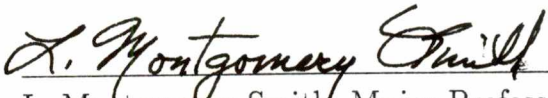
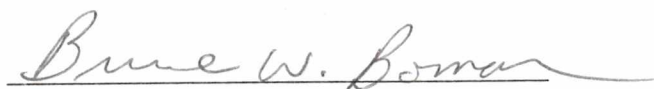


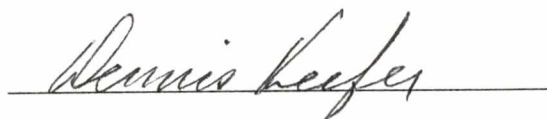
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**ANALYSIS OF RAILGUN MAGNETIC PROBE
SIGNALS TO DETERMINE THE PLASMA ARMATURE
CURRENT DISTRIBUTION**

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Bruno J. Evans
December 1991

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ABSTRACT

Methods were developed for determining the position, velocity, and functional form of a plasma armature from B-dot probe signals. The B-dot probe signal is shown to be a convolution of the armature current density with the B-dot probe impulse response. The methods described here were developed utilizing the knowledge that the probe signal is a convolution.

The method for determining the armature position and velocity utilizes the physical processes governing the plasma armature to model the leading edge of the armature as a unit-step function. The model is convolved with the B-dot probe impulse response to give the probe unit-step response which is a function of the velocity and time of passage of the leading edge of the armature. The unit-step response is compared with the B-dot probe signal using a local-area cross-correlation calculation. Two-parameter iteration determines the time of passage and velocity estimates as the values for which the correlation coefficient is maximized.

The functional form of the plasma armature is estimated by deconvolving the B-dot probe signal to recover the armature current density. Jansson's relaxation based nonlinear iterative method has been developed for use with B-dot probe signals, and it is presented as a method for estimating the armature current density. This approach has advantages over other methods in that only the physical limits of the data need to be known.

Verification of these methods was performed using simulated B-dot probe signals. The simulations indicate that estimates within 10 sampling intervals for the time of passage and 5 percent for the velocity are achievable. Figures are presented of position versus time and velocity versus time for simulated and experimental data. Current density estimates gave improved results over previously used meth-

ods. Plots of deconvolved armature current distributions are shown for simulated and experimental data. Also, Jansson's method estimate is compared to the Wiener filter estimate. Application of these methods to experimental B-dot probe signals has been performed with encouraging results.

CONTENTS

CHAPTER	PAGE
I. INTRODUCTION	1
1.1 Previous Work	2
1.2 Approach	4
II. PROBE SIGNAL	6
2.1 Theory	6
2.2 B-dot Probe Signal	9
III. ARMATURE POSITION AND VELOCITY ESTIMATION	15
3.1 Leading Edge Model	15
3.2 Local-Area Cross-Correlation	17
3.3 Program Development	20
IV. ESTIMATION OF THE CURRENT DISTRIBUTION	22
4.1 Discrete Approximation of the Convolution	22
4.2 Jansson's Method	25
4.3 Filtering	28
4.4 Program Development	30
V. RESULTS	35
5.1 Determining Armature Position and Velocity	35
5.2 Determining Armature Current Distribution	41
VI. CONCLUSIONS	48
BIBLIOGRAPHY	50

CHAPTER	PAGE
APPENDICES	53
Appendix A: Simulated B-dot Probe Signals	54
Appendix B: LACC Program Listing	59
Appendix C: Jansson's Method Program Listing	63
VITA	78

LIST OF FIGURES

FIGURE	PAGE
2.1 B-dot probe geometry	7
2.2 UTSI B-dot probe	7
2.3 Railgun circuit model	11
3.1 B-dot probe unit-step response	18
4.1 Relaxation function	27
4.2 Jansson's method estimate with c selected smaller than the peak amplitude of the current density	31
4.3 Jansson's method estimate with c selected much larger than the peak amplitude of the current density	32
4.4 Jansson's method estimate with c selected 10 percent larger than the peak amplitude achieved with previous iteration	34
5.1 Simulated B-dot probe signal with unit-step response	36
5.2 Comparison of estimated and known times of passage for simulated B-dot probe signals	38
5.3 Comparison of estimated and known velocities for simulated B-dot probe signals	39
5.4 Experimentally acquired B-dot probe signal with the unit-step response evaluated at the estimated time of passage and velocity . . .	40
5.5 Armature position and velocity data for a complete UTSI railgun firing as estimated by the LACC coefficient	42
5.6 Simulated B-dot probe signal with known current density	43
5.7 Comparison of the estimated and known armature current density for the simulated B-dot probe signal	44

FIGURE	PAGE
5.8 Experimentally acquired B-dot probe signal	46
5.9 Comparison of the estimated current density to the experimentally acquired B-dot probe signal which has been plotted in spatial coordinates	47
A.1 Railgun current profile used to construct simulated B-dot probe signals	57
A.2 Armature position and velocity profiles used to construct simulated B-dot probe signals	58

CHAPTER I

INTRODUCTION

Research on electromagnetic railgun launchers has been directed towards developing an electromagnetic means of accelerating masses at velocities an order of magnitude greater than the 2 km/sec achievable with conventional propellants. However, the reliable operation of a plasma armature railgun is limited to about 6.5 km/sec. There has been little progress in increasing the velocity capabilities of railguns beyond this limit. A significant number of questions need to be answered in order to understand the physical processes which degrade railgun performance and thus limit the velocity [1].* In order to evaluate the performance of a railgun, it is essential to understand the plasma armature current density. Current probes (termed B-dot probes) are one of the most common diagnostic instrumentation techniques utilized to make quantitative measurements of the plasma armature current [2].

A B-dot probe is a small cylindrical coil that produces an output voltage proportional to the time rate of change of the magnetic field component parallel to the axis of the coil. As the plasma armature passes by a B-dot probe located near the barrel of the railgun, it produces a voltage pulse whose functional form is dependent upon the orientation of the probe. The most common configuration for B-dot probes is oriented to sense the armature current [2]. B-dot probes oriented in this manner are referred to as armature current probes, and the recorded signal is a bimodal pulse consisting of a positive and a negative portion. However, the B-dot probes on the University of Tennessee Space Institute (UTSI) railgun are oriented to sense the rail current, in which case they are called rail current probes,

* Numbers in brackets refer to similarly numbered references in the Bibliography.

and the signal is a unidirectional pulse. Since these signals depend on the shape of the armature current densities in plasma armature railguns, they have been used to infer the current densities in the plasma.

In this thesis, methods for analyzing the plasma armature current from recorded B-dot probe signals are presented. These methods are based upon the work of Smith and Keefer [3], who showed that the B-dot probe signal is a convolution of the plasma armature current density with a spatially varying impulse response function that is dependent in form upon the velocity. The methods determine the location of the leading edge of the armature, the armature velocity at this location, and estimate the functional form of the plasma armature current density.

1.1 Previous Work

A common technique for determining the armature position as it travels down the barrel of the railgun is to place several probes along the length of the railgun barrel and measuring the time of occurrence of the voltage pulse. The probe position versus time of passage of the armature is often taken as being indicative of the armature motion from which the velocity is inferred. Jamison and Burden [4], using armature current probes, select the first peak of the bimodal pulse as the armature position. Cobb [5] has verified this approach by measuring plasma emission with a photo-diode located at the same position as the B-dot probe, and shown that the leading edge of the armature is approximately adjacent to the probe at first maximum. Parker [2] speaks of integrating the signal from a rail current probe and drawing a line coincident with the most steeply rising segment of the resulting curve to give the armature position. Previously at UTSI, the time of passage of the leading edge of the armature was taken as the time at which the unidirectional pulse of the rail current probe reached one-half its maximum value.

One technique used in determining plasma armature current densities from recorded B-dot probe signals involves fitting an assumed functional form to the B-dot probe signal. Jamison and Burden [4] use a truncated Gaussian curve to calculate numerically the expected magnetic fields, thus giving calculated B-dot probe signals. The procedure involves fitting a five-parameter calculated B-dot probe signal to the measured B-dot probe signal. Cobb [6] has developed a method to determine the current density in the railgun plasma armature by least squares fitting the B-dot probe voltage. The fitted parameters provide information on the armature position and velocity, the current distribution, and the dynamic features of the armature.

Another technique commonly used is deconvolving the B-dot probe signal to recover the plasma armature current density. Bouvier [7] speaks of finding the current density by taking the fast Fourier transform (FFT) of the integral of the B-dot signal and deconvolving it with a geometry-dependent weight function and a Gaussian filter. Previously at UTSI, the Wiener filter approach described by Smith and Keefer [3] has been used to recover plasma armature current densities from B-dot probe signals.

The methods stated for determining armature position and velocity have drawbacks due to their ad hoc and heuristic natures. Neither the known response of the B-dot probe nor the physical processes governing plasma armature current densities are utilized. Often, the techniques rely upon "eyeball" measurements and human operator judgment. The effects of noise upon such measurement methods can be significant but are rarely considered. Thus, a great deal of ambiguity as well as the possibility of error is inherent in these previous approaches.

All of the techniques described for determining the plasma armature current densities give good quantitative information, but they all have drawbacks. The

fitting method used by Jamison and Burden [4] assumes a functional form for the armature current density. With the method used by Cobb [6], assumptions are made concerning the time dependence of the armature current density. The deconvolution approach of Bouvier [7] is not optimal since a Wiener filter provides the best least-squares linear estimate. The Wiener filter approach of Smith and Keefer [3] requires an ad hoc parameter in the absence of noise and data statistics. These and other linear methods also suffer since the final estimate can contain non-physical (negative) peaks.

1.2 Approach

The method described here to determine the armature position and velocity uses a local-area cross-correlation (LACC) calculation developed by Evans and Smith [8]. * This procedure estimates the time at which the leading edge of the plasma armature passes the B-dot probe and its velocity at this location. The technique involves modeling the leading edge of the current profile as a unit-step function because Keefer [9], Sloan [10], and Powell and Batteh [11] have shown that the current density peaks toward the projectile/armature interface. Since it has been shown in [3] that the B-dot probe signal is a convolution of the plasma armature current density with the impulse response of the probe, a series of unit-step B-dot probe responses are calculated for varying velocities to simulate the leading edge of the B-dot probe signal. These curves, limited to a finite region, are then used to calculate cross-correlation coefficients with correspondingly limited regions of the B-dot probe data. Two-parameter iteration determines the peak cross-correlation

* Portions of this thesis are excerpts from an article entitled "A cross-correlation-based method for determining the position and velocity of a railgun plasma armature from B-dot probe signals," written by B. J. Evans and L. M. Smith which is due to be published in the October 1991 *IEEE Transactions on Plasma Science*.

value, thus yielding the optimal values for the time of passage and velocity estimates for the plasma armature.

The method described here to determine the plasma armature current density utilizes the knowledge that the B-dot probe signal is a convolution of the armature current density with the B-dot probe impulse response function. With knowledge of the B-dot probe impulse response function, the plasma armature current density can be recovered from the recorded B-dot probe signal through deconvolution. However, a fundamental limitation of numerical deconvolution schemes is in their inability to deconvolve noisy data successfully. Jansson's relaxation based nonlinear iterative deconvolution method [12] uses constraints of maximum and minimum peak amplitudes, and it has been shown by Crilly [13] to work successfully with noisy data. Successive estimates are constrained by upper and lower amplitude bounds which correspond to the physical limits of the data. The constraining operation is done in a gradual fashion without any truncation of information. The procedure makes corrections based on the difference between the recorded B-dot probe signal and the convolution of the current density estimate with the B-dot probe impulse response function. This method only requires knowledge of the B-dot probe impulse response function and the maximum peak amplitude of the armature current density.

Chapter II derives the B-dot probe signal. In Chapter III, the LACC method for determining the armature position and estimating its velocity is derived. Chapter IV describes Jansson's deconvolution algorithm and develops its use for B-dot probe data. Verification with simulated and experimental data can be found in Chapter V. Conclusions are made in Chapter VI.

CHAPTER II

PROBE SIGNAL

B-dot probes have been utilized in plasma physics experiments for many years. Over the past decade, B-dot probes have become one of the primary diagnostic tools used to assess the performance of railguns [2]. A typical B-dot probe consists of N multiple turns of wire around a form having a cross-sectional area A as shown in Figure 2.1. Each turn has the same area A and normal unit vector $\mathbf{n}$. The N turns are tightly wound so that each turn occupies approximately the same region of space. Over the surface covering A the magnetic field $\mathbf{B}$ is assumed to be uniform since the probes are fixed in space and small compared to the spatial gradients in the magnetic field $\mathbf{B}$ [3]. The B-dot probe produces an output voltage proportional to the time rate of change of the magnetic field component parallel to the axis of the coil $\mathbf{n}$. UTSI B-dot probes utilize the same geometry as shown in Figure 2.1, but they are constructed in a slightly different manner. Two holes are drilled into a cylindrical insulating material, and the turns of wire are wound through the holes as shown in Figure 2.2.

2.1 Theory

The space around a current-carrying conductor is occupied by a magnetic field $\mathbf{B}$. The magnetic induction $\mathbf{B}$ produced at a point $\mathbf{r}$ in space by a distribution of currents is determined by the Biot-Savart law [14],

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi} \int \frac{\mathbf{J}(\mathbf{r}') \times (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} d^3r', \quad (2.1)$$

where $\mathbf{J}(\mathbf{r}')$ is the current density located at the point $\mathbf{r}'$. The magnetic flux Ψ_m is

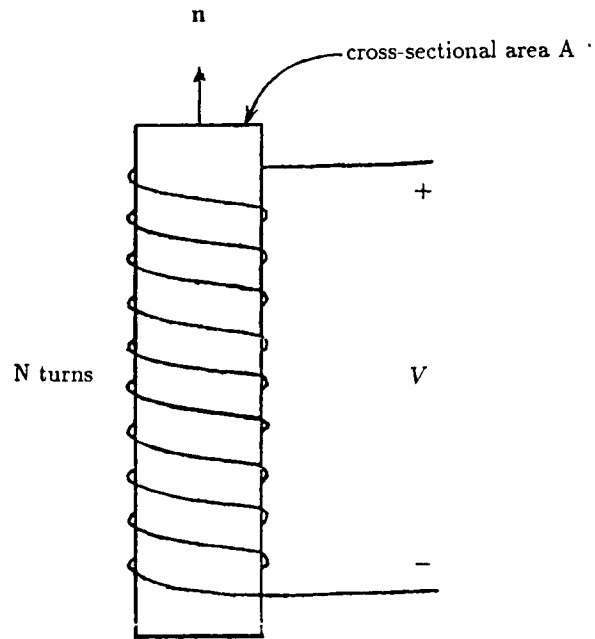


Figure 2.1 - B-dot probe geometry.

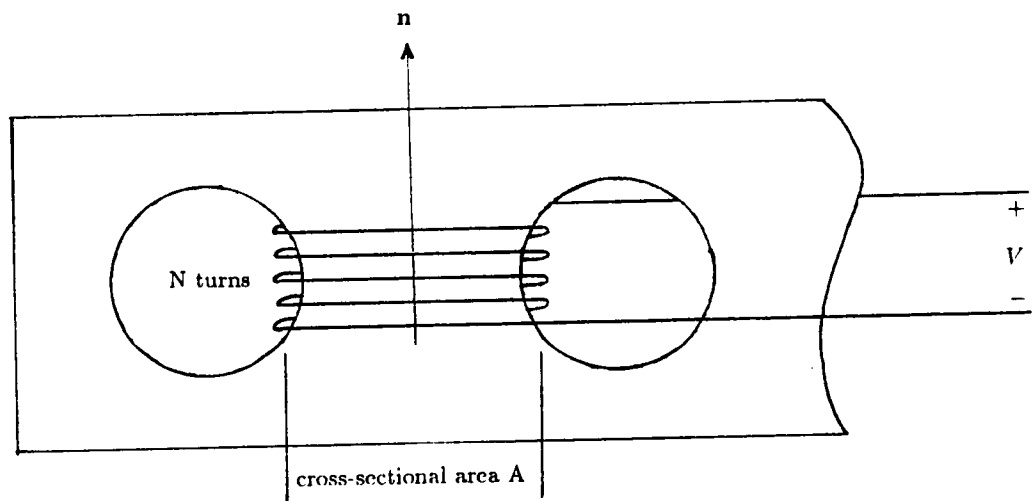


Figure 2.2 - UTSI B-dot probe.

related to $\mathbf{B}$ by

$$\Psi_m = \int_S \mathbf{B} \cdot d\mathbf{S}, \quad (2.2)$$

where the integral is taken over the surface $\mathbf{S}$ that Ψ_m passes through. If the magnetic field $\mathbf{B}$ is uniform over the enclosed surface, then solving the surface integral yields

$$\begin{aligned} \Psi_m &= \mathbf{B} \cdot \mathbf{n}A \\ &= AB_n, \end{aligned} \quad (2.3)$$

where A is the area of the enclosed surface and B_n is the component of the magnetic field in the direction $\mathbf{n}$ which is normal to the surface S .

Faraday is credited with the discovery that a time-changing magnetic flux induces an electromotive force (EMF) in a closed loop linked by that flux. This experimental fact is called Faraday's law [14] and is written

$$\text{EMF} = \frac{d\Psi_m}{dt}. \quad (2.4)$$

Substituting (2.3) into (2.4) yields

$$\text{EMF} = A \frac{dB_n}{dt}, \quad (2.5)$$

where the area of the loop A is assumed constant. If we apply (2.5) to a coil of multiple turns, an EMF appears in every turn and the individual contributions add together. If the coils are tightly wound so that each turn can be said to occupy the

same region of space, the flux through each turn will be the same. Therefore, the induced EMF for a coil of N turns is

$$\text{EMF} = NA \frac{dB_n}{dt}. \quad (2.6)$$

If the rate of change of the flux is in webers/second, the EMF will be in volts. Therefore, the voltage induced at the terminals of a B-dot probe is given by (2.6) and is written

$$V = NA \frac{dB_n}{dt}. \quad (2.7)$$

The signal is proportional to the time rate of change of the magnetic field produced by a distribution of currents. Through some simplifying assumptions, it will be shown that the B-dot probe signal is a convolution of the armature current density with the impulse response function of the B-dot probe.

2.2 B-dot Probe Signal

Smith and Keefer [3] have shown that, under certain simplifying assumptions, a B-dot probe voltage signal consists of a convolution of the armature current density with an impulse response function which can be derived from the armature velocity and the probe geometry and position. The results of Smith and Keefer [3] only considered the current traveling in the rail nearest the B-dot probe. Evans and Smith [8] have expanded this derivation to include the effects of the current traveling in both rails. A derivation can be found in the cited references. The following derivation follows that of Evans and Smith [8], and is presented for completeness and consistency with the present notation.

The railgun circuit model is shown in Figure 2.3 and consists of a current loop lying in the x - y plane. The rails are oriented along the x direction and are modeled as infinitely thin conductors carrying a total gun current I_0 . The B-dot probe is oriented to sense the y component of the magnetic field $\mathbf{B}$, and it is located at a longitudinal distance x from the origin, at a radial distance r_1 from the nearer rail, and at an angle θ_1 from the z direction. The breech of the gun barrel is assumed to lie at a sufficient distance from the probe to approximate $-\infty$.

The armature current distribution is denoted $I_{\text{arm}}(x)$, and is modeled as moving with velocity v in the x direction. As shown in Figure 2.3, it lies in the moving ξ coordinate system, with its leading edge at $\xi = 0$. At time $t = t_o$, the leading edge of the current distribution passes the B-dot probe. Near the time t_o , as the armature passes the probe, a signal pulse is produced that deviates from the quiescent value for a short time interval. For typical railgun firings, this interval is on the order of $100 \mu\text{sec}$. It is assumed that over this time interval, the velocity v and total current I_0 remain constant, and that the shape of the armature current distribution $I_{\text{arm}}(\xi)$ in the moving coordinate system does not change. With these assumptions, the x component of the current in the rails at time t near time t_o is given by

$$I(x') = I_0 - \int_{-\infty}^{x' - [x + v(t - t_o)]} I_{\text{arm}}(\xi) d\xi \quad (2.8)$$

where

$$\int_{-\infty}^{\infty} I_{\text{arm}}(\xi) d\xi = I_0. \quad (2.9)$$

From the Biot-Savart law (2.1), the y component of the magnetic field at the probe location at time t can be expressed explicitly as

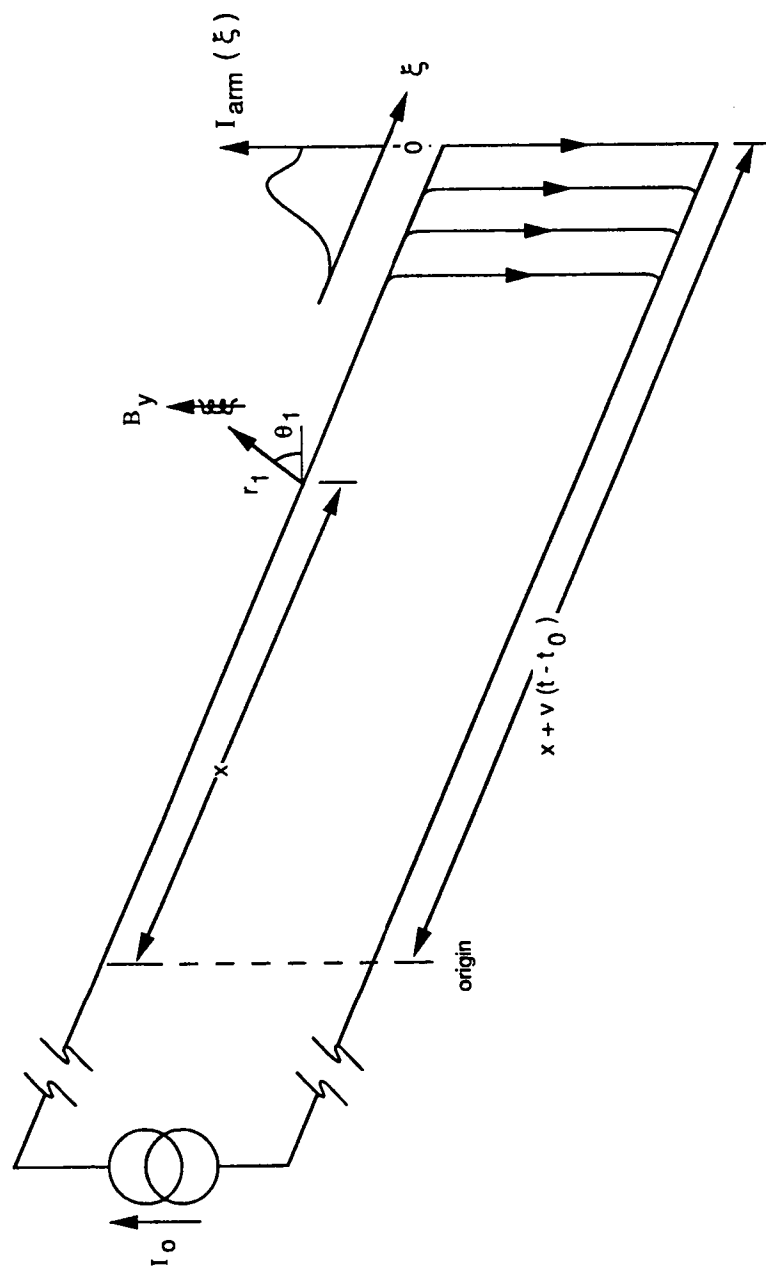


Figure 2.3 - Railgun circuit model.

$$B_y(t) = \frac{\mu_o}{4\pi} r_1 \cos \theta_1 \int_{-\infty}^{\infty} \frac{I(x')}{[r_1^2 + (x - x')^2]^{3/2}} dx'. \quad (2.10)$$

Substituting (2.8) into (2.10) and making the change of variables $\eta = x' - [x + v(t - t_o)]$ yields

$$B_y(t) = \frac{\mu_o}{4\pi} r_1 \cos \theta_1 \int_{-\infty}^{\infty} \frac{\left[I_0 - \int_{-\infty}^{\eta} I_{\text{arm}}(\xi) d\xi \right]}{[r_1^2 + (-\eta - v(t - t_o))^2]^{3/2}} d\eta. \quad (2.11)$$

The measured signal is proportional to the time rate of change of the magnetic field component. Thus, to find the measured signal, (2.11) must be differentiated with respect to time t to yield

$$\begin{aligned} \frac{dB_y}{dt} = \frac{\mu_o}{4\pi} v r_1 \cos \theta_1 \int_{-\infty}^{\infty} & \left[I_0 - \int_{-\infty}^{\eta} I_{\text{arm}}(\xi) d\xi \right] \\ & \cdot \left[\frac{3(v(t_o - t) - \eta)}{[r_1^2 + (v(t_o - t) - \eta)^2]^{5/2}} \right] d\eta. \end{aligned} \quad (2.12)$$

The integral in (2.12) can be integrated by parts, and by applying the boundary condition stated in (2.9), the expression for the time rate of change of the y component of the magnetic field can be written

$$\frac{dB_y}{dt} = \frac{\mu_o}{4\pi} v r_1 \cos \theta_1 \int_{-\infty}^{\infty} \frac{I_{\text{arm}}(\eta)}{[r_1^2 + (v(t_o - t) - \eta)^2]^{3/2}} d\eta. \quad (2.13)$$

The B-dot probe signal is proportional to the expression in (2.13). The integral in (2.13) can be recognized as the one-dimensional convolution of the armature current distribution $I_{\text{arm}}(x)$ with an impulse response function with the substitution

$x = v(t_o - t)$ in the result. The impulse response function of the B-dot probe due to the current traveling in the nearer rail is thus given by

$$h_1(x) = \frac{\mu_o}{4\pi} \frac{vr_1 \cos \theta_1}{[r_1^2 + x^2]^{3/2}}, \quad (2.14)$$

where the convolution is performed the respect to the variable x . Note that the B-dot probe signal is time-varying, and that its temporal variation is dependent in form upon the velocity v .

The B-dot probe impulse response function for the nearer rail is given by (2.14). The impulse response function due to the farther rail can be found in a similar manner. The probe is located a radial distance r_2 from the farther rail and at an angle θ_2 from the z direction. The current in the farther rail is assumed to be given by (2.8) but traveling in the opposite direction. This induces a magnetic field in the y direction opposite in sign to that induced by the current in the nearer rail. The expression for the y component of the magnetic field at the probe location due to the farther rail current is thus given by the negative of (2.10) with the radial distance and angle for the farther rail. By following the same analysis used in determining the impulse response due to the current in the nearer rail, the impulse response function of the B-dot probe due to the current in the farther rail is

$$h_2(x) = -\frac{\mu_o}{4\pi} \frac{vr_2 \cos \theta_2}{[r_2^2 + x^2]^{3/2}}. \quad (2.15)$$

By superposition, the impulse response function of the B-dot probe due to the current in both rails can be expressed as

$$h(x) = \frac{\mu_o}{4\pi} \left[\frac{vr_1 \cos \theta_1}{[r_1^2 + x^2]^{3/2}} - \frac{vr_2 \cos \theta_2}{[r_2^2 + x^2]^{3/2}} \right]. \quad (2.16)$$

It has been shown that the B-dot probe signal is a convolution of the armature current density with the impulse response function of the B-dot probe given in (2.16) where the impulse response function is dependent in form upon velocity. Since the B-dot probe impulse response function is dependent upon time and velocity, we can use this knowledge to determine the time of passage and velocity of the plasma armature from the B-dot probe signal. Knowing that the signal is a convolution, the plasma armature current density can be recovered through deconvolution.

CHAPTER III

ARMATURE POSITION AND VELOCITY ESTIMATION

Since the B-dot probe impulse response function is dependent in form upon time and velocity, it can be used to determine the time of passage and velocity of the armature as it passes the B-dot probe. This method utilizes the physical processes governing the plasma to determine the time the leading edge of the plasma armature passes the B-dot probe and to estimate the armature velocity at this location. The following analysis follows the cross correlation technique developed by Evans and Smith [8] for estimating the armature position and velocity.

3.1 Leading Edge Model

Recent studies have shown that the current density peaks near the projectile/armature interface. Keefer [9], through optical and electrical measurements of current profiles, has shown that the maximum current density occurs near the base of the projectile. He states that this observation is at variance with theoretical predictions that the current maximum should occur toward the rear of the armature as a result of the velocity skin effect. For railgun plasma armatures, thermal mechanisms, which do not exist for solid armatures, tend to move the peak of the current density forward towards the base of the projectile.

Sloan [10] has investigated the role of convective flow processes in determining plasma armature characteristics. He states that many theoretical assessments of plasma armature properties assume a zero flow configuration. However, for high velocities, entrainment of the armature in turbulent boundary layers may lead to the development of convective flow within the armature. The effects of such flow have been examined and give significant departure from the usual zero flow models.

One result of the convective flow process is a peaking of the armature current towards the projectile/armature interface.

Powell and Batteh [11] have analyzed a model of the railgun to study the plasma dynamics. The analysis included determining the electromagnetic fields within the railgun and solving the fluid-mechanical equations of the plasma. Specifically, they derived a set of coupled equations, that when solved, yielded the properties of the armature. The results of numerical analysis of these equations showed that current density peaked near the projectile surface.

Based on the findings stated above, an assumption is made that the functional form of the leading edge of the plasma armature current density can be modeled as a unit-step function,

$$I_{\text{arm}}(x) = u(x) = \begin{cases} 1, & \text{if } x \geq 0; \\ 0, & \text{if } x < 0. \end{cases} \quad (3.1)$$

The amplitude of the current profile is irrelevant in the correlation coefficient calculation, and so it is set equal to unity for simplicity of notation.

Since the B-dot probe signal has been shown to be a convolution of the armature current density with the probe impulse response function, the impulse response function (2.16) can be convolved with the unit-step function (3.1) to give the probe unit-step response

$$h(x) * u(x) = \frac{\mu_o}{4\pi} \int_{-\infty}^x \left[\frac{vr_1 \cos \theta_1}{[r_1^2 + \eta^2]^{3/2}} - \frac{vr_2 \cos \theta_2}{[r_2^2 + \eta^2]^{3/2}} \right] d\eta. \quad (3.2)$$

The probe unit-step response, $f(v(t_o - t)) = h(x) * u(x)|_{x=v(t_o - t)}$, can be found by solving the integral in (3.2) which yields

$$f(v(t_o - t)) = \frac{\mu_o v}{4\pi} \left[\frac{v(t_o - t) \cos \theta_1}{r_1 \sqrt{r_1^2 + v^2(t_o - t)^2}} + \frac{\cos \theta_1}{r_1} - \frac{v(t_o - t) \cos \theta_2}{r_2 \sqrt{r_2^2 + v^2(t_o - t)^2}} - \frac{\cos \theta_2}{r_2} \right]. \quad (3.3)$$

The B-dot probe unit-step response shown in (3.3) is used as a model of the B-dot probe signal for the leading edge of the armature. The probe unit-step response is thus dependent on two parameters, velocity v , and time of passage of the leading edge of the armature t_o , with time t as its independent variable. Figure 3.1 shows the resulting curves for velocities of 750, 1500, 2250 m/sec calculated using position parameters from UTSI B-dot probes. The time of passage of the armature in these curves is found at time zero. Note that as the velocity increases, the slope of the curve at the time of passage ($t_o = 0$) also increases. By comparing the curves to actual B-dot probe signals, the time of passage of the armature can be determined, and its velocity estimated.

3.2 Local-Area Cross-Correlation

The similarity between two signals, $s_1(t)$ and $s_2(t)$, is often determined by finding the linear relationship between them [15]. This linear relationship is often found in terms of a correlation function. It is common to express the correlation as the ratio

$$\rho_{s_1 s_2} = \frac{\int_{-\infty}^{\infty} s_1(t) s_2(t) dt}{\sqrt{\int_{-\infty}^{\infty} s_1^2(t) dt \int_{-\infty}^{\infty} s_2^2(t) dt}}, \quad (3.4)$$

where $\rho_{s_1 s_2}$ is the correlation coefficient. The correlation coefficient can be used to assess the degree of linear dependence between $s_1(t)$ and $s_2(t)$ on a scale from

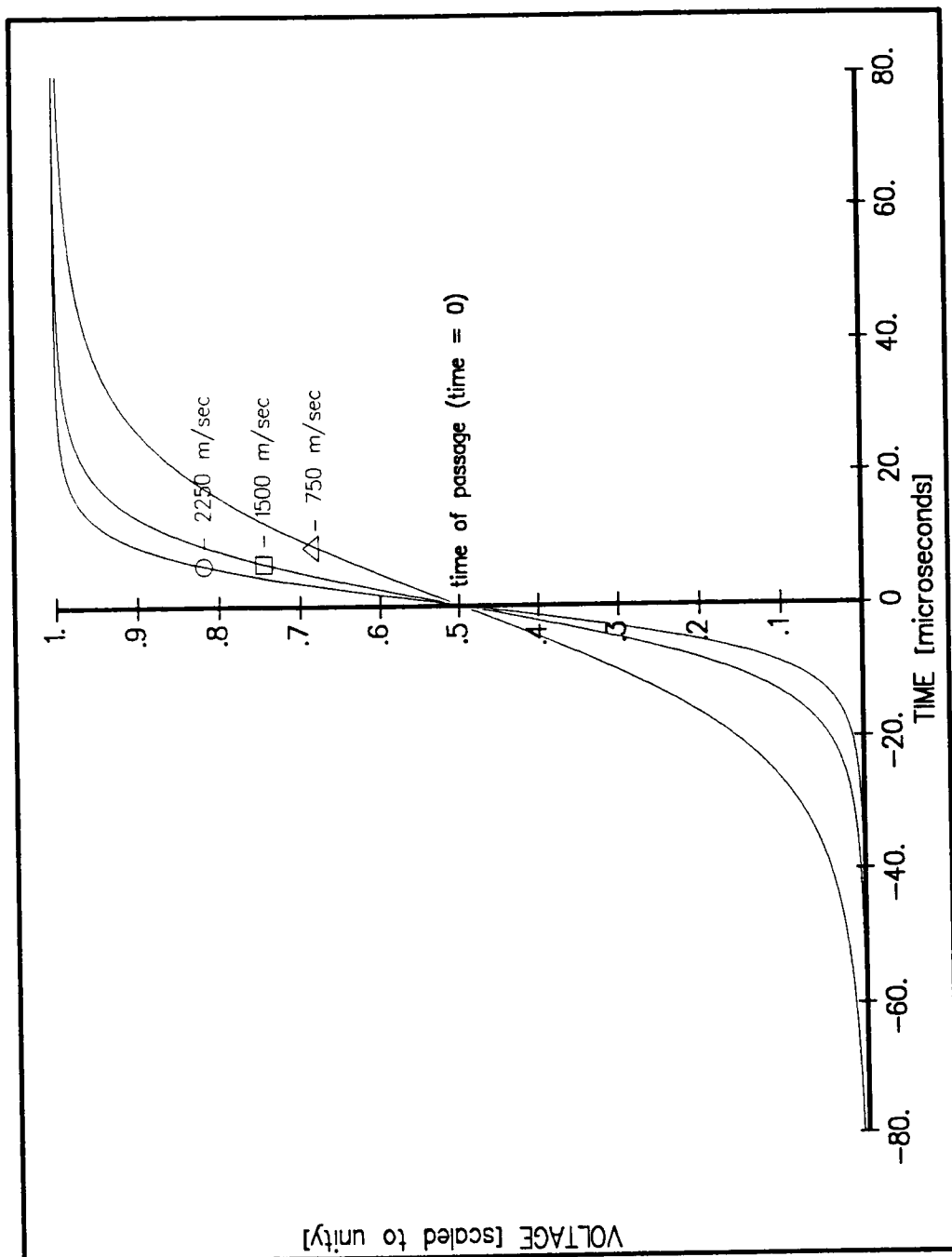


Figure 3.1 - B-dot probe unit-step response.

– unity to + unity. Ideally, the correlation coefficient is unity, but because the relationship between the two signals may be nonlinear and/or there is noise in the measurements the value is often less than unity. However, the closer the calculated correlation coefficient is to unity, the more similar the signals.

In comparing a B-dot probe signal to the probe unit-step response (3.3), a standard method of determining the correlation coefficient cannot be used. The correlation is to be examined over the entire signal, but the unit-step response is only valid for a selected fixed-length interval. The unit-step response is thus calculated for $t_o = 0$, over a selected range of time t , and compared with different intervals of the shifted B-dot probe signal. Modifying the standard equation for determining the correlation coefficient, we define the local-area cross-correlation (LACC) coefficient in the following manner:

$$\rho(\hat{t}_o, \hat{v}) = \frac{\int_{t_1}^{t_2} g(t + \hat{t}_o) f(-\hat{v}t) dt}{\sqrt{\int_{t_1}^{t_2} g^2(t + \hat{t}_o) dt \int_{t_1}^{t_2} f^2(-\hat{v}t) dt}} \quad (3.5)$$

where $g(t + \hat{t}_o)$ is the shifted B-dot probe signal, $f(-\hat{v}t)$ is the probe unit-step response (3.3), $\hat{v}$ is the estimated armature velocity, and $\hat{t}_o$ is the estimated time of passage at which the correlation between the B-dot probe signal and the probe unit-step response is being examined. The limits t_1 and t_2 give the time interval over which the unit-step response model is taken to be valid. The correlation makes a comparison over the stated interval, and it is dependent on both velocity and time. Although the comparison is made only over the defined interval, the B-dot probe signal is shifted when the next interval of the probe signal is to be examined. After the entire probe signal has been examined, the shift and velocity values yielding the maximum correlation coefficient are then taken to be the time of passage of the armature and the estimated armature velocity.

3.3 Program Development

B-dot probe data is acquired by sampling the signal at a uniform sampling rate Δt and stored in digital format for off-line processing. Thus, actual computation must be performed on discrete data. Approximation of the integral in (3.5) by rectangular rule integration yields the LACC coefficient for discretized data:

$$\rho(k\Delta t, \hat{v}) = \frac{\sum_{i=l_1}^{l_2} g((k+i)\Delta t) f(-i\hat{v}\Delta t)}{\sqrt{\sum_{i=l_1}^{l_2} g^2((k+i)\Delta t) \sum_{i=l_1}^{l_2} f^2(-i\hat{v}\Delta t)}}. \quad (3.6)$$

Using a two variable iterative approach, the time of passage, given by $k\Delta t$, and the estimated velocity $\hat{v}$ of the armature are found.

The iterative procedure involves checking the leading edge of the unidirectional B-dot probe signal at the times between 25 and 75 percent of the signal maximum. A computer program is used to determine the point of maximum correlation over this portion of the signal. With a given initial velocity estimate input by the user, the program finds the time of passage for maximum correlation. This value is held fixed while the velocity is varied between 500 m/sec below to 500 m/sec above the initial velocity, until the velocity that gives the largest correlation coefficient is determined. Using the new velocity, the leading edge of the B-dot probe signal is re-examined until the time value of maximum correlation is found. This procedure is repeated until the time of passage estimate converges to within 1 sample interval and the velocity estimate converges to within 1 m/sec.

The time interval over which the unit-step response is taken to be valid was determined through numerical trials using simulated B-dot probe signals. These signals included time-varying current and armature velocity in order to simulate

accurately the B-dot probe response in an actual railgun firing. A full derivation of these simulated B-dot probe signals is given in Appendix A. Using these signals, the time of passage and the estimated velocity were determined using the iterative procedure described previously. The time interval over which the unit-step response can be assumed to be valid was determined by examining several known current densities using different time intervals. The interval was varied until the velocity estimates were within 5 percent and the time of passage estimates were within 10 sampling intervals of the known values. The interval, as defined by the variables l_1 and l_2 , was selected to start and stop at the times where the unit-step response reached 1.5 and 98.5 percent of its maximum value respectively. Note that this interval will vary in length with the value of velocity. These limits provide a range over which a sharply rising leading edge in armature current produces a probe signal that approximates the unit-step response of the B-dot probe.

From an assumption that the leading edge of the plasma armature current density can be modeled as a unit-step function, a correlation calculation can be made to determine the position and velocity of the armature from recorded B-dot probe signals. Verification of this method will be made in Chapter V by displaying results for simulated and experimental B-dot probe signals.

CHAPTER IV

ESTIMATION OF THE CURRENT DISTRIBUTION

Since the B-dot probe signal is a convolution of the plasma armature current density with the impulse response function of the B-dot probe, the current density can be recovered from the B-dot probe signal using a deconvolution technique. The iterative nonlinear deconvolution method developed by Jansson [12] is presented here as a technique for determining the plasma armature current densities from recorded B-dot probe signals.

4.1 Discrete Approximation of the Convolution

In Chapter II, the B-dot probe signal was shown to be a convolution of the armature current density with the impulse response function of the B-dot probe. Assuming that the leading edge of the armature passes the B-dot probe at time $t_o = 0$, the B-dot probe signal, denoted $g(t)$, can be written

$$g(t) = h(x) * I_{\text{arm}}(x)|_{x=-vt} + \epsilon(t), \quad (4.1)$$

where $h(x)$ is the B-dot probe impulse response function, $I_{\text{arm}}(x)$ is the plasma armature current density, and $\epsilon(t)$ represents the noise that inevitably corrupts any experimental signal. The asterisk is a shorthand notation for the convolution integral in (2.13).

If the signal is sampled at a uniform sampling interval Δt , the sequence can be expressed as

$$g(n\Delta t) = h(x) * I_{\text{arm}}(x)|_{x=-vn\Delta t} + \epsilon(n\Delta t). \quad (4.2)$$

The sequence $g(n\Delta t)$ can be axis-reversed, and the convolution written

$$g(-n\Delta t) = \int_{-\infty}^{\infty} I_{\text{arm}}(\eta) h(nv\Delta t - \eta) d\eta + \epsilon(-n\Delta t), \quad (4.3)$$

which can be approximated by

$$g(-n\Delta t) \cong \sum_{m=0}^{M-1} I_{\text{arm}}(m\Delta\eta) h(nv\Delta t - m\Delta\eta) \Delta\eta + \epsilon(-n\Delta t) \quad (4.4)$$

where M is the total number of points in the discrete sequence $I_{\text{arm}}(\eta)$. By choosing $\Delta\eta = v\Delta t$, the summation in (4.4) becomes

$$g(-n\Delta t) \cong \sum_{m=0}^{M-1} I_{\text{arm}}(mv\Delta t) h((n-m)v\Delta t) v\Delta t + \epsilon(-n\Delta t). \quad (4.5)$$

For the remainder of the chapter, the substitutions $g(n)$ for $g(-n\Delta t)$, $I_{\text{arm}}(n)$ for $I_{\text{arm}}(nv\Delta t)$, $h(n)$ for $h(nv\Delta t)v\Delta t$, and $\epsilon(n)$ for $\epsilon(-n\Delta t)$ will be used. With this obvious abuse in notation, the recorded B-dot probe signal can be written as the convolution of two discrete sequences corrupted by a noise sequence as

$$g(n) = \sum_{m=0}^{M-1} I_{\text{arm}}(m) h(n-m) + \epsilon(n). \quad (4.6)$$

The problem is how to recover the sequence $I_{\text{arm}}(n)$ from the observed data $g(n)$. Deconvolution of the B-dot probe signal $g(n)$ is a convenient way of determining the armature current density $I_{\text{arm}}(n)$. Due to the noise associated with practical measurements, the typically encountered deconvolution problem becomes an estimation problem since exact knowledge of the deconvolved time signals is not possible.

Deconvolution of noisy data is a problem that has been extensively studied, and numerous methods exist for calculating an estimate $\hat{I}_{\text{arm}}(n)$ from the recorded B-dot probe signal $g(n)$. An estimation technique utilized by Smith and Keefer [3] is based upon filtering the observed data with a filter designed to minimize the statistical average of the mean square error between the estimate and the input signal. The optimal filter estimate for this approach is the Wiener filter and is given by

$$\hat{I}_{\text{arm}}(n) = F^{-1} \left\{ \frac{H^*(\omega)G(\omega)}{|H(\omega)|^2 + S_{\epsilon}(\omega)/S_{I_{\text{arm}}}(\omega)} \right\}, \quad (4.8)$$

where $\hat{I}_{\text{arm}}(n)$ is an estimate of $I_{\text{arm}}(n)$, $G(\omega)$ and $H(\omega)$ are the Fourier transforms of $g(n)$ and $h(n)$ respectively, $S_{\epsilon}(\omega)$ and $S_{I_{\text{arm}}}(\omega)$ are the power spectral density functions of the noise $\epsilon(n)$ and the armature current density $I_{\text{arm}}(n)$ respectively, and $H^*(\omega)$ represents the complex conjugate of $H(\omega)$. Usually, $S_{\epsilon}(\omega)$ and $S_{I_{\text{arm}}}(\omega)$ are not known, in which case their ratio can be approximated by a positive constant parameter P . The resulting expression is

$$\hat{I}_{\text{arm}}(n) = F^{-1} \left\{ \frac{H^*(\omega)G(\omega)}{|H(\omega)|^2 + P} \right\} \quad (4.9)$$

and is known as the parametric Wiener filter. The expression for the Wiener filter can be easily implemented using an FFT algorithm, making it a popular deconvolution technique.

In general, techniques that take advantage of all *a priori* information will obtain better results. The Wiener filter uses prior knowledge about the noise and data statistics, and in the absence of this information, the parametric Wiener filter can be used with an ad hoc parameter P . Many classes of data have values that are

limited by physical constraints such as non-negativity. Attempts to restore this type of data with the Wiener filter as well as other linear methods may produce non-physical results such as negative artifacts.

4.2 Jansson's Method

Frequently, linear deconvolution reveals little about the true structure that could not already be seen in the original data and produces undesirable artifacts. Nonlinear methods, however, allow the use of constraints based on physical properties, such as non-negativity, to be enforced during the deconvolution process. Relaxation based iterative methods that use constraints of peak non-negativity have been successfully used by Crilly [13] to restore severely overlapped and noisy chromatographic and spectroscopic data. For this type of data, Crilly has shown that Jansson's method [12] provides the best results.

Jansson's iterative approach is based upon the work of Van Cittert [16]. With Van Cittert's approach, successive estimates are achieved by

$$\hat{I}_{\text{arm}}^{k+1}(n) = \hat{I}_{\text{arm}}^k(n) + b \left[g(n) - h(n) * \hat{I}_{\text{arm}}^k(n) \right], \quad (4.10)$$

where $\hat{I}_{\text{arm}}^k(n)$ is the k^{th} estimate of $I_{\text{arm}}(n)$, b is termed the relaxation constant, and the initial estimate is somewhat arbitrarily chosen to be

$$\hat{I}_{\text{arm}}^0(n) = g(n). \quad (4.11)$$

The asterisk in this case denotes the convolution sum as in (4.6). Van Cittert uses the correction factor $b \left[g(n) - h(n) * \hat{I}_{\text{arm}}^k(n) \right]$ to adjust the k^{th} estimate of $I_{\text{arm}}(n)$ based upon the difference between the actual signal $g(n)$ and the convolution

$h(x) * \hat{I}_{\text{arm}}(n)$. The corrections are done gradually and there are no divisions as in the parametric Wiener filter (4.9). However, for large k , the estimate $\hat{I}_{\text{arm}}(n)$ given (4.10) converges to the inverse filter solution [13]. The inverse filter solution may contain spurious values since $H(\omega)$ will have near-zero values at some frequencies, and due to noise, $G(\omega)$ may have finite values. Van Cittert's method does have an advantage over the inverse filter solution in that if the solution starts to diverge or non-physical peaks start to become excessive, the iterations can be stopped.

If the physical limits of the data are known *a priori*, constraints can be incorporated into Van Cittert's equation to take advantage of the prior knowledge. This can be done by modifying the correction term $[g(n) - h(n) * \hat{I}_{\text{arm}}^k(n)]$ by a relaxation function that causes corrections to $\hat{I}_{\text{arm}}^k(n)$ whenever the estimate has non-physical values.

Jansson's method constrains successive iterations to occur between upper and lower amplitude that correspond to the physical limits of the data. The upper amplitude bound is the maximum peak amplitude of the current density estimate and the lower amplitude bound enforces the non-negativity constraint. The deconvolution algorithm is given by

$$\hat{I}_{\text{arm}}^{k+1}(n) = \hat{I}_{\text{arm}}^k(n) + r\{\hat{I}_{\text{arm}}^k(n)\} [g(n) - h(n) * \hat{I}_{\text{arm}}^k(n)] \quad (4.12)$$

with

$$r\{\hat{I}_{\text{arm}}^k(n)\} = b \left[1 - \frac{2}{c} \left| \hat{I}_{\text{arm}}^k(n) - \frac{c}{2} \right| \right], \quad (4.13)$$

where c is the upper amplitude bound, and the first estimate $\hat{I}_{\text{arm}}^0(n)$ is given by (4.11). The relaxation function is plotted in Figure 4.1. By examining Figure 4.1,

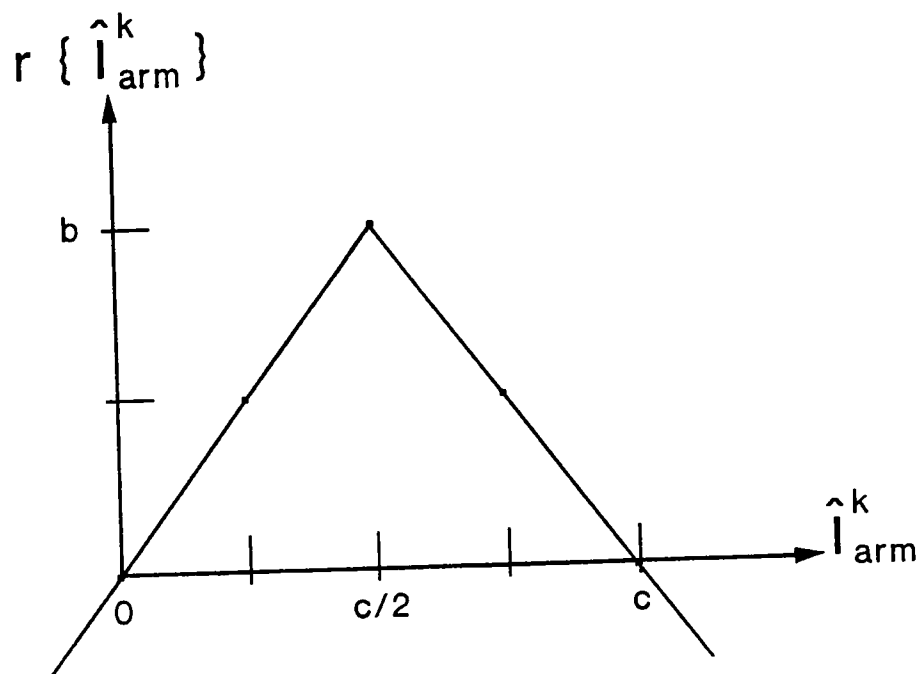


Figure 4.1 - Relaxation function.

it can be seen that $r\{\hat{I}_{\text{arm}}^k(n)\}$ makes positive corrections if the estimate lies within its physical limits (0 to c) and reverse corrections if the estimate has non-physical values. The amount of correction is also weighted less as the estimate approaches the physical limits.

The ability of Jansson's method to converge depends on the selection of the relaxation constant b . If the signal-to-noise ratio of the data is relatively high, b can be large the solution will quickly converge. However, if the signal-to-noise ratio of the data is small, b must be a small number or else the solution will diverge.

In order to determine if the solution has converged, the mean square error (MSE) between the recorded B-dot probe signal and the convolution of the current density estimate with the B-dot probe impulse response function can be examined. The MSE of the k^{th} estimate is given by

$$MSE = \frac{1}{M} \sum_{n=0}^{M-1} \left[g(n) - h(n) * \hat{I}_{\text{arm}}^k(n) \right]^2. \quad (4.14)$$

Convergence can be determined by several means. The most obvious is to minimize the MSE, which may require many iterations. To reduce computational time, the number of iterations can be reduced by stopping the algorithm after the MSE or percent change in the MSE reaches a value specified by the user.

4.3 Filtering

All deconvolution methods are limited in their ability to deconvolve noisy data without introducing any additional spurious components. This limitation is caused by the deconvolution process not only restoring the high frequency components that comprise the well defined features in the signal, but also enhancing the high frequency noise components at an even faster rate. Therefore, it is advantageous to

remove as much noise as possible from the signal before starting the deconvolution process [13]. The noise can be removed from the recorded B-dot probe signal using a lowpass filter.

A filtering scheme known as reblurring [13] provides a way of reducing the high frequency noise in the B-dot probe signal and was found to be necessary for this application. In this method, the signal is prefiltered with the axis-reversed impulse response function to remove high frequency noise components as follows:

$$g'(n) = h(-n) * g(n). \quad (4.15)$$

This requires that in the deconvolution algorithm, the impulse response $h(n)$ should also be modified in the following manner:

$$h'(n) = h(n) * h(-n) \quad (4.16)$$

The new functions $g'(n)$ and $h'(n)$ replace $g(n)$ and $h(n)$ respectively in (4.12). (In this particular application, the impulse response is symmetric, so $h(n) = h(-n)$.) This technique can be looked at as forming the cross-correlation between the B-dot probe data $g(n)$ and the probe impulse response $h(n)$. It is a lowpass filtering operation that removes signal components that are not common to both $g(n)$ and $h(n)$, specifically, the high frequency noise.

In addition to removing the high frequency noise, this filtering technique may also reduce some of the essential high frequency components contained in the B-dot probe signal which enable well defined features, thus reducing the resolution of the deconvolved data. This reduction in resolution requires an increase in the number of iterations in order for the deconvolution process to converge to a given goal.

Therefore, a trade-off exists between noise reduction and computational time when the B-dot probe signal is filtered in this manner.

4.4 Program Development

In applying the iterative algorithm (4.12), it was discovered that $h(n)$ needed to be normalized

$$\sum_{n=0}^{M-1} h(n) = 1. \quad (4.17)$$

This ensures that the difference $g(n) - h(n) * \hat{I}_{\text{arm}}^k(n)$ in the correction term is small. Without this normalization, large differences could result in the correction term causing the solution to diverge rapidly.

The peak amplitude of the plasma armature current density is not known *a priori*. This poses a problem since the wrong selection for c will have adverse effects on the solution. Figure 4.2 shows the effects of choosing c to be smaller than the actual peak amplitude of the estimate $\hat{I}_{\text{arm}}(n)$. The peak of the armature current density is truncated due to the reverse corrections made for estimates whose amplitudes are greater than c . Figure 4.3 shows the effects if c is chosen to be too large. In this case, c was chosen to be twice the peak amplitude of the B-dot probe signal. The largest corrections are made near the peak, resulting in the production of artifacts near the peak not present in the original signal.

A method of determining an approximate peak amplitude for the the estimate of the current density $\hat{I}_{\text{arm}}(n)$ has been developed. In order to determine the approximate amplitude that will be achieved with Jansson's method, one iteration is performed using Van Cittert's method. The value for c is selected to be 10 per cent greater than the maximum amplitude achieved with this iteration. Jansson's

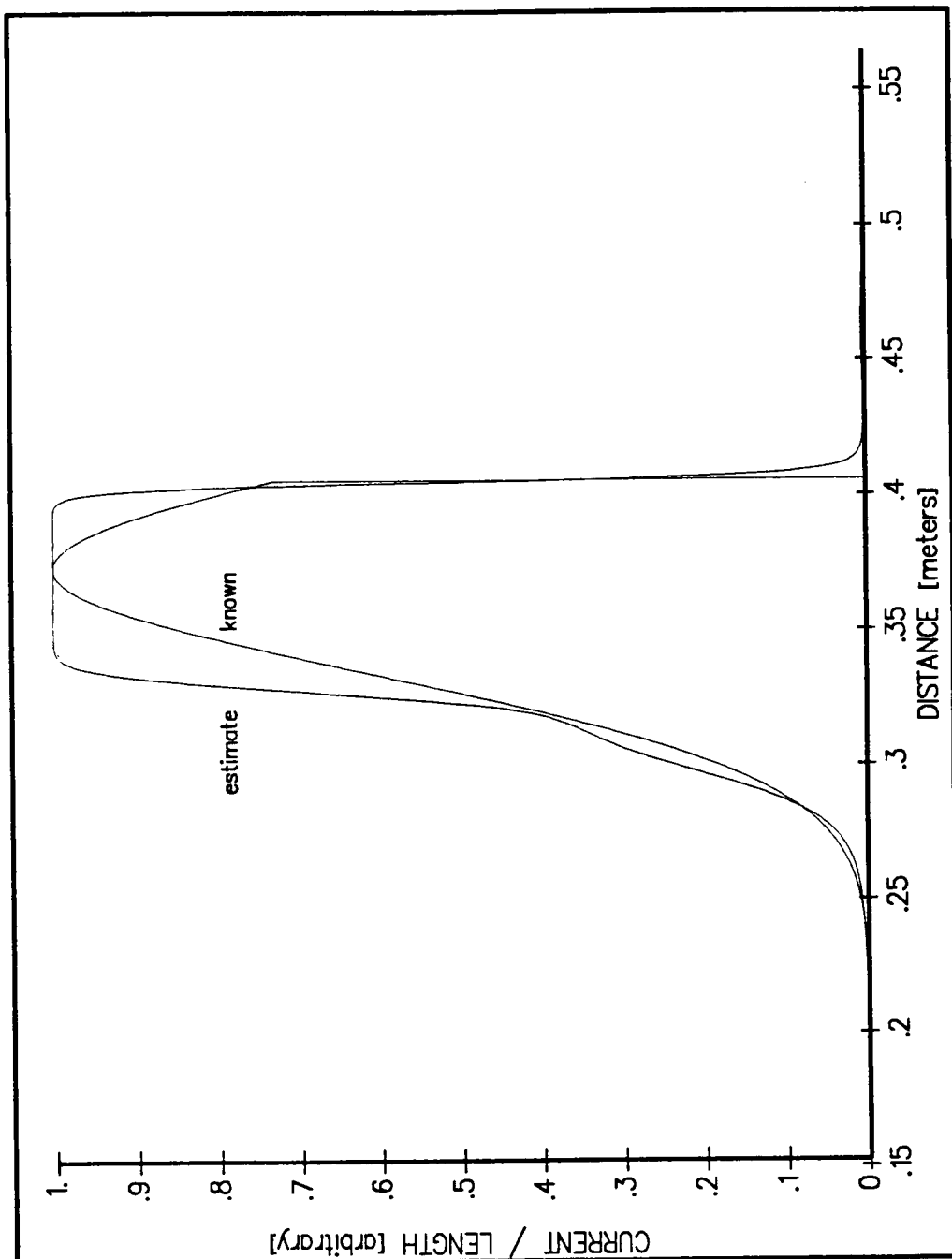


Figure 4.2 - Jansson's method estimate with c selected smaller than the peak amplitude of the current density.

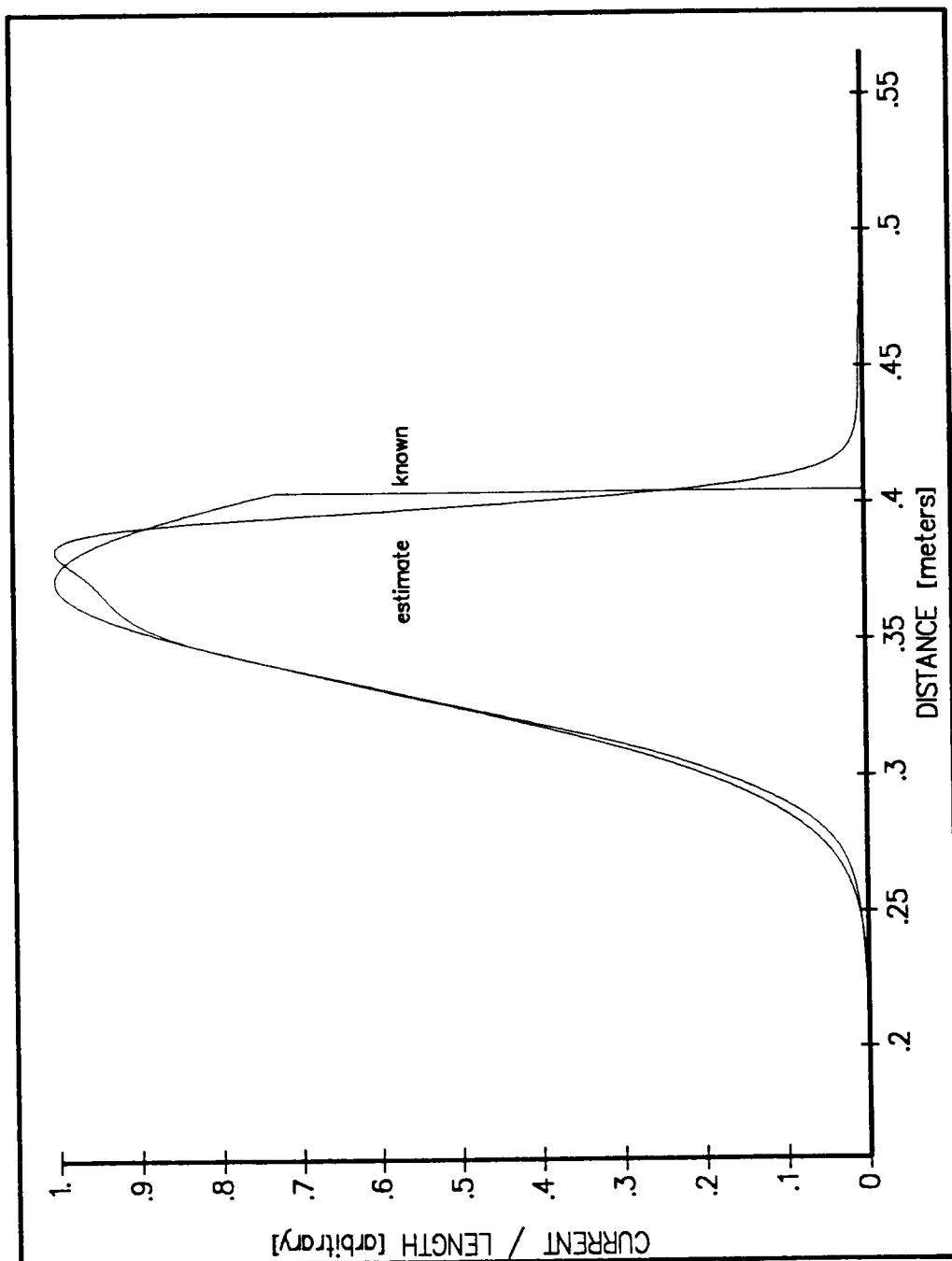


Figure 4.3 - Jansson's method estimate with c selected much larger than peak amplitude of the current density.

method is then implemented with this selection for c . However, after each iteration, the value of c is adjusted to be 10 percent greater than the maximum amplitude achieved with the previous iteration. This method of selecting c has been tested using simulated B-dot probe signals and works extremely well. Figure 4.4 shows the results of deconvolving a simulated B-dot probe signal using this method.

A computer program was written to minimize the MSE between the B-dot probe signal and the estimate convolved with the B-dot probe impulse response function. However, in testing with simulated B-dot probe signals, it required hundreds of iterations for the solution to converge. Upon examining results obtained with the MSE minimization, it was discovered that after the percent change in the MSE was less than 1 percent, there was no noticeable difference in the successive iterations. To reduce the computational time, the program has been modified to allow the user to specify the cutoff point based on the percent change in the MSE.

In using Jansson's method to deconvolve B-dot probe data from the UTSI railgun, it was discovered that acceptable results can be achieved by stopping the iterations when the percent change in the MSE drops below 1 percent. A value of 1.5 for b was found to work well with recorded B-dot probe signals from the UTSI railgun. With the values for the MSE and b selected as stated above, it requires from 50 to 100 iterations for the solution to converge. Upon convergence, the resulting estimate $\hat{I}_{\text{arm}}(n)$ can be scaled using the boundary condition given in (2.9) and plotted in spatial coordinates to give the plasma armature current density.

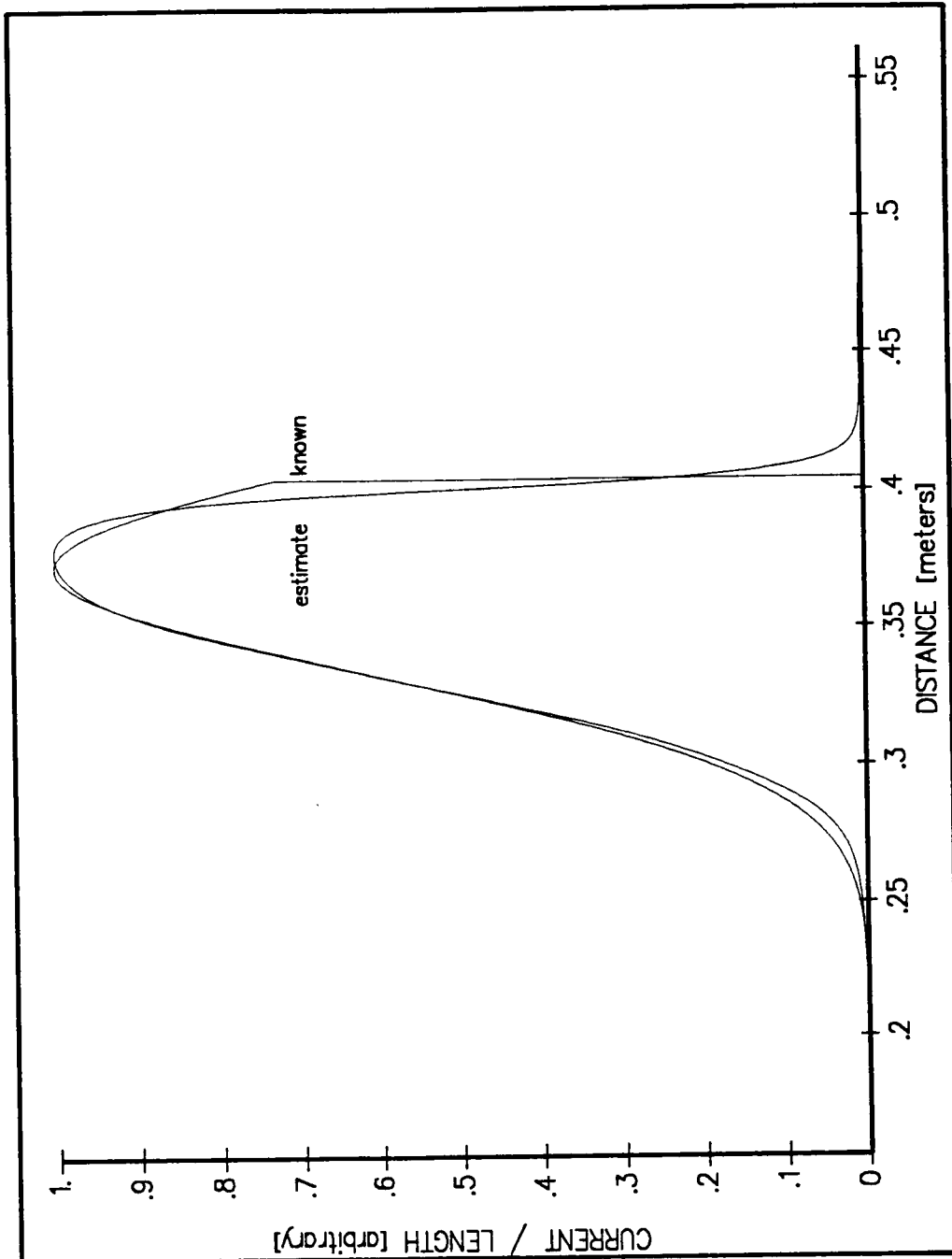


Figure 4.4 - Jansson's method estimate with c selected 10 percent larger than the peak amplitude achieved with previous iteration.

CHAPTER V

RESULTS

To illustrate the effectiveness of the methods described in this thesis, numerical simulations were conducted with simulated and experimental B-dot probe signals. The simulated B-dot probe signals were generated in the manner described in Appendix A. In order to resemble signals recorded from the UTSI railgun, the simulated signals were corrupted with noise by adding uncorrelated Gaussian random numbers with a standard deviation of 0.129 and quantized to 64 levels. The experimental signals used in the following analysis were acquired from the August 25, 1989 square-bore UTSI railgun shot and the February 12, 1991 round-bore UTSI railgun shot.

5.1 Determining Armature Position and Velocity

The validity of the LACC approach in estimating the position and velocity of the armature was examined using simulated B-dot probe signals. Shown in Figure 5.1 is a simulated B-dot probe signal, where the known time of passage and velocity of the armature are 1.2286 msec and 1800 m/sec respectively. The scaled unit step response (3.3) evaluated at the known time of passage and velocity of the armature are also shown in Figure 5.1. Note that the unit step response has been extended beyond the interval over which it is taken to be valid for presentation purposes. Using the iterative procedure described in Section 3.3 to determine the maximum LACC coefficient, the estimated time of passage was determined to be 1.2294 msec and the velocity 1850 m/sec. The estimated time of passage is only 4 sampling intervals from the known value, while the velocity estimate is within 3 percent of the known value.

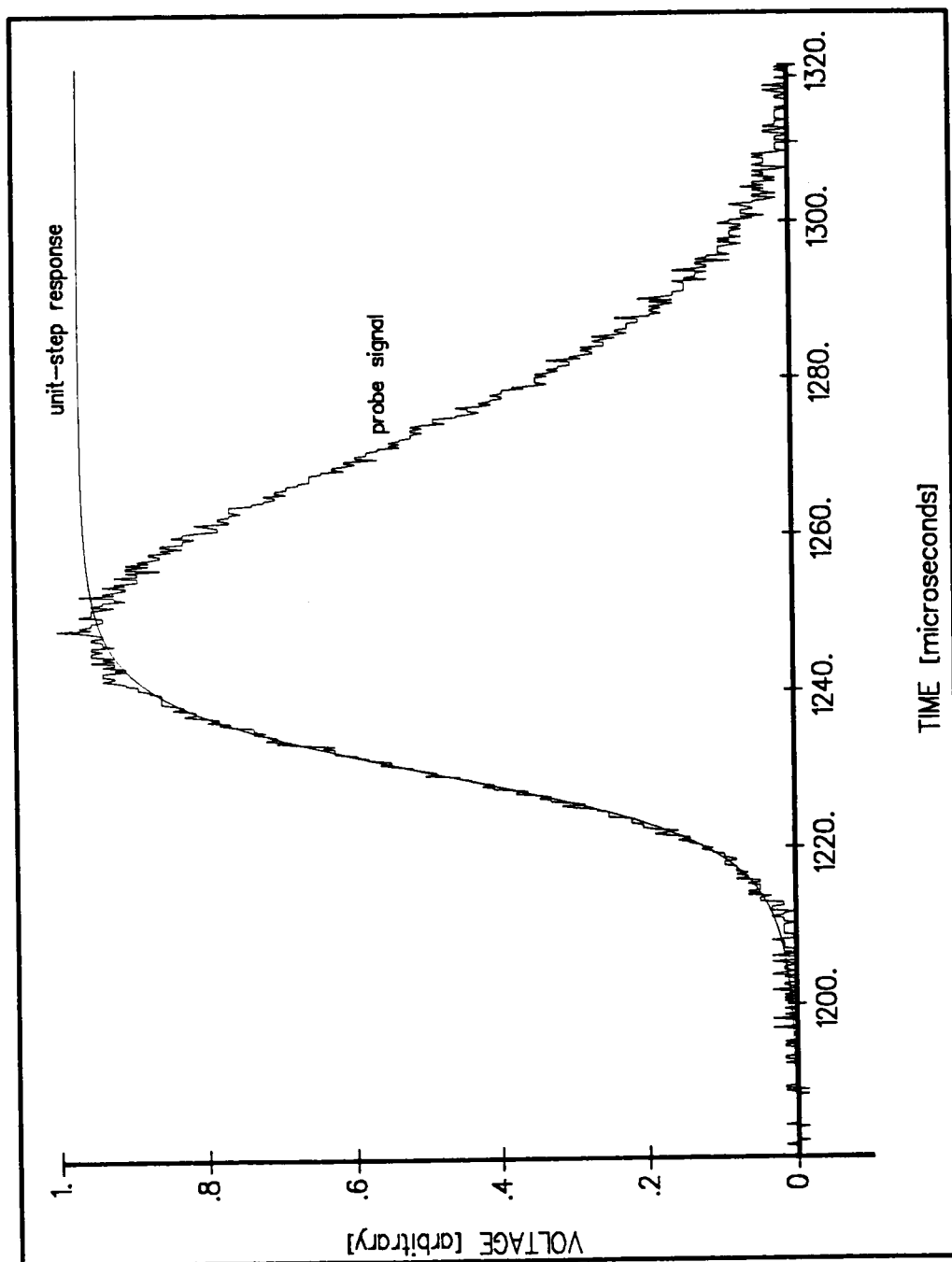


Figure 5.1 - Simulated B-dot probe signal with unit-step response.

Several B-dot probe signals were generated at different known times of passage to simulate a complete railgun firing. Using the position profile shown in Figure A.2, B-dot probe locations were selected to lie at 100 millimeter intervals between 700 and 1800 millimeters (positions similar to the UTSI railgun). The times at these positions were used as the known time of passage for the leading edge of the armature when the simulated B-dot probe signals were generated.

The LACC coefficient was used to estimate the time of passage and the velocity for the B-dot probe signals obtained from the simulated railgun firing. The estimated times of passage (squares) are plotted in Figure 5.2 with the position profile for the simulated railgun firing (solid line), while the velocity estimates (squares) are plotted in Figure 5.3 with the known velocity profile (solid line). The estimated position and velocity results are very encouraging. As shown in Figure 5.2, most of the estimated times of passage are within 10 sample interval of the known times. The estimated velocities shown in Figure 5.3 are very similar to the known velocities (within 5 percent). Simulated B-dot probe signals were constructed with different railgun current, position, and velocity profiles, and similar results were obtained.

The cross-correlation-based method has been used on several UTSI railgun firings to estimate the armature position and velocity. Figure 5.4 shows one example of a digitized B-dot probe signal. Using the LACC coefficient, the time of passage of the armature was estimated to be 0.6174 msec, and the velocity was estimated to be 1600 m/sec. Also shown in Figure 5.4 is the scaled unit-step response evaluated at the estimated armature position and velocity. Note the unit-step response has been extended beyond the interval over which it is taken to be valid for presentation purposes.

B-dot probe signals from an entire UTSI railgun firing were examined. The iterative procedure described in Section 3.3 to maximize the LACC coefficient was

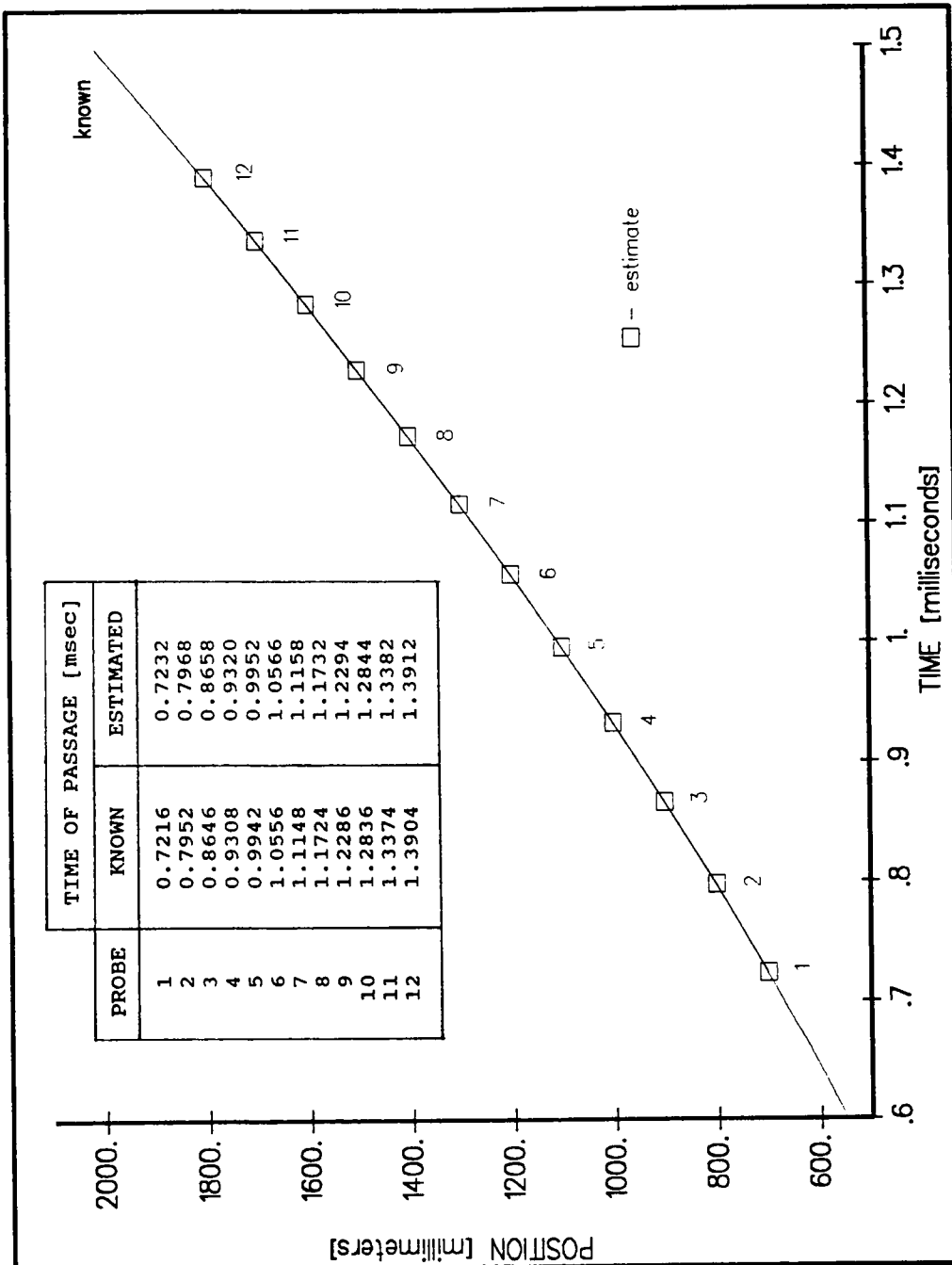


Figure 5.2 - Comparison of estimated and known times of passage for simulated B-dot probe signals.

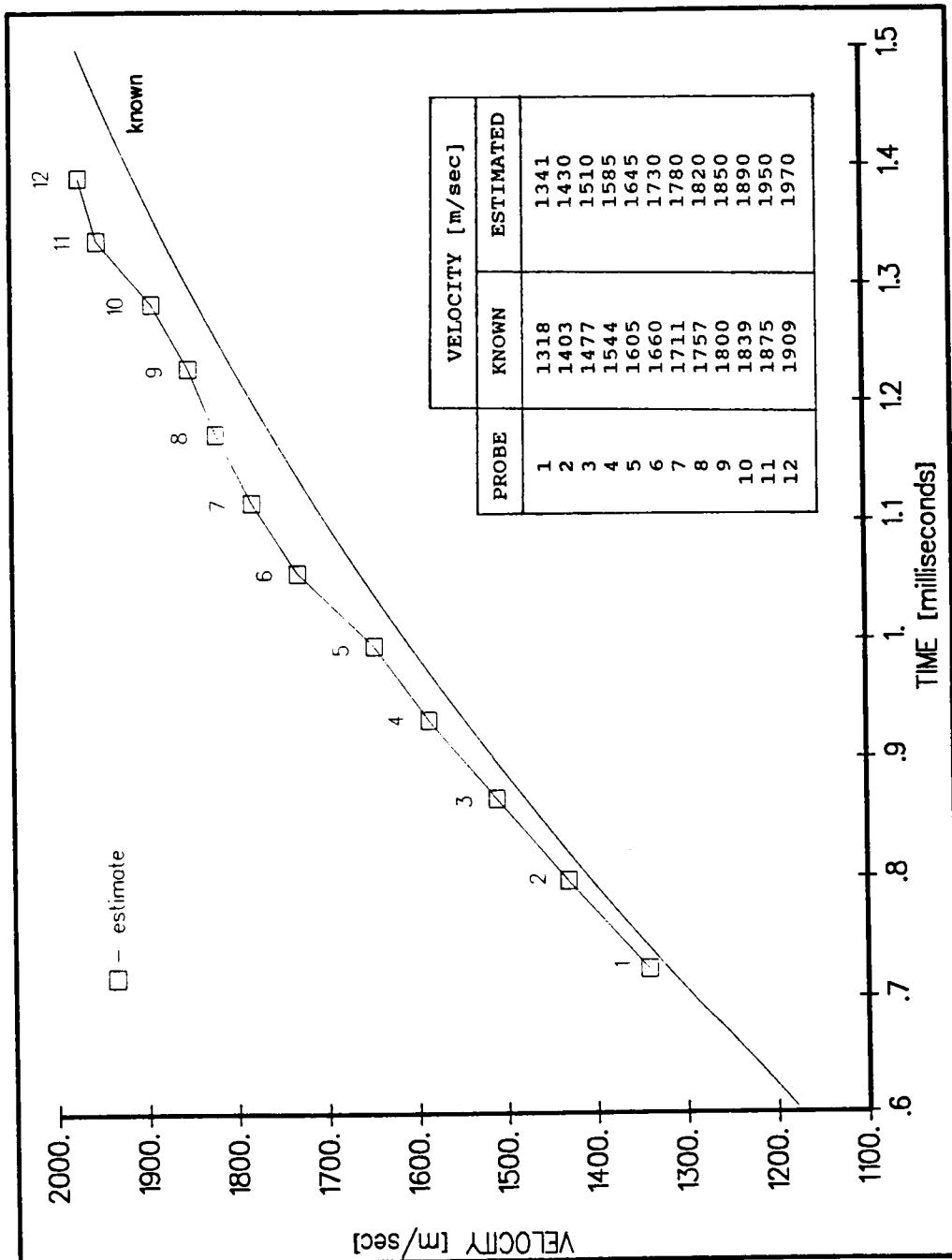


Figure 5.3 - Comparison of estimated and known velocities for simulated B-dot probe signals.

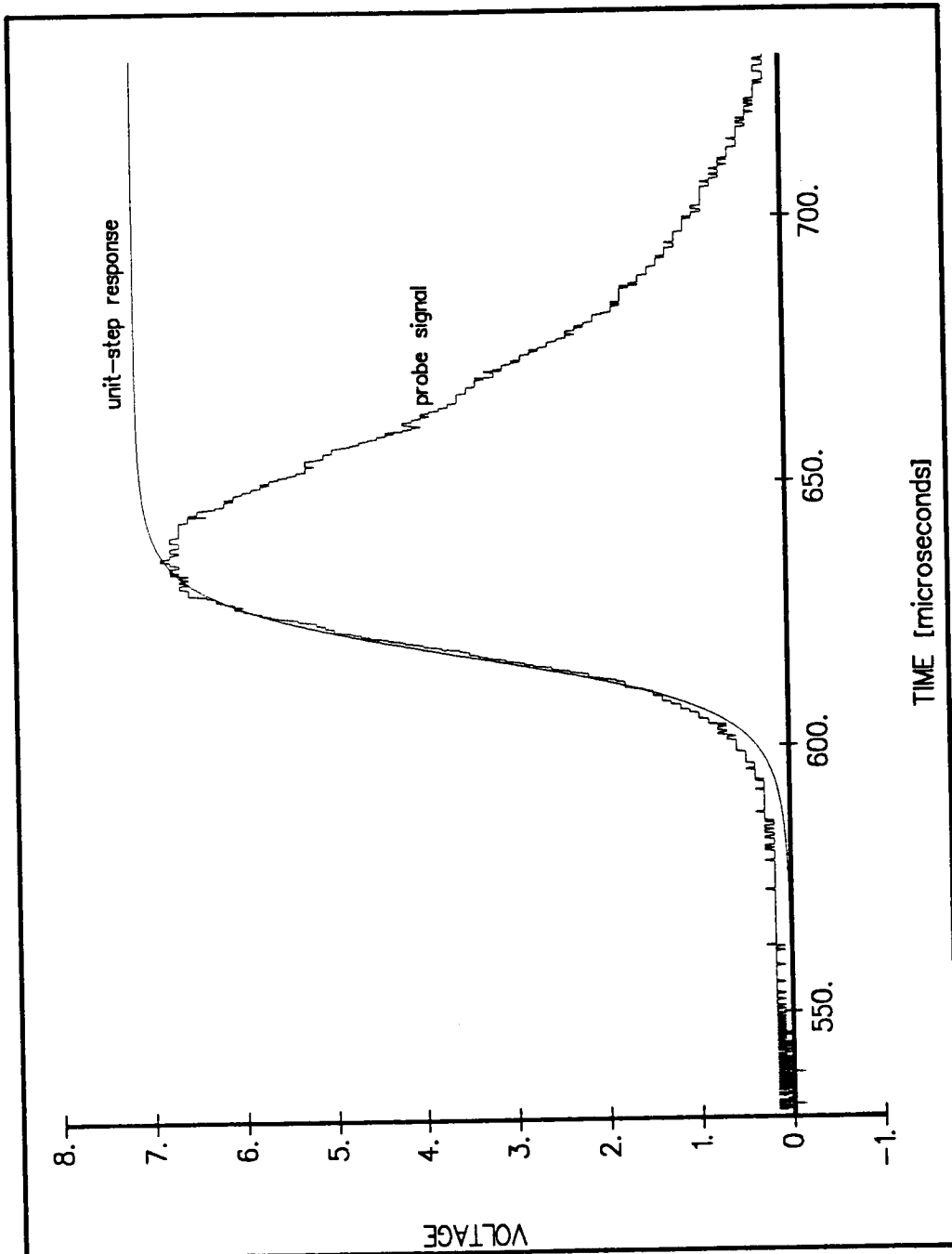


Figure 5.4 - Experimentally acquired B-dot probe signal with the unit-step response evaluated at the estimated time of passage and velocity.

used to estimate the time of passage and the velocity for the B-dot probe signals. The estimated times of passage and velocities are plotted in Figure 5.5. Note the non-monotonic variations in the estimated velocities. The errors are believed to be due to misaligned B-dot probes (numbers 10 and 13), which measured components of the magnetic field produced by the armature current.

The LACC method for estimating armature position and velocity has been adapted for routine use in analyzing B-dot probe signals recorded from plasma armature shots on the UTSI railgun. The iterative procedure described in Section 3.3 for estimating the time of passage of the armature and its velocity at this location has been implemented with a FORTRAN program written for IBM compatible computers. A listing of the program can be found in Appendix B. It requires approximately 3 minutes for the program to compute the time of passage and velocity estimates when running on a system with an 80286 processor and a math co-processor.

5.2 Determining Armature Current Distribution

To examine the effectiveness of using Jansson's method to deconvolve B-dot probe signals, the algorithm was tested on simulated B-dot probe signals. Figure 5.6 shows a simulated B-dot probe signal with its known armature current density axis-reversed and scaled to the time sampling interval. In deconvolving the simulated signal, the iterations were stopped when the percent change in the MSE dropped below 1 percent. Figure 5.7 shows the resulting armature current density estimates obtained using both Jansson's method and the Wiener filter approach. Note that Jansson's method does not produce the "ringing" associated with linear filtering methods. The deconvolution results obtained with Jansson's method using simulated B-dot probe signals are very encouraging. Simulated B-dot probe

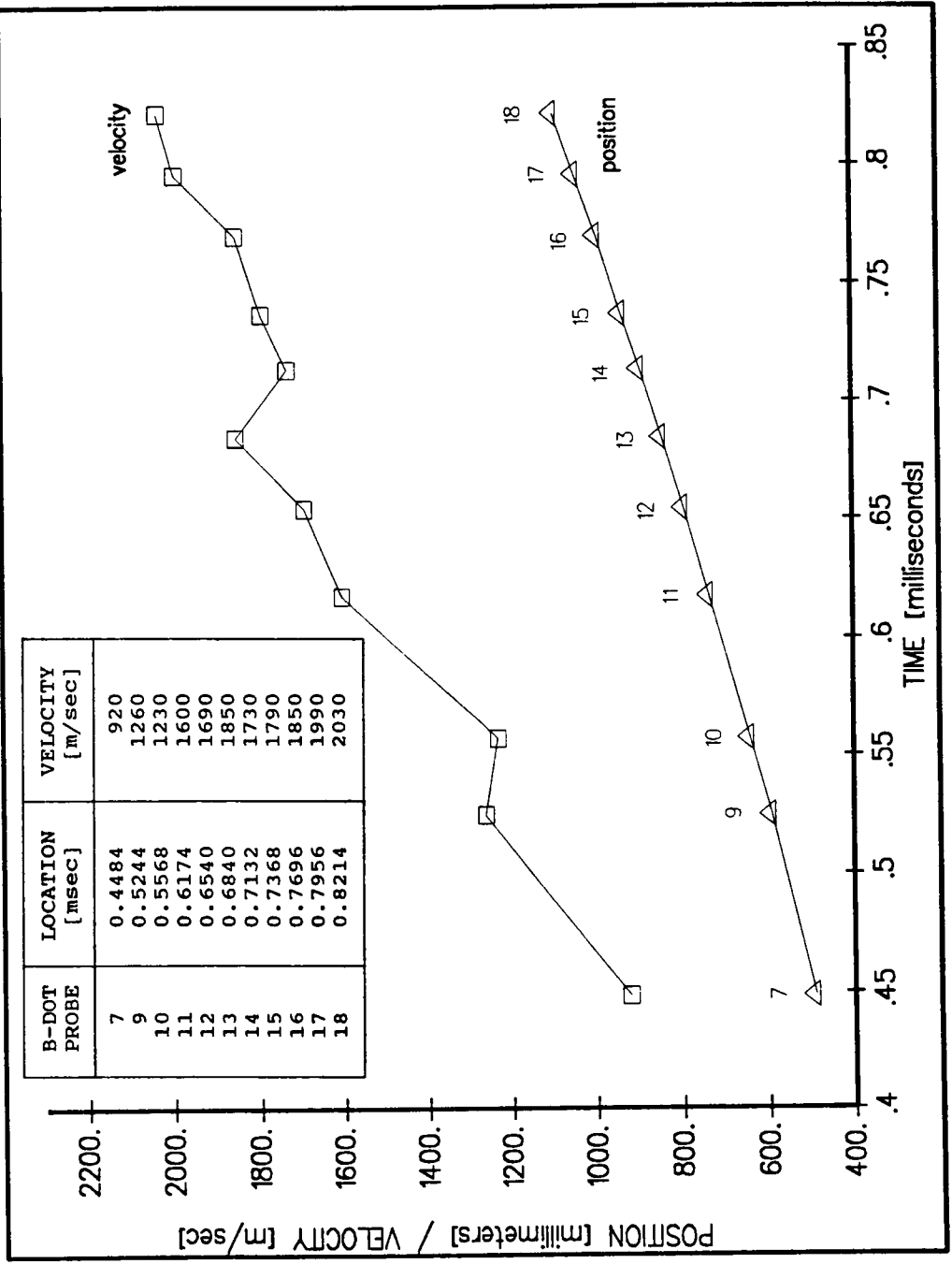


Figure 5.5 - Armature position and velocity data for a complete UTISI railgun firing as estimated by the LACC coefficient.

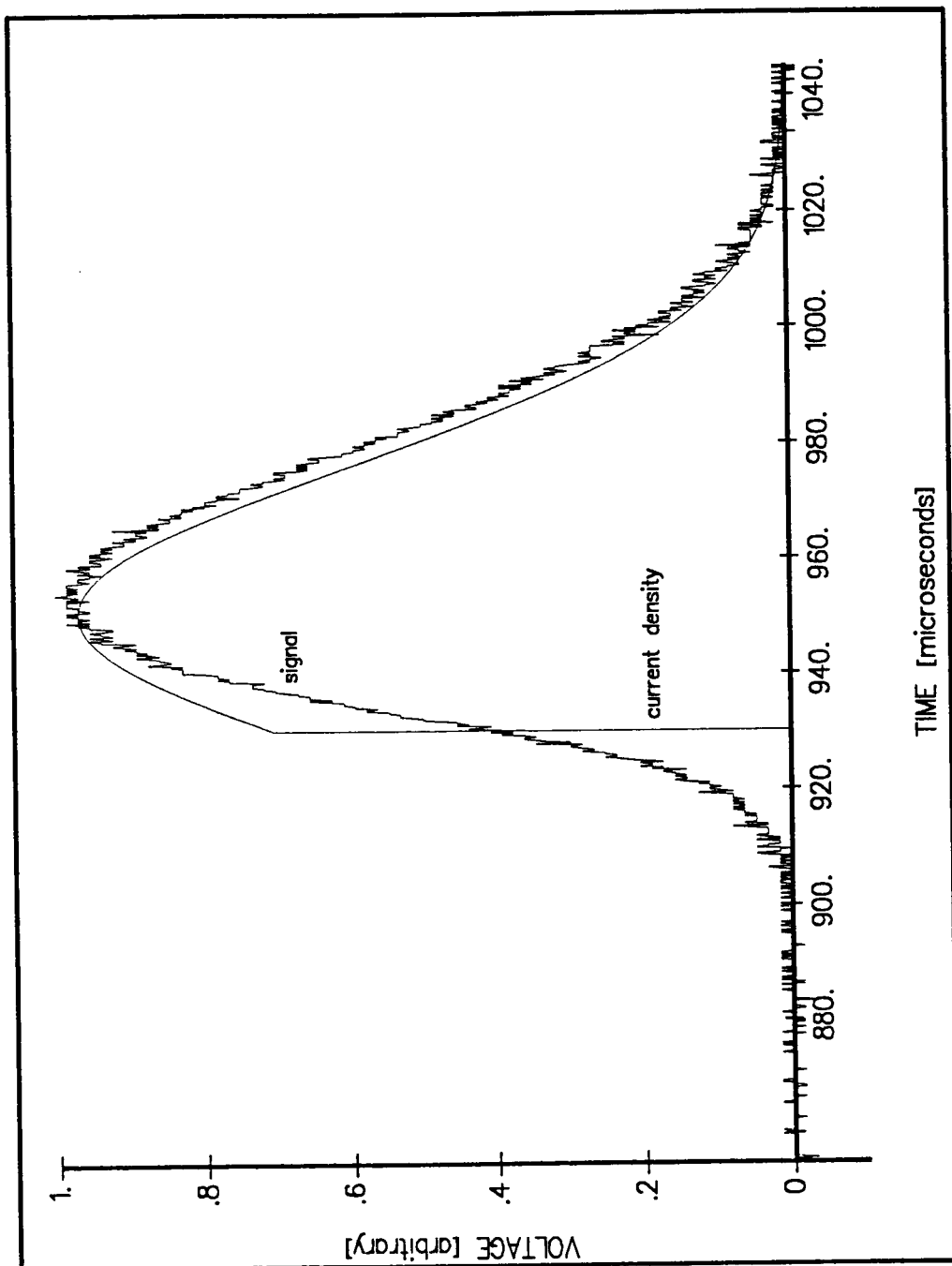


Figure 5.6 - Simulated B-dot probe signal with known current density.

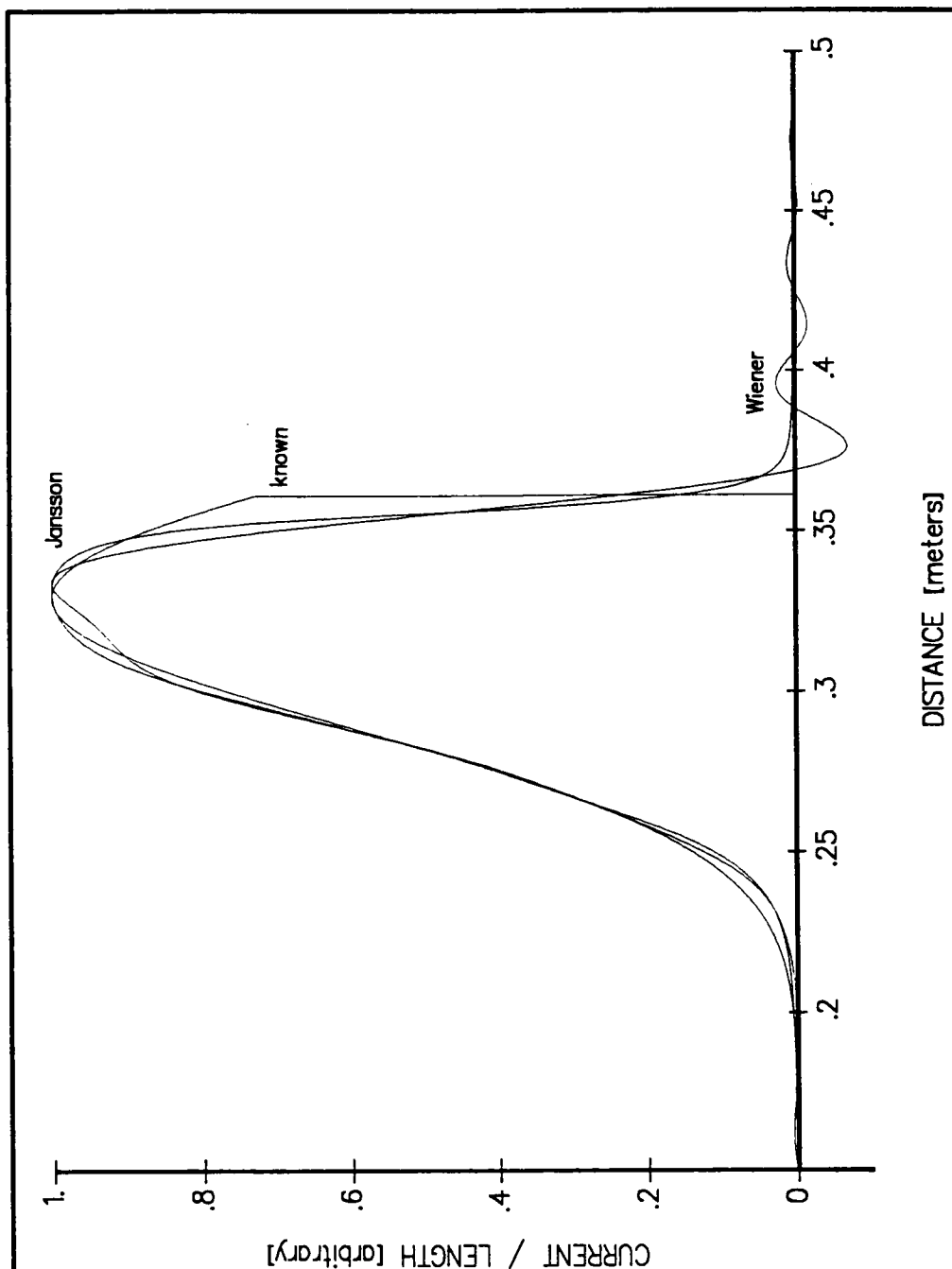


Figure 5.7 - Comparison of the estimated and known armature current density for the simulated B-dot probe signal.

signals were constructed with different rail current, position, and velocity profiles with similar results.

The sensitivity of this deconvolution scheme was examined to see what effects estimated velocity error had on determining the plasma armature current density. It was discovered that for velocities differing as much as 100 m/sec from the known velocity, this method still gave good results.

Jansson's method has been used on several UTSI railgun firings. Figure 5.8 shows one example of a digitized B-dot probe signal. Note the signal in this figure has negative values which are a result of the negative dI/dt of the rail current. Figure 5.9 shows the resulting armature current density after deconvolving the experimental signal using Jansson's method. Also shown in Figure 5.9 is the B-dot probe signal plotted in the spatial coordinate x to compare it to the solution. Note that the negative values have been removed due to the non-negativity constraint enforced by Jansson's method corresponding to the *a priori* knowledge of the physical properties of the armature.

Jansson's deconvolution method for estimating the armature current density has been adapted for routine use in analyzing B-dot probe signals. The algorithm given in (4.12) has been implemented with a FORTRAN program written for IBM compatible computers. A listing of the program can be found in Appendix C. It requires approximately 25 minutes for the program to perform 50 iterations on 2048 samples when running on a system with an 80286 processor and a math co-processor.

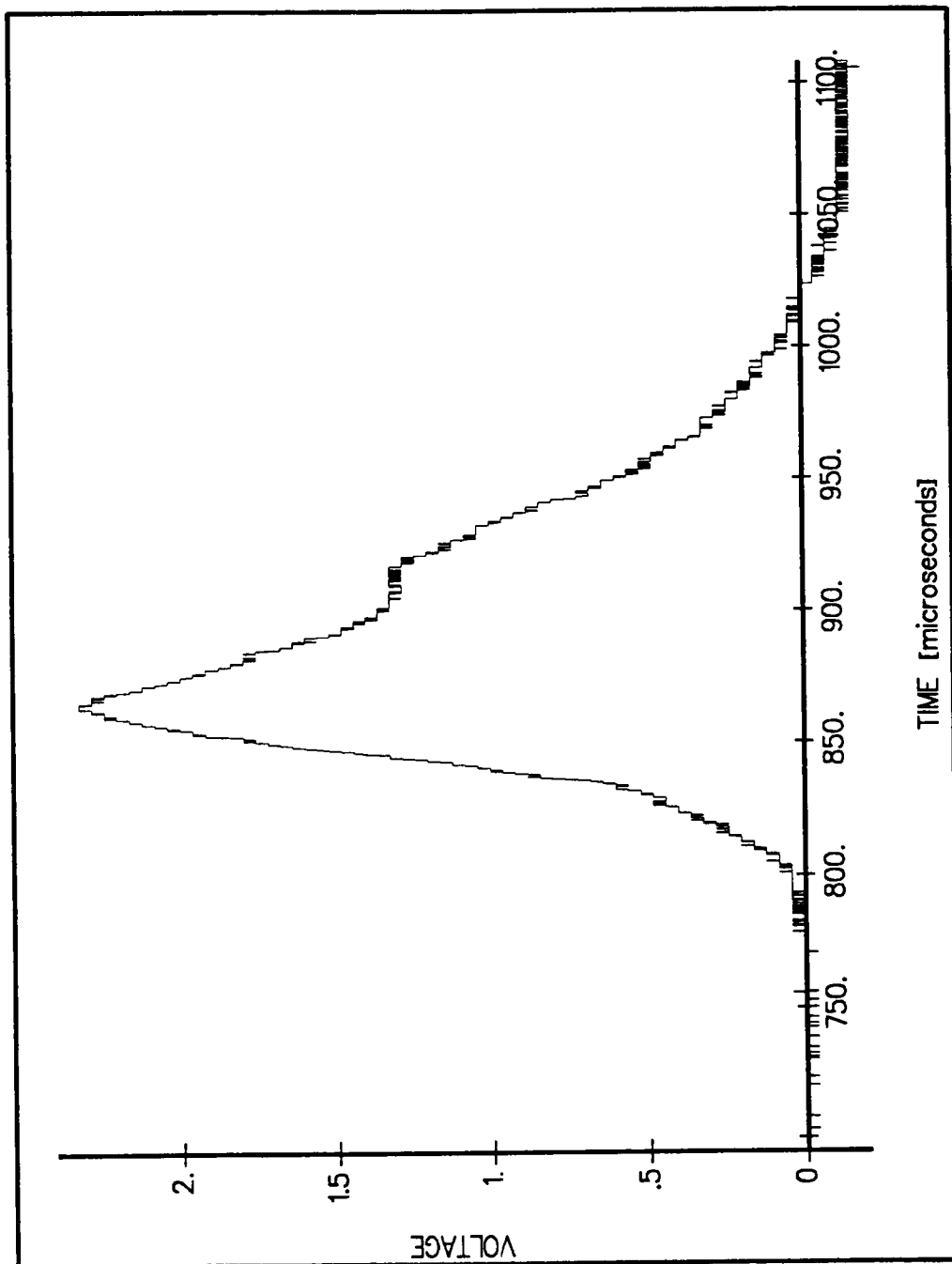


Figure 5.8 - Experimentally acquired B-dot probe signal.

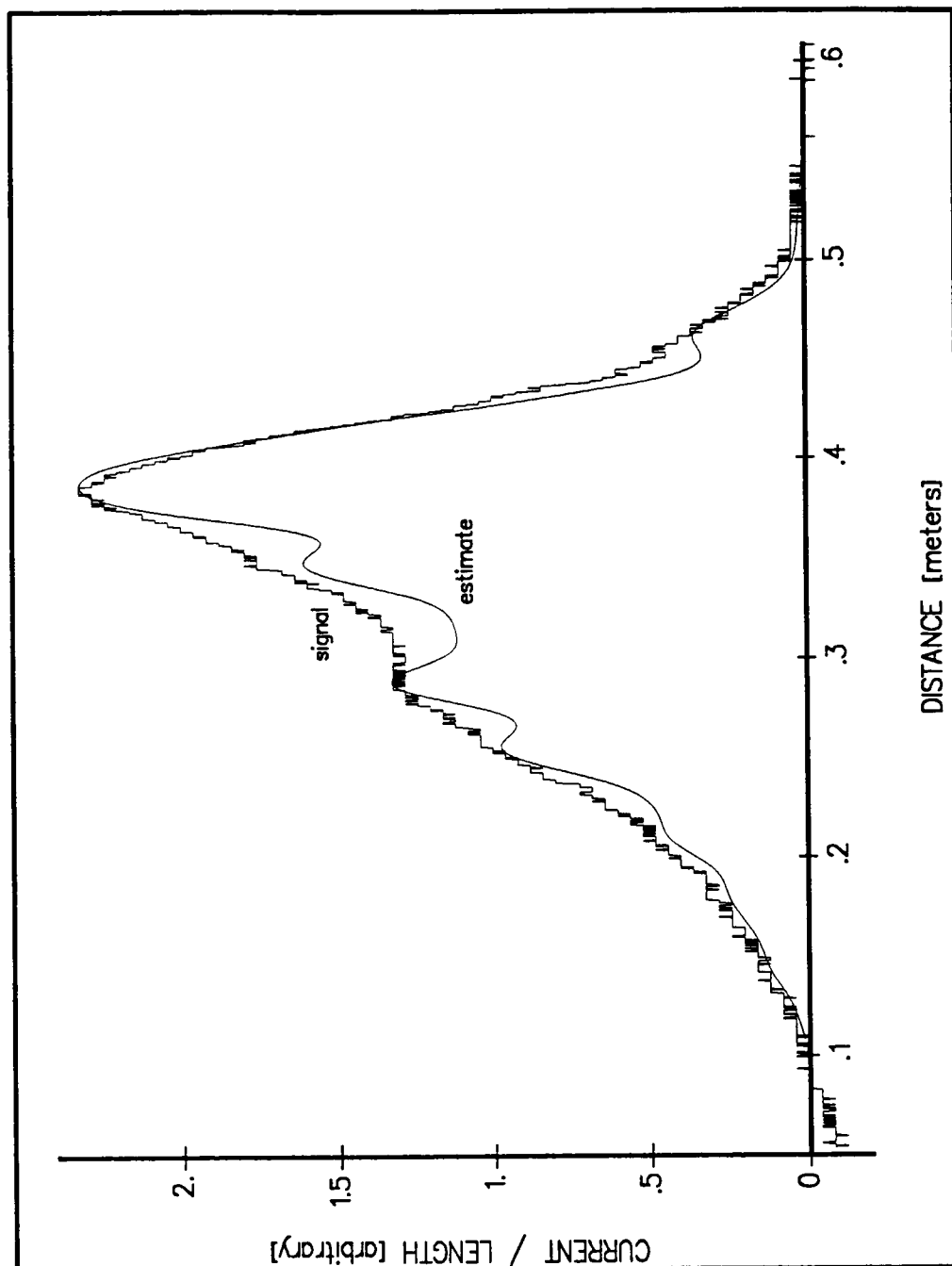


Figure 5.9 - Comparison of the estimated current density to the experimentally acquired B-dot probe signal which has been plotted in spatial coordinates.

CHAPTER VI

CONCLUSIONS

Methods for analyzing the plasma armature current from recorded B-dot probe signals have been presented. These methods utilize the knowledge that the B-dot probe signal is a convolution of the plasma armature current density with the B-dot probe impulse response function. The methods determine the location of the leading edge of the armature, the armature velocity at this location, and estimate the functional form of the current density.

The method for determining the location of the leading edge of the armature and estimating its velocity is an improvement over the ad hoc and heuristic natures of other methods. The physical processes governing the plasma armature current density are utilized to model the leading edge of the current density as a unit-step function, which allows the leading edge of the B-dot probe signal to be modeled as the unit-step response of the B-dot probe impulse response function. The method calculates a local-area cross-correlation coefficient between the B-dot probe signal and the B-dot probe unit-step response using a two-parameter iterative approach. The point of maximum correlation yields the optimal time of passage and velocity estimates for the leading edge of the armature.

The functional form of the armature current density is estimated by deconvolving the B-dot probe signal. There are many deconvolution techniques available that give good estimates, but nonlinear methods that utilize constraints based on the physical limits of the data, give improved results over commonly used linear methods. Jansson's relaxation based nonlinear iterative deconvolution method has been developed for use with recorded B-dot probe signals. The deconvolution algorithm only requires knowledge of the B-dot probe impulse response and the maximum peak

amplitude of the armature current density. Since the peak amplitude is not known *a priori*, a method was developed to calculate an estimate. Examining methods for determining the peak amplitude is an area of continuing research.

Numerical simulations on simulated B-dot probe signals have been conducted to examine the effectiveness of these methods. In determining the position and velocity estimates, accuracies within 10 sampling intervals for the time of passage and 5 percent for the velocity are achievable with the cross-correlation-based method. The position and velocity estimates are displayed in Figure 5.2 and Figure 5.3 respectively. The current density estimates, determined through deconvolution of the simulated signals, have given much improved results over the linear deconvolution schemes previously used as shown in Figure 5.7.

These methods have been applied to actual railgun firings. The time of passage and velocity estimates as determined from experimental signals using the LACC coefficient are shown in Figure 5.5. With the exception of two points, whose estimates are thought to be in error due to misaligned B-dot probes, the results achieved with this method are very encouraging. The armature current density estimate in Figure 5.9 gives an example of the results achievable using Jansson's method to deconvolve experimental B-dot probe signals. The results obtained are an improvement over the previously used Wiener filter.

An area of future research would be including the effects of the time-varying rail current in both the LACC calculation and Jansson's algorithm. In Chapter II, the B-dot probe signal was developed assuming the rail current was constant. By deriving the signal using the time-varying rail current, both methods could be implemented to including this effect. However, this would require a large amount of computations, making both methods extremely slow. As computational speed increases, it may become feasible to implement these methods in this fashion.

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APPENDICES

APPENDIX A

SIMULATED B-DOT PROBE SIGNALS

Examining the effectiveness of the methods presented in this thesis for analyzing the plasma armature current from recorded B-dot probe signals required application to simulated B-dot probe signals. In order to generate B-dot probe signals that resemble B-dot probe signals recorded from railguns, the armature velocity and the rail current must vary with time. The armature current density was chosen to be the product of the time-varying total gun current $I(t)$ with a spatially-varying pulse form $p(x)$, and the velocity was assumed to be a time varying quantity $V(t)$. Note that the 3-dimensional characteristics of the railgun and armature, or the possibility of the armature changing its form were not considered in the following analysis.

The x component of the current in the rails at time t is given by

$$I(x', t) = I(t) \left[1 - \int_{-\infty}^{x' - [x + V(t)(t - t_0)]} p(\xi) d\xi \right] \quad (A.1)$$

with

$$\int_{-\infty}^{\infty} p(\xi) d\xi = 1. \quad (A.2)$$

Using the Biot-Savart law (2.1), the y component of the magnetic field at the probe location due to the current traveling in the nearer rail is given by

$$B_y(t) = \frac{\mu_o}{4\pi} r_1 \cos \theta_1 \int_{-\infty}^{\infty} \frac{I(x', t)}{[r_1^2 + (x - x')^2]^{3/2}} dx'. \quad (A.3)$$

If the rail current expression given in (A.1) is substituted into (A.3), and a change of variables $\eta = x' - [x + V(t)(t - t_o)]$ is made, the resulting expression becomes

$$B_y(t) = \frac{\mu_o}{4\pi} r_1 \cos \theta_1 \int_{-\infty}^{\infty} \frac{I(t) \left[1 - \int_{-\infty}^{\eta} p(\xi) d\xi \right]}{\left[r_1^2 + [V(t)(t - t_o) - \eta]^2 \right]^{3/2}} d\eta. \quad (A.4)$$

Since the measured B-dot probe signal is proportional to the time rate of change of the magnetic field component, the expression in (A.4) must be differentiated with respect to time t . The B-dot probe signal is therefore proportional to

$$\begin{aligned} \frac{dB_y}{dt} = \frac{\mu_o}{4\pi} r_1 \cos \theta_1 \int_{-\infty}^{\infty} \left[1 - \int_{-\infty}^{\eta} p(\xi) d\xi \right] \\ \cdot \frac{d}{dt} \left\{ \frac{I(t)}{\left[r_1^2 + [V(t)(t - t_o) - \eta]^2 \right]^{3/2}} \right\} d\eta. \end{aligned} \quad (A.5)$$

The expression in (A.5) can be simplified by differentiating the expression in the brackets, and integrating by parts. In doing so, the B-dot probe response becomes

$$\begin{aligned} \frac{dB_y}{dt} = \frac{\mu_o}{4\pi} r_1 \cos \theta_1 \left\{ \frac{dI}{dt} \int_{-\infty}^{\infty} \frac{1 - \int_{-\infty}^{\eta} \rho(\xi) d\xi}{\left[r_1^2 + (V(t)(t_o - t) - \eta)^2 \right]^{3/2}} d\eta \right. \\ \left. + I(t) \left[V(t) - (t_o - t) \frac{dV}{dt} \right] \int_{-\infty}^{\infty} \frac{\rho(\eta)}{\left[r_1^2 + (V(t)(t_o - t) - \eta)^2 \right]^{3/2}} d\eta \right\}. \end{aligned} \quad (A.6)$$

Following the same analysis used in finding the B-dot probe response for the current traveling in the nearer rail, the response due to the current traveling in the farther rail can be determined. The resulting expression is opposite in sign of (A.6) with

the radial distance and angle for the farther rail. The overall B-dot probe response is the superposition of both responses.

The spatially-varying pulse form $p(x)$ was assumed to be a truncated Gaussian curve since Jamison and Burden [4], Sloan [9], and others have assumed the functional form of the armature current density to be a truncated Gaussian curve. The spatially-varying pulse form was produced by truncating a Gaussian curve on one side to simulate a current distribution with a discontinuous rise in current. The equation for this pulse form is given by

$$p(x) = \begin{cases} a \cdot \exp \left[-\frac{(x-0.12)^2}{0.0032} \right], & \text{if } x \geq 0.152; \\ 0, & \text{if otherwise,} \end{cases} \quad (\text{A.7})$$

where a is a scaling constant such that $p(x)$ meets the requirement stated in (A.2) and x is in meters. This distribution simulates an armature approximately 15 cm in length. In this thesis, simulated B-dot probe signals were generated using the pulse form given in (A.7). The rail current profile used is shown in Figure A.1, while the armature position and velocity profiles are shown in Figure A.2.

A FORTRAN program was written to calculate simulated B-dot probe signals from the B-dot probe response given the rail current, position, and velocity profiles. The program was implemented on the Center for Laser Applications IBM System/6000 due to the large amount of computations required. The simulated B-dot signals were corrupted with noise by adding uncorrelated Gaussian random numbers. The conductor to probe distances and angles correspond to probe locations in the UTSI railgun ($r_1 = 0.023659$ m; $r_2 = 0.029028$ m; $\theta_1 = 22.74^\circ$; $\theta_2 = 41.26^\circ$). The signals were generated using a $0.2 \mu\text{sec}$ sampling interval.

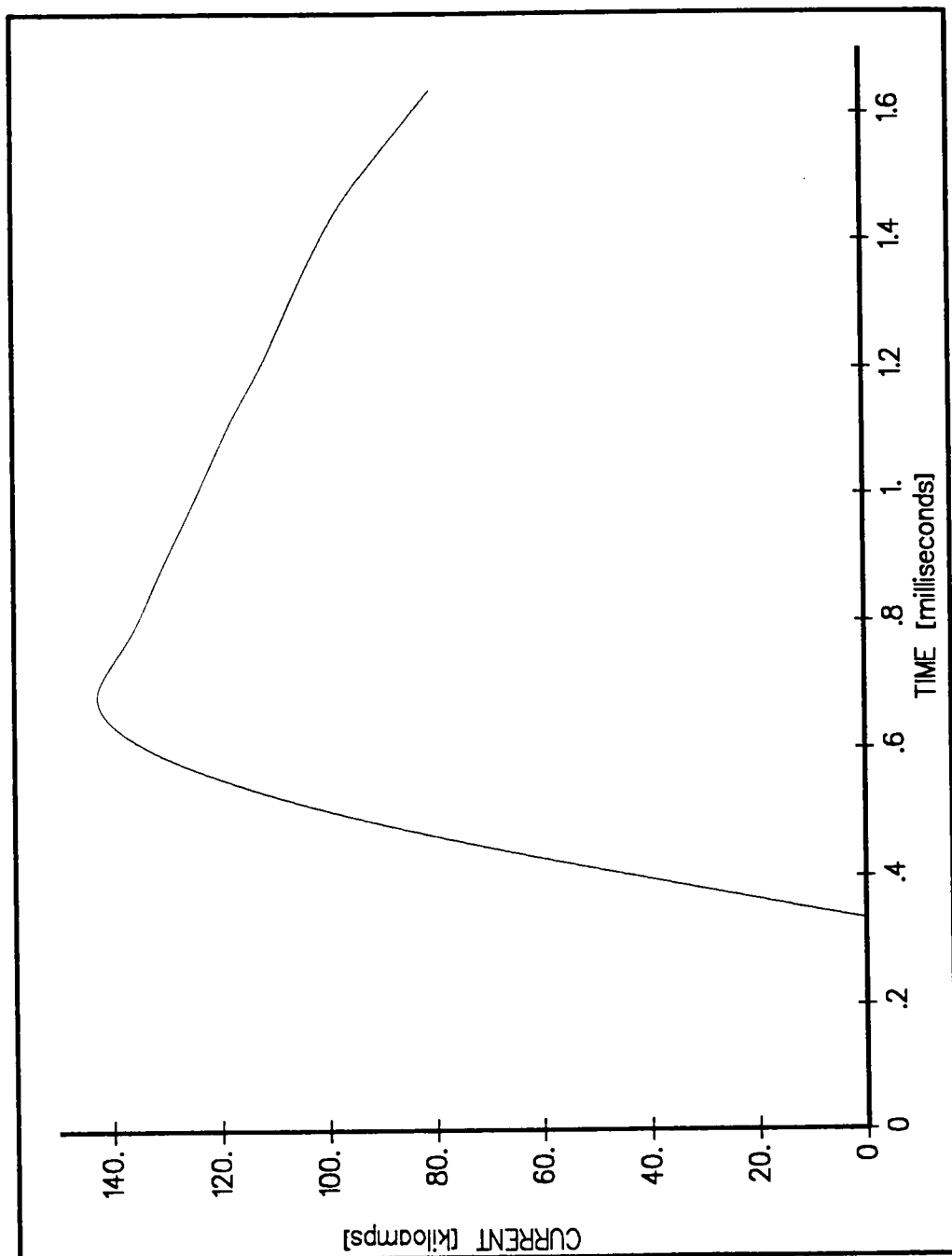


Figure A.1 - Railgun current profile used to construct simulated B-dot probe signals.

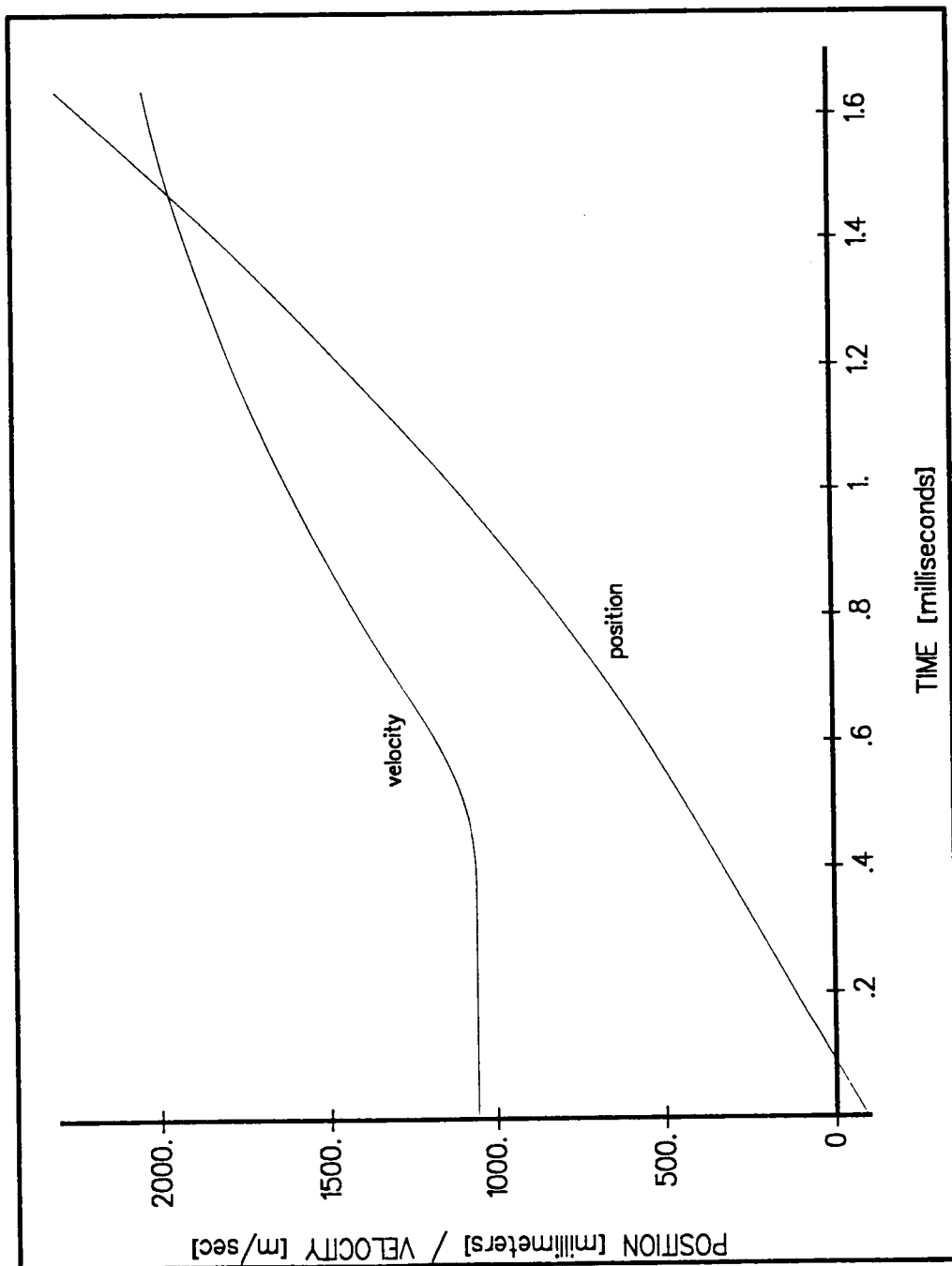


Figure A.2 - Armature position and velocity profiles used to construct simulated B-dot probe signals.

APPENDIX B

LACC PROGRAM LISTING

```

$debug
$storage:2

      REAL fvar,bvar,fbvar
      REAL max,r1,r2,v,dt,p,pbest,vel,pi
      REAL pv,tv,oldvel,oldtime,thetal,theta2
      REAL f(1024),b(1024)
      INTEGER istart,istop,ipts,maxpt
      INTEGER vstep,vstart,vstop,time
      INTEGER hstart(1000),hstop(1000)
      INTEGER i,j,k,nstart,nstop
      INTEGER*2 n
      CHARACTER*30 infile
      DIMENSION x(8192),y(8192)

C
C   Initialize Variables
C
      pi = 3.14159265359
      r1 = 0.023659
      r2 = 0.029028
      thetal = 22.74*pi/180.0
      theta2 = 41.26*pi/180.0
      dt = 0.0000002

      oldvel = 0.0
      oldtime = 0.0

C
C   Determine range unit-step response is valid
C
      OPEN(10, FILE='impulse.dat', STATUS='old')
      READ(10,*) n
      DO 5 i = 1,n
         READ(10,*) hstart(i), hstop(i)
      5 CONTINUE
      CLOSE(10)

C
C   Read B-dot probe data
C
      WRITE(6,1) 'Enter name of data file: '
      READ(5,2) infile
      1 FORMAT($,1X,A)
      2 FORMAT(A)
      OPEN(10, FILE=infile, FORM='unformatted', STATUS='old')
      READ(10) n,(x(i),y(i),i=1,n)
      CLOSE(10)

C
C   Determine leading edge of B-dot probe data
C
      max = 0.0
      DO 20 i = 1,n
         IF (y(i).gt.max) THEN
            max = y(i)
            maxpt = i
         ENDIF
      20 CONTINUE
      DO 30 i = 1,maxpt
         IF (y(i).lt.(0.75*max)) nstop = i
         IF (y(i).LT.(0.50*max)) time = i
         IF (y(i).lt.(0.25*max)) nstart = i
      30 CONTINUE

```

```

C
C Determine starting velocity
C
      pbest = 0.0
      WRITE(*,*) 'Enter starting velocity: '
      READ(*,*) v
      vel = v

C
C Iterative procedure to determine time of passage and velocity
C
100  CONTINUE

      oldvel = vel
      oldtime = time

      WRITE(*,*) 'Checking velocity = ',vel
      istart = hstart(NINT((vel+5.0)/10.0))
      istop = hstop(NINT((vel+5.0)/10.0))
      ipts = istop - istart
      CALL impulse(istart,istop,r1,r2,theta1,theta2,f,vel,dt,max)
      CALL var(ipts,f,fvar)
      DO 210 j = nstart,nstop
        DO 220 k = istart,istop
          b(k-istart+1) = y(j+k)
220    CONTINUE
        CALL var(ipts,b,bvar)
        CALL covar(ipts,f,b,fbvar)
        p = fbvar/(fvar*bvar)
        IF (p.GT.pbest) THEN
          pbest = p
          time = j
        ENDIF
210    CONTINUE

      vstart = INT(vel) - 500
      vstop = INT(vel) + 500
      vstep = 10

      DO 500 i = vstart,vstop,vstep
        pv = 0.0
        tv = 0.0
        v = REAL(i)
        write(*,*) 'Checking velocity = ',v
        istart = hstart(NINT((v+5.0)/10.0))
        istop = hstop(NINT((v+5.0)/10.0))
        ipts = istop - istart
        CALL impulse(istart,istop,r1,r2,theta1,theta2,f,v,dt,max)
        CALL var(ipts,f,fvar)
        DO 520 k = istart,istop
          b(k-istart+1) = y(time+k)
520    CONTINUE
        CALL var(ipts,b,bvar)
        CALL covar(ipts,f,b,fbvar)
        p = fbvar/(fvar*bvar)
        IF (p.GT.pbest) THEN
          pbest = p
          vel = v
        ENDIF
500    CONTINUE
      IF ((oldvel.NE.vel).OR.(oldtime.NE.time)) GOTO 100

```

```

1000  CONTINUE

      oldvel = vel
      oldtime = time

      WRITE(*,*) 'Checking velocity = ',vel
      istart = hstart(NINT((vel+5.0)/10.0))
      istop = hstop(NINT((vel+5.0)/10.0))
      ipts = istop - istart
      CALL impulse(istart,istop,r1,r2,theta1,theta2,f,vel,dt,max)
      CALL var(ipts,f,fvar)
      DO 2010 j = nstart,nstop
        DO 2020 k = istart,istop
          b(k-istart+1) = y(j+k)
2020    CONTINUE
          CALL var(ipts,b,bvar)
          CALL covar(ipts,f,b,fbvar)
          p = fbvar/(fvar*bvar)
          IF (p.GT.pbest) THEN
            pbest = p
            time = j
          ENDIF
2010    CONTINUE

      vstart = INT(vel) - 50
      vstop = INT(vel) + 50
      vstep = 1

      DO 5000 i = vstart,vstop,vstep
        pv = 0.0
        tv = 0.0
        v = REAL(i)
        write(*,*) 'Checking velocity = ',v
        istart = hstart(NINT((v+5.0)/10.0))
        istop = hstop(NINT((v+5.0)/10.0))
        ipts = istop - istart
        CALL impulse(istart,istop,r1,r2,theta1,theta2,f,v,dt,max)
        CALL var(ipts,f,fvar)
        DO 5020 k = istart,istop
          b(k-istart+1) = y(time+k)
5020    CONTINUE
          CALL var(ipts,b,bvar)
          CALL covar(ipts,f,b,fbvar)
          p = fbvar/(fvar*bvar)
          IF (p.GT.pbest) THEN
            pbest = p
            vel = v
          ENDIF
5000    CONTINUE
      IF ((oldvel.NE.vel).OR.(oldtime.NE.time)) GOTO 1000

      write(*,*) 'Best Velocity: ',vel
      write(*,*) 'Time: ',x(time)
      write(*,*) 'Best Correlation: ',pbest

      STOP
      END

      SUBROUTINE IMPULSE(istart,istop,r1,r2,theta1,theta2,f,v,dt,max)

```

```

REAL f(1024)
REAL r1,r2,theta1,theta2,v,dt,x,max,con
INTEGER istart,istop

con = max/(2.0*cos(theta1)/r1 - 2.0*cos(theta2)/r2)
DO 10 i = istart,istop
  x = v * REAL(i) * dt
  f((i-istart)+1) = con
  &      *(cos(theta1)*(x/SQRT(x**2+r1**2)+1.0)/r1
  &      - cos(theta2)*(x/SQRT(x**2+r2**2)+1.0)/r2)
10 CONTINUE

RETURN
END

SUBROUTINE VAR(n,a,dev)

REAL a(n),dev

dev = 0.0
DO 10 i = 1,n
  dev = dev + a(i)**2
10 CONTINUE
dev = SQRT(dev)

RETURN
END

SUBROUTINE COVAR(n,a1,a2,dev)

REAL a1(n),a2(n),dev

dev = 0.0
DO 10 i = 1,n
  dev = dev + a1(i)*a2(i)
10 CONTINUE

RETURN
END

```

APPENDIX C

JANSSON'S METHOD PROGRAM LISTING

```

$debug

      INCLUDE 'fgraph.fi'
      INCLUDE 'fgraph.fd'

      REAL pi,r1,r2,theta1,theta2,dx,dt,scale,b,result,cutoff
      REAL vel(30)
      INTEGER*2 i,j,k,n,npts,len,select,num,dummy2,wait,minit,maxit
      CHARACTER*30 filename,tempfile,outdrive,datadrive
      CHARACTER*30 infile(30)
      CHARACTER bell*2,answer*10,ext*3
      DIMENSION time(8192),dat(8192)
      DOUBLE PRECISION y(2048), h(2048)
      RECORD / rccoord / curpos

C
C  INITIALIZE VARIABLES
C
      npts = 2048
      pi = 3.14159265359
      r1 = 0.023659
      r2 = 0.029028
      theta1 = COS(22.74*pi/180.0)*r1
      theta2 = COS(41.26*pi/180.0)*r2
      r1 = r1*r1
      r2 = r2*r2
      bell = char(27)//char(7)
      wait = 15

C
C  DISPLAY MAIN MENU
C
1  CONTINUE
   CALL clearscreen( $GCLEARSCREEN )
   CALL settextposition(5,26,curpos)
   CALL outtext('Deconvolution of B-dot Data')
   CALL settextposition(6,26,curpos)
   CALL outtext('-----')
   CALL settextposition(9,26,curpos)
   CALL outtext('1) Single B-dot data file')
   CALL settextposition(10,26,curpos)
   CALL outtext('2) Selected B-dot data files')
   CALL settextposition(11,26,curpos)
   CALL outtext('3) All B-dot data files')
   CALL settextposition(15,26,curpos)
   CALL outtext('9) Exit')
   CALL settextposition(18,26,curpos)
   CALL outtext('Enter Selection:')
10  CALL settextposition(18,43,curpos)
   READ(*,*) select
   GOTO (1000,1000,1000),select
   IF (select.EQ.9) GOTO 9999
   CALL settextposition(18,43,curpos)
   CALL outtext('          ')
   GOTO 10

C
C  INPUT DECONVOLUTION PARAMETERS
C
1000 CONTINUE
   CALL clearscreen( $GCLEARSCREEN )
   CALL settextposition(2,25,curpos)
   CALL outtext('Input Deconvolution Parameters')

```

```

CALL settextposition(3,25,curpos)
CALL outtext('-----')
C
C Determine relaxation constant, b, and number of iterations
C
b = 0.0
cutoff = 0.0
minit = 0
maxit = 0
CALL settextposition(6,5,curpos)
CALL outtext('Enter value for b <1.5>:')
CALL settextposition(6,31,curpos)
READ(*,'(a10)') answer
IF (LEN TRIM(answer).EQ.0) THEN
    b = 1.5
    CALL settextposition(6,31,curpos)
    CALL outtext('1.5')
ENDIF
IF (b.NE.1.5) THEN
    CALL CONVERT(answer,result)
    b = result
ENDIF
CALL settextposition(7,5,curpos)
CALL outtext('Percent change in MSE <1.00>:')
CALL settextposition(7,36,curpos)
READ(*,'(a10)') answer
IF (LEN TRIM(answer).EQ.0) THEN
    cutoff = 1.00
    CALL settextposition(7,36,curpos)
    CALL outtext('1.00')
ENDIF
IF (cutoff.NE.(1.00)) THEN
    CALL CONVERT(answer,result)
    cutoff = result
ENDIF
CALL settextposition(8,5,curpos)
CALL outtext('Minimum number of iterations <10>:')
CALL settextposition(8,41,curpos)
READ(*,'(a10)') answer
IF (LEN TRIM(answer).EQ.0) THEN
    minit = 10
    CALL settextposition(8,41,curpos)
    CALL outtext('10')
ENDIF
IF (minit.NE.(10)) THEN
    CALL CONVERT(answer,result)
    minit = INT(result)
ENDIF
CALL settextposition(9,5,curpos)
CALL outtext('Maximum number of iterations <150>:')
CALL settextposition(9,42,curpos)
READ(*,'(a10)') answer
IF (LEN TRIM(answer).EQ.0) THEN
    maxit = 150
    CALL settextposition(9,42,curpos)
    CALL outtext('150')
ENDIF
IF (maxit.NE.(150)) THEN
    CALL CONVERT(answer,result)
    maxit = INT(result)

```

```

ENDIF
c
c Determine drive/directory to write output files
c
CALL settextposition(15,5,curpos)
CALL outtext('Directory for output <CURRENT>:')
CALL settextposition(15,38,curpos)
READ(*,'(a30)') outdrive
CALL settextposition(17,5,curpos)
CALL outtext('Are these values correct (Y/n)?')
CALL settextposition(17,37,curpos)
READ(*,'(a)') answer
IF (LEN_TRIM(answer).EQ.0) answer = 'Y'
IF ((answer(1:1).NE.'Y').AND.(answer(1:1).NE.'y')) GOTO 1000
len = LEN_TRIM(outdrive)
IF (len.NE.0) THEN
  IF (outdrive(len:len).NE.'\\') outdrive(len+1:len+1) = '\\'
ENDIF
GOTO(2000,3000,4000),select
GOTO 1

c
c SINGLE B-DOT DATA FILE
c
2000 CONTINUE
CALL clearscreen( $GCLEARSCREEN )
CALL settextposition(2,20,curpos)
CALL outtext('Deconvolution of a Single B-dot Data File')
CALL settextposition(3,20,curpos)
CALL outtext('-----')
CALL settextposition(6,1,curpos)
GOTO 2100
2050 WRITE(*,'(1x,a2)') bell
WRITE(*,'(''+ ERROR OPENING DATA FILE!'')')
2100 WRITE(*,'(1x,4x,'Enter B-dot filename: ','$)')
READ(*,'(a30)') infile(1)
OPEN(10,FILE=infile(1),FORM='unformatted',STATUS='old',ERR=2050)
WRITE(*,'(''0'',4x,'Enter armature velocity at probe: ','$)')
READ(*,*) vel(1)
dummy2 = setvideomode( $ERESCOLOR )
filename = infile(1)
len = LEN_TRIM(filename)
CALL settextposition(24,(79-(31+len))/2,curpos)
dummy2 = settextcolor( 15 )
CALL outtext('Reading B-dot data from file: '//filename(1:len))
dummy2 = settextcolor( 7 )
READ(10) n,(time(i),dat(i),i=1,n)
dt = (time(n) - time(1))/FLOAT(n-1)/1000.0
CLOSE(10)
CALL DATAPOINTS(n,time,dat,scale)
dx = vel(1)*dt
CALL IMPULSE(npts,theta1,theta2,r1,r2,dx,h)
CALL FILTER(npts,dat,h,y)
CALL JANSSON(npts,b,cutoff,minit,maxit,dat,h,y,infile(1))
CALL settextposition(24,28,curpos)
dummy2 = settextcolor( 15 )
CALL outtext('Press ENTER to Continue')
CALL settextposition(1,1,curpos)
PAUSE ' '
dummy2 = setvideomode( $TEXT80 )
CALL WRITEDATA(npts,infile(1),outdrive,scale,time,y)

```

```

        WRITE(*,'(\)')
        GOTO 1
C
C  SELECTED B-DOT DATA FILES
C
3000  CONTINUE
      CALL clearscreen( $GCLEARSCREEN )
      CALL settextposition(2,19,curpos)
      CALL outtext('Deconvolution of Selected B-dot Data Files')
      CALL settextposition(3,19,curpos)
      CALL outtext('-----')
      CALL settextposition(6,1,curpos)
      num = 0
      WRITE(*,'(''0'',4x,'Enter the names of the B-dot data files''))
      WRITE(*,*)
      GOTO 3100
3050  WRITE(*,'(1x,a2)') bell
      WRITE(*,'(''+'      ERROR OPENING DATA FILE!''a)') infile(i)
3100  i = num + 1
      WRITE(*,'(1x,9x,'Filename ('',i2,''):  '',$)') i
      READ(*,'(a30)') infile(i)
      IF (LEN TRIM(infile(i)).EQ.0) GOTO 3200
      OPEN(10,FILE=infile(i),FORM='unformatted',STATUS='old',ERR=3050)
      CLOSE(10)
      num = num + 1
      GOTO 3100
3200  CONTINUE
      WRITE(*,'(''0'',4x,'Enter armature velocity for each probe''))
      WRITE(*,*)
      DO 3300 i = 1,num
        filename = infile(i)
        len = LEN TRIM(filename)
        WRITE(*,'(1x,9x,'Velocity for ('',a,''):  '',$)')
        &      filename(1:len)
        READ(*,*) vel(i)
3300  CONTINUE
C
C  Main loop
C
      dummy2 = setvideomode( $ERESCOLOR )
      DO 3500 i = 1,num
        OPEN(10,FILE=infile(i),FORM='unformatted',STATUS='old')
        filename = infile(i)
        len = LEN TRIM(filename)
        CALL settextposition(24,(79-(31+len))/2,curpos)
        dummy2 = settextcolor( 15 )
        CALL outtext('Reading B-dot data from file:  '
        &      //filename(1:len))
        dummy2 = settextcolor( 7 )
        READ(10) n,(time(j),dat(j),j=1,n)
        dt = (time(n) - time(1))/FLOAT(n-1)/1000.0
        CLOSE(10)
        CALL DATAPOINTS(n,time,dat,scale)
        dx = vel(i)*dt
        CALL IMPULSE(npts,theta1,theta2,r1,r2,dx,h)
        CALL FILTER(npts,dat,h,y)
        CALL JANSSON(npts,b,cutoff,minit,maxit,dat,h,y,infile(i))
        CALL WRITEDATA(npts,infile(i),outdrive,scale,time,y)
3500  CONTINUE
      CALL settextposition(24,27,curpos)

```

```

dummy2 = settextrcolor( 15 )
CALL outtext('Deconvolutions Completed!')
CALL DELAY(wait)
dummy2 = setvideomode( $TEXTCS0 )
GOTO 1
C
C ALL B-DOT DATA FILES
C
4000 CONTINUE
CALL clearscreen( $GCLEARSCREEN )
CALL settextrposition(2,22,curpos)
CALL outtext('Deconvolution of All B-dot Data Files')
CALL settextrposition(3,22,curpos)
CALL outtext('-----')
CALL settextrposition(6,5,curpos)
C
C Determine data drive/directory and data file extension
C
CALL outtext('Data directory <CURRENT>:')
CALL settextrposition(6,32,curpos)
READ(*,'(a30)') datadrive
CALL settextrposition(7,5,curpos)
CALL outtext('Data file extension <1b>:')
CALL settextrposition(7,32,curpos)
READ(*,'(a3)') ext
IF (LEN_TRIM(ext).EQ.0) THEN
    ext = '1b'
    CALL settextrposition(7,32,curpos)
    CALL outtext(ext)
ENDIF
num = 0
len = LEN_TRIM(datadrive)
IF (len.NE.0) THEN
    IF (datadrive(len:len).NE.'\\') THEN
        datadrive(len+1:len+1)='\'
        len = len + 1
    ENDIF
ENDIF
C
C Open all possible B-dot files to see which ones exist
C
DO 4100 i = 1,30
    IF (i.LT.10) tempfile = 'bd'//char(i+48)//'.'//ext
    IF (i.GE.10) THEN
        j = i/10
        k = i - j*10
        tempfile = 'bd'//char(j+48)//char(k+48)//'.'//ext
    ENDIF
    dummy2 = LEN_TRIM(tempfile)
    filename = tempfile(1:dummy2)
    IF (len.NE.0) filename = datadrive(1:len)//tempfile(1:dummy2)
    OPEN(10,FILE=filename,FORM='unformatted',STATUS='old'
    & ,ERR=4100)
    CLOSE(10)
    num = num + 1
    infile(num) = filename
4100 CONTINUE
WRITE(*,'(''0'',4x,'Enter armature velocity for each probe'')')
WRITE(*,*)
DO 4200 i = 1,num

```

```

        filename = infile(i)
        len = LEN_TRIM(filename)
        WRITE(*, '(1x,9x, 'Velocity for file ',a,': ', $)')
        & filename(1:len)
        READ(*,*) vel(i)
4200 CONTINUE
c
c Main loop
c
        dummy2 = setvideomode( $ERESCOLOR )
        DO 4500 i = 1,num
            OPEN(10,FILE=infile(i),FORM='unformatted',STATUS='old')
            filename = infile(i)
            len = LEN_TRIM(filename)
            CALL settextrposition(24,(79-(31+len))/2,curpos)
            dummy2 = settextrcolor( 15 )
            CALL outtext('Reading B-dot data from file: '
                & //filename(1:len))
            dummy2 = settextrcolor( 7 )
            READ(10) n,(time(j),dat(j),j=1,n)
            dt = (time(n) - time(1))/FLOAT(n-1)/1000.0
            CLOSE(10)
            CALL DATAPOINTS(n,time,dat,scale)
            dx = vel(i)*dt
            CALL IMPULSE(npts,theta1,theta2,r1,r2,dx,h)
            CALL FILTER(npts,dat,h,y)
            CALL JANSSON(npts,b,cutoff,minit,maxit,dat,h,y,infile(i))
            CALL WRITEDATA(npts,infile(i),outdrive,scale,time,y)
4500 CONTINUE
            CALL settextrposition(24,27,curpos)
            dummy2 = settextrcolor( 15 )
            CALL outtext('Deconvolutions Completed!')
            CALL DELAY(wait)
            dummy2 = setvideomode( $TEXTC80 )
            GOTO 1

9999 CONTINUE
        STOP
        END

c-----
c Convert Character Variables to Real Numbers
c
        SUBROUTINE CONVERT(answer,result)
            REAL result
            CHARACTER*10 answer
c
c Remove leading blank spaces
c
1          CONTINUE
            IF (answer(1:1).NE.' ') GOTO 5
            answer = answer(2:10)
            GOTO 1
5          CONTINUE
c
c Ignore everything after next blank space
c
            i = index(answer,' ')
            IF (i.NE.0) answer = answer(1:i-1)
            result = 0.0

```

```

        i = index(answer, '.')
        j = LEN TRIM(answer)
        IF (i.EQ.0) THEN
            DO 10 k = 1,j
                result = result + FLOAT(ICHAR(answer(k:k))-48)*10.0**(j-k)
10         CONTINUE
        ENDIF
        IF (i.NE.0) THEN
            DO 20 k = 1,i-1
                result = result + FLOAT(ICHAR(answer(k:k))-48)*10.0**(i-1-k)
20         CONTINUE
            DO 30 k = i+1,j
                result = result + FLOAT(ICHAR(answer(k:k))-48)/10.0**(k-i)
30         CONTINUE
        ENDIF

        RETURN
        END

c-----
c  Determines the data maximum and fills the array to be deconvolved
c  with the 1024 points on each side of the maximum
c
        SUBROUTINE DATAPOINTS(n,time,dat,maximum)
        REAL maximum
        INTEGER*2 n
        DIMENSION time(1),dat(1)

c
c  Fill arrays with the points around the B-dot maximum
c
        maximum = 0.0
        DO 10 i = 1,n
            IF (dat(i).GT.maximum) THEN
                j = i
                maximum = dat(i)
            ENDIF
10         CONTINUE
            DO 20 i = j-1024,j+1023
                time(i-(j-1024)+1) = time(i)
                dat(i-(j-1024)+1) = dat(i)
20         CONTINUE

        RETURN
        END

c-----
c  Determines the B-dot probe impulse response
c
        SUBROUTINE IMPULSE(npts,theta1,theta2,r1,r2,dx,h)
        REAL dx,theta1,theta2,r1,r2
        INTEGER*2 npts
        DOUBLE PRECISION h(1)

c
c  Determine B-dot probe impulse response function
c
        DO 10 i = 1,npts
            x = dx*float(i-1)
            IF (i.GT.(npts/2)) x = dx*float(i-npts-1)
            x = x*x
            h(i) = (theta1/((r1+x)**1.5)

```

```

      &      -theta2/((r2+x)**1.5))
10      CONTINUE

      RETURN
      END

c-----
c  Lowpass filter (based on impulse response) to enhance convergence
c
      SUBROUTINE FILTER(npts,dat,h,y)
      REAL sum,maxdat,maxy
      INTEGER*2 npts
      DIMENSION dat(1)
      DOUBLE PRECISION filt(2048), f(2048)
      DOUBLE PRECISION h(1),y(1)
c
c  Form filter (Use g to store filter)
c
      DO 10 i = 1,npts
         filt(i) = h(npts - i + 1)
10      CONTINUE
c
c  Filter impulse response function (Use f to hold filtered values)
c  Scale impulse response such that SUM(h) = 1
c
      CALL CONVOLVE(filt,h,f,npts)
      sum = 0.0
      DO 20 i = 1,npts
         h(i) = f(i)
         sum = sum + h(i)
20      CONTINUE
      DO 30 i = 1,npts
         h(i) = h(i)/sum
30      CONTINUE
c
c  Filter recorded data
c
      maxdat = 0.0
      DO 40 i = 1,npts
         y(i) = dat(i)
         maxdat = max(maxdat,y(i))
40      CONTINUE
      CALL CONVOLVE(filt,y,f,npts)
      maxy = 0.0
      DO 50 i = 1,npts
         y(i) = f(i)
         maxy = max(maxy,y(i))
50      CONTINUE
      DO 60 i = 1,npts
         y(i) = y(i)/maxy*maxdat
60      CONTINUE

      RETURN
      END

c-----
c  Iterative deconvolution using Jansson's method
c
      SUBROUTINE JANSSON(npts,b,cutoff,minit,maxit,dat,h,y,filename)

```

```

INCLUDE 'fgraph.fd'

REAL b,c,cutoff,maximum,minimum,maxdat,mindat,range,result
DOUBLE PRECISION error,diff,prev
INTEGER*2 iter,npts,dummy2,xloc,yloc,zero,minit,maxit
CHARACTER*30 filename
DIMENSION dat(1)
DOUBLE PRECISION f(2048),g(2048)
DOUBLE PRECISION h(1),y(1)
RECORD / rccoord / curpos
RECORD / xycoord / xy

CALL clearscreen( $GCLEARSCREEN )
CALL settxtposition(3,5,curpos)
CALL outtext(filename)
CALL settxtposition(3,61,curpos)
CALL outtext('# Iterations:')
WRITE(*,'(\)')

c
c Determine screen scaling
c
      maxdat = 0.0
      mindat = 0.0
      DO 10 i = 1,npts
        maxdat = max(maxdat,dat(i))
        mindat = min(mindat,dat(i))
        g(i) = y(i)
10    CONTINUE
      range = 339.0/(maxdat - mindat)
      zero = 339 - IABS(mindat*range) + 5

c
c Determine first value for C using Van Cittert's Algorithm
c
      CALL CONVOLVE(h,y,f,npts)
      maximum = 0.0
      DO 20 i = 1,npts
        result = 0.0
        result = y(i) + b * ( g(i) - f(i) )
        maximum = max(maximum,result)
20    CONTINUE
      c = maximum*1.1

c
c Enter main loop
c
      iter = 0
      error = 100.0
100   CONTINUE
      prev = error

c
c Display B-dot signal
c
      dummy2 = SETCOLOR( 2 )
      xloc = 640 - 63
      yloc = zero - INT(dat(1)*range)
      CALL moveto(xloc,yloc,xy)
      DO 30 j = 5,npts,4
        xloc = 640 - (j/4 + 63)
        yloc = zero - INT(dat(j)*range)
        dummy2 = LINETO(xloc,yloc)
30    CONTINUE

```

```

CALL CONVOLVE(h,y,f,npts)
c
c Jansson's Algorithm
c
    maximum = 0.0
    minimum = 0.0
    error = 0.0
    DO 40 j = 1,npts
        r = b * (1.0 - (2.0/c) * ABS( y(j)-(c/2.0) ) )
        diff = g(j) - f(j)
        error = error + diff*diff
        y(j) = y(j) + r * ( diff )
        maximum = max(maximum,y(j))
        minimum = min(minimum,y(j))
40    CONTINUE
    c = maximum*1.1
    iter = iter + 1
    CALL setttextposition(3,75,curpos)
    WRITE(*,'(i3,\)' ) iter
    dummy2 = SETCOLOR( 7 )

c
c Check to see if solution is diverging
c maxdat & mindat used since SUM(dat) = 1
c
    IF ((maximum.GT.(2.0*maxdat))
    & .OR.(minimum.LT.(2.0*mindat))) THEN
        CALL setttextposition(24,22,curpos)
        dummy2 = setttextcolor( 15 )
        CALL outtext('Solution Diverging! <Press ENTER>')
        CALL setttextposition(1,1,curpos)
        PAUSE ' '
        dummy2 = setvideomode( $TEXTC80 )
        STOP
    ENDIF

c
c Display result of iteration
c
    DO 50 j = 1,npts,4
        xloc = 640 - (j/4 + 63)
        yloc = zero - INT(y(j)/maximum*maxdat*range)
        dummy2 = SETPIXEL(xloc,yloc)
50    CONTINUE
    dummy2 = SETCOLOR( 4 )
    CALL moveto(0,zero,xy)
    dummy2 = LINETO(639,zero)
    prev = DABS((error-prev)/prev)*100.0
    IF (iter.LT.minit) GOTO 100
    IF ((iter.LT.maxit).AND.(prev.GT.cutoff)) GOTO 100

c
c END!
c
    CALL clearscreen( $GCLEARSCREEN )
    CALL setttextposition(3,5,curpos)
    CALL outtext(filename)
    CALL setttextposition(3,61,curpos)
    CALL outtext('# Iterations:')
    CALL setttextposition(3,75,curpos)
    WRITE(*,'(i3,\)' ) iter

c
c Display B-dot signal and final result

```

```

c      dummy2 = SETCOLOR( 2 )
      xloc = 640 - 63
      yloc = zero - INT(dat(1)*range)
      CALL moveto(xloc,yloc,xy)
      DO 60 j = 5,npts,4
        xloc = 640 - (j/4 + 63)
        yloc = zero - INT(dat(j)*range)
        dummy2 = LINETO(xloc,yloc)
60    CONTINUE
      dummy2 = SETCOLOR( 3 )
      xloc = 640 - 63
      yloc = zero - INT(y(1)/maximum*maxdat*range)
      CALL moveto(xloc,yloc,xy)
      DO 70 j = 5,npts,4
        xloc = 640 - (j/4 + 63)
        yloc = zero - INT(y(j)/maximum*maxdat*range)
        dummy2 = LINETO(xloc,yloc)
70    CONTINUE
      dummy2 = SETCOLOR( 4 )
      CALL moveto(0,zero,xy)
      dummy2 = LINETO(639,zero)

c
c      Scale deconvolved data to unity
c
      DO 200 i = 1,npts
        y(i) = y(i)/maximum
200    CONTINUE

      RETURN
      END

-----
c      Delay 15 seconds
c
      SUBROUTINE DELAY(wait)
      INTEGER*2 ihr,imin,isec,i100th,tsec
      INTEGER*2 iyr,imon,iday,tday,wait
      CALL GETTIM(ihr,imin,isec,i100th)
      CALL GETDAT(iyr,imon,iday)
      tsec = ihr*3600+imin*60+isec+wait
10    CALL GETTIM(ihr,imin,isec,i100th)
      CALL GETDAT(iyr,imon,tday)
      IF (iday.NE.tday) GOTO 20
      IF (tsec.GT.(ihr*3600+imin*60+isec)) GOTO 10
20    CONTINUE

      RETURN
      END

-----
c      Write deconvolved data to disk
c
      SUBROUTINE WRITEDATA(npts,tempfile,outdrive,scale,time,y)
      REAL scale
      INTEGER*2 npts
      CHARACTER*30 filename,tempfile,outdrive
      DIMENSION time(1)
      DOUBLE PRECISION y(1)
c

```

```

c Name output file by removing data drive path, add
c output drive path, and adding extension '.out'
c
      i = index(tempfile,':')
      IF (i.NE.0) tempfile = tempfile(i+1:30)
5     CONTINUE
      i = index(tempfile,'\')
      IF (i.EQ.0) GOTO 10
      tempfile = tempfile(i+1:30)
      GOTO 5
10    CONTINUE
      i = index(tempfile, '.')
      tempfile = tempfile(1:i)//'.out'
      i = LEN_TRIM(tempfile)
      j = LEN_TRIM(outdrive)
      filename = tempfile(1:i)
      IF (j.NE.0) filename = outdrive(1:j)//tempfile(1:i)
      OPEN(10,FILE=filename,STATUS='unknown',FORM='unformatted')
      WRITE(10) npts,(time(i),REAL(y(i)*scale), i=1,npts)
      CLOSE(10)

      RETURN
      END
-----
c Convolve data
c
      SUBROUTINE CONVOLVE(H,Y,F,NPTS)
      DOUBLE PRECISION H(1), F(1), Y(1)
      DOUBLE PRECISION CH(2,2048), CF(2,2048), CY(2,2048)
      INTEGER*2 N, I, LN, NPTS

      ln = 0
5     continue
      ln = ln+1
      n = 2**ln
      if(n.lt.npts) goto 5
      n = 2**ln

      do 10 i = 1,n
         ch(1,i) = h(i)
         ch(2,i) = 0.0
         cy(1,i) = y(i)
         cy(2,i) = 0.0
10    continue

      call fft(ch,ln)
      call fft(cy,ln)

      do 50 i=1,n
         cf(1,i)=cy(1,i)*ch(1,i)-cy(2,i)*ch(2,i)
         cf(2,i)=cy(1,i)*ch(2,i)+cy(2,i)*ch(1,i)
50    continue
      call invfft(cf,ln)
      do 90 i=1,n
         f(i) = cf(1,i)
90    continue

      return
      end

```

```

c-----
      subroutine fft(x,m)
      double precision x(2,2048),t(2),u(2),v(2),w(2)
      integer*2 m
c
      n=2**m
      pi=3.14159265358979
c
      do 20 l=1,m-1
      le=2**(m+1-l)
      le1=le/2
      u(1)=1.0
      u(2)=0.0
      w(1)=cos(pi/float(le1))
      w(2)=-sin(pi/float(le1))
      do 20 j=1,le1
      do 10 i=j,n,le
      ip=i+le1
      t(1)=x(1,i)+x(1,ip)
      t(2)=x(2,i)+x(2,ip)
      v(1)=x(1,i)-x(1,ip)
      v(2)=x(2,i)-x(2,ip)
      x(1,ip)=u(1)*v(1)-u(2)*v(2)
      x(2,ip)=u(1)*v(2)+u(2)*v(1)
      x(1,i)=t(1)
      x(2,i)=t(2)
10      continue
      v(1)=u(1)*w(1)-u(2)*w(2)
      v(2)=u(1)*w(2)+u(2)*w(1)
      u(1)=v(1)
      u(2)=v(2)
20      continue
c
      do 30 i=1,n,2
      ip=i+1
      t(1)=x(1,i)+x(1,ip)
      t(2)=x(2,i)+x(2,ip)
      x(1,ip)=x(1,i)-x(1,ip)
      x(2,ip)=x(2,i)-x(2,ip)
      x(1,i)=t(1)
      x(2,i)=t(2)
30      continue
c
      j=1
      do 40 i=1,n-1
      if(i.ge.j) go to 25
      t(1)=x(1,j)
      t(2)=x(2,j)
      x(1,j)=x(1,i)
      x(2,j)=x(2,i)
      x(1,i)=t(1)
      x(2,i)=t(2)
25      continue
      k=n/2
26      continue
      if(k.ge.j) go to 40
      j=j-k
      k=k/2
      go to 26

```

```

40    j=j+k
c
    return
end

c-----
subroutine invfft(x,m)
double precision x(2,2048),t(2),u(2),v(2),w(2)
integer*2 m

c
    n=2**m
    pi=3.14159265358979
c
    do 20 l=1,m
        le=2**(m+1-l)
        lel=le/2
        u(1)=1.0
        u(2)=0.0
        w(1)=cos(pi/float(lel))
        w(2)=sin(pi/float(lel))
        do 20 j=1,lel
            do 10 i=j,n,le
                ip=i+lel
                t(1)=x(1,i)+x(1,ip)
                t(2)=x(2,i)+x(2,ip)
                v(1)=x(1,i)-x(1,ip)
                v(2)=x(2,i)-x(2,ip)
                x(1,ip)=u(1)*v(1)-u(2)*v(2)
                x(2,ip)=u(1)*v(2)+u(2)*v(1)
                x(1,i)=t(1)
                x(2,i)=t(2)
            10    continue
                v(1)=u(1)*w(1)-u(2)*w(2)
                v(2)=u(1)*w(2)+u(2)*w(1)
                u(1)=v(1)
                u(2)=v(2)
            20    continue
c
                j=1
                do 30 i=1,n-1
                    if(i.ge.j) go to 25
                    t(1)=x(1,j)
                    t(2)=x(2,j)
                    x(1,j)=x(1,i)
                    x(2,j)=x(2,i)
                    x(1,i)=t(1)
                    x(2,i)=t(2)
                25    continue
                    k=n/2
                26    continue
                    if(k.ge.j) go to 30
                    j=j-k
                    k=k/2
                    go to 26
                30    j=j+k
c
                do 40 i=1,n
                    x(1,i)=x(1,i)/float(n)
                    x(2,i)=x(2,i)/float(n)
                40    continue

```

c
return
end

VITA

Bruno J. Evans was born in a U.S. Army Hospital, West Germany, on March 30, 1966. He graduated from Northwest High School in Clarksville, Tennessee in 1984. He attended Tennessee Technological University in Cookeville, Tennessee from 1984 to 1989, graduating with a Bachelor of Science degree in Electrical Engineering. In January 1990, he came to the University of Tennessee Space Institute on a graduate research assistantship where he was awarded the Master of Science degree in Electrical Engineering in August 1991.

After graduating, Mr. Evans plans to pursue a career with research and development opportunities in digital image processing and/or digital systems. He is interested in multidimensional signal processing. In the future, he would like to continue his graduate studies by obtaining a Ph.D in Electrical Engineering.