Sound-ranging meteorological requirements (preliminary report)

Brahan, J. W.; Humphries, J.

Publisher's version / Version de l'éditeur:
https://doi.org/10.4224/21275424
Report (National Research Council of Canada. Radio and Electrical Engineering Division : ERB), 1967-02-20

ERB-753

CONFIDENTIAL

COPY NO.

NATIONAL RESEARCH COUNCIL OF CANADA

RADIO AND ELECTRICAL ENGINEERING DIVISION

SOUND - RANGING METEOROLOGICAL REQUIREMENTS

(PRELIMINARY REPORT)

PHASE A TRIAL RESULTS

J. W. BRAHAN AND J. HUMPHRIES

OTTAWA

FEBRUARY 20, 1967 NRC # 35683

ABSTRACT

During September and December, 1965, trials were held at Camp Shilo, Manitoba, to study the effects of meteorological conditions on sound transmission paths, to determine the meteorological requirements for sound ranging, and to study methods of applying meteorological corrections to locations made by sound ranging. Results from the Phase A trials (September) indicate that the Goodwin correction method results in a significant improvement in location accuracy over that obtained using the weighted-wind correction technique. The results also indicate that meteorological data is required to a height of 2500 metres for source-to-microphone distances of 40 kilometres.

CONTENTS

PLATES

FIGURES

.....cont'd.

Confidential

SOUND-RANGING METEOROLOGICAL REQUIREMENTS

(Preliminary Report)

Phase A Trial Results

— J.W. Brahan and J. Humphries —

During 1963, extensive trials were held to test the feasibility of the Canadian sound-ranging recorder-computer system. The trials were conducted in two phases. Phase I, carried out during the month of June, involved the location of 28 points at ranges varying from 2000 to 10,000 metres. A seven-microphone base of length 7200 metres was used. Phase II took place during September and locations were made of 19 points at ranges varying between 3000 and 20,000 metres. A seven-microphone base of length 12,000 metres was used. The microphone base layouts are shown in Plate I. During Phase I, the base formed by microphones M1A through M7A was used, while during Phase II, the base formed by microphones M1 through M7 was used.

During the trials, meteorological information was obtained by means of radiosonde balloon ascents every hour, wind information being obtained by radar tracking. Data were recorded at 500-ft (152 metres) intervals to a height of 2500 ft (762 metres) with additional measurements being made at 250 ft (76 metres) and 5000 ft (1424 metres).

In computing the locations, a technique similar to the standard method used by the Canadian Army of applying meteorological corrections was used. This consisted of computing a single weighted wind from the wind values at heights of 0, 500, 1000, 1500, and 2000 feet, and using that along with the temperature at 500 ft (152 metres) to compute the corrections to the measured sound arrival times. For the locations made during Phase I, this method appeared to be reasonably effective. The waveforms recorded were simple, and there appeared to be no multiple sound paths. The average radial location error for 33 series, each series consisting of 12 locations, was 66 metres. The average range was 5484 metres which was 0.762 times the base length. Results for individual series are shown in Table I.

During the Phase II trials, a wider variety of meteorological conditions was encountered, and locations were made at longer ranges than during the Phase I trials. The waveforms recorded in many cases were quite complex, indicating that the sound was arriving at the microphones by more than one path. Under these conditions, location errors were considerably higher than one would have expected considering the Phase I results. The average radial location error for 28 series, each series consisting of 10 locations, was 260 metres. The average range was 9857 metres, which was 0.821 times the base length. Results for individual series are shown in Table II.

The results of the trials demonstrated that, with the accurate measurement of sound arrival times and accurate computation facilities provided by the system, significantly more consistent locations were obtained. The major source of error remaining in locating a sound source by sound-ranging methods was in the measurement of meteorological parameters, and in the application of meteorological corrections to the relative arrival times of the sound wave front at the microphones. The weighted-wind technique of computing the meteorological correction was developed, assuming that the corrections would be computed manually with only rudimentary calculating aids available (e.g., slide rules, graphs). This correction method can handle only a limited range of meteorological conditions and under some conditions, such as those encountered during the Phase II trials, breaks down completely. With the introduction of modern data processing equipment, it becomes feasible to consider much more sophisticated methods of applying corrections making use of more detailed meteorological data.

Under conditions favourable to sound ranging, the sound from a source at a long range from the microphone will, in general, arrive at the microphone by a path which takes it to some height above the surface, the maximum height attained by the sound ray being determined by the sound-velocity gradient (considering both the effects of temperature and wind). Under some meteorological conditions, more than one sound path may exist and a quite complex signal will be received at the microphone. The complexity of the sound paths which can exist is illustrated in Fig. 1, which shows the results of a ray-trace computation for one of the meteorological conditions encountered during the Phase II trials. The existence of multiple sound paths is indicated in the figure, as well as the concentration of sound energy or focussing at distinct points. In performing the ray-trace computation, a linear variation was assumed between the points of measurement of the meteorological parameters.

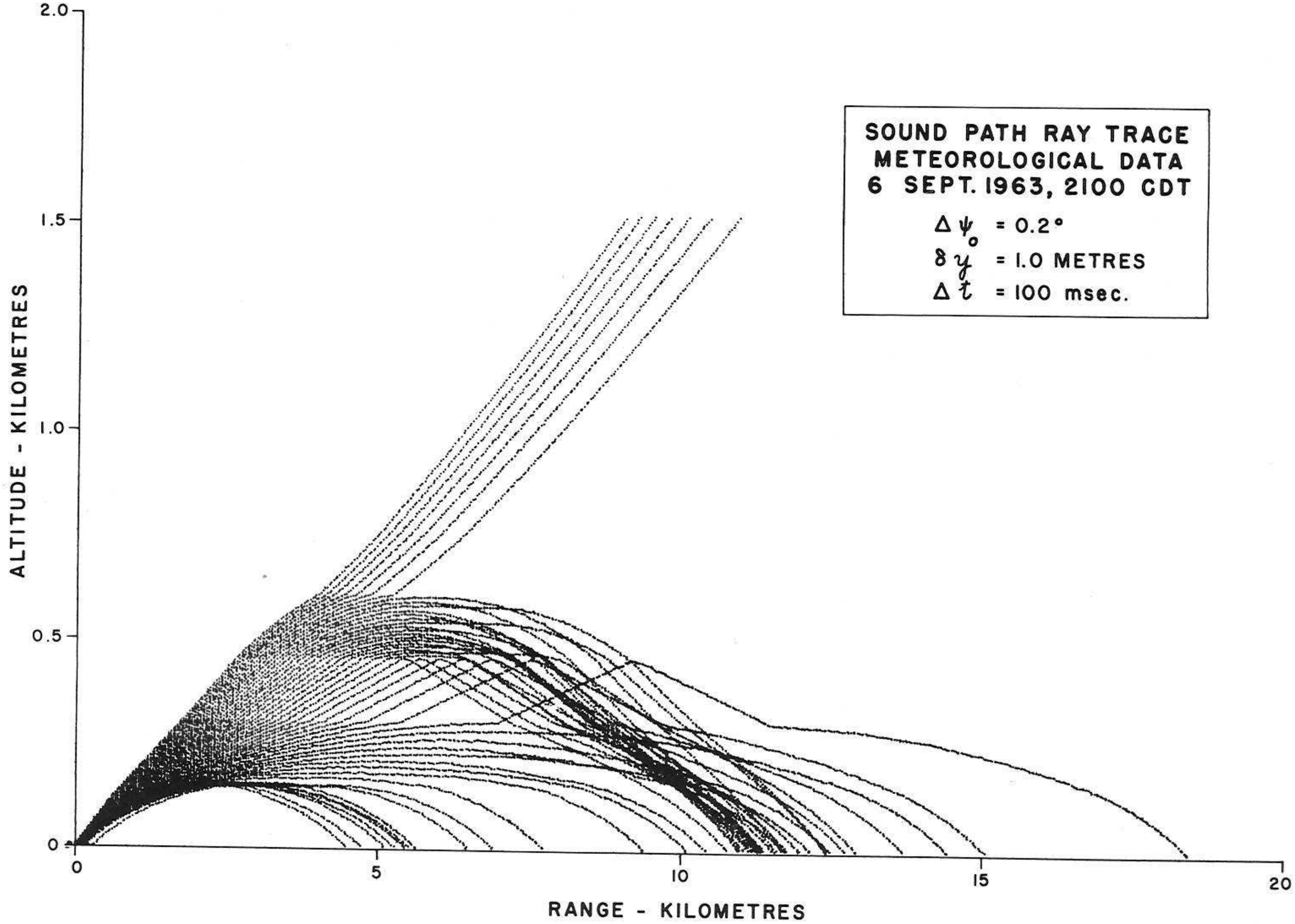


Fig. 1 Sound path ray trace

COMPUTATION OF METEOROLOGICAL CORRECTIONS FOR SOUND RANGING

While the sound travel time between a source and microphone can be determined by tracing the path of the ray for all possible values of the initial angle and then selecting those which give the desired range, the process would be unacceptable because of the time required to perform the computation. A more efficient method is one which was developed by Dr. E.T. Goodwin [1, 2] of the Cambridge Mathematical Laboratory. This method gives the time of flight T of a sound wave from the expression:

$$T = \frac{1}{A} \left\{ R \cos\phi + 2 \int_0^h \left[\left(\frac{A - w(z)}{a(z)} \right)^2 - 1 \right]^{\frac{1}{2}} dz \right\}$$

where h and ϕ are those values for which

$$\frac{\partial T}{\partial h} = \frac{\partial T}{\partial \phi} = 0$$

and h is the maximum height attained by the sound ray, a(z) is the velocity of sound at height z, ϕ is the heading of the sound ray relative to the source-to-microphone line, w(z) is the component of wind velocity along the heading of the sound ray at height z, and $A = a(h) + w(h)$. The assumptions made in arriving at the above expression were that a and w are functions of altitude only, and that there is no vertical component to the wind vector.

INITIAL INVESTIGATION OF THE EFFECTIVENESS OF THE GOODWIN CORRECTION

An initial investigation of the Goodwin correction method was made using the data from the Phase II trials. In performing the computations, a rather simple representation of the meteorological structure was used. It assumed that the wind values and the sound velocity varied linearly between the surface and the maximum height attained by the sound ray. While this approximation was crude, it was not unreasonable considering the limited meteorological information available. A further approximation was made in neglecting the effects of the cross winds. That is, cos ϕ was assumed to be 1. The results for eight series processed using this correction method are shown in Table III, compared with the results obtained using the weighted-wind technique. Each series consisted of ten rounds fired over a period of 3 to 10 minutes and the location errors given in the table are the mean values for each series.

In four of the five series fired during a temperature-inversion condition, the location error was reduced by approximately fifty percent. For the three series fired under clear conditions (normal temperature lapse), improvement in location error was obtained in only one series, the error in the other two being worsened.

While the Goodwin correction resulted in an improvement over the weighted-wind correction, the location errors were still quite high. It was felt that insufficient meteorological data were available to assess properly the effectiveness of the method. Consequently, sound-ranging meteorological trials were planned to gain more detailed information on the effect of meteorological conditions on sound transmission paths, and from this to determine the meteorological-data requirements (including the maximum height to which data is required) and to develop an effective meteorological correction programme for sound ranging.

METEOROLOGICAL TRIALS

The trials were divided into two phases, which will be referred to as Phase A and Phase B to avoid confusion with the 1963 trials. They were carried out at Camp Shilo, Manitoba, during the period September 7 to 25, 1965, and during the period November 23 to December 17, 1965. Thirteen microphone positions were laid out in a T-shaped base as shown in Plate I. Microphone positions M1 to M7 (the south base) were the same as those used during the 1963 Phase II sound-ranging trials. Microphone positions M8 to M13 were equally spaced along a line as close as possible to the right bisector of the south base. The distance from position M1 to position M7 was approximately 12,000 metres, while the distance from position M4 to position M13 was approximately 20,000 metres. All firing took place at position M13. A microphone was buried 3 ft under ground, directly under the muzzle of the gun to record the time of initiation of the sound event.

METEOROLOGICAL CONDITIONS

Five different meteorological conditions were selected and it was planned to fire a series of 25 rounds under each condition. The meteorological conditions selected were:

1. Negative temperature gradient, winds "calm" (wind speed less than 2 metres/second at the surface and less than 10 metres/second at 1600 metres).

2. Negative temperature gradient, "windy" (wind speed greater than 2 metres/second at the surface and greater than 10 metres/second at 1600 metres).

3. Positive temperature gradient, winds calm.

4. Positive temperature gradient, windy.

5. Overcast — solid cloud cover with the cloud base below 1600 metres, winds calm.

It was not possible to obtain the first condition during the Phase A trial period, but firing took place under the other four conditions. The detailed meteorological structures encountered are summarized in Table IV.

A 105 howitzer firing at charge 7 was used for each of the series, and each series was fired with a 90-second interval between rounds. Starting 10 minutes before each series and continuing at 10-minute intervals until 10 minutes after the end of the series, radiosonde soundings were made from position M4. Data were recorded to a maximum height of 3000 metres. Wind data were obtained from the radiosonde flights by tracking with both the GMD radiosonde tracking set and the M33 radar. The GMD equipment recorded the balloon position every 6 seconds while the position was recorded from the M33 radar every 60 seconds. To obtain additional wind data, wind balloons were released every 5 minutes and tracked from a double theodolite base to a maximum height of 1500 metres. Theodolite readings were recorded at 30-second intervals.

In addition to the measurement of upper-air data as described, surface winds, temperature, and humidity were recorded at positions M1, M7, and M13 to obtain some indication of the variation of these parameters over the area of interest. Temperature and humidity were measured at the beginning and end of each series using sling psychrometers. Surface winds were measured at 2-minute intervals during each series using hand held wind-speed and direction indicators.

At position M4, temperature and X, Y, and Z components of wind velocity were measured at heights of 10 metres and 20 metres. Temperature was measured using thermistor elements from a radiosonde package. Wind components were measured using fast response (distance constant 0.74 metre) propeller type anemometers. The information was recorded on magnetic tape in digital form, suitably coded for computer processing. Readings were taken at rates which varied from 30 times per minute to 240 times per minute.

During the Phase B trials, it was originally planned to repeat the tests under the same meteorological conditions chosen for Phase A, but with the ground covered with snow. However, only conditions 2, 3, and 5 were obtained during the trial period. Meteorological measurements were the same as for Phase A, but additional radiosonde flights were made one hour before firing and one hour after firing to the maximum height to which the balloon could be tracked. Also, wind balloons were released from the main camp area, approximately 20,000 metres from the trial site at position 4. These balloons were released 1 hour before firing, at the beginning of firing, and 1 hour after firing and were tracked by an M33 radar located in the camp area (see Plate I). The release times coincided with release times at the trial site so that an indication of variation of upper-air winds with distance could be obtained.

During both Phase A and Phase B, one series was fired to investigate the effect of blast pressure on sound propagation. During the Phase A trials, a series was fired, consisting of ten groups of three rounds each at charges 1, 4, and 7, using a 155 howitzer. The interval between rounds was 90 seconds. During Phase B, a series of ten groups of explosive charges was detonated. Each group consisted of three charges of 1 lb, 5 lb, and 25 lb of plastic explosive. The interval between detonations was 3 to 4 minutes.

PROCESSING OF METEOROLOGICAL DATA

The data from the GMD balloon tracking set are subject to two types of error. Gross errors caused by printer malfunction, and small errors which can result from a variety of causes, such as sharp movements of the balloon due to wind gusts, package swing, noise, etc. To detect the gross errors, the GMD data were plotted and gross errors were immediately obvious as is illustrated in Figs.2 and 3. To reduce the effects of small errors, smoothing techniques were used. Wind speeds were computed from the GMD data using a formula of the type:

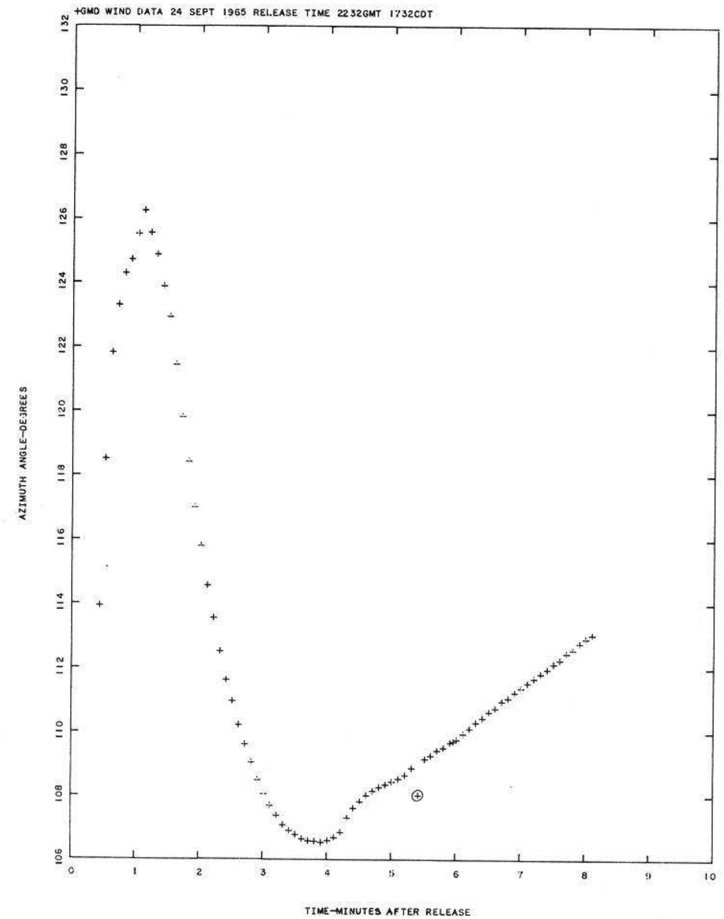


Fig. 2 GMD azimuth angle readings (uncorrected)

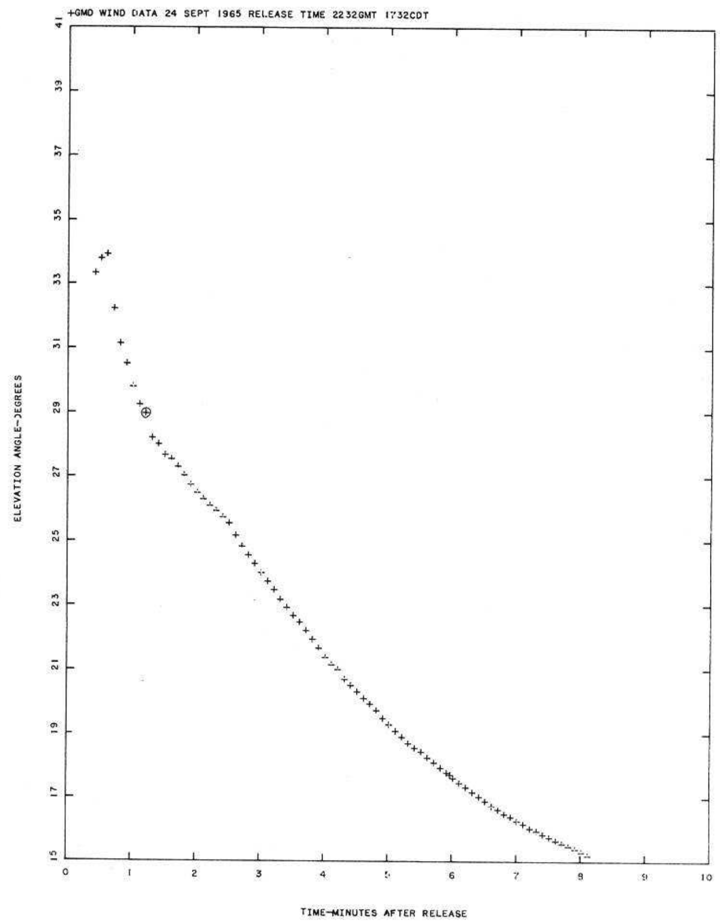


Fig. 3 GMD elevation angle readings (uncorrected)

CONFIDENTIAL

$$W_x = \frac{1}{2}\left(\frac{X_{(I+2)} - X_{(I+4)}}{T_{(I+4)} - T_{(I+2)}} + \frac{X_{(I+1)} - X_{(I+3)}}{T_{(I+3)} - T_{(I+1)}}\right),$$

where W_x is the component of the wind speed in the east-west direction, $X_{(I+J)}$ represents the balloon position relative to the GMD antenna projected on the east-west line, and $T_{(I+J)}$ represents the time of measurement. Readings of balloon position were taken at 6-second intervals; thus, the time period over which individual wind values were obtained was 24 seconds. This corresponds to a layer thickness of approximately 120 metres. The index I was incremented in steps of 2 resulting in wind values being obtained at approximately 60-metre intervals.

Double theodolite wind data to 500 metres were added to the GMD data by interpolating data from each balloon flight so that values were available at 50-metre intervals. The double theodolite wind data were then interpolated in time in order to obtain wind values at times corresponding to the GMD wind data times. The double theodolite wind data thus obtained were added to the GMD wind data to give a better definition of the wind structure in the first few hundred metres above the surface.

Further smoothing of the wind data was obtained by using a least-squares curve-fitting technique. A sixth-order curve fit was applied to the X and Y components of the wind vector. Thus the wind structure is represented by two sixth-order polynomials giving W_x and W_y in terms of height z.

Radiosonde temperature, pressure, and humidity data were used to compute an effective temperature (sonic temperature) using the expression:

$$T_{eff} = T\left(1 + 0.16\,\frac{VP}{P}\right)^2,$$

where T is the temperature in degrees absolute, VP is the water vapour pressure, P is the atmospheric pressure, and T_{eff} is the temperature at which the air can be assumed to have zero humidity with respect to sound velocity.

Sound velocity was then computed from the effective temperature using the expression:

$$V = V_o\left(\frac{T_{eff}}{273.16}\right)^{\frac{1}{2}}$$

where V_0 is the velocity of sound at 0°C and T_{eff} is the effective or sonic temperature in degrees absolute.

Smoothing of the temperature data was obtained, as it was for the wind data, by applying a sixth-order curve fit to the sound-velocity data. Thus the temperature structure is represented by a sixth-order polynomial giving sound velocity in terms of height z.

Time Smoothing of Meteorological Data

Short-term fluctuations in wind velocity will be reflected in the results obtained from individual balloon soundings. Also, variations in instruments will result in slight variations between data from different flights even though the meteorological conditions remain constant. To reduce the effects of these variations on the results, the meteorological corrections were computed, using data obtained by means of a running-average technique. Data from groups of three successive flights were combined, applying weights of 1, 2, and 1, so that $\bar{D}_2 = (D_1 + 2D_2 + D_3)/4$, $\bar{D}_3 = (D_2 + 2D_3 + D_4)/4$, and so on. Thus from six soundings, four data sets would be obtained in this way. The effective time of the data thus computed was arrived at by supplying the same weighting to the release times.

Data Processed to Date

All the data from the Phase A trials have been processed with the exception of the surface data recorded at positions M1, M7, and M13, and the data recorded at position M4 at heights of 10 and 20 metres. Approximately 50% of the data from the Phase B trials have been processed. Data from the Phase A trials only are presented in this report, since the data from the Phase B trials are not sufficiently complete.

COMPARISON OF COMPUTED SOUND TRAVEL TIMES WITH MEASURED VALUES

Sound travel times were computed using the Goodwin method with the meteorological data obtained using the smoothing techniques described above. The times were also computed from the same meteorological data using the weighted-wind technique. Typical results are shown in Figs. 4 - 9. Where more than one path was predicted by the Goodwin method, the path of least time was used. All measurements of sound arrival times at the microphones were made using the first arrival where more than one sound arrival was indicated on the record. Figures 4 - 6 show the measured and computed times for microphones M1, M4, and M7 for the series fired on Sept. 24, 1965.

CONFIDENTIAL

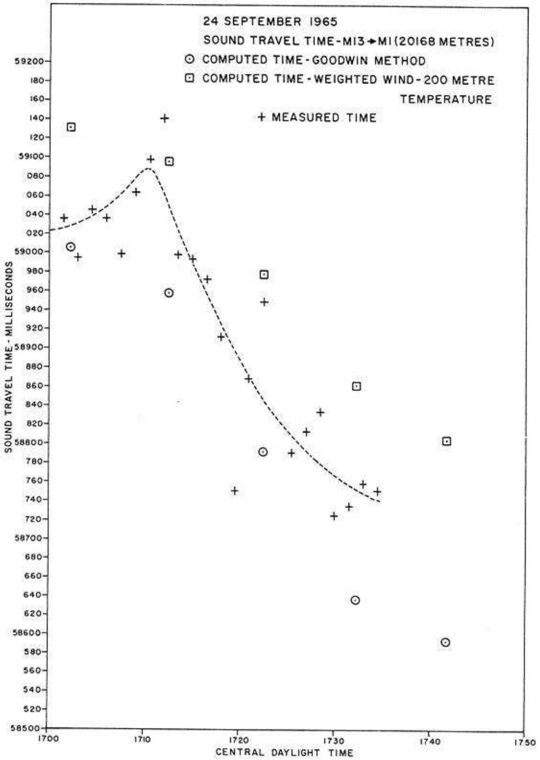


Fig. 4

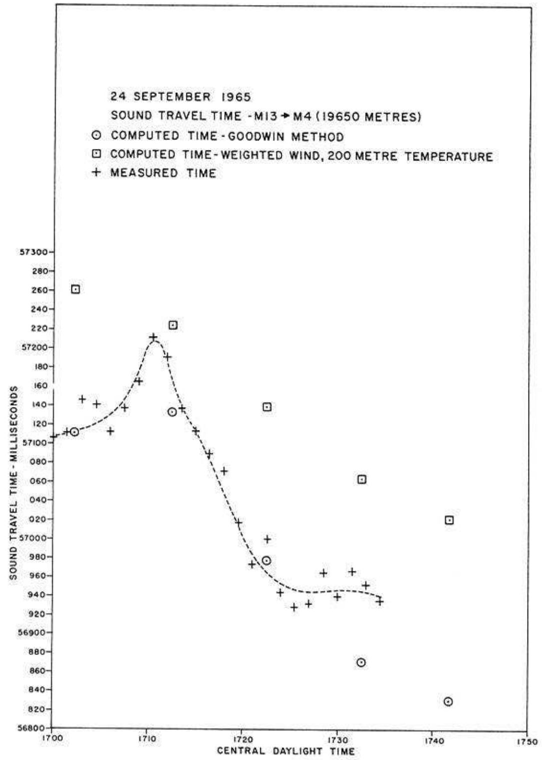


Fig. 5

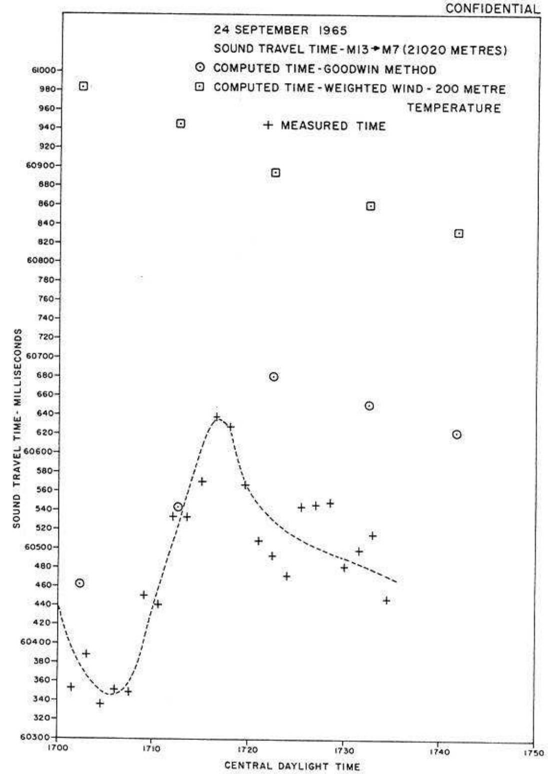


Fig. 6

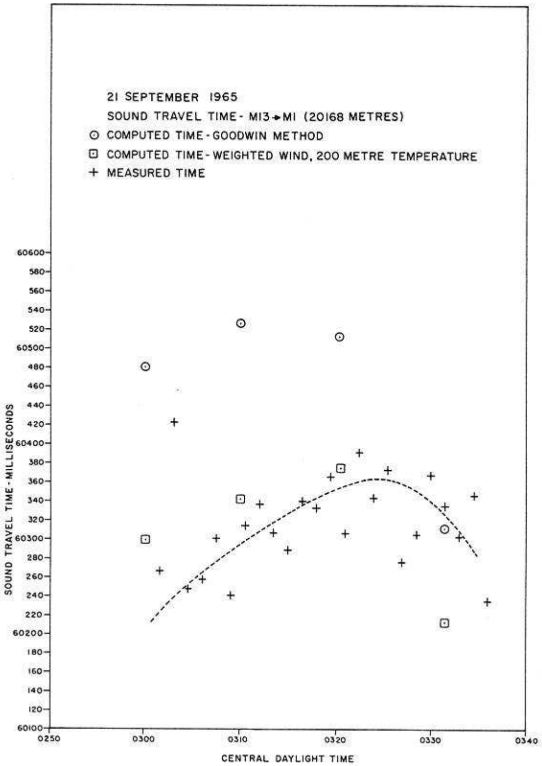


Fig. 7

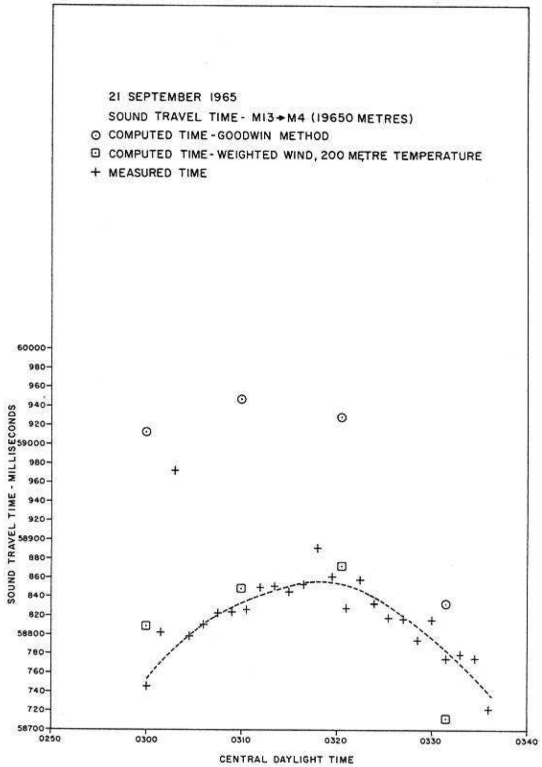


Fig. 8

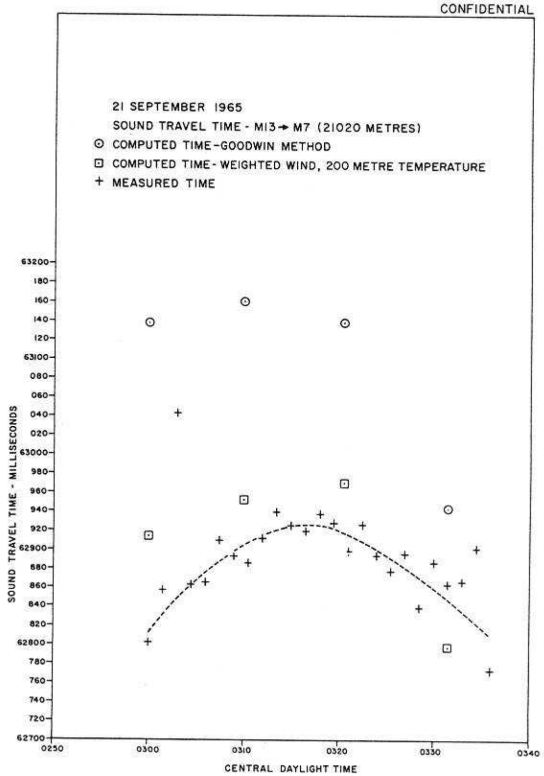


Fig. 9

During this series, marked changes in sound travel times from source to microphones took place. For the paths from the sound source to M1 and to M4 (Figs. 4 and 5), the sound travel time increased slightly from the start of the series to a maximum at approximately 1710 CDT. Then a very sharp decrease in sound travel time took place. For the sound path to M1, if one computes the average sound travel time for shots 7, 8, and 9, a value of 59.101 seconds is obtained, corresponding to an effective shot time of 1710.5 CDT. For shots 22, 23, and 24, the average sound travel time to M1 is 58.748 seconds and the effective shot time is 1733 CDT. Thus, during a period of 22.5 minutes, a change in sound travel time of 0.353 second has occurred. For the sound path to M4, a slightly smaller change (0.254 second) took place over a shorter period of time (15 minutes). Considering these changes in sound travel time, which took place over a relatively short period, the agreement between computed times and measured times is quite good, the Goodwin method resulting in somewhat better agreement than the weighted-wind method. The Goodwin method gives a much better indication of the sudden change in sound travel times, particularly in the case of the path to M4 (Fig. 5).

Considering the sound path to M7 (Fig. 6), one finds that the change in sound travel time during the series is considerably different than for the other two paths. Again, a sudden change occurred, but in this case, the sound travel time increased sharply from a minimum at approximately 1706 CDT to a maximum at approximately 1716 CDT and then decreased. In this case, the agreement between the Goodwin computed sound travel time and measured values is not as good as for the previous two paths considered. However, the Goodwin method does result in a significantly better agreement with the measured values than does the weighted-wind method.

For the paths to all three microphones the Goodwin method results in values which tend to follow the curve of measured sound travel time vs. clock time, while the weighted-wind method results in values which show almost a linear change of sound travel time with clock time. For none of the three paths does the weighted-wind method give an indication of the sudden changes in sound travel time which occurred.

Figures 7-9 show a comparison between computed and measured times to M1, M4, and M7 for the series fired on September 21, 1965. In this case, the Goodwin computed times are significantly longer than measured times. However, the variation of sound travel time with clock time shows good agreement between computed and measured times.

One source of error may be the response time of the temperature-sensing element in the radiosonde package. The ascent rate is approximately 5 metres per second and the time constant of the radiosonde temperature element is 6 seconds. The data processed to date do not include any correction for the response time of the temperature-sensing element. Thus, if steep temperature gradients exist, the temperature data will be in error. The results shown in Figs. 7-9 would tend to confirm this. During the firing of this series, a very steep positive temperature gradient existed (0.034°C per metre to 250 metres). This steep temperature gradient coupled with the low wind-speed gradient which was present would indicate that it was the temperature function which primarily determined the maximum height of the sound path. Since the accuracy of the temperature measurements would be more adversely affected by the response time of the temperature-sensing element during conditions of a large temperature gradient, one would expect larger errors under these conditions if the element response time is significant. If such is the case, a significant improvement in agreement between measured and computed times can be expected for this series when the temperature function is corrected for the response time of the temperature element. The data processed to date do not include any correction for response time. However, methods of correcting the temperature data for the time constant of the sensing element are being investigated.

Meteorological Correction

A comparison of computed and measured sound travel times gives an indication of the accuracy of the computing method and the possible sources of error. However, a comparison of the computed correction with the correction required to the measured values to produce zero location error can be related more directly to the resulting location error. Figures 10-13 show such a comparison for the two series discussed above. Figure 10 shows the comparison between computed and required corrections for an effective shot time of 1703 CDT and an effective meteorological data time of 1702 for the series fired September 24. The curve showing the required correction exhibits two quite distinct sections. The points for microphones M1, M2, and M3 are very close to lying on one straight line while the points for microphones M4 through M7 appear to fall on another straight line. This would indicate that the sound is arriving at the two groups of microphones by means of distinctly separated paths. This conclusion is verified by the Goodwin correction, which indicates that the sound waves arriving at microphones M1, M2, and M3 reach a maximum height of 100, 150, and 150 metres, respectively, while for microphones

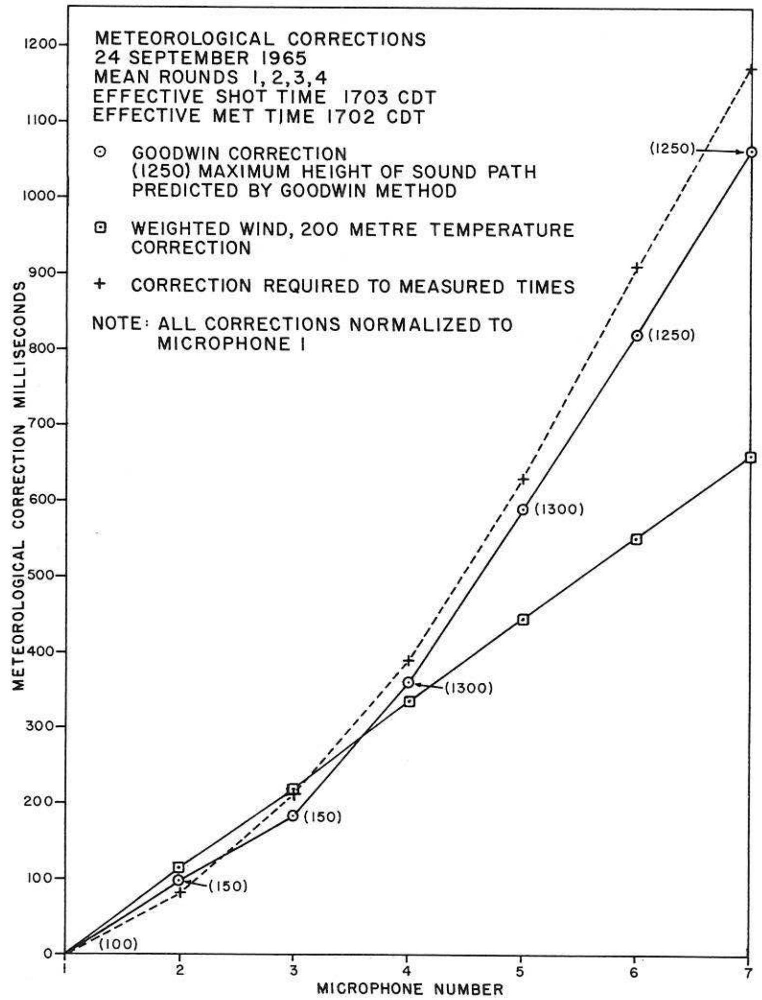


Fig. 10

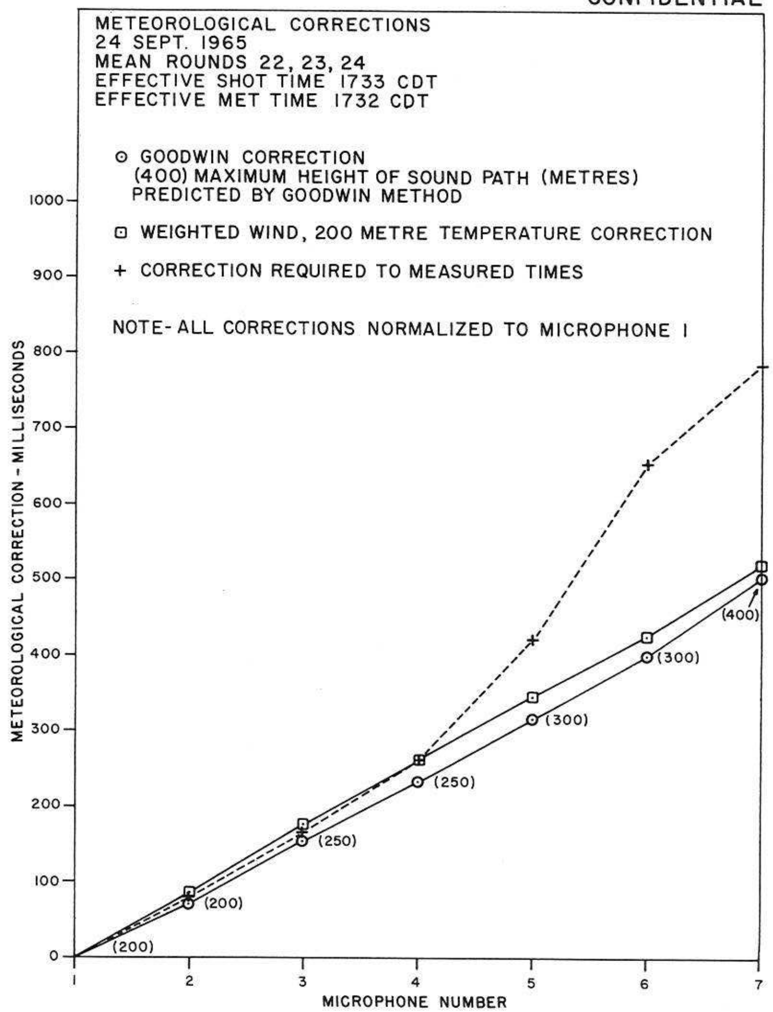


Fig. 11

Comparison of computed and required corrections

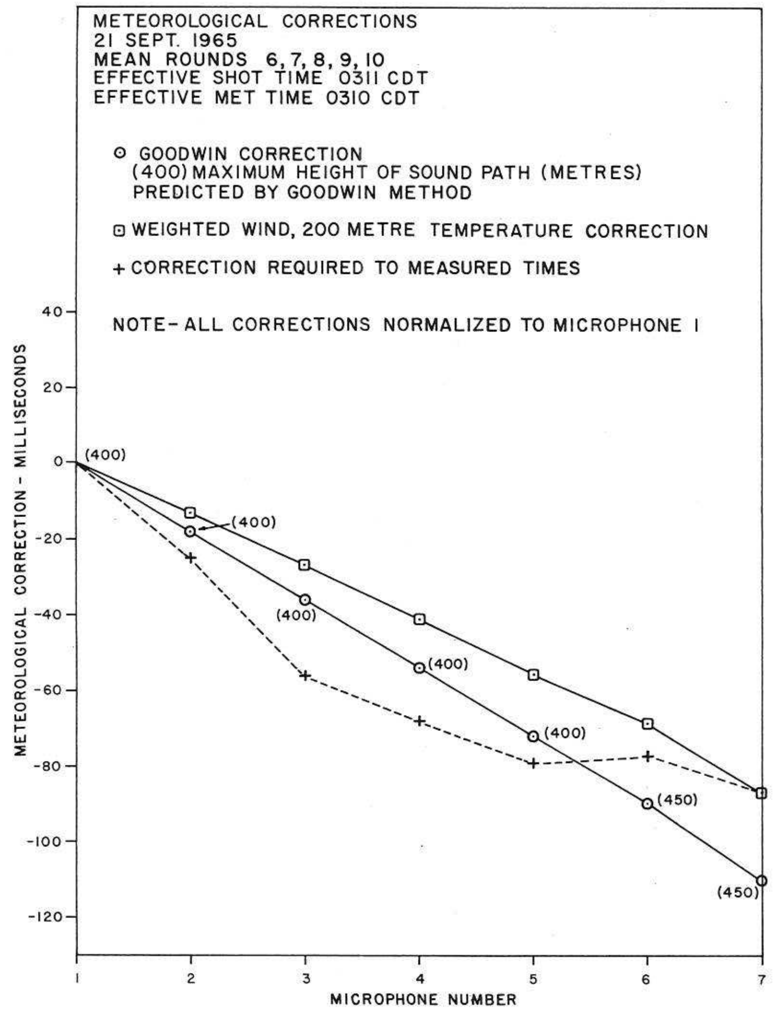


Fig. 12

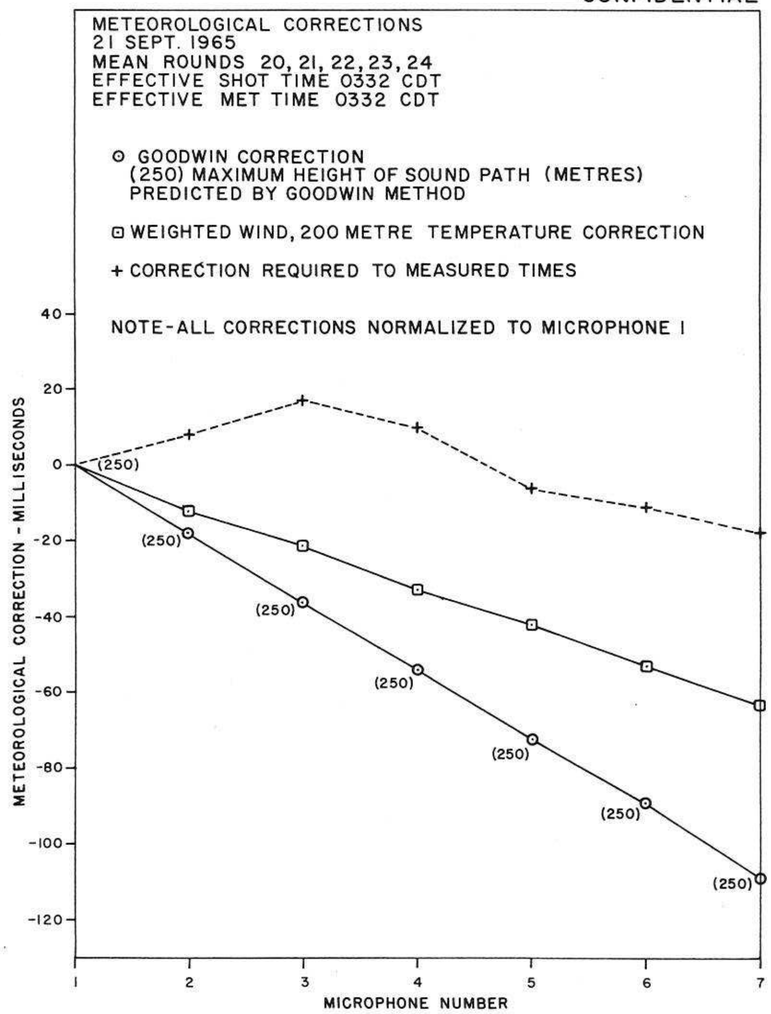


Fig. 13

Comparison of computed and required corrections

M4 through M7 the maximum heights are 1300, 1300, 1250, and 1250 metres. It should be noted that in this case, as in the others shown in Figs. 11-13, the weighted-wind corrections lie on or very close to a straight line and could be termed a "linear" correction. This type of correction could not handle the situation illustrated in Fig. 10.

Results for later rounds in the same series are shown in Fig. 11. In this case, the Goodwin method has not predicted the higher-velocity paths which are indicated by the measured values for microphones M5 through M7. Figures 12 and 13 illustrate the correction comparison for two sets of data from the series fired on September 21. In this case, the Goodwin method predicts maximum heights which are approximately the same for each source-to-microphone path, resulting in a "linear" correction. As noted earlier, a very steep positive temperature gradient existed during the firing of this series, and some improvement is to be expected from the correction of the temperature function for the response time of the temperature-sensing element.

It is to be noted that all corrections shown in Figs. 10-13 have been normalized to microphone M1. As it is the relative values of arrival times, or time differences, which are important, it is the slopes of the curves which should be emphasized in the comparison of computed and measured values, rather than their absolute values.

EFFECT OF METEOROLOGICAL CORRECTION ON LOCATION ERRORS

Locations were made using the measured sound arrival times at the south microphone base and meteorological corrections were computed by the following methods:

1. Goodwin The computations were made using a sixth-order curve fit to 2000 metres. The sound travel times and effective velocities were computed at height intervals of 50 metres and the path of least time was selected.

2. Weighted wind correction The sixth-order curve fit to 2000 metres was used and data were computed from the curves to obtain a single weighted wind. The temperature used was that at 200 metres, which was obtained from the curve fit to the sound velocity.

3. Weighted wind – individual weighting The same method was used as in 2 above, but in this case, the weighting function was based on the wind velocity along the source-to-microphone path so that seven weighted winds were obtained, one for each microphone. Again the temperature at 200 metres, obtained from the curve fit, was used.

4. No meteorological correction In this case, a standard sound velocity of 337.596 metres per second was used, and no correction was applied.

The results obtained for each series are shown in Table V and in Figs. 14-18. In all cases, the arrival time measurements were made on the first detectable portion of the sound signal received at the microphones. Of the six series fired, one was not processed because the signals received at the south microphone base were too weak. This was the series fired on September 25 under meteorological conditions No. 4 (positive temperature gradient, windy). The series fired on September 12 was the first series fired, and it was found that there was insufficient gain in the microphone amplifiers. This, in effect, limited the dynamic range of the system and caused difficulty in determining the exact start of the sound signal. The last three rounds in the series could not be processed because of the very poor signal-to-noise ratio.

Two criteria have been used in comparing the effectiveness of the different meteorological correction methods. These are the over-all average location error, and the number of locations within a specified accuracy. In considering the average location error, the Goodwin method results in an average error which is less than one-third of that obtained using the weighted-wind method. Considering the individual average location errors for each of the five series the Goodwin method results in more accurate locations for all but one series, the one fired on September 21. This was the series which was discussed above, during which a very steep positive temperature gradient existed.

In a comparison of the number of locations within a specified accuracy, two limits have been chosen, 100-metres and 200-metres radial error (approximately 0.5% and 1.0% of range). The total number of locations obtained with less than 100-metres radial error, using the Goodwin method, was more than three times the number obtained using

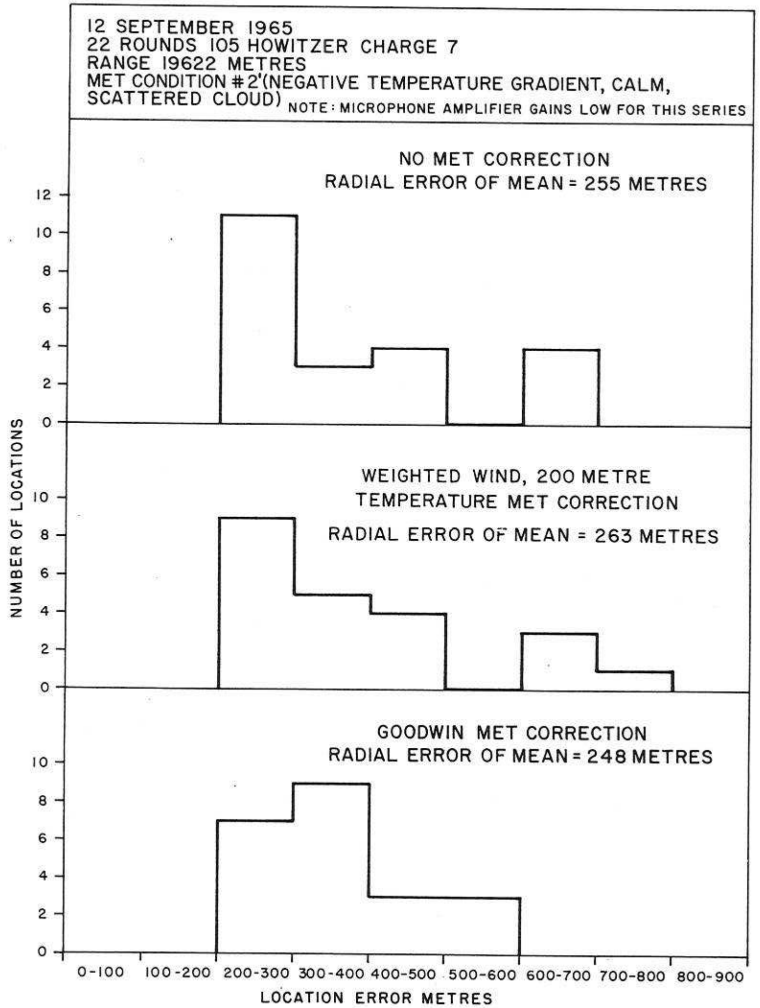

12 SEPTEMBER 1965
22 ROUNDS 105 HOWITZER CHARGE 7
RANGE 19622 METRES
MET CONDITION #2'(NEGATIVE TEMPERATURE GRADIENT, CALM, SCATTERED CLOUD)
NOTE: MICROPHONE AMPLIFIER GAINS LOW FOR THIS SERIES
NO MET CORRECTION
RADIAL ERROR OF MEAN = 255 METRES
WEIGHTED WIND, 200 METRE
TEMPERATURE MET CORRECTION
RADIAL ERROR OF MEAN = 263 METRES
GOODWIN MET CORRECTION
RADIAL ERROR OF MEAN = 248 METRES
NUMBER OF LOCATIONS
0-100 100-200 200-300 300-400 400-500 500-600 600-700 700-800 800-900
LOCATION ERROR METRES

Fig. 14

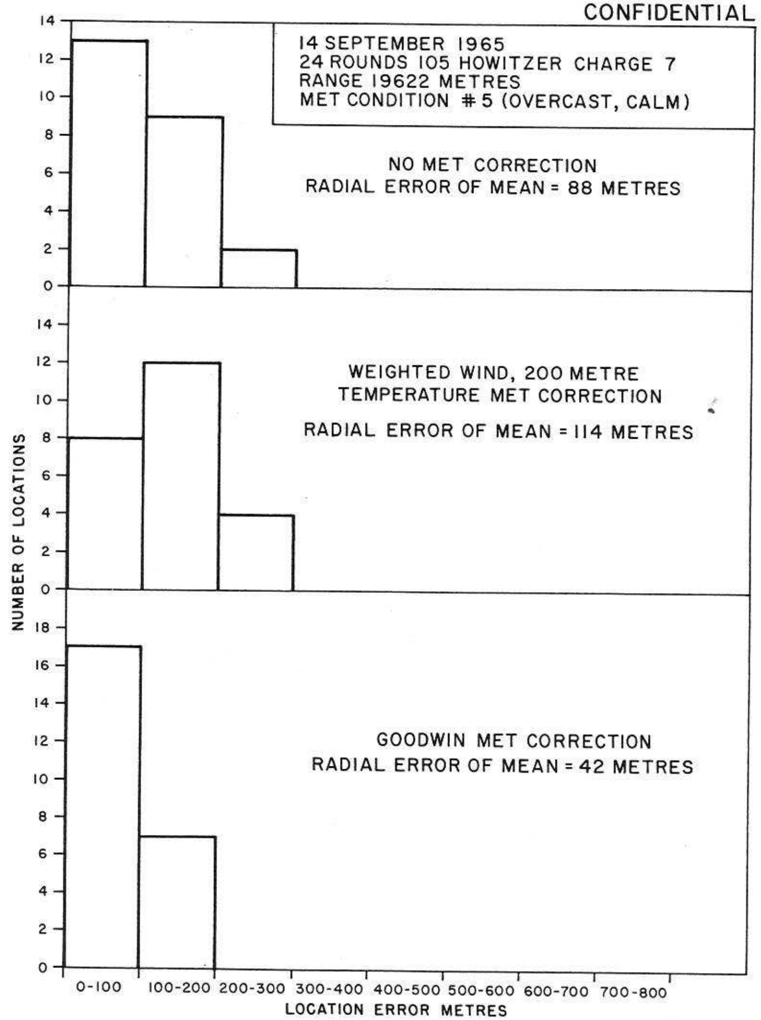

14 SEPTEMBER 1965
24 ROUNDS 105 HOWITZER CHARGE 7
RANGE 19622 METRES
MET CONDITION #5 (OVERCAST, CALM)
NO MET CORRECTION
RADIAL ERROR OF MEAN = 88 METRES
WEIGHTED WIND, 200 METRE
TEMPERATURE MET CORRECTION
RADIAL ERROR OF MEAN = 114 METRES
GOODWIN MET CORRECTION
RADIAL ERROR OF MEAN = 42 METRES
NUMBER OF LOCATIONS
0-100 100-200 200-300 300-400 400-500 500-600 600-700 700-800
LOCATION ERROR METRES

Fig. 15

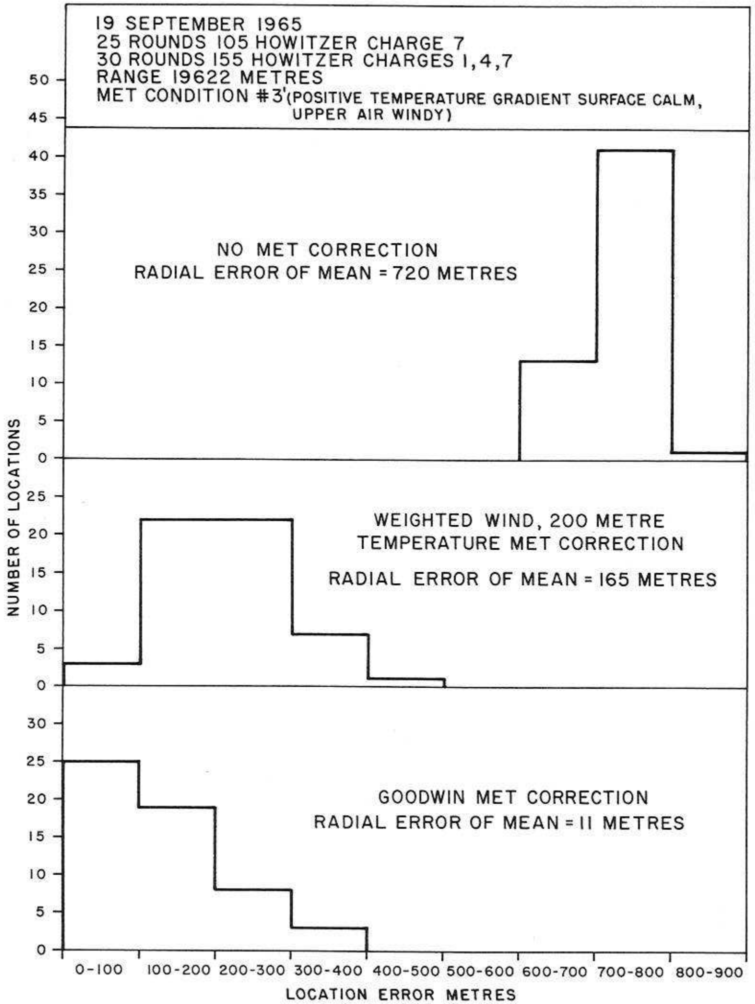

19 SEPTEMBER 1965
25 ROUNDS 105 HOWITZER CHARGE 7
30 ROUNDS 155 HOWITZER CHARGES 1,4,7
RANGE 19622 METRES
MET CONDITION #3 (POSITIVE TEMPERATURE GRADIENT SURFACE CALM, UPPER AIR WINDY)
NO MET CORRECTION
RADIAL ERROR OF MEAN = 720 METRES
WEIGHTED WIND, 200 METRE TEMPERATURE MET CORRECTION
RADIAL ERROR OF MEAN = 165 METRES
GOODWIN MET CORRECTION
RADIAL ERROR OF MEAN = 11 METRES
NUMBER OF LOCATIONS
0-100
100-200
200-300
300-400
400-500
500-600
600-700
700-800
800-900
LOCATION ERROR METRES

Fig. 16

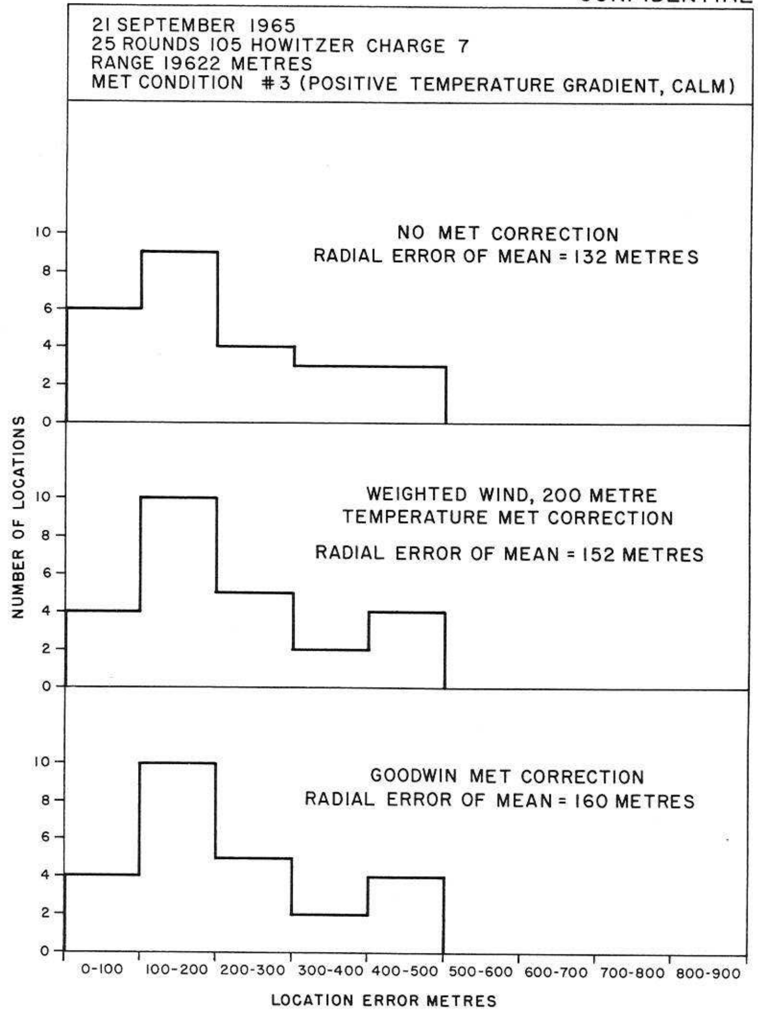

21 SEPTEMBER 1965
25 ROUNDS 105 HOWITZER CHARGE 7
RANGE 19622 METRES
MET CONDITION #3 (POSITIVE TEMPERATURE GRADIENT, CALM)
NO MET CORRECTION
RADIAL ERROR OF MEAN = 132 METRES
WEIGHTED WIND, 200 METRE TEMPERATURE MET CORRECTION
RADIAL ERROR OF MEAN = 152 METRES
GOODWIN MET CORRECTION
RADIAL ERROR OF MEAN = 160 METRES
NUMBER OF LOCATIONS
0-100
100-200
200-300
300-400
400-500
500-600
600-700
700-800
800-900
LOCATION ERROR METRES

Fig. 17

the weighted-wind method. Considering all locations (149), 33% were within 100 metres and 59% within 200 metres using the Goodwin correction, while 10% were within 100 metres, and 40% within 200 metres using the weighted-wind correction technique. If the series fired on September 12 is eliminated from the totals, because of the limited dynamic range of the system at that time as explained above, the total number of locations is reduced to 127. Of these, 39% of the locations were within 100 metres and 69% within 200 metres, using the Goodwin correction, while the corresponding figures for the weighted-wind correction are 12% and 47%.

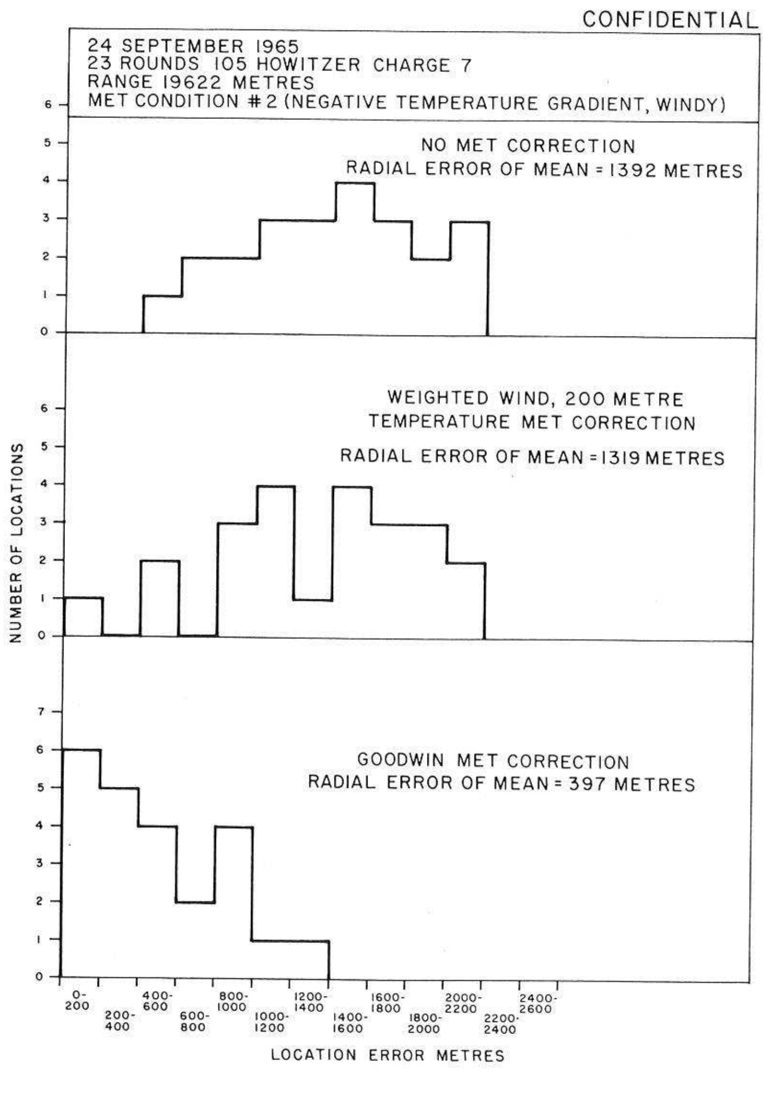


Fig. 18

When the results of individual series are compared, the Goodwin method results in an improvement in all but two series, fired on September 12 and September 21, and the results for these two series were the same using the Goodwin method as they were when using the weighted-wind method, insofar as the number of locations within 100 and 200 metres is concerned.

The results obtained by applying the weighted-wind technique to individual source-to-microphone paths proved to be disappointing. They were in most cases worse than those obtained using no meteorological correction.

CHANGES IN SOUND PATHS

The series fired on September 24 was particularly interesting because of the apparent change in sound paths which took place during firing. Four shots fired during this series are shown in Plate II. The display was set with shot number 1 so that the sweep started at the beginning of the sound signal on each channel. Shots Nos. 12, 15, and 25 were then read onto the display without changing the settings, so that the relative changes in arrival times could be seen. It is interesting to note the change in signal waveform, particularly for microphones 1 and 2. Shot No. 1 shows a strong signal arriving at microphones 1 and 2 a short time after the start of the signal. These signals are barely discernible on shot No. 12, about 16.5 minutes later, and have disappeared completely on shot No. 15, 21 minutes after shot No. 1. Also of interest is the increase in time difference as the series progresses, between microphone 7 and microphone 3, which is the first microphone to receive the signal.

Sound paths for this series were computed, using the Goodwin method, and the predicted values of maximum height of sound travel are shown in Table VI. Where two paths are predicted, the height for the path of least time is indicated by an asterisk. It is interesting to note that initially two paths are predicted for each microphone and, as time progresses, the higher paths gradually disappear until, 40 minutes after the first meteorological data set, no high path is predicted for any microphone.

In a further analysis of this series, velocity values, computed using the Goodwin method, were interpolated to provide sound-velocity information at 1-minute intervals. In all cases, the computed path of least time was used in selecting the velocities. Locations were then made using this interpolated velocity data to determine the "meteorological data time" which gave the minimum location error. It was found that rounds 1 through 11 (1700 - 1716 CDT) had minimum location error using a meteorological data time of 1705 to 1707 CDT. During rounds 12 to 17 (1718 - 1727 CDT) a transition took place indicating that the paths taken by the sound were changing. Rounds 18 to 25 (1728 - 1736 CDT) had minimum location error, using a meteorological data time in the region of 1717 CDT.

When we consider these results, the waveforms shown in Plate II, and the correction curves shown in Figs. 10 and 11, it appears that at least two sound paths existed for each microphone at the beginning of the series and one of these paths (the higher) gradually disappeared, or lowered as the series progressed. It appears from Figs. 10 and 11, that the path of the sound arriving at microphone 4 has definitely changed (and possibly the path of the sound arriving at microphone 5) from a high path to the same low paths taken by the sound arriving at microphones 1, 2, and 3. Microphones 6 and 7 still appear to be receiving the sound by means of a path which is different from the other microphones, but this path has changed by as much as 385 milliseconds (for microphone M7) during the half-hour period 1703 CDT to 1733 CDT. Under conditions such as those encountered in this series, some improvement in location accuracy may be obtained by making use of more than one predicted path and choosing the best path on the basis of the degree of uncertainty in the resulting locations.

MAXIMUM HEIGHT OF METEOROLOGICAL DATA

For the five series examined, the Goodwin correction computations indicated that the maximum heights attained by the sound rays arriving at the microphones did not exceed 500 metres, with the exception of the series fired on September 24. During this series, the computations predicted sound paths as high as 1300 metres for sound rays arriving at the microphones. However, the maximum source-to-microphone distance used in these computations was 21,020 metres. To obtain information on the maximum heights attained by the sound ray in travelling over greater distances, computations were performed for source-to-microphone distances of 30 and 40 km, using meteorological data to a maximum height of 2650 metres. The maximum heights attained by the sound ray for ranges of 30 and 40 km were 1850 metres and 1950 metres, respectively. When computations were performed using meteorological data to 2000 metres, the indicated maximum height of the ray path was 2000 metres. As this was the limit of computation, the results could not be considered valid. It appears that for source-to-microphone distances of 40 km, meteorological information is required to a height of 2500 metres. If the maximum source-to-microphone distances are limited to 20,000 metres, then meteorological data to a maximum height of 1800 to 2000 metres should suffice.

SUMMARY

Based on the data processed to date (only the Phase A data have been considered) it appears that the Goodwin correction method offers a significant improvement in location accuracy over that obtained using the weighted-wind technique. This is particularly true for meteorological conditions that cause sound signals arriving at one part of the base to follow a much higher path than is followed by signals arriving at the other part. When the sound signals received at the microphones are arriving via paths which all have the same or approximately the same maximum height, and are relatively close to the surface, the difference between the Goodwin method and the weighted-wind method is not as pronounced.

For the Goodwin method to be effective it must be capable of determining the path taken by the sound ray in traveling from the sound source to the microphone. In order to do this, an accurate knowledge of the meteorological structure must be available. It appears from the results of the Phase A trials that meteorological data is required to a height of 2500 metres. An estimate of the accuracy of the meteorological data gathered during the Phase A trials has been made on the basis of the standard deviation of temperature and wind velocity measurements at the surface and at 500 metres. This resulted in figures of ±0.7°C for temperature and ±1.4 metres per second for wind velocity. The estimate of temperature accuracy does not include effects of the time constant of the temperature-sensing element in the radiosonde (other than the effects resulting from differences in rate of ascent). Thus the accuracy of temperature measurement is probably somewhat worse than ±0.7°C.

It would be desirable to have a somewhat better accuracy of measurement of temperature (±0.5°C) and wind velocity (±0.5 metres/second), particularly in the region below 1000 metres.

Several questions remain to be answered. The Goodwin method has not predicted all the sound paths indicated by the recordings. This may be due to insufficient accuracy in defining the meteorological structure, either as a result of measurement errors or as a result of the smoothing techniques employed. When smoothing is applied to eliminate small errors, sharp discontinuities in temperature and wind structure tend to be smoothed. It remains to examine the effect of using velocity data from all possible sound paths, with the sound arrival time data, to determine the best location (on the basis of uncertainty of location obtained). Consideration must also be given to the frequency of meteorological soundings required to produce effective meteorological corrections. Related to this last point is the question of the use that can be made of meteorological measurements made at or near the surface at very frequent intervals.

It is hoped that it will be possible to provide information on these questions in the final report which will be written when processing of the Phase B data is completed.

ACKNOWLEDGMENT

The authors are indebted to the officers and men of the Royal Canadian School of Artillery and 1 Locating Battery who provided the facilities and the personnel for the trials. In particular, the authors are indebted to Capt. C.M.H. Pachal who organized the gathering of the meteorological data and to Major T. Boldt who was responsible for the detailed administration of the trials.

References

1. E.T. Goodwin, Long-distance sound-ranging. NATO Document No. AC/117-D/79, 9 August 1963.

2. The calculation of meteor corrections for use in the location of enemy guns by sound ranging methods Part III. External Ballistics Department, Ordnance Board Report EBD No.18, Nov. 1941 (Restricted).

Results of 1963 Phase I Sound-Ranging Trials

Series	Date	Range from base centre (metres)	Bearing relative to normal to base	Temperature gradient	Wind speed at 500 ft (ft/sec)	Radial error of mean of series (12 rounds) (metres)
1B2.5	25 June	2000	-45°	-	17	44
6B2.5	25 June	2000	-30°	-	30	22
22B2.5	26 June	2000	+30°	-	5	30
2B2.5	25 June	3000	-45°	-	17	10
7B2.5	27 June	3000	-30°	-	7	24
23B2.5	26 June	3000	+30°	-	5	14
3B2.5	25 June	4000	-45°	-	8	5
8B2.5	25 June	4000	-30°	-	25	201
15B2.5	19 June	4000	0°	-	27	29
15M4.2	27 June	4000	0°	-	13	91
24B2.5	26 June	4000	+30°	-	5	2
24M4.2	27 June	4000	+30°	-	8	93
4B2.5	25 June	5000	-45°	-	12	22
9B2.5	27 June	5000	-30°	-	5	13
16B2.5	20 June	5000	0°	-	22	19
25B2.5	26 June	5000	+30°	-	5	17
5B2.5	27 June	6000	-45°	-	5	86
5B5.0	25 June	6000	-45°	-	15	219
5B2.5	26 June	6000	-45°	-	10	148

(continued)

TABLE I (concluded)

Results of 1963 Phase I Sound-Ranging Trials

Series	Date	Range from base centre (metres)	Bearing relative to normal to base	Temperature gradient	Wind speed at 500 ft (ft/sec)	Radial error of mean of series (12 rounds) (metres)
10B2.5	27 June	6000	-30°	-	5	11
17B2.5	24 June	6000	0°	-	30	24
17M4.2	27 June	6000	0°	-	15	84
26B2.5	26 June	6000	+30°	-	5	27
11B2.5	27 June	7000	-30°	-	5	102
18B2.5	24 June	7000	0°	-	25	35
27B2.5	26 June	7000	+30°	-	5	72
12B2.5	26 June	8000	-30°	-	12	110
12B2.5	27 June	8000	-30°	-	5	67
19B2.5	24 June	8000	0°	-	25	35
28B2.5	26 June	8000	+30°	-	5	32
28M4.2	27 June	8000	+30°	+	11	30
20B2.5	24 June	9000	0°	-	20	273
21B2.5	24 June	10,000	0°	-	20	194
MEAN		5,484				66

TABLE II

Confidential

Results of 1963 Phase II Sound-Ranging Trials

Series	Date	Range from base centre (metres)	Bearing relative to normal to base	Temperature gradient	Wind speed at 500 ft (ft/sec)	Radial error of mean of series (12 rounds) (metres)
4-90	5 Sept.	13,700	0°	+	31	454
5-90	5 Sept.	16,300	0°	+	31	301
6-90	5 Sept.	18,800	0°	+	23	158
3-90	5 Sept.	11,500	0°	+	23	29
2-105	5 Sept.	9,000	0°	+	23	23
1-105	5 Sept.	5,000	0°	+	11	91
10-90	6 Sept.	11,700	30°	-	18	196
11-90	6 Sept.	15,100	30°	-	20	454
12-90	6 Sept.	20,700	30°	-	20	207
9-105	6 Sept.	9,900	30°	-	14	369
8-105	6 Sept.	6,700	30°	-	14	150
7-105	6 Sept.	4,000	30°	-	18	167
10-90	6 Sept.	11,700	30°	+	18	254
11-90	6 Sept.	15,100	30°	+	10	177
12-90	6 Sept.	20,700	30°	+	10	366
9-105	6 Sept.	9,900	30°	+	10	511
8-105	6 Sept.	6,700	30°	+	10	155
7-105	6 Sept.	4,000	30°	+	12	30
16-90	7 Sept.	7,400	45°	-	27	98

(continued)

TABLE II (concluded)

Confidential

Results of 1963 Phase II Sound-Ranging Trials

Series	Date	Range from base centre (metres)	Bearing relative to normal to base	Temperature gradient	Wind speed at 500 ft (ft/sec)	Radial error of mean of series (12 rounds) (metres)
17-90	7 Sept.	9,000	45°	-	27	62
16-90	7 Sept.	7,400	45°	+	15	448
15-105	7 Sept.	5,900	45°	+	10	630
17-90	7 Sept.	9,000	45°	+	10	650
18-90	7 Sept.	11,800	45°	+	10	796
14-105	7 Sept.	4,500	45°	+	10	46
13-105	7 Sept.	3,000	45°	+	10	80
13-105	9 Sept.	3,000	45°	-	17	162
14-105	9 Sept.	4,500	45°	-	17	212
MEAN		9,857				260

TABLE III

Confidential

Results of Preliminary Investigation of Goodwin Correction Method Using Data from Phase II 1963 Trials

Series	Date	Range from base centre (metres)	Bearing relative to normal to base	Temperature gradient	Wind speed at 500 ft (ft/sec)	Radial error of mean of series (10 rounds) (Metres)	
						Weighted-wind meteorological correction	Approximate Goodwin correction
15-105	7 Sept.	5,900	45°	+	10	630	384
17-90	7 Sept.	9,000	45°	+	10	650	291
18-90	7 Sept.	11,800	45°	+	10	796	314
14-105	7 Sept.	4,500	45°	+	10	46	105
13-105	7 Sept.	3,000	45°	+	10	80	47
10-90	6 Sept.	11,700	30°	-	18	196	365
9-105	6 Sept.	9,900	30°	-	14	369	278
8-105	6 Sept.	6,700	30°	-	14	150	242

TABLE IV

Confidential

Meteorological Conditions for Phase A Sound-Ranging Meteorological Trials 1965

12 September, 1965

GENERAL SYNOPSIS: Sky cover: broken condition; winds calm; pressure slowly increasing; cloud type; SC 5000 ft.

Time CDT	Effective Temperature °C			Wind Speed Metres/Second (Direction)	
	Surface	250 Metres	500 Metres	Surface	500 Metres
2205	9.2	11.0	8.7	0(--)	1.4 (305°)
2226	10.8	10.0	8.0	0(--)	0.5 (249°)
2247	10.5	9.5	8.1	0(--)	2.1 (289°)
2300	10.0	8.7	7.0	2.1(10°)	3.6 (327°)
2312	10.4	9.4	7.4	3.6(25°)	2.3 (19°)

Average Temperature Gradient	0-250 metres	-0.00184°C/metre
Average Temperature Gradient	0-500 metres	-0.0046°C/metre
Average Wind Speed Gradient	0-500 metres	+0.00168 metres/sec/metre

(continued)

TABLE IV

Confidential

Meteorological Conditions for Phase A Sound-Ranging Meteorological Trials 1965

14 September 1965

GENERAL SYNOPSIS: Sky cover: Overcast with a ceiling approximately 1400 ft; winds calm; pressure decreasing; cloud type: ST 10/10. Very light rain.

Time CDT	Effective Temperature °C			Wind Speed Metres/Second (Direction)	
	Surface	250 Metres	500 Metres	Surface	500 Metres
1520	9.6	6.5	4.4	1.0 (10°)	7.0 (35°)
1531	9.8	5.8	3.9	2.1 (10°)	5.6 (27°)
1543	9.8	6.3	4.4	2.6 (0°)	6.7 (21°)
1555	9.9	6.1	4.0	0 (--)	3.6 (13°)
1606	9.9	7.1	4.6	1.5 (0°)	6.3 (23°)
1617	9.9	7.2	5.4	2.1 (20°)	6.4 (38°)

Average Temperature Gradient 0-250 metres -0.0132 °C/metre

Average Temperature Gradient 0-500 metres -0.0112 °C/metre

Average Wind Speed Gradient 0-500 metres +0.0088 metres/sec/metre

(continued)

Meteorological Conditions for Phase A Sound-Ranging Meteorological Trials 1965

19 September 1965

GENERAL SYNOPSIS: Skies clear; wind very light at surface; pressure rising then steady.

Time CDT	Effective Temperature °C			Wind Speed Metres/Second(Direction)	
	Surface	250 Metres	500 Metres	Surface	500 Metres
2350	2.2	6.9	4.4	1.0 (251°)	16.2 (273°)
0001	2.2	6.2	4.2	1.0 (241°)	15.3 (273°)
0012	1.3	6.5	4.7	1.0 (234°)	16.0 (271°)
0023	1.1	3.9	2.0	1.0 (236°)	16.6 (275°)
0032	1.1	9.9	6.3	1.0 (233°)	14.6 (275°)
0043	2.1	5.2	1.8	1.3 (226°)	16.9 (276°)
0052	1.8	6.4	4.1	1.0 (224°)	15.4 (275°)
0103	2.0	6.8	4.4	1.0 (222°)	15.2 (274°)
0113	2.2	6.9	4.8	1.3 (224°)	15.3 (274°)
0123	2.2	6.4	4.4	1.0 (227°)	14.5 (279°)
0134	1.6	5.6	4.0	0.8 (232°)	12.6 (279°)
0144	1.7	8.1	4.7	1.0 (225°)	13.4 (278°)
0152	2.2	6.8	5.1	0.8 (224°)	13.0 (280°)
0203	1.2	5.3	4.2	1.0 (231°)	13.2 (276°)

Average Temperature Gradient 0-250 metres +0.0188°C/metre

Average Temperature Gradient 0-500 metres +0.0049°C/metre

Average Wind Speed Gradient 0-500 metres +0.027 metres/sec/metre

(continued)

TABLE IV

Confidential

Meteorological Conditions for Phase A Sound-Ranging Meteorological Trials 1965

21 September 1965

GENERAL SYNOPSIS: Skies clear; winds calm; pressure falling slowly

Time CDT	Effective Temperature °C			Wind Speed Metres/Second (Direction)	
	Surface	250 Metres	500 Metres	Surface	500 Metres
0250	0.8	7.8	5.4	0 (--)	2.0 (136°)
0300	0.8	10.0	8.1	0.3 (119°)	3.3 (143°)
0310	0.9	10.9	8.8	0 (--)	3.1 (140°)
0320	1.2	6.2	8.0	0 (--)	3.2 (145°)
0332	1.2	11.2	8.8	0 (--)	3.0 (147°)
0342	1.0	11.0	9.2	1.0 (138°)	2.8 (152°)

Average Temperature Gradient	0-250 metres	+0.034°C/metre
Average Temperature Gradient	0-500 metres	+0.0142°C/metre
Average Wind Speed Gradient	0-500 metres	+0.0054 metres/sec/metre

(continued)

Meteorological Conditions for Phase A Sound-Ranging Meteorological Trials 1965

24 September 1965

GENERAL SYNOPSIS: Skies scattered condition; ceiling 9000 ft lowering to 4000 ft; visibility good; light rain towards end of period; winds 12 knots; pressure falling slowly; clouds SC and AC.

Time CDT	Effective Temperature °C			Wind Speed Metres/Second (Direction)	
	Surface	250 Metres	500 Metres	Surface	500 Metres
1651	11.6	8.8	6.6	3.7 (303°)	13.7 (276°)
1703	11.7	9.2	7.8	3.3 (290°)	12.8 (273°)
1712	11.5	9.2	7.8	5.6 (289°)	13.3 (273°)
1723	11.3	9.0	7.6	3.8 (298°)	12.7 (279°)
1732	11.2	9.2	7.0	4.9 (302°)	13.2 (286°)
1742	10.9	8.5	6.6	3.2 (305°)	13.4 (288°)
1751	10.8	8.9	6.9	3.5 (289°)	13.4 (295°)

Average Temperature Gradient 0-250 metres -0.0092°C/metre

Average Temperature Gradient 0-500 metres -0.0082°C/metre

Average Wind Speed Gradient 0-500 metres +0.0184 metres/sec/metre

TABLE V

Location Accuracies Obtained with Different Methods of Applying Meteorological Correction

		GOODWIN METEOROLOGICAL CORRECTION				INDIVIDUAL PATH WEIGHTED WIND			
Date	Meteorological Condition	Radial Error of Mean (metres)	Number of Locations Within 100M	Number of Locations Within 200M	Total Number of Locations	Radial Error of Mean	Number of Locations Within 100M	Number of Locations Within 200M	Total Number of Locations
12 Sept.	Negative temperature gradient, calm, scattered clouds	248	0	0	22	1039	0	0	22
14 Sept.	Negative temperature gradient, calm, overcast	42	17	24	24	240	5	10	24
19 Sept.	Positive temperature gradient, "calm", (windy above surface)	11	25	44	55	159	1	15	55
21 Sept.	Positive temperature gradient, calm	160	4	14	25	131	2	12	25
24 Sept.	Negative temperature gradient, windy	397	3	6	23	1779	0	0	23
TOTALS			49	88	149		8	37	149
Radial Error of Mean of all Locations = 87 metres						Radial Error of Mean of all Locations = 376 m			

		WEIGHTED WIND METEOROLOGICAL CORRECTION				NO METEOROLOGICAL CORRECTION			
Date	Meteorological Condition	Radial Error of Mean (metres)	Number of Locations Within 100M	Number of Locations Within 200M	Total Number of Locations	Radial Error of Mean	Number of Locations Within 100M	Number of Locations Within 200M	Total Number of Locations
12 Sept.	Negative temperature gradient, calm, scattered clouds	263	0	0	22	255	0	0	22
14 Sept.	Negative temperature gradient, calm, overcast	114	8	20	24	88	13	22	24
19 Sept.	Positive temperature gradient, "calm", (windy above surface)	165	3	25	55	720	0	0	55
21 Sept.	Positive temperature gradient, calm	152	4	14	25	132	6	15	25
24 Sept.	Negative temperature gradient, windy	1319	0	1	23	1392	0	0	23
TOTALS			15	60	149		19	37	149
Radial Error of Mean of all Locations = 280 metres						Radial Error of Mean of all Locations = 364 m			

Confidential

TABLE VI

Maximum Heights of Sound Ray Path Predicted by Goodwin Correction Method for 24 September 1965

Met. Time CDT	Maximum Height of Sound Ray Path (Metres) to:						
	M1	M2	M3	M4	M5	M6	M7
1702	100* 1350	150* 1300	150* 1300	150 1300*	200 1300*	250 1250*	300 1250*
1712	150* 1350	150* 1350	200* 1350	200* 1350	250 1350*	300 1350*	1350
1723	200	200	250	250* 1350	300* 1400	350* 1400	350 1450*
1732	200	200	250	250	300	300* 1350	400* 1400
1742	200	250	250	300	300	350	400

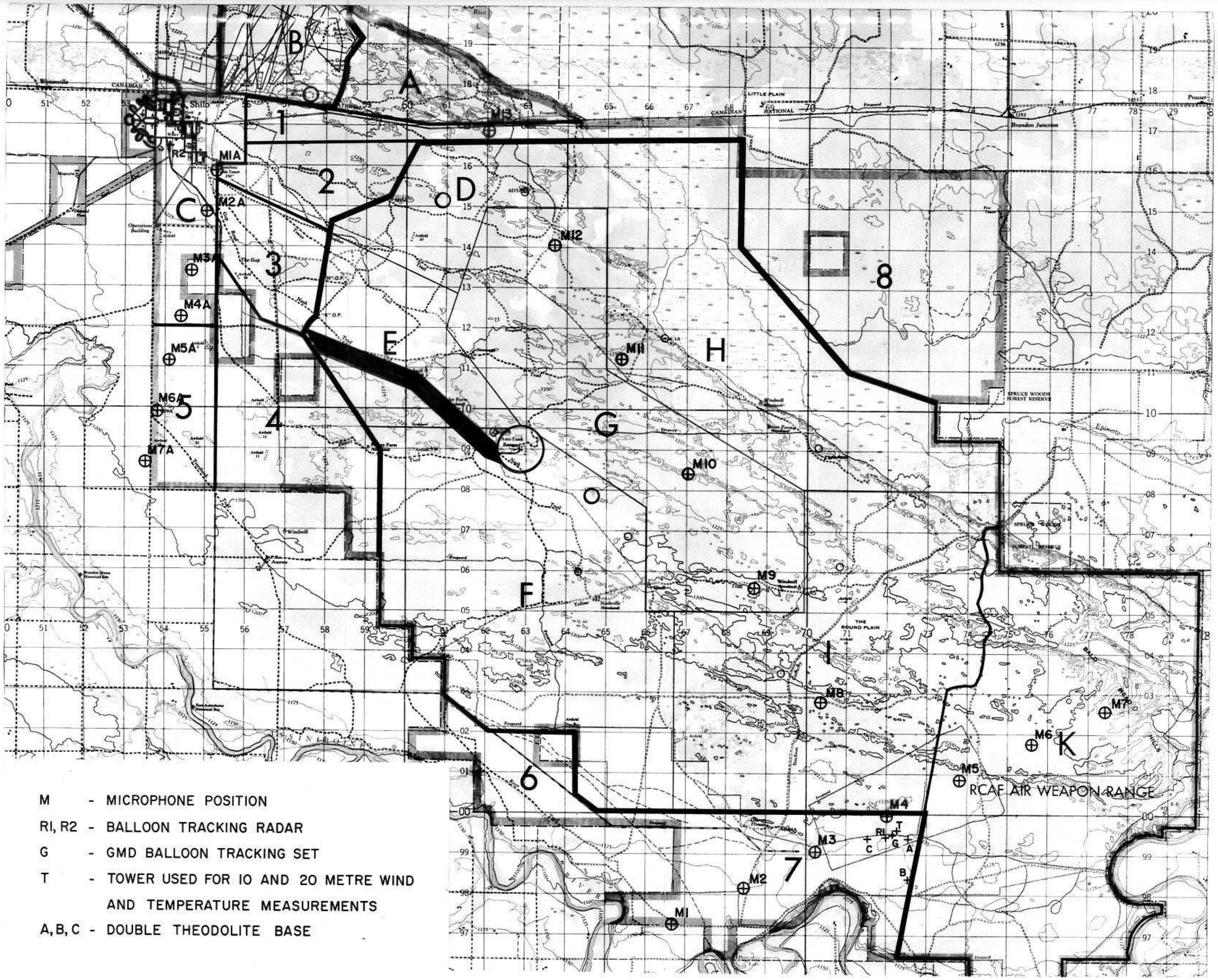
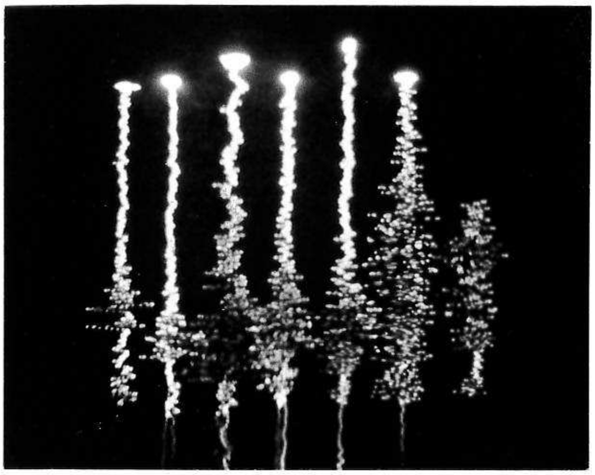
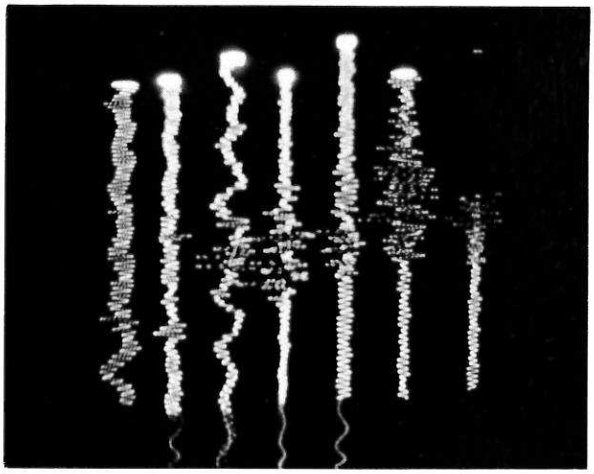


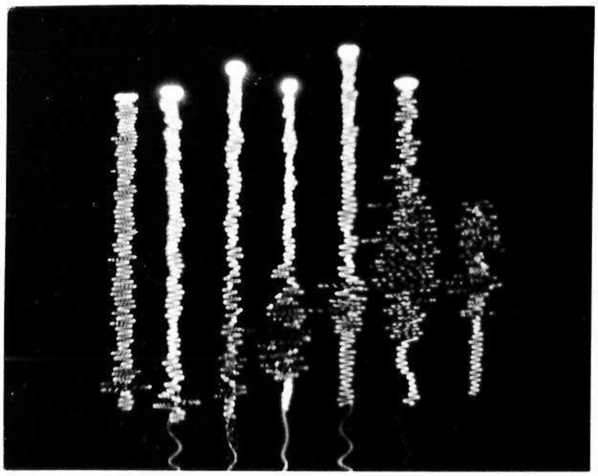
Plate I — Microphone positions for 1963 and 1965 trials



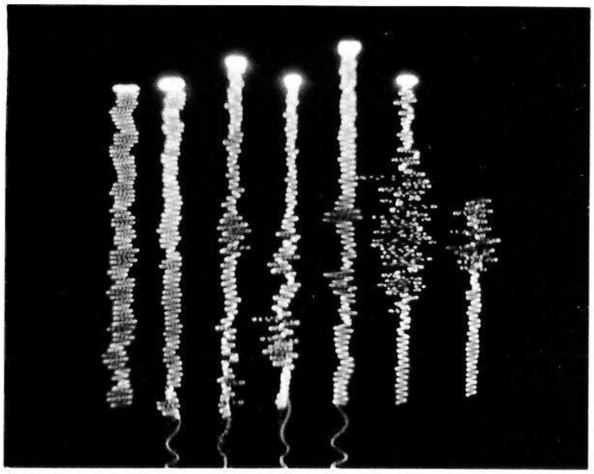
Mic. no. 1 2 3 4 5 6 7
Shot no. 1 1700 CDT



Mic. no. 1 2 3 4 5 6 7
Shot no. 12 1716 CDT



Mic. no. 1 2 3 4 5 6 7
Shot no. 15 1721 CDT



Mic. no. 1 2 3 4 5 6 7
Shot no. 25 1736 CDT

Plate II — Sound waveforms 24 Sept. 1965