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ACCURACY REQUIREMENTS FOR THE MEASUREMENT OF METEOROLOGICAL PARAMETERS WHICH AFFECT ARTILLERY FIRE

By

William C. Barr

April 1972

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White Sands Missile Range, New Mexico

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13. ABSTRACT

The results of an artillery effectiveness methodology, which was originally developed to determine target location accuracies, have been applied to determine the accuracy requirements for the measurement of those meteorological parameters which affect artillery fire. Based on certain criteria, the effectiveness methodology determines the maximum allowable error in the displacement of the center of the effects pattern from the center of the target. This maximum error is then related to the errors in the meteorological parameters which produce it. To do this in a consistent manner, specific measuring systems must be considered to determine those parameters which are measured independently. In this study, the standard radiosonde system has been analyzed, and the accuracy requirements for this system have been determined.

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CONTENTS

INTRODUCTION

To have accurate and effective artillery fire, it is necessary to measure those meteorological parameters, such as temperature, density and wind, which affect the trajectory of a projectile. Since all measurements are subject to error, it is necessary to attempt to determine what measurement accuracies are required for effective artillery fire. This information could then be used to establish design criteria for those future meteorological measuring systems, at least part of whose mission will be to provide meteorological data in support of artillery fire. The purpose of this study was to try to determine realistic accuracy requirements for the measurement of those meteorological parameters which affect artillery fire.

DISCUSSION

A study conducted by the Combat Development Command Artillery Agency at Fort Sill, Oklahoma [1], on artillery effectiveness was originally made to determine target location accuracy requirements for artillery fire, but the methodology appears to be directly applicable to an objective determination of the accuracy requirements of the meteorological parameters needed for artillery fire. Since much of the subsequent work will make use of this methodology, a discussion of it is in order.

In discussing this artillery effectiveness methodology, one needs to define certain terms used in this study area. The following is taken from [1] and [2]:

1. Effects Pattern Area: The area within which damage can occur to personnel or materiel due to cannon volleys.

2. Target Area: A specified enemy area which is to be engaged.

3. Lethal Area: A measure of the casualty potential of a projectile bursting in or over a specified target area. In mathematical terms, let the function, $P(x,y)$, in the plane be the probability that a target with its center located at the point (x,y) will suffer a casualty from a projectile which bursts at the origin $(0,0)$. The lethal area is then defined as

---

[1] US Army Combat Developments Command, 1967, "A Study of Target Location Accuracy Requirements for Artillery Weapons - Army 1975 (U)," Vol. I.

[2] Spears, O. S., 1966, "A Model for Determining Target Location Accuracy Requirements," Preprints for the U. S. Army Operations Research Symposium, Part I.

$$A_L = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} P(x,y)dxdy \qquad (1)$$

i.e., A_L is a probability-of-casualty integral in the plane. A_L has the dimensions of an area such as square meters; hence, the term lethal area.

While A_L has the dimensions of an area, it must not be considered as a simple geometric configuration, for implicit in it are considerations of the "hardness" or shielding of the target. Obviously, P(x,y) and hence, A_L, will be different for exposed targets than for shielded ones.

In standard artillery effectiveness theory, the fraction of damage within the effects pattern due to a volley is given by

$$f = 1 - e^{-\frac{NA_L}{A_p}} \qquad (2)$$

where N is the number of rounds in the volley and A_p is the effects pattern area. The fraction of damage within the target area is then given by F = Cf, where C is the fraction of the target covered by the effects pattern or the "coverage" of the target.

Now for a given weapon system using a given ammunition, firing in a volley, N, A_L, and A_p are fixed and hence f is fixed; therefore any change in F is due only to a change in C.

The fractional change in F is therefore given by

$$\frac{dF}{F} = \frac{dC}{C}. \qquad (3)$$

This is about as far as one can go in general. To obtain further results, specific representations for A_p and A_T, the target area, must be given.

In the effectiveness model considered here, the effects pattern area and the target area are assumed to be circles with radii R_p and R_T, respectively.

Figure 1 illustrates the well-known "cookie cutter" concept. The coverage of the target by the effects pattern is given by the ratio of the shaded area, a, to the target area, A_T; i.e.,

$$C = \frac{a}{A_T} \qquad (4)$$

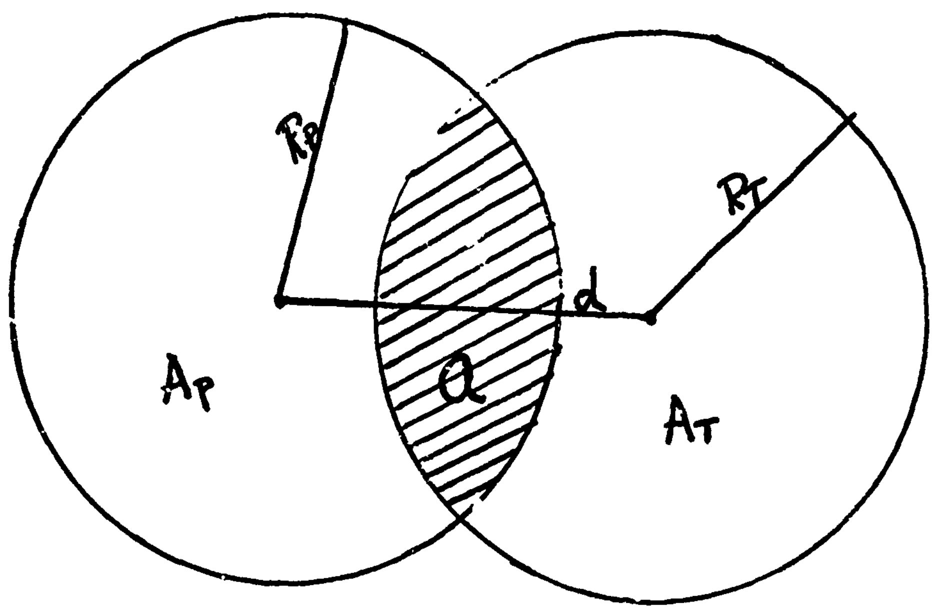

Figure 1. Illustrates the "cookie cutter" concept and shows some of the quantities used in calculating the coverage.

The quantity, d, is the distance that separates the centers of the two circles. There are four cases taken from [1].

Case I. If $R_p \geq d+R_T$, the target is completely covered by the effects pattern and C = 1.0.

Case II. If $R_T \geq R_p+d$, then the effects pattern area is entirely within the target area and

$$C = \frac{R_p^2}{R_T^2} . \tag{5}$$

Case III. If $d \geq R_p+R_T$ the effects pattern does not intersect the target and C = 0.

Case IV. The circles intersect and

$$C = \frac{R_p^2}{\pi R_T^2} \text{ ARCCOS} \left[\frac{R_p^2 - R_T^2 + d^2}{2dR_p}\right]$$

$$+ \frac{1}{\pi} \text{ ARCCOS} \left[\frac{R_T^2 - R_p^2 + d^2}{2dR_T}\right]$$

$$- \frac{1}{2\pi R_T^2} [2R_p^2R_T^2 + 2R_p^2d^2 + 2R_T^2d^2 - R_p^4 - R_T^4 - d^4]^{1/2} . \tag{6}$$

These equations allow the coverage to be calculated for all cases.

The model assumes that changes in effectiveness within the target area are due solely to changes in the coverage of the target by the effects pattern.

Three sources of error are considered; they are weapon system error, survey error, and target location error.

Assume that the distance, d, that separates the center of the effects pattern area from the center of the target area, is related to the various error sources by

$$d^2 = K^2[\varepsilon_{ws}^2 + \varepsilon_s^2 + \varepsilon_{tl}^2] \tag{7}$$

where ε_{ws}, ε_s, and ε_{tl} are the weapon system, survey, and target location errors, respectively. The errors are taken to be circular probable errors. The quantity K is a constant, chosen to give a desired statistical assurance. In this study K = 1.823, which gives a statistical assurance of 90%.

The procedure for calculating the target location errors is as follows: the Coverage, C, is calculated for the case where there is no target location error from

$$d^2 = K^2[\varepsilon_{ws}^2 + \varepsilon_s^2] \tag{8}$$

since ε_{ws} and ε_s are known. The target location error is then incremented and a new coverage, C', is calculated from

$$d'^2 = K^2[\varepsilon_{ws}^2 + \varepsilon_s^2 + \varepsilon_{tl}^2]. \tag{9}$$

When the new coverage, C', yields some specified allowable fractional reduction in coverage from the initial coverage, C, i.e.,

$$\frac{C-C'}{C} = 5\%,\ 10\%,\ 15\% \tag{10}$$

then the value of ε_{tl} thus obtained is the required target location accuracy.

The objective of the effort being reported is to relate the total allowable error due to meteorological effects, as determined by the effectiveness methodology, to the three parameters -- wind, temperature, and density -- that produce it. For the total allowable error due to meteorological effects, the same values obtained for target location error from the effectiveness methodology will be used. If ε is the probable error of displacement of the artillery fire from the center of the target and ε_W, ε_T and ε_ρ are the probable errors in wind, temperature, and density, respectively, then

$$\begin{aligned}\varepsilon^2 = {} & U_W^2\,\varepsilon_W^2 + U_T^2\varepsilon_T^2 + U_\rho^2\varepsilon_\rho^2 + 2r_{WT}U_WU_T\varepsilon_W\varepsilon_T \\ & + 2r_{W\rho}U_WU_\rho\varepsilon_W\varepsilon_\rho + 2r_{T\rho}U_TU_\rho\varepsilon_T\varepsilon_\rho \end{aligned} \tag{11}$$

where U_W, U_T and U_ρ are the unit effects for wind, temperature, and density, respectively, and the r's are the correlation coefficients between the parameters indicated by the subscripts.

As a further simplification, it can be assumed that the wind does not correlate with either temperature or density. Then $r_{WT} = r_{W\rho} = 0$ and

$$\varepsilon^2 = U_W^2\varepsilon_W^2 + U_T^2\varepsilon_T^2 + U_\rho^2\varepsilon_\rho^2 + 2r_{T\rho}U_T U_\rho \varepsilon_T \varepsilon_\rho . \tag{12}$$

For the units of the errors given in Equation (12) to be consistent with the units of the unit effects as given in the firing tables, ε_W must be given in knots, and ε_T and ε_ρ are the fractional errors in temperature and density expressed as percentage deviations from the standard atmosphere.

A problem which arises in an attempt to apply Equation (12) is the determination of the correlation between the temperature and density. If, for example, the temperature and density were measured independently of each other, then one could assume that the respective errors do not correlate and then $r_{T\rho} = 0$, but this is rarely the case. Most meteorological measuring systems do not measure density directly but rather measure other parameters such as temperature and pressure and then calculate the density from them. Thus, the errors in density are not independent of the errors in the parameters from which they are calculated.

In solving this problem, the correlation coefficient, $r_{T\rho}$, will not be directly determined. The approach taken will be to derive an equation analogous to Equation (12) where all errors will be expressed in terms of those parameters which are independently measured. It will then be assumed that the errors in these independently measured parameters do not correlate. Note should be taken of the fact that in using this approach the analysis depends on the particular measuring system being considered.

The first and currently the most important measuring system to consider is the standard radiosonde system. In this system the two parameters which are independently measured are pressure and temperature, and all other quantities are calculated from them.

In this study, the effects of humidity are being neglected. Since for most realistic situations the total effect of humidity produces a difference between actual temperature and virtual temperature of a few degrees at most, the effect of errors in the measurement of humidity would be the introduction of small errors in this temperature difference. It seems, therefore, that including humidity is an unnecessary complication.

In the following analysis, it will be assumed as is done in error theory that small errors can be treated as differentials. For example, if one has a quantity, Z, which is a function of two independent variables X and Y, i.e.,

$$Z = f(X, Y)$$

and X_i, Y_i and Z_i are a particular set of values of the variables with means $\overline{X}$, $\overline{Y}$ and $\overline{Z}$ and errors about the mean

$$\begin{aligned} \Delta X_i &= X_i - \overline{X} \\ \Delta Y_i &= Y_i - \overline{Y} \\ \Delta Z_i &= Z_i - \overline{Z}, \end{aligned} \tag{13}$$

then

$$\Delta Z_i = \frac{\partial Z}{\partial X} \Delta X_i + \frac{\partial Z}{\partial Y} \Delta Y_i \tag{14}$$

where the partial derivatives are evaluated at $X = \overline{X}$ and $Y = \overline{Y}$. Exactly the same result is obtained from expanding $Z = f(X,Y)$ in a Taylor Series and neglecting terms higher than first order; i.e.,

$$Z = f(X,Y) = f(\overline{X},\overline{Y}) + \left(\frac{\partial f}{\partial X}\right) (X-\overline{X}) + \left(\frac{\partial f}{\partial Y}\right) (Y-\overline{Y}) \tag{15}$$

$$\Delta Z = Z - f(\overline{X},\overline{Y}) = \left(\frac{\partial f}{\partial X}\right)\Delta X + \left(\frac{\partial f}{\partial Y}\right)\Delta Y \tag{16}$$

and for particular values of the variables

$$\Delta Z_i = \left(\frac{\partial f}{\partial X}\right)\Delta X_i + \left(\frac{\partial f}{\partial Y}\right)\Delta Y_i \tag{17}$$

where again all partial derivatives are evaluated at the mean values. This procedure can obviously be extended to any number of indepenaent variables.

In applying this procedure to the artillery problem, the unit effects play the role of the partial derivatives. A particular error in range, Δr_i, may therefore be written

$$\Delta r_i = U_W \Delta W_i + U_T \Delta T_i + U_\rho \Delta \rho_i \tag{18}$$

where ΔW_i is a wind error in knots and ΔT_i and $\Delta \rho_i$ are fractional errors in temperature and density, respectively, measured in percent deviation from the standard atmosphere.

For the standard radiosonde system the following equations are applicable:

$$dP = -\rho g dz \tag{19}$$

$$P = \rho RT \tag{20}$$

and

$$T = T_o - \gamma z \tag{21}$$

where P is the pressure, ρ is the density, z is the altitude, g is the acceleration of gravity, R is the gas constant for air, T_o is the surface temperature and γ is the lapse rate.

From Equation (20)

$$\rho = \frac{P}{RT} \, . \tag{22}$$

Taking differentials one obtains for the errors

$$d\rho = \frac{dP}{RT} - \frac{P}{RT^2} dT. \tag{23}$$

Dividing Equation (23) by ρ and using Equation (22) gives

$$\frac{d\rho}{\rho} = \frac{d\rho}{P} - \frac{dT}{T} \tag{24}$$

or

$$\Delta\rho = \Delta P - \Delta T \tag{25}$$

for the fractional errors.

Now with the standard radiosonde system an error in pressure can cause an error in temperature because an error in pressure produces an error in altitude and then the measured temperature is assigned to this incorrect altitude. The temperature error therefore consists of two parts, one due to the error in the temperature sensor itself, $\Delta T(T)$, and the other due to the error in pressure, $\Delta T(P)$. For the total temperature error one has

$$\Delta T = \Delta T(T) + \Delta T(P). \tag{26}$$

Substituting for ρ in Equation (19) from Equation (22) gives

$$dP = -\frac{Pg}{RT} dz \tag{27}$$

and differentiating Equation (21) gives

$$dz = -\frac{dT}{\gamma}\,. \tag{28}$$

Substituting Equation (28) into Equation (27) gives

$$\frac{dP}{P} = \frac{g}{\gamma R}\frac{dT}{T} \tag{29}$$

or

$$\Delta T(P) = \frac{\gamma R}{g}\,\Delta P \tag{30}$$

as the temperature error due to pressure.

The total temperature error is then

$$\Delta T = \Delta T(T) + \frac{\gamma R}{g}\,\Delta P \tag{31}$$

and the total density error is

$$\Delta\rho = \Delta P - \left(\Delta T(T) + \frac{\gamma R}{g}\,\Delta P\right). \tag{32}$$

By substitution of Equations (31) and (32) into Equation (18), there results for a particular error in range:

$$\Delta r_i = U_W \Delta W_i + [U_T - U_\rho]\Delta T_i(T)$$

$$+ \left[(U_T - U_\rho)\frac{\gamma R}{g} + U_\rho\right]\Delta P_i\,. \tag{33}$$

The mean-square error of a set of N measurements of the range error, Δr_i, is given by

$$\varepsilon^2 = \frac{1}{N}\sum_{i=1}^{N}(\Delta r_i)^2. \tag{34}$$

Therefore, from Equation (33)

$$\varepsilon^2 = U_W{}^2\,\frac{\sum\limits_{i=1}^{N}(\Delta W_i)^2}{N} + [U_T - U_\rho]^2\,\frac{\sum\limits_{i=1}^{N}(\Delta T_i(T))^2}{N}$$

$$+ [(U_T - U_\rho)\frac{\gamma R}{g} + U_\rho]^2 \frac{\sum_{i=1}^{N}(\Delta P_i)^2}{N}$$

$$+ 2U_W[U_T - U_\rho] \frac{\sum_{i=1}^{N}(\Delta W_i)(\Delta T_i(T))}{N}$$

$$+ 2U_W[(U_T - U_\rho)\frac{\gamma R}{g} + U_\rho] \frac{\sum_{i=1}^{N}(\Delta W_i)(\Delta P_i)}{N}$$

$$+ 2[U_T - U_\rho][(U_T - U_\rho)\frac{\gamma R}{g} + U_\rho] \frac{\sum_{i=1}^{N}(\Delta T_i(T))(\Delta P_i)}{N} . \tag{35}$$

Equation (35) can be simplified in the following manner.

In the first three terms on the right hand side of Equation (35)

$$\frac{1}{N}\sum_{i=1}^{N}(\Delta W_i)^2 = \varepsilon_W^2 \quad \text{the mean square error in the wind} \tag{36}$$

$$\frac{1}{N}\sum_{i=1}^{N}(\Delta T_i(T))^2 = \varepsilon_T^2 \quad \text{the mean square error in the temperature} \tag{37}$$

and

$$\frac{1}{N}\sum_{i=1}^{N}(\Delta P_i)^2 = \varepsilon_P^2 \quad \text{the mean square error in the pressure.} \tag{38}$$

The cross-product terms can be expressed as

$$\frac{1}{N}\sum_{i=1}^{N}(\Delta W_i)(\Delta T_i(T)) = r_{WT}\varepsilon_W\varepsilon_T \tag{39}$$

$$\frac{1}{N}\sum_{i=1}^{N}(\Delta W_i)(\Delta P_i) = r_{WP}\varepsilon_W\varepsilon_P \tag{40}$$

and

$$\frac{1}{N}\sum_{i=1}^{N}(\Delta T_i(T))(\Delta P_i) = r_{TP}\varepsilon_T\varepsilon_P \tag{41}$$

where the r's are the correlation coefficients between the variables indicated by the subscripts. Now assuming, as before, that the errors in the independently measured quantities do not correlate, then all the cross-product terms are zero and Equation (35) becomes

$$\varepsilon^2 = U_W^2\varepsilon_W^2 + [U_T-U_\rho]^2\varepsilon_T^2 + [(U_T-U_\rho)\frac{\gamma R}{g} + U_\rho]^2\,\varepsilon_\rho^2. \tag{42}$$

Equation (42) relates the total allowable error, ε, whose value is given by the effectiveness methodology, to the three unknown meteorological errors, ε_W, ε_T, and ε_p. Thus there is one equation and three unknown quantities. To determine ε_W, ε_T and ε_p, some additional assumptions must be made. A simple and quite reasonable device is to make the allowable error in a particular parameter inversely proportional to the composite unit effect for that parameter; i.e.,

$$\varepsilon_W = \frac{\alpha}{|U_W|} \tag{43}$$

$$\varepsilon_T = \frac{\alpha}{|U_T - U_\rho|} \tag{44}$$

$$\varepsilon_p = \frac{\alpha}{|(U_T-U_\rho)\frac{\gamma R}{g} + U_\rho|} \tag{45}$$

where the absolute is taken because only rms errors are being considered.

This gives

$$\alpha = \frac{\varepsilon}{\sqrt{3}}. \tag{46}$$

The principle being applied here is that the parameter to which the projectile is most sensitive should be measured most accurately.

Equations (43), (44), (45), and (46) are used to calculate the allowable errors in wind, temperature, and pressure.

RESULTS

Reference I gives a summary of the results of the effectiveness methodology. In this study, the allowable errors for a fixed reduction in coverage were calculated for a range of target sizes assumed to occur in practice and for three modes of fire, battery volley fired in parallel sheaf, battery volley fired in open sheaf and battalion volley. The calculations were performed for the four tube artillery weapon systems, the 105mm Howitzer, the 155mm Howitzer, the 175mm Gun and the eight-inch Howitzer. The results of all these calculations are summarized by giving the allowable errors for each weapon to insure no more than a 10% reduction in target coverage for all the targets considered, for 75% of the targets considered and for 50% of the targets considered. In determining the allowable meteorological errors, only the cases of all the targets and 75% of the targets were used. These data are reproduced in Table I for reference.

In calculating the allowable meteorological errors from the data in Table I, the number of possible combinations of range, charge and weapon are almost endless. To reduce the problem to manageable size, the following approach was taken. Since the unit effects increase with increasing range, it should be sufficient to take the unit effects for some reasonable long range. In this study the criterion chosen was to use two-thirds maximum range for each charge of each weapon.

The results of the calculations for the standard radiosonde system are presented in Table II for all the targets considered, and Table III for 75% of the targets considered. (See Appendix A.) The range listed is the nominal two-thirds maximum range for each charge of each weapon. In general, for the lower charges and shorter ranges, the required accuracies are quite ample and are met by the current radiosonde system. The higher charges and longer ranges leave something to be desired. The biggest problem appears to be in the wind measurement accuracy and also in the wind variability. Due to the relatively high variability of the wind, it is doubtful whether a wind measurement which is a few hours old has an accuracy any better than 4-5 knots.

CONCLUSIONS

The application of an artillery effectiveness methodology to the analysis of a particular meteorological measuring system appears to be a reasonable method for obtaining realistic accuracy requirements.

TABLE I

Maximum allowable errors to insure that no more than 10% reduction in coverage will occur in meters circular error probable (CEP)

For All Targets

Battery Volley Parallel Sheaf		
105mm Howitzer	17 meters	CEP
155mm Howitzer	28 meters	CEP
8-inch Howitzer	25 meters	CEP
175mm Gun	40 meters	CEP
Battery Volley Open Sheaf		
105mm Howitzer	28 meters	CEP
155mm Howitzer	36 meters	CEP
8-inch Howitzer	31 meters	CEP
175mm Gun	48 meters	CEP
Battalion Volley		
105mm Howitzer	37 meters	CEP
155mm Howitzer	38 meters	CEP
8-inch Howitzer	32 meters	CEP
175mm Gun	50 meters	CEP

TABLE I (CON'T)

75% Of Targets

Battery Volley, Parallel Sheaf

105mm Howitzer	20 meters	CEP
155mm Howitzer	29 meters	CEP
8-inch Howitzer	25 meters	CEP
175mm Gun	43 meters	CEP

Battery Volley, Open Sheaf

105mm Howitzer	29 meters	CEP
155mm Howitzer	39 meters	CEP
8-inch Howitzer	32 meters	CEP
175mm Gun	73 meters	CEP

Battalion Volley

105mm Howitzer	38 meters	CEP
155mm Howitzer	44 meters	CEP
8-inch Howitzer	33 meters	CEP
175mm Gun	78 meters	CEP

TABLE II

Allowable errors for the standard radiosonde system in the indicated meteorological parameters for all targets, with the four indicated cannon weapons.

* * * * * * * * * * * * * * CANNON-105MM * * * * * * * * * * * * *

(ALL TARGETS)

BATTERY VOLLEY, PARALLEL SHEAF

		---- ALLOWABLE ERRORS ----		
CHARGE	RANGE (METERS)	WIND (KNOTS)	TEMPERATURE (% OF STANDARD)	PRESSURE
1	2300	14.02	7.55	7.26
2	2500	12.27	6.13	5.79
3	3100	9.81	4.27	4.16
4	3800	5.77	2.65	2.89
5	4900	2.04	9.81	1.58
6	6000	0.91	0.78	0.72
7	7300	0.92	2.80	0.49

BATTERY VOLLEY, OPEN SHEAF

		---- ALLOWABLE ERRORS ----		
CHARGE	RANGE (METERS)	WIND (KNOTS)	TEMPERATURE (% OF STANDARD)	PRESSURE
1	2300	23.09	12.44	11.96
2	2600	20.21	10.10	9.54
3	3100	16.17	7.03	6.85
4	3800	9.51	4.37	4.76
5	4900	3.37	16.17	2.60
6	6000	1.50	1.28	1.19
7	7300	1.51	4.62	0.80

BATTALION VOLLEY

		---- ALLOWABLE ERRORS ----		
CHARGE	RANGE (METERS)	WIND (KNOTS)	TEMPERATURE (% OF STANDARD)	PRESSURE
1	2300	30.52	16.43	15.80
2	2600	26.70	13.35	12.61
3	3100	21.36	9.29	9.05
4	3800	12.57	5.77	6.29
5	4900	4.45	21.36	3.44
6	6000	1.98	1.70	1.57
7	7300	2.00	6.10	1.06

TABLE II (CONT)

* * * * * * * * * * * * * * CANNON-155MM * * * * * * * * * * * * * * * * * *

(ALL TARGETS)

BATTERY VOLLEY, PARALLEL SHEAF

- - - - ALLOWABLE ERRORS - - - -

CHARGE	RANGE (METERS)	WIND (KNOTS)	TEMPERATURE (% OF STANDARD)	PRESSURE (% OF STANDARD)
1G	2700	20.21	8.98	11.10
2G	3400	13.47	5.99	7.40
3G	4300	10.10	3.76	4.65
4G	5400	3.37	17.96	2.55
5G	6600	1.63	1.70	1.18
3W	4500	9.51	3.59	4.44
4W	5500	2.61	5.39	2.19
5W	6600	1.63	1.82	1.17
6W	8000	1.67	2.38	0.82
7W	9700	1.63	0.58	0.55
8	12000	1.48	0.33	0.36

BATTERY VOLLEY, OPEN SHEAF

- - - - ALLOWABLE ERRORS - - - -

CHARGE	RANGE (METERS)	WIND (KNOTS)	TEMPERATURE (% OF STANDARD)	PRESSURE (% OF STANDARD)
1G	2700	25.98	11.55	14.27
2G	3400	17.32	7.70	9.51
3G	4300	12.99	4.83	5.97
4G	5400	4.33	23.09	3.28
5G	6600	2.10	2.19	1.52
3W	4500	12.23	4.62	5.71
4W	5500	3.35	6.93	2.82
5W	6600	2.10	2.34	1.51
6W	8000	2.14	3.06	1.05
7W	9700	2.10	0.74	0.70
8	12000	1.91	0.43	0.40

BATTALION VOLLEY

- - - - ALLOWABLE ERRORS - - - -

CHARGE	RANGE (METERS)	WIND (KNOTS)	TEMPERATURE (% OF STANDARD)	PRESSURE (% OF STANDARD)
1G	2700	27.42	12.19	15.07
2G	3400	18.28	8.13	10.04
3G	4300	13.71	5.10	6.31
4G	5400	4.57	24.38	3.47
5G	6600	2.22	2.31	1.60
3W	4500	12.91	4.88	6.03
4W	5500	3.54	7.31	2.98
5W	6600	2.22	2.47	1.59
6W	8000	2.26	3.23	1.11
7W	9700	2.22	0.78	0.74
8	12000	2.01	0.45	0.48

TABLE II (CONT)

* * * * * * * * * * * * * * CANNON-175MM * * * * * * * * * * * * * * *

(ALL TARGETS)

BATTERY VOLLEY, PARALLEL SHEAF

CHARGE	RANGE (METERS)	ALLOWABLE ERRORS: WIND (KNOTS)	ALLOWABLE ERRORS: TEMPERATURE (% OF STANDARD)	ALLOWABLE ERRORS: PRESSURE (% OF STANDARD)
1	10100	2.49	0.98	0.89
2	14700	2.38	0.48	0.41
3	21800	1.61	0.25	0.21

BATTERY VOLLEY, OPEN SHEAF

CHARGE	RANGE (METERS)	ALLOWABLE ERRORS: WIND (KNOTS)	ALLOWABLE ERRORS: TEMPERATURE (% OF STANDARD)	ALLOWABLE ERRORS: PRESSURE (% OF STANDARD)
1	10100	3.11	1.17	1.06
2	14700	2.86	0.58	0.49
3	21800	1.94	0.30	0.25

BATTALION VOLLEY

CHARGE	RANGE (METERS)	ALLOWABLE ERRORS: WIND (KNOTS)	ALLOWABLE ERRORS: TEMPERATURE (% OF STANDARD)	ALLOWABLE ERRORS: PRESSURE (% OF STANDARD)
1	10100	3.24	1.22	1.11
2	14700	2.98	0.60	0.51
3	21800	2.02	0.32	0.26

TABLE II (CONT)

* * * * * * * * * * * * * * * CANNON-8 IN * * * * * * * * * * * * * * *

(ALL TARGETS)

BATTERY VOLLEY, PARALLEL SHEAF

CHARGE	RANGE (METERS)	WIND (KNOTS)	TEMPERATURE	PRESSURE
		---- ALLOWABLE ERRORS ----	(% OF STANDARD)	
1	3700	13.12	5.55	6.86
2	4400	10.31	3.90	4.82
3	5300	4.01	4.81	3.05
4	6400	1.44	0.94	1.24
5	7800	1.47	6.28	0.87
6	9300	1.47	0.92	0.60
7	11200	1.46	0.36	0.41

BATTERY VOLLEY, OPEN SHEAF

CHARGE	RANGE (METERS)	WIND (KNOTS)	TEMPERATURE	PRESSURE
		---- ALLOWABLE ERRORS ----	(% OF STANDARD)	
1	3700	16.27	6.88	8.51
2	4400	12.78	4.84	5.98
3	5300	4.97	5.97	3.79
4	6400	1.79	1.16	1.54
5	7800	1.83	7.78	1.08
6	9300	1.83	1.14	0.74
7	11200	1.81	0.44	0.50

BATTALION VOLLEY

CHARGE	RANGE (METERS)	WIND (KNOTS)	TEMPERATURE	PRESSURE
		---- ALLOWABLE ERRORS ----	(% OF STANDARD)	
1	3700	16.80	7.11	8.78
2	4400	13.20	4.99	6.17
3	5300	5.13	6.16	3.91
4	6400	1.85	1.20	1.59
5	7800	1.89	8.03	1.11
6	9300	1.89	1.18	0.76
7	11200	1.87	0.46	0.52

TABLE III

Allowable errors for the standard radiosonde system for 75% of the targets, with the indicated cannon weapons.

* * * * * * * * * * * * * * CANNON-105MM * * * * * * * * * * * * * * *

(75% OF TARGETS)

BATTERY VOLLEY, PARALLEL SHEAF

CHARGE	RANGE (METERS)	WIND (KNOTS)	TEMPERATURE (% OF STANDARD)	PRESSURE (% OF STANDARD)
		---- ALLOWABLE ERRORS ----		
1	2300	16.50	8.88	8.54
2	2600	14.43	7.22	6.81
3	3100	11.55	5.02	4.89
4	3800	6.79	3.12	3.40
5	4900	2.41	11.55	1.86
6	6000	1.07	0.92	0.85
7	7300	1.08	3.30	0.57

BATTERY VOLLEY, OPEN SHEAF

CHARGE	RANGE (METERS)	WIND (KNOTS)	TEMPERATURE (% OF STANDARD)	PRESSURE (% OF STANDARD)
		---- ALLOWABLE ERRORS ----		
1	2300	23.92	12.88	12.39
2	2600	20.93	10.46	9.88
3	3100	16.74	7.28	7.09
4	3800	9.85	4.53	4.93
5	4900	3.49	16.74	2.70
6	6000	1.55	1.33	1.23
7	7300	1.56	4.78	0.83

BATTALION VOLLEY

CHARGE	RANGE (METERS)	WIND (KNOTS)	TEMPERATURE (% OF STANDARD)	PRESSURE (% OF STANDARD)
		---- ALLOWABLE ERRORS ----		
1	2300	31.34	16.88	16.23
2	2600	27.42	13.71	12.95
3	3100	21.94	9.54	9.29
4	3800	12.91	5.93	6.47
5	4900	4.57	21.94	3.53
6	6000	2.03	1.74	1.61
7	7300	2.05	6.27	1.09

TABLE III (CONT)

* * * * * * * * * * * * * * * CANNON-155MM * * * * * * * * * * * * * * * *

(75% OF TARGETS)

BATTERY VOLLEY, PARALLEL SHEAF

CHARGE	RANGE (METERS)	WIND (KNOTS)	TEMPERATURE (% OF STANDARD)	PRESSURE (% OF STANDARD)
		---- ALLOWABLE ERRORS ----		
1G	2700	20.93	9.30	11.50
2G	3400	13.95	6.20	7.66
3G	4300	10.46	3.89	4.81
4G	5400	3.49	18.60	2.65
5G	6600	1.69	1.75	1.22
3W	4500	9.85	3.7	4.60
4W	5500	2.70	5.58	2.27
5W	6600	1.69	1.88	1.21
6W	8000	1.73	2.46	0.85
7W	9700	1.69	0.60	0.56
8	12000	1.54	0.34	0.37

BATTERY VOLLEY, OPEN SHEAF

CHARGE	RANGE (METERS)	WIND (KNOTS)	TEMPERATURE (% OF STANDARD)	PRESSURE (% OF STANDARD)
		---- ALLOWABLE ERRORS ----		
1G	2700	28.15	12.51	15.46
2G	3400	18.76	8.34	10.31
3G	4300	14.07	5.24	6.47
4G	5400	4.69	25.02	3.56
5G	6600	2.27	2.37	1.64
3W	4500	13.25	5.00	6.18
4W	5500	3.63	7.51	3.05
5W	6600	2.27	2.53	1.63
6W	8000	2.32	3.31	1.14
7W	9700	2.27	0.80	0.76
8	12000	2.07	0.46	0.50

BATTALION VOLLEY

CHARGE	RANGE (METERS)	WIND (KNOTS)	TEMPERATURE (% OF STANDARD)	PRESSURE (% OF STANDARD)
		---- ALLOWABLE ERRORS ----		
1G	2700	31.75	14.11	17.44
2G	3400	21.17	9.41	11.63
3G	4300	15.88	5.91	7.30
4G	5400	5.29	28.23	4.01
5G	6600	2.57	2.67	1.85
3W	4500	14.94	5.65	6.98
4W	5500	4.10	8.47	3.45
5W	6600	2.57	2.85	1.84
6W	8000	2.62	3.74	1.28
7W	9700	2.57	0.90	0.86
8	12000	2.33	0.52	0.56

TABLE III (CONT)

* * * * * * * * * * * * * * CANNON-175MM * * * * * * * * * * * * * * * *

(75% OF TARGETS)

BATTERY VOLLEY, PARALLEL SHEAF

			---- ALLOWABLE ERRORS ----	
CHARGE	RANGE (METERS)	WIND (KNOTS)	TEMPERATURE (% OF STANDARD)	PRESSURE
1	10100	2.79	1.05	0.95
2	14700	2.56	0.52	0.44
3	21800	1.74	0.27	0.22

BATTERY VOLLEY, OPEN SHEAF

			---- ALLOWABLE ERRORS ----	
CHARGE	RANGE (METERS)	WIND (KNOTS)	TEMPERATURE (% OF STANDARD)	PRESSURE
1	10100	4.74	1.79	1.62
2	14700	4.35	0.88	0.74
3	21800	2.95	0.46	0.38

BATTALION VOLLEY

			---- ALLOWABLE ERRORS ----	
CHARGE	RANGE (METERS)	WIND (KNOTS)	TEMPERATURE (% OF STANDARD)	PRESSURE
1	10100	5.06	1.91	1.73
2	14700	4.64	0.94	0.79
3	21800	3.15	0.49	0.41

TABLE III (CONT)

* * * * * * * * * * * * * * * CANNON-8 IN * * * * * * * * * * * * * * * * * *

(75% OF TARGETS)

BATTERY VOLLEY, PARALLEL SHEAF

CHARGE	RANGE (METERS)	WIND (KNOTS)	TEMPERATURE	PRESSURE
			---- ALLOWABLE ERRORS ---- (% OF STANDARD)	
1	3700	13.12	5.55	6.86
2	4400	10.31	3.90	4.82
3	5300	4.01	4.81	3.05
4	6400	1.44	0.94	1.24
5	7800	1.47	6.28	0.87
6	9300	1.47	0.92	0.60
7	11200	1.46	0.36	0.41

BATTERY VOLLEY, OPEN SHEAF

CHARGE	RANGE (METERS)	WIND (KNOTS)	TEMPERATURE	PRESSURE
			---- ALLOWABLE ERRORS ---- (% OF STANDARD)	
1	3700	16.80	7.11	8.78
2	4400	13.20	4.99	6.17
3	5300	5.13	6.16	3.91
4	6400	1.85	1.20	1.59
5	7800	1.89	8.03	1.11
6	9300	1.89	1.18	0.76
7	11200	1.87	0.46	0.52

BATTALION VOLLEY

CHARGE	RANGE (METERS)	WIND (KNOTS)	TEMPERATURE	PRESSURE
			---- ALLOWABLE ERRORS ---- (% OF STANDARD)	
1	3700	17.32	7.33	9.06
2	4400	13.61	5.15	6.36
3	5300	5.29	6.35	4.03
4	6400	1.91	1.24	1.64
5	7800	1.94	8.28	1.15
6	9300	1.94	1.21	0.79
7	11200	1.92	0.47	0.54

APPENDIX A

In this appendix an example of the method of calculation of the allowable errors appearing in Tables II and III will be given. It should be noted, however, that the allowable errors listed in these tables should not be thought of as continuous functions of the indicated range. As mentioned in the text, the range given in the tables is the nominal two-thirds maximum range for the indicated charge and weapon. Each entry is therefore to be considered separately.

As an illustration, one of the "odd" appearing entries in the table will be calculated. Consider the 155 Howitzer firing in battery volley, open sheaf with charge 3W. The allowable error in range for this mode of fire is given in Table I as 36 meters. The quantity α is therefore given by

$$\alpha = \frac{36}{\sqrt{3}} = 20.78 \text{ meters.}$$

Referring to Firing Table FT 155-AH-2, for the unit effects, we obtain for a range of 4500 meters

$$U_W = 1.7 \frac{\text{MET}}{\text{KNOT}}$$

$$U_T = 0$$

and

$$U_\rho = 4.5 \frac{\text{MET}}{1\%}.$$

Using Equations (43), (44), and (45) in the text, we have

$$\varepsilon_W = \frac{\alpha}{|U_W|} = \frac{20.78}{1.7} = 12.2$$

$$\varepsilon_T = \frac{\alpha}{|U_T - U_\rho|} = \frac{20.78}{4.5} = 4.6$$

$$\varepsilon_P = \frac{\alpha}{\left|(U_T - U_\rho)\frac{\gamma R}{g} + U_\rho\right|}.$$

and with $\frac{\gamma R}{g} = 0.19$,

$$\varepsilon_P = \frac{20.78}{3.645} = 5.7.$$

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