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Automatic Test Equipment Calibration/Performance Verification Evaluation and Research Program (JLC/DoD Subtask 30702)

Thomas F. Leedy and Barry A. Bell

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Electronics and Electrical Engineering
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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

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AUTOMATIC TEST EQUIPMENT CALIBRATION/PERFORMANCE VERIFICATION EVALUATION AND RESEARCH PROGRAM

Thomas F. Leedy and Barry A. Bell

Abstract

This work describes an experimental approach to verify the performance of selected third generation automatic test systems. As part of an ongoing project, this work builds on previous research in methods to characterize the accuracy of test systems measuring ac and dc voltages. This report describes the methods used to characterize a high frequency ac voltage source covering a voltage range of approximately 225 mV to 2.8 V rms over a frequency range of 50 kHz to 10 MHz. In addition, the characterization of a precision phase angle generator, designed and built at NBS, is described. Finally, the measurement results obtained with an automatic test system, using a new software operating system and the ac, dc, and phase angle transport standards, are discussed in detail.

Key words: ATE; automatic test systems; calibration; characterization; evaluation; field testing; performance test; third generation system.

PREFACE

The work described in this report is a continuation of the project that was performed by NBS in response to a request by the Joint Logistics Commanders Panel on Automatic Testing (JLC/AT). The initial work on this project is described in NBSIR 82-2601 "Automatic Test Equipment Calibration/Performance Verification Evaluation and Research Program (JLC/DoD Subtask 30702) Part II." That initial report, along with its Executive Summary - Part I, describes in detail the background, objectives, and approach used by NBS in a cooperative program with DoD to assess the requirements necessary for the proper calibration support of automatic test equipment (ATE). Additionally, the initial report contains descriptions of experiments performed to determine the feasibility of applying portable calibration sources, characterized by NBS, directly to the unit-under-test (UUT) interface device adapter terminals of automatic test equipment systems located in two different DoD facilities.

This current report details two aspects of the work performed during 1982. The first part is the characterization of additional electrical sources used to evaluate automatic test equipment: the changes in output of an ac voltage as a function of frequency, harmonic content, and temperature at frequencies to 10 MHz, and the investigation of environmental effects upon the stability of a precision NBS-designed phase angle generator. The second aspect of the work reported here is the result of additional tests performed at a DoD facility on an automatic test system which used new software to enhance its accuracy.

1. CHARACTERIZATION OF THE AC SIGNAL SOURCE BETWEEN 50 kHz and 10 MHz

1.1 Selection and Characteristics of the AC Signal Source

An important aspect of this project was the selection and characterization of a stable, portable signal source that could be used to provide stimulus signals to ATE systems under test. The most economical and expedient source proved to be a commercial meter calibrator that could provide a wide range of ac and dc signals in the ranges commonly measured by ATE systems. An additional desirable feature incorporated in the calibrator is the ability to control the output voltages and frequencies by means of an IEEE-488 standard interface. This feature permits efficient collection of test data and ease of controlling the calibrator when it is interfaced to the ATE system.

The ac voltage source contained in the meter calibrator is comprised of two subsystems which have the following characteristics. The first subsystem is an ac signal source that is capable of providing a maximum voltage of 1100 V ac (rms) at selected frequencies between 50 Hz and 50 kHz. At the higher frequencies, the maximum voltage available is reduced. For example, the maximum available voltage at 20 kHz is 110 V ac (rms), and at the maximum frequency of 50 kHz, it is 20 V ac (rms). The effective output impedance of this ac source is essentially zero since four-wire sensing may be used to correct voltage drops between the internal ac voltage generator and the effective load. The second ac subsystem provided in the meter calibrator is a wideband source which provides voltages from 300 μV to 3.16 V ac (rms) over a range of discrete frequencies from 10 Hz to 10 MHz. The output impedance of the wideband subsystem is 50 ohms. For correct operation of this output, 50-ohm coaxial cables and a 50 ohm load impedance are required. The output port of the wideband ac source is a BNC-type female panel connector. The subject of the present investigation is the wideband output, over the frequency range of 50 kHz to 10 MHz.

1.2 Method of Characterization of the Wideband Output

This section describes the sources of error that affect the amplitude of the ac signal applied to the interface of the ATE system and the experimental methods employed to determine the magnitude of these errors. The following sources of errors were investigated: (1) the losses associated with the cabling connecting the ac voltage source to the ATE system, (2) the errors in the thermal voltage converter and attenuators used to determine the amplitude of the applied signal at the ATE interface, and (3) the errors due to losses associated with the connectors used in the cabling connecting the ac voltage source to the ATE system. The first two sources of errors were assumed to be frequency dependent while the third was assumed to be a simple resistive loss, independent of frequency. In addition, the first two sources of errors were considered to be systematic errors that could be corrected by applying a frequency-dependent correction factor to the measured voltage amplitude. The resistive losses at the connectors were random and unpredictable in nature. These losses changed each time a connection in the cabling was changed. However, if the cable connections were undisturbed, these losses remained constant. All cable and connector losses were considered to be independent of the amplitude of the applied ac signal.

1.2.1 Uniformity of the Output Voltage Over the Frequency Range of 50 kHz to 10 MHz

A primary consideration in the performance verification of the ac voltage measurement capability of ATE systems is the ability to provide accurately known ac stimuli directly to the input terminals of the system under evaluation. Over the frequency range of 50 kHz to 10 MHz, small inductances and capacitances associated with the conductors between the calibration source and the ATE system become important, especially at the higher frequencies. If not properly accounted for, losses in the cable between the wideband source and the interface to the ATE system introduce a source of systematic uncertainty. The manufacturer of the particular source used in this case specifies that the amplitude variations of the wideband output are less than ±0.6 percent over the 50 kHz to 10 MHz frequency range, provided that the source is terminated with a 50-ohm resistive load at the end of 0.3 m (1 ft.) of RG-58/AU cable. This specification is reasonable if the source is used to calibrate small "bench-type" voltmeters. However, to connect the source to a large ATE system, a 1.5 m (5 ft.) cable is typically required.

In order to determine the cable losses as a function of frequency, a thermal voltage converter which had been characterized over the range of 50 kHz to 10 MHz was used to measure the amplitude of the ac signal at the 50-ohm output of the voltage source at 24 frequencies between 50 kHz and 10 MHz. The 1.5 m cable was then connected to the 50-ohm output of the signal source and the voltage remeasured at the opposite end of the cable using the same thermal converter. The ratio of the two voltage measurements, at each frequency, was then calculated and used as a correction factor to account for cable losses. For example, using this method it was determined that the 1.5 m cable attenuates the ac signal approximately 0.6 percent at 10 MHz. One source of error in this method of determining cable loss would be short-term amplitude instabilities in the output voltage of the wideband source between the first and second voltage measurements at each frequency. However, it is believed that this source of error is small compared to other uncertainties in the measurement process. Unless otherwise specified, all ac voltage measurements reported herein were made using a 1.5 m length of RG-58/CU cable connected to the wideband output.

To accurately determine the voltage at the input of the ATE system, a standard thermal converter and a set of two attenuators (to extend the voltage range of the converter) were used. The methods used to measure the ac voltage as a function of frequency was similar to those reported previously [1][1]. The use of a thermal converter has proven to be a useful method of comparing two ac voltages at different frequencies [2]. In this work, a higher frequency voltage is compared to a lower frequency reference voltage. This technique requires that the frequency response of the thermal converter and attenuators be known over the range of frequencies being investigated. Figure 1 shows a block diagram of the apparatus used to make these measurements.

The standard thermal voltage converter has a voltage range of approximately 0.2 to 0.45 V ac (rms). To measure voltages in excess of 0.45 V ac (rms), a set of two precision 50-ohm coaxial attenuators was used that had power attentuations of 6 and 10 dB. The attenuators had been characterized by the manufacturer as varying in attenuation by no more than ±0.1 dB from dc to 3 GHz. In addition, the attenuators were measured at dc by the staff in the Electrosystems Division at NBS Washington, and at 30 MHz by the staff in the Microwave Metrology group at NBS, Boulder, CO. The insertion loss at dc was measured by applying a voltage, V_{in}, (typically 0.3V) to the input of the attenuator and measuring the output voltage of the attenuator, V_{out}, with the attenuator terminated into 50 ±0.1 ohms. Both the input and output voltages were measured with a precision digital voltmeter. The insertion loss θ was then calculated as

[1] Numbers in brackets refer to the literature references listed at the end of this report.

$$\Theta\ (dB) = 20 \log (V_{out}/V_{in}).$$

The insertion loss at 30 MHz was determined by a technique which compares the attenuator to be calibrated to a precision waveguide-below-cutoff (piston) attenuator. The results of these measurements were:

Frequency	Nominal Attenuation	Measured Attenuation	Uncertainty	
dc	6.0 dB	5.996 dB	±0.002 dB	
30 MHz	6.0 dB	6.003 dB	±0.007 dB	
dc	10.0 dB	10.004 dB	±0.002 dB	30
MHz	10.0 dB	10.001 dB	±0.006 dB	

Since the uncertainties of the attenuation measurements were comparable to the differences of the measured attenuations at dc and 30 MHz, the errors associated with the changes in frequency were neglected for both attenuators. By use of the attenuators, either individually or in series, the voltage measurement range of the 0.45 V ac (rms) thermal voltage converter was extended to 2.8 V ac (rms).

The thermal voltage converter standard used for these measurements has an ac-dc difference of less than ±0.03 percent over the frequency range of 50 kHz to 10 MHz. The uncertainty of the ac-dc difference was ±0.1 percent or less over this same frequency range. The ac-dc difference was measured by the staff in the Electricity Division of NBS, Washington, over the frequency range of 50 kHz to 1 MHz and by the staff in the Microwave Metrology group of NBS, Boulder, over the frequency range of 1 MHz to 10 MHz.

Figure 2 shows the experimental apparatus used to compare the amplitude of the wideband output of the source contained in the meter calibrator with the reference standard at 1 kHz over a voltage range of 0.2 V to 2.8 V ac (rms). The procedure used the precision digital voltmeter to determine the amplitude of a 1 kHz signal from the wideband output of the meter calibrator (at point B in figure 2) in terms of the precision ac reference and ratio transformer (at point A). The voltmeter was first connected to point B and the nominal valve of the voltage supplied by the meter calibrator was read and recorded. The voltmeter was then connected to point A and the ratio transformer adjusted to obtain the same voltmeter reading. The setting of the ratio transformer, when multiplied by 10 V ac (rms), was then equal to the voltage output of the wideband source. The comparison procedure to determine the high frequency voltage in terms of the 1 kHz signal consisted of three additional steps. First, a 1 kHz signal from the source was applied to the thermal voltage voltage converter. The 1 kHz signal had the same nominal amplitude (to within 1 percent) as the high frequency signal to be measured. Two measurements were then made using the precision digital voltmeter. The dc thermocouple output voltage of the converter was measured and recorded as E_1 by connecting the digital voltmeter to point C in figure 2. The ac voltage applied to the thermal voltage converter was measured and recorded as the reference voltage, V_r by connecting the digital voltmeter to point B in figure 2. The second step consisted of maintaining the frequency of the output signal source at 1 kHz and varying its amplitude such that the output signal was first 1 percent less than the reference voltage, V_r, and then 1 percent greater than the reference voltage. As the amplitude of the reference voltage was varied by ±1 percent, the corresponding thermocouple output voltages were measured and recorded as E_2 and

E_3, respectively. In the third step, the source was set to the desired high frequency (in the range of 50 kHz to 10 MHz) and the thermocouple output was measured again and recorded as E_4. Ideally, the thermocouple output at the higher input frequencies, E_4, should be identical to the thermocouple voltage generated by the 1 kHz signal, E_1, if the rms values of these two input voltages are equal. Using the values of E_1, E_2, E_3, E_4, and V_r, the corrected value of the output voltage of the wideband source V_h was calculated by interpolation over the range of E_2 to E_3 as follows:

$$V_h = \left[1 + 0.02 \left(\frac{E_4 - E_1}{E_3 - E_2}\right) \right] V_r .$$

The derivation of this equation, along with the errors associated with its use, are given in Appendix A.

The uncertainty in the determination of the 1 kHz output amplitude of the ac source, over the range of 0.45 to 2.8 V ac (rms), was estimated to be less than ±0.06 percent. This value consists of the root sum of squares of the following components: The 10 V, 1 kHz precision ac voltage reference standard was estimated to have an uncertainty of ±0.03 percent, the ratio transformer has an uncertainty of ±0.005 percent ratio error at 1 kHz, and the ac-dc difference of the thermal converter contributes no more than ±0.03 percent uncertainty. These three components contribute an uncertainty of ±0.043 percent. In addition, an uncertainty of ±0.015 percent was added to account for changes in connector resistance in the measurement system. The uncertainty associated with changes in connector resistance is discussed later in this section. The ±0.06 percent overall uncertainty of the calibrated wideband source, therefore, was considered to be sufficiently low for use in verifying the performance of an ATE station with a ±3 percent rms measurement accuracy specification.

The data represented in figure 3 shows the change in output amplitude of the wideband source as a function of frequency relative to the 1 kHz reference voltage at three voltage levels: 0.2 V, 0.3 V, an 2.0 V ac (rms).

Figure 4 shows similar data obtained when the thermal voltage converter was connected with a 1.5 m (5 ft.) cable to the wideband output of the ac source. Notice that the cable produces attenuation, especially at frequencies above 1 MHz. The deviations relative to the output at 1 kHz are well within +0.2 and -0.8 percent. Knowing the loss of the cable as a function of frequency permits a table of correction factors to be calculated to compensate for the cable losses and the small variations in the signal source as a function of frequency.

One advantage to using the above method of characterizing the output of the wideband source is the ability to quickly verify its performance at selected voltages and frequencies using only attenuators and a thermal voltage converter. A second advantage of this method is that it is not necessary to connect and disconnect components in the 50-ohm signal path. The output of the wideband source may be determined while the source is connected to a high impedance (e.g. 1 megohm) input of the ATE system. The reconfiguration of a low-impedance signal path can introduce errors arising from variations in connector resistance. For example, if the change in the connector resistance is 0.1 ohm, an apparent error of approximately 0.2 percent will be observed in a 50-ohm system for a 1 V ac (rms) output signal from the source. Thus, a relatively small change in the cable or connector resistance will introduce an appreciable change in the measured signal. Such errors arising from changes in resistance are aggravated in systems that use small coaxial connectors such as BNC-types since the mating areas, and therefore the current carrying surfaces, are small. Also, small connectors are easily damaged in subtle ways that are not visually noticeable.

The effects of repeatedly connecting and disconnecting a BNC connector were briefly investigated during this work. A 50-ohm coaxial termination was repeatedly connected and disconnected from a mating BNC socket twenty times. The average resistance of the twenty observations was 50.311 ohms with a standard deviation (1 sigma) of 0.49 ohms. For comparison, twenty measurements performed on the same termination that was not disturbed between measurements yielded a mean value of 50.030 ohms with a standard deviation of 0.006 ohms. The observed resistance values for this experiment are shown in Table 1. Thus, the random errors introduced in the determination of the output voltage of the source due to variation in connector resistance could be expected to be approximately one percent if it were necessary to connect and disconnect the system.

1.2.2 Effects of Ambient Temperature

Changes in temperature can have a significant effect on the performance of precision electronic equipment . For example, the operating point (bias) of solid-state devices and the values of precision resistors are susceptible to temperature changes. To investigate the temperature sensitivity of the wideband source, the unit was placed in a chamber where the temperature could be controlled and monitored over a range of 0° to 40°C. The output amplitude of the source was measured at each of three voltage levels (0.2, 0.5, and 2.0 V ac (rms)), at seven frequencies (1 kHz, 50 kHz, 100 kHz, 500 kHz, 1 MHz, 5 MHz, and 10 MHz), and at 5 temperatures (0°, 10°, 23°, 30°, and 40°C). For each of these 105 combinations of output voltage, frequency, and temperature, the change in the output voltage was measured using the thermal voltage converter, attenuators, and precision DVM described above. At each test point, the source was programmed to provide an output, corrected for the variations in cable loss and the small output deviations of the wideband source described previously. Figure 5 shows the measured changes in the output of the wideband source over the temperature range of 0° to 40°C. The data points shown in this figure represent various combinations of frequencies and voltages used to characterize the change in wideband output voltage as a function of temperature. Over this temperature range, the maximum change in the ac output voltage for all voltage/frequency combinations measured was less than +0.2 and -0.1 percent. Since the source was not subjected to more than a 5°C departure from the nominal 25°C reference temperature during any field test, the uncertainty was conservatively estimated to be no greater that ±0.10 percent.

1.2.3 Harmonic Distortion and Spurious Outputs of the AC Signal

The spectral purity of the signal from the wideband source was measured to determine the magnitude of the harmonics and spurious outputs, since these contribute to the distortion of the output signal from a pure sine wave. Such undesired signals, if of sufficient magnitude, would result in errors in measurements made by average or peak voltage responding ATE systems. However, since true rms measurements were always used to determine the ac amplitude from the source, both in the characterization of the source by NBS and at the ATE station, the distortion of the signal did not contribute to inaccuracies in the voltage measurements.

The spectral purity measurements were made primarily to verify that the ac source complied with the manufacturer's specification which state that the harmonic distortion is -40 dB or less (relative to the fundamental) at frequencies less than 5 MHz, and less than -32 dB above 5 MHz. Additionally, the spurious outputs are specified to be less than -50 dB relative to the fundamental at all frequencies.

Two typical spectrum analysis plots of amplitude versus frequency are shown in figures 6 and 7. These plots were acquired by applying a signal from the output of the wideband source to a heterodyne-type spectrum analyzer. The amplitude of the signal analyzed was 0 dBm which corresponds to approximately 0.2236 V rms. This is the voltage required to dissipate 1 mW in a 50 ohm load. The figures show the relative output of the source as a function of frequency at output frequencies of 2 and 10 MHz, respectively.

Both figures 6 and 7 show the presence of harmonics of the fundamental frequency at the output of the wide-band source. In addition, other signals not harmonically related to the output were detected. For example, figure 6 shows a signal located at 11 MHz. To account for the presence of this signal, the operation of a phase-locked loop incorporated in the wide band oscillator must be understood. Figure 8 shows the block diagram of the wide band oscillator. To generate frequencies from 100 kHz to 10 MHz, a signal from a fixed frequency, 20 MHZ reference oscillator is mixed with a signal from a voltage-controlled oscillator which has a range of 20.1 to 30 MHz. The voltage-controlled oscillator is controlled by a phase detector which compares the output of a divide-by-N counter and a fixed 100 kHz reference signal derived from the 20 MHz reference oscillator. To produce a 2 MHz oscillator output, the divide-by-N counter is set to divide by 220 producing a 100 kHz signal. This counter undergoes a major transition (one-half of its binary elements change state) at an 11 MHz rate. A small portion of this 11 MHz signal is spuriously coupled into the output of wide-band source. Likewise, other signals from the phase-locked loop contribute spurious outputs at frequencies near the fundamental frequency of the wide band output. These are seen in figures 6 and 7 as discrete spectral lines symmetrically located at frequencies around the fundamental frequency. It is not unusual for signal sources that incorporate digital synthesizers to produce spurious outputs. The amplitudes of the spurious outputs of the wideband source used in this study, however, meet the manufacturer's specifications.

2. CHARACTERIZATION OF THE NBS PHASE ANGLE GENERATOR

2.1 Selection of the Phase Angle Generator

Low frequency phase angle measurements are performed extensively by both military and commercial ATE systems. For example, many aircraft systems use electromechanical transducers such as synchros and resolvers in navigational and flight control systems. Such transducers convert angular position to an electrical phase angle signal which, in turn, is converted to a control signal. To support such aircraft systems, many ATE systems have precise phase measurement capability. In selecting a means for characterizing this capability, an evaluation was made of commercial instrumentation as well as the NBS Phase Angle Calibration Standard.

The use of commercial test equipment as calibrated transport standards to characterize ATE systems is attractive since commercial equipment is readily available and inexpensive compared to custom instrumentation. However, in attempting to use two commercial function generators configured as a dual-channel phase angle generator, it was not possible to achieve the accuracies necessary to characterize the types of ATE systems that are being investigated. To measure the random errors produced by the two function generators, a commercial phase meter with 0.01 degree resolution was connected directly to the outputs of the two function generators using equal lengths of RG-58/CU cable. The analog output of the phase meter was then measured using a precision digital voltmeter. An estimate of the measurement uncertainty of the combination of phase meter and voltmeter was obtained by applying a 3 V ac (rms), 1000 Hz signal to both channels of the phase meter simultaneously. The results of 99 measurements yielded a random error (1 σ) of ±0.010 degrees and a systematic error of 0.024 degrees. The commercial equipment exhibited a one standard deviation value of 0.074 degrees when 720 phase measurements were made at seven frequencies, over a frequency range of 50 Hz to 5 kHz, and phase angles of five degree increments from 0 to 355 degrees. For all tests, the amplitude of both channels of the commercial phase generator was fixed at 3 V ac (rms).

A similar test using the NBS Phase Angle Calibration Standard had a one standard deviation of 0.015 degrees. Since many of the ATE systems currently in use are specified to be accurate to ±0.1 degree, it was decided to use the NBS Phase Angle Calibration Standard for subsequent phase angle work. Figures 9 and 10 show the relative measurement errors of the data obtained from the phase meter for the commercial phase angle generator and the NBS Phase Angle Calibration Standard, respectively, over the frequency range of 50 Hz to 5 kHz.

These plots show the difference between the measured phase and the setting of the phase angle generator. The vertical axis has the units of electrical degrees of phase angle and the horizontal axis is the nominal frequency in Hz. The total length of the lines at each of the seven test frequencies denotes the range of all the observations at that frequency. The ends of the lines correspond to the maximum and the minimum of the observations, while the height of the "box" denotes the one standard deviation value of all observations. The short, horizontal line in the box indicates the average of all observations at a given frequency. The width of the box has no significance. (This type of data presentation is used several times in this report). Additionally, figures 9 and 10 show dashed lines representing the limits of the sum of random (±0.010 degrees) and systematic (±.024 degrees) errors of the measurement process.

2.2 Temperature and Line Voltage Characterization of the Phase Angle Generator

2.2.1 Effects of Ambient Temperature

The change in phase of the output of the NBS Phase Angle Calibration Standard was measured at five temperatures over a temperature range of 10° to 30°C for output frequencies between 50 Hz and 5 kHz and at various phase angle settings. During these tests, the output voltage of both channels was fixed at 5 V ac (rms). The phase meter and voltmeter combination was the same as used previously to measure the phase output of the NBS Phase Angle Calibration Standard. Only the NBS Phase Angle Calibration Standard was subjected to temperature changes during this experiment. A total of 1260 measurements were made at various combinations of frequencies, phases, and temperatures. Figure 11 shows the results of these measurements. It is apparent that neither the average nor the standard deviation of these measurements change significantly with temperature.

This result is consistent with the principles which are employed in the NBS Phase Angle Calibration Standard to generate phase angles. Essentially, two sine waves are digitally synthesized with a pair of digital-to-analog converters (DAC) by applying successive 16-bit digital codes to the converters which represent digital equivalents to an ideal sine function. As the codes to one DAC are offset in phase with respect to the other, a relative phase shift results in the pair of sine waves that is accurate to approximately ±5 to ±10 millidegrees [3]. To minimize phase shift associated with the output amplifiers, an automatic feedback circuit is used that compensates for residual differential phase shifts.

Precise measurements of highly accurate phase angle signals, such as produced by the NBS Phase Angle Calibration Standard, are limited by noise internal to the measurement equipment. Typically, the internal noise of a commercial phase meter, as was used here, is sufficient to produce a standard deviation (1σ) of approximately ±10 millidegrees in the phase measurement. The data presented in figure 11 shows no statistical change in output phase over the temperature range of 10°C to 30°C. Statistical analysis of the data shown in figure 11 using the F-test shows that there is less than a 10 percent probability of a change in the measured phase depending on temperature over the frequency and temperature ranges measured. The F-test is a statistical method which may be used to determine the probability that the standard deviations of two sets of observations are equal. Thus, it was concluded that there was no additional uncertainty of the phase angle measurements attributable to temperature changes of the NBS Phase Angle Calibration Standard.

2.2.2 Effects of Power Line Voltage Changes

The change in the output of the NBS Phase Angle Calibration Standard with respect to input power line voltage was measured at four combinations of frequency and phase. These were 50 and 5000 Hz, and 90 and 270 degrees, respectively. Using the same phase angle measurement equipment described above, no change in readings could be measured over a range of line voltages from 105 to 135 V ac (rms). Again, this was an expected result since the standard uses well-regulated power supplies and digital techniques to generate the phase angle.

3. INCORPORATION OF COMPUTER/CONTROLLER INTO MEASUREMENT SYSTEM

3.1 Description of the System

A portable desk-top computer/controller was obtained to control the NBS transport standards used to characterize ATE systems. Use of the new controller has several advantages over the previous system. Since the controller is portable, it is possible to run test programs that verify the functioning and accuracy of the transportable signal sources against basic standards such as zener references and ac/dc thermal converters at the test site in an efficient manner. Additionally, the resultant data may be recorded, correction factors computed, and instruments controlled via the IEEE-488 standard interface. For example, the correction factors required to compensate for cable losses when using the wideband output source between 50 kHz and 10 MHz can be determined at the ATE site prior to and after the ATE system has been characterized. Such capability increases the confidence in measurements that are made on site.

The computer/controller can also be used to efficiently generate the sequence of test voltages, frequencies, and phases used during the characterization of an ATE system. The test sequences are stored in data files that are accessed by a program written in BASIC. For example, if a sequence of dc voltages is to be applied to an ATE station, the program reads the sequence of voltages, programs the meter calibrator to output these stored voltages, and also reads a digital voltmeter connected to the meter calibrator output to assure that these dc voltages are truly present. In this manner, the digital voltmeter and the ATE system measure the same dc voltage at nearly the same time. When the ATE system finishes reading and recording its value of the dc voltage, it generates a "test complete" pulse. This pulse causes the program in the computer/controller to advance and the transport source to output the next stored value. The process repeats until the entire sequence has been measured by the ATE system. Such a system has proven very valuable since it allows for easy modification of the range and sequence of the applied stimuli.

4. FIELD TESTS OF AN ATE SYSTEM

After characterizing the additional stimulus sources, the next major task was to use these sources to evaluate an ATE system. The ATE system evaluated was an AN/USM-410 (EQUATE)[2] located at the U.S. Army Depot, Tobyhanna, PA.

This particular ATE system had a partial implementation of new software for the run-time system. One objective of making measurements at this field site was to determine the effects of the new software on the performance of the EQUATE station. It should be emphasized that although essentially the same ac and dc tests were conducted using the new software as were conducted previously at this site, the time between tests was over a year. Consequently, comparisons of data contained in this report with data reported previously may not be completely attributable to software changes, since adjustments and repairs may have occurred during the interval between tests. The same uncertainty assignments as used before for the NBS dc and ac source were deemed valid for this test, i.e., ±200 ppm for dc voltage and ±1200 ppm for ac voltage to 50 kHz.

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[2] In order to adequately describe the systems and experiments discussed in this report, commercial equipment and instruments are identified by manufacturer's name or model number. 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.

4.1 DC and AC Voltage Tests

The basic test procedures used for the dc and ac voltage tests were the same as those reported previously except that the computer/controller was used to program the sequence of voltages supplied by the dc/ac source instead of using the tape cassette unit built into the source. Also, some test sequences were shortened by eliminating replications of measurements.

Briefly, the procedure consists of using measurement programs written in ATLAS to instruct the ATE station to determine the voltages present on pin pairs at the PIU interface. Data is input to the ATLAS program from the ATE keyboard instructing the system to connect these pin pairs to the measurement bus internal to the ATE station. The system then executes two MEASURE commands. The first MEASURE command causes a voltage measurement in the autoranging mode, whereas the second MEASURE command causes a remeasurement of the voltage with the same applied voltage but with the ATE system in the fixed range appropriate for the applied voltage. In this manner, the proper range for making the voltage measurement is determined prior to making the final measurement which is recorded and printed by the EQUATE system. At the end of a measurement cycle, a "test complete" pulse is generated from a designated set of pin pairs to signal the computer/controller that the next voltage is to be measured.

The latest dc measurements consist of a sequence of 282 voltage levels applied to the PIU at various pin pairs and measured by the ATE station. The voltage levels covered the range of ±0.1 through ±195 V dc. As each voltage was applied to the PIU, it was measured by a precision digital voltmeter and the value recorded to provide confidence that the proper voltage was present during the test. In six instances the ATE station failed to properly measure a +195 V dc signal, and once it failed to measure a -195 V dc signal. In each of the six cases when a malfunction occurred at +195 V dc, the system reported a measurement of 1.0242847 V dc. The data resulting from the seven malfunctions were eliminated from further analysis. Of the remaining 275 measurements which included 31 measurements at +195 and -195 V dc, the mean error was 0.134 percent with an estimated standard deviation of the mean of 0.284 percent. The range of all 275 measurements was calculated to be 0.986 percent. The error, or departure from nominal, was defined in percent as

$$\text{Percent Error} = \frac{(\text{NBS Source - Measurement})}{\text{Measurement}} \times 100 \ .$$

Figure 12 shows the distribution of the departures from nominal as a function of applied voltage using the aforementioned data presentation. This distribution may be compared to the data shown in figure 13 taken over a year ago. The old data consisted of 438 observations over the same voltage range of -195 to +195 dc and had a mean error of -0.209 percent with an estimated standard deviation of the mean of 3.93 percent. The range of the measurement errors was calculated to be 49.8 percent. Thus, the latest dc measurements were much more consistent than those taken previously.

The most recent ac voltage measurements on the EQUATE station were made over a frequency range of 50 Hz to 50 kHz, at voltages of 0.3 to 130 V ac (rms). The same combinations of voltage and frequency were used for these measurements as were used previously except that the maximum voltage applied was

130 V ac (rms) as opposed to 70 V ac (rms) used previously. The distribution of errors as a function of applied voltage for the newest data is shown in figure 14. Figure 15 shows a similar plot for the previously obtained data. In the latest test, test system malfunction was noted, and the average error of 183 observations was -0.154 percent as compared to -0.918 percent obtained a year ago. The estimated standard deviation of the mean and the range of the error observations were 1.127 and 13.6 percent, respectively, for the newest data. These values compare with 1.89 and 22.15 percent, for the standard deviation of the mean and the range, respectively, for the previous error data.

It was not possible to measure ac voltage in the range of 50 kHz to 10 MHz in our latest tests on the EQUATE system at Tobyhanna, PA. Presently, it is believed that the software program for establishing the proper path through the PIU to the high-speed sampling unit (necessary for measuring ac voltages in excess of 50 kHz) may be incorrect. This measurement capability will be the subject of study in the next field test.

4.2 Phase Angle Measurements

Using the NBS Phase Angle Calibration Standard, the accuracy of 37 phase angle measurements was determined at 10° increments over the range of 0 to 350 degrees, at voltage levels of 1.0 and 5.0 V ac (rms), and at various frequencies between 60 and 4500 Hz. The error of the phase angle measurements was calculated as

$$\text{Error (degrees)} = \text{NBS Source} - \text{Measurement}.$$

Notice that the error is in units of degrees which is more appropriate to phase angle measurements than percent. The distribution of phase angle measurement errors is shown in figure 16. The mean difference between the NBS Phase Angle Calibration Standard and the values measured by the ATE system was -0.01 degrees with an estimated standard deviation of the mean of 0.09 degrees. Since these measurements were not performed previously, there is no comparison data. However, these measured values are well within the range of errors expected from published specifications for the EQUATE system [4].

4.3 Summary

This work, along with the previous work already cited [1], demonstrates the feasibility of performing on-site tests of ATE systems at the interface connector using well-calibrated transport standards. In this manner independent verification of the accuracy specifications for basic ac and dc voltage, phase, and pulse duration can be established. Tests performed in this manner may be effective at detecting hidden sources of errors in large ATE systems that may degrade their accuracy. Errors arising from losses in the signal paths between the interface connector and the measurement devices internal to the ATE system, noise interference from surrounding equipment, and malfunctions of the computer software and/or hardware may be detected by on-site tests. Often, such errors may go undetected by traditional calibration techniques which involve the removal of the measurement device from the ATE system and calibration of the device at a remote metrology laboratory.

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2. H. K. Schoenwetter, "AC Voltage Calibrations for the 0.1 Hz to 10 Hz Frequency Range," NBS Technical Note 1182, (Sept. 1983).

3. R. S. Turgel and N. M. Oldham, "NBS Phase Angle Calibration Standard", NBS Technical Note 1144, U.S. Department of Commerce, National Bureau of Standards, July 1981.

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5. R. S. Turgel, "A Comparator for Thermal AC-DC Transfer Standards," Instrument Society of America Transactions, 6, 4, pp. 287, (1968).

APPENDIX

The Linear Approximation of a Thermal Voltage Converter Transfer Characteristic

The dc voltage output, E, of a thermal voltage converter (TVC) which has an ac voltage, V, applied to the input may be approximated by

$$E = k\,V^n .$$

where k and n are constants that depend on the construction of the TVC [5]. Since the current through the TVC is proportional to the voltage across the input terminals, one may write

$$E = k\,I^n ,$$

In the following discussion it is assumed that over a short interval of V (on the order of one percent change) both the resistance of the TVC and the parameter n remain constant. Figure 17 shows E plotted as a function of V for a typical TVC. The departure from linearity has been greatly exaggerated in this plot for the purpose of clarity.

The procedure described in section 1.2.1 used to measure the amplitude of a high-frequency (50 kHz to 10 MHz) voltage in terms of a lower frequency (1 kHz) consists of four steps:

1. Apply a 1 kHz signal of amplitude V_r to the input of the thermal converter. Use the attenuators, if necessary, at the input of the TVC to reduce the signal amplitude to less than the maximum specified voltage of the TVC. The value of V_r must be independently measured. Record the value of V_r and the output voltage of the TVC, E_1.

2. Decrease the amplitude of the 1 kHz signal from V_r to a value of $(1-\alpha) \times V_r$. In this work, α is 0.01, which corresponds to a one percent decrease in the applied voltage to the TVC. Record the output voltage of the TVC, E_2.

3. Increase the amplitude of the 1 kHz signal to a value of $(1 + \alpha) \times V_r$. Record the output voltage of the TVC, E_3.

4. Remove the 1 kHz signal and apply a high-frequency voltage, V_h, of nominal value V_r. Record the output voltage of the TVC, E_4.

It is now possible to calculate the value of the high-frequency voltage in terms of the low-frequency data. A line is constructed which is tangent to the V, E curve at point V_r, E_1 and has a slope defined by the pair of coordinates $[(1 - \alpha) \times V_r, E_2]$ and $[1 + \alpha) \times V_r, E_3]$. The slope of this line is defined as the change in E divided by the corresponding change in V, and is

$$\text{Slope} = m = \frac{\Delta E}{\Delta V} = \frac{E_3 - E_2}{(1 + \alpha) \times V_r - (1 - \alpha) \times V_r}$$

$$= \frac{E_3 - E_2}{2\ \alpha\ V_r} \ .$$

For any value of E, a corresponding value of V can be found along the line tangent to the V, E curve. Thus, for a value of E equal to E_4, which was recorded when the high-frequency voltage V_h was applied to the TVC,

$$E_4 - E_1 = m \times (V_h - V_r) \ ,$$

or

$$V_h - V_r = \frac{1}{m} \times (E_4 - E_1) \ .$$

Substituting for m and solving for V_h,

$$V_h = \frac{2\ \alpha\ V_r}{E_3 - E_2}\ (E_4 - E_1) + V_r$$

$$= [\frac{2\alpha}{E_3 - E_2}\ (E_4 - E_1) + 1]\ V_r$$

$$= [1 + 2\ \alpha\ (\frac{E_4 - E_1}{E_3 - E_2})]\ V_r \ .$$

There is an error associated with interpolating a straight-line tangent to the V, E curve. An ac input voltage to the TVC, V_a, will produce an output voltage E_o, which is a slightly nonlinear function of V. However, using the approximation method described above will yield an interpolated value of input voltage V_I for an output voltage of E_o. The difference between V_a and V_I may be expressed as

$$V_I - V_a = [1 + 2\ \alpha\ (\frac{E_o - E_1}{E_3 - E_2})]\ V_r - k\ V_a^n \ .$$

The fraction of error introduced by the interpolation process will then be

$$\frac{V_I - V_a}{V_a} = [1 + 2\ \alpha\ (\frac{E_o - E_1}{E_3 - E_2})]\ \frac{V_r}{V_a} - kV_a^{n-1} \ .$$

The V, E characteristic of the TVC used in this work was measured over a range of one-half to maximum input voltage. The values of k and n were determined over this range by regression analysis to be 0.0229 and 1.79, respectively. Figure 18 shows the errors associated with a one percent change of input voltage around a nominal input of 0.45 V (rms). Using the linear interpolation method causes errors in the calculated voltage of approximately 40 parts per million compared to the value determined from an exact evaluation of the equation of the V, E characteristic. This is a small error compared to other sources of error in the measurement of high-frequency voltages. The advantage of the linear interpolation method resides in the fact that the parameters of k and n need not be known exactly, the computation effort is easier, and characterization of high-frequency voltages may be performed quickly at an ATE site.

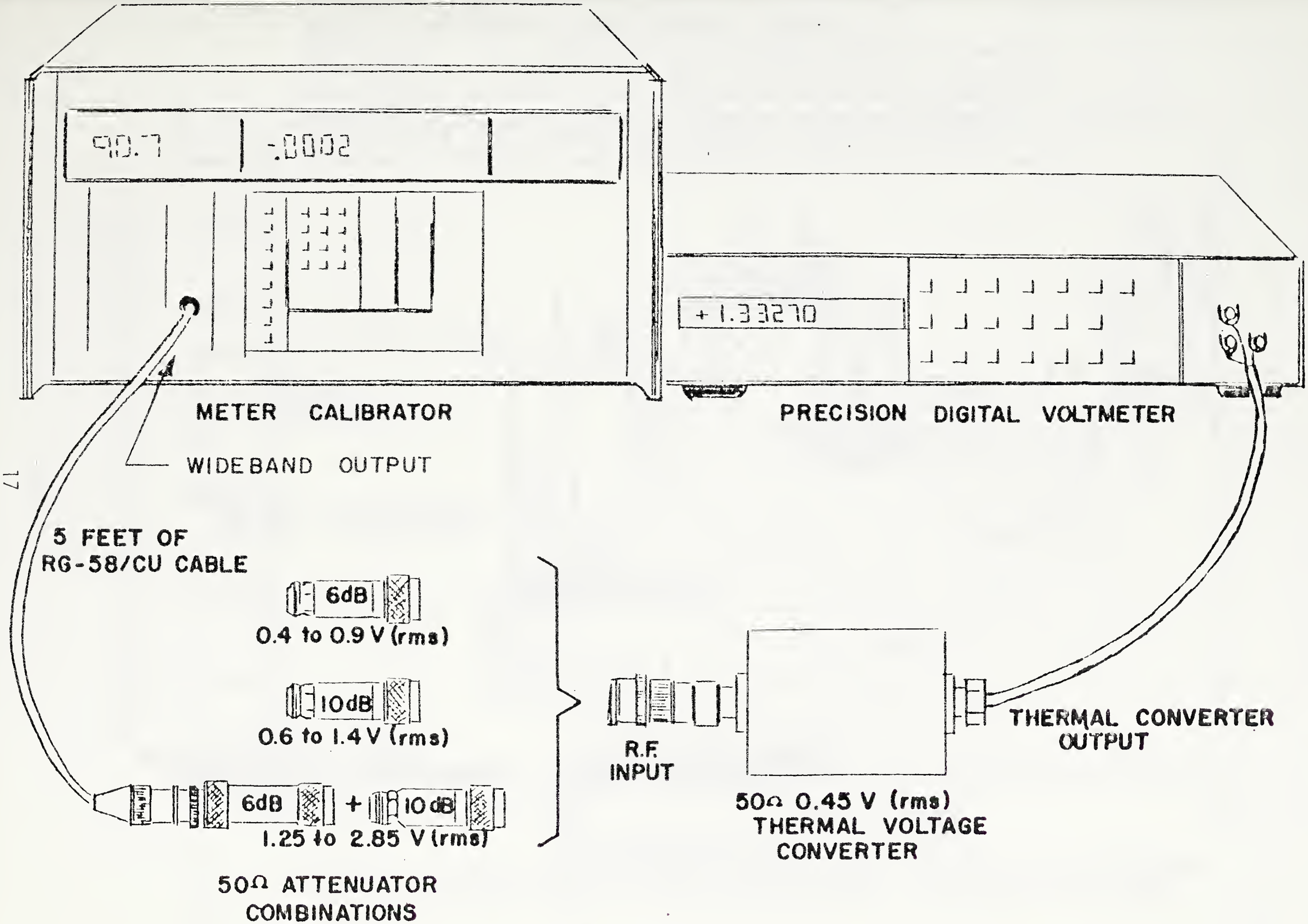

Figure 1. Block diagram of apparatus used to make wideband voltage measurements. The output of the wideband source is connected to the thermal converter either directly, or through a 6 dB, 10 dB, or a series combination of 6 and 10 dB attenuators.

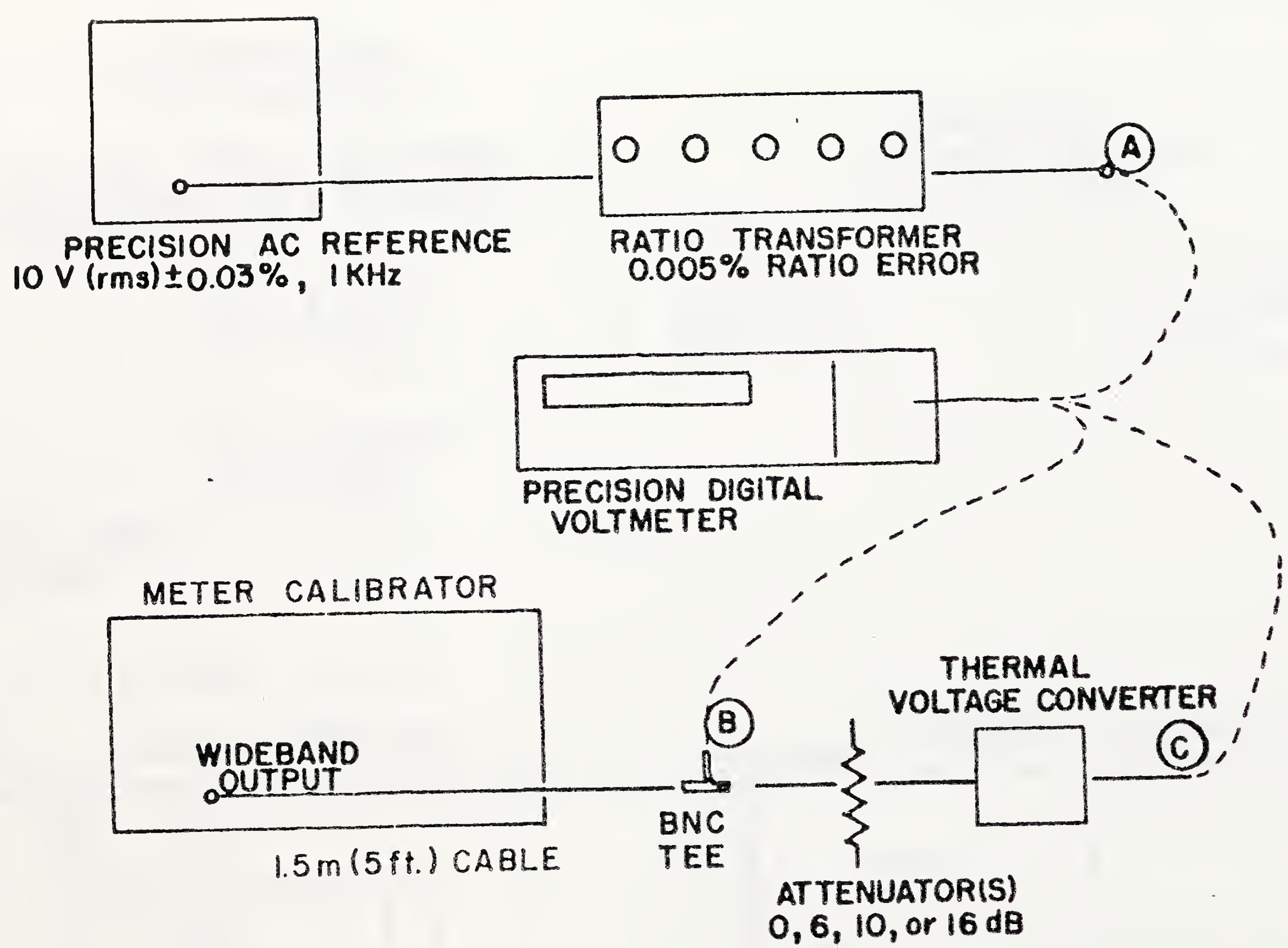

Figure 2. Experimental apparatus used to compare the source with the reference standard at 1 kHz. The precision digital voltmeter is first connected to point A in order to calibrate the ac measurements of the voltmeter in terms of the precision ac reference and ratio transformer. The voltmeter is then connected to points B and C to measure the 1 kHz ac amplitude of the wideband source, and the dc output of the thermal voltage converter, respectively.

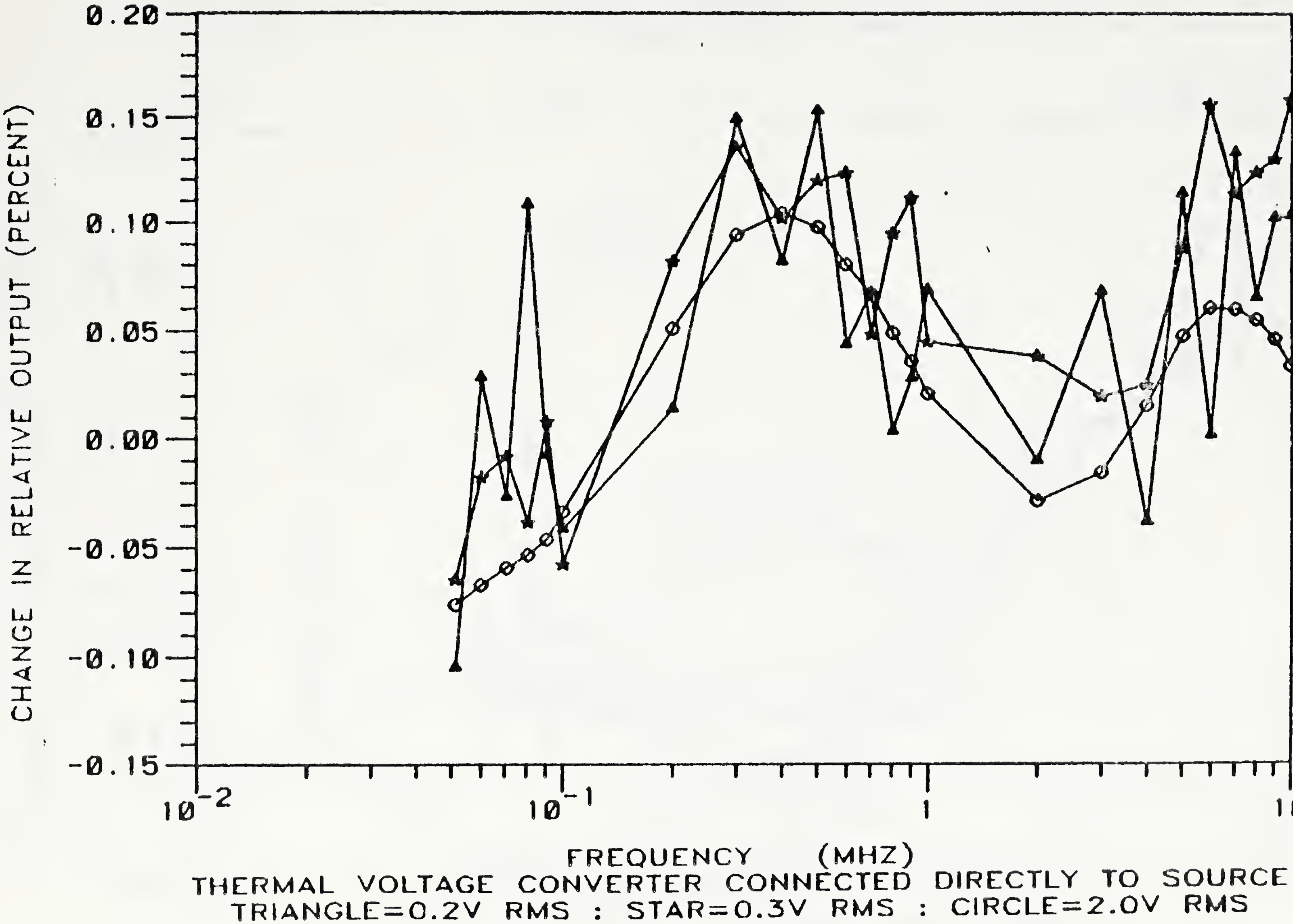

Figure 3. Change in relative output of wideband source as a function of frequency, with respect to 1 kHz and measured directly at the wideband output connector.

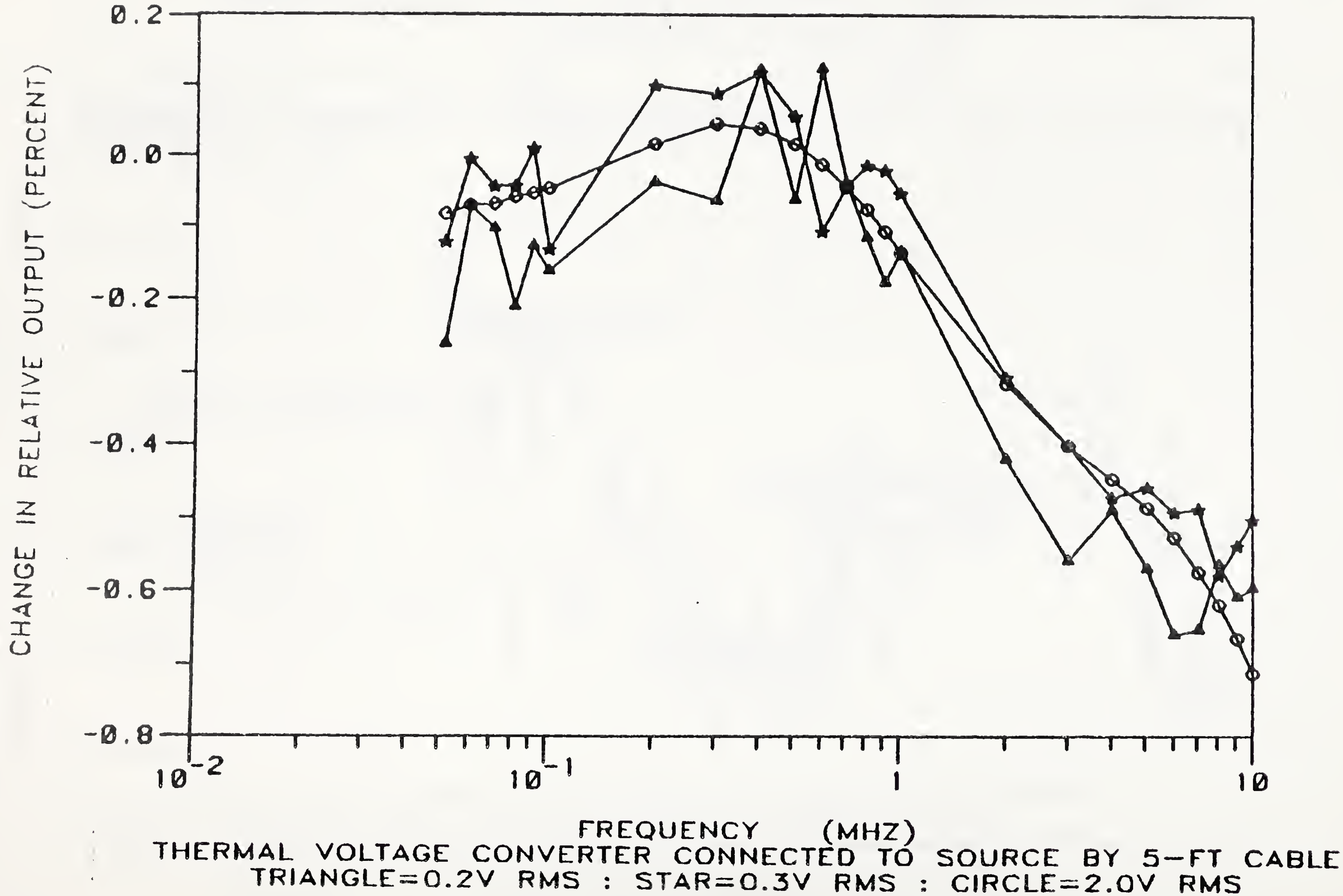

Figure 4. Change in relative output of wideband source with respect to 1 kHz as a function of frequency and measured at the end of 1.5 m (5 feet) of coaxial cable.

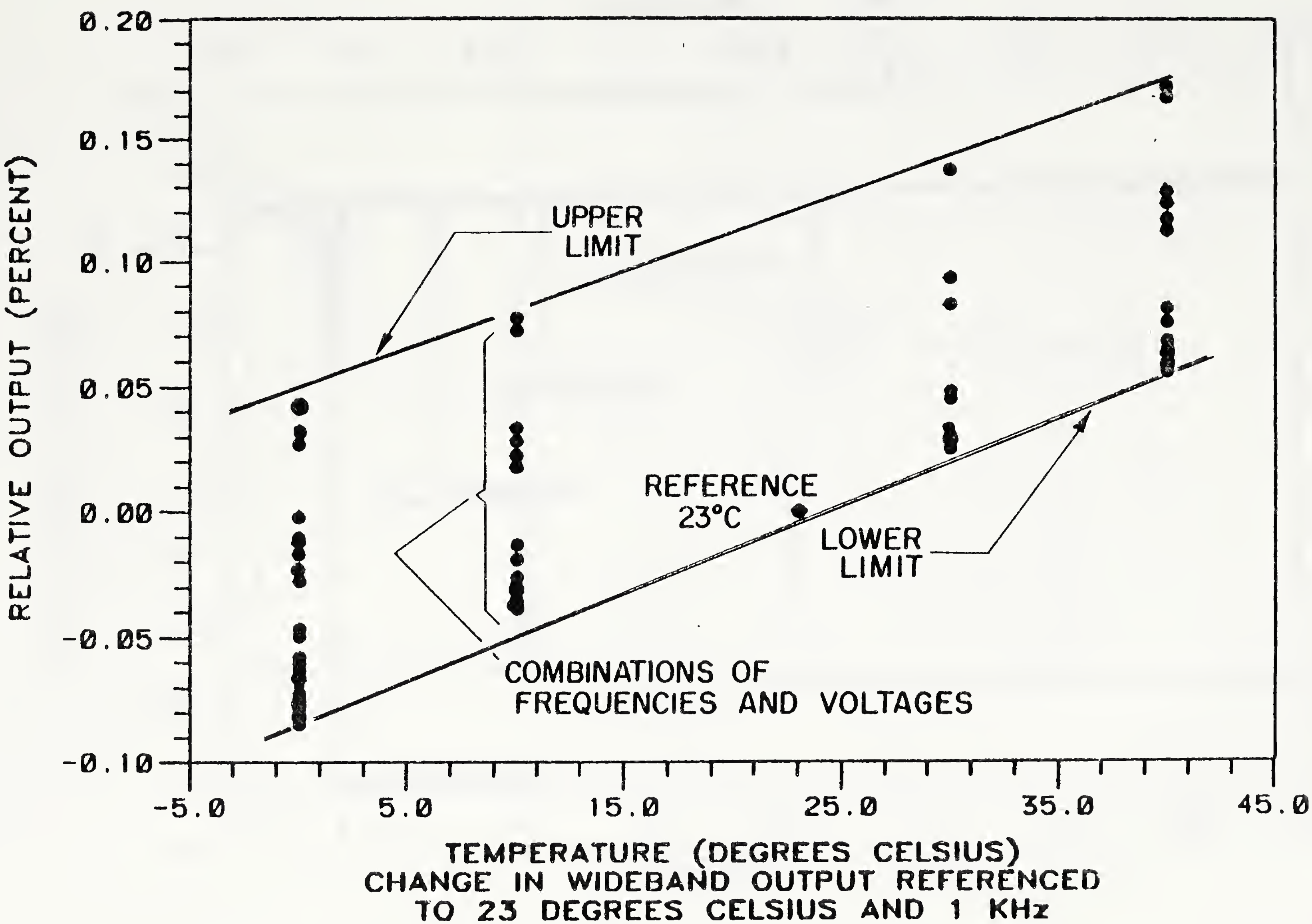

Figure 5. Change in output amplitude of the wideband source as a function of temperature.

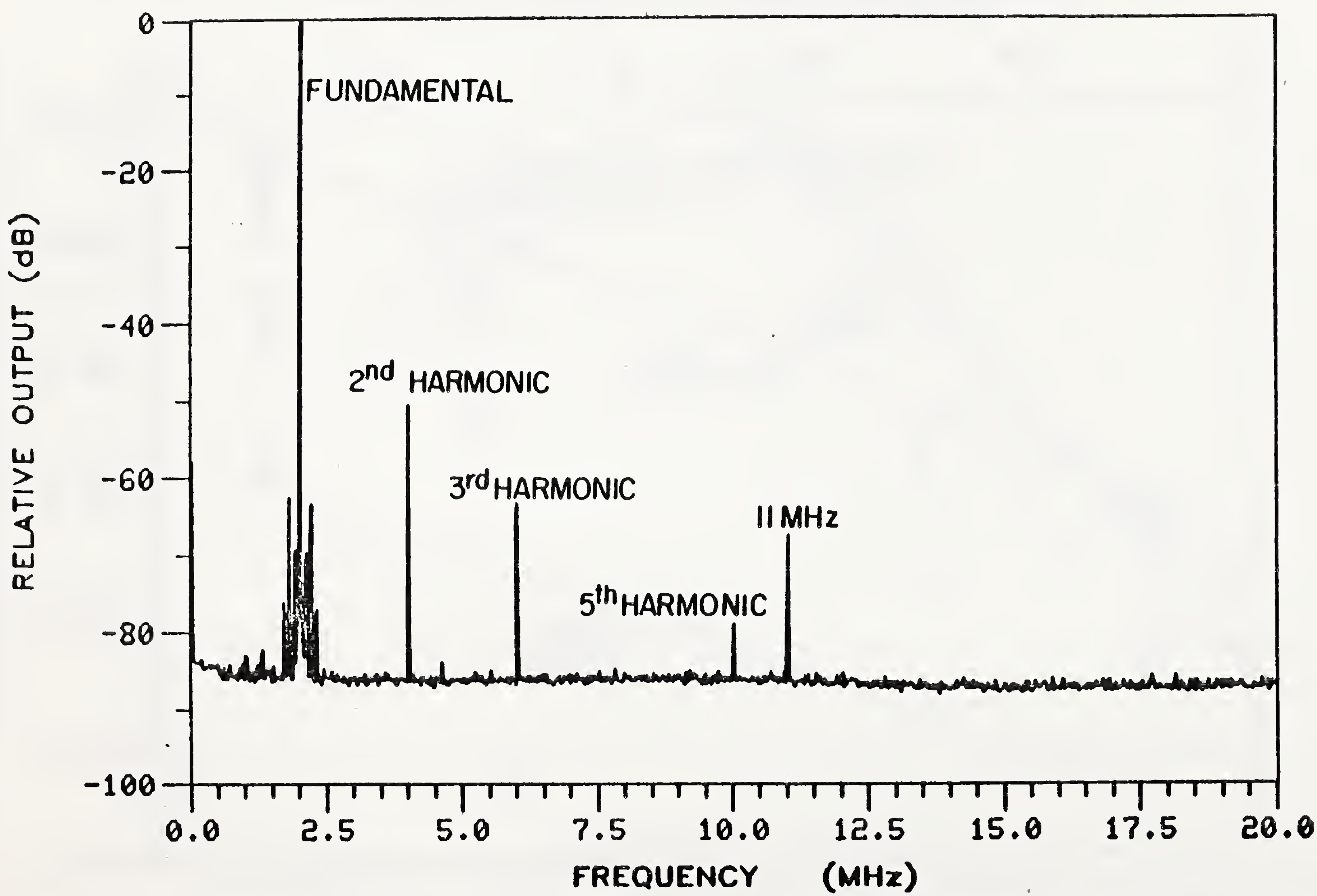

Figure 6. Spectrum of wideband source output at 2 MHz.

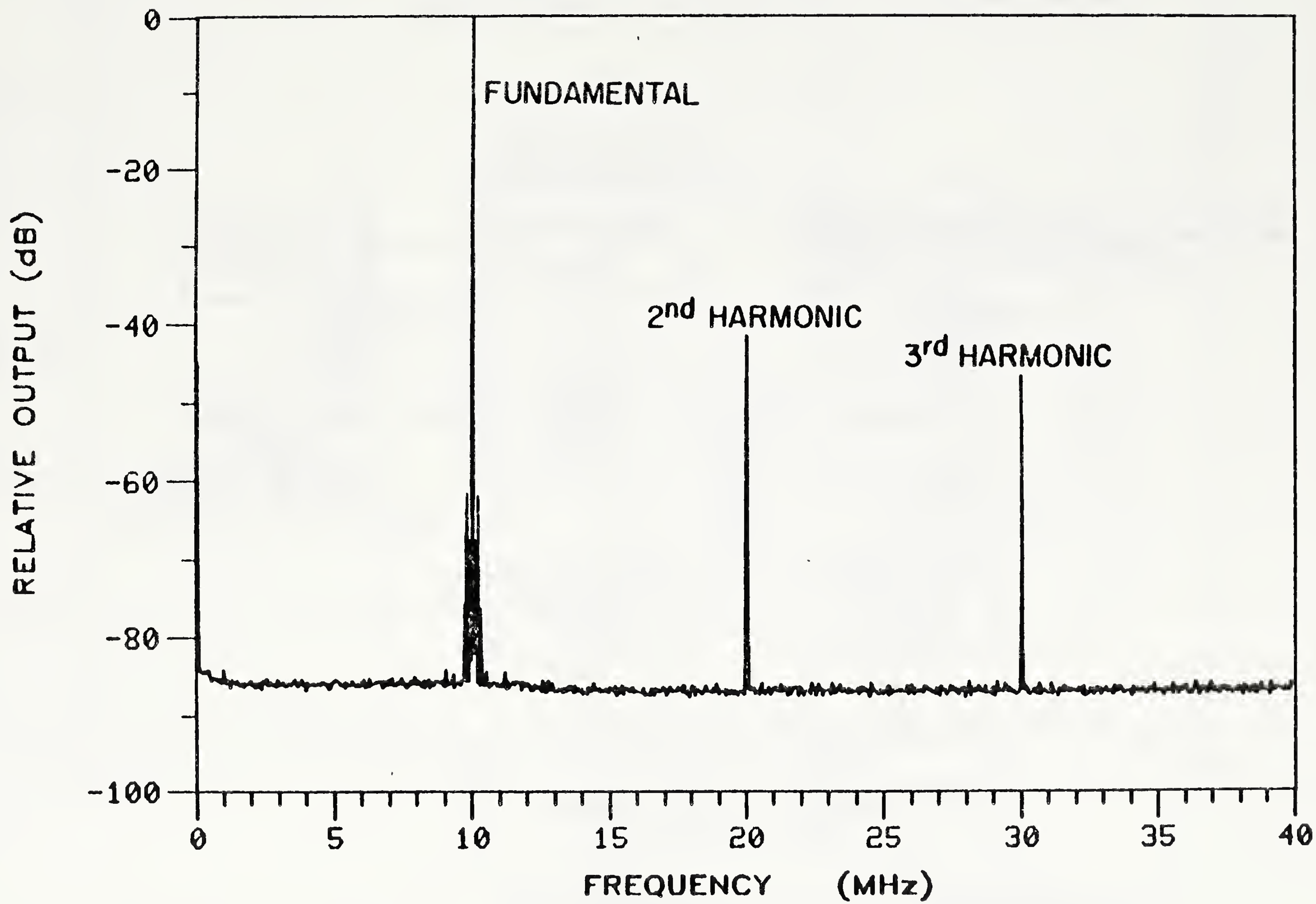

Figure 7. Spectrum of wideband source output at 10 MHz.

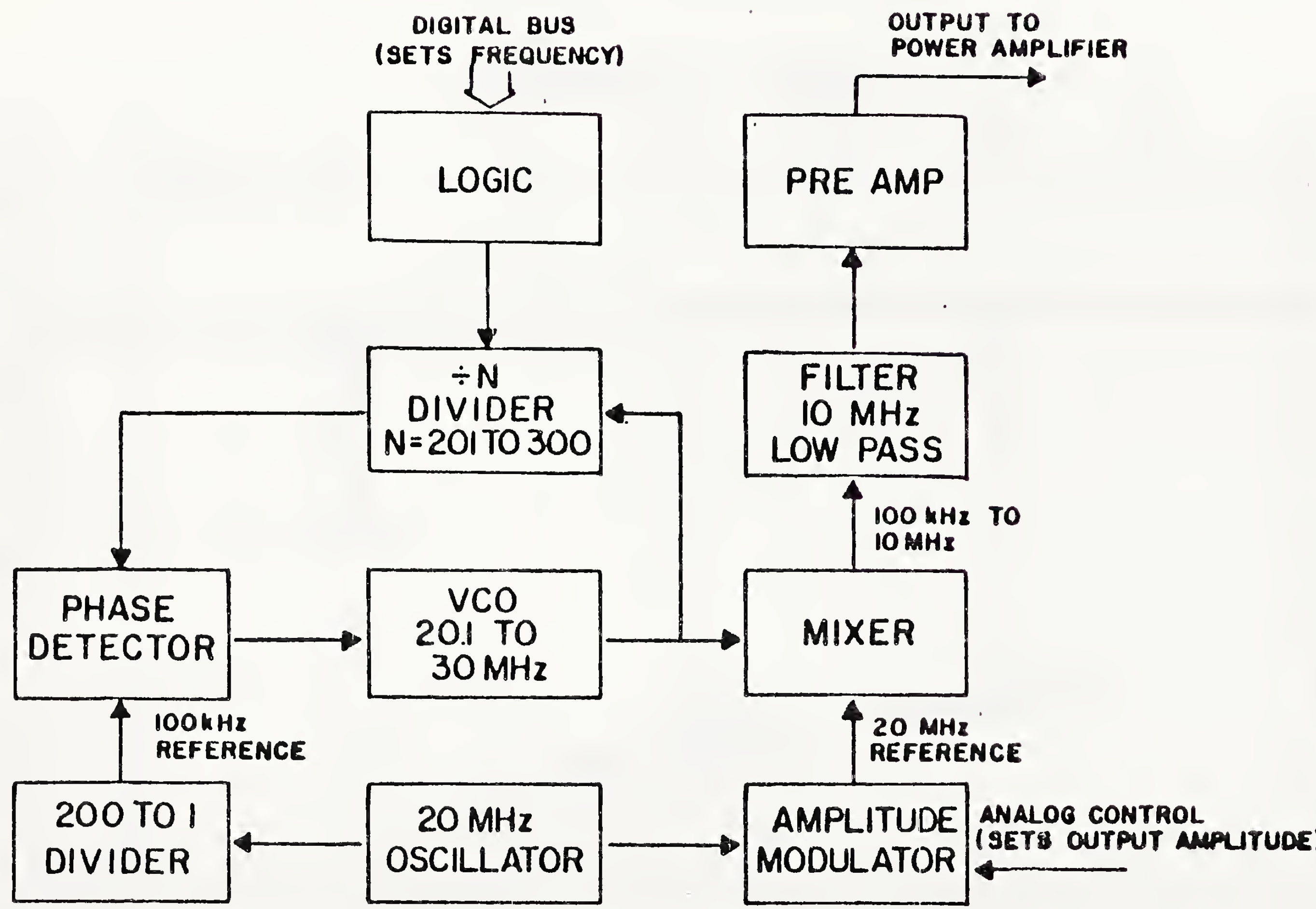

Figure 8. Block diagram of oscillator used in wideband source.

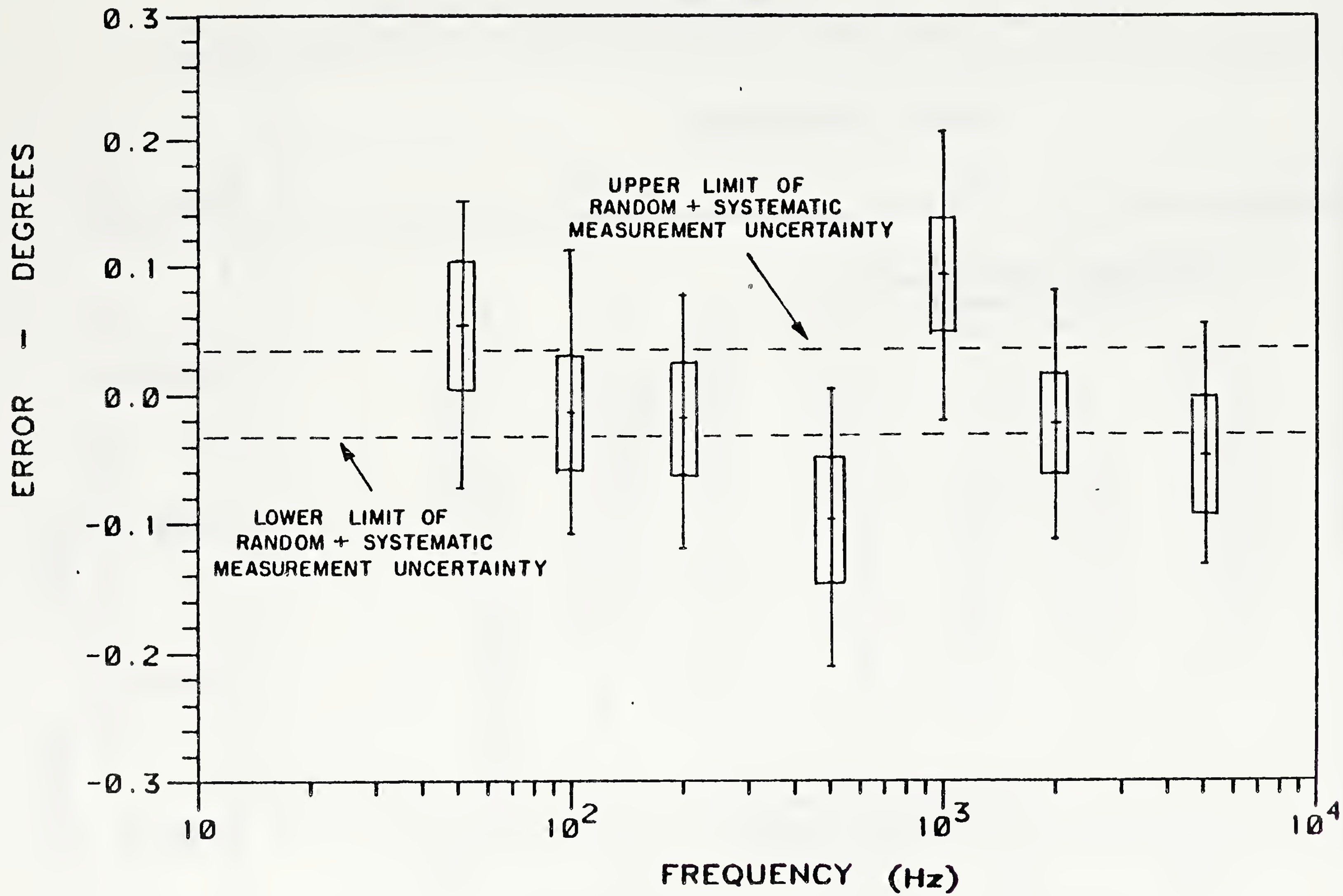

Figure 9. Relative errors of a commercial phase angle generator measured by the phase angle meter.

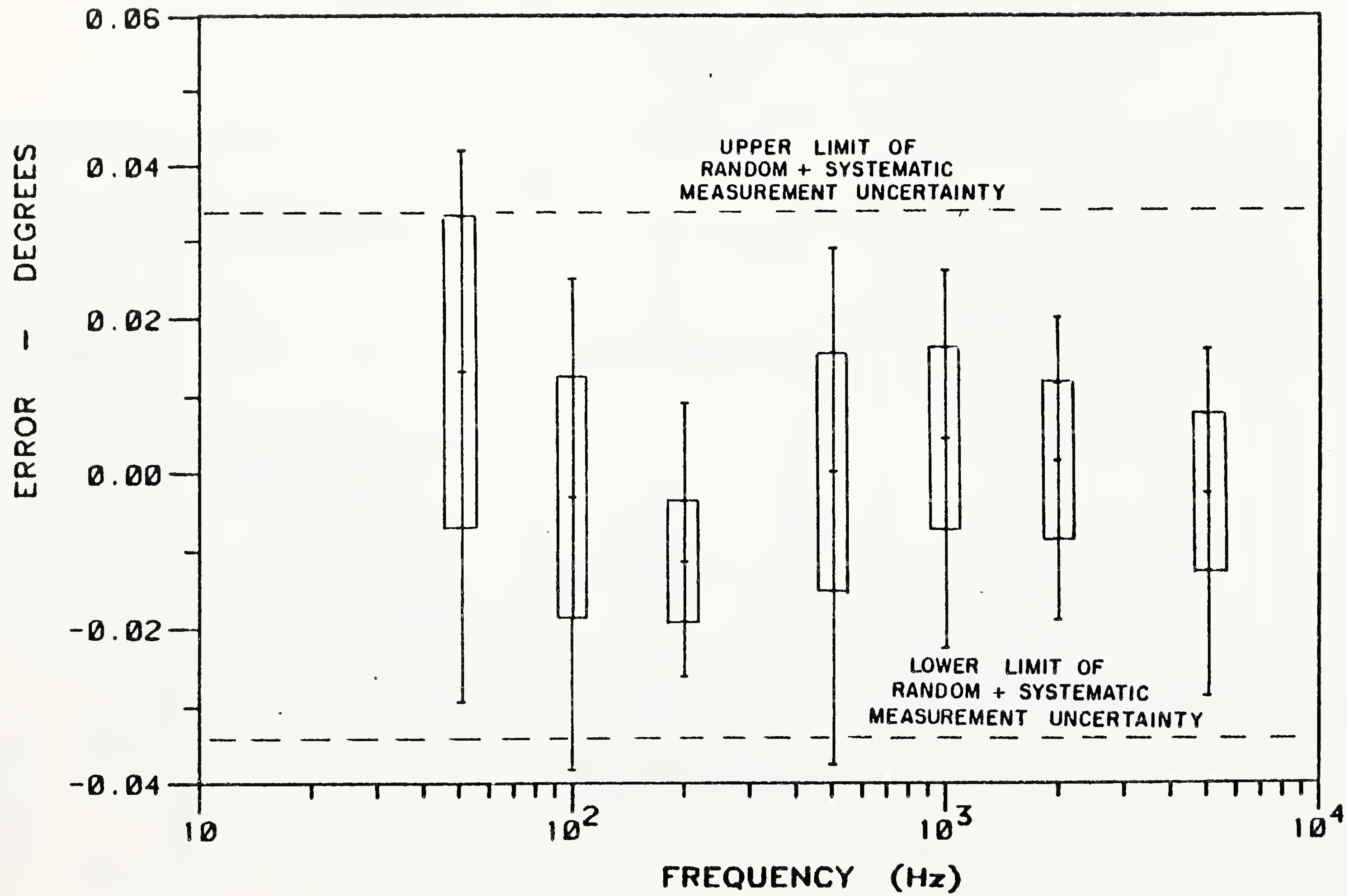

Figure 10. Relative errors of the NBS Phase Angle Calibration Standard measured by the phase angle meter.

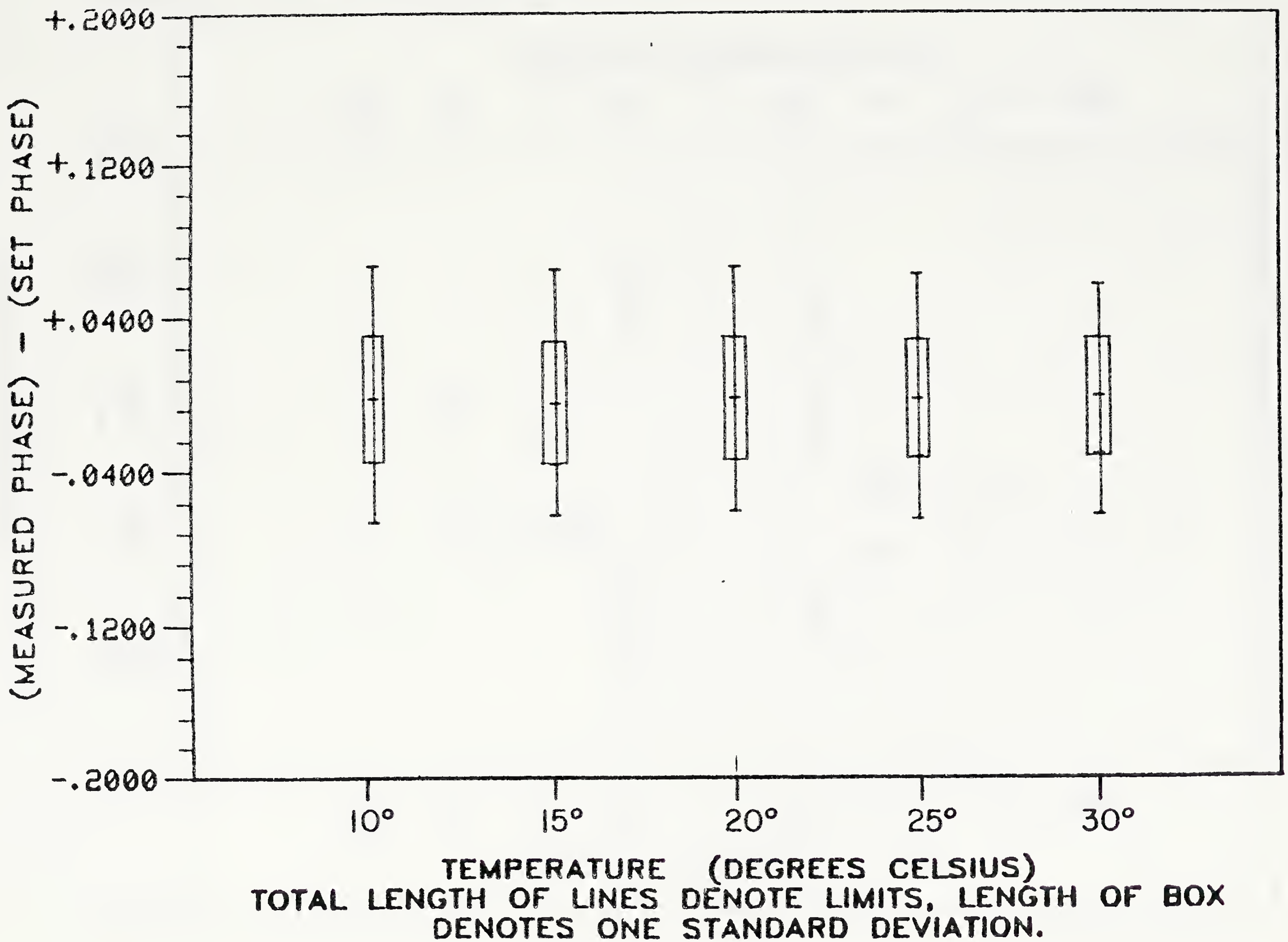

Figure 11. Relative errors of the NBS Phase Angle Calibration Standard measured by the phase angle meter and plotted as a function of temperature.

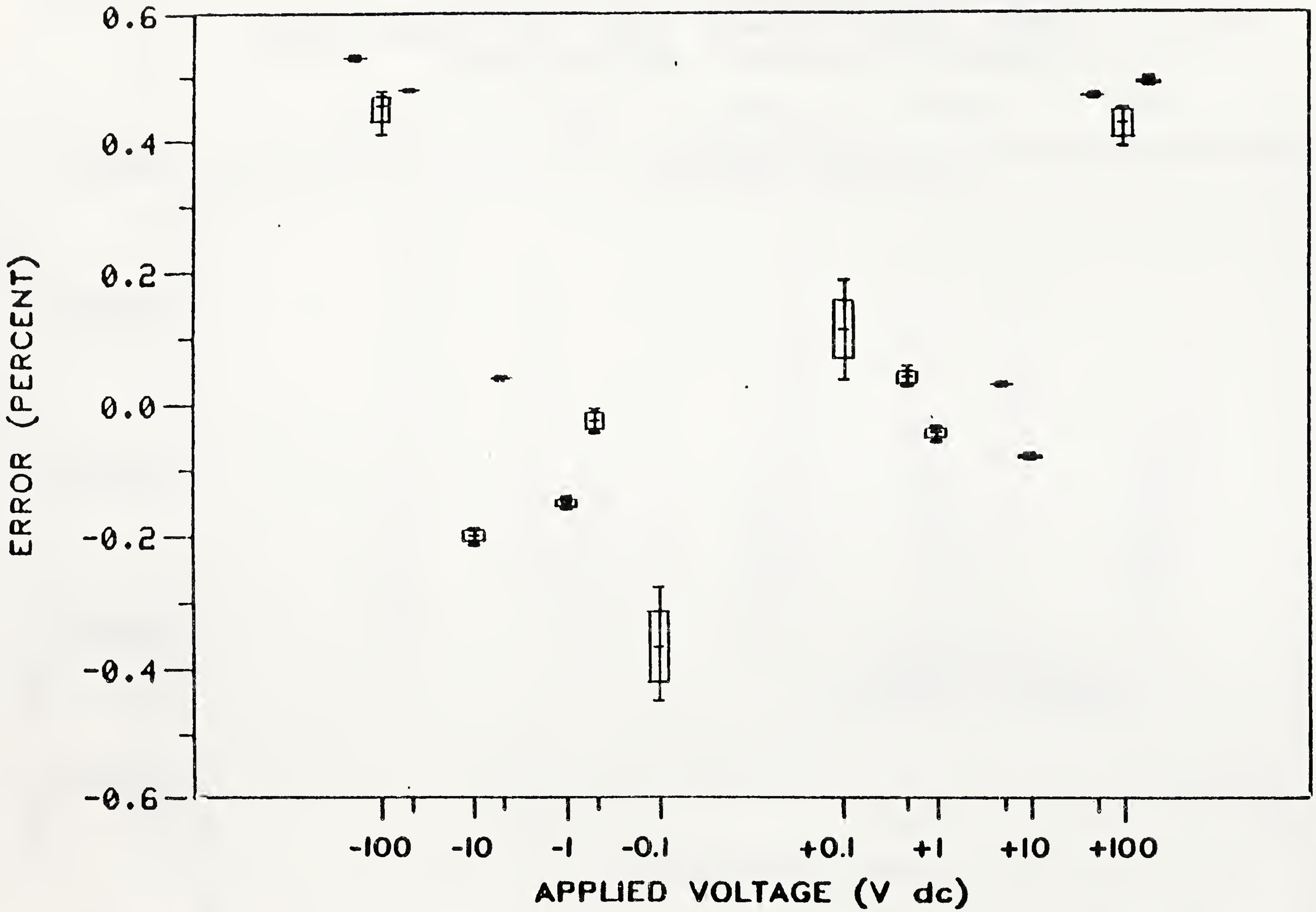

Figure 12. The percentage error of voltage measurements over the range of -195 to +195 V dc as obtained from the September 1982 data.

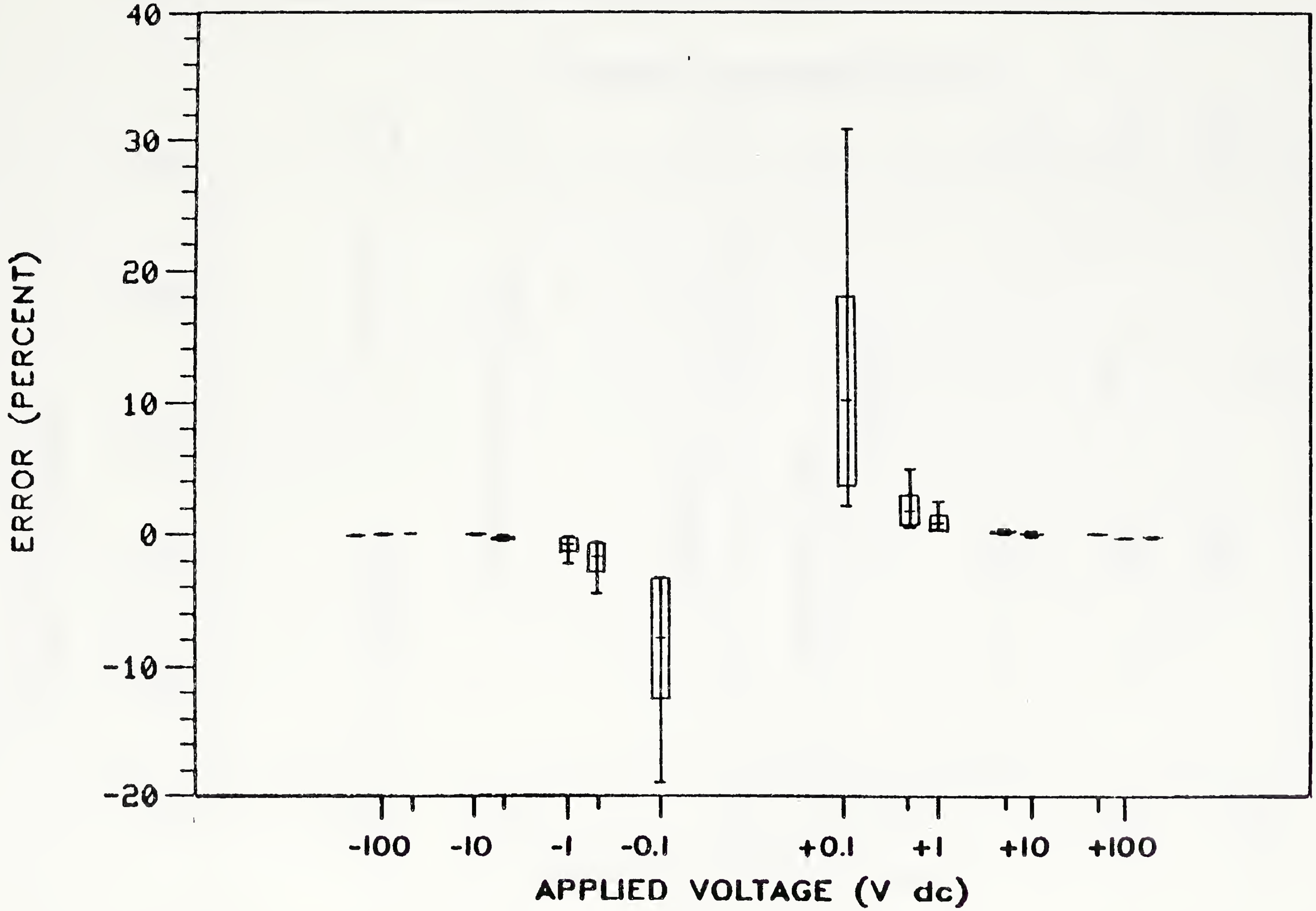

Figure 13. The percentage error of voltage measurements over the range of -195 to +195 V dc as obtained from the April 1981 data.

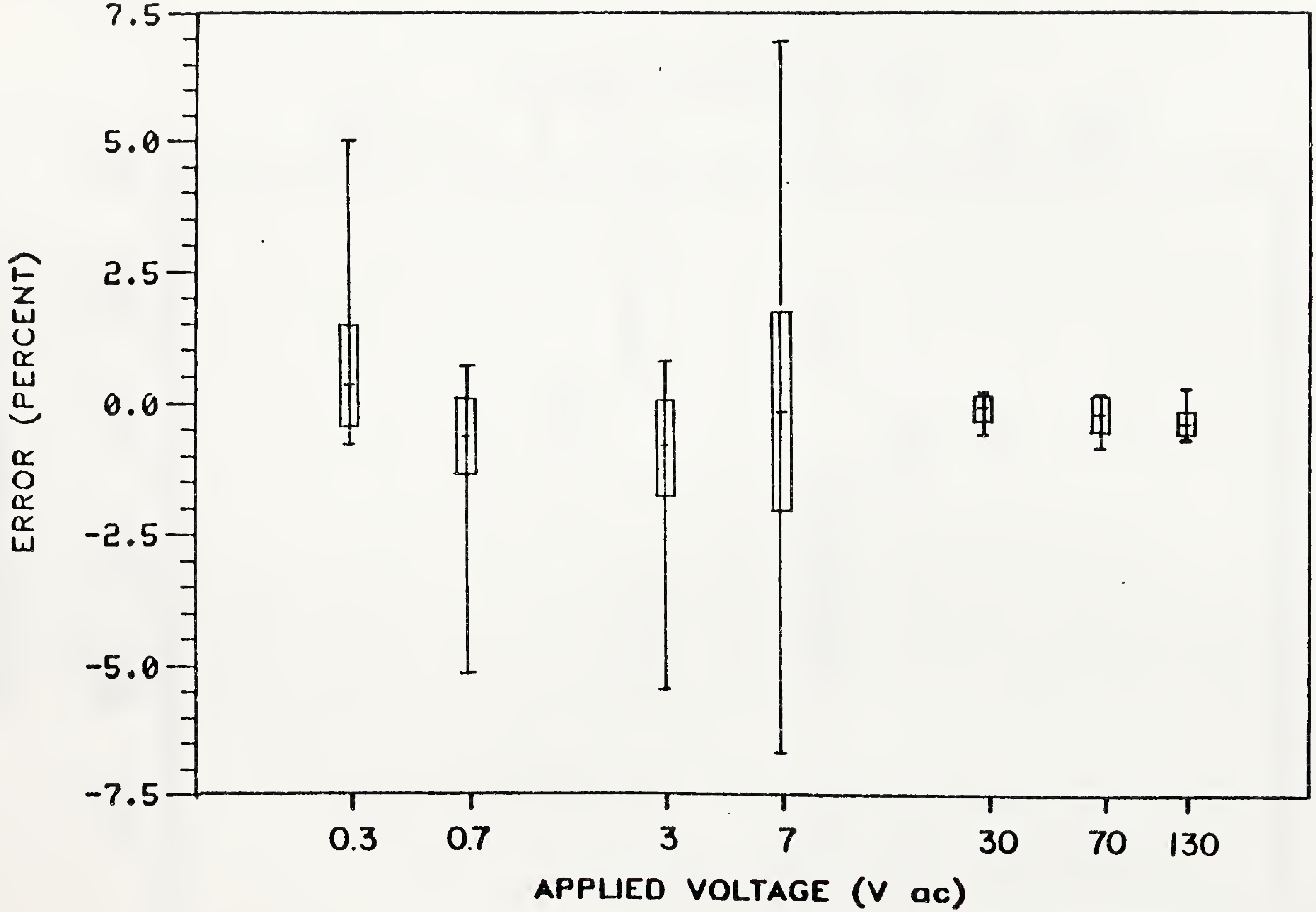

Figure 14. The percentage error of voltage measurements over the range of 0.3 to 130 V ac (rms) as obtained from the September 1982 data.

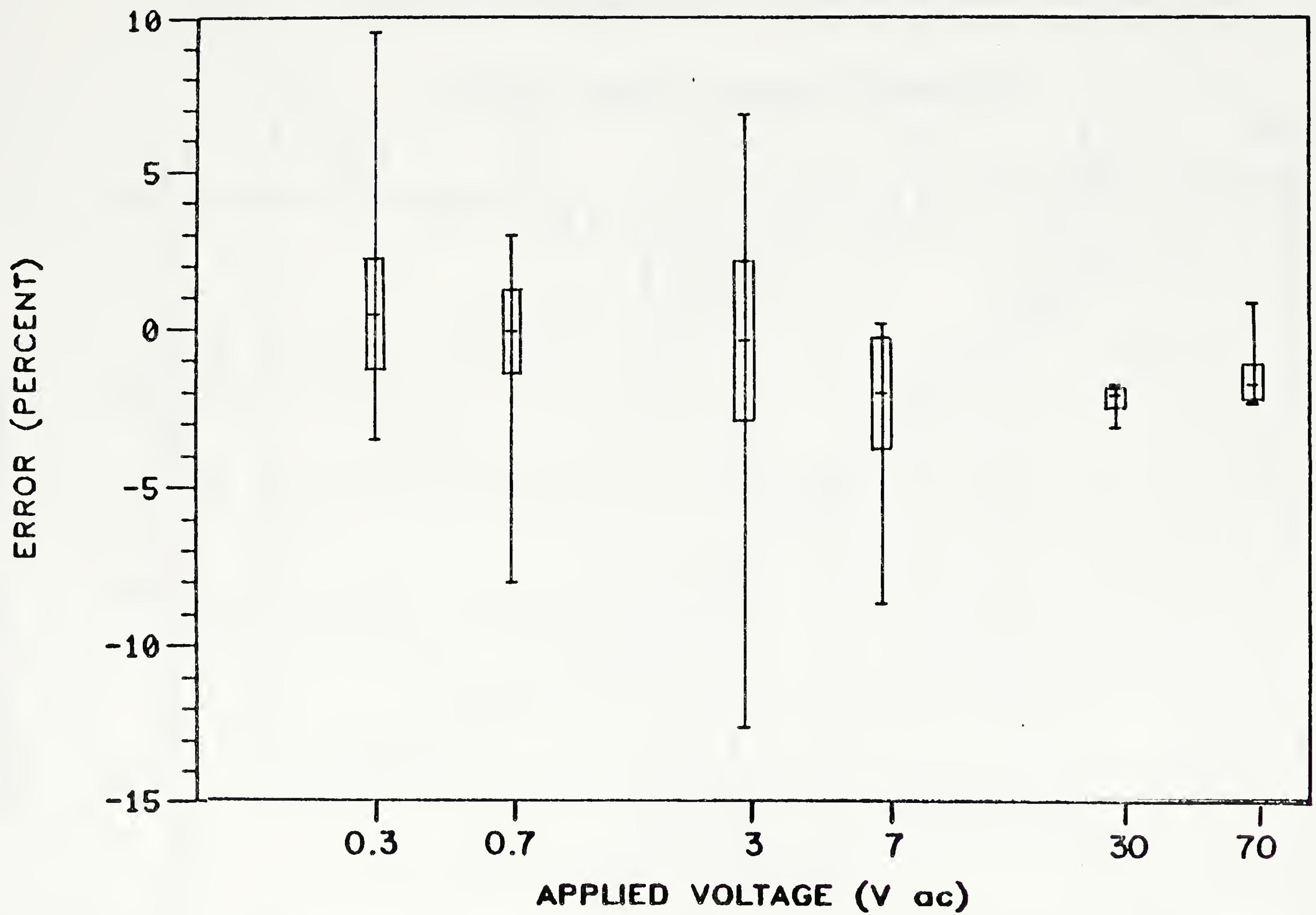

Figure 15. The percentage error of voltage measurements over the range of 0.3 to 70 V ac (rms) as obtained from the April 1981 data.

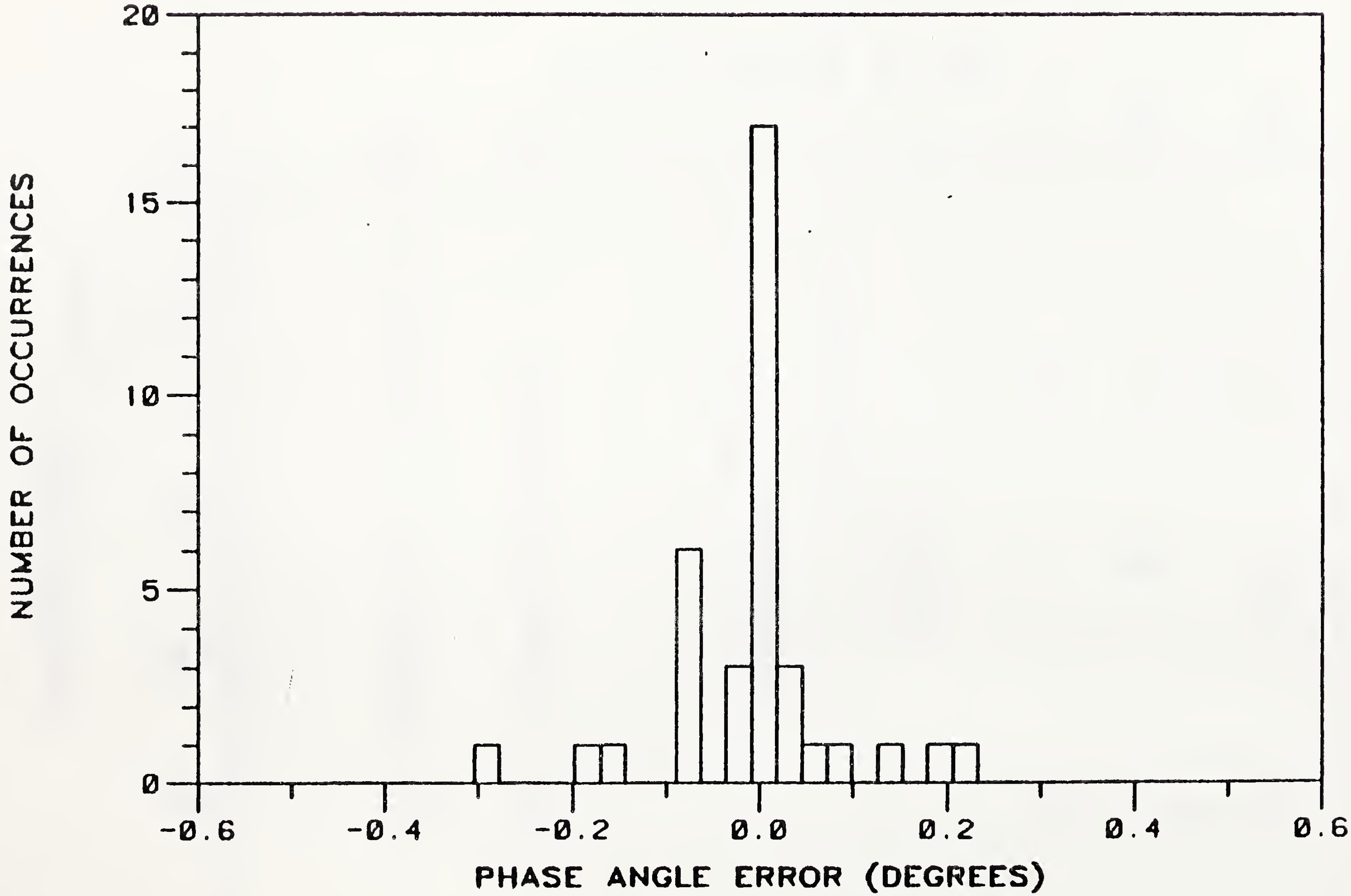

Figure 16. A histogram of the deviations of phase angle error as obtained from the September 1982 data.

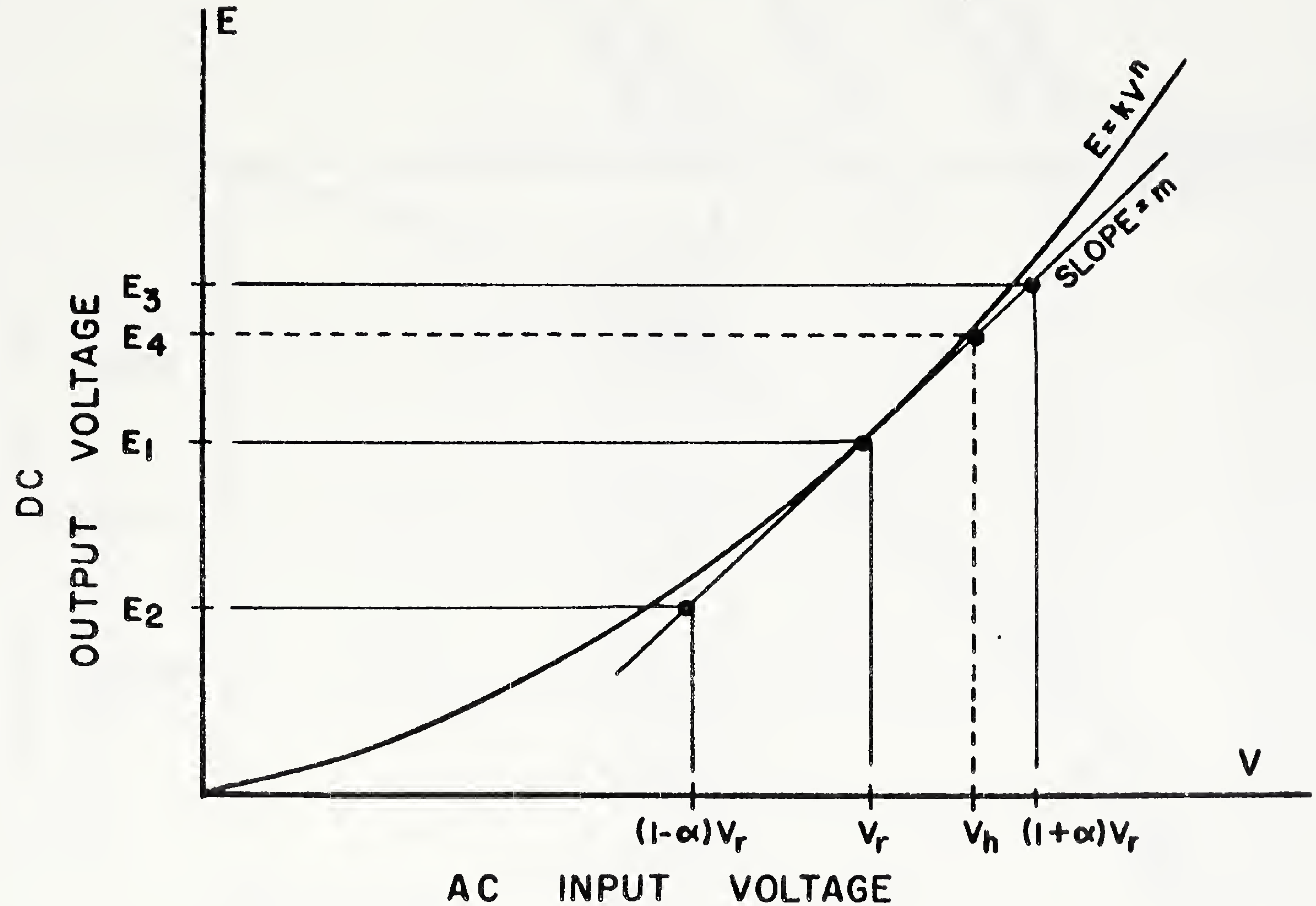

Figure 17. A plot of the relationship between the ac input voltage, V, and the dc output voltage, E, for a thermal voltage converter.

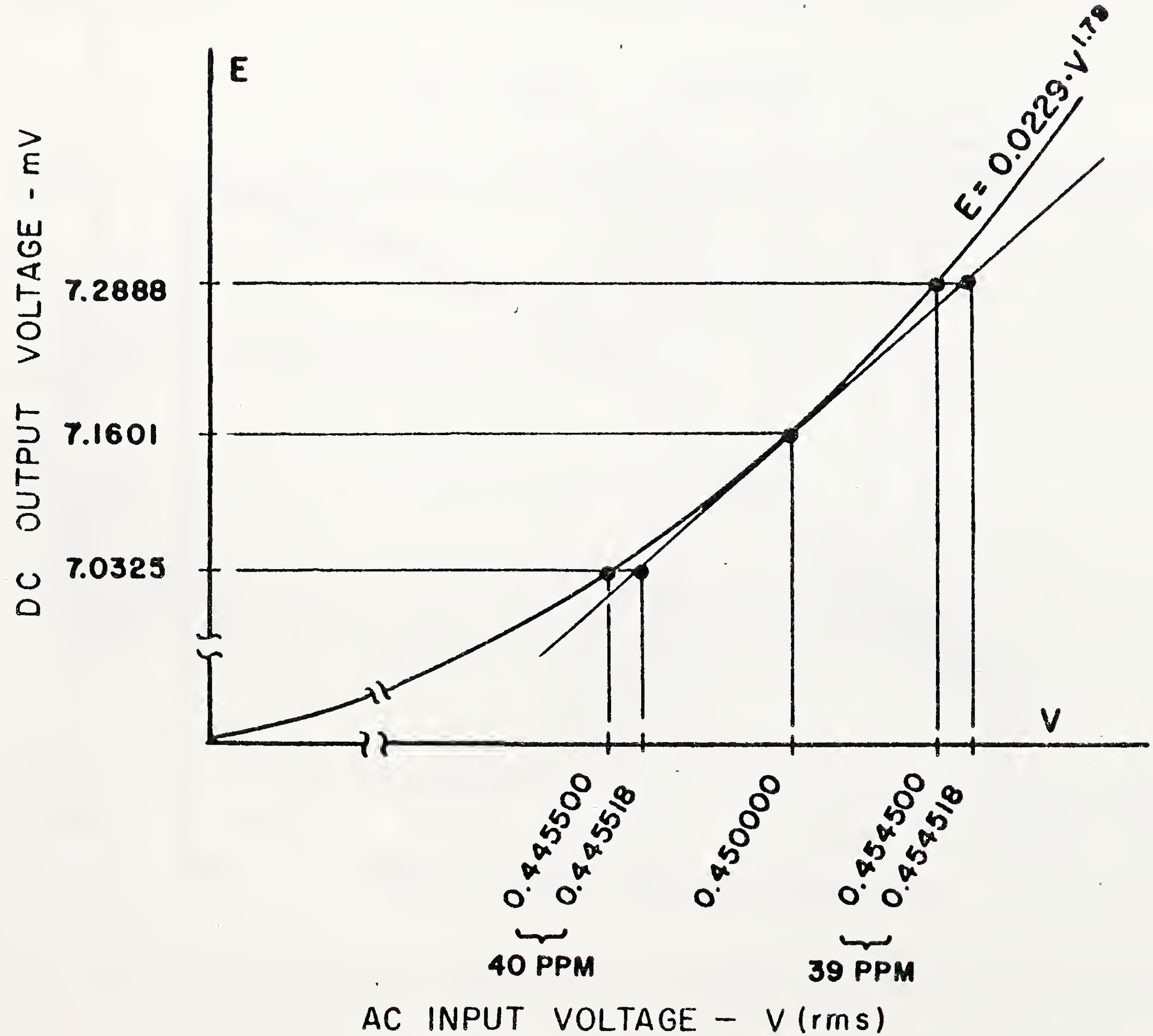

Figure 18. A plot of typical errors encountered by using the straight-line interpolation method described in Appendix A.

Table 1. Measured variations in contact resistance of a BNC connector.

Observation Number	Connector Undisturbed Between Observations	Connector Disconnected and Reconnected Between Observations
1	50.031	50.321
2	50.031	50.321
3	50.031	50.350
4	50.032	50.630
5	50.029	50.318
6	50.030	50.155
7	50.029	50.327
8	50.029	50.277
9	50.030	50.320
10	50.029	50.321
11	50.029	50.327
12	50.031	50.325
13	50.030	50.335
14	50.030	50.414
15	50.031	50.009
16	50.031	50.307
17	50.033	50.237
18	50.032	50.317
19	50.029	50.300
20	50.033	50.310
Average of 20 Observations:	50.030	50.311
Standard Deviation of 20 Observations:	0.006	0.488

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This work describes an experimental approach to verify the performance of selected third generation automatic test systems. As part of an ongoing project, this work builds on previous research in methods to characterize the accuracy of test systems measuring ac and dc voltages. This report describes the methods used to characterize a high frequency ac voltage source covering a voltage range of approximately 225 mV to 2.8 V rms over a frequency range of 50 kHz to 10 MHz. In addition, the characterization of a precision phase angle generator, designed and built at NBS, is described. Finally, the measurement results obtained with an automatic test system, using a new software operating system and the ac, dc, and phase angle transport standards, are discussed in detail.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

ATE; automatic test systems; calibration; characterization; evaluation; field testing; performance test; third generation system.

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