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ARTILLERY ACCURACY: SIMPLE MODELS TO ASSESS THE IMPACT OF NEW EQUIPMENT AND TACTICS

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U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
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This report describes some simple yet realistic ways to examine the effect of current trends in hardware and tactics on the accuracy of conventional artillery munitions. Examples are provided to illustrate the main points. A computer program that models predicted fire techniques is also included in this report.

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1. INTRODUCTION

This report examines some simple but realistic ways to quantify the impact of hardware design and tactical employment of cannon artillery on the delivery accuracy of conventional artillery munitions. The genesis of this report is the 1982 Systems Analysis Working Group for Direct Support Weapon System (DSWS).[1,2] One of the chief concerns of this working group was to evaluate how different design features being proposed for future self-propelled howitzers and different operational procedures would interact to affect the overall accuracy of artillery fire.

To answer these questions, equations were developed to determine the errors associated with the two basic delivery techniques - adjusted fire (registration/transfer) and predicted (unadjusted) fire. These equations incorporate a realistic treatment of the effects of changes in hardware and tactics on these delivery methods. For example, the addition of onboard navigation/orientation systems has an impact on both types of fire but in very different ways. If adjusted fire is used, then the errors in position/orientation are partially accounted for by correction factors such as VE or Range K.[3] Consequently, little improvement in accuracy occurs when adding the navigation system. Using predicted fire, however, one cannot account for these errors (the errors are not "adjusted out") and they are present in their entirety in the fall of shot. Thus, an onboard navigation system does provide a dramatic improvement in delivery accuracy if "shoot and scoot" tactics without survey support are employed.

The models described below allow one to quantify the effects of hardware improvements and changes in tactical employment of cannon artillery on their overall delivery accuracy. Parameter values derived from real-world tests are used whenever possible. A detailed description of the development of the models is being prepared and will be published as a Ballistic Research Laboratory report.[4]

2. GENERAL COMMENTS

2.1 Comments on Delivery Accuracy in General. Artillery delivery techniques are categorized as either adjusted or predicted fire, and all design features of current and proposed systems are evaluated by noting their effect on accuracy in one or both of these categories. The reader is referred to Sections 3.1 and 4.1 for definitions of these delivery techniques.

The accuracy equations using these techniques are written to provide first round fire for effect estimates in range and deflection for both air and ground bursts. Mean point of impact (MPI) accuracies can be obtained by deleting the round to round or precision variance in the appropriate places (but not in all instances, as explained in the text). It will be seen that in most cases air burst delivery error estimates - in both precision and accuracy - are smaller than corresponding ground burst estimates. This is due to the fact that the effects of many nonstandard conditions on time of flight correlate with and offset their effects on range. Only when independent fuze setting errors, such as fuze to fuze variation (precision), become very large will air burst estimates become larger than corresponding ground burst values. Approximations to convert ground burst unit corrections to equivalent air burst values are provided in Appendix A.

The error budget provided in Appendix A has been used to generate the accuracy estimates. This error budget is derived from recent artillery accuracy studies conducted by the Ballistic Research Laboratory (BRL), the US Army Materiel Systems Analysis Activity (AMSAA), the Human Engineering Laboratory (HEL), and the US Army Field Artillery School (USAFAS). Wherever necessary, the justification or rationale for the error magnitudes has been provided. Improvements or modifications in the simple assumptions or the limited data base are expected, but the values as shown should be representative of achievable levels of delivery accuracy.

The examples given in Appendix A are designed to show how to relate design options and tactics to the appropriate delivery technique and how the changes in hardware and tactics can be incorporated explicitly in the models. More importantly, the examples will illustrate the net effect in accuracy estimates when improvements in artillery systems hardware are made or when artillery tactics are changed.

All conventional cannon/projectile/propellant combinations (including base bleed shells, extended range shapes, new propellant geometries, etc.) can be analyzed using the models as described. Moving targets and guided munitions are not considered.

2.2 Comments on the Use of Registration and Transfer Techniques. A few remarks are needed on the use of any device, such as a radar, that provides real time position data for artillery shells. Such devices can be adapted to any howitzer, provided the unit has the proper fire control capability. From the use of such a device that gives real time shell location, at least two types of position data can be obtained - relative position (gun to shell) and should hit/did hit data (shell to known point and gun to shell). The relative position data allow one to compute adjusted elevation, deflection, and fuze setting data to account for existing met and muzzle velocity conditions. Should hit/did hit data permit the additional inclusion of the gun's position/orientation errors in the adjusted aiming data, since the shell position can be referenced to a known should hit point. In addition, if one howitzer uses a device to adjust its fire and provides those corrections to other howitzers in that position, then additional location, orientation, and velocity errors of those howitzers must be included to estimate their accuracy.

Finally, if the gun moves and/or a new met message is received, the unit must decide whether to keep the orginal adjustment factor. This factor includes corrections for the previous position, met staleness, and ballistic/technical fire control (ballistic model) errors. Only the last category might remain constant under these conditions. The unit must choose among keeping the adjustment factors and retaining additional uncorrelated errors due to moving and/or met, discarding the factors and living with uncorrected ballistic data, or using the registering device more frequently. The models and error budget are currently set up to address these types of questions (see examples in Appendix A).

2.3 Comments on Adjusted Fire versus Predicted Fire. There are several important distinctions between adjusted fire and predicted fire (as defined in this work) which had to be accounted for in the models and error budget. These will be treated in some detail in the sections describing these areas, but a few general points should be noted. Adjusted fire techniques using, for example, a VE or Range K based on firings on a known point have historically been preferred by the artillery, since they reduce the effects of unmeasured or unknown error sources as well as errors in measuring met, velocity, position, etc. In simple terms, the unknown errors are "adjusted out" of the system. These more conventional adjustment techniques are, of course, well suited to a relatively static war without a serious counter-battery threat.

On the other hand, predicted fire delivery methods are well suited to a more fluid war with counter-battery threats. In recent years, the artillery has leaned more towards predicted delivery techniques for obvious reasons. However, the disadvantage to predicted fire is that all significant sources of error must be precisely measured and frequently updated. These basic ideas should be kept in mind when considering the best choices for hardware and tactics. Ideally, the choices should lead to a system which has the potential for the accuracy of adjusted fire with the survivability advantages of predicted fire.

3. DELIVERY ACCURACY MODELS FOR ADJUSTED FIRE TECHNIQUES

3.1 Background Information. Adjusted fire techniques use information from previous missions (e.g., precision registrations, radar sensings, or observer adjustments onto known points) to reduce unknown errors due to staleness in met, position/orientation errors, ballistics, etc. The information is usually contained in adjustment factors such as VE, Range K, total deflection correction, or fuze setting correction that are used to compute the aiming data to enter the fire for effect phase. The ability to "adjust out" all these errors reduces the demands on ballistic, navigation, and met sensors.

The models developed for these procedures[5] are capable of estimating the effect of delays between the time when adjusted data are obtained and when a mission is conducted, distance between the target and the point of adjustment (registration range), change in gun location/orientation due to displacement ("shoot and scoot" tactics), transfer of corrections between guns (if the base piece is used to adjust), and the methods used to adjust fire (radar, precision registration, etc.). Using this model to estimate the above effects on accuracy, the impact of a wide variety of hardware and operational features (e.g., how often and what type of adjustment factors are computed, the effect of changes in gun positions or new met data) can be assessed. The various levels of accuracy under these conditions can then be compared in a manner consistent with predicted fire accuracies described later in this report.

3.2 The Model - General.

Range: $$\sigma_{Rn} = \{\sigma^2_{prec} + \sigma^2_{met} + \sigma^2_{vel} + \sigma^2_{trans} + \sigma^2_{loc}\}^{1/2} \tag{3.2.1}$$

Deflection: $$\sigma_D = \{\sigma^2_{prec} + \sigma^2_{met} + \sigma^2_{trans} + \sigma^2_{loc} + \sigma^2_{aim}\}^{1/2} \tag{3.2.2}$$

Elements of equation 3.2.1 (range accuracy errors) for the adjusted fire techniques are further defined as:

σ^2_{prec} = round-to-round variability in range or deflection. Air burst and ground burst values are found in Table G of the appropriate Firing Tables. Note that values in an operational environment will probably be <u>larger</u>.

σ^2_{met} = $\sigma^2_{staleness}$ (error due to age of the met message) , if using same message used when adjusting;

= $\sigma^2_{instrument}$ (error due to met measurements) + $\sigma^2_{staleness}$, if a new message is received.

σ^2_{vel} = occasion to occasion variability, if single gun used; occasion to occasion variability + tube-to-tube variability, if correction transferred to another gun.

$\sigma^{2\dagger}_{trans}$ = error at the target range (X_T) due to using velocity corrections established at the registration range (X_R) to absorb all other errors as well;

$$= \sigma^2_{reg}\left(\frac{\Delta X_T}{\Delta V} \Big/ \frac{\Delta X_R}{\Delta V}\right)^2 + \sigma^2_{pos_o}\left(\frac{\Delta X_T}{\Delta V} \Big/ \frac{\Delta X_R}{\Delta V} - 1\right)^2$$

[†] This form corresponds to using velocity as the adjustment factor for range. Other choices for adjustment factor are possible, e.g., Range K, but σ^2_{trans} would be comparable in magnitude. The σ^2_{trans} equation has the following form for devices using the Range K technique. Both the Battery Computer System (BCS) and Graphical Firing Table (GFT) use this form of adjustment factor.

$\sigma^2_{trans\ (range)}$ = error at the target range (X_T) due to using a percentage change in range (called Range K) established at the registration range (X_R) to represent the combined effects of all error sources.

$$= \sigma^2_{reg}\left(\frac{X_T}{X_R}\right)^2 + \sigma^2_{pos_o}\left(\frac{X_T}{X_R} - 1\right)^2 + (\sigma^2_{dens} + \sigma^2_{ball/TFC})\left(\frac{\Delta X_R}{\Delta D} \cdot \frac{X_T}{X_R} - \frac{\Delta X_T}{\Delta D}\right)^2$$

$$+ \sigma^2_{temp}\left(\frac{\Delta X_R}{\Delta T} \cdot \frac{X_T}{X_R} - \frac{\Delta X_T}{\Delta T}\right)^2 + \sigma^2_{wind}\left(\frac{\Delta X_R}{\Delta W} \cdot \frac{X_T}{X_R} - \frac{\Delta X_T}{\Delta W}\right)^2 + \sigma^2_{vel}\left(\frac{\Delta X_R}{\Delta V} \cdot \frac{X_T}{X_R} - \frac{\Delta X_T}{\Delta V}\right)^2$$

$$+ \quad (\sigma^2_{dens} + \sigma^2_{ball/TFC}) \left[\frac{\Delta X_T}{\Delta D} - \left(\frac{\Delta X_R}{\Delta D} \bigg/ \frac{\Delta X_R}{\Delta V}\right) \frac{\Delta X_T}{\Delta V}\right]^2$$

$$+ \quad (\sigma^2_{temp} \left[\frac{\Delta X_T}{\Delta T} - \left(\frac{\Delta X_R}{\Delta T} \bigg/ \frac{\Delta X_R}{\Delta V}\right) \frac{\Delta X_T}{\Delta V}\right]^2$$

$$+ \quad (\sigma^2_{wind} \left[\frac{\Delta X_T}{\Delta W} - \left(\frac{\Delta X_R}{\Delta W} \bigg/ \frac{\Delta X_R}{\Delta V}\right) \frac{\Delta X_T}{\Delta V}\right]^2$$

The σ^2_{trans} components in range are further defined as:

σ^2_{reg} = variability in MPI (Mean Point of Impact) of adjusting rounds

$\approx (\frac{2}{3}\sigma_{prec})^2$ for precision registration

$\sigma^2_{pos_0}$ = variability in gun position (base piece).

$$\left.\begin{array}{r}\sigma^2_{dens}\\ \sigma^2_{temp}\\ \sigma^2_{wind}\end{array}\right\} = \begin{array}{l}\text{errors at time of "registration. As best case, use}\\ \sigma^2_{instruments}\text{; add staleness as appropriate.}\\ \text{(See Error Budget Table.)}\end{array}$$

$\sigma^2_{ball/TFC}$ = variability about mean ballistic performance and ability to produce firing solutions (technical fire control). (See page 13.)

σ^2_{loc} = error in onboard navigation, survey, or map spot. This is only used if gun moves from position at which adjustment data were obtained or correction factors are passed to another gun position. It is assumed to be uncorrelated with $\sigma^2_{pos_0}$. (See discussion under Predicted Fire.)

Elements of equation 3.2.2 (deflection accuracy errors) for the adjusted fire technique are further defined as:

σ^2_{prec} = round-to-round variability in deflection.

σ^2_{met} = $\sigma^2_{staleness}$, if using same message used when adjusting

$\sigma^2_{instrument} + \sigma^2_{staleness}$, if a new message is received

$$\sigma^2_{trans} = \sigma^2_{reg_D} + \sigma^2_{wind_D} \left(\frac{\Delta D_R}{\Delta W} - \frac{\Delta D_T}{\Delta W}\right)^2$$

The σ^2_{trans} components in deflection are further defined as:

$\sigma^2_{reg_D}$ = error in deflection MPI of adjusting rounds. Initial orientation/position errors are absorbed into $(\frac{2}{3}\sigma_{prec_D})^2$

$\sigma^2_{wind_D}$ = variability in crosswind at time of "registration"

σ^2_{loc} = error in onboard navigation, survey, or map spot.

σ^2_{aim} = error in gun pointing (hardware).† This is less than one milliradian for elevation and is not included in range equation. (See discussion in Appendix A).

3.3 The Model - Registration and Transfer. This model is just a slight variation of the general version described above. The principal change is in the term σ^2_{reg} which is part of the transfer error (σ^2_{trans}). In the present case, we chose the following representation:[6,7]

$$\sigma^2_{reg} = (\sigma^2_{radar} + \sigma^2_{prec}) /n$$

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†If firing charts with pins are used, add error due to this source.

where n = the number of rounds used in adjustment (sensed by radar). This produces a lower bound of $\sigma^2_{reg} = \frac{\sigma^2_{prec}}{n}$ when $\sigma^2_{radar} = 0$. To find a more realistic value, we used existing data from experiments conducted with the Fieldguard radar registration system using HE M107 shellfired from the M109 155 mm howitzer at Charge 7.[8] Based on this information (see footnote for derivation), we use $\sigma^2_{radar} \approx \sigma^2_{prec}$ in range and deflection.[9]†

Two types of radar registration and adjustment missions were modeled - immediate transfer and delayed transfer. By immediate transfer, it is meant that fire is delivered on a target within ± 2 km of the adjustment or registration range immediately after using the radar to register. Under delayed transfer, four cases are examined:

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†Fieldguard data received from Mr. C. Lebegern, BRL, indicate that $2\sigma_{Rn} \approx 100$ meters and $2\sigma_D \approx 50$ meters for firings conducted using HE M107 shell from M109 howitzer, Charge 7, at 13-14 km range. Using the simple model

$$\{\sigma^2_{MPI} + \sigma^2_{prec}\}^{1/2} = \sigma_{Rn}$$

we have

$$2(\sigma^2_{MPI} + \sigma^2_{prec})^{1/2} \approx 100 \Rightarrow \sigma_{MPI} = (50^2 - 30^2)^{1/2} = 40 \text{ meters.}$$

Then if

$$\sigma^2_{MPI} = \frac{\sigma^2_{radar} + \sigma^2_{prec}}{1}, \Rightarrow \sigma_{radar} = (40^2 - 30^2)^{1/2} \approx 30 \text{ meters} = \sigma_{prec_{Rn}}$$

where n=1 as Fieldguard uses one "pilot" or adjustment round. In exactly the same manner, we find for deflection that

$$\sigma_{radar} \approx 20 \text{ meters} \approx \sigma_{prec_D}$$

Finally, if we assume that σ_{radar} is proportional to range and use the constant of proportionality established with Fieldguard at 13 km, we have, as a rule of thumb, that $\sigma_{radar} \approx \sigma_{prec}$.

Case	Met(1) Message	Gun Position
a	Concurrent with Registration	Same as Registration Position
b	Concurrent with Registration	Different than Registration Position
c	Not Concurrent with Registration	Same as Registration Position
d	Not Concurrent with Registration	Different than Registration Position

(1) Maximum staleness not to exceed 2 hours in all cases.

Note that (b) ≈ (a) if survey or navigation errors are small and that (c) is not a likely case if shoot and scoot tactics are used. Also, notice that if position errors are not large, then met and ballistic errors will be major portions of correction factors. Of these two errors, met is the most variable implying that staleness may dictate how often the radar is used. Finally, the main difference between (b) and (d) (likewise (a) and (c)) is that the use of a different met message also implies the addition of met instrument and staleness errors. Since the met message is different from the registration met, errors such as staleness that were absorbed into the registration correction factor will now appear when using the new met.

Immediate Transfer Model

Range: $$\sigma_{Rn} = \{\sigma^2_{prec} + \sigma^2_{trans}\}^{1/2} \tag{3.3.1}$$

Deflection: $$\sigma_{D} = \{\sigma^2_{prec} + \sigma^2_{trans} + \sigma^2_{aim}\}^{1/2} \tag{3.3.2}$$

where

$$\sigma^2_{reg} = \frac{\sigma^2_{radar} + \sigma^2_{prec}}{n} \approx \frac{2\,\sigma^2_{prec}}{n}$$

Delayed Transfer Model

Range: σ_{Rn} = same as in general model (3.3.3)

Deflection: σ_D = same as in general model but with σ^2_{reg} as in immediate transfer equations. In order to estimate $\sigma^2_{staleness}$ without instrument error, use the relation $\sigma^2_{staleness} = \sigma^2_{total} - \sigma^2_{0}$ hours from error budget in Appendix A. (3.3.4)

4. DELIVERY ACCURACY MODELS FOR PREDICTED (UNADJUSTED) FIRE TECHNIQUES

4.1 Background Information. This section addresses the second category of artillery delivery techniques, predicted fire. This procedure is characterized by the fact that no adjustments are made to the aiming data to try to correct for the unknown errors in ballistics, position/orientation, or met staleness/instrumentation. Instead, the most current gun location, muzzle velocity, and computer met message information are used to enter fire for effect with the first round. The equations described below can be used to estimate the accuracy of current or proposed systems by selecting the proper values for the error sources. It is expected that future systems such as the Howitzer Improvement Program (HIP) and the Advanced Field Artillery System - Cannon (AFAS-C) can achieve equivalent levels of accuracy if they have the same quality navigation/pointing systems and comparable technical fire control capabilities. Differences in precision due to improvements in propellant and cannon design will not produce significant differences in total system accuracy for the ranges considered in this report. The predicted fire model described below has been coded in BASIC and is provided along with an example of an input file in Appendix B.

4.2 The Model.

Range: $$\sigma_{Rn} = \{\sigma^2_{prec} + \sigma^2_{ball/TFC} + \sigma^2_{met} + \sigma^2_{loc} + \sigma^2_{vel}\}^{1/2} \qquad (4.2.1)$$

Deflection: $$\sigma_{D} = \{\sigma^2_{prec} + \sigma^2_{ball/TFC} + \sigma^2_{met} + \sigma^2_{aim} + \sigma^2_{loc}\}^{1/2} \qquad (4.2.2)$$

where σ^2_{prec} = round-to-round variability in range or deflection. Air burst and ground burst values are found in Table G of the appropriate Firing Tables. Note that values in an operational environment will probably be larger.

$\sigma^2_{ball/TFC}$† is defined as the variability due to aerodynamics and ballistic model (technical fire control) fitting. (See footnote for discussion.)

where $\sigma^2_{met} = \sigma^2_{instr} + \sigma^2_{staleness}$.

σ^2_{loc} = error in gun position due to navigation, survey or map spot depending on system/tactics. Map spot can of course be used as an upper bound in all cases. If onboard navigation is used, we assume time and distance traveled limits of four hours and 15 km, respectively, from calibration point. (See Appendix A, Table 1. Error Budget)

$\sigma^2_{aim} = \sigma^2_{lay} + \sigma^2_{chart} + \sigma^2_{hardware}$ for M109A2/A3;

$= \sigma^2_{hardware}$ for automatic pointing systems.

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†To estimate $\sigma^2_{ball/TFC}$ we used the data presented in BRL MR 1960[9] and the Vitro Laboratories Report.[10] Taking the value of σ_{drag} = .65 percent * range (Vitro Report) as a nominal value for aerodynamic/ballistic modeling error and extracting $\sigma^2_{met\ instr}$ so as not to double count this last error, we have σ_{drag} = .5 percent * range. The analogous number for deflection (BRL MR 1960) was almost entirely attributable to met instrumentation and so has been considered negligible in this report.

σ^2_{vel} is parameterized depending on how the M90 velocimeter is used, wear state of cannon, etc. Values range from 1 to 5 m/s standard deviation. The M90 error is ignored (<< 1 m/s). Nominal first round error is approximately 3 m/s (σ) while subsequent round values can be approximated by $\frac{\sigma^2_{vel}\text{ (precision)}}{n\text{ (\# rds fired)}}$.[†]

5. CONCLUSIONS

Using the models described in this paper the user and developer can quickly assess the impact of changes in hardware and artillery tactics on cannon delivery accuracy. The models, however, provide only a rough estimate of accuracy. The utility of these models is in their ability to quickly assess the proposed change with respect to its effect on delivery accuracy. This will allow the analyst to focus only on those parameters that are significant in the error budget. The benefit in using these models is in reducing the level of effort on detailed accuracy studies with more complex models by focusing only on those parameters critical to the error budget.

Based on a cursory analysis of the results of this limited study, it appears that a technique similar to that described for a radar adjustment will provide the best compromise in design features from the point of view of accuracy. It provides the potential to quickly adjust any round - dumb or smart - within five milliradians CEP[††] of an aimpoint using the immediate transfer mode. This potential is not available with predicted fire methods. In

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[†] No trends (round to round) are assumed to exist.

[††] CEP = .5887($\sigma_{Rn} + \sigma_D$)

addition, using the delayed transfer with a change in gun position should provide accuracy shoot and scoot type of operation. Finally, adjusted fire techniques as a class are less demanding on the number and quality of ballistic sensors, position/orientation systems, and met data, since correction factors can be used to help offset errors from these sources. An in-depth analysis to include considerations of current and proposed operational concepts, cost tradeoffs, command, and control considerations, etc., will be published as a result of the Department of the Army directed Field Artillery Accuracy Improvement Analysis which began in January 1989 and is scheduled for completion by the third quarter FY 90.

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APPENDIX A

Example Problems and Error Budget

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EXAMPLE PROBLEMS AND ERROR BUDGET

1. ASSUMPTIONS

The following list of assumptions was suggested by Mr. J. Brooks, Systems Analysis Working Group/DSWS, to constrain the range of examples used to show how the models described in this document can be implemented.

1.1 Howitzers.
M109A2/3 - current system w/BCS
HIP - onboard navigation/orientation and fire control

1.2 Ammunition.
M483A1 DPICM
M119A2 propellant
M577 mechanical time fuze

1.3 Range - 15 km.

1.4 Air Burst Mission Accuracy.

1.5 Met Staleness - Two Hours or less.

1.6 M90 Velocimeter for Each Gun.

1.7 "Radar" Registration Capability - One per Battery.

1.8 No More Than 60 Minutes per Position.

2. EXAMPLE PROBLEMS

2.1 Predicted Fire Using M109A2. In this example it is assumed that each position has been surveyed and a met message with two hours staleness (including instrument error) is available. The M90 has been used periodically to eliminate velocity bias due to wear. With this information, we know we will use the equations in paragraphs 4.2.1 and 4.2.2 of this report and will go to the error budget on page A8 to select the appropriate magnitudes.

$$\begin{aligned}
\sigma_{Rn} &= \{\sigma^2_{prec} + \sigma^2_{ball/TFC} + \sigma^2_{met} + \sigma^2_{loc} + \sigma^2_{vel}\}^{1/2} \\
&= \{34^2 + 49^2 + 84^2 + 15^2 + 29.5^2\}^{1/2} \\
&= 108 \text{ meters} \\
\sigma_D &= \{\sigma^2_{prec} + \sigma^2_{ball/TFC} + \sigma^2_{met} + \sigma^2_{aim} + \sigma^2_{loc}\}^{1/2} \\
&= \{13^2 + 0^2 + 49^2 + 60^2 + 15^2\}^{1/2} \\
&= 80 \text{ meters} \\
\text{CEP} &= .5887\ (108 + 80) \approx 111 \text{ meters}
\end{aligned}$$

The principal error source which could drive the inaccuracy of this case higher is σ^2_{loc}. If survey data is unavailable and σ_{loc} increases from 15 to 110 meters, the inaccuracy will increase: e.g., CEP ≈ 170 meters using the map spot technique.

2.2 Registration/Transfer Missions Using M109A2. In this example, we take the existing howitzer and use a radar registration to reduce errors in ballistics/technical fire control, met, aiming, and location. These errors will be absorbed or replaced by the adjustment error, σ^2_{reg}, and transfer error, σ^2_{trans}, throughout, as described in section 2.2

of this report. If we consider only the case of immediate transfer to a target by the same gun as used in adjustment (a 1km transfer) and a met message with one hour staleness - <u>a best case possible</u> - we will use equations 3.3.1 and 3.3.2 of this report and the appropriate error magnitudes in the error budget to find

$$\begin{aligned} \sigma_{Rn} &= \{\sigma^2_{prec} + \sigma^2_{trans}\}^{1/2} \\ &= \{34^2 + (35^2 + 20^2)\}^{1/2} \\ &= 53 \text{ meters} \end{aligned}$$

$$\begin{aligned} \sigma_{D} &= \{\sigma^2_{prec} + \sigma^2_{trans} + \sigma^2_{aim}\}^{1/2} \\ &= \{13^2 + (13^2 + 6^2) + 50^2\}^{1/2} \\ &= 54 \text{ meters} \end{aligned}$$

or CEP = .5887 (53 + 54) = 64 meters.

In the range plane, σ^2_{trans} is computed as $\sigma^2_{reg} \left(\frac{\Delta X_T}{\Delta V} / \frac{\Delta X_R}{\Delta V}\right)^2 + \ldots$ where $\sigma^2_{reg} = \frac{\sigma^2_{radar} + \sigma^2_{prec}}{n} \approx \frac{2\sigma^2_{prec}}{2} = 34^2$, $\left(\frac{\Delta X_T}{\Delta V} / \frac{\Delta X_R}{\Delta V}\right)^2 = (1.04)^2$

$34^2\,(1.04)^2 \approx 35^2$ and the remaining variances† summed to approximately 400 m^2.

In the deflection plane $\sigma^2_{reg} \approx \frac{2\,\sigma^2_{prec}}{2} = 13^2$ and $\sigma^2\ wind_D \left(\frac{\Delta D_R}{\Delta W} - \frac{\Delta D_T}{\Delta W}\right)^2$ $= 4^2 \,.\, (1.5)^2 \approx 6^2$.

---

†Assume σ_{loc} = 15 meters and use the 1 hour staleness met parameters with $\sigma_V \approx 2$ m/s.

If a delayed transfer, another gun, or movement to another position occurs, equations 3.3.3 and 3.3.4 of this report must be used and the CEP will, of course, increase accordingly.

2.3 Predicted Fire Using HIP Howitzer. In this example, we return to the model in section 4 of this report and proceed exactly as in paragraph 4.2. Since adequate survey was assumed in paragraph 4.2 and since the major difference in accuracy between the M109A2 and HIP is the addition of onboard navigation, the delivery accuracy estimates for these two examples will be nearly the same. Some improvement in the deflection plane could be achieved by reducing σ_{aim} if onboard fire control and autopointing are included. If this is the case, errors due to both chart reading and laying are eliminated and σ_D will change from 80 meters to 67 meters.

One final point should be noted. If survey is not available, the M109A2 crew might be forced to revert to map spotting while the HIP crew could still use the navigation/orientation system (assuming calibration points are available). Accuracy for the M109A2 would be considerably degraded in this case but not that of the HIP.

2.4 Radar Registration Capability Missions Using HIP. Assume that a radar has been used to obtain correction factors and that another gun in the battery has a mission less than an hour later. To estimate the accuracy in this case, we use equations 3.3.3 and 3.3.4 of this report with one hour staleness and additional location and velocity errors since we have changed guns.

Thus, we have

$$\sigma_{Rn} = \{\sigma^2_{prec} + \sigma^2_{met} + \sigma^2_{vel} + \sigma^2_{trans} + \sigma^2_{loc}\}^{1/2}$$

$$= \{34^2 + (66^2 - 14^2) + (29.5)^2 + (35^2 + 20^2) + 25^2\}^{1/2}$$

$$= 92 \text{ meters}$$

and $\sigma_D = \{\sigma^2_{prec} + \sigma^2_{met} + \sigma^2_{trans} + \sigma^2_{aim} + \sigma^2_{loc}\}^{1/2}$

$$= \{13^2 + (40^2 - 8^2) + (13^2 + 6^2) + 40^2 + 25^2\}^{1/2}$$

$$= 64 \text{ meters}$$

$$\text{CEP} = .5887 \ (94 + 64) \approx 93 \text{ meters}$$

Notice that σ^2_{met} should only include staleness since instrument errors are included in the correction factors.

Now, assume that the same gun used to derive the radar adjustment has moved to another position and is working with a new met message. In this case, equations in paragraph 3.3.3 and 3.3.4 of this report are used to compute:

$$\sigma_{Rn} = \{\sigma^2_{prec} + \sigma^2_{met} + \sigma^2_{vel} + \sigma^2_{trans} + \sigma^2_{loc}\}^{1/2}$$

$$= \{34^2 + 84^2 + 18^2 + (35^2 + 20^2) + 25^2\}^{1/2}$$

$$= 104 \text{ meters}$$

and $\sigma_D = \{\sigma^2_{prec} + \sigma^2_{met} + \sigma^2_{trans} + \sigma^2_{aim} + \sigma^2_{loc}\}^{1/2}$

$$= \{13^2 + 49^2 + (13^2 + 6^2) + 40^2 + 25^2\}^{1/2}$$

$$= 71 \text{ meters}$$

$$\text{CEP} = .5887 \ (106 + 71) \approx 104 \text{ meters}$$

Notice that σ^2_{met} includes both instrument and staleness since we have not corrected for this particular met message and that σ^2_{vel} is less than the above case since we have not changed guns. We have used σ_{loc} = 25 meters in the above case but this value could increase if the time and/or distance restrictions noted in the error budget are exceeded or the calibration is poor.

All the values listed in Table 1 are for air burst ("constant time") missions using the M483A1 shells with a target range of 15 km. The unit corrections used to convert errors in met and velocity into meters can be derived from Tables F and J in the appropriate Firing Tables as follows:

$$\frac{\Delta X}{\Delta \rho}_{\text{Air Burst}} = \frac{\Delta X}{\Delta \rho}_{\text{Ground Burst}} + \frac{\Delta FS}{\Delta \rho} \cdot \frac{\Delta X}{\Delta FS} \quad \text{for } \rho = \text{air density}$$

and similarly for air temperature, wind speed and muzzle velocity. $\frac{\Delta X}{\Delta \rho}_{\text{Ground Burst}}$ is found in Table F at the appropriate range, $\frac{\Delta FS}{\Delta \rho}$ is found in Table J at the appropriate fuze setting (FS) and $\frac{\Delta X}{\Delta FS} \approx$ terminal velocity in the range plane. Note that the unit correction from Table F is always opposite in sign to its counterpart in Table J and thus the air burst unit correction is less than the ground burst unit correction. If ground burst error magnitudes are desired, simply use the values in Table F to convert met and velocity errors into meters. The ground and air burst error magnitudes for deflection are equal, i.e., no conversion is needed. (The time effect is not significant.)

TABLE 1 Error Budget Table
(see next page for discussion/remarks)

	Error Magnitudes (in meters)		
Error Source	σ_{Range}	σ_{Defl}	Remarks
Battery Location			
Survey	15	15	
Navigation	25	25	See (1) below.
Map Spot	110	110	HELBAT I and II data
Met Message			See (2) below
(Instr) 0 hour staleness	14	8	σ_{wind} = .8 kts, σ_{den} = .15%, σ_{temp} = .25%
1 hour staleness + instr	66	40	σ_{wind} = 4 kts, σ_{den} = .4%, σ_{temp} = .3%
2 hours staleness + instr	84	49	σ_{wind} = 4.9 kts, σ_{den} = .69%, σ_{temp} = .57%
4 hours staleness + instr	122	71	σ_{wind} = 7.2 kts, σ_{den} = .97%, σ_{temp} = .79%
No met message	341	109	σ_{wind} = 11 kts, σ_{den} = 6.6%, σ_{temp} = 3.0%
Ballistics/Technical Fire Control	48	-	See footnote on page 13 of this report.
Transfer Errors	20	6	Excludes σ^2_{reg}; assumes one hour staleness at registration/adjustment time
Registration/Adjustment			
Precision Reg. (6 rounds)	31	9	These are used in σ^2_{trans} term in models
RADAR (2 rounds)	34	13	RADAR based on Fieldguard data (see paragraph 3.3 in this report.)
Muzzle velocity (MV)			
MVs known for each weapon	18	-	σ = 1.5 m/sec
MVs known for base piece & transferred	29.5	-	σ = 2.1 m/sec
MVs applied from dissimilar proj/lot/charge	70	-	σ = 5 m/sec
Aiming	-	40-60	See (3) below.
Round to Round (Precision)	34	13	Estimates based on M483A1 using Zone 8 (M119A2). Combat values may be even larger

(1) Based on a limited set of test data collected by the Combat Systems Test Activity (CSTA) in December 1981 at Aberdeen Proving Ground, we estimated that for the 15-25 km courses and three to four hour elapsed time between calibrations the standard deviation in location due to errors in the Litton and Singer navigation/orientation systems was 25 meters in easting and northing. We used the rule σ = .6(range of errors) = .6(40) = 24 meters. Please note that without recalibration this error estimate continues to grow with rough estimates ranging from σ = .002(d) to .004(d) where d = distance traveled since calibration and σ is standard deviation in easting and northing.

(2) The 0 hour staleness values are considered equal to instrument measuring errors. The one and two hour values include the instrument error and "pure" staleness estimates can be obtained by subtracting the zero hour variance from the appropriate error magnitude squared. The one hour staleness level is considered about the best possible case for predicted fire calculations.

(3) The same test data noted in (1) above provided good estimates of the standard deviation in pointing (elevation and deflection) for the navigation/orientation systems. Since the elevation error was much less than one mil, we have ignored it. The deflection error was approximately 2.7 milliradian (1 σ) or 40 meters at our 15 km range. If the current system using charts and aiming circles is considered, then one must add these variances yielding the 60 meter value (using a four milliradian aiming error).

APPENDIX B

Predicted Fire Computer Program and Sample Output

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PREDICTED FIRE COMPUTER PROGRAM AND SAMPLE OUTPUT

The following is a simplified computer program that provides accuracy errors based on the model and error budget provided in this report and data from tabular firing tables. This program provides delivery accuracy estimates for predicted fire only. However, the program can be modified to represent alternative firing techniques as explained in this report.

This program is written in BASIC. Data from the Tabulating Firing Table (TFT) is input into a file that is utilized by the program. The file must be input in the exact order below. Specific arguments and files for this data are as follows:

Line	Argument	Data File	Comments
1	Range in meters	(TFT)	
2	Charge	(TFT)	
3	Projectile	(TFT)	
4	Time fuze correction for density	(TFT)	(Table J, columns 8-9, enter table with (Table F) (average the fuze setting for graze burst at target range values).
5	Time fuze correction for temperature	(TFT)	(same argument as above, columns 6-7).
6	Time fuze correction for range wind	(TFT)	(same argument as above, columns 4-5).
7	Time fuze correction for muzzle velocity	(TFT)	(same argument as above, columns 4-5).
8	Angle of fall in mils	(TFT)	(Table G, column 8, at target range).
9	Terminal velocity in m/sec	(TFT)	(Table G, column 10, at target range).
10	Round to round variability in range	(TFT)	Table G, column 7, at target range for fuze, time; if using PD fuzes, use column 3).
11	Range wind, air temperature, air density corrections	(TFT)	(Table F, columns 12-17, at target range; average of increase and decrease values).
12	Muzzle velocity correction for 1 m/sec	(TFT)	Table F, average columns 10-11).
13	Round to round variability in deflection	(TFT)	(Table G, column 4, at target range).
14	Crosswind component correction	(TFT)	(Table F, column 9, at target range).

The following is an example of an input file that must be created using Firing Table (FT) 155-AN-1, Firing Charge 8, Shell DPICM (M483A1), with time fuze M577, at target range of 15,000 meters. For example, line one in the data file is the target range in meters, line 13 is the range probable error at 15,000 meters.

1. 15000 RANGE_IN_METERS
2. 8 CHARGE
3. 2 PROJECTILE_1(HE)_2(DPICM)_3(RAP)

† 4. .1 TI_FUZE_CORRECTION_FACTOR_FOR_DENSITY(TBL_J/FS_FOR_RANGE)_ENTER_0_FOR_FZ_PD

† 5. .022 TI_FUZE_CORRECTION_FACTOR_FOR_TEMP(TBL_J/FS_FOR_RANGE)_ENTER_0_FOR_FZ_PD

† 6. .005 TI_FUZE_CORRECTION_FACTOR_FOR_RANGE_WIND_ENTER_0_FOR_PD

† 7. .05 TI_FUZE_CORRECTION_FACTOR_FOR_MUZZLE_VELOCITY_ENTER_0_FOR_PD

† 8. 734 FALL_ANGLE_IN_MILS_TBL_G_AT_TGT_RANGE_ENTER_0_FOR_PD

† 9. 310 TERMINAL_VELOCITY_IN_M/SEC_AT_TGT_RANGE_ENTER_0_FOR_PD

10. 45 ENTER-RD_TO_RD_VAR_RG_TBL_G_TFT_AT_TGT_RG
11. 17.1, 8.6, 67.25 ENTER_RWIND_,AIRTEMP,AIRDENSITY_TBL_F_TFT
12. 25.55 ENTER_AVE_MV_CORRECTION_FOR_1M/S_TBL_F_TFT
13. 13 ENTER_RD_TO_RD_VAR_IN_DF_TBL_G_TFT
14. .66 ENTER_CROSSWIND_COMPONENT_CORRECTION_TBL_F_TFT.

---

†Note: If firing a PD fuze, lines 7-12 will be 0 as there will be no fuze corrections used in the calculations.

Computer Program

```
10 OPEN "I", #1, "DATA"
20 IF EOF(1) THEN END
30 PRINT "COMMON ASSUMPTIONS-BCS ACCURACY,VELOCIMETER,FFE ONLY"
40 INPUT#1, RANGE, A$
50 PRINT "RANGE"; RANGE
60 INPUT#1, CHARGE, A$
70 PRINT "CHARGE"; CHARGE
95 INPUT#1, PROJECTILE, A$
100 PRINT "PROJECTILE"; PROJECTILE
180 PRINT "CALCULATIONS FOR RANGE ACCURACY"
185 PRINT
190 PRINT
200 XBAL = RANGE*.005
201 INPUT#1, DENT, A$
202 INPUT#1, TEMPT, A$
203 INPUT#1, WINDT, A$
204 INPUT#1, MUZT, A$
205 INPUT#1, FALL, A$
206 INPUT#1, VELT, A$
209 PRINT
210 PRINT
220 PRINT "XBAL FOR PD FUZE";XBAL
221 XCOS=(COS(FALL/1000))*VELT
223 TWIND=WINDT*XCOS
224 TDEN=DENT*XCOS
225 TMUZ=MUZT*XCOS
226 TTEMP=TEMPT*XCOS
227 INPUT#1, XRR, A$
```

```
†228 XRR=XRR/.6745
 229 PRINT "XRR";XRR
 230 INPUT#1, RWIND, ATEMP, ADEN, A$, B$, C$
 231 INPUT "ENTER MET WIND STALENESS";MWIN
 232 INPUT "ENTER MET DENSITY STALENESS";MDEN
 233 INPUT "ENTER MET TEMPERATURE STALENESS"; MTEM
 240 XMET=SQR(((RWIND-TWIND)*MWIN)^2+((ATEMP-TTEMP)*MTEM)^2+((ADEN-
     TDEN)*MDEN)^2)
 250 PRINT "XMET=";XMET
 253 BALT=XBAL/ADEN
 254 XBAL=BALT*(ADEN-DENT*(XCOS))
 256 PRINT "XBAL FOR TIME FUZE";XBAL
 260 INPUT "ENTER HOW. LOC ERROR IN RG.,15M(SVY),25M(NAV),110M(MAPSPOT)"; XLOC
 270 INPUT#1, MVV, A$
 300 INPUT "ENTER MV ERROR OCCASION TO OCCASION"; MV
 310 PRINT
 320 XVEL=(MVV-TMUZ)*MV
 330 PRINT "XVEL=";XVEL
 340 XRNG=SQR(XRR^2+XBAL^2+XMET^2+XLOC^2+XVEL^2)
 350 PRINT
 360 PRINT "XRNG=";XRNG
 370 PRINT
 380 PRINT "CALCULATIONS FOR DEFLECTION ACCURACY"
 390 INPUT#1, YRR, A$
†391 YRR=YRR/.6745
 392 PRINT "YRR";YRR
```

---

†Used to convert probable errors to a standard deviation.

```
400 INPUT#1, YCW, A$

410 YMET=(RANGE/1000*YCW)*MWIN

420 PRINT "YMET=";YMET

430 INPUT "ENTER DF ERROR YDF (4 MILS FOR CURRENT SYSTEM,2.7 MILS FOR HIP)";YDF

440 YAIM=YDF*RANGE/1000

450 PRINT "YAIM=";YAIM

460 INPUT "ENTER HOWITZER LOC ERROR IN
    DF,15M(SYV),25M(NAV),110M(MAPSPOT)";YLOC

470 YRNG=SQR(YRR^2+YMET^2+YAIM^2+YLOC^2)

480 PRINT

490 PRINT "YRNG=";YRNG

500 PRINT

510 PRINT

520 CEP=.5887*(XRNG+YRNG)

530 PRINT "CEP="CEP
```

The following is output using the data provided on the previous pages and the program. The following terms are defined for reference.

XBAL - ballistic error in range
XMET - errors in range due to met
XVEL - errors in range due to muzzle velocity variation
XRNG - total error in range
YMET - errors in deflection due to met
YAIM - errors in deflection due to aiming inaccuracy
YRNG - total error in deflection
CEP - circular error probable - total error in range and deflection
MWIN - met wind staleness
MTEM - met temperature staleness
MDEN - met density staleness
YRR - precision error in deflection
XRR - precision error in range

RUN 1

In this example, it was assumed that the howitzer (HIP) has an onboard navigation capability (25 meters by 25 meters accuracy), that the howitzer's automatic pointing error is 2.7 mils, that the muzzle velocity error is 2.1 m/sec, and that met staleness is two hours.

```
COMMON ASSUMPTIONS-BCS ACCURACY,VELOCIMETER,FFE ONLY
RANGE 15000
CHARGE 8
PROJECTILE 2


CALCULATIONS FOR RANGE ACCURACY
XBAL FOR PD FUZE 75
```

```
XRR 34
ENTER MET WIND STALENESS? 4.9
ENTER MET DENSITY STALENESS? .69
ENTER MET TEMPERATURE STALENESS? .57
XMET= 84
XBAL FOR TIME FUZE 49
ENTER HOW. LOC ERROR IN RG.,15M(SVY),25M(NAV),110m(MAPSPOT)? 25
ENTER MV ERROR OCCASION TO OCCASION ? 2.1
XVEL= 29.5
XRNG= 110

CALCULATIONS FOR DEFLECTION ACURACY
YRR= 13
YMET= 48.5
ENTER DF ERROR YDF (4MILS FOR CURRENT SYSTEM,2.7 MILS FOR HIP)? 2.7
YAIM= 40.5
ENTER HOWITZER LOC ERROR IN DF,15M(svy),25M(nav),110M(mapspot)? 25


YRNG= 69
  CEP= 106
```

RUN 2

Using the same input data, yet increasing the howitzer location error from 25 meters to 110 meters (map spot accuracy) and increasing the aiming error from 2.7 to 4 mils, the impact of HIP's on board self location aiming capability on total delivery error can be seen.

```
COMMON ASSUMPTIONS-BCS ACCURACY,VELOCIMETER,FFE ONLY
RANGE 15000
CHARGE 8
```

```
PROJECTILE 2


CALCULATIONS FOR RANGE ACCURACY

FUZE TI


XBAL FOR PD FUZE 75

XRR= 34

ENTER MET WIND STALENESS? 4.9

ENTER MET DENSITY STALENESS? .69

ENTER MET TEMPERATURE STALENESS? .57

XMET= 84

XBAL FOR TIME FUZE 49

ENTER HOW. LOC ERROR IN RG.,15M(SVY),25M(NAV),110M(MAPSPOT)? 110

ENTER MV ERROR OCCASION TO OCCASION (EITHER 1 OR 2 M/SEC)? 2.1

XVEL= 29.5

XRNG= 154


CALCULATIONS FOR DEFLECTION ACCURACY

YRR= 13

YMET= 48.5


ENTER DF ERROR YDF (4MILS FOR CURRENT SYSTEM,2.7 MILS FOR HIP)? 2.7

YAIM= 60


ENTER HOWITZER LOC ERROR IN DF,15M(SVY),25M(NAV)110M(MAPSPOT)? 110

YRNG= 135

  CEP= 170
```

Removal of the self location aiming capability, assuming all other variables are constant, increases the delivery CEP from 106 m to 170 m.

Again using the same input data as Run #1, but using the standard met message (assuming there is no met message available), the effect on delivery accuracy using standard met can be seen.

RUN 3

```
COMMON ASSUMPTIONS-BCS ACCURACY,VELOCIMETER AVAILABLE,FFE ONLY
RANGE 15000
CHARGE 8
PROJECTILE 2
CALCULATIONS FOR RANGE ACCURACY
FUZE TI

XBAL FOR PD FUZE 75
XRR 34
ENTER MET WIND STALENESS? 11
ENTER MET DENSITY STALENESS? 6.6
ENTER MET TEMPERATURE STALENESS? 3
XMET= 341
XBAL FOR TIME FUZE 49

ENTER HOW. LOC ERROR IN RG.,15M(SVY),25M(NAV),110M(MAPSPOT)? 25
ENTER MV ERROR OCCASION TO OCCASION? 2.1

XVEL= 29
XRNG=348
```

```
CALCULATIONS FOR DEFLECTION ACCURACY
YRR 13
YMET= 109
ENTER DF ERROR YDF (4 MILS FOR CURRENT SYSTEM,2.7 MILS FOR HIP)? 2.7
YAIM= 40
ENTER HOWITZER LOC ERROR IN DF,15M(SVY),25M(NAV),110M(MAPSPOT)? 25
YRNG= 120
  CEP= 275
```

Comparing Run #1 with Run #3, we see that having no met message (using standard met) significantly increases the delivery error from 106 m to 275 m.

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