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USASRDL Technical Report 2224

ANALYSIS OF BALLISTIC METEOROLOGICAL EFFECTS ON ARTILLERY FIRE

by

Raymond Bellucci

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September 1961

U.S. ARMY SIGNAL RESEARCH AND DEVELOPMENT LABORATORY

FORT MONMOUTH, N. J.

U. S. ARMY SIGNAL RESEARCH AND DEVELOPMENT LABORATORY
FORT MONMOUTH, NEW JERSEY

September 1961

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ANALYSIS OF BALLISTIC METEOROLOGICAL EFFECTS ON ARTILLERY FIRE

Raymond Bellucci

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U. S. ARMY SIGNAL RESEARCH AND DEVELOPMENT LABORATORY

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ABSTRACT

This report presents the results and conclusions derived from a series of meteorological soundings taken in conjunction with howitzer firings at Fort Sill, Oklahoma, during March and April 1958. The tests provided information for determining the relative importance of ballistic and meteorological sources of error in the artillery system. Estimates are given for the error arising from existing meteorological sounding equipment, space and time variability of meteorological data, and of gunnery and ballistics.

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ANALYSIS OF BALLISTIC METEOROLOGICAL EFFECTS ON ARTILLERY FIRE

INTRODUCTION

The inclusion of meteorological corrections when aiming an artillery weapon is necessary for accurate firing. In the past, the limited accuracy of devices to measure the parameters of the atmosphere permitted only gross corrections to be applied. More recently, however, the anticipated use of new concepts in future army operations has increased the need for improvement in the accuracy of weapons systems. These concepts include the following:

1. New tactical concepts requiring a high degree of mobility and a 360-degree sector of fire for field artillery.

2. The use of atomic energy projectiles requiring the capability of hitting a target with the first round.

3. The utilization of rockets and missiles for field artillery.

Because these new concepts require an improvement in weapons accuracy, USCONARC Board No. 1, in December 1956, requested that a comprehensive study of meteorological ballistic corrections for artillery and missiles be made to improve firing accuracy. This request was transmitted to USASRDL in January 1958 from OCSigO, and work was undertaken by this Laboratory under Task 3-31-15-412, "Study of Ballistic Corrections for Artillery and Missiles."

The USASRDL study program was divided into two phases: 1) A program of test firings to provide data for the determination of the relative importance of various sources of error in the artillery system. These sources of error include inaccuracies arising from existing meteorological sounding equipment, space and time variability of the atmosphere, and errors of gunnery and ballistics. The results of these tests will help to determine the philosophy to be followed in the development of future equipment. The tests were made at Fort Sill during the months of March and April 1958. 2) A study contract (Contract DA36-039 SC-78068) with Melpar Inc., Boston, Mass., consisting of the following major phases:

a) Determination of the errors of existing systems in measuring the variables of the atmosphere.

b) Study of the effects of atmospheric time and space variability on the validity of ballistic messages.

c) Study of meteorological parameters and their relation to the totality of error in present gunnery practice, leading to decisions concerning meteorological accuracy requirements.

d) Study of the effects of various methods for increasing the accuracy of meteorological data through such techniques as interchange of data among units of the field army, statistical treatment of data, map techniques, etc.

e) Design of an optimum system for obtaining the meteorological information required for artillery and other field army needs, including nuclear fallout.

The series of meteorological soundings in conjunction with howitzer firings (Phase 1) was designed as an extensive field test to: 1) determine the significance of the meteorological error as compared to the over-all gunnery system error in present operational techniques, and 2) determine whether improvement might be made in the meteorological system and/or equipment which would enhance the techniques of unobserved firings.

The participating agencies in the firing tests, BRL, USAAMS, and USASRDL, agreed that the tests should provide data for 1) comparison of ballistic winds and densities computed from Rawin Set AN/GMD-1, Rawin Set AN/GMD-2, and paired theodolites (winds only); 2) determination of significant error sources introduced within the meteorological system; 3) determination of quantitative improvement of multiple-station meteorological data over single-station data in gunnery accuracy; 4) comparison of post-corrected firing results, using meteorological data of varying staleness and at varying distances from the firing site; and 5) determination of the over-all gunnery system error and of the meteorological component.

The responsibilities for conducting the tests were divided among the participating agencies as follows:

USAAMS. 1) Organizing, scheduling, and conducting the firing program at Fort Sill, and providing weapons, crews, and ammunition; 2) scheduling metro sections available at Fort Sill for the test period; 3) determining burst locations; 4) providing for measured muzzle velocity data; and 4) reduction of firing data, using field procedures.

BRL. 1) Formal preparation and dissemination of the design of experiment and 2) ballistic reductions of firing data, using standard BRL techniques.

USASRDL. 1) Organizing and providing observations required; 2) obtaining data from scheduled Weather Bureau and Air Force soundings made within the surrounding area at the time of the tests; 3) making computations with an IBM computer of center-of-impact registrations (CI's) fired; and 4) making computations and comparisons of meteorological data obtained by various equipments.

DISCUSSION

General

Firing tables are based on actual firings of a weapon and its ammunition under a set of conditions accepted as standard. Thus, under these standard conditions, data taken directly from the firing tables would hit the target.

The failure of a shot to hit the target is due to a combination of variations from standard. Major causes of these variations are:

1. Meteorology. Wind, air density, and temperature affect the flight of the projectile, causing it to vary from standard.

2. Muzzle-Velocity Variation. Standard muzzle velocity for any type of weapon is known, and firing-table ranges are based on that figure. However, any given lot of ammunition may vary widely from standard; in fact, it is seldom at standard velocity, and may vary from round to round in the same lot of ammunition. This change from standard is known as MVV, or muzzle velocity variation.

3. Other Ballistic Effects. Projectile weight and powder temperature when not at standard may cause a variation from firing-table data. These factors are normally included with the meteorological message corrections although they have nothing to do with the atmosphere.

Other variations from standard will be caused by tube wear on the piece, nonuniform ramming in the case of separate loading ammunition, coppering, moisture content of the powder, and many other factors affecting the velocity of the projectile or its ballistic coefficient.

The data analysis for the firing tests is based on the assumption that if all known corrections for nonstandard conditions are applied to the observed location of a number of rounds, the resultant range and deflection should equal the standard firing-table data. In other words, if all ballistic and meteorological variations from standard could be determined, the total correction for these conditions when applied to the center of impact (CI) should locate the CI at the point indicated by the firing tables.

The amount by which the known corrections fail to bring the range and deflection up to the standard firing-table data is the error or missed distance involved in hitting a target. This error can be represented mathematically by the following formula:

$$\sigma_R^2 = \sigma_{RM}^2 + \sigma_B^2 + \sigma_E^2 + 2\rho_{RMB}\sigma_{RM}\sigma_B + 2\rho_{RME}\sigma_{RM}\sigma_E + 2\rho_{BE}\sigma_B\sigma_E$$

$$\sigma_D^2 = \sigma_{DM}^2 + \sigma_E^2 + 2\rho_{DME}\sigma_{DM}\sigma_E ,$$

where

σ_R^2 is the range variance in meters,

σ_D^2 is the deflection variance in meters,

σ_M^2 is the variance due to meteorological effects,

σ_B^2 is the variance due to ballistic effects,

σ_E^2 is the unexplained variance, and includes experimental error in this case.

ρ_{RMB}, ρ_{RME}, and ρ_{BE} are correlation coefficients between the factors.

Since no estimates of the correlations between the factors are available, the equations were simplified to the following:

$$\sigma_R^2 = \sigma_{RM}^2 + \sigma_B^2 + \sigma_E^2.$$

$$\sigma_D^2 = \sigma_{RM}^2 + \sigma_E^2 \text{ where } \sigma_E^2 \text{ also contains the correlation factors.}$$

It was decided to study the effect of three factors which could seriously affect the value of σ_R^2 and σ_D^2. These factors include time lag between meteorological measurement and use (time variability), distance between meteorological stations and firing position (distance variability), and effect of different types of training given to the meteorological teams which made the meteorological observations.

Design of Experiment

The experimental design adopted by Ballistics Research Laboratory to fulfill the requirements set up by the test plan was a 4 x 4 latin square with two replications in which three factors--days, distance, and meteorological teams--were to be studied for 0-, 2-, 4-, and 6-hour time lapses. A schedule of eight testing days was arranged at Fort Sill, Oklahoma, under the auspices of The Army Artillery and Missile School. Each testing day had four ballistic meteorological flights scheduled for each of the participating meteorological teams designated by the letters A through D. These teams, together with their base sets, were rotated from site to site according to the latin square design indicated in Table 1 (with the distances of each station from the gun position).

Table 1. Schedule of Rotation of Base Sets

Days	Date	FP 511 (1 mile)	FP 402 (4 miles)	FP 8 (10 miles)	FP 652 (17 miles
1	29 Mar	A	B	C	D
2	1 Apr	B	C	D	A
3	8 Apr	C	D	A	B
4	10 Apr	D	A	B	C
5	12 Apr	D	A	B	C
6	14 Apr	B	D	C	A
7	17 Apr	A	C	D	B
8	21 Apr	C	B	A	D

The flights were to be made at 0600, 0800, 1000, and 1200 hours. Two center-of-impact registrations were to be fired concurrently with the meteorological flights of 0800 and 1200 hours. Two artillery weapons, a 105-mm howitzer and an 8-inch howitzer, were selected for the firings and were fired

at fixed azimuths and quadrant elevation angles, the range for both weapons being approximately 9,000 meters. The center-of-impact registrations were, when taken in conjunction with the measured muzzle velocity, designed to provide a standard by which the accuracy of the meteorological message could be measured.

The howitzers used for firing the center-of-impact registrations were provided by Technical Operations engineering units stationed at Fort Sill. The same howitzer, in appropriate caliber, was used for each test day in order to avoid variations in the characteristics of the weapon. All firings took place under the supervision of the Gunnery Department of the Artillery and Missile School. Howitzers were located to an accuracy of 1 in 3000, carefully bore-sighted and laid by base angle with an aiming circle. All ammunition was of the same lot number for each caliber. All projectiles were of the same general weight classification (number of squares) and were, in addition, weighed prior to firing. Average powder temperature was taken for those rounds to be fired in any particular CI. Two seating rounds were fired prior to shooting the CI. Actual muzzle velocity for each round was taken by means of a radar doppler chronograph, then corrected for density of the air, powder temperature, and projectile weight. Muzzle droop was measured. Elevation was obtained by use of the gunner's quadrant. Standard methods were used by the flash platoon of each observation battalion to provide angles for the location of the CI.

Personnel and Equipment

The meteorological teams were divided into two general classifications: those operating base sets (A through D) and those operating check sets (E through K). Base sets were used to obtain data of primary interest and were stationed at carefully selected sites to obtain data called for by the latin square experimental design. Check sets were used to verify data obtained by the base sets, although complete coverage of each site was not possible. All base sets used the AN/GMD-1A for obtaining the meteorological data. These base sets were manned by teams whose training and experience varied considerably. Two of the six check sets, used to obtain additional data, were rotated. One of these contained a Rawin Set AN/GMD-2. Two of the remaining four sets, designated by the letters J and K, were located, respectively, 50 miles south of Fort Sill and 50 miles west of Fort Sill.

Location of Base Sets

The sites selected for the AN/GMD's used by teams A through D were located in an approximately westerly direction from the howitzer positions and were designated by the corresponding firing point numbers taken from the Fort Sill trigonometrical list. The distances varied from one mile to 17 miles, as shown in Table 1. Figure 1 gives a graphical representation of all the stations involved in the experiment.

In addition to the Meteorological Teams, two photo theodolites, operated by U. S. Army Signal Research and Development Laboratory personnel, were set up in the vicinity of FP 511 and FP 402 for determining the accuracy of the AN/GMD-1A.

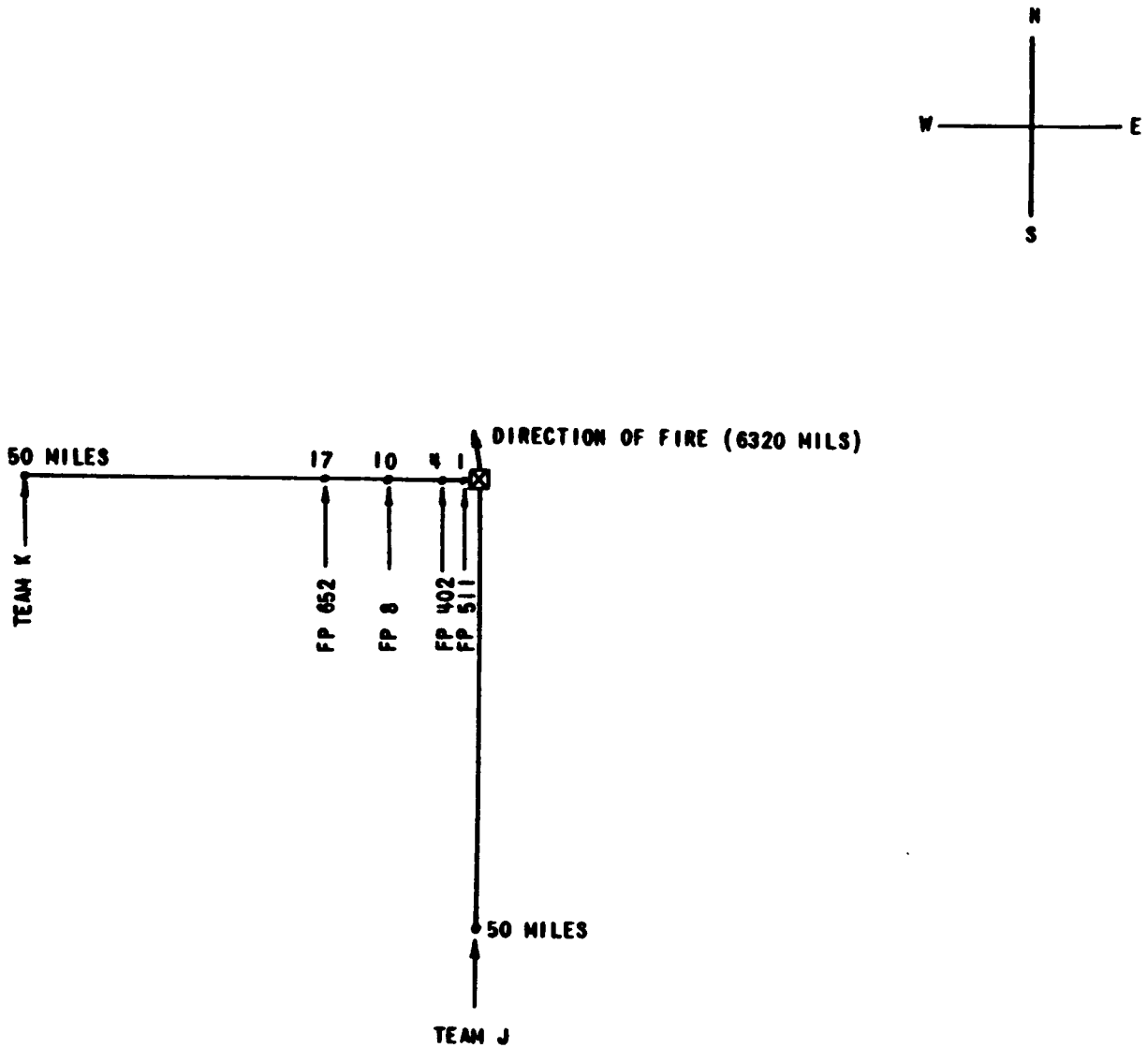

FIG. 1 LOCATION OF METEOROLOGICAL TEAMS

Data Analysis

The 4 x 4 latin square design with two replications made it possible to analyze four sets of latin squares for zero-hour time lapse, four sets of latin squares for two-hour time lapse, and two sets of latin squares for four-and six-hour time-lapses. For example, the meteorological flights of 0800 and 1200 hours, which were made concurrently with the howitzer firings on each of the eight testing days, provided the following latin squares:

1 set for the first 4 days (first square) for the firings at 0800 (CI_1).

1 set for the last 4 days (second square) for the firings at 0800 (CI_1).

1 set for the first 4 days (first square) for the firings at 1200 (CI_2).

1 set for the last 4 days (second square) for the firings at 1200 (CI_2).

The missed distance, or the amount by which the known corrections failed to bring the range and deflection up to the firing table data, served as the input to each cell of the latin squares.

RESULTS

Experimental Error

The missed distance depends upon the accuracy of the equipment used to measure variations from standard and other parameters of the experiment. Among these are the accuracy with which the fall of the shot is observed and surveyed, initial laying of the weapons firing the CI's, and accuracy of muzzle-velocity measurements. In the meteorological field, the accuracy with which meteorological devices can measure temperature, density, and wind velocity must also be taken into account.

The combination of the above factors represents the experimental errors intrinsic in this particular project. These are shown in Table 2 for all the latin square designs. With the exception of two latin squares, the experimental error was fairly constant for all designs. In both cases, the experimental error was much lower than average, and occurred in the second square: one for the two-hour time lapse, and the other for the six-hour time lapse. The experimental errors were averaged for each square to determine whether there was evidence of a learning process in the experiments. These are given in Table 3 and shown graphically in Figs. 2 and 3. In all cases the experimental error for the second square was smaller than that in the first square. This seems to indicate that, as the experiment progressed, the personnel involved in the experiment became more proficient in performing their duties.

To obtain a reasonable estimate of the experimental error for both weapons for a range of 9,000 meters, the errors for all latin squares were averaged, resulting in values for the range experimental error of 32 meters for the 105-mm howitzer and 27 meters for the 8-inch howitzer. The deflection experimental error was found to be, respectively, 10 meters and 7 meters for the 105-mm howitzer and 8-inch howitzer.

Table 2. Experimental Error in Meters

Latin Square	CI	Time Interval in Hours	105-mm Howitzer		8-inch Howitzer	
			Range	Deflection	Range	Deflection
1	1	0	33	18	29	12
2	1	0	30	6	29	5
1	2	0	32	8	28	5
2	2	0	24	9	18	6
1	1	2	43	8	38	5
2	1	2	15	6	13	4
1	2	2	35	8	30	5
2	2	2	29	6	24	4
1	2	4	33	18	29	12
2	2	4	31	15	27	3
1	2	6	44	8	38	5
2	2	6	15	6	13	4
Average			32	10	27	7

Table 3. Experimental Error in Meters

Latin Square	Time Interval in Hours	105-mm Howitzer		8-inch Howitzer	
		Range	Deflection	Range	Deflection
1	0	33	20	29	13
2	0	27	8	24	6
Average		30	11	26	8
1	2	39	8	34	5
2	2	23	6	19	4
Average		32	7	28	5
1	4	33	18	29	12
2	4	31	5	27	3
Average		32	13	28	9
1	6	44	8	38	5
2	6	15	6	13	4
Average		32	7	28	5

All standard deviation averages computed from formula $\bar{\sigma} = \left[\frac{1}{n} \sum_{i=1}^{n} \sigma_i^2 \right]^{1/2}$

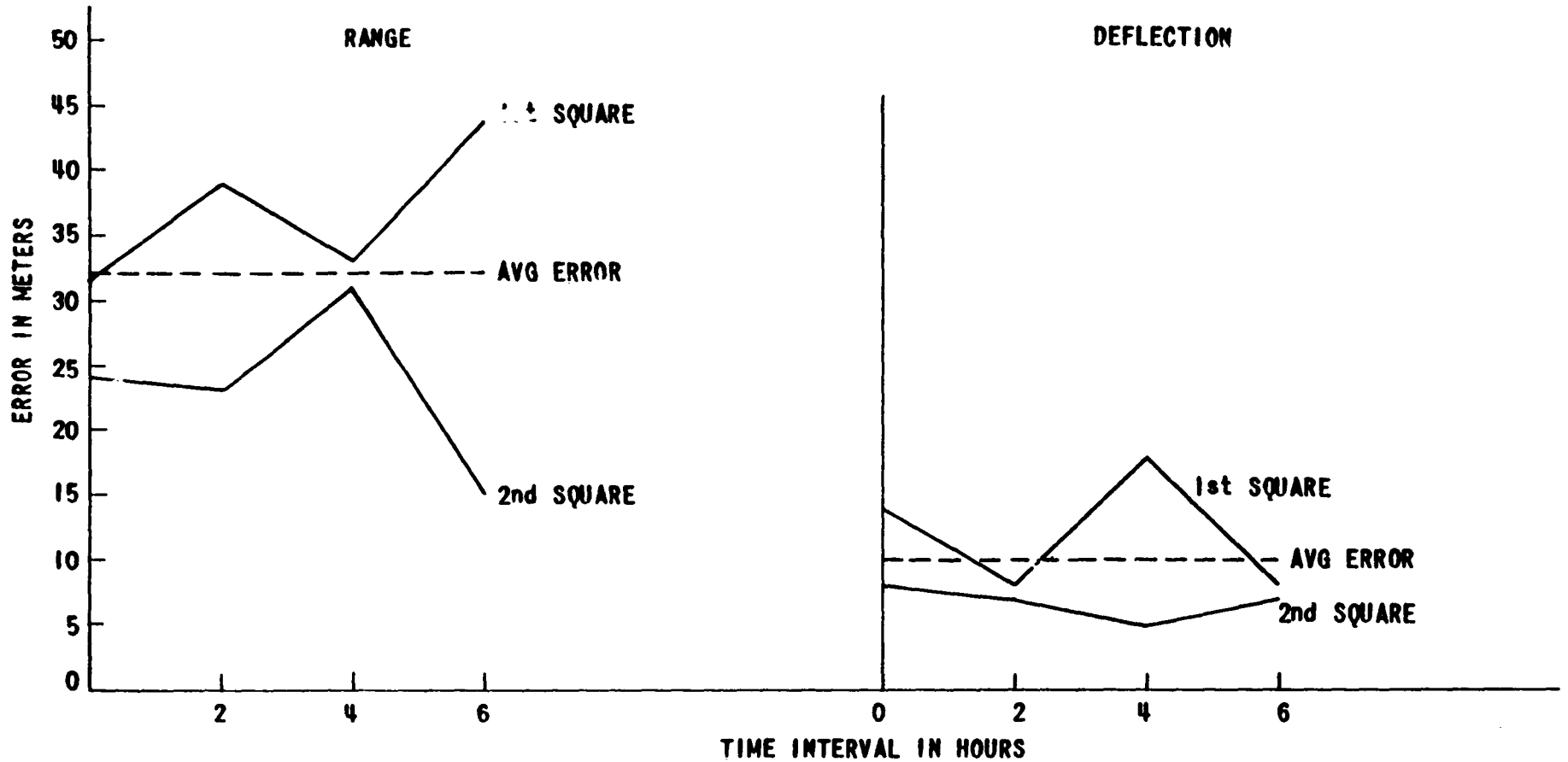

FIG. 2 EXPERIMENTAL ERROR, 105-mm HOWITZER

Comparison of Meteorological Teams

The reliability of meteorological data submitted by any meteorological team is dependent on the efficiency and degree of training of the personnel and the state of maintenance of the equipment. The component of variance due to different teams and equipment was obtained. The results showed that while the capabilities of the four base-set meteorological teams (A through D) seemed to vary widely in training and experience, the difference between the meteorological teams was not significant.

Distance Variability

It has been generally accepted in artillery circles that the validity of a meteorological message depends on the distance from the center of the trajectory of the weapon to the point at which the meteorological message was taken, the message becoming less valid as the distance between these two points increases. The experiment indicated that the distance variability occurring among stations with a spread of 17 miles is insignificant.

Two other stations, while not part of the experimental design, were included in the experiment. These stations were located at Sheppard Air Force Base (50 miles south of the gun positions) and at Altus Air Force Base (50 miles west of gun positions). These stations developed meteorological messages concurrently with stations A through D.

In addition to these stations, a mythical multiple sounding station, composed of the four base stations, was also formed. The composite metro message produced for each flight was a combination of the data derived from the base sets (A through D) located at these stations. The average for each element of data (density, temperature, windspeed, and direction) was combined into one message.

A comparison between the current meteorological messages obtained from the four base stations; Sheppard AFB, Texas; Altus AFB, Oklahoma; and the mythical multiple sounding station was made. The results of this comparison are shown in Table 4. A significant difference for the range error was

Table 4. Distance Variability in Meters

Station	Distance From Trajectory	Error in Standard Deviation Units	
		Range	Deflection
511	1 mile west	37	17
402	4 miles west	48	17
8	10 miles west	35	17
652	17 miles west	43	16
Composite or Multiple Sounding	8 miles west	33	15
Altus AFB	50 miles west	63	19
Sheppard AFB	50 miles south	97	29

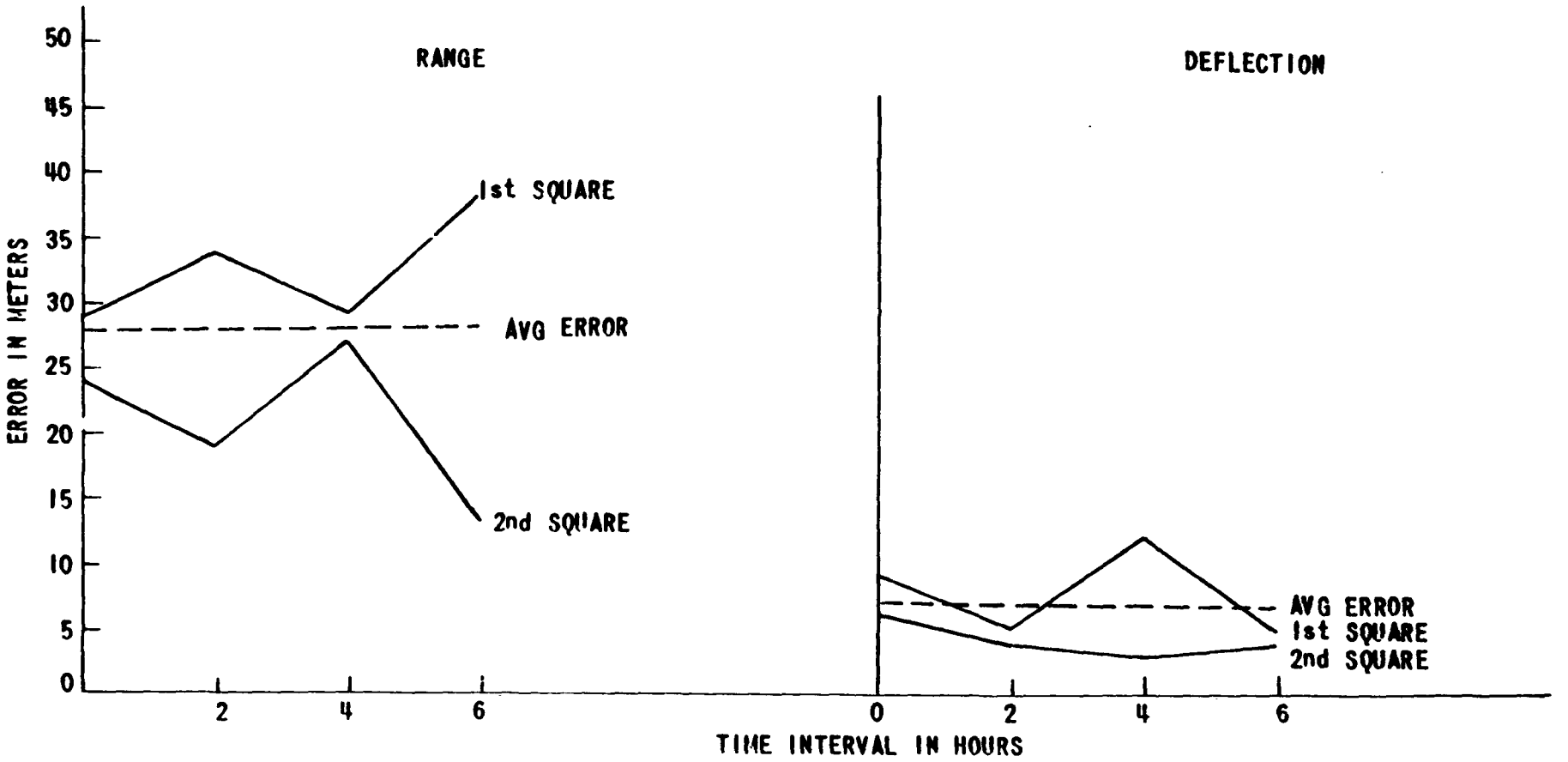

FIG. 3 EXPERIMENTAL ERROR, 8-INCH HOWITZER

obtained for both stations located 50 miles from the trajectory, while only the station 50 miles south of the trajectory showed a significant difference for the deflection error. It should be noted that the magnitude of the errors increased from approximately two to one for station 50-W to approximately three to one for stations 50-S, indicating that the position of the meteorological station in relation to the gun position is important.

The mythical multiple-sounding station showed a slight but statistically insignificant improvement over the single-sounding station.

Time Variability

The extent by which a meteorological message deteriorates because of staleness or elapsed time between the firing of an artillery weapon and the computation of a meteorological message has been the subject of considerable study. It was determined by U. S. Army Signal Research and Development Laboratory and reported in Technical Memorandum No. M-1913 dated August 1957 that the time variability of ballistic winds for each component increased systematically according to the formula $\sigma_t = 2.3t^{\frac{1}{2}}$, where t is the time interval in hours and σ_t is the standard deviation in miles per hour.

In this experiment, the day-to-day component of the variance provided a measure of the combined meteorological error and the ballistic error. The results indicated that the day-to-day component of the variance for both weapons for range and deflection was significant for all time lapses (0, 2, 4, and 6 hours) and increased with increasing time lapse. The results for each latin square are given in Table 5. No estimate could be made for the latin square (210) because the component of variance was smaller than the experimental error.

The combined estimate of the time variability was averaged for all squares for each time lapse and is given in Table 6. The estimate of the meteorological error was obtained by removing the ballistic effects (obtained from Ballistic Research Laboratory Report No. 1210 dated April 1959) from the combined estimates for each time interval. The zero hour estimate of σ RM for both guns is of the same order of magnitude as the experimental error. However, the range metro error for 2, 4, and 6 hours remained significant.

In the case of the deflection metro error (σ D), no known sources of error could be removed from the zero-hour time lapse to reduce σ D to the same order of magnitude as the experimental error as in the case of σ RM. The difference in the zero-hour time-lapse values for σ D and σ E could be due to interaction effects not accounted for in the experiment or possibly correlation between metro and experimental error, as indicated in the discussion at the beginning of this report.

Least-squares curves were computed for the range metro error (σ RM) and the deflection metro error (σ D) for each gun. These curves are shown in Fig. 4 (curves A, C and D). In addition, theoretical time-lapse curves for each gun were also plotted (curves B and E). They were obtained by converting the time variability formula $\sigma t = 2.3t^{\frac{1}{2}}$ to meters by multiplying the

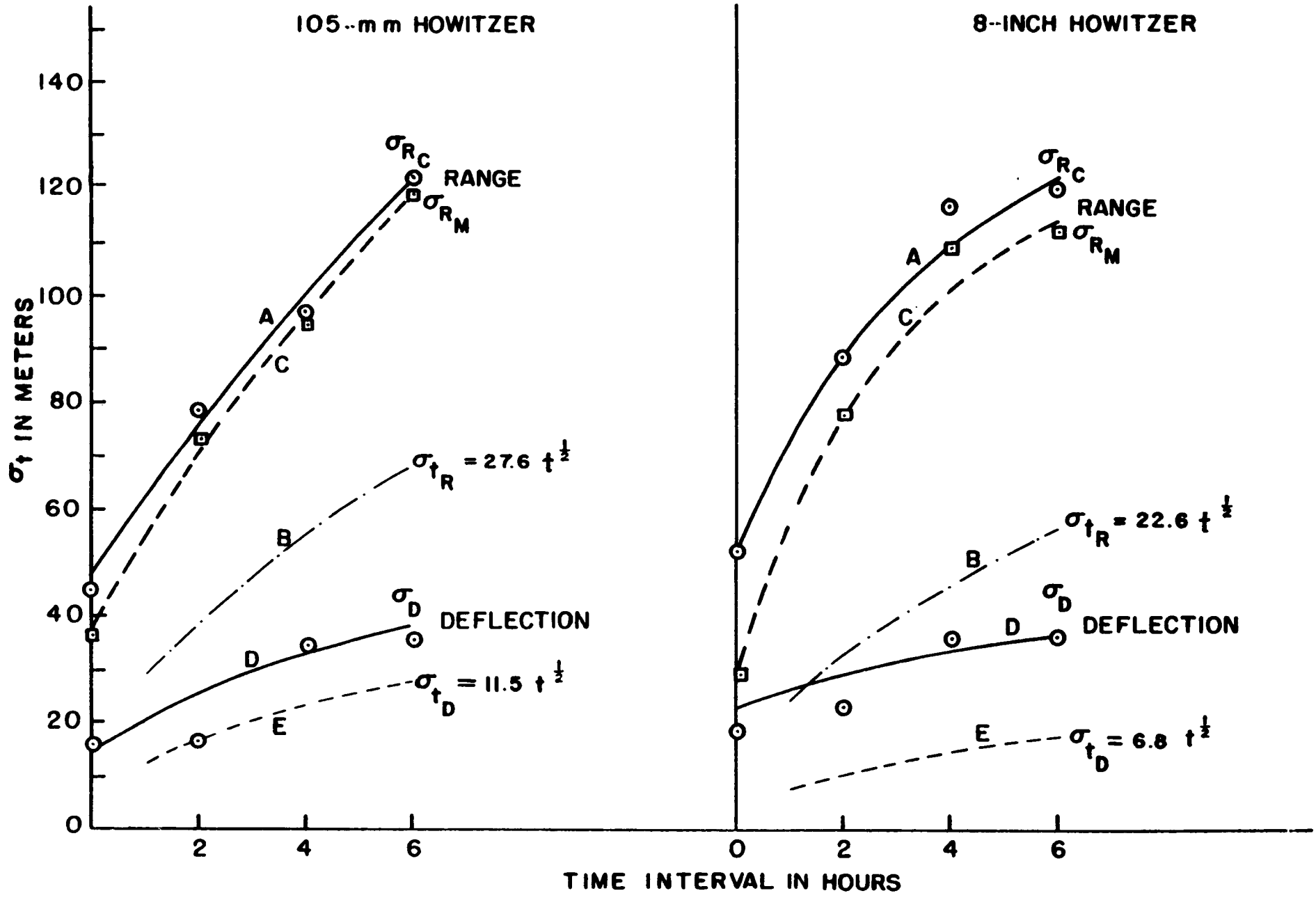

FIG. 4 TIME VARIABILITY

Table 5. Combined Estimate of Time Variability in Meters

Latin Square	CI	Time Interval in Hours	105-mm Howitzer σ_R	105-mm Howitzer σ_D	8-inch Howitzer σ_R	8-inch Howitzer σ_D
1	1	0	25	16	47	9
2	1	0	--	13	27	14
1	2	0	71	11	67	21
2	2	0	27	22	57	27
1	1	2	117	16	107	8
2	1	2	53	14	27	16
1	2	2	64	14	63	27
2	2	2	64	22	115	33
1	2	4	54	37	36	41
2	2	4	127	35	162	34
1	2	6	133	34	102	39
2	2	6	113	36	134	33

σ R = Combined estimate (ballistic + metro)

σ D = Deflection error

Table 6. Time Variability in Meters

Time Interval in Hours	105-mm Howitzer σ_R	105-mm Howitzer σ_{RM}	105-mm Howitzer σ_{DM}	8-inch Howitzer σ_R	8-inch Howitzer σ_{RM}	8-inch Howitzer σ_{DM}
0	46	37	16	52	28	19
2	79	74	17	89	78	23
4	98	95	35	117	109	36
6	123	120	36	120	112	36

σ R = Combined estimate (ballistic + metro)

σ RM = Range metro error

σ DM = Deflection metro error

constant by the weighting factors given in firing tables 105-H-5 and 8-J-2 for the 105-mm howitzer and the 8-inch howitzer.

The curves seem to indicate that 1) the experimental curves for σRM and σD are similar in shape to the standard curves, 2) the magnitudes of the metro time-lapse errors for both range and deflection are larger than the theoretical, and 3) the difference between σ RM and σ tR increases with time, while the difference between σ D and σ tD is invariant with time.

If it is assumed that the difference between curves D and E is a measure of the unexplained error and remove this value from σ D, then the zero time-lapse value for both guns is reduced to the order of magnitude of the experimental error. The portion of the deflection variance removed from the 105-mm howitzer and the 8-inch howitzer was found to be, respectively, one-ninth and one-fourth of the variance of the range error. This is consistent with the proportional value of the wind effects for range and deflection (three to one, and two to one).

Accuracy of AN/GMD-1A and AN/GMD-2

Two photo theodolites were employed to track the test flights as a check on the ability of the AN/GMD-1A to measure accurately the ballistic wind speed and azimuth. One photo theodolite was located at FP-511, and the other theodolite at FP-402. Both theodolites tracked the balloon released at FP-511. Ballistic winds for lines 3 and 4 were obtained for eleven flights. The vector error of the AN/GMD-1A (using the phototheodolites as standard) was 1.5 knots for line 3 and 1.2 knots for line 4.

Seven flights were analyzed for comparison of the AN/GMD-1A and the AN/GMD-2. The results of the comparative analysis revealed no significant difference in the ballistic winds obtained by the two AN/GMD-s, indicating that the AN/GMD-1A is of the same order of accuracy as the AN/GMD-2.

CONCLUSIONS

The conclusions drawn from this experiment, while qualitative in nature, indicate that:

(1) The training, experience, and capabilities of the four base-set meteorological teams were adequate for the experiment and did not significantly contribute to the meteorological error. However, the fact that they were able to develop meteorological messages of sufficient accuracy for the experiment does not overrule the effect of training. Training has an effect on the time in which a metro message can be computed and distributed. This would necessarily affect the age of the data. The experimental results were analyzed retroactively; consequently, these effects were not evident in the analysis.

(2) A distance of 20 miles (30 km) between stations is not a significant factor where firings are to be made in terrains similar to the Fort Sill area. As the distance was increased to 50 miles, the error due to distance doubled for the station 50 miles west of the trajectory and tripled for the station 50 miles south of the gun position, significantly affecting the metro error.

(3) The composite metro message obtained from multiple-sounding stations within a radius of 20 miles (30 km) in the Fort Sill area did not significantly reduce the metro error obtained from a single-sounding station. The reason for this can be seen easily when it is remembered that there was no significant difference between the metro messages produced by the stations within a 20-mile (30 km) radius. Consequently, a combination of the message could not produce any significant improvement. However, a reduction in measurement error is possible, since the error of the mean is dependent on the number of stations.* Moreover, if the stations 50 miles south and 50 miles west had been included, the composite message thus produced would be significantly better than the individual message of these two stations, with no significant loss in accuracy as compared with the individual message of the stations within the 20-mile radius.

(4) The error due to meteorological staleness is the most important factor. The combined estimates of the range metro error (ballistic and meteorological) and deflection metro error are significant for all conditions of staleness. The ballistic effects (σ_B) and estimated range metro error (obtained by removing the ballistics effects from the combined metro error) for zero hours staleness were of the same order of magnitude as the experimental error.

(5) The time-variability for the estimated metro error for both range and deflection was significant for 2, 4, and 6 hours. These values of σ_{RM} were much larger than those obtained by USASRDL in previous experiments, indicating that unexplained factors had entered into the estimates of σ_{RM}. The unexplained factors for the range metro were also a function of time, ranging between 30 meters and 50 meters for the 105-mm howitzer and between 35 meters and 60 meters for the 8-inch howitzer. This amounts to approximately 3 knots for both guns, or equivalent to one-hour time-variability error.

(6) The AN/GMD-1A gives ballistic winds to the same order of accuracy as the AN/GMD-2, the vector error being approximately 1.5 knots for line 2 and 1.2 knots for line 4.

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*The standard error of the mean is $\sigma_m = \frac{\sigma}{\sqrt{n}}$ where σ_m is the standard error of the mean.

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