and use of the nomograms is faster and should give more accurate locations.

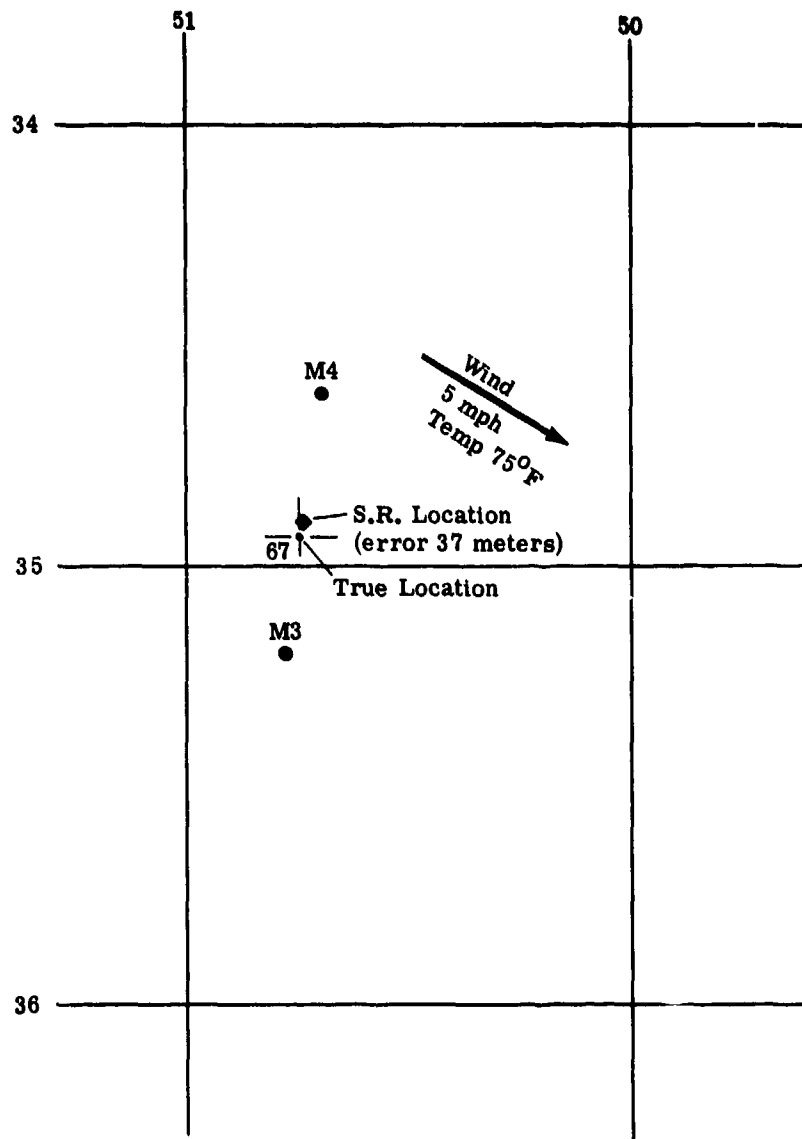


FIGURE 6. TRIAD PLOT FOR DATA IN TABLE II. Six-microphone, four-second straight base line. ● plotted points.

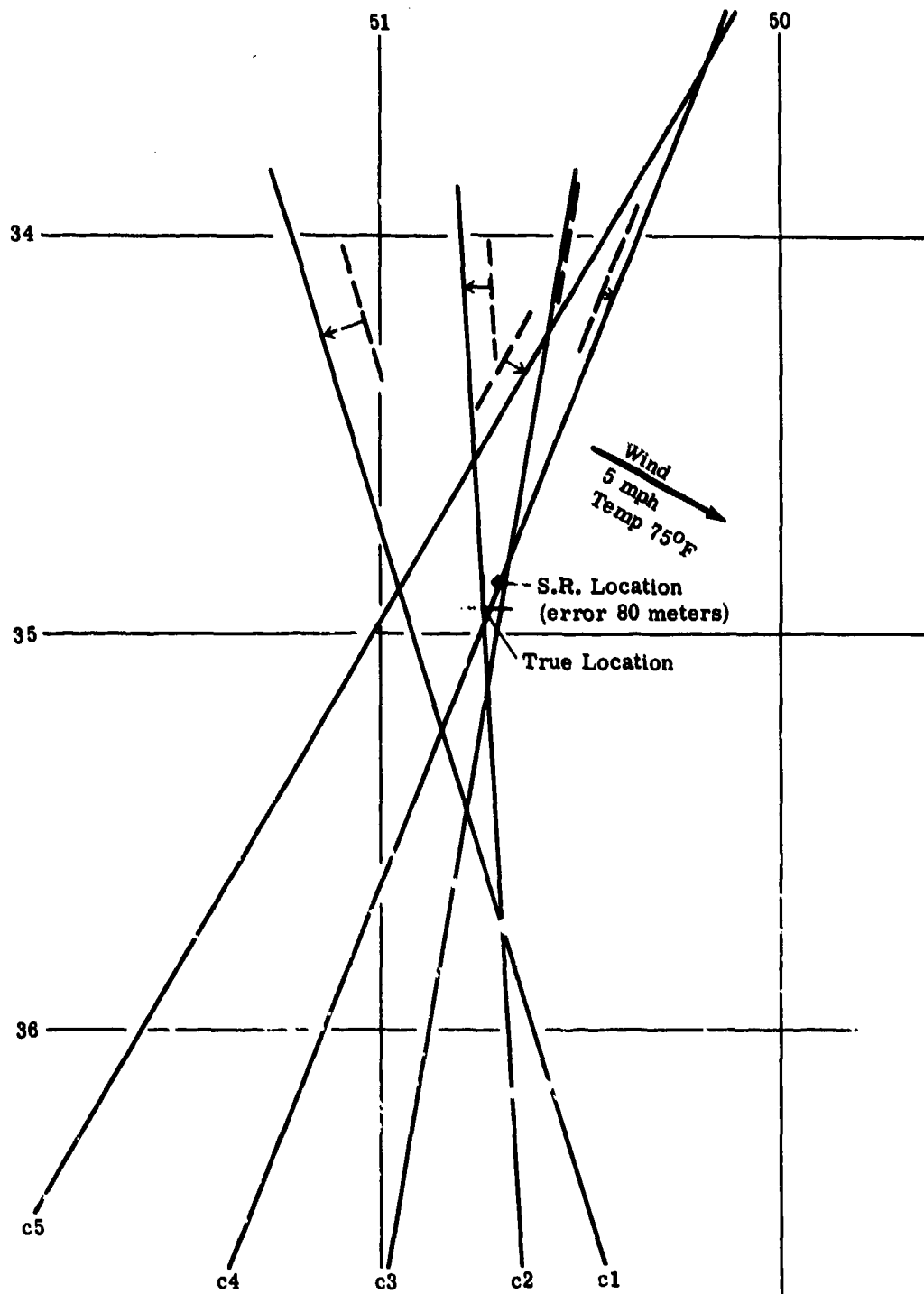


FIGURE 7. CONVENTIONAL PLOT FOR DATA IN TABLE II. Six-microphone, four-second straight base line. — — preliminary plot. — final plot.