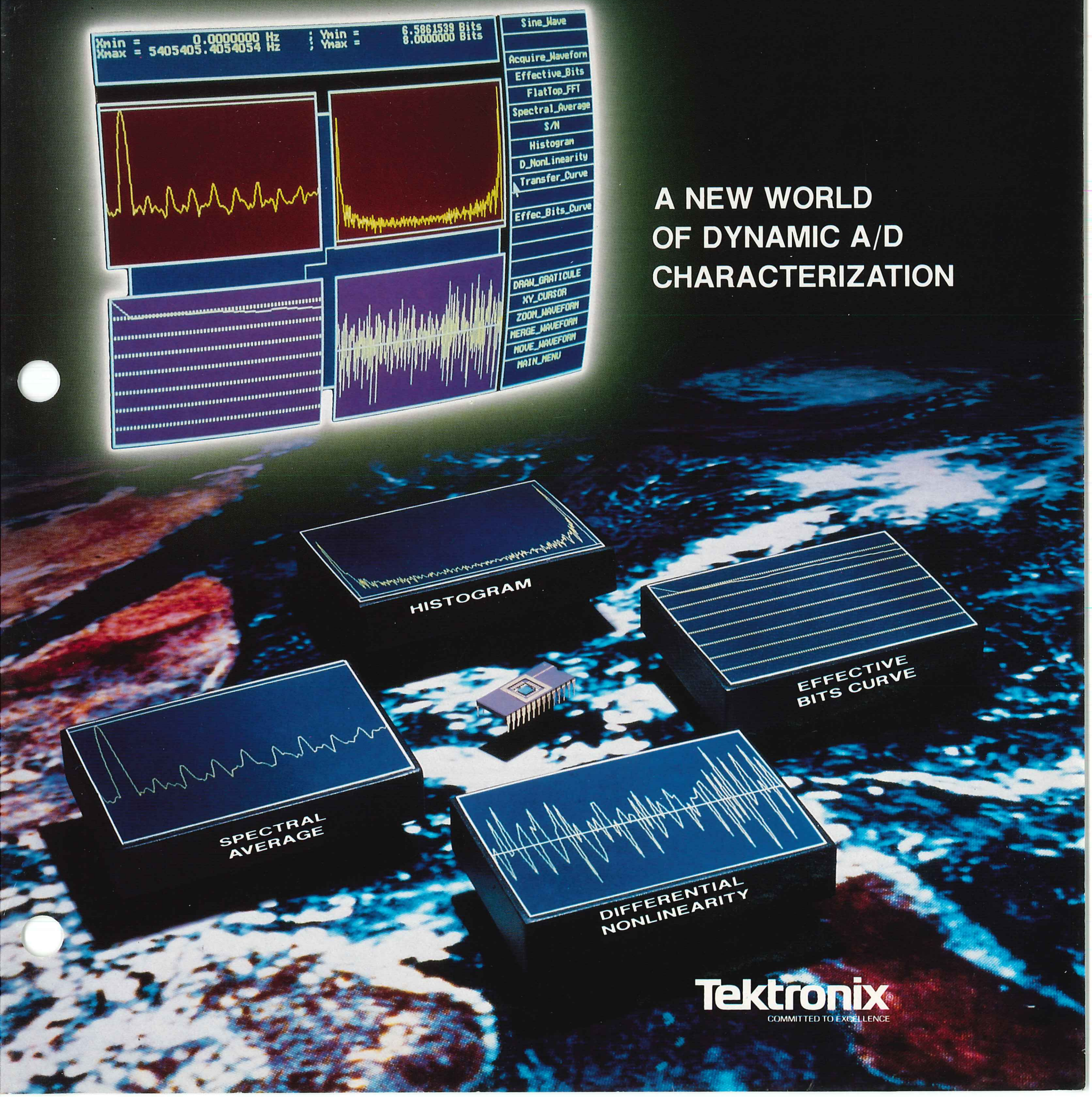
TEK APPLICATION INFORMATION

VOL. 13 NO. 2
SUMMER 1988

HANDSHAKE

NEWSLETTER OF INSTRUMENTATION AND INSTRUMENT SYSTEMS



A NEW WORLD OF DYNAMIC A/D CHARACTERIZATION

Tektronix
COMMITTED TO EXCELLENCE

Prices in HANDSHAKE

Many of you have requested that we include prices with products described in **HANDSHAKE**. While we realize this is important information when considering a product, we'd like to give you some reasons why we don't print prices in **HANDSHAKE**.

First of all, each issue of **HANDSHAKE** has a long lifetime — many of you file old issues and use them as references. As a result, we often get reply cards from issues that are six or seven years old. This information would become "dated" much sooner if prices were included.

Second, **HANDSHAKE** is an international publication; prices of products listed in **HANDSHAKE** vary both by country and the current exchange rate. In order to provide prices for all of our readers, we would need to print multiple versions. Even then, fluctuations in exchange rates would make them inaccurate before they were even delivered.

Now we don't want to leave the impression that we don't care about your need for information. As a good source for product prices, we recommend the Tektronix product catalog.

For products not listed in the catalog or if you don't have a catalog handy, U.S. customers, can get current prices via a toll-free, no-obligation phone call to the Tektronix National Marketing Center. Besides prices, you can get answers to any questions not answered by **HANDSHAKE** as well as information on product availability.

For our international readers, Tektronix has offices in most major cities around the world with a staff ready to quote price and availability based upon local exchange rates. If you are not sure of the location of your nearest Tektronix Sales Office, call the applicable Tektronix area office listed below.

Q&A

Q I would like to use the HC100 Color Plotter with instruments that are not listed as having an interface for the HC100 (see **The HC100 — Perfect companion for Tektronix digital storage oscilloscopes**, Winter 1987/88 **HANDSHAKE**). Can this be done?

A A recent addition to Signal Processing and Display software (SPD) is a driver for the HC100 Color Plotter. This allows plotting displays from several instruments that do not interface directly with the HC100.

An even larger number of instruments can gain access to the HC100 if GURU II (GPIB User's Resource Utility) software is used in conjunction with SPD. Waveforms acquired by GURU can be passed to SPD using the ADIF data interchange format. For information on Tektronix instruments that can be interfaced using this scheme, refer to the **MS-DOS Tekware At A Glance** table in the Winter 1987/88 **HANDSHAKE**. This issue also describes ADIF.

SPD Version 2.1 and GURU II Version 3.0 are required for HC100 and ADIF compatibility. Contact your local Tektronix Sales Office or representative for update information.

Douglas Howard
Measurement Systems Division

Q Is there any way to make the job of checking and debugging the cabling of a TSI 8150 Test System Interface configuration simpler and easier?

A A software package called EZ-Switch is currently being shipped with all TSI-8150 systems. This software runs on the PEP 301 Systems Controller to provide a software front-panel for the TSI 8150. The display provides a menu listing of all cards and modules currently installed in the TSI 8150. When a card is selected on the menu, a pictorial view shows the current settings of the relays for this card/module. You can easily change the state of a specific relay on the screen, either with the mouse or with the cursor keys; the appropriate command is automatically sent to the TSI 8150 to change the configuration.

If you currently own a TSI 8150 and would like a copy of EZ-Switch, contact your local Tektronix Sales Office or representative.

Sid Blachford
Measurement Systems Division

Questions?

Do you have a question on signal measurements? Send it to **HANDSHAKE** Q&A, M/S 02-382, P.O. Box 500, Beaverton, OR 97077, or use the Comments section of the reply card to send in your question. We'll get a personal answer to you as soon as possible and print questions of general interest in future Q&A columns. Your name and name of your company will be used with the printed question unless you specifically request that it be withheld.

Manager and Editor: A. Dale Aufrecht
Production Editor: Anita Hicks
Graphic Design: Phil Malyon
Typesetting: Interface Typesetting
Printing: Dynagraphics, Inc.

Use the reply card in this issue to request a free subscription to **HANDSHAKE**.

For information on articles in this issue or to contribute articles for publication, contact the **HANDSHAKE** Staff toll free at 1-800-835-9433, EXT 1623, or write to **HANDSHAKE**, Group 157 (M/S 02-382), P.O. Box 500, Beaverton, OR 97077.

HANDSHAKE is provided free of charge by Tektronix, Inc., as a forum for people interested in instrumentation and instrument systems. As a free forum, statements and opinions of the authors should be taken as just that — statements and opinions of individual authors. Material published in **HANDSHAKE** should not be taken as or interpreted as statement of Tektronix policy or opinion unless specifically stated to be such.

Also, neither **HANDSHAKE** nor Tektronix, Inc., can be held responsible for errors in **HANDSHAKE** or the effects of these errors. The material in **HANDSHAKE** comes from a wide variety of sources, and, although the material is edited and believed to be correct, the accuracy of the source material cannot be fully guaranteed. Nor can **HANDSHAKE** or Tektronix, Inc., make guarantees against typographical or human errors, and accordingly no responsibility is assumed to any person using the material published in **HANDSHAKE**.

Copyright © 1988 Tektronix, Inc. All rights reserved. Printed in U.S.A. Tektronix products are covered by U.S. and foreign patents, issued and pending. Information in this publication supersedes that in all previously published material. Specification and price change privileges reserved.

Tektronix, Inc., is an equal opportunity employer.

TEKTRONIX, TEK, and TEKWARE are trademarks of Tektronix, Inc.

IBM PC, PC/XT, and PC/AT are trademarks of International Business Machines Corporation. Centronics is a trademark of Centronics Corporation. PC-TALK is a trademark of The Headlands Press. Hayes and Smartmodem are trademarks of Hayes Microcomputer Products, Inc. Turbo Pascal is a trademark of Borland International.

FOR MORE INFORMATION:

United States readers can use the postpaid reply card in this issue to request a free subscription to **HANDSHAKE** or more information on products described in this issue. For product prices and information, call the Tektronix National Marketing Center 1-800-426-2200.

International readers please contact the Tektronix Sales Representative for your country. To find the address of your representative, contact the following Tektronix area offices:

Central & South America, Asia, Australia, and Japan
Phone: (503) 627-1915

France, Africa
Phone: 33 (169) 86 81 81

Federal Republic of Germany
Phone: 49 (221) 77220

United Kingdom
Phone: 44 (6284) 6000

Northern Europe Area
Phone: 31 (2503) 65265

Southern Europe Area
Phone: 41 (42) 219192

Eastern Europe and Middle East
Phone: 43 (222) 68-66-02-0

Canada
Phone: (705) 737-2700

A look inside

As components used in product design become more complex, the testing process to determine their performance becomes equally more complicated. But that doesn't mean that the testing process has to become more difficult for the user.

The feature product in this issue is the PTS101 A/D Characterization Test System — a product which makes the complex task of testing A/D components as easy as selecting a test from a menu. The article **Asynchronous dynamic testing of A/D converters** describes the process of testing A/Ds. Then the article **Dynamic characterization of A/D converters** describes how the PTS101 from the Measurement Systems Division makes those tests both easily and accurately and goes through a sample test.

For more information on component testing, the application article **Isolating failures on multi-pin devices** describes how the new S370FA Failure Analysis system from Measurement and Accessory Products can reduce the time required to isolate faults in multi-pin devices. Other new products from this division are described in the articles **Testing high-power devices** and **Software makes device testing easier.**

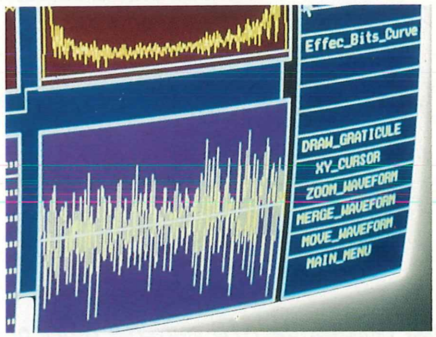
The application article **Wind tunnel automation** describes how programmable instrumentation can be used to update older installations at considerable savings in both time and dollars. A second application article describes how to set up a remote test system using the RS-232-C interface and a pair of modems. To round out this issue, we have an article on warranty options for your test system.

If you would like help with any of your test and measurement applications, contact your local Tektronix Field Office or sales representative. And tell them you read about it in **HANDSHAKE!**

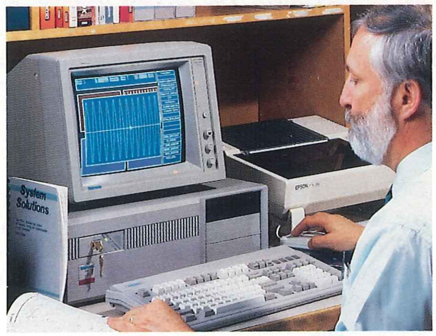
A. Dale Aufrecht
HANDSHAKE Editor

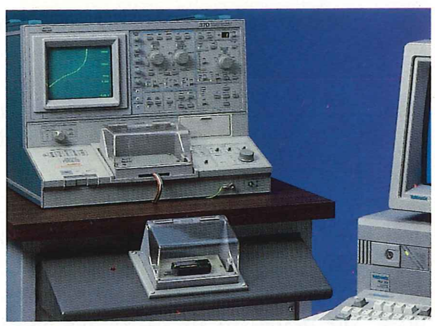
For information or prices on products described in this issue, call the Tektronix National Marketing Center 1-800-426-2200

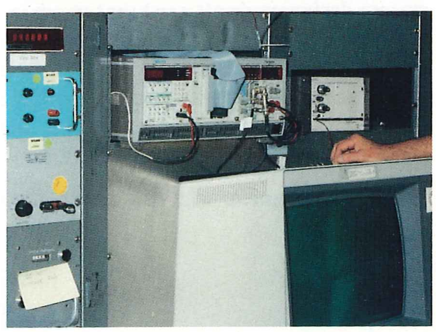
Table of contents

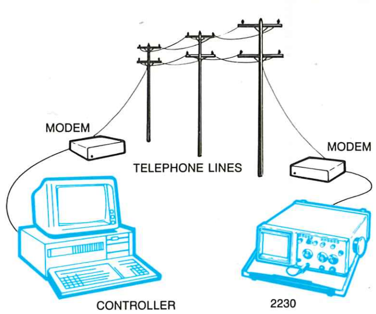


Graphic design by Phil Malyon.
Photography by Mike Ketchum,
Tektronix Photo Studio









Asynchronous dynamic testing of A/D converters

Y.C. Jenq, Ph.D.
Electronic Systems Lab
Tektronix, Inc.

Abstract

In the design of digitizer systems, the A/D converter is one of the major components whose performance must be evaluated. The process involves examining the A/D chip performance, first in an evaluation board, and then in the prototype environment. Without specialized measurement techniques, this is a difficult or impossible task to do. This article describes the problems encountered with typical A/D converter designs and how measurements can be made to uncover them.

Problems encountered in digitizer system design

Every system engineer would like to design the ideal analog-to-digital converter (A/D) system with the characteristics shown in Figure 1. The analog input signal is sampled at a uniform time interval T. The sampled data is then processed by a quantizer with a staircase type of transfer characteristic.

For a perfect A/D, a line through the middle of each stairstep would result in a straight line passing through the origin at a 45 degree angle. Any deviation from the ideal indicates an error. If the line does not pass through the origin, the A/D has offset error. If the angle of the line is not 45 degrees, the A/D has gain error. If the line is not straight, the A/D has nonlinearity error.

The sampling error in Figure 2 is indicated by the symbol Δ. Note that the figure shows an obvious nonlinearity error. Defining the gain error and the offset error is not that easy, however. Normally, you can try to fit a straight line to the curvy transfer characteristic (the dotted line) and define gain and offset errors accordingly.

A model of a real-life A/D is shown in Figure 3. The model indicates all the important errors that are, in practice, encountered in an A/D. These are sampling time offset, gain error, DC offset, and amplifier nonlinearity.

Different engineers have varying evaluation requirements for A/Ds. The A/D designer must find out everything about the A/D transfer characteristic in order to improve the design of the A/D, but most system designers don't need that much information. For example, the designer who plans to use an A/D in a digital spectrum analyzer is concerned about harmonic distortion due to nonlinearity and the signal-to-noise ratio of the A/D system.

The test engineer who uses digital data to make waveform parameter measurements wants to know the equivalent additive noise power or the effective bits.

AC characterization of A/D converters

Until recently, most A/D characterization focused on DC tests, despite the fact that an A/D is primarily used to digitize AC signals. This article presents four test procedures which measure the dynamic (or AC) performance of an A/D; effective bits, noise floor and integral nonlinearity, histogram and differential nonlinearity, and clock or aperture jitter. These test procedures are algorithm (software) based, therefore, they only require a low-distortion sine wave test signal. A sine wave is chosen because it can be precisely defined mathematically and is easy to generate with low harmonic distortion. Because the measurements are made asynchronously, they can be easily implemented in desktop controller based hardware systems.

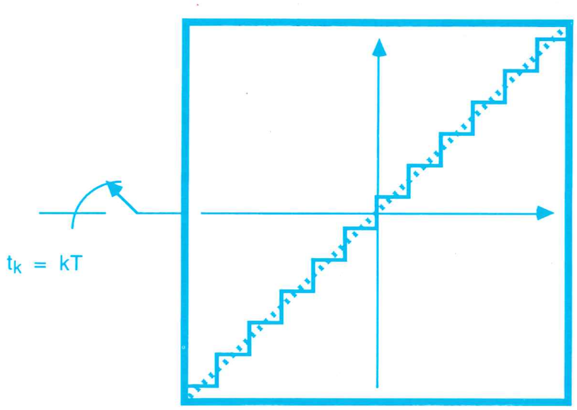


Figure 1. *Transfer characteristics of the ideal A/D system.*

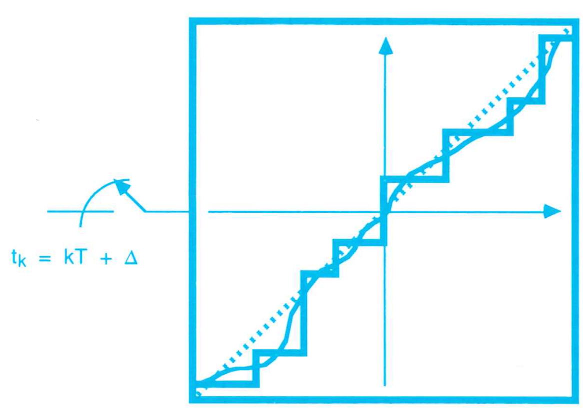


Figure 2. *Transfer characteristics of real-life A/D system.*

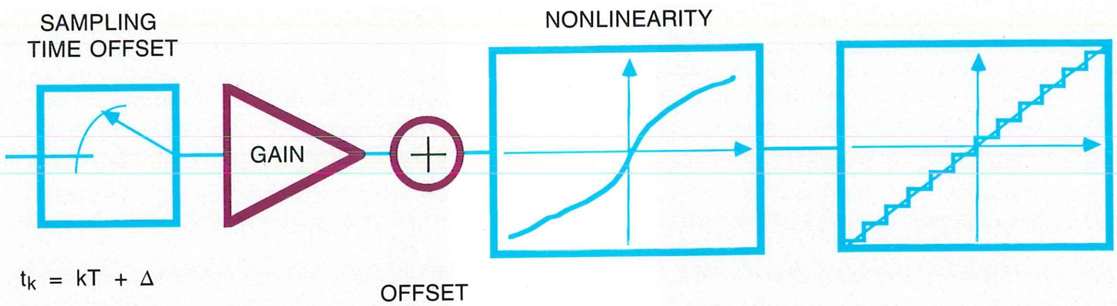


Figure 3. *Model of real-life A/D converter showing source of errors.*

The effective bits measurement

A commonly used definition of effective bits is based upon the assumption that the quantization noise is uniformly distributed and the quantization errors from sample-to-sample are statistically independent. Based upon these assumptions, effective bits can be defined as:

$$B = \mathrm{Log}_2 \left(\frac{\mathrm{FullScale}}{\sqrt{12}\ \mathrm{RMSE}} \right) \qquad [1]$$

where:

B = effective bits
FullScale = full scale of the digitizer
RMSE = root mean square error of the digitized signal

To use this equation for effective bits measurement, one has to choose a test signal in order to compute RMSE. A commonly used test signal is a sine wave, with frequency at about one third of the sampling rate of the digitizer. This choice of frequency is reasonable because it is less than the Nyquist rate and is high enough to test the dynamic response of the digitizer.

This approach is simulated in a computer and the results are shown in the third column of Table 1 under the heading Ideal Effective Bits. It's seen that for an ideal digitizer with resolution higher than five bits, this definition gives reasonably good results (i.e., computed effective bits agree with the designed resolution of the digitizer). When the resolution is below four bits, this definition underestimates the true resolution. So, as long as we're interested in digitizers with resolution greater than five bits, this definition is quite reasonable.

To implement this approach in a real-life situation is not so straightforward. In the simulated mode, one knows precisely the four parameters of the input sine wave — amplitude, frequency, phase, and DC offset. However, in practice one has only the "digitized sine wave record."

A widely used method is the so called "minimum mean square error sine fitting" algorithm[1]. There are many variations on the implementation of the fitting algorithm. This approach is basically a gradient-search method which operates iteratively. Two common problems with this iterative approach are that the convergence is not guaranteed and the results from different runs may not be consistent due to possible trapping at a local minimum. If one wishes to guarantee the convergence by choosing a small step size in the iteration, experience indicates that it usually takes a long time to converge[2].

In view of these difficulties, we propose using the sine parameter estimation algorithm described in reference 3 to estimate the four parameters of the input sine wave. Then the estimated sine wave is used as if it were the actual input sine wave to compute the effective bits of the digitizer using Eq. [1]. This approach is simulated in a computer and the results are shown in the second column of Table 1 under the heading Simulated Effective Bits. As can be seen in Table 1, the algorithm developed produces extremely consistent results if the A/D has 4 bits or greater resolution. In addition, this algorithm guarantees an effective bits result for any input data record. It produces results rapidly — typical calculation time is less than one second.

Measuring noise floor and integral nonlinearity

A standard method for measuring the noise floor and the harmonic distortion due to integral nonlinearity is to take the FFT plot of a digitized sine wave record. However, the result of the FFT plot is not always easy to interpret because each point in that plot is just a realization of a random variable.

A method used to avoid this problem is to use the spectral averaging technique detailed in reference 4. The spectral-averaging test repeatedly acquires asynchronous digitized sine wave waveform records and performs a Discrete Fourier Transform (DFT) to compute the magnitude response. The computed magnitude responses are then averaged point-by-point. The averaged spectrum plot can reveal the

Table 1

Simulated and Ideal Effective Bits

Number Of Bits	Simulated Effective Bits	Ideal Effective Bits*
12	11.99	11.99
10	10.00	10.00
8	8.03	8.01
6	6.01	5.98
5	4.99	4.94
4	3.98	3.91
3	3.02	2.87
2	2.18	1.81

* Assuming no errors in parameter estimation.

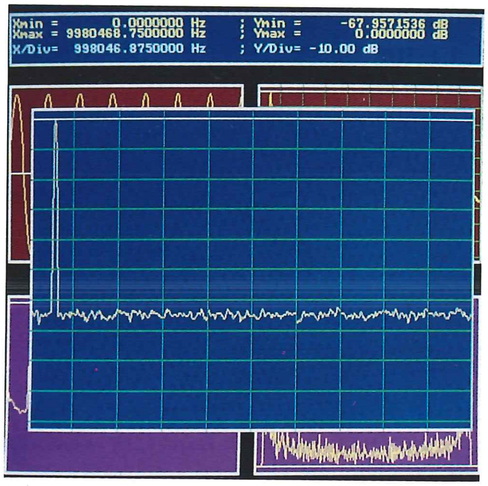


Figure 4. *Averaged magnitude spectrum of an ideal 7-bit A/D converter.*

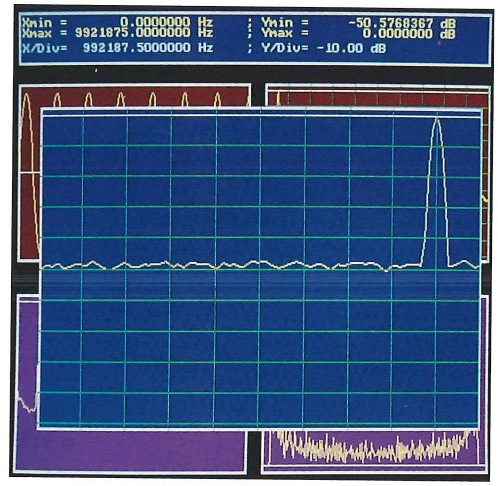


Figure 5. *Averaged magnitude spectrum of an ideal 15-bit A/D converter with 1% clock jitter.*

noise floor (or S/N) of an A/D system and all the harmonics generated by the nonlinearity. An ideal "B"-bit A/D with a full scale input sine wave should show no harmonic distortion and a noise floor as a function of B, N, and E_B given by:

$$10 \text{ Log (S/N)} = 6.02 \text{ B} + 10 \text{ Log } (3N/\pi E_B) \text{ dB} \quad [2]$$

where:

- B = effective bits
- N = number of data points in each waveform record of the DFT calculation
- E_B = equivalent noise bandwidth[5] of the window function used in the DFT calculation

Figure 4 shows the averaged magnitude spectrum plot of a simulation. The input signal is a sine wave with almost full scale amplitude which is sampled at 20 megasamples per second and then digitized by an ideal 7-bit A/D. Using the four-term Blackman-Harris window, the record length is 1024. In each waveform record, a random phase is generated for the sine wave to simulate the asynchronous acquisition as encountered in the experiment.

To help speed up the convergence process, we also added white gaussian noise with standard deviation of a quarter of an LSB to the waveform samples. This should raise the noise floor by about 2.4 dB if this white noise is **additive** to the quantization noise[4]. Thus we should expect to see the noise floor at about 66.6 dB below the peak. From Figure 4, it is seen that the noise floor is at about 65.5 dB below the peak. One possible factor contributing to the 1.1 dB discrepancy is that the input signal frequency does not line up perfectly with the bin-frequency of the DFT. Another possible reason is that the additive noise, with a quarter of an LSB standard deviation before the quantization, **is not** purely additive.

Histogram test and differential nonlinearity

A pure sine wave input is digitized by an A/D under test at sampling times that are asynchronous to the input signal. The relative number of occurrences of the distinct digital output codes is termed code density. The data is viewed in the form of a normalized histogram showing the frequency of occurrence of each code from zero to full scale. An output "zero" code density indicates a missing code. A shift in density from the ideal indicates a linearity error.

Differential nonlinearity of each code can be computed from the histogram as detailed in reference 6. As suggested in this reference, better accuracy can be obtained by using the cumulated histogram CH(i) of i bins instead of the i-th histogram bin H(i), i.e.:

$$CH(k) = \sum_{i=0}^{i=k} H(i)$$

Assuming that the transition levels are V_i, i = 0, 1, 2... with the boundary condition $V_o = -A$ (where A is the amplitude of the input sine wave), it can be shown that:

$$V_i = -A \cos(\pi \, CH(i)/N_t) \quad [3]$$

where:

- N_t = total number of data points collected

It's important to note that A can, in general, not be known to great precision, but being a linear factor in Eq. [3], all transition levels can be normalized to A so its inaccuracy will not affect the precision of the differential nonlinearity measurement.

Clock jitter measurement

As mentioned earlier, the digital data acquired by a real-life A/D system is corrupted by "noise," and this noise is a combined effect of many sources which include quantization noise, integral and differential nonlinearities, thermal noise, sampling clock jitter, etc. As a result, it is generally very difficult to measure the effect of each individual noise source such as clock jitter from the digitized data acquired from the very same A/D system. However, if the clock jitter is the dominating factor, then the effect of that noise can be measured.

Recently, a new digital spectrum analysis theory for non-uniform sampling systems has been reported[7]. If one treats the clocking jitter as a non-uniform sampling system with random sampling offsets, then the theory developed in reference 7 can be used to measure the standard deviation of the clock jitter. If one performs spectral averaging as described in the previous section, then it can be shown that the "noise floor" due to the clock jitter can be approximated by the following equation:

$$S/N = -20 \left[\text{Log}(2\pi) + \text{Log}(f_o/f_s) + \text{Log}(\delta_r)\right] + 10 \text{ Log}(N/2\,E_B) \text{ dB} \quad [4]$$

where:

f_o = input sine wave frequency
f_s = sampling frequency
δ_r = standard deviation of the clock jitter measured as a percentage of the average sampling period

Figure 5 shows the results of a simulated 15-bit A/D with one percent clock jitter. It can be seen that the input frequency is about one half of the sampling frequency and, therefore, the S/N should be about 50 dB according to Eq. [4]. It's clear from Figure 5 that the simulation result agrees well with the prediction. Therefore, the measured S/N can be used to compute the standard deviation of the clock jitter.

Conclusions

In this article we presented test procedures which measure four important dynamic performance specifications of an A/D; effective bits, noise floor and integral nonlinearity, histogram and differential nonlinearity, and clock (or aperture) jitter. These test procedures are algorithm (software) based requiring only the capability of generating a pure sine wave stimulus and acquiring it asynchronously. As a result, this testing methodology is flexible and can be easily implemented without difficult and expensive hardware instrumentation techniques.

References

1. B.E. Peetz, A.S. Muto, and J.M. Neil, "Measuring Waveform Recorder Performance," **Hewlett-Packard Journal,** Nov. 1982, pp. 21-29.

2. R. Anderson, Private Communication.

3. Y.C. Jenq and P. Crosby, "Sinewave Parameter Estimation Algorithm With Application to Waveform Digitizer Effective Bits Measurement," **IEEE IMTC/88,** San Diego, California, April 19-22, 1988.

4. Y.C. Jenq, "Measuring Harmonic Distortion and Noise Floor Of An A/D Converter Using Spectral Averaging," **IEEE IMTC/88,** San Diego, California, April 19-22, 1988.

5. F.J. Harris, "On The Use Of Windows For Harmonic Analysis With The Discrete Fourier Transform," **Proceedings of the IEEE,** Vol. 66, No. 1, Jan. 1978, pp. 51-83.

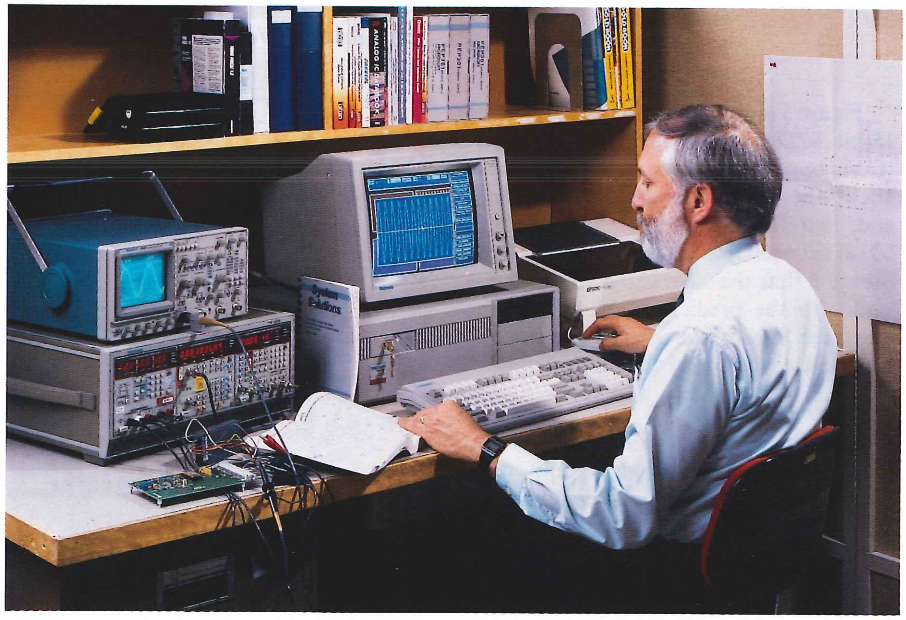
6. J. Doernberg, H.S. Lee, and D. Hodges, "Full Speed Testing Of A/D Converters," **IEEE Journal of Solid State Circuits,** Vol. SC-19, No. 6, December 1984, pp. 820-827.

7. Y.C. Jenq, "Digital Spectra of Non-Uniformly Sampled Signals: Theory And Applications, Part I — Fundamentals And High Speed Waveform Digitizers," **IEEE Transactions on Instrumentation and Measurement,** Vol. IM-37, No. 2, June 1988.

NOTE: *The papers listed in references 3, 4, and 7 are available from the author upon request at: Tektronix, Inc., M/S 50-370, P.O. Box 500, Beaverton, OR 97077.*

Dynamic characterization of A/D converters

Chris Bednarek
Personal Test Systems Marketing Manager
Measurement Systems Division
Tektronix, Inc.



The PTS101 A/D Converter Characterization Test System provides dynamic testing and characterization of A/D converters. Shown with the Tektronix 2246 Oscilloscope and auxiliary TM 5000 Modular Test Equipment.

The PTS101 A/D Converter Characterization Test System

Over the last few years analog-to-digital converter (A/D) technology has made rapid advancements in digital signal processing, yet design and test engineers still have no easy way of analyzing A/D performance. Today, most engineers use rack-and-stack bench instruments that typically provide unprocessed data and incomplete information. These systems are difficult to set up and often have a poor user interface.

Tektronix had the same A/D test problem until we developed the PTS101 for our internal design and evaluation engineers. The PTS101 allows system designers and evaluation engineers to obtain a complete evaluation of designs and products quicker than before, using state-of-the-art tools. New or infrequent operators find the system exceptionally easy to understand; they can be using the system to full capability in just a few minutes. An open system architecture ensures that the PTS Series can grow to meet future measurement needs.

The Tektronix PTS Series of personal test systems is aimed at providing design and test engineers complete solutions for engineering prototype testing and component evaluation.

PTS101 system description

The PTS101 consists of integrated hardware and software designed to test and evaluate the performance of A/Ds up to 20 megasamples/second (MSps) and 10 bits. With the addition of the optional Tektronix SG 5010 Programmable Oscillator, the PTS101 system can test 12-bit A/Ds up to 400 kilosamples/second. Expansion to higher sampling frequencies and resolution is available.

Tektronix-developed windowed software, called POLARIS, provides a user friendly interface that controls both the measurement sequence and all system elements, including PC instrumentation cards and auxiliary GPIB instruments. The software features a proprietary, high-performance, effective-bit measurement algorithm for dynamic A/D testing and includes spectrum analysis and histogram software for complete analysis. A system diagram is shown in Figure 1.

Development of a system such as the PTS101 has been made possible by the advent of high-speed desk-top controllers such as the Tektronix PEP 301. The PEP 301 Systems Controller, which is used as the PTS101 system platform, contains a high-performance Intel 80386/387 processor, 1 megabyte of main memory (expandable), and a 40 megabyte hard disk. It runs MS-DOS application programs including MS-DOS Tekware available from Tektronix. The PEP 301 also features an EGA/VGA graphics system and a GPIB port with instrument control software. See the Winter 1987/88 **HANDSHAKE** for further information on the PEP 301.

Two specially designed instrumentation cards are installed in the controller: An Arbitrary Waveform Generator Card (AWG) generates test signals for the device-under-test (DUT). An Acquisition Memory Card (ACQM) acquires test data from the DUT.

The AWG Card generates a low-distortion sine wave signal for testing A/Ds. The output is 1 volt peak-to-peak into 50 ohms; frequency range is 1 Hz to 6.7 MHz in 1.25 Hz steps with harmonic distortion of less than −60 dB for signals up to 5 MHz and less than −57 dB for signals to 6.7 MHz. In addition to sine wave output, it also provides square, triangle, and sawtooth waves. Data tables may be easily created to develop truly "arbitrary" waveforms.

The ACQM Card and associated data-acquisition probes acquire up to 16 data channels plus clock at speeds of up to 20 megasamples/second. Input logic threshold levels can be programmed between −5 to +5 volts. This card transfers data into controller memory for processing.

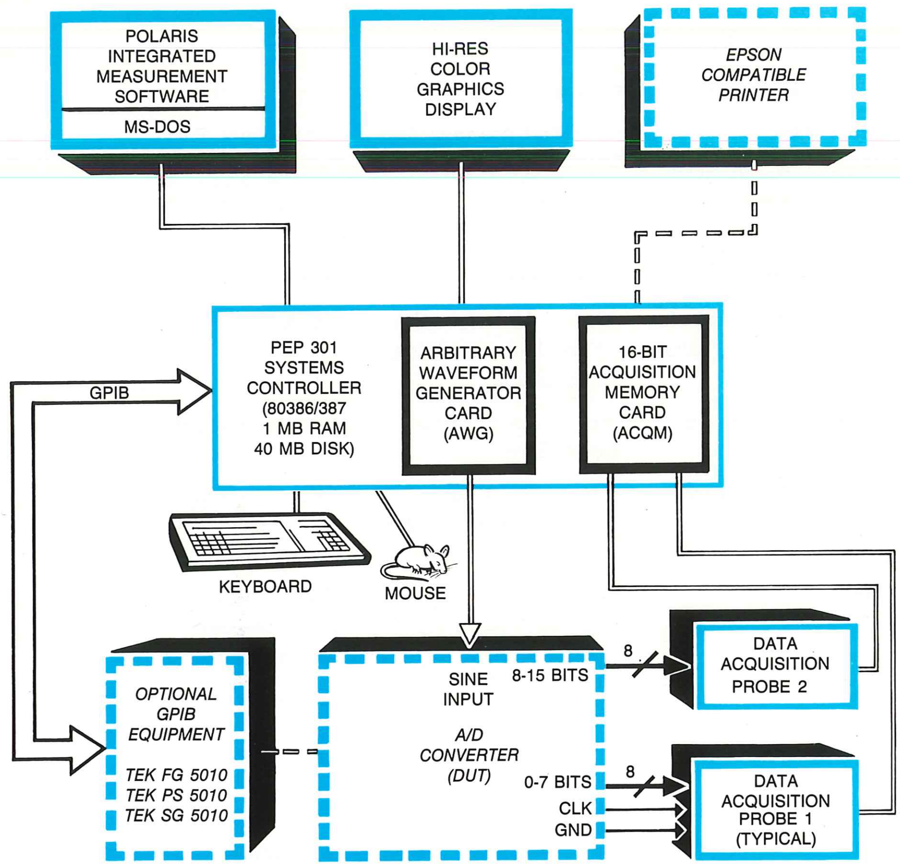


Figure 1. *Block diagram of PTS101 A/D Characterization Test System.*

The GPIB Card allows the addition of GPIB instruments such as Tektronix TM 5000 Series power supplies, high-performance generators, counters, DVMs, and oscilloscopes for a flexible, expandable system. Control of these instruments is easy and straightforward through the GPIB access port.

Referring to the block diagram shown in Figure 1, the A/D under test is connected to the sine wave output of the AWG; the A/D data outputs are connected to the Acquisition Memory Card via the data acquisition probes. A Tektronix PS 5010 Programmable Power Supply provides power for the DUT and a Tektronix FG 5010 Programmable Function Generator provides the clock signal input.

The POLARIS measurement software consists of five measurement windows, a conversation window, and a menu window (see Figure 2). Each of the measurement windows can be used to display graphical results such as waveforms, while the conversation window is used for input and output of test parameters. The menu window is used for selection of system functions. All displays are on a high-resolution color monitor, for ease of use and identification. System functions are invoked by use of a mouse. Only measurement parameter inputs are made from the keyboard.

The POLARIS software is presented as an open architecture and is written in Borland Turbo Pascal V4.0. A large section of the source code is supplied with the system, along with the Turbo Pascal compiler. This allows the user easy modification or tailoring of system functions and utilities.

Example tests of an A/D converter

Following is the step-by-step evaluation/test procedure of an A/D. Table 1 provides a summary of the tests provided and identifies the common errors uncovered. For this test we chose the TDC1048 — an 8-bit, 20 megasamples/second A/D from TRW. This A/D is used for a variety of applications, among them video signal processing.

A typical test sequence would proceed as follows: First, A/D_TESTING is selected from the main menu. The system prompts for the sine wave input frequency; assume an input frequency of 1.2345 MHz. Next, the output of the A/D under test must be acquired. The system prompts for the sampling clock frequency and record length. If new test parameters are not entered, stored default values are used. In this case we will accept the default values of 20 MSps and a record length of 256 points, respectively.

The system asks for a display window and then continuously displays the sine

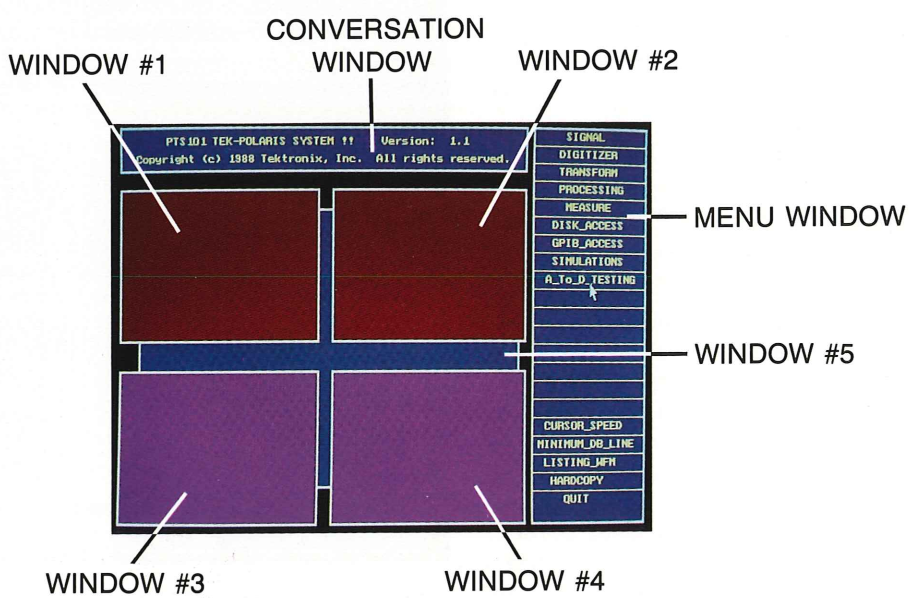


Figure 2. *Windowed display.*

Table 1

A Summary of A/D Converter Dynamic Performance Tests Made By The PTS101

Converter Error	Effective Bits Test	FFT Test	Spectral Average Test	Histogram Test
Differential Nonlinearity	Yes — Part of RMS error	Yes — As elevated noise floor	Yes — As elevated noise floor	Yes — Read out numerically as %LSB
Missing Codes	Yes — Part of RMS error	Yes — As elevated noise floor	Yes — As elevated noise floor	Yes — As bins with zero counts
Integral Nonlinearity	Yes — Part of RMS error	Yes — As harmonics of fundamental aliased to baseband	Yes — As harmonics of fundamental aliased to baseband	N/A
Aperture Uncertainty	Yes — Part of RMS error	Yes — As elevated noise floor	Yes — As elevated noise floor	No — Averaged out
Noise	Yes — Part of RMS error	Yes — As elevated noise floor	Yes — Read out numerically as elevated noise floor	No — Averaged out
Gain Error	No	No	N/A	Yes — Shows in peak-to-peak distribution
Offset Error	No	No	N/A	Yes — Read out numerically as % of full-scale peak-to-peak value

N/A = Not Applicable

wave input signal to the A/D. The offset and gain of the A/D under test can be set using the sine parameters in the conversation window.

The first test made is effective bits. The EFFECTIVE_BITS measurement is selected by clicking the mouse on the corresponding menu item. This example test is made for an input frequency of 1.2345 MHz; the measured effective bits is 7.11. Repeating this measurement several times shows a high degree of measurement repeatability. The effective bits measurement determines the equivalent quantization noise for the DUT compared to an ideal quantizer of the same resolution.

EFFECTIVE_BITS_CURVE is selected as the next test to perform. The system measures effective bits of the DUT at 10 separate frequencies and the results are graphed as a frequency-vs-effective bits curve (see Figure 3A). The entire measurement takes less than five seconds. This type of measurement can be used for production testing of A/Ds. The XY cursor feature can be used to examine points of interest. Results may be archived using a compatible printer or by saving waveform data to disk.

The FLATTOP_FFT menu selection provides a one-shot FFT with a flat-top (or Blackman-Harris) window. This window gives a −92 dB sidelobe performance, enabling the user to make close-in spurious response measurements. The PTS101 computes a one-shot FFT with a record length of 256 points in less than one second.

Figure 3B shows the fundamental at 1.2345 MHz. A one-shot FFT measurement

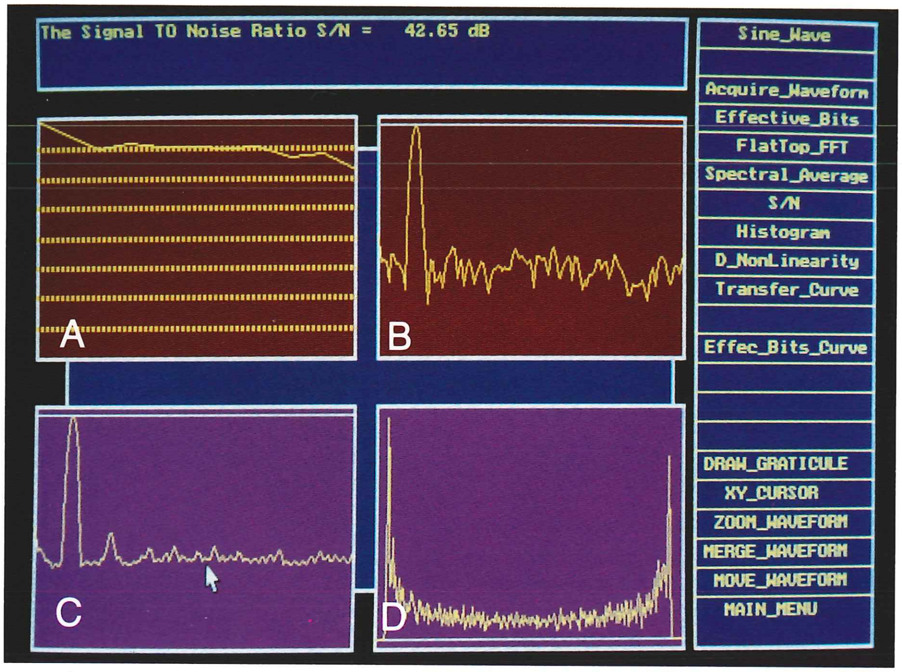


Figure 3. *Windowed display for example test. A. Effective bits curve; B. Flat-top FFT measurement; C. Spectral Averaging measurement; D. Histogram.*

contains both the spurious signals related to the fundamental and noise. This makes it difficult to separate the non-synchronous noise components from the harmonic components. In the next step, we use an averaging technique to remove the uncorrelated noise.

The SPECTRAL_AVERAGING measurement averages out the non-synchronous output components from the DUT. For our example, the test is stopped after 20 averages, which takes about 10 seconds to complete. In Figure 3C, the fundamental is at 1.2345 MHz and the first harmonic is at 2.46 MHz and over 40 dB down. The noise floor is indicated at −51.5 dB. The XY cursor or graticule can be invoked to measure how far down the noise floor and the harmonics are from the fundamental. The white horizontal line at the top of the display is automatically set at the reference level of 0 dB.

The zoom feature can be used to expand any portion of interest. When invoked, any portion of the waveform can be expanded and displayed on screen. Scaling parameters are automatically reset so numerical measurements can be made using the XY cursor.

Signal-to-noise-ratio (S/N) can be determined by processing the FFT. Simply select S/N, point to an FFT window, and click. The signal-to-noise ratio is calculated in a fraction of a second and the results are displayed in the conversation window. In this case, the result is −42.65 dB, which closely matches the value for an ideal 8-bit A/D.

The HISTOGRAM measurement determines code density. The data is viewed in the form of a normalized histogram showing the frequency of occurrence of each code (Figure 3D). Code-density data can be used to compute the transition level of all bits. This provides a full picture of the transfer characteristic of the A/D.

Since the histogram measurement accumulates data, it needs to run a while.

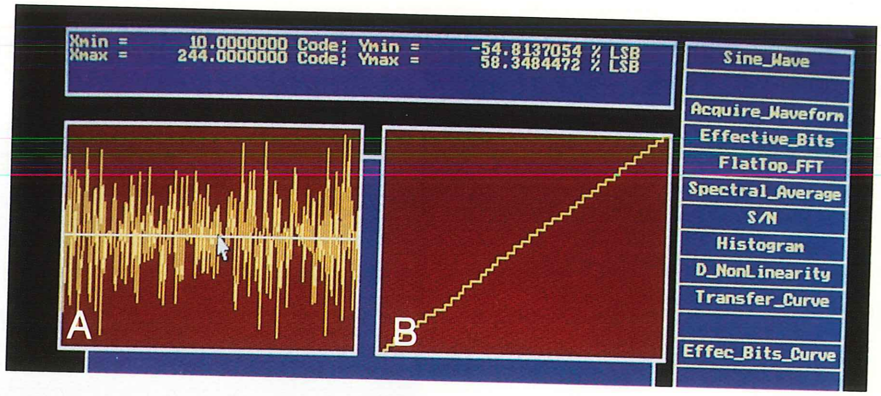


Figure 4. *Windowed display for example test (cont'd). A. Differential nonlinearity; B. Transfer curve.*

Statistically good data will be obtained if 250,000 points are accumulated. For an 8-bit A/D, the system achieves this result in a few minutes. The curve will smooth out and when the desired level is achieved, it can be stopped with a click on the histogram window. The cursor is used to examine any "bins" which visually appear to be zero. Any missing codes indicate a non-monotonic A/D. A shift in the code density indicates nonlinearity error.

Differential nonlinearity is derived from the histogram. If the sine wave was not set exactly to full scale, it's desirable to remove the end points of the differential nonlinearity display. In this case, the end points represent erroneous data. We can visually scan the display and see if the endpoints reach zero, or use the cursor to examine them. Then, the zoom feature can be used to remove the end points where no codes appear. The differential nonlinearity in percent-of-LSB (least-significant bits) is indicated as ± ½ LSB for this DUT (Figure 4A). This result is indicated in the conversation window.

Our final test for this session, transfer curve, is derived from differential nonlinearity. The zoom feature is useful to select an area of interest on the differential nonlinearity waveform. First, use the cursor to find a large excursion in percent LSB. Then, zoom in on the part of the waveform of interest and click on the transfer curve. The display in Figure 4B shows errors in the familiar transfer curve. This is a useful display when debugging A/D systems since it can quickly show gross errors in A/D system design.

Summary

For the design or system engineer, A/Ds represent the successful combination of the latest VLSI analog and digital chip technology. But this has brought with it a challenging set of performance measurements in order to evaluate final system designs.

Because the A/D is used primarily in non-DC applications, dynamic performance measurements are necessary. The PTS101 provides this dynamic performance characterization. Furthermore, the POLARIS software system provides rapid computations and repeatable measurements in a highly interactive and easy-to-use environment.

Want more information?

Would you like to know more about the capabilities of the PTS101 A/D Characterization Test System? Contact your local Tektronix Field Office or sales representative. For additional information, including a no-charge video tape showing the PTS101 in operation, use the reply card in this issue. U.S. readers can call the Tektronix National Marketing Center toll free — 1-800-426-2200. And tell them you read about the PTS101 in **HANDSHAKE**.

Isolating failures on multi-pin devices

Ben Coker
Failure Analyst
Integrated Circuits Organization
Tektronix, Inc.

The S370FA Failure Analysis System provides a quick method of locating failures in multi-pin devices.

Up to now, pin-to-pin characterization for semiconductor device failure analysis has primarily been a manual process. It's a tedious task that's becoming increasingly time-consuming and expensive as pin counts grow. Even with a custom switching matrix, a failure analyst can expect to spend over two hours isolating troublespots in a typical 132-pin device. With the complexity of many new devices now demanding pin counts approaching and sometimes exceeding 200, the problem of locating faults becomes exponentially more difficult.

Now, with new programmable test systems, pin-to-pin characterization can be executed in minutes, freeing analysts from the most time-consuming and error-prone operation in integrated-circuit failure analysis.

The typical failure-analysis process

Once a device has left production, it's GO/NO-GO tested by high-speed automatic-test equipment (ATE) to assure that it operates within the specified output parameters of the device. These parameters, which include breakdown voltage and leakage current, fully characterize the device and are normally described on a product data-specification sheet.

If the device fails at any point, it is sent to the failure-analysis group for more extensive manual testing. Here, a pin-to-pin current-leakage test is performed first to isolate the pins that are at fault, or operating outside the accepted parametric "window." In this way, a starting point is defined that allows the failure analyst to zero-in on the problem.

Once the faulty pin(s) are defined, the device is taken apart to expose the die surface and wire bonds. These are then inspected to detect possible flaws (e.g., opens, shorts, or intermittent connections). If the problem is still not isolated, each level of the chip is stripped away and examined, beginning with the top passivation layer. If necessary, device junctions that define doping levels are also carefully examined.

At best, the failure analysis process is tedious and time-consuming, but some parts of the process can be substantially aided by automated techniques. In particular, the process of screening pin-to-pin leakage is an ideal candidate for programmed automation.

Speeding up the isolation process

The emergence of high-performance test and measurement systems under programmable computer control has revolutionized the way multi-pin devices can now be analyzed. Capable, in general, of both in-circuit static as well as some functional testing, such systems can be configured to perform a variety of different tests. By using standard general-purpose instruments, the manufacturer can avoid costly, specialized ATE systems dedicated to specific types of testing. This not only creates a system that is versatile, but dramatically reduces the overall cost of the system, and shortens the time required to test a device. As a result, new manufacturing designs may be easily accommodated with little added cost, thus minimizing test system obsolescence. Above all, readily configured automated systems optimize the probability of isolating the majority of device faults.

A typical test system consists of a systems controller, test interface, switching matrix, and test adapter, all connected to power supply, stimulus, and measurement instruments through the GPIB (general-purpose interface bus) and coaxial cabling. The test fixture itself can be adapted to interface to components ranging in complexity from multi-pin devices to circuit boards or modules containing multiple electronic components.

The Tektronix S370FA Failure Analysis System is an example of a general-purpose

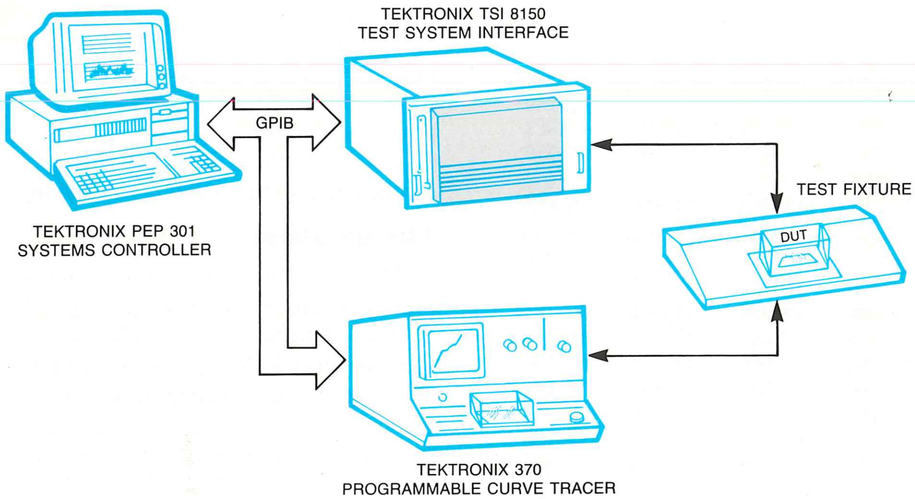


Figure 1. *The S370FA Failure Analysis System can reduce the time required to isolate faults in multi-pin devices from hours to just minutes.*

test system used to isolate failures that develop in multi-pin devices. It consists of a Tektronix 370 Programmable Curve Tracer, the Tektronix PEP 301 Systems Controller, a Tektronix TSI 8150 Test System Interface, a test fixture, and applications software. Figure 1 shows a block diagram of the test system.

Control of the entire system, including the complex switching matrix required to route the proper signals through the device-under-test (DUT), is achieved by the PEP 301 Systems Controller over the GPIB communications link. Through a series of multiplexed signals and commands, the proper stimulus is applied to the appropriate pins of the DUT, with the results routed to the measurement instruments.

Pin-to-pin characterization of a device is accomplished by the 370 Curve Tracer under program control. Control settings are determined by the test program to accommodate each new test parameter. The results are transferred directly to the system controller for storage and analysis.

Building a statistical database

As each new group of samples is tested, results may be added to a stored database. These are then used as a "window" of mean and standard deviations for each subsequent device that is tested. Because this statistical database is the most accurate representation of the device process, a known-good or "control" device does not have to be used for comparison, further reducing the probability of not rejecting a bad device. The incidence of improper screening could conceivably increase, for example, if the control device itself bordered on the edge of acceptance parameters.

Building a statistical database upon "real" results has another advantage. As each new batch of devices is fabricated, the process itself may cause resulting parameters — hence the standard deviation — to shift slightly from the previous norm. If a resulting device is tested against the standard deviations of a previous process, it may be rejected even though it performs well within an acceptance window based on its own process parameters. By including results from each new process batch in the accumulated database, however, the acceptance window is adjusted to include deviations that more realistically reflect device parameters.

More versatile testing

In designing a test system for failure analysis, two approaches could be taken for making measurements. In one approach, a GPIB-controllable current source, DC switching matrix, and a digital voltmeter could be configured to make automatic GO/NO-GO decisions quickly. Once a fault has been isolated, however, the failure analyst must test the anomalous pins with a manual curve tracer to determine the nature of the fault.

An automated system that contains a GPIB-controllable curve tracer under software control offers a more economical solution. Once a device has been automatically determined to operate outside the acceptance window, it can easily be tested in a manual mode by the curve tracer to characterize the current/voltage curve for the anomalous pins. This is accomplished by displaying the results on the curve tracer screen, which shows the signal waveform along with digital readouts of vital parameters.

```
CONFIG        SET UP/RUN        REPORT        DATA        QUIT

              Automatic run
              Manual run
                               AUTOMATIC RUN INPUT SCREEN

                               Part Type:  155-0320-00 SUB

                               Number of Samples:  7

                               Test Current:  10  u Amps

                               Type of test: 2  Max voltage: 80

                     Enter report title: TEST RUN A
                     Check that protective cover over part is closed.
              Press <S> to START test, <A> to ABORT test, <R> to REDO screen

                     CAUTION: ANY EXISTING RESULT FILES WILL BE LOST!
```

Figure 2. *Screen-driven menus enable users to easily specify the package style and part type of the device being tested, as well as its proper pin allocations.*

Part: 155-0320-00 SUB
Number of pins: 24
Number of samples: 7
Measurements in volts

Run date: 06/07/88
Test Type: Comprehensive
Current: 10 u Amps
* reject data

Pin	Sample1	Sample2	Sample3	Sample4	Sample5	Sample6	Sample7
1	1.220	> 80.000*	1.215	1.205*	1.210	1.215	> 80.000*
2	> 80.000	> 80.000	> 80.000	> 80.000	> 80.000	> 80.000	> 80.000
3	19.700	19.700	19.850	19.500	19.950	19.700	19.550
4	19.700	19.600	19.750	19.650	19.950	19.700	19.650
5	19.650	19.450	19.800	19.500	19.950	19.700	19.650
6	19.700	19.600	19.800	18.150	15.100*	19.700	19.650
7	0.730	0.725	0.725	0.725	0.725	0.725	0.720
8	19.700	19.700	19.800	17.650	19.900	19.700	19.700
9	19.650	19.700	19.800	19.600	19.950	19.700	19.700
10	19.800	19.900	19.950	19.750	20.200	19.800	19.900
11	19.650	19.600	19.750	15.600*	18.600	19.650	19.650
12	0.000	0.000	0.000	0.000	0.000	0.000	0.000
13	0.755	0.750	0.755	0.750	0.750	0.755	0.750
14	0.740	0.735	0.740	0.730	0.735	0.740	0.730
15	0.915	0.910	0.910	0.905	0.910	0.910	0.905
16	0.910	0.905	0.905	0.905	0.905	0.910	0.905

Add or remove flags? (Y/N) N

Figure 3. *Hard-copy printouts of both test results and reference data for every pin tested can be obtained easily from the failure-analysis data base.*

Software control and analysis

There are several vital elements in creating a software-based failure-analysis system. First, the user interface must be designed to be as straightforward and easy to use as possible. In the S370FA Failure Analysis System, for example, a screen-driven menu (see Figure 2) permits the user to specify any generic package style (up to 189 pins) and part type (e.g., 741 op amp) for testing.

In the "setup and run" phase of device configuration, the program is told how many parts are to be tested, what leakage current is required as a test criteria, and the maximum voltage that can be applied to the device. To test the device, the user simply presses a key that begins the operation.

Report generation is the next phase of failure analysis. The user can display curves on the curve tracer or computer screen, print hard-copy reports for later analysis (Figure 3), or store results on disk. In addition to actual results, hard-copy printouts of reference data (the mean, standard deviation, and number of test samples) for each device pin can also be obtained.

Once the operator has obtained test results, several analysis options are available. The data can be compared with previously stored results in order to automatically flag abnormal or "anomalous" readings. If automatic comparisons are not desired, flags may be manually placed on the screen to indicate any limitations that should be imposed on future incoming data. This is especially important in establishing parametric limits for the initial database.

With each group of samples that is tested, the user has the option of either merging or not merging the new data with the database. This becomes especially important when results from a suspected faulty process might potentially compromise future testing accuracy. The user also has the option of making corrections to the database. This editing feature allows any errors that may creep in — especially during initial screen flagging of data — to be weeded out so the database is not corrupted. Indication of any problems in the reference database may be readily seen when reference data is printed out.

If the sample devices have been properly selected, as few as 30 samples are required to provide a good database upon which to base testing. The fact that test results can be accepted or rejected at any time for inclusion in the database provides a fresh approach to real-world testing. Such an approach can easily integrate any changes in characteristics due to process variability.

The database

There are three stages in creating the overall database for device testing. The "master" database contains a listing of all relay switches in the system, hence it's a mapping of every possible connection to the DUT interface. This complete map of the system stores the route of every pinout from the 370 Curve Tracer to the DUT — up to 189 pins. At any one time, the system can test a single pin against any number of reference pins.

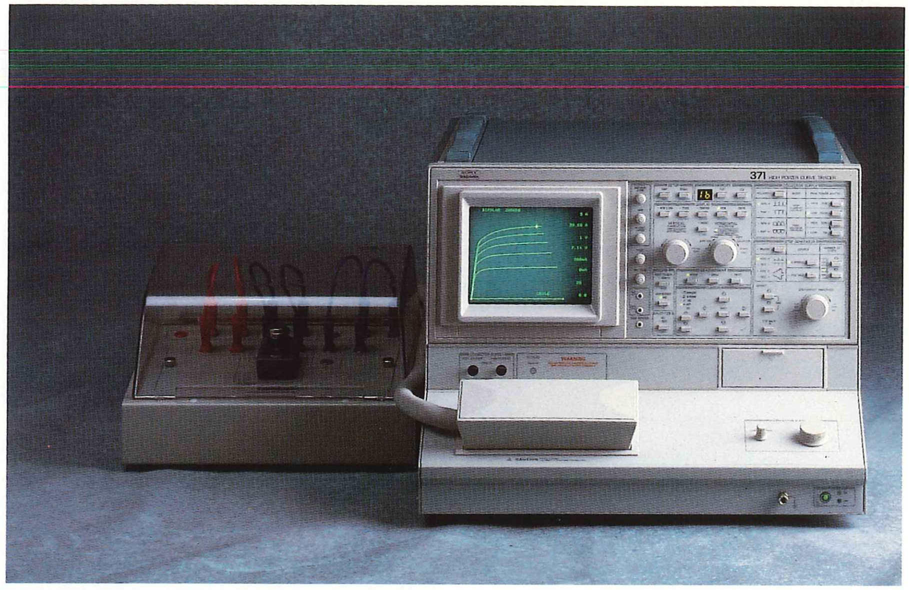
The "package-style" database is used to map only those device pins that are necessary for a generic package style. This database is selected by the user via a screen menu during test configuration. The "part-type" database, also selected during test configuration, delineates which pins and associated relays are to be used as a test reference and which are not. The result is that only one relay is mapped for each device pin. This database also contains the statistical reference data used to automatically flag test measurements.

More information

For more information on the S370FA Failure Analysis System, 370 Curve Tracer, or PEP 301 Systems Controller, contact your local Tektronix Field Office or sales representative. U.S. customers can call the Tektronix National Marketing Center toll-free for prices, information, or to place an order — 1-800-426-2200. And tell them you read about it in **HANDSHAKE.**

Based upon an article by the author which appeared in **Microelectronic Manufacturing and Testing,** *May 1988.*

Testing high-power devices



The 371 High Power Curve Tracer provides both high current and high voltage test capability for testing high-power devices.

The Tektronix 371 High Power Curve Tracer extends the range of programmable testing of semiconductor devices. Sharing many of the features of the companion 370 Programmable Curve Tracer (see **Add programmability to your curve-tracer measurements** in the Fall 1986 **HANDSHAKE**), the 371 is designed for high-power testing while the 370 is optimized for low-current measurements.

The 371 has two basic modes of operation. The pulsed-collector mode provides high-current pulses — up to 400 amps peak — for testing the "on-characteristics" of a device (h_{FE}, saturation voltage, etc.). This mode permits testing up to 3,000 watts. Since the collector supply is pulsed, the average power remains low, allowing peak-value testing without requiring a heat sink.

The high-voltage mode provides a rectified sine wave — up to 3 kilovolts — for testing "off-characteristics" (breakdown voltage, leakage current, etc.).

The device-under-test (DUT) is mounted in a safety enclosure which prevents the operator from contacting dangerous voltages. Devices up to 8 x 5 x 4.8 inches (20.3 x 12.7 x 12.0 centimeters) can be tested. Kelvin-sensing test adapters plug into the test fixture. Clip leads are provided for connecting to large devices.

Shared features

The 371 shares many features with the 370:

- **GPIB programmability** for fully automatic testing under program control
- **Bubble memory cassette** for non-volatile storage of up to 16 families of curves and up to 16 front-panel setups
- **Test sequencing** for semi-automatic sequencing through up to 16 tests without an instrument controller
- **Sweep mode** for convenient viewing of curves in the pulsed mode without looping or excessive heating of the DUT
- **Digitized waveforms** for a crisp, bright CRT display that is flicker free
- **Dot cursors** for automatic readout of vertical and horizontal coordinates at the cursor
- **Window mode** for defining a rectangular window on the display for Go/No-Go testing
- **Text mode** for addition of up to 24 characters to the display for labeling tests, identifying devices, or adding comments
- **Plotter interface** for high-quality hard copies of displays to either Centronics or GPIB plotters

Plus unique 371 features

In addition to the features shared with the 370, the 371 provides some unique capabilities which make it ideal for high-power device testing:

- **Automatic calculations** of DC and small-signal beta at the intercept points in the dot cursor and window mode; slope resistance and horizontal intercept value (early voltage) when using the function-line cursor
- **Pulsed collector supply** for testing high-power devices at rated peak power levels without overheating or damaging the DUT — duty cycle of the collector supply is reduced to less than 0.5 percent
- **Step Generator sweep mode** provides swept V_{BE} measurements
- **Pulsed step generator offset** permits base/gate offset without heating of DUT
- **Ability to short base to emitter or gate to source** without external connection

For details

To get more information on the 371 High Power Curve Tracer or the 370 Programmable Curve Tracer, contact your local Tektronix Field Office or sales representative. U.S. Customers can call the Tektronix National Marketing Center toll free for prices or information — 1-800-426-2200. And be sure to tell them you read about the 370 and 371 in **HANDSHAKE.**

Software makes device testing easier

Tektronix Tekware software, the 370 Programmable Curve Tracer, and the PEP 301 Systems Controller work together to make device testing easy.

The right tools

The task of building a test system can be made much easier if the right tools are available. One set of tools available to users of Tektronix programmable instruments is Tekware software. Tekware includes a variety of application and utility packages designed to ease your system building task. For information on MS-DOS Tekware, see **MS-DOS Tekware At A Glance** in the Winter 1987/88 **HANDSHAKE**; for a complete listing of Tekware packages, check the appropriate box on the reply card in this issue.

Two Tekware packages are available that are designed to extend the measurement capabilities of the 370 Programmable Curve Tracer. These are the 370 Utility Software and the 370 Device Testing Software.

370 Utility Software

This package links the 370 Programmable Curve Tracer and the Tektronix PEP 301 Systems Controller or an IBM PC, PC/XT, or PC/AT. Menus provide easy-to-use access to features that simplify curve-tracer operations. Users can easily create customized device tests based upon the provided routines using their own algorithms.

Routines provided allow you to acquire and store curves, save 370 front-panel settings, display device curves on the controller screen, and output test results to a variety of peripherals.

A powerful feature of the utility software is the built-in test-program generator. Programming skills are not required to create automatic device-test programs. Example programs are included to help you design your device-specific programs. Writing and debugging test programs is easy with the use of an optional ASCII text editor. BASIC source code is also included so you can create custom applications.

370 Device Test Software

This package automates pass/fail testing of two- or three-lead devices with the 370 Programmable Curve Tracer and the PEP 301 Systems Controller or an IBM PC, PC/XT, or PC/AT. Test procedures are built into the software, so there is no need to write test programs. Also, curve tracer knowledge is not required to begin device testing; the controller takes over the task of operating the 370.

To customize the program to test your device, parameter limits are entered in a spread-sheet format. Pop-up menus prompt the user to select from a list of common device types such as bipolars, FETs, diodes, etc. Once a device type is specified, a number of common DC tests can be selected. This easy-to-use operation simplifies and speeds device design, failure analysis, incoming inspection, device screening, quality-control testing, etc.

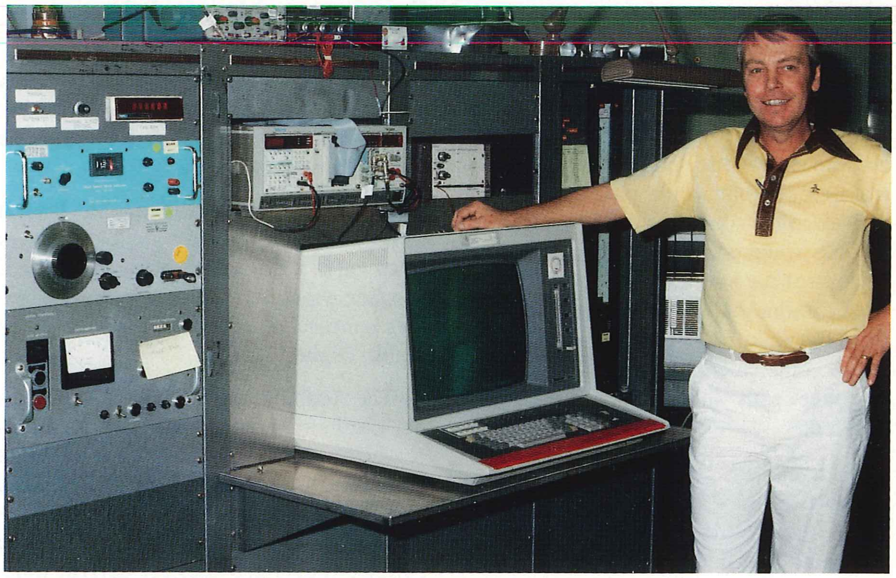
To order

To order either of these Tekware packages, U.S customers can call the Tektronix National Marketing Center toll free — 1-800-426-2200. Or contact your local Tektronix Field Office or sales representative. Specify S48P104 Option 01 for the 370 Utility Software or S48P401 Option 01 for the 370 Device Test Software. And be sure to tell them you saw it in **HANDSHAKE**.

For data sheets describing these products, check the appropriate box on the reply card in this issue.

Wind tunnel automation

Joe A. McHam
U.S. Army Atmospheric Sciences Lab
White Sands Missile Range, NM 88002



The author shown with the wind tunnel automation system.

The wind tunnel test facility at the White Sands Missile Range was installed in 1961. The facility was designed to test and calibrate wind-sensor devices used in support of numerous White Sands Missile Range projects. At the time of design, the system used the latest state-of-the-art equipment and technology available. The facility was equipped with a 72-inch Joy 2000 series fan capable of wind currents up to 85 miles per hour (mph). Control circuitry was included for varying the pitch of the fan blades, enabling the operator to obtain the desired wind speeds in the test chamber.

The test chamber was originally equipped with a pitch and yaw device for special applications. A study revealed unacceptable Eddy currents and the device was removed which restricted the tunnel to calibration of wind instruments.

Calibrating wind speed — before

The method of measuring the wind current in the test chamber, although accurate within specifications, was extremely slow and painstaking. The following paragraphs will attempt to explain the procedures previously required to obtain the desired test speeds.

Speeds from 0.5 to 10 mph. A complement of four different size Eddy-shedding bars was used to arrive at the 0.5 to 10 mph speeds, and a hot-wire temperature probe was used to determine the frequency produced by the Eddy-shedding bars. The hot-wire probe was positioned at a precise distance behind the Eddy-shedding bar.

The signal from the hot-wire probe was amplified 40 decibels for display on an oscilloscope. An audio signal was connected to the horizontal input of the oscilloscope for displaying a Lissajous waveform. When the waveform stabilized, the frequency of the audio signal was read on an electronic counter.

A chart referencing frequency in hertz versus miles per hour was then consulted to determine wind speed. If the correct speed was indicated, the calibrator could proceed to the next desired speed. If the desired speed was not achieved, repositioning the Eddy-shedding bars or varying the fan speed/blade pitch would be required.

The physical positioning of the Eddy shedding bars was extremely tedious. The entire procedure required practice, practice, and more practice to achieve the desired accuracy.

Speeds from 10 to 30 mph and above. The process was sometimes faster in obtaining calibrated speeds in excess of 10 mph. Fan speed was manually increased by adjusting a potentiometer which controlled the voltage supplied to the fan through a Ramsey Control Unit. The fan was set to the speed the calibrator felt comfortable with using an electro-mechanical indicator that gave a "ballpark" figure. This visual indicator had to be constantly recalibrated and reset to produce this ballpark figure.

As soon as the wind currents in the test chamber stabilized, the calibrator could make an accurate dynamic pressure reading using a water manometer connected to a Prandtl tube. The Prandtl tube measured direct and static pressure from the wind currents in the test chamber. If the pressure was incorrect, the fan blade pitch or fan speed was changed to directly affect the wind currents in the test chamber.

Sufficient time had to be allowed for the currents to stabilize between adjustments. When the correct reading was achieved, precise speed was determined mathematically based on air velocity and temperature inside the test chamber and barometric pressure from an aneroid barometer outside the chamber. This procedure possibly introduced an error factor, since barometric pressure inside the chamber decreases as the wind currents increase.

This lengthy procedure was repeated for wind speeds of 10, 15, 20, 25, and 30 mph. A complete calibration of each sensor required 3 to 4½ hours.

Automating the wind tunnel

After a Tektronix 4054 Graphics System was obtained through the surplus equipment pool, efforts were made to use it to control the Joy 2000 fan and collect the data needed for automation. Tektronix was contacted to ascertain the possibility of interfacing the 4054 to the control equipment. A call to Ramsey Control gave assurance that they could provide a control module that would plug directly into the existing control unit. The plug-in module would take either current or voltage to control the speed of the Joy 2000 fan. These phone calls and the help received from the manufacturers were very reassuring. A complement of hardware that would interface with the existing system was ordered:

- Tektronix PS 5004 Programmable Power Supply
- Tektronix DM 5010 Programmable Digital Multimeter
- Tektronix DC 5009 Programmable Universal Counter/Timer
- Tektronix MI 5010 Programmable Multifunction Interface
- Tektronix 50M40 Programmable Relay Scanner Card
- Tektronix TM 5006 Mainframe
- Validyne MCI-3 Mainframe
- Validyne TC-243 Thermocouple Amplifier
- Validyne CD-18 Carrier Demodulator Amplifiers (2)
- Validyne AP-20 and CP-10 Pressure Sensors

Total cost to implement automation was $12,290. This resulted in a 600% increase in capacity for the wind-sensor calibration facility.

Programmable module functions

Each programmable module receives power as well as the required communications from the host controller through the TM 5006 mainframe via GPIB.

The DM 5010 Programmable Digital Multimeter samples the analog voltages from each wind sensor being calibrated. Frequency output of digital-type wind sensors is measured by the DC 5009 Programmable Digital Counter.

The 50M40 Programmable Relay Scanner Card switches the output of each sensor being tested. This unit also provides switching for the pressure transducers. The MI 5010 Programmable Multifunction Interface serves as the controller for the 50M40. It also provides the current time-of-day (after initial settings by the operator).

The precision PS 5004 Programmable Power Supply provides 0-10 volt DC control voltage to vary the speed of the Joy 2000 fan. This voltage is linked through the Ramsey Control Unit. In the event of an over-voltage condition, the Ramsey Control Unit has a built-in safety factor that prevents the fan from over-speeding.

Figure 1 shows a block diagram of the wind tunnel automation system as implemented.

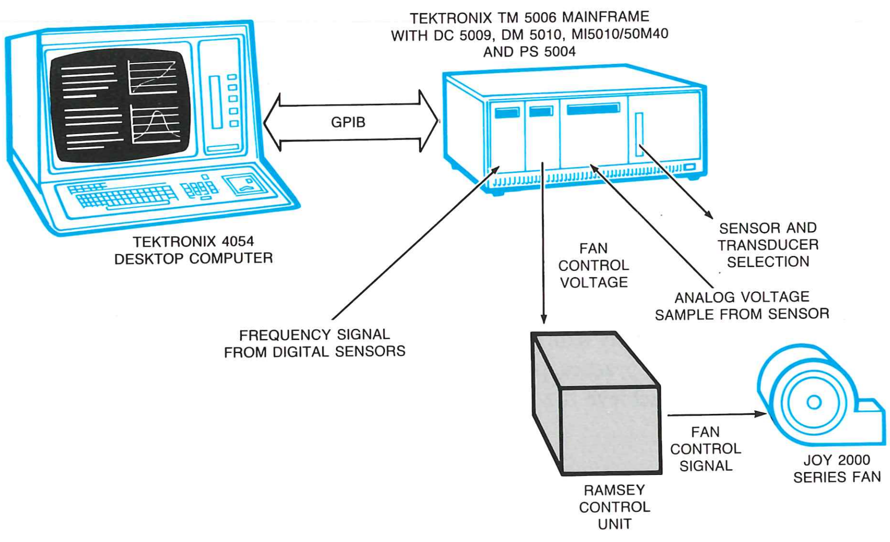


Figure 1. *Block diagram of wind tunnel automation system.*

Calibrating wind speed — after

The following procedure now exists at the wind test facility: The calculation of wind speed, production of calibration data in user format, and control of the Joy 2000 fan are under complete software control. Customer data is printed out in the engineering units required. In addition, a graph showing the performance of each sensor calibrated is available upon request.

Each instrument is calibrated within ±1 mph. If the instruments do not meet this specification, they are rejected. To ensure correct performance, each instrument is given a complete electrical and mechanical overhaul before the calibration procedure begins.

During the several months of testing and evaluation, the overall system was found to be within the ±1.0 mph tolerance specifications required. Accuracy was checked against wind sensors certified by the National Bureau of Standards.

The wind-sensor calibration system is under programmable control at all times. It is very flexible and allows changes to be made in a matter of moments to meet additional requirements. The standard calibration intervals are 0.5, 2.0, 5.0, 10.0, 15.0, 20.0, 25.0, and 30.0 mph.

Each calibration period is on the average of nine minutes. The program has built-in delays that allow ample time for the wind currents in the test chamber to settle.

For more information

To get information on the Tektronix TM 5000 Modular Test Instruments, contact your local Tektronix Field Office or sales representative. U.S. customers can call 1-800-426-2200 toll free for information or prices. And be sure to tell them you read about it in **HANDSHAKE.**

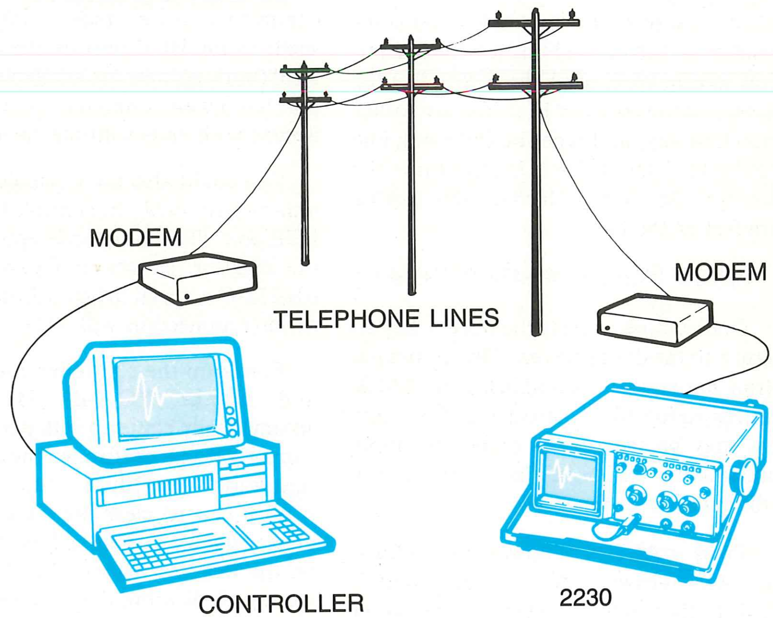
NOTE: The Tektronix 4054 Controller used in this application is no longer in production. However, Tektronix produces several instrument controllers suitable for this application. Contact your local Tektronix Field Office or sales representative for assistance.

The author wishes to thank Doug Rupp, Tektronix Sales Engineer, Albuquerque, for his assistance in this project.

Making the remote connection

Ray Kennedy
Applications Engineer
Portable Test Instruments Division
Tektronix, Inc.

Add a system controller, two modems, and telecommunications software to a 2230 Option 12 Digital Storage Oscilloscope for a remote measurement system.



In the Fall 1987 issue of **HANDSHAKE**, the tutorial article **Using the RS-232-C as an instrument interface** discussed the technical aspects of the RS-232C interface — particularly as it relates to use as an instrument interface. In this article, we want to look at a specific application using the RS-232-C to establish a remote measurement system.

The following equipment was used to create the remote-measurement system described in this article:

- A Tektronix 2230 Digital Storage Oscilloscope with the Option 12 RS-232-C interface
- A Tektronix PEP 301 Systems Controller or IBM PC/compatible running under MS-DOS 2.0 or higher
- An external Hayes-compatible 300/1200 baud modem at the 2230 site
- A Hayes-compatible 300/1200 baud modem (external or internal) at the controller site
- A telecommunications program running on the controller
- The commercial phone system between the controller site and the 2230 site

Putting it all together

We covered a lot of technical detail in the first article; here's where it pays off. Anyone familiar with system setup and installation knows that Mr. Murphy likes to get into the act whenever and wherever he can. Knowing the details of what's supposed to be going on can help you stay in control of the situation. If unfamiliar with the RS-232-C interface, review the tutorial article in the Fall 1987 issue before proceeding.

The following describes the typical procedure used to establish modem communications between a Tektronix PEP 301 Systems Controller (or an IBM PC/compatible) and the Tektronix 2230 Digital Storage Oscilloscope over commercial telephone lines. Other instruments or controllers can be substituted if applicable changes are made in the procedure.

The first step is to define what your application will have to do, and then choose an appropriate data encoding format. You'll probably want to transfer waveforms around (you bought a DSO, right?) and, since phone lines are notorious for noise, using Hex format is recommended.

Due to the low cost and ready availability of PC-Talk III telecommunications software, we've chosen to use it in this discussion. If you plan on using a different telecommunications package, alter the procedures to match your particular software; however, the general concepts are the same.

With any system installation it's best to verify operation of the pieces individually or in small sub-sections before connecting everything together. If the pieces all do their part, the final installation will be more of a verification than a troubleshooting session.

Configuring the software

At this point, you need to install and configure PC-TALK III. You may run it from either a hard disk or from floppy. Log onto the desired drive and create a directory for the PC-Talk program. Move into this new directory and copy the file "PC_TALK.EXE" from your original PC-TALK III diskette. Once copied, store your original diskette in a safe location.

To configure PC-Talk III, move into the PC-Talk directory and type "PC-TALK" followed by a carriage return (<CR>) to invoke the program. Press <ALT-F> after the introductory screen to set the program defaults. Change the indicated settings to match those listed below.

Baud Rate	1200
Parity	E
Data Bits	7
Stop Bits	1
Echo	Y
Comm.port	COM1:

Press <ESC-CR> when done and answer "Y" to the next two questions to save these changes to disk as the defaults.

Now, we'll define a function key to perform the initialization command sequence required by the scope when it's first turned on. First press the <ALT-K> key combination to call up the Function Key Definition screen. Now press the <R> key for revise, followed by <F1> (or any other Function key) and type the following line EXACTLY AS SHOWN in response to the prompt. Be sure to include the closing bracket at the end.

```
REMOTE ON;FLOW ON;DATA ENCDG:HEX;}
```

Once defined, press the <X> key to return to the dialog screen. This command string has now been saved in the PC-TALK configuration file (on disk) and, from now on, may be sent to the scope by simply pressing the <F1> key (or whichever key you chose to define).

Press <ALT-X> now to return back to DOS (answer "Y" to the "quit?" prompt that follows). Turn off the power to the controller at this time.

Setting up the 2230

Now set up the 2230 parameters to match those you defined for the telecommunications program. Setting the switches on the side panel of the 2230 as shown in Figure 1 establishes the following communications parameters:

Baud Rate	1200
Parity Enable	ON
Parity	Even
Line Terminator	CR

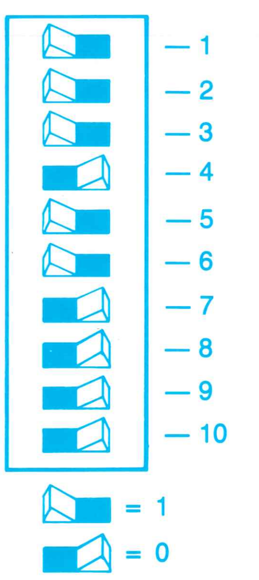


Figure 1. *2230 side-panel switch settings.*

Connect a straight-through RS-232-C cable between the COM1: port (DTE) on the controller (the COM ports have male connectors — i.e., pins — inside the D-shell) to the DCE port on the side of the 2230 (both genders are available; the DCE port has female connectors — i.e., sockets). Secure both ends with the correct screws.

You could also use a female-to-female null-modem cable to connect to the 2230 DTE port. (This would conceptually match the diagram shown in Figure 2 of the RS-232-C tutorial article.) Either method of interconnection will work.

Power up the controller and the 2230, and invoke PC-Talk III. It will automatically come up with parameters set correctly if you performed the earlier configuration procedure correctly. Press <ALT-C> to clear the screen and then press <CR>. You should see "READY;" on the display. This is the 2230 prompt message indicating that it's waiting for a command. If you don't see "READY;", recheck all the steps up to this point.

If everything seems to have gone alright up to here, it's time to check the automatic setup of the 2230. Type "REM?", "FLO?" and "DATA?" to query these settings. Note that REMote is OFF, FLOw control is OFF, and DATA encoding is BINARY. Now press <F1> on the PC key board to send the pre-defined "command macro" to the scope.

Now, issuing the "REM?", "FLO?", and "DATA?" queries should return the newly-set values of "ON", "ON", and "HEX" respectively. This verifies the automated scope setup procedure, which should be run anytime the scope is powered up.

Getting a waveform

Now we're going to grab a waveform from the scope and save it to a diskette or the hard disk. Later, we'll send it back to the scope to verify bi-directional waveform transfers.

The first thing we'll do is turn on flow control at the controller end to work with the flow control enabled in the scope. This is done by pressing <ALT-O>, enabling PC-TALK to check for and send the flow-control characters to keep the controller and scope communication buffers from overflowing. (Pressing <ALT-O> again will disable flow control if required later, but don't do it now.)

Now type the "DATA?" query to view the current SOURCE and TARGET settings. If changes are required, you may change them by simply typing the correct command back to the scope. (For example, DATA SOURCE:REF 1.)

In preparation for waveform transfer, type the "WAVFRM?" query command on the command line, but don't press <CR> yet.

Pressing <ALT-R> at this point causes PC-Talk to prompt for a file name to save the yet-to-be-captured data into. Specifying just the file name will cause the file to be saved in the current directory on the currently-logged disk (see <ALT-F> command). You may optionally specify a drive and path to save the data to, using the normal DOS file-name conventions. For our demonstration, just call it "GET-WFM1.HEX".

Press <CR> to send the pre-typed command and cause the scope to transmit the waveform back over the RS-232-C connection to the controller. As the transfer takes place, notice that the targeted disk drive access light comes on several times as the data is saved to disk.

The data you see on your controller screen consists of the waveform preamble ("WFMPRE WFID....") terminated by a semicolon, immediately followed by the curve data ("CURVE #H ..."), also terminated by a semicolon. Since the curve data is encoded in hexidecimal format, it only contains the characters 0-9 and A-F. When you see a semicolon appear after a large block of hex-encoded data, you know that you've received the entire waveform. Press <ALT-R> to terminate the reception of data and close the disk file.

We're going to send the waveform back to the scope and store it in a reference memory. Set the target for the waveform by typing "DATA TARGET:REF2". (If you want to save a 4K waveform to disk, specify "DATA TARGET:REF4" instead). Once the target is specified, use the scope's vertical position control to move the acquisition display slightly so you'll be able to see the stored waveform come back over the interface.

Send the waveform back by pressing <ALT-T> and supplying the name of the waveform file to be sent — in this case, "GET-WFM1.HEX". After a short delay, you should see the waveform appear on the scope's display.

Going remote — locally

Now that we know that both ends of our system play together, we'll next add in the middle. This involves disconnecting the scope from the controller, installing modems for both of those devices, setting the modems up properly, and connecting the modems into the phone system.

Power down both the controller and the 2230 and disconnect the RS-232 cable at both ends. Locate the controller close to a phone line with either touch-tone or pulse dialing capabilities. Many corporate phone systems use some other means of dialing (and some even have different wiring schemes); these types of phone systems WILL NOT work without special modifications.

Locate the 2230 close to a second phone line with similar touch-tone/pulse dialing capabilities. If possible, find a work area where both lines are within a few feet of each other. This will minimize running back and forth, and allow you to concentrate on the job at hand.

Set up the modems as per the manufacturer's recommendations. If you're using an internal modem in the controller, make sure to set it up so as not to conflict with the COM1: serial port on your controller. However you set up the modem, the PC-Talk software must be set to match the COM port being used (either assigned by jumpers on an internal modem, or by the physical connection to a COM port for an external modem). You can change where PC-Talk thinks the modem is using the <ALT-F> command.

Modems, for the most part, simply modulate and demodulate the signals sent to them. "Smart" modems have some additional features, one of which (auto answer) is needed in our system. Since a communication session needs to be initiated, and since either a person or a computer will decide when to initiate the phone call, the modem at the controller end will have "originate" status. Conversely, the modem at the 2230 end should have "answer" status since it is the device to be called.

What we want to do is set up the 2230 modem to "answer the phone". On Hayes Smartmodem 300/1200 modems this is done by prying the cover off of the front of the modem and setting dip-switch #5 to the up (answer) position. All other switches should be at their factory-default positions. Figure 2 illustrates how the switches should be set for this demonstration.

The modem at the controller end should be set in a similar fashion except switch #5 should be in the down position (originate).

After properly setting the modem switches at each end, replace the covers, and connect the modems into the phone system using the 4-wire cables provided with the modems. Note the phone number at the 2230 end of the installation.

NOTE: In some states, you are required to notify the local phone company that you have connected telecommunications equipment into their network. Check your local regulations and notify the proper agencies.

After double-checking all connections, both to equipment and to the phone lines, power everything up. Invoke the PC-Talk program and press <ALT-D>. This accesses the dialing directory and allows you to revise (add, delete, change) or dial entries in the directory. We want to add the 2230's phone number into the directory, and then later dial it to establish the communication link.

To add the entry, press <R> for "revise or add to directory". You can have up to 60 entries in the directory. At the prompt, pick one not being used and then supply the information requested. An example of how to fill in the directory entry follows:

Name:	Remote 2230 (your site ID)
Phone Number:	XXX-XXXX (your 2230's number)
Communication parameters OK (Y/N)?	N
Baud Rate:	1200
Parity:	E
# Data Bits:	7
# Stop Bits:	1
Are remaining parameters OK (Y/N)?	Y

You are then asked if your entry is OK. If so, answer "Y" to the prompt; otherwise, answering "N" will take you back to the beginning so you can change the entry. When all is well, answer "Y", and the directory will be updated.

Next, we need to set the modem dialing command to match the phone system your controller modem is connected to. Press <R> again to revise the directory, and this time answer with "M" (for modem command) when asked for the type of modification. If your phone system uses only pulse-dialing, your new dialing command should be "ATDP", whereas touch-tone systems use the command "ATDT". Enter the command appropriate for your phone system.

Now you're ready to test the installation. When you see the "Dial Entry #:" prompt, respond with the number of the directory entry you just created for your remote 2230. You'll hear your modem go "off hook" and dial the number. If everything is set up correctly, you'll hear a high-pitched squeal for a second or so, then the message "CONNECT" should appear on your controller screen, verifying that the phone link has been established.

When you get the "CONNECT" message, do the same things we did earlier when the 2230 was connected directly to the controller. For example, get back the instrument ID, send the setup macro back to the 2230, and transfer waveforms in both directions. This validates the functionality of the modem-link system. If you don't get the "CONNECT" message, double check all your connections and go back through the procedures to verify that everything has been done properly.

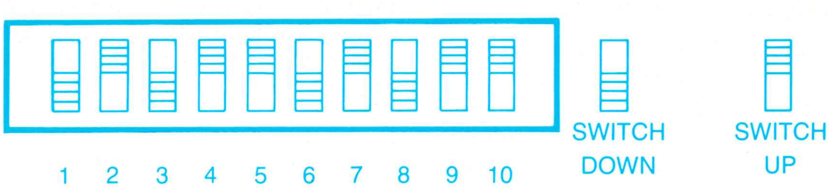


Figure 2. *Switch Settings for Hayes Smartmodem 300/1200 — 2230 end only.*

Now we're talking

When you're satisfied that everything is working as it should, it's time to try it in your real-world, remote environment. If you were fortunate enough to have either the controller or the 2230 set up at its final site, that end of the system won't have to be touched. More likely, however, one (or both) of the sections will have to be moved to its final location.

Power down the equipment and carefully package whatever needs to be transported. Once at the new site, unpackage everything and duplicate the previous setup. The one thing that has probably changed is the 2230's phone number. Note this new number, power up the remote equipment and get back to the controller site to perform the final checkout.

You'll need to change the modem program's dialing directory to accommodate the new location of the 2230, so press <ALT-D>, and make the change. Once made, you can call the new site to verify the installation as before.

Whether your application problem demands measurements in another part of your building or half-way around the world, the 2230 Digital-Storage Oscilloscope with the Option 12 RS-232-C interface places the solution within your grasp!

Need more information?

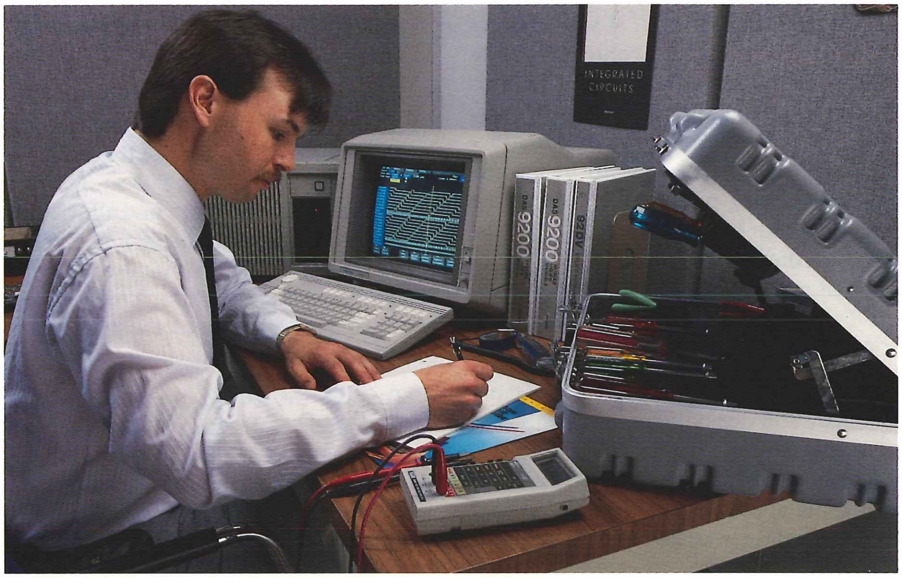
For more information on the Tektronix 2230 Digital Storage Oscilloscope or other Tektronix products that use the RS-232-C interface, contact your local Tektronix Field Office or representative. U.S. customers can call the Tektronix National Marketing Center toll free for prices or information — 1-800-426-2200. And tell them **HANDSHAKE** sent you!

For a copy of the application note which this and the previous RS-232-C article were derived from, request application note 41W-6748, **Making the Remote Connection**, or check the box on the reply card.

TEK SERVICE NOTES

Warranty-Plus: On-site service for Tektronix Test Systems

Paula Bartell
Marketing Communications Manager
Customer Service Division
Tektronix, Inc.



Warranty-Plus provides on-site service for Test Systems products. This assures maximum system performance at lowest cost.

Tektronix-quality warranty

All Tektronix products are backed by a comprehensive warranty for parts and labor. When you receive a new Tek product, you expect maximum performance — and Tektronix promises satisfaction! Now, Tek Service makes customer satisfaction even more convenient with on-site *Warranty-Plus* for Test Systems products.

What is *Warranty-Plus*?

Warranty-Plus is an option that can be purchased with your Tektronix product before shipment. It is referred to as *Warranty-Plus* because warranty-like coverage can be stretched to three years for Test Systems products and up to five years for Instrumentation products. In addition to parts and labor, safety modifications and mandatory upgrades, *Warranty-Plus* includes scheduled calibrations, preventive maintenance, priority repair services, and reduced costs over alternative service offerings.

Test systems enjoy added features

Warranty-Plus for Test Systems adds the feature of on-site service. You no longer have to retain packaging materials, process shipping paperwork, or pay high costs of freight and transit insurance. Tek Service will come to your site. With our priority response policy and our ability to come to you, your Test Systems products will enjoy maximum uptime and efficiency!

What are the test systems options?

On-site *Warranty-Plus* options for Test Systems products include:

- Installation option
- One-year coverage
- Two-years coverage
- Three-years coverage

Installation ensures immediate productivity. When you purchase your installation option, Tek Service:

- Sets up and initializes your product
- Configures and integrates each Tek product for optimum performance
- Installs Tek standard software
- Runs tests to verify functionality
- Demonstrates basic operations for key users

The one, two, and three-year *Warranty-Plus* options complement standard product warranties by extending the coverage window and providing scheduled calibrations or preventive maintenance. Our factory-trained Specialist will come to your site to:

- Exercise diagnostics and run tests to verify functionality
- Confirm performance to published specifications
- Adjust any CRTs for optimal information display
- Replace worn or marginal components
- Inspect interfacing, internal and external cables, and connectors
- Complete the service call with product cleaning

On-site *Warranty-Plus* means savings!

With *Warranty-Plus*, Tektronix is able to provide the best service coverage at the least cost to our customers. Your investment is tested and protected from day one, ensuring peak operating efficiency at installation and for the length of your option coverage. The cost? *Warranty-Plus* contracts are priced lower than annual customer-site support agreements. And when you buy products on a volume basis, quantity discounts apply to *Warranty-Plus* options also. Another benefit is an easy conversion to a maintenance agreement when the option term ends. If you start with a Tektronix *Warranty-Plus* contract and follow it with a quality Tektronix Service plan, you'll save! You'll save money with a continuous product support package. And you'll save costly downtime caused by non-optimal performance that can be avoided with routine calibrations or preventive maintenance. Purchasing *Warranty-Plus* ensures your Tektronix product operates at peak performance and provides maximum return on your investment.

How do you order *Warranty-Plus*?

Ask your Sales Representative to include On-site *Warranty-Plus* options in your purchase. They can be added to your product purchase order, or they can be written on a separate purchase order. To apply, *Warranty-Plus* purchases must be made before the product ship date.

On-site *Warranty-Plus* options are now available for the following Tektronix Test Systems products: DAS 9200-Series Digital Analyzers, most 11000-Series Systems, PEP 301 Systems Controller, 7250 Transient Digitizing Oscilloscope, and S370FA Failure Analysis System.

For more information, about *Warranty-Plus*, Maintenance Agreements, and our many other U.S. Service offerings, contact your local Tektronix Service Representative shown in Table 1.

Table 1

U.S. Tektronix Service Representatives

State	City	Contact	Phone
California	Irvine	Doug Mills	(714) 660-8080
California	Santa Clara	Joe Lewis	(408) 496-0800
Colorado	Denver	Greg Thomas	(303) 799-1000
Florida	Orlando	Dwain Cox	(407) 249-1600
Georgia	Atlanta	Nolan Wimer	(404) 449-4770
Illinois	Chicago	Carl Smith	(312) 259-7580
Maryland	DC	Lovell Wilson	(301) 948-6316
Massachusetts	Boston	Ted Rak	(617) 861-6800
Michigan	Detroit	Dave Meyer	(313) 478-5200
Minnesota	St. Paul	George Loughry	(612) 484-8571
New Jersey	Woodbridge	John Holme	(201) 636-8616
New York	Syracuse	Nick Farnett	(315) 455-6661
Oregon	Beaverton Factory Service	Jim Frame	(503) 642-8600
Pennsylvania	Philadelphia	Bill Bartlett	(215) 825-6400
Texas	Houston	Ron Sutton	(713) 933-3000
Texas	Dallas	Don McKenzie	(214) 550-0525

CLASSES AND SEMINARS

Tektronix offers classes and workshops for the convenience of Tektronix customers with application, operational, or service training needs. Here's the schedule of classes and workshops to be offered in the near future.

Product Service Training Classes

Tektronix Service Training provides new technicians the skills and techniques required for effective maintenance of Tektronix products. In addition, it brings experienced technicians up-to-date on maintenance of new products. Call Tektronix Service Training, 1-800-835-9433, ext. WR1407 to register for the following classes.

CLASS	LOCATION	DATES
465B/475A Portable Oscilloscope	Atlanta, GA	Nov 7-11
2215/35/36 Portable Oscilloscopes	Atlanta, GA	Nov 14-18
2465A Portable Oscilloscope	Atlanta, GA Santa Clara, CA	Sept 26-Oct 7 Jan 30-Feb 10
7904/7633 Laboratory/Storage Oscilloscopes	Irvine, CA	Dec 5-17
7912HB Programmable Digitizer	Beaverton, OR	Oct 3-14
7854 Waveform Processing Oscilloscope	Beaverton, OR	Oct 24-Nov 11
TM 500 Calibration Package	Boston, MA	Sept 12-23
113XX Programmable Oscilloscopes	Beaverton, OR	Oct 31-Nov 4
114XX Programmable Oscilloscopes	Beaverton, OR	Nov 7-11

In addition to classroom instruction, Tektronix Service Training has a variety of training packages and video tapes available for self-study. Classes are also available for maintenance of other Tektronix products. Call for further information.

Workshop and class sizes are limited. We recommend that you enroll early. Other classes are planned beyond this schedule. For more information or to register, call the numbers listed above.

We retain the option to cancel or reschedule classes or workshops.

IG Customer Training Workshops

Call Tektronix IG Customer Training, 1-800-835-9433, ext. 430 to register for the following workshops.

CLASS	LOCATION	DATES
2230 Digital Measurements	Beaverton, OR Wash. DC	Sept 14 Oct 5
2430A Advanced Digital Measurements	Beaverton, OR Wash. DC	Sept 15-16 Oct 6-7
11401/11402 Waveform Measurements	Beaverton, OR Wash. DC	Sept 20 Oct 11
11401/11402 Advanced Waveform Measurements	Beaverton, OR Wash. DC	Sept 20-21 Oct 11-12
11301/11302 Measurement and Analysis	Beaverton, OR Wash. DC	Sept 23 Oct 14
Fundamentals of Digital Oscilloscopes	Beaverton, OR Wash. DC	Sept 13 Oct 4
Instrumentation Control	Beaverton, OR Wash. DC	Sept 22 Oct 13

Most of the above workshops are available in a self-study format. On-site training is also available. For information call 1-800-835-9433, ext 430.

HANDSHAKE
Group 157 (02-382)
Tektronix, Inc.
P.O. Box 500
Beaverton, Oregon 97077

Address Correction Requested.

BULK RATE
U.S. POSTAGE
PAID
Tektronix, Inc.

HANDSHAKE
LEWIS R MC CALLUM
47-704

49W-7095