Evaluation of A Multimegavolt Impulse Measurement System

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EVALUATION OF A MULTIMEGAVOLT IMPULSE MEASUREMENT SYSTEM

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I. INTRODUCTION

The accepted techniques for measuring the high voltage pulses used for testing power system apparatus in the United States are described in the voluntary standard issued by the Institute of Electrical and Electronic Engineers, "High Voltage Testing Techniques," IEEE-4. This document is essentially the same as International Electrotechnical Commission Publication 60-3.

The basic assumptions underlying this standard are summarized in a publication by the International Research Group Renardieres on Impulse Measuring Systems (IRR-IMS group). Basically, it is assumed that the measuring system can be modeled as a two terminal pair network. The relationship between the input and the output is

\[
\begin{bmatrix}
V_i(s) \\
I_i(s)
\end{bmatrix} = [A]
\begin{bmatrix}
V_o(s) \\
I_o(s)
\end{bmatrix}
\]

where \( V \) is the voltage, \( I \) is the current, the subscripts \( i \) and \( o \) refer to input and output respectively and \( s \) is the Laplace operator. Formally, the matrix \( A \) is represented as
The voltage transfer function, $H(s)$, is defined as the voltage ratio when the output current is zero, i.e.,

$$H(s) = V_o(s)/V_i(s) = 1/A_{11}(s).$$

The divider ratio, $N$, is then defined as

$$N = A_{11}(o) = \lim_{s \to 0} [A_{11}(s)].$$

It should be noted that in some cases, e.g., capacitor dividers with a resistor in the low impedance element, $A_{11}(s)$ may not be defined at zero. In this case, to represent the ratio as a single real number, $A_{11}(s)$ must be frequency independent over the frequency range of interest. The assumption of frequency independence over the range of frequencies of interest is implicit because the divider must attenuate equally all frequencies contained in the input signal.
These fundamental considerations highlight two important facets of the calibration of impulse measurement systems:

- determination of the divider ratio -- a single real number by which output voltage is multiplied to determine the input voltage, and,

- verification that the transfer characteristics of the system are frequency independent over a sufficiently-wide frequency range so that this single real number is valid for the waveform to be measured.

The divider ratio can be measured using a variety of techniques which are generally, but not exclusively, based on comparison of the input and output voltages at a single frequency or a series of discrete frequencies.

The frequency dependence of $A_{ll}(s)$ is generally determined in the time domain by measuring the response of the system to a voltage step. Obviously, the frequency dependence can also be measured in the frequency domain by performing measurements throughout all frequency ranges of interest. Because these latter measurements are difficult and time consuming, time domain measurements are generally performed.

The purpose of this investigation was to determine experimentally the adequacy of measurements of the response to a voltage step in large scale, practical measurement systems. There are valid technical reasons
to question measurement accuracy in such systems. These are based on the fact that a practical measurement system is not well-correlated with the model outlined above. Obvious discrepancies include the following items:

- The measurement system is not an ideal two-terminal pair network. The constraint of current equality in the input terminal pairs and in the output terminal pairs cannot be easily realized, particularly because of ground currents which cannot always be confined to specified paths.

- Inductive and capacitive couplings among the pulse generating circuit, the measuring circuit beyond the divider terminals, and the divider itself introduce signals in addition to those specified at the terminals of the divider. (An unusual phenomenon in this category is the cavity resonance of the entire high voltage hall.\(^2\) This resonance, however, was not observed in this investigation).

- It is not technically feasible to apply a voltage step directly between two widely separated input terminals. Leads, therefore, must be used to connect the terminals to a step generator. Because the lead geometries are different in the tests of the step response and the measurements of high voltage transients, the entire divider circuitry is modified. The significance of lead effects must be determined.
The relatively small signals encountered in the determination of the step response may be contaminated by extraneous electro-magnetic interference.

These problems have long been recognized and a considerable amount of effort has been devoted to verifying that measurements with uncertainties of the order of a few percent can be performed. An area where inaccuracies of a few percent are difficult to attain is the measurement of impulses which are chopped on the front. As a demonstration of this exception, IEEE-4 describes a technique to correct the crest value of a front-chopped impulse in those cases in which the response time of the measuring system is more than 5% of the risetime of voltage pulse. Unfortunately, range of applicability of this correction is poorly documented. This fact is emphasized, as this is the only correction for which the standard explicitly suggests agreement between the parties involved before the correction is applied.

The approach taken in this investigation was to verify that all of the parameters in Duhamel's integral (also referred to as the convolution integral)\(^3,4\) could be measured with sufficient accuracy to guarantee that corrections based on the measured response to a step would permit meaningful measurements of the voltage waveform. Duhamel's integral can be expressed as

\[
N V_o(t) = \int_0^t \Theta'(\tau) V_i(t-\tau) \, d\tau, \quad [5]
\]
where \( t \) is an integration variable, \( \Theta'(t) \) is the time derivative of the unit step response, \( V_1 \) is the input voltage, \( V_0 \) the output voltage, and \( N \) is the divider ratio as defined in Eq. 4. This equation dictates the measurement program -- the input and output voltage, the divider ratio and the step response each must be measured.

Measurements of the divider ratio, the step response and the output voltage are conventional in a modern, high voltage test laboratory. It is assumed that the input can be determined from these three measurements. To verify this assumption, the input is also measured using a second divider which introduces only negligible distortion in the applied waveform. To provide evidence that the characteristics of this second divider are appropriate for the desired measurement, two low voltage checks are performed. First a low voltage (100-1000 V) ramp, having about the same time-to-crest as the high voltage pulse, is applied to the divider under test. The input and output voltages are measured with an oscilloscope. Using the same experimental setup, the test is repeated using the second divider to measure the input voltage. Comparison of these results provides information with which to judge the validity of the approach.

It should be noted that the low voltage tests using two dividers are technically difficult. The output voltages typically range from 0.01-0.1 V peak. Electromagnetic interference and ground impedance make measurements at this level challenging in an industrial high voltage laboratory.
This test protocol was originally developed and employed with mixed success by the IRR-IMS group for an experimental session in the summer of 1976 at the high voltage laboratory of Electricité de France.

Section II of this report describes the design, construction and testing of the resistor dividers, the ramp generator, and the step generator. The software used to evaluate the measurements is given in Section III. Section IV presents the results of tests performed at the high voltage laboratory of the Bonneville Power Administration. Section V summarizes the data analysis results. Finally, Section VI summarizes the results of the measurements and suggests possible implications.

II. APPARATUS

II.1 Divider Design, Construction, and Calibration

II.1.a Introduction

The basic design of the impulse divider had been developed by other workers. In principle, the high impedance element is a non-inductive resistor having a resistance of approximately 10,000 Ω. The resistance distribution along the resistor is chosen to match approximately the capacitance distribution, which is controlled primarily through the choice of the size and position of the divider's guard ring(s). Two dividers were constructed -- one designed to measure standard lightning impulses up to about 350 kV peak and the other designed to measure standard lightning impulses up to approximately 1 MV peak. During the
high voltage tests, it was only necessary to use the larger divider, so only it will be described in detail. The remainder of this subsection is a description of the design, construction, and calibration of this divider.

II.1.b 1 MV Divider

A photograph of the completed 1 MV divider is shown in Fig. 1. The high impedance element consists of three discrete resistors. Each resistor is nominally 1 meter long and 5 cm in diameter. To obtain a somewhat non-uniform resistance distribution, which approximately matches the capacitance distribution, the three resistors were designed to have nominal resistances of 2500 Ω, 3500 Ω, and 4000 Ω. It should be noted that a computer program has been developed to optimize the design of resistor dividers. Because of the availability of design information for dividers of this size, however, it was not judged necessary to incur the expense of duplicating that program. The resistors were wound using resistance wire that had a resistance of 26.2 Ω/m. To obtain a non-inductive resistor, two nominally equal windings were used, wound in opposite directions one on top of the other and connected in parallel. Each winding consisted of more than 1000 turns; the exact number of turns depended on the desired resistance.

The resistors were wound using a lathe, so the actual resistance was determined by the available pitch settings. The completed resistors had values of 2729 Ω, 3483 Ω, 3945 Ω.
Fig. 1 The resistor divider, NBS-1, rated at one million volts.
The divider's low impedance element has a nominal resistance of 1 Ω and consists of two 2-Ω pieces of resistance wire connected in parallel. Each of the 2-Ω resistors is twisted to minimize its inductance. With this low value of resistance, the effect of low-side capacitance (e.g., from cables or the measuring instrument) was judged to be negligible. This judgement is based on the maximum frequency which can be generated in the high voltage circuit, $f_{\text{max}}$. This frequency can be estimated as

$$f_{\text{max}} = \frac{c}{4(h_G + h_C)} ,$$

where $c$ is the speed of light, $h_G$ is the height of the generator, and $h_C$ is the height of the front capacitor. To calculate $f_{\text{max}}$, it was assumed $h_G = 2h_C$ which in general should overestimate $f_{\text{max}}$. In Fig. 2, the maximum frequency is superimposed on a plot of the calculated magnitude of low side impedance versus frequency (using the conservative assumption that low side capacitance is 1000 pF (equivalent to about 10 m of coaxial cable)). It should be emphasized that this plot does not constitute proof of measurement accuracy. It does, however, indicate that the design of the divider low-side is probably adequate for the measurement of the voltage pulses in a wide range of measurement applications.
Fig. 2  Low-side impedance (solid line) as a function of frequency and theoretical maximum frequency (dashed line) as a function of generator height.
The design of the guard ring was done experimentally. The size was estimated from experience with other dividers of the same physical dimensions and voltage ratings. Low voltage tests were performed to document the relationship between the size of the guard ring and the response to a voltage step.

The divider was calibrated by four different methods, consisting of three low-voltage measurements:
- step-response
- dc voltage ratio
- resistances (plus calculation)
and one high voltage measurement:
- comparison with an electro-optic Kerr system, of the measurement of the peak value of a high voltage impulse.

A typical low-voltage step response is shown in Fig. 3. Average step height from such oscillograms with an applied voltage of 135.5 V was 12.80 mV, from which a divider ratio of 10590:1 was obtained. The uncertainty of this method was about ±1%, primarily attributable to errors in resolving the spacing of the traces on the photographic record. By digitizing the entire oscillogram and correcting for all distortion in the oscilloscope screen and photographic reproduction, it is, in principle, possible to reduce this uncertainty -- perhaps by as much as a factor of ten. In this case, the only correction applied was for errors in the vertical gain of the oscilloscope. For the position on the screen of the response shown in Fig. 3, this correction was negligible.
Applied Voltage: 135.5 V
Vertical Scale: 5 mV/Div
Horizontal Scale: 200 ns/Div

Fig. 3 Typical step response of NBS-1.
Non-negligible distortions were observed, however, for trace positions significantly higher or lower on the screen.

To check the overall performance of the divider, the response time was measured using five different values of the damping resistor ($R_D$ in Fig. 5). These data are shown in Fig. 4. From a least-squares linear fit, the equivalent input capacitance was found to be 95.8 pF with a standard deviation of 5 pF.

Measurement of the dc voltage ratio was performed using two digital voltmeters. Typical results are presented in the following table.

<table>
<thead>
<tr>
<th>$V_{in}$ (volts)</th>
<th>$V_o$ (volts)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>60.20</td>
<td>0.00567</td>
<td>10620</td>
</tr>
<tr>
<td>74.12</td>
<td>0.00698</td>
<td>10620</td>
</tr>
<tr>
<td>99.90</td>
<td>0.00940</td>
<td>10630</td>
</tr>
<tr>
<td>127.28</td>
<td>0.01198</td>
<td>10620</td>
</tr>
<tr>
<td>151.46</td>
<td>0.01425</td>
<td>10630</td>
</tr>
<tr>
<td>175.21</td>
<td>0.01649</td>
<td>10630</td>
</tr>
</tbody>
</table>

The resistances which must be measured in order to calculate the ratio are shown in the circuit of Fig. 5. In this figure, $R_D$ is the damping resistor, $R_H$ is the divider high-side resistor, $R_L$ is the low-side resistor, $R_T$ is the terminator resistor at the input to the oscilloscope, $R_1$ is the resistance of the center conductor of the coaxial cable connecting the divider with the oscilloscope and $R_2$ is the resistance of the shield of that cable. From this circuit,
Fig. 4  Response time of NBS-1 as a function of damping resistance.

Slope = 95.8 ± 5 pF
Fig. 5  Equivalent circuit of NBS-1 with damping resistor and cable termination.
\[ V_{in}/V_o = \left( R_\tau/R_{LL} \right) \left( R_1 + R_2 + R_\tau \right)/R_\tau, \]  

where

\[ R_{LL} = R_L || (R_1 + R_2 + R_\tau), \]

and

\[ R_\tau = R_{LL} + R_H + R_D. \]

The measured values were

\[ R_\tau = 10360 \ \Omega \]
\[ R_{LL} = 0.977 \ \Omega \] \[ R_1 + R_2 + R_\tau = 50.34 \ \Omega \]
\[ R_\tau = 50.26 \ \Omega.\]
Calculations from these measurements yield a divider ratio of 10620:1, which agrees with Table 1 values.

The test circuit for the simultaneous measurement of the high voltage pulse using both an electro-optic Kerr system and the divider is shown in Fig. 6. The pulse transformer provides an approximately rectangular pulse with a full-width at half maximum of about 6 μs. To perform an accurate measurement of the divider low-side peak voltage, a suppressed-zero technique is used. The response of the Kerr cell is shown in Fig. 7. The peak voltage applied to the cell is determined from the equation:

\[
\frac{I}{I_m} = \sin^2 \left( \frac{\pi (V/V_m)/2}{2} \right)
\]

where \( I/I_m \) is the relative transmittance of the Kerr system, \( V \) is the applied voltage and \( V_m \) is a constant determined by the cell geometry and the properties of the electro-optic fluid.

Dividing this voltage by the measured peak of the divider output yielded a divider ratio of 10560:1, within 0.7% of the low voltage values discussed earlier. The applied voltage was approximately 150 kV peak during these tests. During the development and testing of various configurations of the low impedance element of the divider, a series of high voltage tests was performed using both the square wave and a 1.2 x 50 μs standard
Fig. 6 Test circuit for high voltage calibration of NBS-1.
Fig. 7  Typical response of Kerr system to high voltage pulse. 
I=I_m is the maximum transmittance of the system while 
I=0 is the minimum.
lightning impulse. The choice was determined by convenience and availability of pulse sources, because it was assumed that the rates of change of both waveshapes were sufficiently slow that the measured ratio would be independent of pulse shape. While no systematic investigation of this assumption was performed, a spot check indicated that the divider ratios measured using the two waveforms differed by only about 0.1%.

The results of the four determinations of the divider ratio are shown in the following table:

<table>
<thead>
<tr>
<th>Measurement Method</th>
<th>Ratio</th>
<th>Deviation From Average %</th>
</tr>
</thead>
<tbody>
<tr>
<td>dc voltage</td>
<td>10620:1</td>
<td>+0.2</td>
</tr>
<tr>
<td>resistance</td>
<td>10620:1</td>
<td>+0.2</td>
</tr>
<tr>
<td>step response</td>
<td>10590:1</td>
<td>-0.1</td>
</tr>
<tr>
<td>comparison with Kerr system</td>
<td>10560:1</td>
<td>-0.4</td>
</tr>
</tbody>
</table>

II.2 Ramp Generator

A voltage ramp with a nominal slope of 500 V/μs, chopped after approximately 1 μs (V₀ ~ 500 volts), is required for the low-voltage calibration of the high voltage divider. The circuit used to generate this ramp is shown in Fig. 8. It is essentially a modification and optimization of an earlier circuit used in unpublished experiments at Electricité de France. Voltage, V, is furnished by a conventional low-current dc power supply. Capacitor, C, which serves as an "infinite" source during ramp generation, is charged slowly through resistor, R, which also serves to limit the power supply current after the circuit fires. Switching gap, G₁, is adjusted to break down when voltage V₁
Fig. 8 Ramp generator circuit.
equals the desired value, usually about 10 kV. \( G_1 \) consists of two 2.5 cm brass spheres, operating in air. \( L, C_1, R_1, R_h, \) and \( R_L \) act to generate and shape a ramp voltage across \( C_1 \) after \( G_1 \) fires. Gap \( G_2 \), similar in construction to \( G_1 \), chops the ramp at the desired voltage. Output voltage \( V_0 \) is applied directly to the divider under test, and to a storage scope (not shown) via two cascaded 10:1 attenuators.

Once placed in operation, the circuit functions as a relaxation oscillator, with a period determined by \( RC, V \) and the setting of gap \( G_1 \). The scope is triggered by a 30 cm diameter loop antenna placed 20-30 cm from gap \( G_1 \).

The response of the elemental circuit of Fig. 8 is easily calculated. With the valid assumption that the time constant \( RC \) is much larger than the ramp time, that \( C \) is much larger than \( C_1 \), and that \( G_1 \) fires instantaneously, output voltage is

\[
V_0 = V_1 R_L \left[ 1 - e^{-at} \left( \cos bt + \frac{a}{b} \sin bt \right) \right] / (R_1 + R_2) \quad [11]
\]

and ramp slope is

\[
\rho_o = \frac{dV_o}{dt} = V_1 R_L q \left( e^{-at} \sin bt \right) / b(R_1 + R_2) \quad [12]
\]
where \( R_2 = R_h + R_L \)

\[
a = \frac{p}{2}
\]

\[
b = \frac{\sqrt{4a - p^2}}{2}
\]

and

\[
p = \frac{(R_1/L) + (1/R_2C_1)}{}
\]

\[
q = \frac{(R_1 + R_2)/R_2LC_1}{2}
\]

Equations (11) and (12) are valid until \( G_2 \) fires, after which the response is of no interest beyond the fact that \( V_0 \) collapses very rapidly, i.e., is truly "chopped".

The response of the circuit of Fig. 8 is shown in Fig. 9 for \( V = 8.5 \text{ kV} \). This calculation is useful in ascertaining appropriate component values to be used in the initial design of the circuit. However, at these speeds stray capacitances and inductances play very important roles in determining the shape of the final wave. These stray parameters are never well known. Furthermore, their inclusion in the basic circuit creates an intolerably complicated and tedious analytical situation. Therefore, after the analytical first cut, design of the circuit was primarily experimental, consisting of varying the physical size, location and orientation of the circuit parameters, and observing
Fig. 9 Calculated response of ramp generator circuit.
the effects of these changes on the waveform. It may be noted in passing
that the waveshape is much more sensitive to the size and orientation of
the inductor than to any of the other parameters.

The efficiency of this design procedure is demonstrated by comparing
Figs. 10a and 10b. The former shows a typical $V_0$ wave early in the design
process, the latter the output wave of the final circuit. In Fig. 10b,
with applied voltage $V_1 \approx 8.5$ kV, peak $V_0 \approx 525$ volts, chop time
$\approx 1.02 \mu s$, and the slope near the peak $\approx 520$ V/\mu s. The wave is clean and
the chop is sharp ($\approx 150$ volts in 30 ns). This is close to the design
goals.

The final circuit layout is shown in Fig. 11. The open, "breadboarded"
layout on a large ground plane was found to be the simplest means of
controlling strays and pick-up in order to optimize the waveform. Component
descriptions are as follows:

<table>
<thead>
<tr>
<th>Component</th>
<th>Values</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$</td>
<td>5 M $\Omega$</td>
<td>Rated 1 mA steady-state, &gt; 20 kV flashover</td>
</tr>
<tr>
<td>$C$</td>
<td>0.75 $\mu F$</td>
<td>Two 1.5 $\mu F$, 5 kV capacitors in series</td>
</tr>
<tr>
<td>$C_1$</td>
<td>0.1 $\mu F$</td>
<td>Four 0.1 $\mu F$, 5 kV capacitors in series-parallel</td>
</tr>
<tr>
<td>$L$</td>
<td>$\approx 7$ $\mu H$</td>
<td>35 turn air core solenoid, wound on</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.8 cm OD x 23 cm plastic form</td>
</tr>
<tr>
<td>$R_1$</td>
<td>3.0 $\Omega$</td>
<td>6 turn, handwound, #24 resistance wire on</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.6 cm OD x 7.6 cm form</td>
</tr>
<tr>
<td>$R_h$</td>
<td>9.3 $\Omega$</td>
<td>7 turn, handwound, #30 resistance wire on</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.6 cm OD x 7.6 cm form</td>
</tr>
<tr>
<td>$R_L$</td>
<td>1.1 $\Omega$</td>
<td>1 turn, handwound, #30 resistance wire on</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.6 cm OD x 5 cm form</td>
</tr>
<tr>
<td>$G_1$</td>
<td>-----</td>
<td>2.5 cm brass spheres in hardwood frame, air gap screw-adjusted</td>
</tr>
<tr>
<td>$G_2$</td>
<td>-----</td>
<td>Similar to $G_1$, except sphere diameter = 1.90 cm</td>
</tr>
<tr>
<td>Gnd Plane</td>
<td>-----</td>
<td>30 x 45 x 0.16 cm aluminum sheet, mounted on plywood base.</td>
</tr>
</tbody>
</table>
Fig. 10 Upper photo (a) shows output of generator as first constructed. Lower photo (b) shows output with component location and orientation optimized.
Fig. 11  Ramp generator.
II.3 Step Generator

The step generator is a conventional circuit based on a commercially-available mercury-wetted-contact relay (Fig. 12). A dc power supply provides a bias voltage through a current limiting resistor to a normally open contact of the relay. For the tests performed during this work, the dc voltage level is typically between 100 V and 150 V. A digital voltmeter is used to record accurately the voltage on the normally-open contact. When a pulse is applied to the coil of the relay, the normally-open contact is "instantaneously" shorted to the grounded contact. No attempt is made to determine accurately the actual risetime of the step. Using this generator, however, response times of measurement systems as short as 20-25 ns have been measured. This provides an upper bound on the risetime of the step.

Two operational constraints on this generator should be emphasized. One is the occasionally overlooked fact that for resistor dividers the magnitude of the voltage step must be determined at the relay side of the current-limiting resistor which is between the dc power supply and the relay. For capacitor or series RC dividers, however, the voltage at the power supply is the voltage step.

A second operational difficulty is the fact that the step generator, in order to simulate the high voltage measuring circuit, is usually at least the height of the divider away from the divider base. It is, however, necessary that the ground terminal of the relay remain at the same potential as the base of the divider. Because high voltage laboratory
Fig. 12  Step generator circuit.
grounding systems are designed to accommodate high voltage, high current signals, it is sometimes necessary to make special provisions to insure accurate measurement of the response of the system to a low voltage, low current step.

III. COMPUTER ANALYSIS OUTLINE

III.1 Introduction

The coding required to perform the actual integration is a small fraction of the total program which is required.

First, data are converted to digital form for use by the computer. This is done in either of two ways:

1. Direct conversion using a transient recorder (very fast A/D converter with memory), or,

2. Indirect conversion using oscillographs for recording and subsequent digitizing by means of a graphics tablet with a computer interface.

Next, the digital image of the waveform is converted to a standard format for use by the software. Data from the transient recorder or graphic tablet is entered into computer memory via an interface link.

The data, once in memory, is converted from \((X,Y)\) pairs of coordinates back into time-referred voltage values. After the various data conversion steps are performed, there are many options for dealing with the data sets in computer memory.
In addition to removing dc offsets and correcting algebraic signs of all waveforms, the step response of the divider under test must be normalized to a positive unit-step in order to perform the Duhamel's Integral computation.

To obtain accurate results, the data are smoothed, using a polynomial fitting subroutine called SMOOTH. After these adjustments, a calculation of the system output is performed through application of Duhamel's Integral to the measured input wave and step response.

After calculation of the theoretical output, the measured output is compared using CORRELATE, which calculates the average error and its standard deviation as well as instantaneous percent error. The waveforms involved may also be printed for plotting or further inspection.

The program is structured as a small main program handling filing, input/output, all operator functions, and subroutine control, with most of the numerical work handled by small subroutines. This configuration was found to be quite efficient as well as very easy to debug, maintain, and expand. All permanent data are stored as integers in the main-program in one of 12 columns. Each column has a capacity of 600 data points and a two-column work space is held in common. This limits access to main data storage while allowing free access to workspace.

To conserve limited minicomputer-core space, as well as execution time, all data are held in 1/2 word integer format rather than full-word floating-point despite the loss of accuracy. Thus, each column of data
must have a scale-factor to reconstruct the real value of each data
point. The sample interval and number of samples is read in at the
beginning of a run, and remains constant. The operation of the control
section is interactive, i.e., as each task is finished, control returns
to the operator to select the next task. A string of control commands
may also be prerecorded on a floppy disc for unattended "batch" processing.

III.2 Program Description

The program listing is given in the Appendix of this report. The
purpose of this section is to provide a functional description of the
various tasks performed by the software to clarify the considerations
that went into the data analysis.

The main program and all essential subroutines are written in
Fortran V. The code is specifically intended to be used on a 16-bit
Interdata\textsuperscript{8} minicomputer. It would require minor modifications to be used
with different computers.

The subroutine organization is shown in Fig. 13. A brief functional
description of each of the tasks follows listed by mnemonic and grouped
by activity.

List of Tasks by Mnemonic and Function

Utility (Input/Output)

RE [a]  Read data directly from a mass storage file into memory
        by indicated operand column

WR [a]  Write data to a mass storage file, on logical unit OU,
        from column a
RL      Read file label from logical unit, IU
WL      Write file label on logical unit, OU, after rewind
WR [a]  Write filemark on logical unit a
RF [a]  Rewind logical unit a

Control and Miscellaneous

LA [a]  Label column a (using a 12 character alphanumeric label)
CP [ab] Copy data and labels from column a to column b
IU [a]  Set input logical unit to a
OU [a]  Set output logical unit to a
LU      List units; display values of IU and OU and list all unit numbers assigned by the operating system
PA      Pause into the operating system with easy return
KI      Kill run - returns control to main program entry point; permits change in operating parameters without destroying data memory
EN      End run - close all mass storage files, next logical unit assignments and return to the operating system

Data Input Routines

TA [a]  Tablet data input; reads data in graphics table format, corrects (X,Y) pairs for rotation and scaling, generates a constant-sample-interval data set compatible with main program data array, and stores this in column a. Due to the nature of the input medium and the whole process, great care must be exercised in retracing the scope trace to provide data for this operation. For calibration of the graphic tablet output in terms of photograph divisions, a special procedure is followed: the corners of a 2 cm x 2 cm square from anywhere in the graticule is entered, along with six points along some "baseline", preferably a "ground-line" trace. This is done both before and after data are entered. Data are separated from calibration marks by a pair of points in the same location (before and after data).
This routine automatically scales and corrects the input data for minor trace (baseline) rotation with respect to the tablet axes, gives error messages for unusual conditions, allows for interactive "data-saving" patches during a run, e.g., if it cannot find the proper scaling numbers, or to correct minor errors made at the tablet, uses subroutine XYVDT to convert X,Y pairs to a compatible data set for the rest of the program, and it assumes no pulseshape for operation.

SK [a] Skip 'a' data sets (graphics tablet format) on logical unit IU

XY [a] Reads (X,Y) coordinate pairs from control terminal, converts to standard data set to store in column a. Generates a standard, compatible data set using time and voltage scaling, same as TA (tablet) routine but without leading and trailing automatic scaling, rotation numbers. Input time and voltage scales must be in units of seconds/nib or volts/nib, where 1 nib is the resolution of the table output. It provides a chance to correct errors after data are entered. It also allows observation of the data when the run is finished.

MI [a] Reads data from a Biomation8 B100 Transient Recorder via MIDAS8 interface, stores data in column a

FP Reads data from a transient recorder until the first peak is observed. Prints out the true peak value and the position, virtual risetime and rate-of-rise of impulse.

Data Analysis Routine

PO [abc] If columns a,b represent the voltage and the current in a waveform, column c (output) will represent instantaneous power.

IM [a] Uses subroutine NEARST to locate peak (single maximum value).

Searches before and after an apparent peak to insure that the true peak has been located, calculates the value of the peak and its location in time.

Calculates the virtual risetime which is defined as 1.67 times the time interval between the points which are 30% and 90% of the peak value on the rise of a voltage pulse and as 1.25 times the time interval between the points which are 10% and 90% of the peak value on the rise of a current pulse.
Calculates the virtual rate of rise which is the ratio of the peak value and the virtual risetime.

Calculates the virtual origin which is a time defined as the time at which the voltage waveform reaches 30% of its peak value minus 0.3 times the virtual risetime for a voltage wave and, for a current wave, as the time at which the current waveform reaches 10% of its peak value minus 0.1 times the virtual risetime.

Calculates the virtual fall time which is defined as the time interval between the virtual origin and the time at which either the voltage or current waveform returns to a value of 50% of the peak after the peak has been reached.

SM [ab] Fits the data in column a to a third order polynomial, five points at a time, creating column b (non-destructive).

CO [abc] Calculates the average percent difference and standard deviation between data in columns a and b and stores instantaneous error in column c.

PI [abc] If an input waveform is in column a and a step response in column b, this subroutine uses Duhamel's integral to calculate an output waveform which is in column c.

NO [a] If column a contains a step response, it will be normalized to a positive unit step by altering the scale factor and assuming average of last five data points represents 1. This routine can be used to eliminate dc offsets from a waveform or to normalize the response of a Kerr system.
Auxiliary Subroutines

ROTSCA -- Corrects for rotation and scaling of (X,Y) coordinate data from graphics tablet (used by TA).

XYVDT -- Converts (X,Y) coordinate data set into constant-sample-interval data set for TA and XY routines.

NEARST -- Finds the nearest data point in a column of data to the specified value, returns its location and error.

FIXDTA -- Fits any floating-point data set into an integer column, finds best scale factor.

RELEASE -- Releases interface driver for subsequent use.

MIDAS -- Interface driver, sends one line of commands, one line of data.

CONURT -- Converts interface ASCII output to 16-bit integer, reconstructs transient recorder output.

WAIT -- Interrupts operating system, waits for operator to press 'RUN' button on front panel of CPU.

CLOSE -- Closes all mass storage files.

SYSTEM -- Allows a FORTRAN program to execute operating system instructions by passing them through this routine as a character string.
READ 1 -- Reads one character from logical unit 5 and returns to
program without carriage return.

IV. EXPERIMENTAL MEASUREMENTS

IV.1 Introduction

A series of measurements was performed in the high voltage laboratory
of the Bonneville Power Administration (BPA), Vancouver, Washington. During
these measurements, the primary measurement devices were three high voltage
dividers. One was the resistor divider, rated at one million volts, which
was described earlier. For convenience of notation, this divider is
referred to as NBS-1.

The second divider was a resistor divider owned by the Bonneville
Power Administration. This divider, which is referred to as BPA-R, is
approximately 6.5 m tall and consists of counterwound resistor sections
in a porcelain enclosure. Either one of two low-side resistances could
be selected. Measured resistance values for this divider are presented
in Table 3.

TABLE 3: MEASURED RESISTANCES DIVIDER BPA-R

<table>
<thead>
<tr>
<th></th>
<th>Value from earlier BPA data</th>
<th>Value measured using BPA bridge during test period</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Impedance Element</td>
<td>11630 Ω</td>
<td>11616 Ω</td>
</tr>
<tr>
<td>Low Impedance Element #1</td>
<td>43.88 Ω</td>
<td>44.05 Ω</td>
</tr>
<tr>
<td>Low Impedance Element #2</td>
<td>14.64 Ω</td>
<td>---</td>
</tr>
</tbody>
</table>
The third divider referred to as BPA-C, is a mixed (RC) divider approximately 15 m high and rated at 4.5 MV, shown schematically in Fig. 14. The high impedance element consists of a number of identical resistor-capacitor units in series, each unit consisting of a 2250 pF capacitor and a 50 Ω resistor (these values were provided by the manufacturer and not reverified as a part of this investigation). The series capacitance had been measured by the BPA staff to be 433.43 pF. The primary components of the low impedance element are a resistive and capacitive element bolted to the base of the divider, a cable -- with impedance matching series resistor R located at the divider -- to connect the divider to the oscilloscope, and the cable termination located at the input to the oscilloscope.

The capacitance at the base of the divider $C_L$, has a value 0.9641 μF. The resistance $R_L$ is zero, a modification which was apparently performed after the original construction of the divider. The individual resistors which originally constituted this resistance were still in place but had been shunted by soldered pieces of wire. The cable-matching resistor had a value of 50.48 Ω.

The terminator is a series of switch-selectable circuits, three of which are shown in Fig. 14. Switch position (1) permits direct connection of the cable to the oscilloscope input. Position (2) applies a terminator as shown. The remaining switch positions select other terminator-attenuator combinations. All terminators were designed to have nominal equivalent single series RC elements of 0.95 μF and 50 Ω.
Fig. 14  Mixed divider (RC) with cable termination.
The divider ratio for a variety of divider terminator settings was determined at low voltage from the capacitance ratio. The calculated values are given in Table 4 along with the ratio determined from the step response at the one setting at which step response measurements were performed.

**TABLE 4: BPA-C DIVIDER RATIO MEASUREMENTS**

<table>
<thead>
<tr>
<th>Nominal Ratio</th>
<th>Ratio from Capacitance Measurements</th>
<th>Ratio from Step-Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>2334</td>
<td>--</td>
</tr>
<tr>
<td>4000</td>
<td>4636</td>
<td>4570</td>
</tr>
<tr>
<td>8000</td>
<td>9272</td>
<td>--</td>
</tr>
<tr>
<td>10000</td>
<td>11115</td>
<td>--</td>
</tr>
<tr>
<td>14000</td>
<td>16191</td>
<td>--</td>
</tr>
<tr>
<td>20000</td>
<td>23197</td>
<td>--</td>
</tr>
</tbody>
</table>

Table 4 shows that all the calculated ratios and the one ratio determined from the step-response are significantly different from the corresponding nominal ratios. This may be due to a modification of the divider's low-side after its manufacture. The difference between the ratio determined from capacitance measurements and that determined from the step-response (1.4%) is within the combined uncertainties of the two measurements.

During the two one-week test periods the following measurements were performed:

- step response of NBS-1
- step response of BPA-R
- step response of the combination of NBS-1 and BPA-R
- ramp response of the combination of NBS-1 and BPA-R
- step response of BPA-C
- step response of the combination of NBS-1 and BPA-C
- ramp response of the combination of NBS-1 and BPA-C.

Each of these measurements are described individually in the following sections.

IV.2 Step Response of NBS-1

The step-response of NBS-1 was measured in both BPA indoor high-voltage laboratories. The response time and divider ratio were consistent with those measured at NBS.

IV.3 Step Response of BPA-R

Step response measurements with various values of damping resistor are shown in Fig. 15. Note that for low values of the damping resistor two types of oscillation are apparent. One is a lower-frequency oscillation -- about 4 MHz -- attributable to a resonance between the lead inductance and divider capacitance which the damping resistor of higher value removes. The higher frequency oscillation -- about 30 MHz -- is apparently intrinsic to the divider.

In an effort to insure that the measured response was the true response to a voltage step and not due to an error in the design and/or construction of the test circuit, a variety of checks were made. A number of different configurations of the connections of the various devices to the ground mat were attempted. As a general observation, changes in the
Fig. 15 Typical step responses of BPA-R.
ground configuration produced slight changes in the high frequency oscillations, but no change yielded a substantive improvement. In addition, the following steps were taken:

- the stranded high voltage lead was replaced by a solid high voltage lead;

- tests were made in which the location of the cable connecting the divider to the oscilloscope was changed;

- an isolation transformer, provided by BPA, was used to separate the oscilloscope from the power system ground;

- an isolation transformer was used to separate the ground of the dc power supply from the power system ground.

None of these adjustments produced a significant modification of the high frequency oscillations.

IV.4 Step Response of the Combination of NBS-1 and BPA-R

One of the measurements performed was the simultaneous recording of the same waveform using the two different dividers. One purpose of these tests was to insure that the signal in one measuring circuit did not influence the response of the other measuring circuit. Using the circuit shown in Fig. 16, the following measurements were performed:
- the step response of NBS-1 with BPA-R disconnected from the step generator, i.e., the measurement circuit was open at the step generator, and the BPA-R measurement loop was grounded at the step generator;

- the step response of BPA-R with NBS-1 open and with NBS-1 grounded at the step generator;

- the simultaneous step responses with both measurement systems connected to the step generator.

No difference in the step response was discernible in any of the configurations. This was the anticipated result.

IV.5 Ramp Response of the Combination of NBS-1 and BPA-R

The same sequence of measurements outlined above was performed with the step generator replaced by the low-voltage ramp generator. The significant result of these measurements is shown by the photographs in Fig. 17. These photographs show a simultaneous measurement of the same ramp using NBS-1 and BPA-R. Note the high frequency oscillations in the measurement using BPA-R. It is assumed that these are due to the same source as the high frequency oscillations in the step response. From
Simultaneous Measurements

NBS-1
5 mV/Div Vertical
200 ns/Div Horizontal

BPA-R
100 mV/Div Vertical
200 ns/Div Horizontal

Fig. 17 Input ramp (upper photo) and response of BPA-R (lower photo).
the response of NBS-1, it can be seen that the ramp is chopped approximately 1.2 $\mu$s after the pulse is initiated. The oscillations in the BPA-R measurement system, therefore, persist into the time domain relevant for tests on power system apparatus. Information provided by the staff of BPA indicated that these oscillations are also apparent during high voltage tests using a standard lightning impulse and so are not merely an artifact of the low voltage calibration procedure.

Because the oscillations are apparently intrinsic to the BPA-R measurement system, and because they persist throughout the time domain of interest for these tests, it was concluded that this measurement system was inappropriate for the $\pm 3\%$ accuracy desired in these tests. For that reason the remainder of the experimentation and analysis was performed using BPA-C.

IV.6 Step Response of BPA-C

The step response of BPA-C was measured in the outdoor test area. The experimental arrangement is shown in Fig. 18. Measurements were made using damping resistors having values of 0, 61, 103, 141, 184, 269, and 451 $\Omega$. A plot of the response time vs. damping resistance is shown in Fig. 19. The slope of the least-squares fit to the data points indicates that the input capacitance of the divider is $780 \pm 40$ pF. The input capacitance was also measured using a capacitance bridge. In the square loop arrangement -- the arrangement in which the step response was measured -- the input capacitance was 820 pF. If the high voltage lead is run along a
Fig. 19  Response time of BPA-C as a function of damping resistance.
diagonal of the original square loop, the input capacitance is 790 pF. Because the disagreement between the input capacitance as determined from the step response and as measured using bridge techniques is somewhat larger than anticipated, it was judged to be prudent to attempt to identify the source of the difference.

An examination of the step response data, Fig. 20, shows that there is a difference between the level at which the step was triggered and the position of the zero line as evidenced by a vertical gap of about 5 mV between the base line and the start of the step trace. An investigation of the circuit indicated that there is a 60 Hz signal with peak-to-peak amplitude of approximately 6 mV appearing on the oscilloscope screen with no input signal applied to the divider, Fig. 21a. If everything is left in the same physical location but the divider low-side is electrically disconnected from the divider high-side, the signal amplitude is reduced to about 3 mV peak-to-peak, Fig. 21b. If the low-side is reconnected to the divider, but the ground connection is broken, the peak-to-peak amplitude of the 60-Hz signals is 3 mV, Fig. 21c. From these data, it is inferred that approximately equal signals are coming from the divider and from pick-up in the low-side and connecting cables. There are a variety of 60-Hz sources in the vicinity of the outdoor laboratory including a non-interruptable 13.8 kV supply line about 18-20 m from the divider.

As a result of this investigation, it was concluded that it was not feasible to perform a low-voltage calibration of the divider in the outdoor test area, so the divider was moved inside the high voltage laboratory.
$R_D = 184\, \Omega$

10 mV/Div Vertical

500 ns/Div Horizontal

Fig. 20  Typical step response of BPA-C during outdoor tests.
Fig. 21 Output of divider with no input (a); output with only the divider low-side and cable connected to the oscilloscope (b); output with shield of cable open-circuited at divider.
The physical arrangement of the divider in the laboratory is shown in Fig. 22. In this configuration, the measured input capacitance was 790 pF. In the indoor laboratory, the 60-Hz signal was negligible and to within experimental uncertainty the response time of the measuring circuit was the product of the input capacitance of the divider, as measured by the capacitance bridge -- and the value of the damping resistor. This result indicates that the low-voltage measuring system is behaving in a manner consistent with the theoretical model used for system calibration.

IV.7 Step Response of the Combination of NBS-1 and BPA-C

Before BPA-C was moved into the indoor laboratory, step responses were recorded in the outdoor test area using the measurement circuit shown in Fig. 18. Again the following measurements were performed:

- step response of BPA-C with NBS-1 grounded and "open" at the step generator;

- step response of NBS-1 with BPA-C grounded and "open" at the step generator;

- simultaneous responses of both NBS-1 and BPA-C to the same voltage step.

As before, no interaction between the two circuits was observed. As described in the previous section, the induced 60-Hz signal in the system made this data unsuitable for quantitative analysis. Because both
Fig. 22 Experimental arrangement for indoor step-response measurements of BPA-C.
these data and the measurements taken using NBS-1 and BPA-R indicated no interaction between the circuits, this set of measurements was not repeated in the subsequent indoor tests. Step responses of the dividers in the high voltage laboratory were, of course, measured and are shown in Fig. 23.

IV. 8 Ramp Response of the Combination of NBS-1 and BPA-C

Ramp responses were obtained using both high and low voltage ramps. These responses were used to perform the calculations described in the next section of this report.

The low voltage ramp measurements were identical to those performed using NBS-1 and BPA-R, described above. Typical data showing the ramp measured with NBS-1, BPA-C and directly measured using a low-voltage attenuator are shown in Fig. 24.

The circuit for the measurement with the high voltage ramp is shown in Fig. 25. A conventional Marx generator applied a high voltage pulse to a sphere gap. The voltage across the sphere gap was measured using both NBS-1 and BPA-C. High voltage damping resistors were constructed and were used in each measuring circuit. The high voltage ramp responses of the two measuring systems in the high voltage configuration using the high voltage damping resistors are shown in Fig. 26.

V. DUHAMEL'S INTEGRAL CALCULATIONS

To verify that the measuring system is well characterized, it is necessary to insure that Duhamel's Integral computation of the output waveform predicts the measured waveform.
Fig. 23  Step responses of BPA-C and NBS-1 inside high voltage laboratory.
Low Voltage Ramp Measurements

BPA-C

NBS-1

Direct

Fig. 24 Ramp measured with BPA-C, NBS-1, and directly from generator (simultaneous measurements).
Fig. 26 Typical ramp responses of BPA-C and NBS-1 (simultaneous measurements).
Data from three different experimental set-ups are summarized in Table 5. The first set of data was taken with a low voltage ramp measured simultaneously using the divider BPA-C and a low-voltage attenuator. The Duhamel's Integral calculation used the step response of BPA-C, measured in the experimental configuration, and the directly measured waveform to calculate the output waveform from BPA-C. Measured and calculated outputs are compared in columns 2-4.

The second set of data presented is the result of a simultaneous measurement of a low-voltage ramp using NBS-1 and BPA-C. In this case it is assumed that the waveform as measured by NBS-1 is the input to BPA-C. The comparison between the calculated and measured outputs is shown in columns 5-7.

The final set of data is the result of a simultaneous measurement of a high-voltage ramp using NBS-1 and BPA-C. Again it is necessary to assume that the output waveform from NBS-1 is the input waveform to BPA-C. These results are presented in columns 8-10.

The magnitude of the average difference obtained is within expected experimental uncertainty. Each calculation required four measurements -- the step response of each divider and the ramp response of each divider. The step response was needed both to determine the divider ratios and to perform the integration. The ramp was recorded and digitized for the integration and transcription of results. The accuracy of recording and transcription is estimated to be of order 1%, so an average difference of less than about 2% is probably coincidental.
<table>
<thead>
<tr>
<th>Time (µs)</th>
<th>Calculated Output (V)</th>
<th>Measured Output (V)</th>
<th>Difference % of Peak</th>
<th>Calculated Output (V)</th>
<th>Measured Output (V)</th>
<th>Difference % of Peak</th>
<th>Calculated Output (kV)</th>
<th>Measured Output (kV)</th>
<th>Difference % of Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>20.7</td>
<td>23.7</td>
<td>-1.0</td>
<td>9.6</td>
<td>15.8</td>
<td>-2.0</td>
<td>25.0</td>
<td>19.5</td>
<td>+1.8</td>
</tr>
<tr>
<td>0.3</td>
<td>40.1</td>
<td>40.7</td>
<td>-0.2</td>
<td>27.1</td>
<td>36.4</td>
<td>-3.0</td>
<td>46.4</td>
<td>41.3</td>
<td>+1.7</td>
</tr>
<tr>
<td>0.4</td>
<td>61.8</td>
<td>63.0</td>
<td>-0.4</td>
<td>46.9</td>
<td>58.9</td>
<td>-3.8</td>
<td>93.1</td>
<td>88.2</td>
<td>+1.6</td>
</tr>
<tr>
<td>0.5</td>
<td>88.0</td>
<td>87.1</td>
<td>+0.3</td>
<td>68.1</td>
<td>85.6</td>
<td>-5.6</td>
<td>124.0</td>
<td>121.0</td>
<td>+1.0</td>
</tr>
<tr>
<td>0.6</td>
<td>118.0</td>
<td>115.0</td>
<td>+1.0</td>
<td>94.4</td>
<td>106.0</td>
<td>-3.7</td>
<td>154.0</td>
<td>154.0</td>
<td>---</td>
</tr>
<tr>
<td>0.7</td>
<td>153.0</td>
<td>148.0</td>
<td>+1.6</td>
<td>126.0</td>
<td>137.0</td>
<td>-3.5</td>
<td>176.0</td>
<td>181.0</td>
<td>-1.7</td>
</tr>
<tr>
<td>0.8</td>
<td>190.0</td>
<td>184.0</td>
<td>+2.0</td>
<td>160.0</td>
<td>166.0</td>
<td>-1.9</td>
<td>210.0</td>
<td>207.0</td>
<td>+1.0</td>
</tr>
<tr>
<td>0.9</td>
<td>230.0</td>
<td>220.0</td>
<td>+3.2</td>
<td>197.0</td>
<td>195.0</td>
<td>+0.6</td>
<td>233.0</td>
<td>233.0</td>
<td>---</td>
</tr>
<tr>
<td>1.0</td>
<td>271.0</td>
<td>260.0</td>
<td>+3.0</td>
<td>234.0</td>
<td>232.0</td>
<td>+0.6</td>
<td>254.0</td>
<td>257.0</td>
<td>-1.0</td>
</tr>
<tr>
<td>1.1</td>
<td>311.0</td>
<td>399.0</td>
<td>+4.0</td>
<td>273.0</td>
<td>272.0</td>
<td>+0.3</td>
<td>278.0</td>
<td>278.0</td>
<td>---</td>
</tr>
<tr>
<td>1.2</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>312.0</td>
<td>313.0</td>
<td>+0.3</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

Average Difference  1.7%  Average Difference  2.3%  Average Difference  0.9%
VI. CONCLUSIONS

The data presented indicate that, under the conditions of this test, a Duhamel's Integral calculation is valid for a 4.5 MV divider. From this it can be inferred that the measured response of this divider to a low voltage step provides sufficient information about the transfer function of the measurement system to predict the response to the specific pulses used in this test.

Although this is a significant first step, more work remains to completely characterize the measuring system. Specific individual investigations which would be desirable include:

- measurements of higher voltage, faster ramps where the higher time rate of change of the current may provide more significant coupling between the voltage generating circuit and either of the two measuring circuits;

- development of methods to evaluate the transfer functions of the measurement systems outdoors in situations where the 60-Hz signals make low voltage measurements unfeasible;

- development of more convenient calibration methods which will permit rapid recalibration of the measurement system in each configuration used in an industrial laboratory.
The necessity to develop fast, convenient, accurate methods to evaluate measurement system behavior cannot be overemphasized. A change in divider location or in lead configuration significantly changes the divider ratio. For large dividers, such as the one tested here, variations of the ratio of several percent can occur for the measurement of the peak value of a standard lightning impulse. For faster pulses, even very small changes in the circuit configuration may have significant impact on the divider ratio. It is, therefore, necessary to verify the magnitude of the ratio in each configuration of the measurement circuit.

The low-voltage step response method used here (presented in the standard IEEE-4), although proven to be correct in this application, requires very accurate low voltage measurements under adverse circumstances. Routine application of the technique, therefore, requires experienced, highly trained measurement specialists. Until improved calibration methods are proven to be accurate, industrial high voltage laboratories will be forced to develop specific training programs for laboratory staff or tolerate unspecified, but probably significant, measurement errors.

VII. REFERENCES


8. Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.
APPENDIX 1

LISTING OF SOFTWARE USED FOR
DATA ANALYSIS
INTEGER*2 NA(600,12)
REAL DV(12), DATE(5), XNAME(5), COLAB(12,3)
COMMON /SCRAT/WORK(600)
IMPICIT INTEGER*2 (1-N)

1001 LOU=2
LIU=1
WRITE(6,101)
101 FORMAT('ENTER DATE, TIME, N, DT')
READ(5,102)DATE,N,DT
102 FORMAT(A3,14,E10.3)
IF(N.GT.600)WRITE(6,114)N
114 FORMAT('N GREATER THAN 600 = ',14,' OVERLAP WILL OCCUR ****')
WRITE(6,102)DATE,N,DT
1000 WRITE(6,103)
103 FORMAT('Y')
READ(5,104)12,K1,K2,K3
104 FORMAT(A2,1X,321)
WRITE(6,104)12,K1,K2,K3
IF(K1.GT.12.OR.K2.GT.12.OR.K3.GT.12)GOTO 21
IF(I2.NE.'SM'.OR.K1.EQ.K2)GOTO 1
DV(K2)=DV(K1)
CALL SMOOTH(NA(1,K1),NA(1,K2),N)
GOTO 1000
1 IF(I2.NE.'CO')GOTO 2
CALL CORREL(NA(1,K1),NA(1,K2),DV(K1),DV(K2),N)
DO 116 I=1,N
NA(I,K3)=1/FIX(WORK(I)*1000.)
116 CONTINUE
DV(K3)=1.
GOTO 1000
2 IF(I2.NE.'DI'.OR.K3.EQ.0)GOTO 3
D3=DV(K1)*DV(K2)
CALL DUHAME(NA(1,K1),NA(1,K2),N,D3)
CALL FIXDTA(NA(1,K3),DV(K3),N)
GOTO 1000
3 IF(I2.NE.'IM')GOTO 4
CALL IMPULS(NA(1,K1),N,DV(K1),DT)
GOTO 1000
4 IF(I2.NE.'HO')GOTO 45
CALL NORMAL(NA(1,K1),N,DV(K1))
GOTO 1000
45 IF(I2.NE.'PO')GOTO 5
D3=DV(K1)*DV(K2)
DO 46 I=1,N
WORK(I)=D3*NA(I,K1)*NA(I,K2)
46 CONTINUE
CALL FIXDTA(NA(1,K3),DV(K3),N)
GOTO 1000
5 IF(I2.NE.'MI')GOTO 6
CALL IMPULS(NA(1,K1),N,DV(K1))
GOTO 1000
5 IF(I2.NE.'PI')GOTO 6
IF(12.NE.,'FP') GOTO 7
CALL FASTPK
GOTO 1000
IF(12.NE.,'TA') GOTO 9
CALL FITAB(LIU,NA(1,K1),N,DV(K1),DT)
GOTO 1000
IF(12.NE.,'SK') GOTO 85
CALL SKIP(LIU,K1)
GOTO 1000
IF(12.NE.,'XY') GOTO 9
CALL XYDATA(NA(1,K1),N,DV(K1),DT)
GOTO 1000
IF(12.NE.,'RE') GOTO 95
READ(LIU,109)(COLABL(K1,J),J=1,3),DV(K1)
READ(LIU,110)(NA(I,K1),I=1,N)
FORMAT(1116)
GOTO 1000
IF(12.NE.,'LA') GOTO 10
WRITE(6,106)
FORMAT('ENTER LABEL (12 CHARs.)')
READ(5,115)(COLABL(K1,J),J=1,3)
FORMAT(3A4)
GOTO 1000
IF(12.NE.,'UR') GOTO 11
WRITE(LOU,109)(COLABL(K1,J),J=1,3),DV(K1)
WRITE(LOU,110)(NA(I,K1),I=1,N)
GOTO 1000
IF(12.NE.,'RL') GOTO 12
READ(LIU,111)DATE,XNAME,NC,N1,DT1
FORMAT(5A3,5A4,12,14,E12.5)
WRITE(6,111)DATE,XNAME,NC,N1,DT1
GOTO 1000
IF(12.NE.,'WL') GOTO 13
REWRITE
WRITE(6,112)
FORMAT('ENTER NUMBER OF DATA SETS (12), Filename (20)')
READ(5,113)NC,XNAME
FORMAT(12,5A4)
WRITE(LOU,111)DATE,XNAME,NC,N,DT
GOTO 1000
IF(12.NE.,'LU') GOTO 14
CALL SYSTEM('LU',2)
WRITE(6,105)LIU,LOU
FORMAT('INPUT UNIT=',21,' OUTPUT UNIT=',21)
GOTO 1000
IF(12.NE.,'CP') GOTO 15
DV(K2)=DV(K1)
DO 141 I=1,N
C ***** SKIP II DATA SETS ON TABLET FILE *****
DE 2 I=1,II
1 READ(LU,401)NEOD,NX,NX,NX,NX,NX,NX,NX,NX,NX
   401 FORMAT(A1,16.7(1X,16))
      IF(NEOD.EQ.'.')GOTO 1
      READ(LU,402)N,XSCALE,YSCALE
   402 FORMAT(14,2E10.3)
      WRITE(6,402)N,XSCALE,YSCALE
2 CONTINUE
RETURN
END

SKIP   FUNC/SUB
  0   EXT FUNC
  .P   EXT FUNC
  LU   FORM PAR
  II   FORM PAR
  NX   INT2 VAR
  2   LABEL
  I   INT4 VAR
  1   LABEL
  401  LABEL
  0H   EXT FUNC
  NEOD  INT4 VAR
  402  LABEL
  N   INT4 VAR
  XSCALE  REAL VAR
  YSCALE  REAL VAR
SUBROUTINE XYDATA(NA,N,DV,DT)
C ****** GENERATE (X,Y) DATA SET, CONVERT TO (V,DT) ******
INTEGER*2 NA(600), N
REAL DV, DT
IMPLICIT INTEGER*2 (I-N)
COMMON /SCRAT/NBX(600), NBY(600)
WRITE(6,101)
101 FORMAT('ENTER NO. OF POINTS, TIME AND VOLTAGE SCALES, DATA')
READ(5,102)N1, DT1, DV
102 FORMAT(13,2E10.3)
DT1=DT/DT1
READ(5,103)(NBX(I), NBY(I), I=1,N1)
103 FORMAT(1X, IS, 1X, IS)
WRITE(6,104)(NBX(I), NBY(I), I=1,N1)
104 FORMAT(4(' ',215,3X))
1 WRITE(6,105)
105 FORMAT('CHANGE A PAIR?')
CALL READ(NY)
IF(NY.EQ. 'N')GOTO 2
IF(NY.EQ. 'Y')GOTO 3
WRITE(6,104)(NBX(I), NBY(I), I=1,N1)
3 WRITE(6,106)
106 FORMAT('ENTER I.X,Y')
READ(5,107)I1, NX, NY
107 FORMAT(13,1X, IS, 1X, IS)
NBX(I1)=NX
NBY(I1)=NY
GOTO 1
2 CALL XYVD(NA,N,N1, DT1)
RETURN
END
XYDATA  FUNCTION
.O  EXTFUNC
.P  EXTFUNC
NA  FORMPAR
N  FORMPAR
DV  FORMPAR
DT  FORMPAR
SCRAT COMMON X'0960'
NBX  INT2VAR
NBY  INT2VAR
101 LABEL 0H  EXTFUNC
102 LABEL 1H  EXTFUNC
103 LABEL 1 INT2VAR
DT1  REAL VAR
104 LABEL 1 INT2VAR

SUBROUTINE MREAD(NA,N,DV)
C **** MIDAS-READING ROUTINE ****
INTEGER*2 NA(600),NCMD(8),N
IMPLICIT INTEGER*2 (1-N)
WRITE(6,503)
503 FORMAT('ENTER D.R. V. SCALE')
READ(5,505)DR,DV
505 FORMAT(2E10.3)
DV=DV*DR/128.
WRITE(6,504)
504 FORMAT(' P U S H "R U N" B U T T O N W H E N R E A D Y ')
53 CALL WAIT
DO 51 I=1,N
CALL MIDAS(34,NCMD,NA(I),2,NSTAT)
DATA NCMD/'2343','T1','T2','R','S8','T3','B1','0 '/
CALL CONVRT(NA(I),2)
IF(NSTAT.EQ.0)GOTO 51
WRITE(6,501)NSTAT,1
501 FORMAT('MIDAS ERROR ',I3,' AT ',I4)
GOTO 53
51 CONTINUE
CALL RELEASE(34)
RETURN
END
MREAD SUB FUNC
.0 EXT FUNC
.P EXT FUNC
NA FORM PAR
N FORM PAR
DV FORM PAR
NCMD INT2 VAR
503 LABEL
5H EXT FUNC
505 LABEL
DH REAL VAR
504 LABEL
53 LABEL
WAIT EXT FUNC
51 LABEL
I INT2 VAR
MIDAS EXT FUNC
NSTAT INT2 VAR
CONVRT EXT FUNC
501 LABEL
RELEASE EXT FUNC
SUBROUTINE FASTPK
C **** FAST PEAK-FINDING ROUTINE ****
INTEGER*2 NOCMD(8)
IMPLICIT INTEGER*2 (I-N)
COMMON /SCRAT/NA(1200)
WRITE(6,503)

503 FORMAT('ENTER D.R., V. SCALE, T. SCALE')
READ(5,505)DR,DV,DT

505 FORMAT(3E10.3)
DV=DV*DR/128.
WRITE(6,504)

504 FORMAT(' PUSH "RUN" BUTTON WHEN READY')
CALL WAIT
DO 42 I=1,1200
CALL MIDAS(34,NOCMD,NA(I),2,NSTAT)
DATA NOCMD/'2343','T1','T2','R','S0','T3','B1','0 '/
CALL CONVT(NA(I),2)
IF(NSTAT.EQ.0)GOTO 43
WRITE(6,501)NSTAT,I

501 FORMAT(' MIDAS ERROR =',I3,' AT ',I4)
GOTO 41

43 DO 42 J=1,10
J1=I-J
IF(J1.LT.0.OR.NA(I).GT.NA(J1))GOTO 42
GOTO 44

42 CONTINUE
WRITE(3,507)I,NA(I)

507 FORMAT(' NO PEAK FOUND--',I4,I6)

44 ND3=1
ND5=1/2
DO 45 I=ND5,ND3
DO 46 J=1,ND5
J1=I-J
ND2=MINT2(I+J,ND3)
IF(NA(I).LE.NA(J1).OR.NA(I).LT.NA(ND2))GOTO 45

46 CONTINUE
DO 47 J=1,10
J1=I-J
IF(NA(I).NE.NA(J1))GOTO 48

47 CONTINUE

45 CONTINUE

48 V=DV*NA(I)
TIME=DT*ND3
NDATA=IFIX(0.3*ND3)
CALL NEAREST(NA,NDATA,NEAR,1,ND3,LOC1)
WRITE(6,505)NEAR,LOC1,NA(LOC1)
NDATA=IFIX(0.9*ND3)
CALL NEAREST(NA,NDATA,NEAR,1,ND3,LOC2)
WRITE(6,506)NEAR,LOC2,NA(LOC2)

506 FORMAT(1X,I6,1X,I4,1X,I6)
SUBROUTINE ROTSCA(N,SCALE,DXSCALE,DT,K)
C**** CALCULATE ROTATION, SCALING FOR DATA FROM TABLET ****
INTEGER*2 N
LOGICAL K
IMPLICIT INTEGER*2 (I-N)
COMMON /SCAT/COX(600),COY(600)
ROUND(A)=IFX(2.*A+1.)/2
K=.FALSE.
N=N-24
N2=13
IF(IABS(NBY(N+13)-NBY(N+14)).LE.1.AND.IABS(NBY(N+13)-NBY(N+14))
1.LE.1)GOTO 1
J1=N+9
J2=N+24
WRITE(6,101)(NBX(J),NBY(J),J=1,20),(NBX(J),NBY(J),J=J1,J2)
101 FORMAT(1X,16)
WRITE(6,102)N,N2
102 FORMAT(4,' PAIRS START AT ',4,' ENTER NEW LIMITS')
READ(5,103)N,N2
103 FORMAT(214)
1 X1=XSCALE*8./((NBX(3)-NBX(1))-NBX(4)-NBX(1))
Y1=YSCALE*8./((NBX(2)-NBX(1))+NBX(3)-NBX(4))
J1=N+N2+2
X2=XSCALE*8./((NBX(J1+2)-NBX(J1+1)+NBX(J1+3)-NBX(J1))
Y2=YSCALE*8./((NBX(J1+1)-NBX(J1)+NBX(J1+2)-NBX(J1+3))
J1=J1+4
X3=0.
Y3=0.
DO 2 J=1.5
J2=J1+J
Y2=Y3+FLOAT(NBY(J2)-NBY(J1))/(NBX(J2)-NBX(J1))
J2=J+5
X3=X3+FLOAT(NBY(J2)-NBY(5))/(NBX(J2)-NBX(5))
2 CONTINUE
X3=X3/5.
Y3=Y3/5.
WRITE(6,104)X3,X1,Y1,Y3,X2,Y2
104 FORMAT(5,'BEFORE',5,'AFTER ',5,'OK?')
CALL READ1(NY)
IF(NY.EQ.'R')RETURN
IF(NY.EQ.'Y')GOTO 5
IF(NY.EQ.'B')GOTO 3
X2=X1
Y2=Y1
Y3=X3
GOTO 5
3 IF(NY.EQ.'A')GOTO 4
X1=X2
GOTO 5
WRITE(6,105)X1,X2,Y1,Y3,X3,Y2
105 FORMAT(5,'BEFORE',5,'AFTER ',5)
4 WRITE(6,102)N,N2
READ(5,103)N,N2
GOTO 5
5 DT=DT*2./ABS(X1+X2)
   YSCALE=(Y1+Y2)/2.
   X3=ATAN((X3+Y3)/2.)
   IF(NY.NE.*2.*)GOTO 6
   DT=DT*2.
   YSCALE=YSCALE/2.
6 X4=COS(X3)
   Y4=SIN(X3)
   X5=X4*NBX(N2)+Y4*NBY(N2)
   Y5=X4*NBX(N2)-Y4*NBX(N2)
   N2=N2+1
   DO 7 I=1,N
      J1=N2-I
      NBX(I)=IROUND(X4*NBX(J1)+Y4*NBY(J1)-X5)
      NBV(I)=IROUND(X4*NBX(J1)-Y4*NBX(J1)-Y5)
7 CONTINUE
   RETURN
   END

ROTSCA  FUNC/SUB
   Q  EXT   FUNC
   P  EXT   FUNC
   N  FORM  PAR
   XSACE  FORM  PAR
   YSCALE  FORM  PAR
   DT  FORM  PAR
   K  FORM  PAR
SCRAT  COMMON  X'0960'
   NBX  INT2  VAR
   NBV  INT2  VAR
   IROUND  STATE  FH
   A  FORM  PAR
   IFIX  EXT  FUNC
   N2  INT2  VAR
   IABS  EXT  FUNC
   IABS2  EXT  FUNC
   I  LABEL
   J1  INT2  VAR
   J2  INT2  VAR
   101  LABEL
   @H  EXT  FUNC
   J  INT2  VAR
   102  LABEL
   103  LABEL
   X1  REAL  VAR
SUBROUTINE IMPULS(NA,N,DT)
INTEGER*2 NA(600),N
IMPLICIT INTEGER*2 (I-N)
IROUND(A) = (IFIX(2.*A)+1)/2
CALL NEARST(NA,32767,NEAR,1,N,LOC1)
LOC2K=LOC1/2
DO 34 I=LOCPK,N
DO 32 J=1,LOCPK
ISRC=I-J
JSRC=MINO2(I+J,N)
IF(NA(I).LE.NA(ISRC).OR.NA(I).LT.NA(JSRC))GOTO 34
32 CONTINUE
DO 33 J=1,10
ISRC=I-J
IF(NA(I).NE.NA(ISRC))GOTO 35
33 CONTINUE
WRITE(6,310)
WRITE(6,310)
CALL READ1(HWAVE)
IF(HWAVE.NE.'V'.AND.HWAVE.NE.'I')GOTO 35
WRITE(6,308)LOC1,LOCPK,IPAKE
308 FORMAT('1X,14.1X,14,'PEAK ={16/'ERROR LOC. VALUE'}')
JSRC=IROUND(0.3*IPAKE)
IF(HWAVE.EQ.'I')JSRC=IROUND(0.3*IPAKE)
CALL NEARST(NA,JSRC,NEAR,1,LOCPK,LOC1)
WRITE(6,309)NEAR,LOC1,NA(LOC1)
309 FORMAT('1X,14.1X,14,1X,14)
JSRC=IROUND(0.9*IPAKE)
CALL NEARST(NA,JSRC,NEAR,1,LOCPK,LOC2)
WRITE(6,309)NEAR,LOC2,NA(LOC2)
TRISE=1.67*(LOC2-LOC1)*DT
IF(HWAVE.EQ.'I')TRISE=1.25*(LOC2-LOC1)*DT
RATE=DV*IPAKE/TRISE
TORG=DT+LOC1-0.3*TRISE
IF(HWAVE.EQ.'I')TORG=DT+LOC1-0.1*TRISE
JSRC=IROUND(0.5*IPAKE)
CALL NEARST(NA,JSRC,NEAR,1,LOCPK,LOC1)
WRITE(6,309)NEAR,LOC1,NA(LOC1)
THALF=DT+LOC1-TORG
VPEAK=DV*IPAKE.
ENERGY = ENERGY + (NA(1) * NA(1) * D)

36 CONTINUE

WRITE(6,312) VPEAK, TRISE, RATE, TORIG, THALF, ENERGY

312 FORMAT('PEAK VALUE=', E12.5, 'VIRTUAL FRONT TIME=', E12.5, 'RATE-
10F-RISE=', E12.5, 'VIRTUAL ORIGIN=', E12.5, 'V. FALL TIME=', E12.5,
2'ONE-OHM ENERGY=', E12.5, ' JOULES')

39 RETURN

END

IMPULS FUNC/SUB

.IQ EXT FUNC

.P EXTRUN FUNC

.NA FORM PAR

.NH FORM PAR

.DV FORM PAR

.DT FORM PAR

.IROUND STATE FN

.A FORM PAR

.IFIX EXT FUNC

.NEARST EXT FUNC

.NEAR INT2 VAR

.LOC1 INT2 VAR

.LOCPK INT2 VAR

34 LABEL

.I INT2 VAR

32 LABEL

.J INT2 VAR

.ISRCH INT2 VAR

.JSRCH INT2 VAR

.MIN02 EXT FUNC

33 LABEL

35 LABEL

307 LABEL

30H EXT FUNC

39 LABEL

.IPEAK INT2 VAR

318 LABEL

.READ1 EXT FUNC

.MJAVE INT2 VAR

309 LABEL

309 LABEL

.LOC2 INT2 VAR

.TRISE REAL VAR

.RATE REAL VAR

.TORIG REAL VAR

.THALF REAL VAR

.VPEAK REAL VAR

.D REAL VAR

36 LABEL
SUBROUTINE SMOOTH(NA1,NA2,N)
C     SMOOTH TO 5TH DEGREE POLYNOMIAL  ***  MOD 24 JUL 78
INTEGER*2 NA1(600),NA2(600),N
IMPLICIT INTEGER*2 (I-N)
IROUND(A)=((IFIX(2.*A)+1)/2
ND2=NA1(1)
ND3=NA1(2)
DO 1 I=5,N
ND1=ND2
ND2=ND3
ND3=NA1(I-2)
ND4=ND3-ND2-NA1(I-1)
ND4=ND4+ND4+ND3
ND4=ND4+ND4+ND1+NA1(I)
NA2(I-2)=ND3-IROUND(0.857143E-1*ND4)
IF(I.GT.5)GOTO 1
NA2(1)=ND1-IROUND(0.142857E-1*ND4)
NA2(2)=ND2+IROUND(0.571428E-1*ND4)
1 CONTINUE
NA2(N-1)=NA1(N-1)+IROUND(0.571428E-1*ND4)
NA2(N)=NA1(N)+IROUND(0.142857E-1*ND4)
RETURN
END

SMOOTH        FUNC/SUB
.0      EXT FUNC
..P     EXT FUNC
.XA1      FORM PAR
.XA2      FORM PAR
.XN      FORM PAR
.IROUND     STATE FH
.XA      FORM PAR
..IFIX     EXT FUNC
.XND2     INT2 VAR
.XND3     INT2 VAR
.X1      LABEL
.XI      INT2 VAR
.XND1     INT2 VAR
.XND4     INT2 VAR
.XW      EXT FUNC
SUBROUTINE CORREL(NA1, NA2, DV1, DV2, N)

C ***** CORRELATION OF TWO COLUMNS OF DATA ***** MOD 01 AUG 78

INTEGER*2 NA1(600), NA2(600), N
COMMON /SCRAT/ WORK(600)
IMPLICIT INTEGER*2 (1-N)
SIG2=0.
ERROR=0.
D1=NA2(N)*DV2
DO 21 I=1,N
ERR=(DV1*NA1(I)-DV2*NA2(I))/D1
WORK(I)=ERR
ERROR=ERROR+ERR
SIG2=SIG2+ERR**2
21 CONTINUE
ERROR=ERROR/N
SIG2=ABS(SIG2/N-ERROR**2)
STDDEV=SORT(SIG2)
WRITE(6,202)ERROR,STDDEV
202 FORMAT(‘ AVG. ERROR =‘, E12.5,’ STD DEV =‘, E12.5)
RETURN
END

CORREL FUNC/SUB
.O EXT FUNC
.P EXT FUNC
NA1 FORM PAR
NA2 FORM PAR
DV1 FORM PAR
DV2 FORM PAR
N FORM PAR

SCRAT COMMON X’0960’
WORK REAL VAR
SIG2 REAL VAR
ERROR REAL VAR
D1 REAL VAR
.IJ EXT FUNC
21 LABEL
I INT2 VAR
ERR REAL VAR
.R EXT FUNC
ABS EXT FUNC
STDDEV REAL VAR
SORT EXT FUNC
202 LABEL
.OH EXT FUNC
SUBROUTINE DUHAMEL(NA1,NA2,N,DV)
C **** PERFORM1 DUHAMEL'S INTEGRAL CALCULATION **** MOD 01 AUG 78
INTEGER*2 NA1(600),NA2(600),N
COMMON /SCRAT/WORK(600)
IMPLICIT INTEGER*2 (I-N)
A1=DV*NA1(1)
DO 33 J=1,N
WORK(J)=A1*NA2(J)
33 CONTINUE
DO 35 I=2,N
A1=DV*(NA1(I)-NA1(I-1))
DO 34 J=1,N
J1=J-I+1
WORK(J)=WORK(J)+A1*NA2(J1)
34 CONTINUE
35 CONTINUE
RETURN
END
D U H A M E  FUNC/SUB
."Q" EXT FUNC
."P" EXT FUNC
NA1 FORM PAR
NA2 FORM PAR
N FORM PAR
DV FORM PAR
SCRAT COMMON X'0960'
WORK REAL VAR
A1 REAL VAR
."W" EXT FUNC
33 LABEL
J INT2 VAR
35 LABEL
I INT2 VAR
34 LABEL
J1 INT2 VAR
SUBROUTINE NORMAL(HA,N,DV)
C ***** NORMALIZE DATA ***** MOD 08 AUG 78
INTEGER*2 NA(600),NSET, N
REAL DV, PLACE(4)
IMPLICIT INTEGER*2 (1-N)
IROUND(A)=((IFIX(2.*A)+1)/2
1 WRITE(6,101)
101 FORMAT('WHAT TYPE DATA SET? (S,K,P)'
CALL READ1(NSET)
NZERO=NA(1)
C KERR='K':PULSE='P':STEP='S'.
IF(NSET.NE.'S')GOTO 2
DV=5./(NA(N-4)+NA(N-3)+NA(N-2)+NA(N-1)+NA(N)-5*NZERO)
2 DO 3 I=1,N
NA(I)=NA(I)-NZERO
3 CONTINUE
RETURN
C UNTESTED--MAKES SCALE FACTOR A POWER OF 10. :
XLOG=ALOG10(DV)
DV=10.**(INT(XLOG)-1)
SCALE=10.**(XLOG-INT(XLOG))
DO 4 I=1,N
NA(I)=IROUND(NA(I)*SCALE)
4 CONTINUE
RETURN
END
NORMAL  FUNC/SUB
.Q  EXT FUNC
.P  EXT FUNC
NA  FORM PAR
N  FORM PAR
DV  FORM PAR
NSET  INT2 VAR
PLACE  REAL VAR
IROUND  STATE FN
A  FORM PAR
IFIX  EXT FUNC
1  LABEL
101  LABEL
QH  EXT FUNC
READ1  EXT FUNC
NZERO  INT2 VAR
2  LABEL
.w  EXT FUNC
3  LABEL
I  INT2 VAR
XLOG  REAL VAR
ALOG10  EXT FUNC
INT  EXT FUNC
SUBROUTINE XY PDT(NA.N1,DT)
C *** CONVERT X.Y PAIRS TO CONSTANT-INTERVAL SET *** MOD 24 JUL 78
INTEGER*2 NA(600),N1
IMPLICIT INTEGER*2 (I-H)
COMMON /SCRAT/NBX(600),NBY(600)
IROUND(A)=(IFIX(2.*A)+1)/2
IWIDTH=I+1/N1/20
LOC=1
DO I=I,N
IMIN=MAX02(LOC-IWIDTH,1)
IMAX=MIN02(IMIN+IWIDTH,N1-I)
ISEARCH=IROUND(DT*I)
CALL NEAREST(NBX,ISERCH,NEAR,IMIN,IMAX,LOC)
IMIN=MAX02(LOC-IWIDTH,1)
IMAX=MIN02(LOC+IWIDTH,N1-1)
DYDX=0.
IRUN=IMAX-IMIN+1
DO J=IMIN,IMAX
IF(NBX(J).NE.NBX(J+1))GOTO 3
NBY(J+1)=(NBY(J)+NBY(J+1))/2
IRUN=IRUN-1
J=MIN02(J+1,IMAX)
3 CONTINUE
DYDX=DYDX+FLOAT(NBY(J+1)-NBY(J))/(NBX(J+1)-NBX(J))
2 CONTINUE
DYDX=DYDX/IRUN
NA(I)=NBY(LOC)+IROUND(DYDX*(DT*I-NBX(LOC)))))
1 CONTINUE
RETURN
END

XY PDT   FUNC/SUB
.O   EXT FUNC
.P   EXT FUNC
NA    FORM PAR
N    FORM PAR
N1    FORM PAR
DT    FORM PAR
SCRAT    COMMON               X'0960'
SUBROUTINE NEARST(NA,NDATA,NEAR,IMIN,IMAX,LOC)
C ***** FIND POINT IN SET NEAREST TO NDATA ***** MOD 24 JUL 78
INTEGER*2 NA(600),NDATA,NEAR,IMIN,IMAX,LOC
IMPLICIT INTEGER*2 (I-N)
NEAR=32767
DO 1 I=IMIN,IMAX
ND1=IABS(NA(I)-NDATA)
NEAR=MIN02(NEAR,ND1)
IF(NEAR.EQ.ND1)LOC=I
1 CONTINUE
RETURN
END
NEARST FUNC/SUB
.O EXT FUNC
.P EXT FUNC
.NA FORM PAR
.NDATA FORM PAR
.NEAR FORM PAR
.IMIN FORM PAR
.IMAX FORM PAR
.LOC FORM PAR
.I LABEL
.I INT2 VAR
.ND1 INT2 VAR
.IABS EXT FUNC
.IABS2 EXT FUNC
.MIN02 EXT FUNC
SUBROUTINE FIXDTA(NA,DV,N)
C ***** STORE F.P. Workspace in integer column ***** MOD 01 AUG 78

INTEGER*2 NA(600),N
REAL DV,PLACE(4)
COMMON /SCRAT/WORK(600)
IMPLICIT INTEGER*2 (I-N)
IROUND(A)=IFIX(2.*A)+1)/2
XMAX=0.
DO 1 I=1,N
XMAX=AMAX1(XMAX,ABS(WORK(I)))
1 CONTINUE
DV=XMAX/1000
DO 2 I=1,N
NA(I)=IROUND(WORK(I)/DV)
2 CONTINUE
RETURN
END

FIXDTA FUNCTION
.O EXT FUNC
.P EXT FUNC
NA FORM PAR
DV FORM PAR
N FORM PAR
PLACE REAL VAR
SCRAT COMMON X'0960'
WORK REAL VAR
IROUND STATE FN
A FORM PAR
IFIX EXT FUNC
XMAX REAL VAR
1 LABEL
I INT2 VAR
AMAX1 EXT FUNC
ABS EXT FUNC
.U EXT FUNC
2 LABEL
### REL PROGS:

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### ABS PROGS:

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### COMMON-BLOCKS:

F69E SCRAT.

### UNDEFINED:

**NONE**
### Evaluation of a Multimegavolt Impulse Measurement System

**R.E. Hebner, D.L. Hillhouse, and R.A. Bullock**

The calibration of a 4.5 MV impulse divider was evaluated by measuring both the input and output waveforms and the response of the divider to a low voltage step. The measured output was compared to an output calculated from the step response and the measured input waveform using Duhamel's Integral. The validity of the approach for this large measurement system was demonstrated for the specific waveforms studied.