**DAHLGREN DIVISION**
**NAVAL SURFACE WARFARE CENTER**
Dahlgren, Virginia 22448-5100

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# AN INTERPOLATION PROCEDURE TO PATCH "HOLES" IN A GROUND AND FLIGHT TEST DATA BASE (MARS)

**BY ARMIDO R. DIDONATO**

**WARFARE SYSTEMS DEPARTMENT**

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The technology for intercepting a threat missile (TM) by an interceptor missile (IM) requires numerous ground and flight tests to establish its validity. A huge amount of information is compiled from these tests and is contained, in a particular case, in the MARS (Mission Analysis Reporting Suite) data base. Often "holes" occur in the data, that is, some desired data is not contained in the data base. The objective here is to give an example of how an interpolation procedure can supply estimates for missing data using only the experimental data.

The example given herein is based on simulated notational data rather than on the MARS data, since the latter is classified. The example is taken from the following scenario: A TM is launched from Asia with Washington, D.C. as the target. Once it is acquired, an IM is launched from Alaska. The TM can first be intercepted, exoatmospherically, at t=t1 and continuously until t=tc. The interval [t1,tc] is called the time launch window (TLW).

The problem is to develop vector interpolation functions **BP** and **BV**, the burnout position and velocity of the IM for any times in the TLW, that are dependent on the time to intercept, threat position, threat velocity, and closing velocity of the IM.

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# FOREWORD

The analyses described in this report are based on a problem originated by Mr. Said Saadi (W60), namely to develop procedures for filling in data gaps in the MARS (Mission Analysis Reporting Suite) data base. The study carried out is exploratory in nature but does give a beginning to addressing Mr. Saadi's problem.

The author is indebted to Mr. Saadi for helpful discussions and a review of this report. This document was also reviewed by Mr. Emmanuel Skamangas (W10), Head, Warfare Systems Development Division.

The editing expertise of Mr. David M. Bozicevich (CX7) is recognized and appreciated.

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DONALD L. BURNETT, Head
Warfare Systems Department

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## GLOSSARY

The numeral at the end of each item is the page number where the item is first used.

$\mathrm{B1^m(k1)}$ – Normalized input data for [T1], 6

$\mathrm{B2_s^m(k2)}$ – Normalized simulated data for [T2], 9

$\mathrm{B^1(k)}$ – Defined by (7), 3, 4

$\mathrm{B^m(k)}$ – Normalized $\mathrm{b^m(k)}$, 3

$\mathrm{J1^m}$ – Integer variable, 4

$\mathrm{J\Gamma^m}$ – Array given by (18), 5

$\mathrm{J^m}$ – Integer variable, 4

$\mathrm{S_{i,j}(k)}$ – Defined by (6), 4

$\mathrm{X1_i(k1)}$ – Normalized input data for [T1], 6

$\mathrm{X2_i(k2)}$ – Normalized input data for [T2], 9

$\mathrm{X_i(k)}$ – Normalized $\mathrm{x_i(k)}$, 3

$\Gamma_n^m$ – An array of nonlinear parameters, 4

$\gamma_1^m$ – An element of $\Gamma_n^m$, 4

$\overline{\mathrm{x}}_1$ – Mean over k of $\mathrm{x_i(k)}$, 3

$\mathrm{b^1(k)}$, bx – $\mathrm{k^{th}}$ x-position coordinate at burnout of the IM, 3

$\mathrm{t_c}$ – Time at which TLW closes, 1

[T1] – Additional input times to optimize nonlinear parameters, 6

[T0] – Data array of times used to determine LS parameters, 2

$[\mathrm{x_1(k)}]$ – [T0] times of flights in TLW to intercept, 3

**BP** – Burnout position of the IM, 1

**BV** – Burnout velocity of the IM, 1

**CV** – Closing velocity of the interceptor, 2

**TP** – Threat position, 1

**TV** – Threat velocity, 2

**GLOSSARY (Continued)**

AME – Absolute maximum error, 7

ErrorT2 – Error, (36), 9

ErrT2 – Maximum absolute error, (38), 9

IM – Intercepter missile, 1

LS – Least squares, 2

M – Number of data points in [T0], 2

MARS – Mission Analysis Reporting Suite, 1

N – The number of $x_i$, 5

NT – The number of linear LS parameters, 5

TLW – Time launch window, 1

TM – Threat missile, 1

# I. INTRODUCTION

The technology for intercepting a threat missile (TM) by an interceptor missile (IM) requires numerous ground and flight tests to establish its validity. A huge amount of information is compiled from these tests and is, in a particular case, referred to as the MARS (Mission Analysis Reporting Suite) data base. Often "holes" are observed in the data, that is, some desired data is not contained in the data base. The objective in this report is to give an example of how an interpolation procedure can supply estimates for missing data using only the available experimental data.

The example chosen is based on simulated notational data rather than on the MARS data, since the latter is classified. However, the simulation is designed to be more of a challenge for interpolations, since the data from the simulation are less smooth than that generated from MARS.

The example is taken from the following scenario, with all action taking place exoatmospherically, unless noted otherwise: A threat missile (TM) is launched from Asia with Washington, D.C. as the target. Once it is acquired, time is set to zero and an IM is launched from Alaska. It is assumed to fly in powered flight from launch for tpow seconds, say tpow = 158 seconds. At that time the IM will have arrived at a burnout position (**BP**) with a given velocity (**BV**). These quantities are determined by a three-dimensional flyout fan of trajectories, usually supplied by the IM designer. A particular trajectory is chosen from the flyout fan giving a **BP** that depends on the time of flight for the IM to fly ballistically to the threat at position (**TP**). Then **BV** is determined by an iterative process to result in intercept. Thus, at a time $t_1$ beyond tpow, when intercept is first possible, a "time launch window" (TLW) is opened and continues to stay open as time increases, until intercept is no longer feasible, say at $t_c$ when the threat reenters the atmosphere or perhaps the **BP** and/or **BV** required at that time can no longer be achieved.

It is assumed then that it can be first intercepted at the time of flight, $t = t_1$, and continuously at all times thereafter until it is no longer possible at $t_c$. The TLW is defined by the time interval $[t_1, t_c]$.

The problem specifically set then is to develop vector time functions, dependent on the time to intercept, threat position, threat velocity, and closing velocity of the IM, that can be used as interpolation functions for the burnout positions, **BP**, and burnout velocities, **BV**, of the IM at any specified times in the TLW.

## II. INTERPOLATION FUNCTIONS

The interpolation functions will require estimating some linear and some nonlinear parameters. The linear parameters will be determined by least squares (LS) and the nonlinear ones by assigning them values over a spectrum of possibilities to be described.

At M times, in equal increments, $\Delta t$, throughout the TLW, M **BP**'s and M **BV**'s required for intercept are assumed available as input for $[T0] = (t_1, t_1 + \Delta t, t_1 + 2\Delta t \ldots, t_1 + (M-2)\Delta t, t_c)$. We will also use the notation

$$[T0] = [t(k)], \quad t(k) \equiv t_1 + (k-1)\Delta t,\ t(M) = t_c \quad k = 1, 2, \ldots, M-1, \quad (1)$$

where the [.] brackets are used to denote a column vector. The equal time increment in [T0] is used to deal with a desirable uniform collection of data, but it is not a critical requirement.

Additional inputs required are the **TP**, the threat velocity, **TV**, and the closing velocity of the IM, **CV**, for each t in T0. Thus, for definiteness, we seek estimates for the burnout position, $\mathbf{BP} \equiv (bx, by, bz)$, and velocity of the IM, $\mathbf{BV} \equiv (bu, bv, bw)$, for t in $[t_1,\ tc]$ which includes [T0]. The argument (k) appears; it always refers to the $k^{th}$ time of [T0]. For example, t(k) refers to the $k^{th}$ element of [T0].

Additional notation is introduced to simplify expressing subsequent mathematical quantities. Let

$$
\begin{array}{llll}
[\mathrm{b}^1(\mathrm{k})] & \equiv & \mathrm{bx} & \to \mathrm{IM\ k^{th}\ x - position\ coordinate\ at\ burnout} \\
[\mathrm{b}^2(\mathrm{k})] & \equiv & \mathrm{by} & \to \mathrm{IM\ k^{th}\ y - position\ coordinate\ at\ burnout} \\
[\mathrm{b}^3(\mathrm{k})] & \equiv & \mathrm{bz} & \to \mathrm{IM\ k^{th}\ z - position\ coordinate\ at\ burnout} \\
[\mathrm{b}^4(\mathrm{k})] & \equiv & \mathrm{bu} & \to \mathrm{IM\ k^{th}\ x - velocity\ component\ at\ burnout} \\
[\mathrm{b}^5(\mathrm{k})] & \equiv & \mathrm{bv} & \to \mathrm{IM\ k^{th}\ y - velocity\ component\ at\ burnout} \\
[\mathrm{b}^6(\mathrm{k})] & \equiv & \mathrm{bw} & \to \mathrm{IM\ k^{th}\ z - velocity\ component\ at\ burnout} \\
[\mathrm{x}_1(\mathrm{k})] & \equiv & [\mathrm{T0}] & \to \mathrm{M,\ IM\ times\ of\ flight\ in\ TLW\ to\ intercept} \\
[\mathrm{x}_2(\mathrm{k})] & \equiv & [\mathrm{tx}] & \to \mathrm{M,\ x - position\ coordinates\ of\ the\ threat} \\
[\mathrm{x}_3(\mathrm{k})] & \equiv & [\mathrm{ty}] & \to \mathrm{M,\ y - position\ coordinates\ of\ the\ threat} \\
[\mathrm{x}_4(\mathrm{k})] & \equiv & [\mathrm{tz}] & \to \mathrm{M,\ z - position\ coordinates\ of\ the\ threat} \\
[\mathrm{x}_5(\mathrm{k})] & \equiv & [\mathrm{tu}] & \to \mathrm{M,\ x - velocity\ components\ of\ the\ threat} \\
[\mathrm{x}_6(\mathrm{k})] & \equiv & [\mathrm{tv}] & \to \mathrm{M,\ y - velocity\ components\ of\ the\ threat} \\
[\mathrm{x}_7(\mathrm{k})] & \equiv & [\mathrm{tw}] & \to \mathrm{M,\ z - velocity\ components\ of\ the\ threat} \\
[\mathrm{x}_8(\mathrm{k})] & \equiv & [\mathrm{cu}] & \to \mathrm{M,\ closing\ x - velocity\ components\ of\ the\ IM} \\
[\mathrm{x}_9(\mathrm{k})] & \equiv & [\mathrm{cv}] & \to \mathrm{M,\ closing\ y - velocity\ components\ of\ the\ IM} \\
[\mathrm{x}_{10}(\mathrm{k})] & \equiv & [\mathrm{cw}] & \to \mathrm{M,\ closing\ z - velocity\ components\ of\ the\ IM.}
\end{array} \tag{2}
$$

Each $[\mathrm{x_i(k)}]$ is a column array with M specified elements and $\overline{\mathrm{x}}_\mathrm{i} \equiv \underset{\mathrm{k}}{\mathrm{mean}}([\mathrm{x_i(k)}])$. For example: $\Delta$t=100, $[\mathrm{x_1(k)}] = [900, 1000, 1100, 1200, ..., 2520]$, M = 18, $\overline{\mathrm{x}}_1 = 1745.556$. Note: TLW = [900, 2520].

The Euclidean norm of the vector $\beta$ with M real components is defined by

$$
\|\beta\| \equiv \left[\sum_{\mathrm{k}=1}^{\mathrm{M}} \beta(\mathrm{k})^2\right]^{1/2}. \tag{3}
$$

Now instead of using the $\mathrm{x_i}$ in the LS equations below, we have, using the mean and the Euclidean norm for each $\mathrm{x_i}$, the new normalized dimensionless variables:

$$
\begin{array}{lllll}
\mathrm{X_i(k)} & \equiv & [\mathrm{x_i(k)} - \overline{\mathrm{x}}_\mathrm{i}]/\|[\mathrm{x_i} - \overline{\mathrm{x}}_\mathrm{i}]\|, & \mathrm{i} = 1, ..., \mathrm{N}, & \mathrm{N} = 10, \\
\mathrm{B^m(k)} & \equiv & [\mathrm{b^m(k)} - \overline{\mathrm{b^m}}]/\|[\mathrm{b^m} - \overline{\mathrm{b^m}}]\|, & \mathrm{m} = 1, ..., 6, & \mathrm{k} = 1, ..., \mathrm{M}.
\end{array} \tag{4}
$$

The argument (k) of a function refers to the $k^{th}$ element of [T0]. It is assumed that M data points of all the normalized variables of (4) are available. The LS analysis allows nonlinear expressions in these variables. Nevertheless, the problem of determining the LS constants remains linear and is classical.

The LS equations follow, with $i = 1, \ldots, N$ and $j = i, \ldots, N$. Also two integer variables $J^m$, $J1^m$ are introduced, with $J^m \epsilon [1, N-1]$, $J1^m \epsilon [J^m+1, N)]$ together with a variable $\Gamma_n^m$ that can take three possible values, for each m. They are used as exponential fitting parameters with

$$\Gamma_n^m \equiv \begin{cases} \gamma_1^m & \text{if} \quad 1 \leqslant n \leqslant J^m \\ \gamma_2^m & \text{if} \quad J^m < n \leqslant J1^m \\ \gamma_3^m & \text{if} \quad J1^m < n \leqslant N, \quad m = 1, ..., 6. \end{cases} \tag{5}$$

The role of $J^m$ and $J1^m$ will be described below. The interpolation time functions for $B^m$ are determined by the RH side of equations (6)-(12).

$$S_{i,j}(k) \equiv \mathrm{sign}(X_i(k) * X_j(k)), \quad k = 1, \ldots, M \tag{6}$$

$$B^1(k) \sim \sum_{i=1}^{N} a_i X_i(k) + \sum_{i=1}^{N} \sum_{j=i}^{N} A_{i,j} S_{i,j}(k) |X_i(k)|^{\Gamma_i^1} |X_j(k)|^{\Gamma_j^1} \tag{7}$$

$$B^2(k) \sim \sum_{i=1}^{N} b_i X_i(k) + \sum_{i=1}^{N} \sum_{j=i}^{N} B_{i,j} S_{i,j}(k) |X_i(k)|^{\Gamma_i^2} |X_j(k)|^{\Gamma_j^2} \tag{8}$$

$$B^3(k) \sim \sum_{i=1}^{N} c_i X_i(k) + \sum_{i=1}^{N} \sum_{j=i}^{N} C_{i,j} S_{i,j}(k) |X_i(k)|^{\Gamma_i^3} |X_j(k)|^{\Gamma_j^3} \tag{9}$$

$$B^4(k) \sim \sum_{i=1}^{N} d_i X_i(k) + \sum_{i=1}^{N} \sum_{j=i}^{N} D_{i,j} S_{i,j}(k) |X_i(k)|^{\Gamma_i^4} |X_j(k)|^{\Gamma_j^4} \tag{10}$$

$$B^5(k) \sim \sum_{i=1}^{N} e_i X_i(k) + \sum_{i=1}^{N} \sum_{j=i}^{N} E_{i,j} S_{i,j}(k) |X_i(k)|^{\Gamma_i^5} |X_j(k)|^{\Gamma_j^5} \tag{11}$$

$$B^6(k) \sim \sum_{i=1}^{N} f_i X_i(k) + \sum_{i=1}^{N} \sum_{j=i}^{N} F_{i,j} S_{i,j}(k) |X_i(k)|^{\Gamma_i^6} |X_j(k)|^{\Gamma_j^6}. \tag{12}$$

The system of equations given by (7)-(12) can be written as one expression, i.e.,

$$\mathrm{B^m(k)} \sim \sum_{i=1}^{N} \mathrm{a_i^m\, X_i(k)} + \sum_{i=1}^{N}\sum_{j=i}^{N} \mathrm{A_{i,j}^m\, Z_{i,j}^m(k)}, \tag{13}$$

where

$$\mathrm{a_i^1 = a_i, a_i^2 = b_i, ..., a_i^6 = f_i, A_{i,j}^1 = A_{i,j}, A_{i,j}^2 = B_{i,j}, ..., A_{i,j}^6 = F_{i,j}}, \tag{14}$$

$$\mathrm{Z_{i,j}^m(k) \equiv S_{i,j}(k)\, |X_i(k)|^{\Gamma_i^m}\, |X_j(k)|^{\Gamma_j^m}}. \tag{15}$$

Thus, assigning a value in (13) to m, say 3, would also refer explicitly to (9). Also, to clarify the use of $\mathrm{J^m}$ and $\mathrm{J1^m}$ with $\Gamma_\mathrm{n}^\mathrm{m}$, (5), say for m=1, the following quantities appear in (7):

$$\mathrm{|X_1|^{\Gamma_1^1}, |X_2|^{\Gamma_2^1}, |X_3|^{\Gamma_3^1}, |X_4|^{\Gamma_4^1}, |X_5|^{\Gamma_5^1}, |X_6|^{\Gamma_6^1}, |X_7|^{\Gamma_7^1}, |X_8|^{\Gamma_8^1}, |X_9|^{\Gamma_9^1}, |X_{10}|^{\Gamma_{10}^1}}. \tag{16}$$

Then, for example, if $\mathrm{J^1 = 3}$, and $\mathrm{J1^1 = 7}$, (16) becomes, from (5),

$$\mathrm{|X_1|^{\gamma_1^1}, |X_2|^{\gamma_1^1}, |X_3|^{\gamma_1^1}, |X_4|^{\gamma_2^1}, |X_5|^{\gamma_2^1}, |X_6|^{\gamma_2^1}, |X_7|^{\gamma_2^1}, |X_8|^{\gamma_3^1}, |X_9|^{\gamma_3^1}, |X_{10}|^{\gamma_3^1}}. \tag{17}$$

From (13) we see, for each m, there are $\mathrm{NT = N + N(N+1)/2}$ linear parameters to determine and, in addition, five others, namely,

$$\mathrm{J\Gamma^m \equiv (J^m,\ J1^m, \gamma_1^m, \gamma_2^m, \gamma_3^m)}, \tag{18}$$

for a total of 70 when N=10. Assuming the elements of $\mathrm{J\Gamma^m}$ are assigned values, then for each value of $\mathrm{m = 1, ..., 6}$ there is an LS problem to solve for the variables

$$\boldsymbol{\xi}^\mathrm{m} \overset{\mathrm{(NT\,x\,1)}}{\equiv} \left[\mathrm{a_1^m, a_2^m, \ldots, a_N^m, A_{1,1}^m, A_{1,2}^m, \ldots, A_{1,N}^m, A_{2,2}^m, A_{2,3}^m, \ldots, A_{N,N}^m}\right]. \tag{19}$$

The right hand side of the LS equations is given by

$$\mathbf{B^m} \overset{\mathrm{(M\,x\,1)}}{\equiv} \mathrm{[B^m(1), B^m(2), \ldots, B^m(M)]}, \tag{20}$$

and the LS matrix is given by

$$\mathbf{XZ}^{\mathrm{m}} \equiv \overset{(\mathrm{M\,x\,NT})}{\begin{bmatrix} \mathrm{X_1(1)} & \dots & \mathrm{X_N(1)} & \mathrm{Z^m_{1,1}(1)} & \dots & \mathrm{Z^m_{1,N}(1)} & \dots & \mathrm{Z^m_{N,N}(1)} \\ \mathrm{X_1(2)} & \dots & \mathrm{X_N(2)} & \mathrm{Z^m_{1,1}(2)} & \dots & \mathrm{Z^m_{1,N}(2)} & \dots & \mathrm{Z^m_{N,N}(2)} \\ \vdots & \cdots & \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ \mathrm{X_1(M)} & \dots & \mathrm{X_N(M)} & \mathrm{Z^m_{1,1}(M)} & \dots & \mathrm{Z^m_{1,N}(M)} & \dots & \mathrm{Z^m_{N,N}(M)} \end{bmatrix}}. \tag{21}$$

Hence, in matrix-vector form, we have

$$\mathbf{XZ}^{\mathrm{m}}\,\boldsymbol{\xi}^{\mathrm{m}} = \mathbf{B}^{\mathrm{m}}. \tag{22}$$

Solving this system of linear equations, one obtains

$$\boldsymbol{\xi}^{\mathrm{m}} = (\mathbf{XZ}^{\mathrm{m}}_{\mathbf{T}}\,\mathbf{XZ}^{\mathrm{m}})^{-1}\mathbf{XZ}^{\mathrm{m}}_{\mathbf{T}}\,\mathbf{B}^{\mathrm{m}}, \tag{23}$$

where $\mathbf{XZ}^{\mathrm{m}}_{\mathbf{T}}$ denotes the transpose of $\mathbf{XZ}^{\mathrm{m}}$.

The maximum error generated by an LS analysis generally occurs in the vicinity of midway between the data points. In this light, we employ additional input similar to the original normalized input, as given by (4). This new input data will be taken at points

$$\begin{aligned} \mathrm{t1(1)} &= (\mathrm{t(1)+t(2)})/2, \qquad [\mathrm{T1}] = (\mathrm{t1(1)}, ..., \mathrm{t1(M-1)}), \\ \mathrm{t1(k1)} &= \mathrm{t1(1)} + (\mathrm{k1}-1)\Delta\mathrm{t}, \quad \mathrm{k1} = 1, ..., \mathrm{M}-1. \end{aligned} \tag{24}$$

and is denoted by

$$\begin{aligned} \mathrm{X1_i(k1)} &\equiv [\mathrm{x1_i(k1)} - \overline{\mathrm{x}}_\mathrm{i}]/\|\mathrm{x1_i} - \overline{\mathrm{x}}_\mathrm{i}\|, \qquad \mathrm{i} = 1, ..., \mathrm{N} = 10, \\ \mathrm{B1^m(k1)} &\equiv [\mathrm{b1^m(k1)} - \overline{\mathrm{b^m}}]/\|\mathrm{b1^m} - \overline{\mathrm{b^m}}\|, \quad \mathrm{m} = 1, ..., 6. \end{aligned} \tag{25}$$

The argument (k1) of a function refers to the $\mathrm{k1^{th}}$ element of [T1].

It remains to explain how the elements of $\mathrm{J\Gamma^m}$ are chosen. For a fixed m, say m equals one, the integer variables $\mathrm{J^1}$ and $\mathrm{J1^1}$ are sequenced through the integers 1 to N-1 and $\mathrm{J^1}+1$ to N, respectively. Then $\gamma^1_1, \gamma^1_2, \gamma^1_3$ are varied each in turn through a range of real values, say [0,5], at initial increments of $\Delta = .2$. At each assignment of these variables, $\mathrm{J^1}$, $\mathrm{J1^1}$, $\gamma^1_1$, $\gamma^1_2$, $\gamma^1_3$, an LS solution over [T0] is carried out and the absolute maximum error (AME) over [T0], ErrT0, and [T1], ErrT1, is noted. This procedure is iterated varying $\mathrm{J}^1$, $\mathrm{J1}^1$, $\gamma_1^1$, $\gamma_2^1$, $\gamma_3^1$, systematically as described above. The best values for the elements of $\mathrm{J}\Gamma^1$ are those that minimize the AMEs over the iterations. The entire process is repeated with reduced ranges for each variable with a smaller $\Delta$. For example, say, $\mathrm{J}^1 = 2, \mathrm{J1}^1 = 8, \gamma_1^1 = 2.0$, $\gamma_2^1 = .75$, $\gamma_3^1 = 1.0$; the ranges of these elements are then reduced by setting $\mathrm{J}^1 = [1, 3], \mathrm{J1}^1 = [7, 9], \gamma_1^1 = [1.8, 2.2]$, $\gamma_2^1 = [.55, .95]$, $\gamma_3^1 = [0.8, 1.2]$ and $\Delta = \Delta/2 = 0.1$, obtaining, in general, a smaller overall AME. The iteration process is again carried out with $\Delta = .05$ and .025 with the final results after minimizing the AME given by, say, $\mathrm{J}\Gamma^1 = (\mathrm{J}^1 = 3, \mathrm{J1}^1 = 7, \gamma_1^1 = 1.925, \gamma_2^1 = .700, \gamma_3^1 = 2.120)$.

The AME over [TO] is defined as

$$\mathrm{ErrT0} \equiv \max_{\mathrm{k}} |\mathrm{B^m(k)} - \sum_{\mathrm{i=1}}^{\mathrm{N}} \mathrm{a_i^m}\, \mathrm{X_i(k)} - \sum_{\mathrm{i=1}}^{\mathrm{N}} \sum_{\mathrm{j=i}}^{\mathrm{N}} \mathrm{A_{i,j}^m}\, \mathrm{Z_{i,j}^m(k)}|, \tag{26}$$

and the AME over [T1], using (24) and (25), is

$$\mathrm{ErrT1} \equiv \max_{\mathrm{k1}} |\mathrm{B1^m(k1)} - \sum_{\mathrm{i=1}}^{\mathrm{N}} \mathrm{a_i^m}\, \mathrm{X1_i(k1)} - \sum_{\mathrm{i=1}}^{\mathrm{N}} \sum_{\mathrm{j=i}}^{\mathrm{N}} \mathrm{A_{i,j}^m}\, \mathrm{Z1_{i,j}^m(k1)}|, \tag{27}$$

where

$$\mathrm{Z1_{i,j}^m(k1)} \equiv \mathrm{S_{i,j}(k1)}\, |\mathrm{X1_i(k1)}|^{\Gamma_\mathrm{i}^\mathrm{m}}\, |\mathrm{X1_j(k1)}|^{\Gamma_\mathrm{j}^\mathrm{m}}. \tag{28}$$

## III. NUMERICAL EXAMPLE WITH GRAPHS

Considering the example described in the Introduction, we are now in a position to report some numerical results. We start, as described, with a TM flying from Asia with Washington, D.C. as a target, with the IM launch site in Alaska. It is assumed the powered flight of the IM takes 158 seconds to reach a burnout position. A fictitious flyout fan is used; thus all data is unclassified. The threat position at t=0 is (-1456954, 5437427, 3250043) and its velocity is (296, -1106, 7404). The Alaska launch site coordinates are

(-2334397, -1347764, 5780581). All data refers to an ECEF frame. Position coordinates are in meters and velocity coordinates are in meters per second. The input data is generated from Fortran programs described in [1] under Case #1.

The threat is first acquired at time zero. The intercept window opens 900 seconds later and remains open until the window closes when the threat reenters the atmosphere at t=2520 seconds. So data for the $\mathrm{x_i}$ (see (2)) will be taken in equal time intervals (see (2), (4)), $\Delta \mathrm{t} = 20$ from t=900 to t=2520. Thus $\mathrm{M} = 82$. This array of times is denoted by [T0].

In the previous section, two sets of time data were introduced, belonging to TLW, namely, [T0], as above, and [T1]. The two time sets were made up of times at equal intervals, namely,

$$[\mathrm{T0}] = (\mathrm{t_1}, \mathrm{t_2}, ..., \mathrm{t_M}), \quad \mathrm{t_M} = \mathrm{t_c}, \tag{29}$$

$$[\mathrm{T1}] = (\frac{\mathrm{t_1} + \mathrm{t_2}}{2}, \frac{\mathrm{t_2} + \mathrm{t_3}}{2}, ..., \frac{\mathrm{t_{M-1}} + \mathrm{t_M}}{2}). \tag{30}$$

Assigning specific values, we have

$$[\mathrm{T0}] = (900,\ 920,\ ...,\ 2500,\ 2520), \tag{31}$$

$$[\mathrm{T1}] = (910,\ 930,\ ...,\ 2490,\ 2510). \tag{32}$$

Associated with each set were other input quantities (normalized), $\mathrm{X_i(k)}$ and $\mathrm{X1_i(k1)}$, respectively, for each time, i.e., for each k and k1 (see (4), (24), (25)). At each of these intercept times belonging to [T0] and [T1], it is assumed the following ECEF data are available:

IM Burnout position, **BP**

IM Burnout velocity, **BV**

Threat position, **TP**

Threat velocity, **TV**

IM Closing velocity, **CV** .

Then, using this data, a set of functions is developed for which least square parameters are determined together with the assigned nonlinear parameters, $J\Gamma^m$, (18). These functions are then tested by using them to interpolate for **BP** and **BV** at a set of times

$$\begin{aligned} [T2] &= (\frac{3t_1 + t2}{4}, \frac{t_1 + 3t_2}{4}, \frac{3t_2 + t_3}{4}, \ldots, \frac{3t_{M-1} + t_M}{4}, \frac{t_{M-1} + 3t_M}{4}), \quad (33) \\ [T2] &= (905, 915, 925, \ldots, 2505, 2515), \quad (34) \end{aligned}$$

as well as at times [T0] and [T1]. Corresponding to (25)

$$\begin{aligned} X2_i(k2) &\equiv [x2_i(k2) - \overline{x}_i]/\|x2_i - \overline{x}_i\|, & k2 &= 1, \ldots, 2M - 2, \\ B2_s^m(k2) &\equiv [b2^m(k2) - \overline{b^m}]/\|b2^m - \overline{b^m}\|, & m &= 1, \ldots, 6. \end{aligned} \quad (35)$$

where $x2_i$ is the same function as $x_i$ but evaluated at times [T2] rather than [T0]. The subscript s of $B2_s^m(k2)$ indicates that B2 comes from simulated data in reference [1] and is used here as "truth data." The argument (k2) of a function refers to the $k2^{th}$ element of [T2]. The errors in estimating $B2_s^m(k2)$ are determined from:

$$\text{ErrorT2} \equiv B2_s^m(k2) - \sum_{i=1}^{N} a_i^m \, X2_i(k2) - \sum_{i=1}^{N} \sum_{j=i}^{N} A_{i,j}^m \, Z2_{i,j}^m(k2), \quad (36)$$

$$Z2_{i,j}^m(k2) \equiv S_{i,j}(k2) \, |X2_i(k2)|^{\Gamma_i^m} \, |X2_j(k2)|^{\Gamma_j^m}. \quad (37)$$

The absolute maximum error is given by

$$\text{ErrT2} \equiv \max_{k2} |B2_s^m(k2) - \sum_{i=1}^{N} a_i^m \, X2_i(k2) - \sum_{i=1}^{N} \sum_{j=i}^{N} A_{i,j}^m \, Z2_{i,j}^m(k2)|. \quad (38)$$

Programs in Fortran 95 and MatLab were developed to obtain the results listed below in Table 1.

Table 1. Final Values for JΓ, (18), and Errors (26), (27), (38)

| m | $J^m$ | $J1^m$ | $\gamma_1^m$ | $\gamma_2^m$ | $\gamma_3^m$ | ErrT0 | ErrT1 | ErrT2 |
|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 9 | 4.850 | 0.900 | 2.275 | 581 | 882 | 2533 |
| 2 | 5 | 7 | 2.275 | 2.45 | 1.000 | 436 | 784 | 1348 |
| 3 | 4 | 8 | 1.625 | 0.900 | 1.000 | 200 | 593 | 830 |
| 4 | 2 | 7 | 3.000 | 1.500 | 0.725 | 0.221 | 0.442 | 0.820 |
| 5 | 2 | 6 | 3.825 | 1.4000 | 1.000 | 0.155 | 0.434 | 0.590 |
| 6 | 4 | 5 | 2.700 | 1.625 | 1.000 | 0.152 | 0.548 | 0.632 |

In Table 1, m=2 refers to the y-coordinate burnout position. The next five columns are used to record the values of the nonlinear parameters in $J\Gamma^m$ so that, as in (16) and (17), one has for m=2:

$$|X_1|^{\Gamma_1^2}, |X_2|^{\Gamma_2^2}, |X_3|^{\Gamma_3^2}, |X_4|^{\Gamma_4^2}, |X_5|^{\Gamma_5^2}, |X_6|^{\Gamma_6^2}, |X_7|^{\Gamma_7^2}, |X_8|^{\Gamma_8^2}, |X_9|^{\Gamma_9^2}, |X_{10}|^{\Gamma_{10}^2} \quad (39)$$

$$|X_1|^{\gamma_1^2}, |X_2|^{\gamma_1^2}, |X_3|^{\gamma_1^2}, |X_4|^{\gamma_1^2}, |X_5|^{\gamma_1^2}, |X_6|^{\gamma_2^2}, |X_7|^{\gamma_2^2}, |X_8|^{\gamma_3^2}, |X_9|^{\gamma_3^2}, |X_{10}|^{\gamma_3^2}. \quad (40)$$

The last three columns of Table 1 list the errors in the estimates for **BP** and **BV** for the three sets of times, [T0], [T1], [T2]. In the case m=1, the estimates are given for the x-component of **BP** for $B^1, B1^1, B2_s^1$. The maximum error for the latter, over [T2], is 2533 meters, occurring at an IM intercept time of TE(82)=1715. The results are considered satisfactory considering the complex nature of the functions (see Figure 1A below). In addition, using the interpolated values, at TE(82)=1715, for **BP** and **BV**, the miss distance of the IM at the target is 100.24 meters, which should also be acceptable.

The figures that follow, 1A, 1B, 1C, ..., 6A, 6B, 6C, show the six different types of functions that were fitted and the errors that were observed. Figures mA, m=1,2,3,4,5,6, contain plots of the positive term in (36) as a function of t $\epsilon$ [T2]. Figures mB show the plots of the sum of the two negative terms in (36) taken with plus signs. Figures mC contain the errors observed, (36).

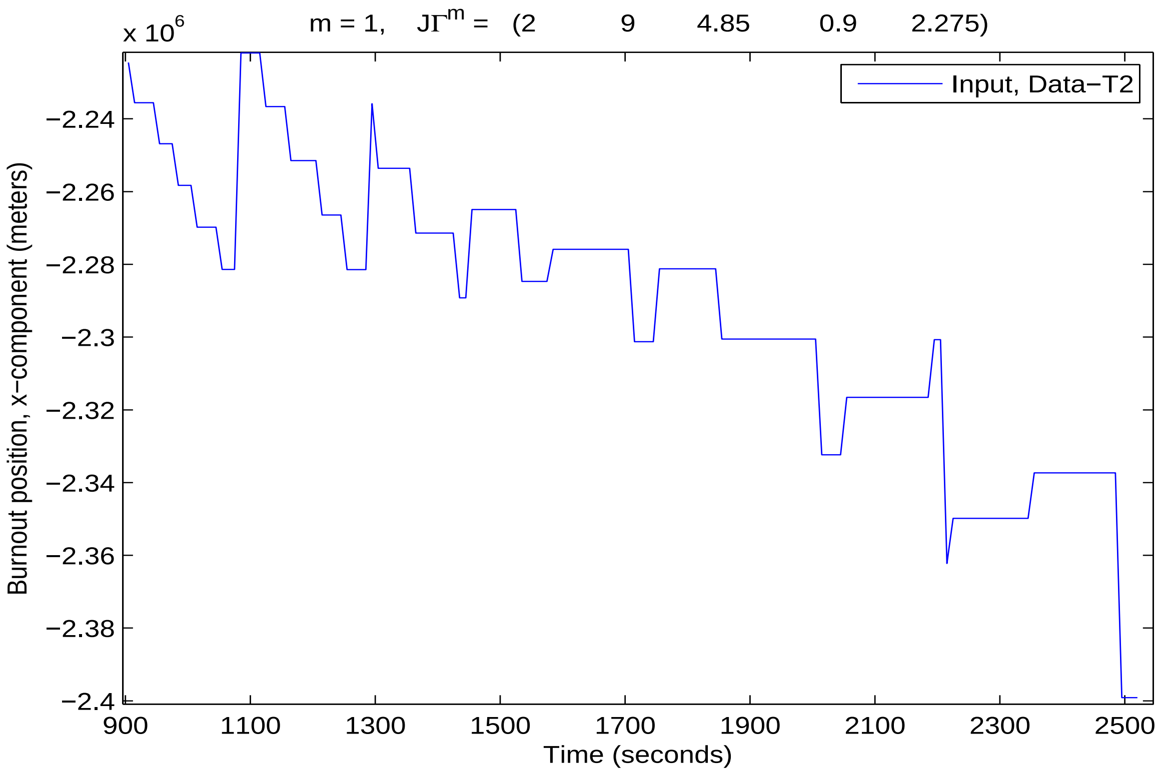


Figure 1A. x-Component of Input Burnout Position versus Time [T2]

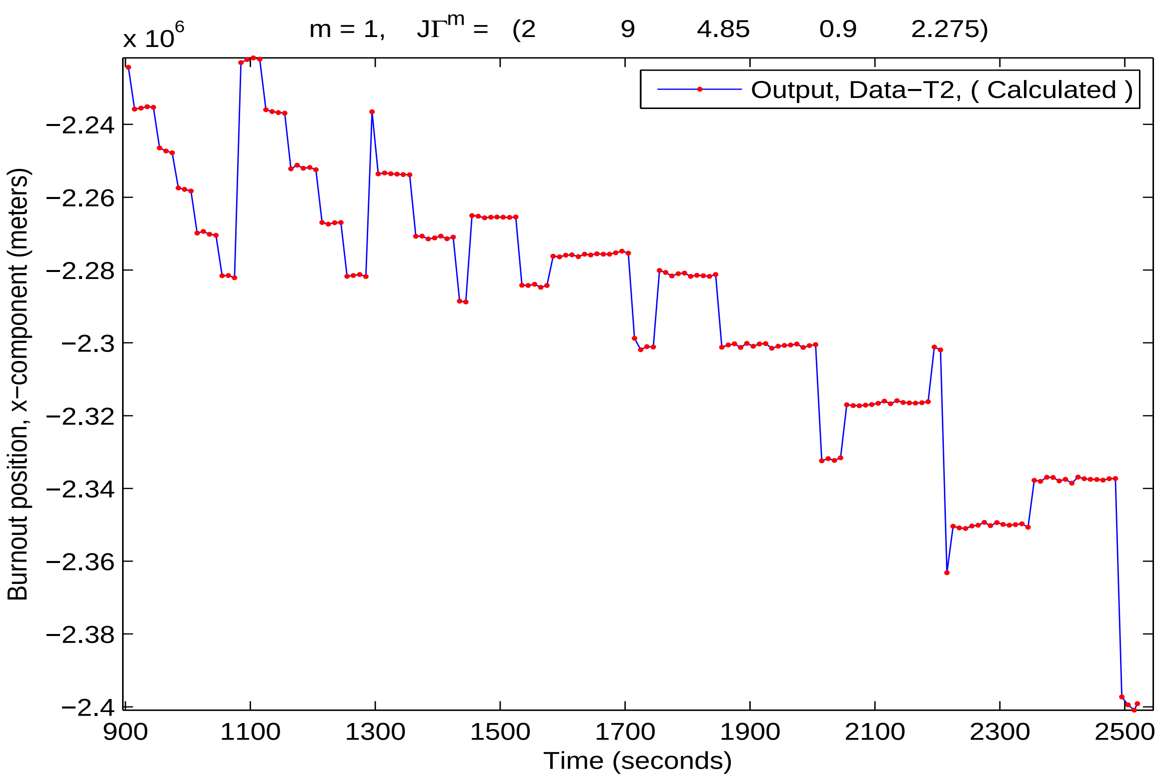


Figure 1B. x-Component of Output Burnout Position versus Time [T2]

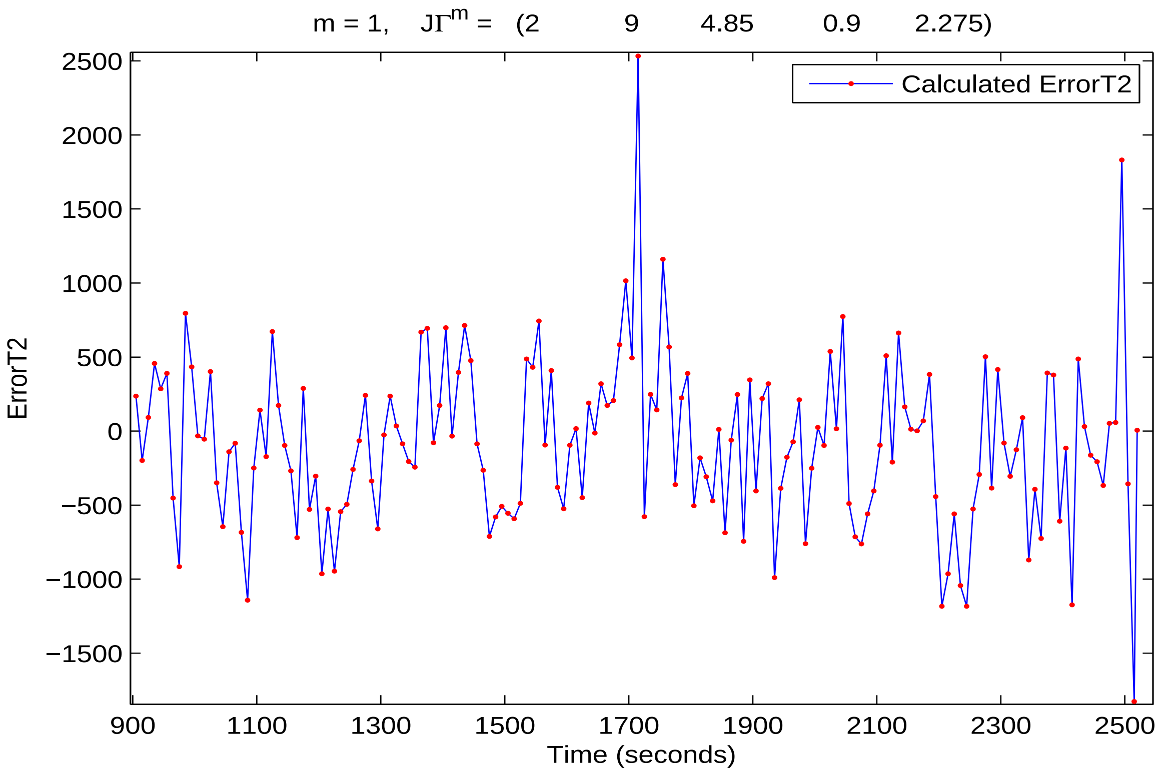


Figure 1C. Error in x-Component of Burnout Position versus Time [T2]

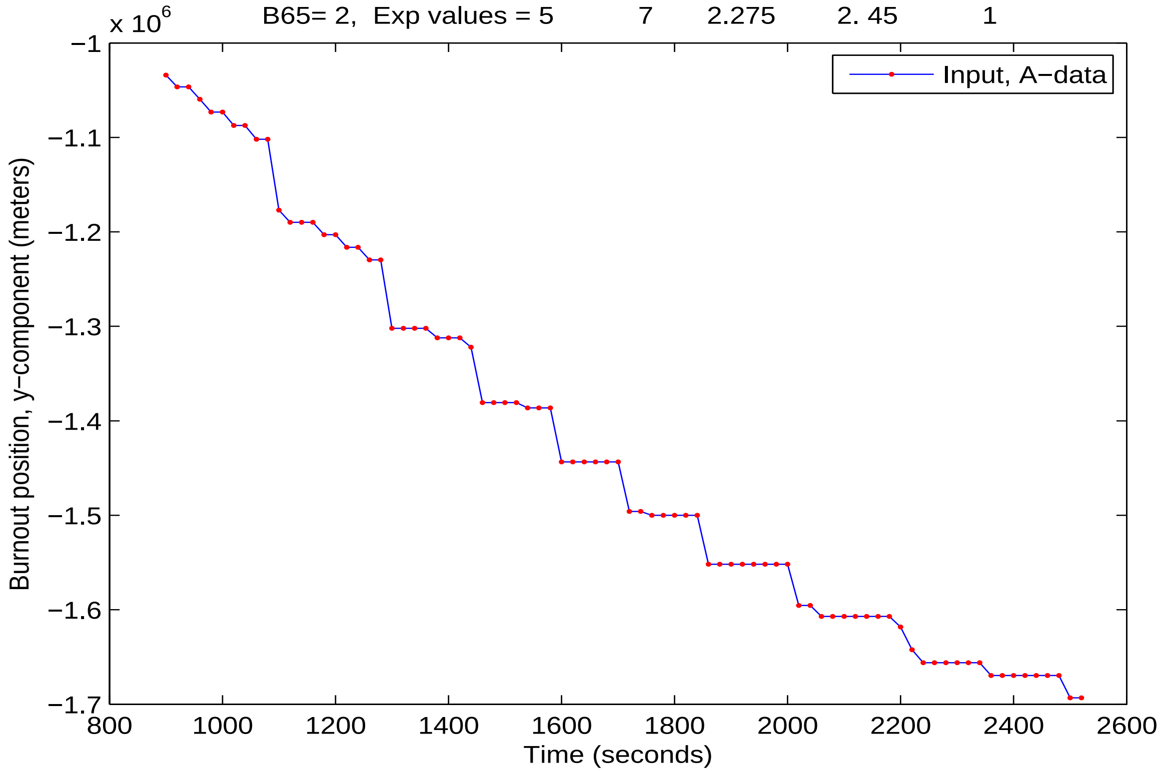


Figure 2A. y-Component of Input Burnout Position versus Time [T2]

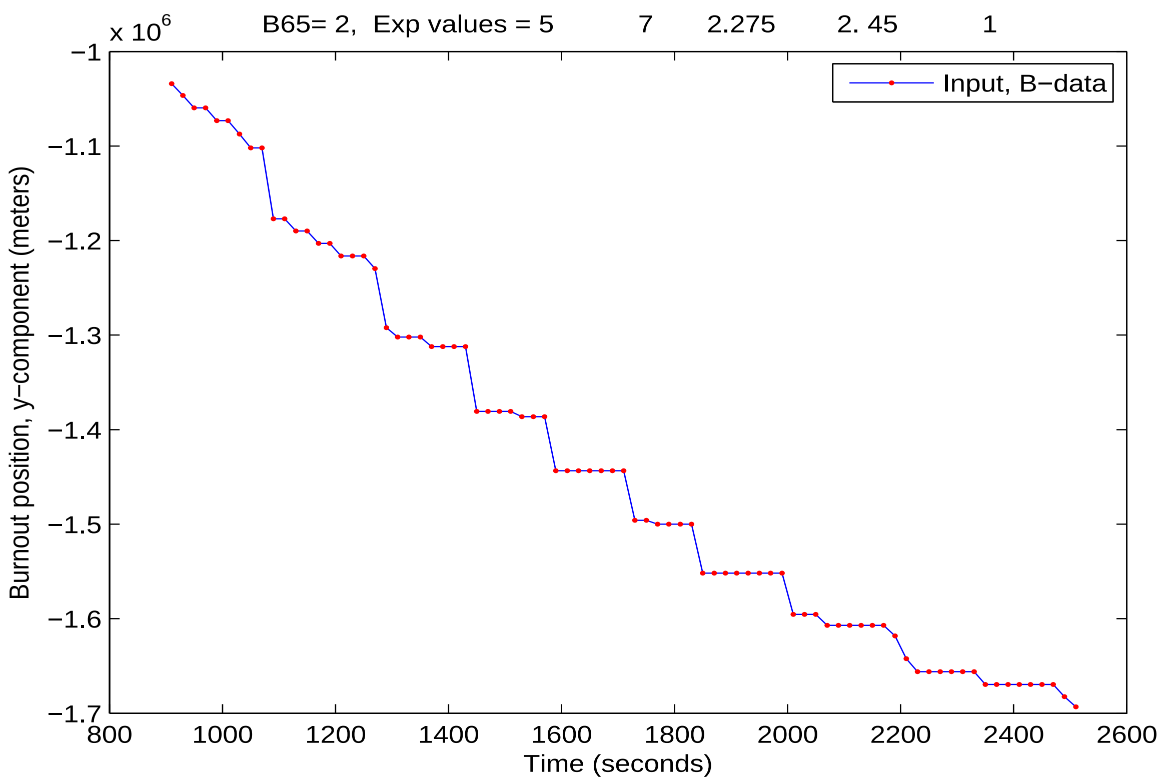


Figure 2B. y-Component of Output Burnout Position versus Time [T2]

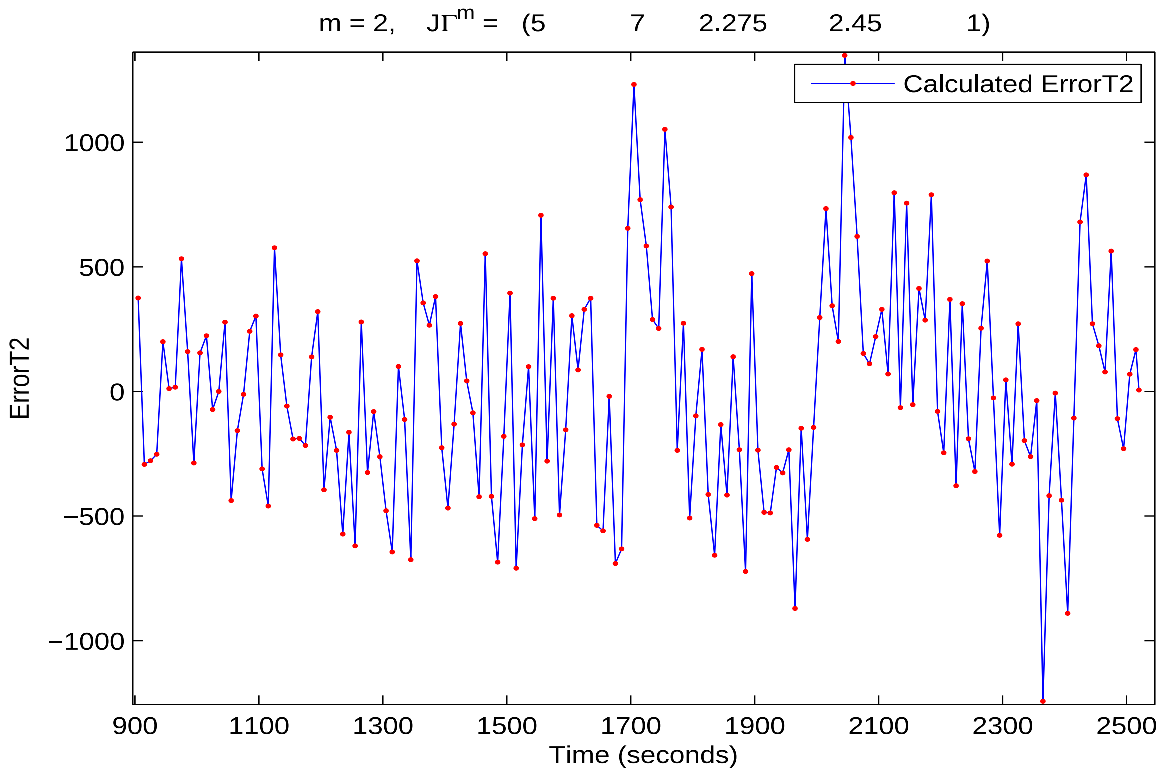


Figure 2C. Error in y-Component of Burnout Position versus Time [T2]

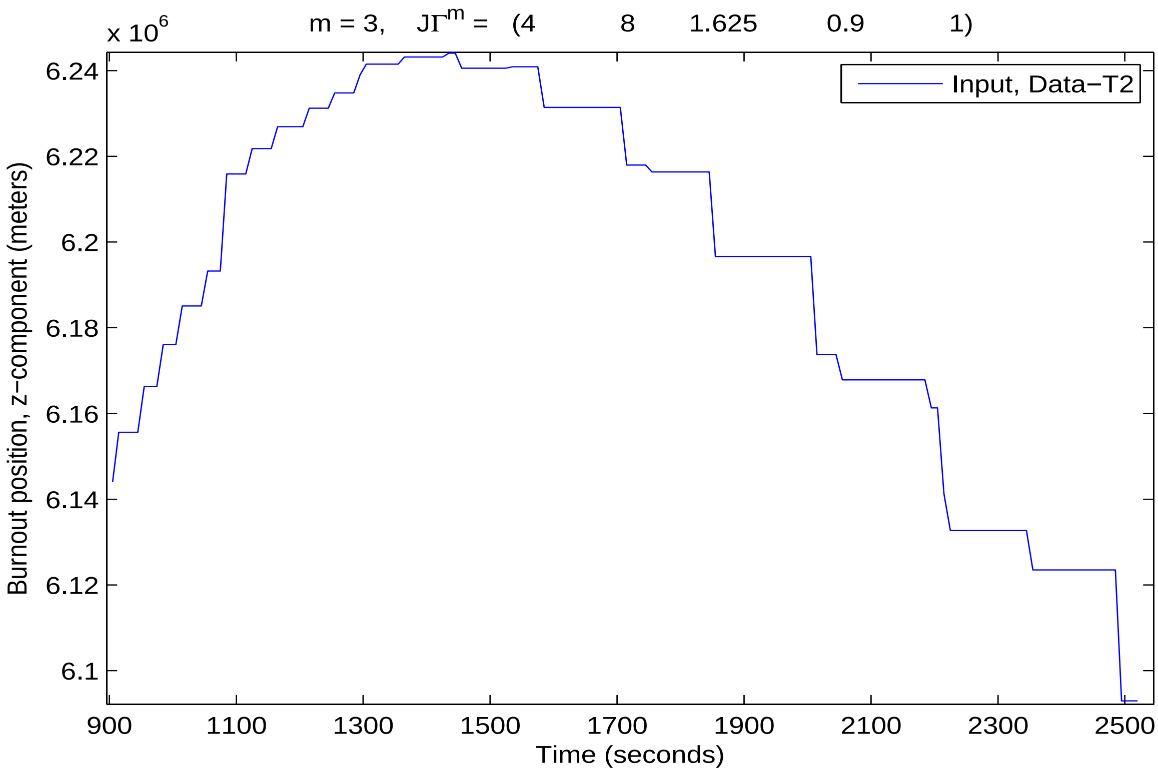


Figure 3A. z-Component of Input Burnout Position versus Time [T2]

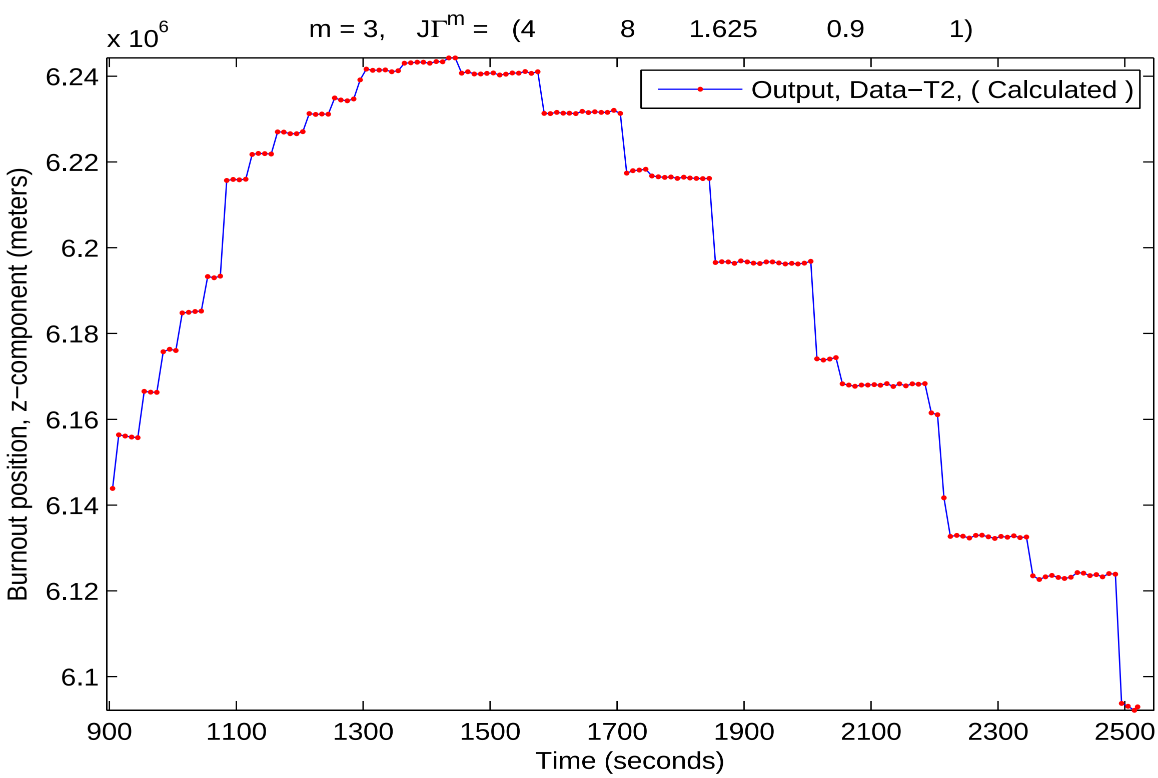


Figure 3B. z-Component of Output Burnout Position versus Time [T2]

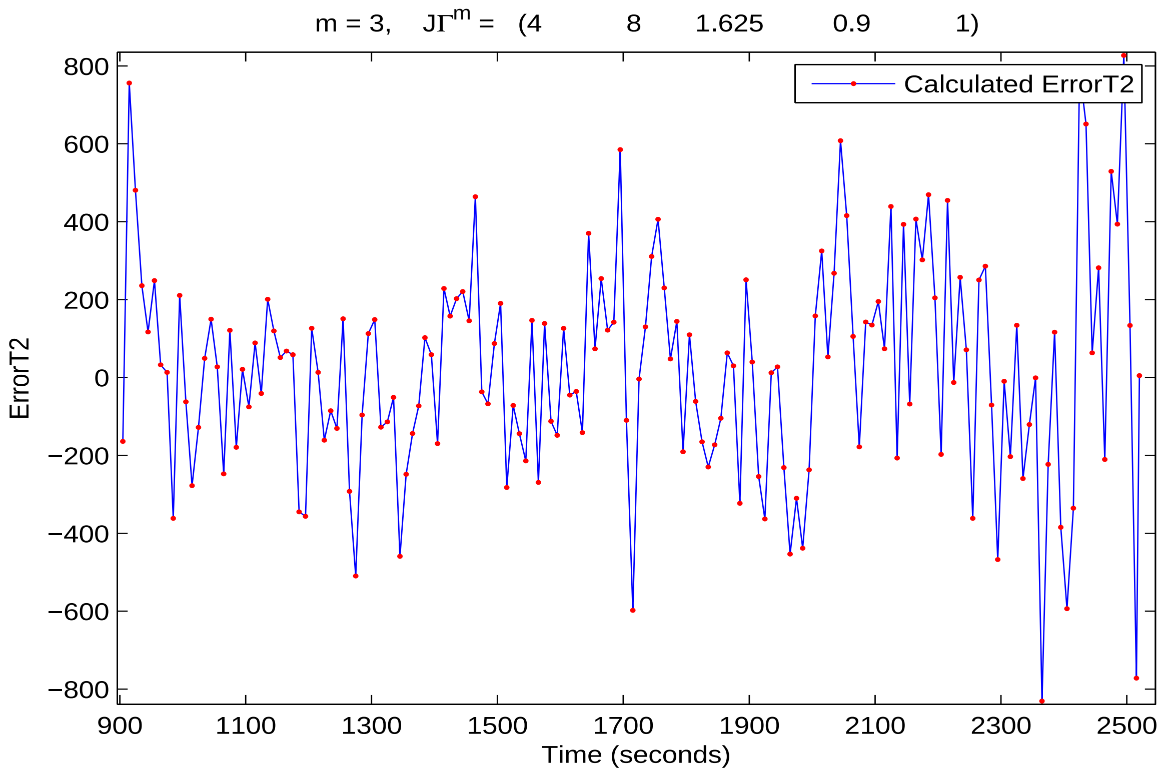


Figure 3C. Error in z-Component of Burnout Position versus Time [T2]

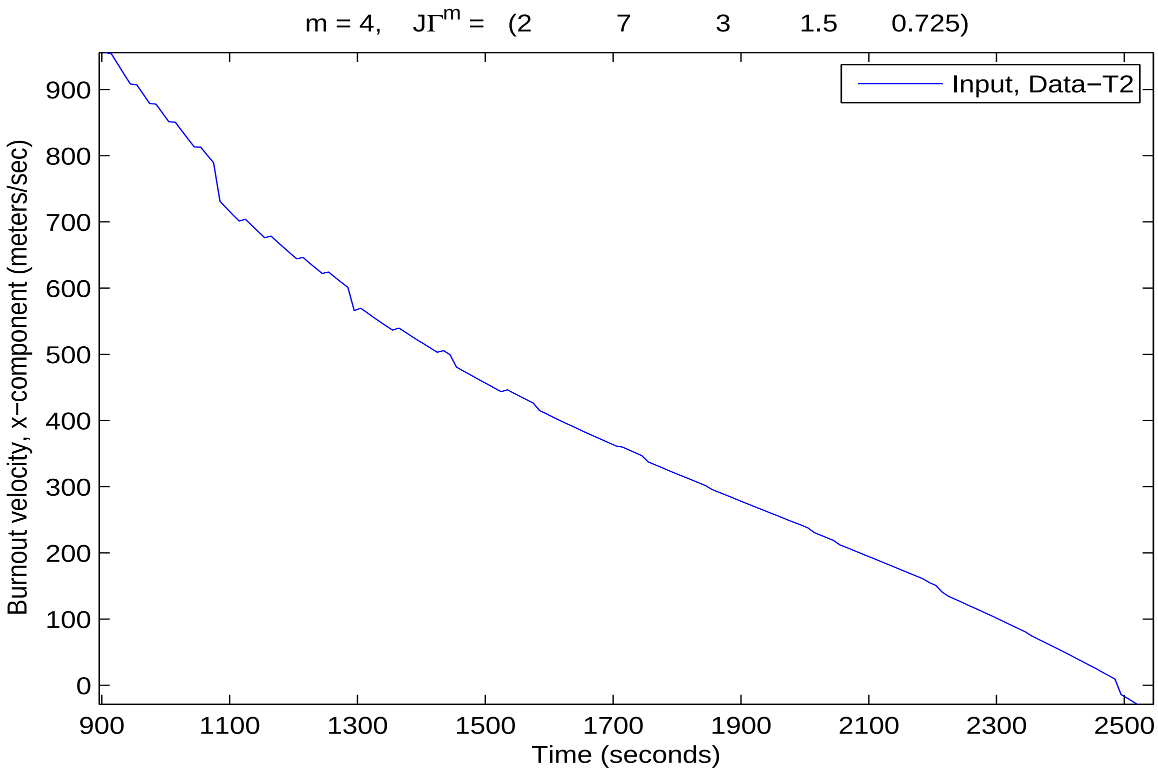


Figure 4A. x-Component of Input Burnout Velocity versus Time [T2]

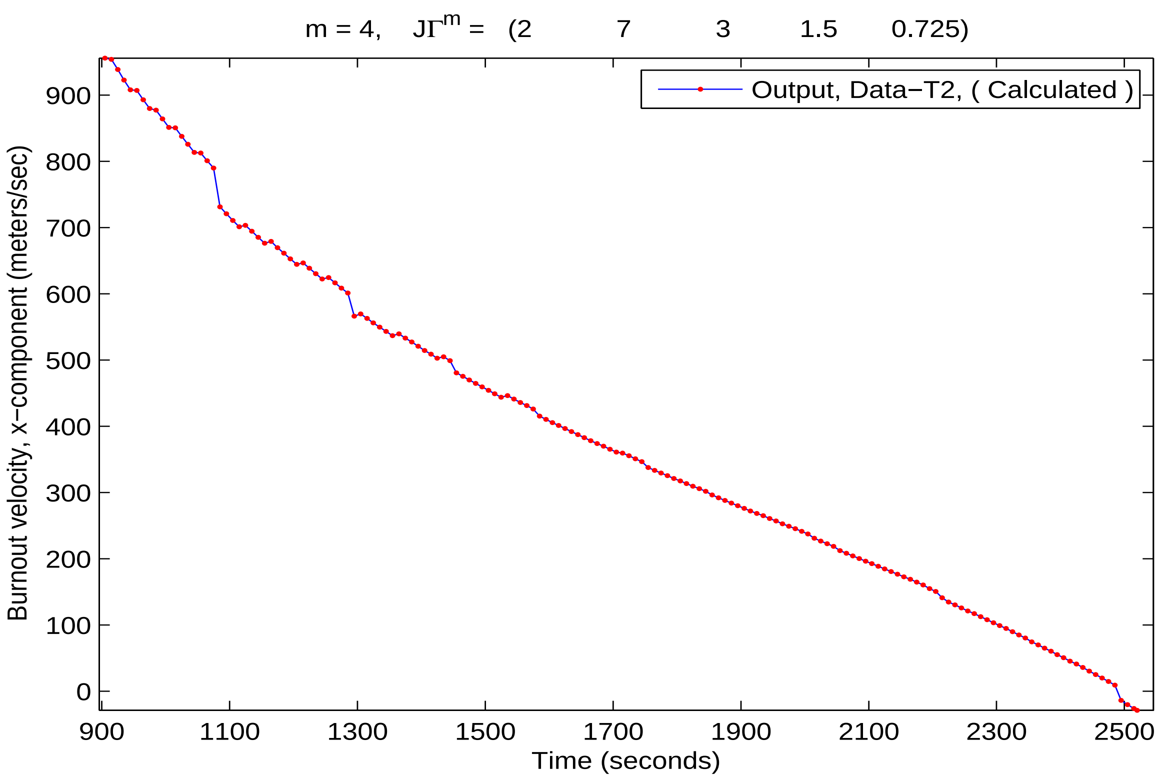


Figure 4B. x-Component of Output Burnout Velocity versus Time [T2]

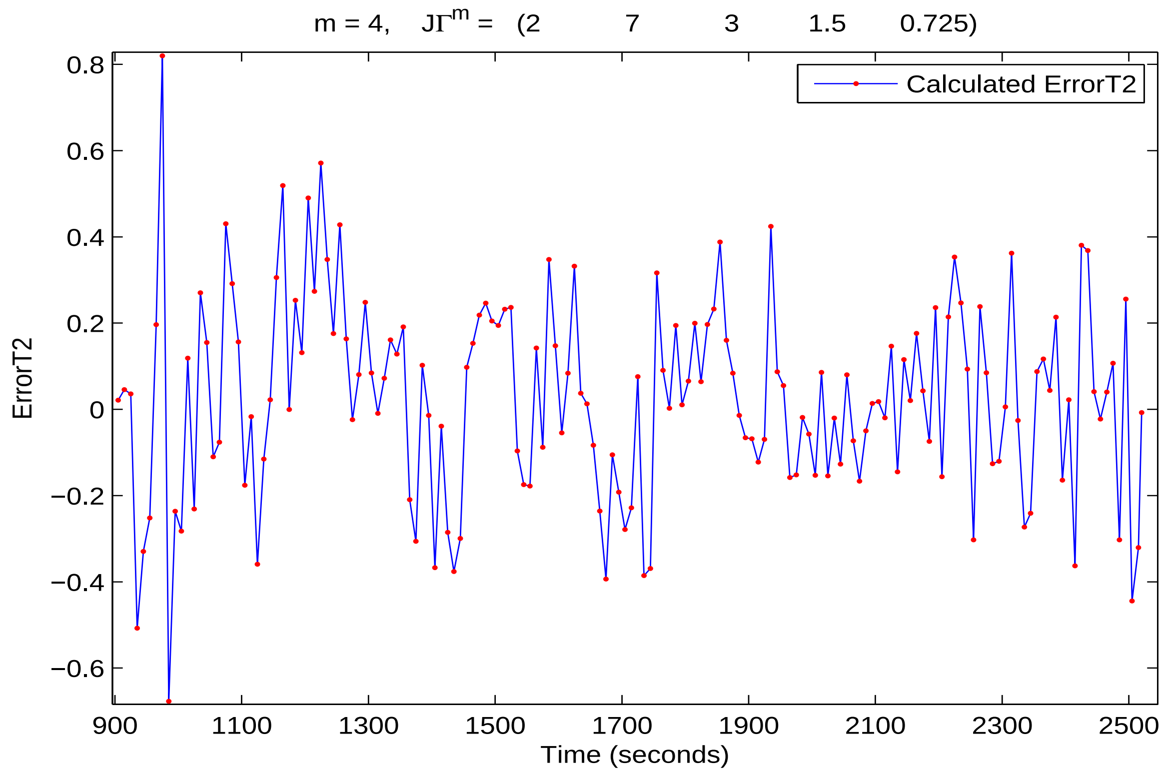


Figure 4C. Error in x-Component of Burnout Velocity versus Time [T2]

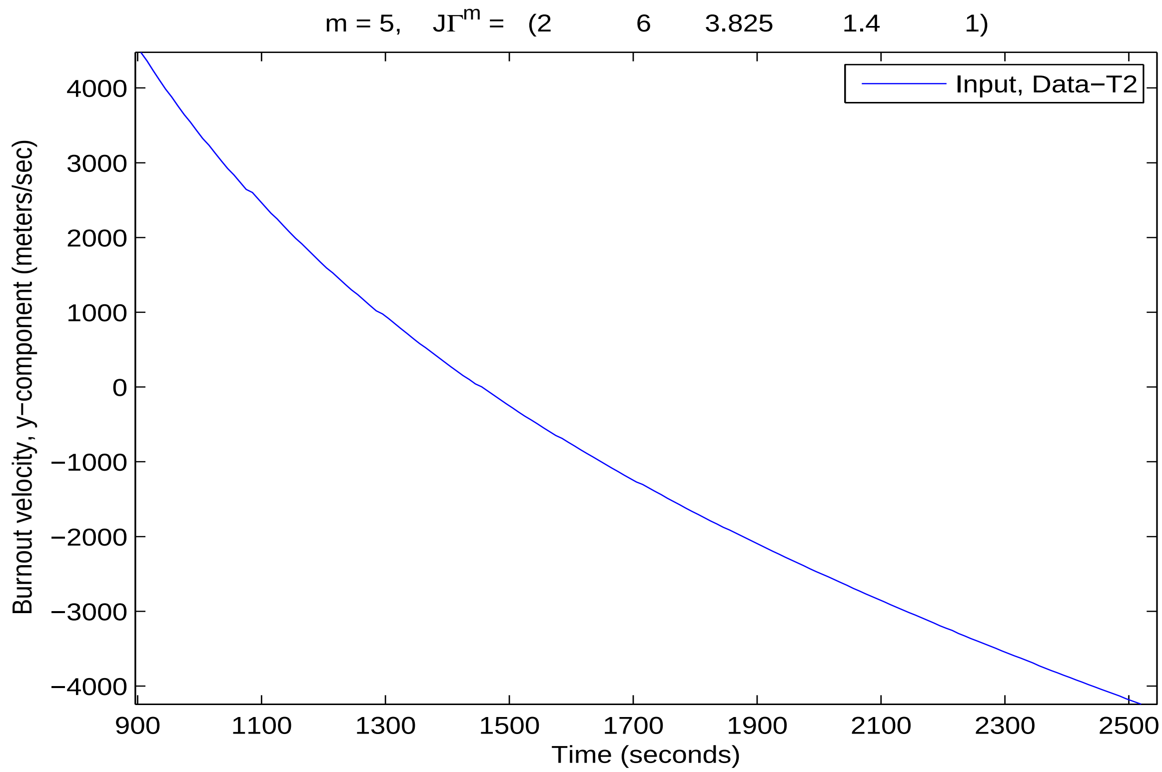


Figure 5A. y-Component of Input Burnout Velocity versus Time [T2]

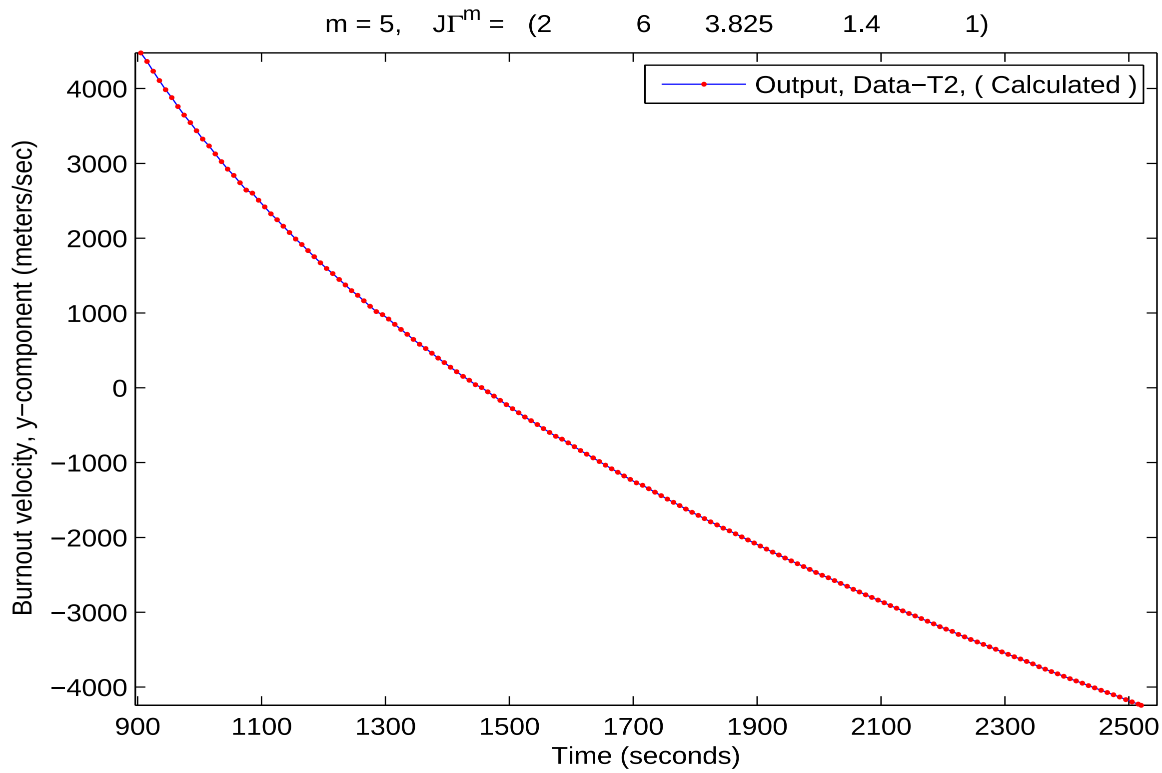


Figure 5B. y-Component of Output Burnout Velocity versus Time [T2]

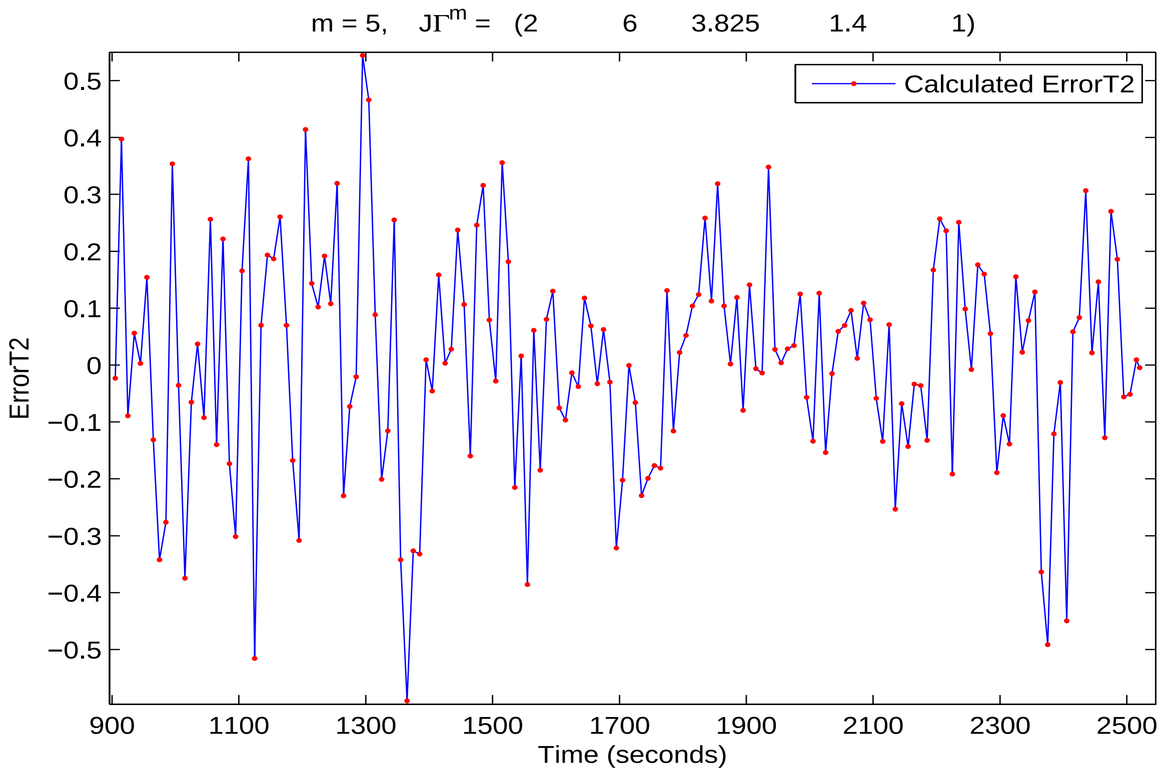


Figure 5C. Error in y-Component of Burnout Velocity versus Time [T2]

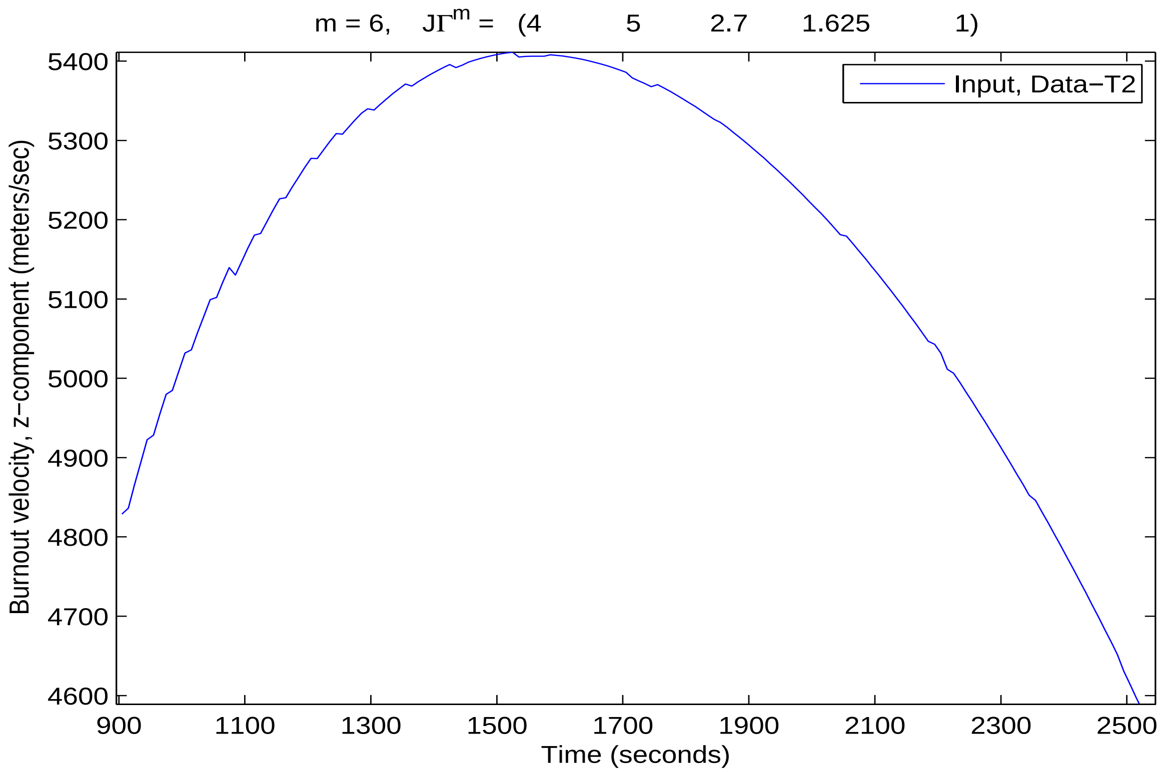


Figure 6A. z-Component of Input Burnout Velocity versus Time [T2]

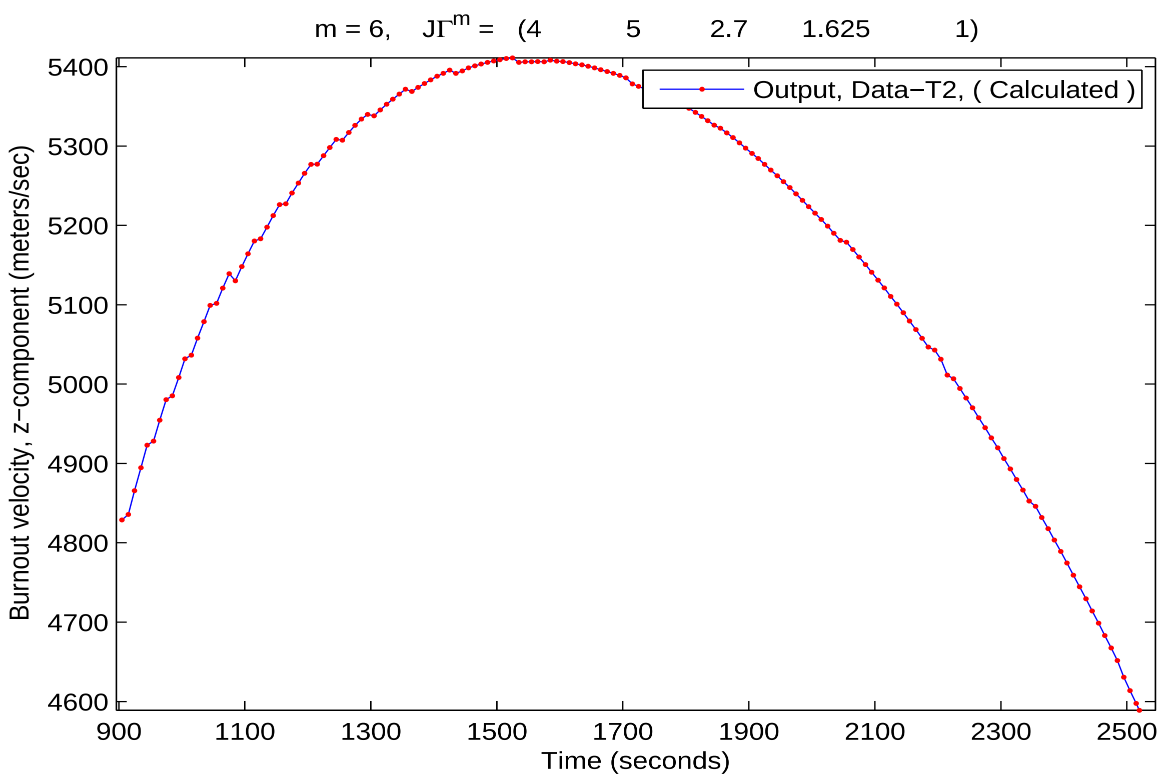


Figure 6B. z-Component of Output Burnout Velocity versus Time [T2]

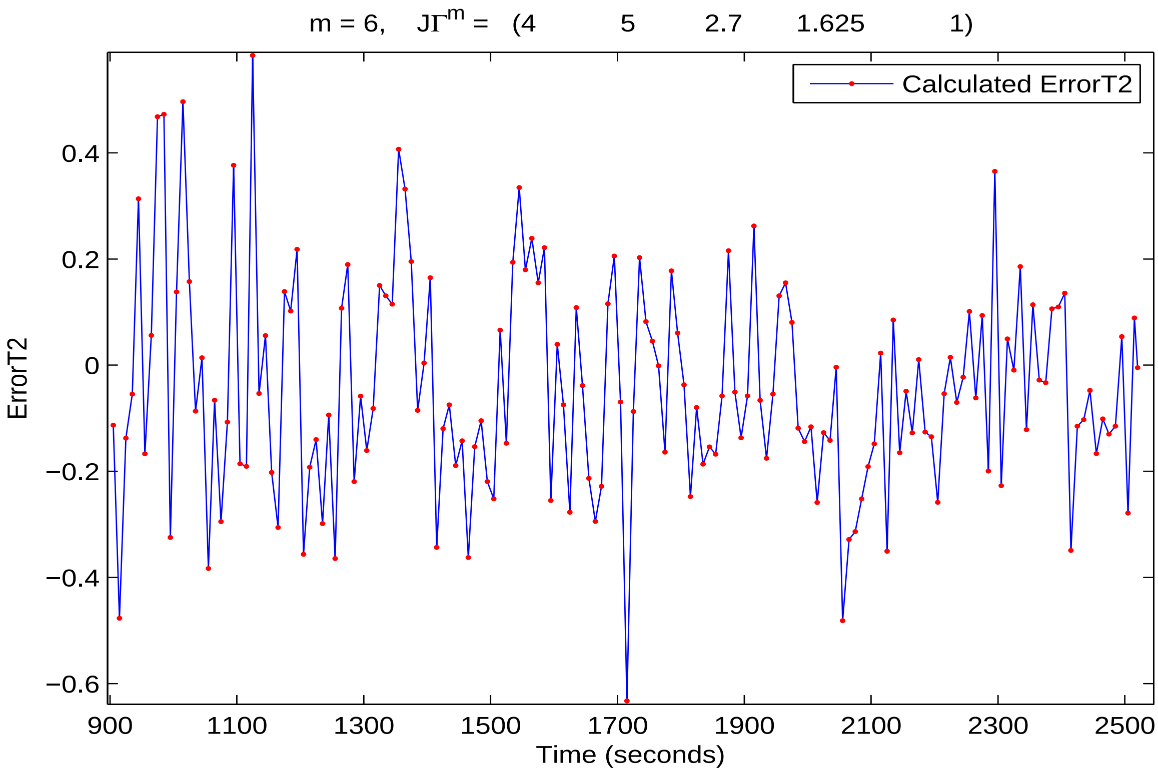


Figure 6C. Error in z-Component of Burnout Velocity versus Time [T2]

## IV. REFERENCES

1. DiDonato, A. R., *FAST Calculation of Time Launch Windows Burnout Positions and Velocities of an Interceptor Versus a Threat*, NSWCDD/TR-01/143, April 2002, Naval Surface Warfare Center, Dahlgren Division, Dahlgren, VA 22448-5100.

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