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Automatic Pulse Parameter Determination with the Computer Augmented Oscilloscope System

Abstract: The Computer Augumented Oscilloscope System (CAOS) is a special computer terminal facility intended for laboratory experiments involving waveforms and their interpretation. The system provides digital acquisition of waveform data, system control and calibration, data analysis, and graphic and alphanumeric display.

Pulse parameter determination requires the use of all system capabilities since a) hardware and software options must be chosen or controlled, b) the pulse waveform must be digitized, c) the appropriate analytical algorithms must be applied to the data and d) the results of analysis must be displayed. Specific attention is given to the algorithms required for pulse parameter determination and a new procedure for determining base and top magnitude of a pulse waveform is presented.

Introduction

A significant trend toward the automation of laboratory experiments has emerged in the past several years. This trend has origins in the realization that automation frequently improves efficiency, permits the execution of experiments that otherwise could not be performed and minimizes the amount of detail with which the experimenter must cope.

The Computer Augmented Oscilloscope System (CAOS) provides automation for the laboratory experimenter who is concerned with waveforms and their interpretation. Figure 1 shows the CAOS laboratory ensemble, which includes a modified sampling oscilloscope, the CAOS terminal and the telephone data set that couples the ensemble to a remote computer. CAOS hardware, its features and its operation have been described previously [1] and the following operational summary is adequate in this paper. By appropriate entries on the terminal's alphameric and function keyboards, an experimenter may invoke programs which:

- digitize and store in the computer a waveform displayed on the oscilloscope;
- analyze the waveform data thus stored;
- display raw waveform data;
- display calculated graphical results;
- display calculated numerical results;
- calibrate an oscilloscope sampling channel;

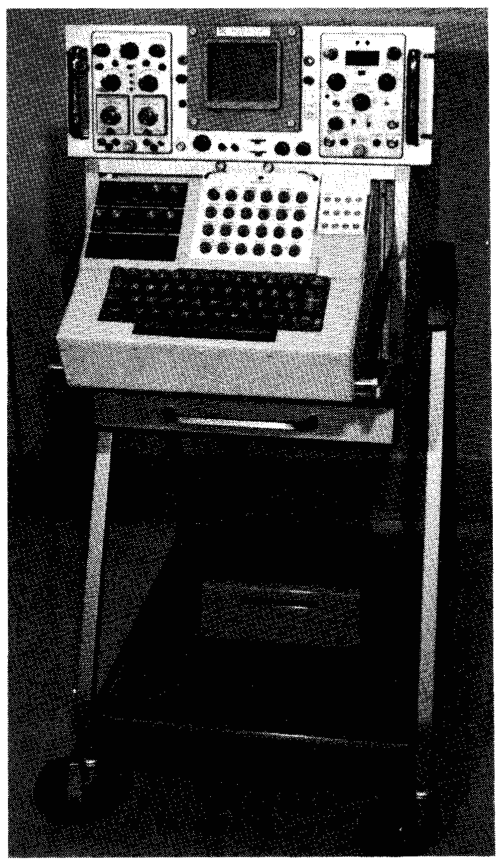


Figure 1 CAOS laboratory ensemble.

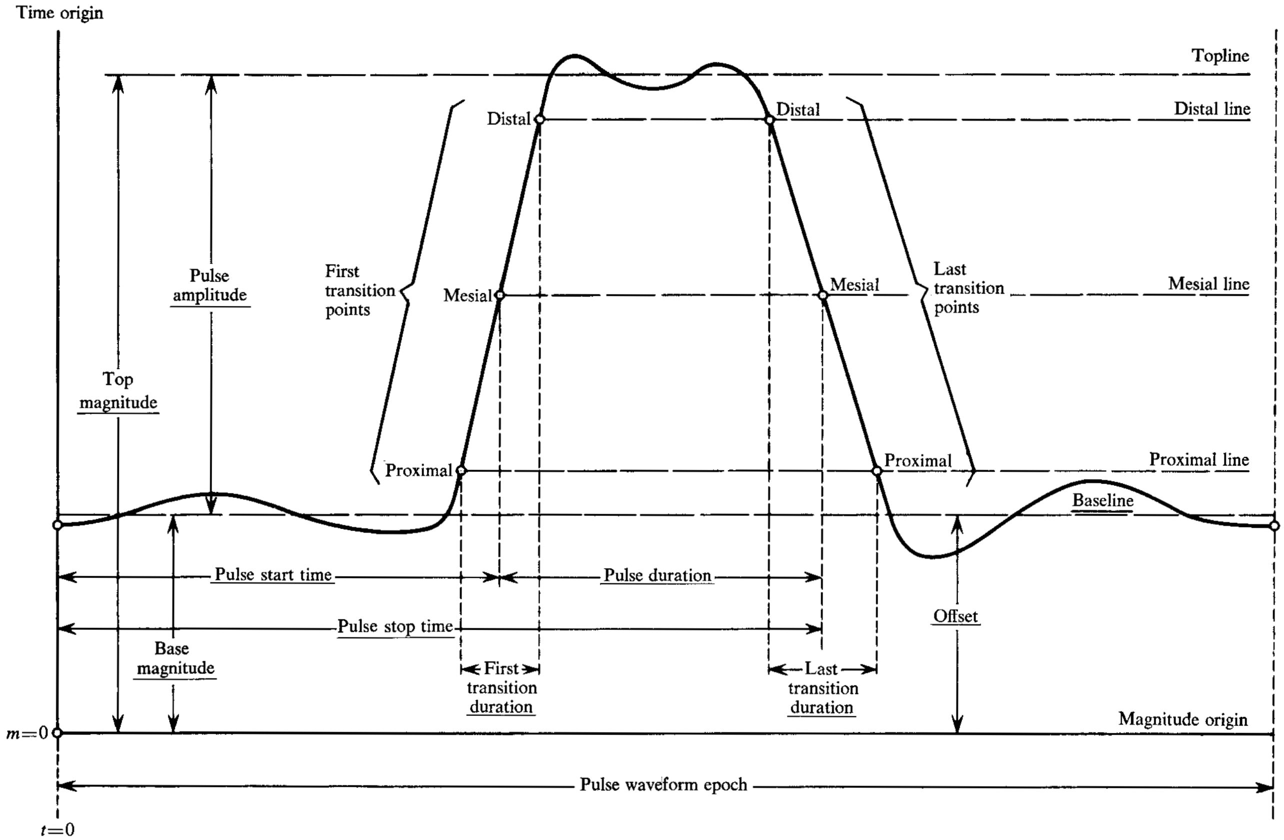


Figure 2 Pulse waveform nomenclature.

- display instructional or diagnostic information; and
- permit the specification of options to be used in the execution of programs.

All of the operations listed above are, in effect, self-terminating. When an operation terminates, the oscilloscope is available for use in its conventional stand-alone fashion.

CAOS has potential application in numerous experimental situations. With suitable software the system can emulate a number of conventional laboratory instruments (e.g., spectrum analyzer, distortion analyzer, phase meter, etc.). Beyond emulation, and solely as a function of the analysis and display software, the system permits the development of new techniques [2] and instruments. This paper describes one such instrument, a pulse parameter analyzer. An algorithm for determining the base and top magnitudes of a waveform is discussed and some examples of pulse parameter determination are given.

Pulse parameter analysis

Typically, pulse parameter analysis involves the evaluation of a waveform which is displayed on an oscilloscope or an x–y plotter. Figure 2 shows a pulse waveform and the reference lines and points which the experimenter, either literally or figuratively, superimposes on the waveform in the course of the analytical process. Using these superimposed geometrical constructs, the experimenter determines the magnitude of the parameters of interest. The entire process entails considerable subjective judgment.

Some instruments (e.g., the Tektronix Type 567 Digital Readout Oscilloscope) provide a degree of automatic parameter determination, but no instrument, to our knowledge, provides automatic determination of the eleven major pulse parameters which are underlined in Fig. 2. More importantly, no known instrument incorporates adequate techniques for determining base magnitude and top magnitude, the two crucial parameters on which all other parameter determinations depend.

Pulse waveform nomenclature

Figure 2 shows the nomenclature used throughout this paper. The eleven pulse parameters to be determined are underlined and all other reference lines and points required in intermediate steps are identified. Although the nomenclature in Fig. 2 appears somewhat novel, the authors use it because it is the only available nomenclature that is complete, internally consistent and general enough to satisfy all needs.

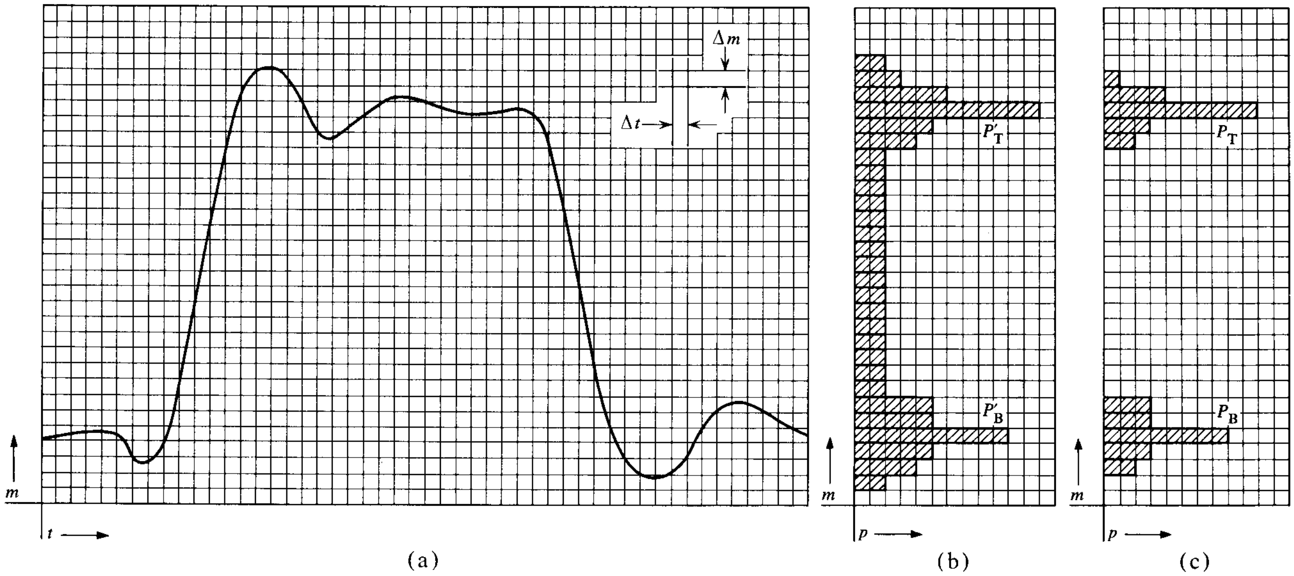


Figure 3 (a) Pulse waveform with superimposed rectangular grid, (b) initial probability distribution histogram, (c) final probability distribution histogram.

The nomenclature of Fig. 2 does not imply any new procedure in pulse parameter analysis which, quite conventionally, involves the sequential determination of:

1) base magnitude,
2) top magnitude,
3) pulse amplitude,
4) proximal, mesial, and distal line locations either:
   a) as percentages of the pulse amplitude, or
   b) as absolute values,
5) proximal, mesial and distal point locations on the first and last transitions, and
6) the magnitudes of all other parameters from computed differences between appropriate line and/or point pairs.

Base and top magnitude determination

The sequence that is outlined immediately above illustrates the importance of the base and top magnitude determinations. They are the first parameters evaluated, and their values are prerequisite to all other evaluations. Conventional methods for determining these two parameters involve either:

- estimates of their magnitudes by the experimenter from his observation of, or his graphical constructions on, the waveform, or
- location of single points on the waveform base and the waveform top by some procedure, where the magnitudes of the points so located are taken to be the base and top magnitudes.

The first technique is fraught with undesirable subjective factors, and the second can lead to bizarre results when applied to the "dirty" pulse waveforms frequently encountered in practice. Clearly, a technique which eliminates subjective judgment and which yields "reasonable" and consistent results for a wide variety of pulse waveforms is needed.

CAOS software incorporates an algorithm for the determination of base and top magnitudes that was first suggested by a former colleague, K. Maling [3]. This algorithm is based on the determination of the probability density of the waveform data within the pulse waveform epoch and is closely related to a technique independently suggested by Boatwright [4]. A graphical description of the algorithm follows:

1) Assume that a pulse waveform, such as that shown in Fig. 3(a), has a superimposed rectangular grid in which each elementary rectangle has dimensions Δt and Δm.
2) Construct the initial probability distribution histogram as follows:
   a) for each horizontal stripe (of width Δm) count the number of elementary rectangles through which the waveform passes.
   b) at the magnitude corresponding to the location of the horizontal stripe, draw a histogram element whose length is proportional to the count. (This procedure yields the truncated bimodal distribution of Fig. 3(b) in which P'_B and P'_T are identified.)
3) Count the number of transitions in the pulse waveform. (In Fig. 3(a) there are 2.)
4) Subtract the count obtained in 3, above, from each histogram element of Fig. 3(b) to produce the final probability distribution histogram, Fig. 3(c). This procedure removes contributions from the transitions and produces

the two separate truncated distributions P_B and P_T. 5) Calculate the values of the means and the modes, in m, of P_B (and P_T). Either the mean or mode of P_B (or P_T) may be chosen as the base (or top) magnitude.

The previous graphical presentation yields crude results, but as Δt and Δm become smaller the magnitudes of the means (or modes) of P_T and P_B become more refined measures of the base and top magnitudes. The technique is particularly applicable in CAOS since Δt is equal to the number of waveform sample points and Δm is determined by the resolution of the A/D converter which digitizes the magnitude of each sampled point.

The algorithm given above yields two possible values for the base (or top) magnitude, and a choice must be made. However, one additional factor is pertinent. The probability density algorithm is inappropriate, and sometimes fails for pulse waveforms that have bases (or tops) of substantially zero duration (e.g., sawtooth waveforms, exponential waveforms, etc.). In these cases the peak value of the waveform is the appropriate choice. In the CAOS pulse parameter determination program, which is discussed in a later section, the authors resolve the choice between mean, mode and peak by providing independent selection for base magnitude and top magnitude wherein for each:

- the mode of the probability distribution corresponding to the pulse base (or top) is the default option. This option should be taken when results that are consistent with conventional observed results for pulse waveforms with bases (or tops) of significant duration are desired.
- the peak magnitude of the waveform base (or top) is included as a selectable option which, in general, should be taken when a base (or top) has substantially zero duration.
- the mean of the probability distribution corresponding to the pulse base (or top) is also included as a selectable option. This option should be taken when results having the highest possible precision for pulse waveforms with bases (or tops) of significant duration are desired.

CAOS programming system

Before describing the pulse parameter determination program used with CAOS, a brief description of the CAOS Programming System (CAPS) and its interaction with an application program, the computer and the terminal is necessary. Figure 4 shows a system block diagram in which the information flow between the major constituents is indicated. As described in a previous paper [1], the CAOS terminal hardware executes a set of wired-in instructions in response to information (i.e., commands and, where applicable, data) from the computer. Typically, any useful CAOS operation entails the execution of a sequence of these wired-in instructions. Sequences for all such operations are included in the CAPS software, a library of FORTRAN routines which may be called by any application program. Typical examples are:

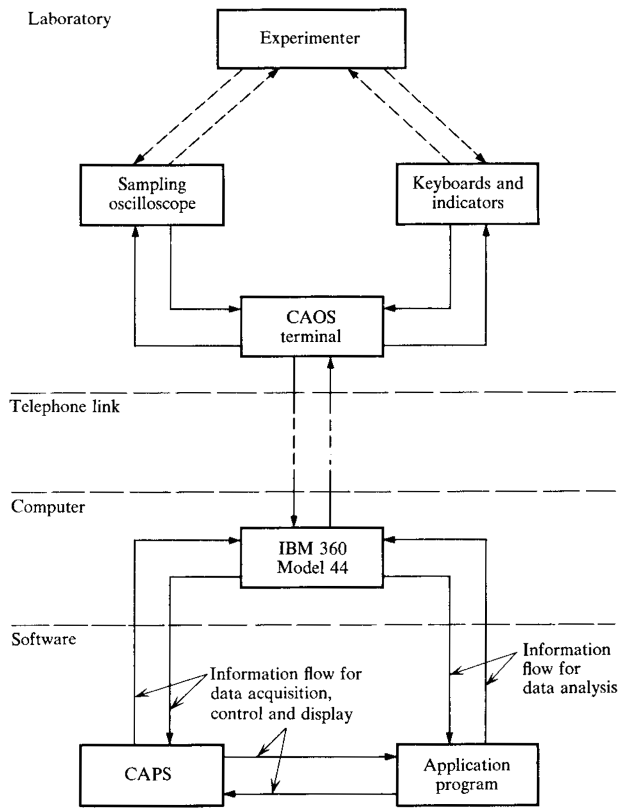


Figure 4 System block diagram.

- DIGA (or DIGB)—digitize the waveform on Channel A (or B) of the oscilloscope.
- CALAKY (or CALBKY)—calibrate Channel A (or B).
- ERASTR—erase a specified storage screen.
- WRTLIN—write a line of EBCDIC text on a specified storage screen.
- RDLINE—read a line of EBCDIC text entered via the alphanumeric keyboard.

In addition, CAPS contains interpretive and supervisory routines which activate applications programs in response to keyboard entries.

An application program may contain up to 24 routines, each of which is associated with one of the 24 available function keys. Figure 5 shows the function keyboard overlay card for the pulse parameter determination program. With this card inserted, CAPS interprets each function key depression as a call for the execution of a specific routine in its associated application program. CAPS thus renders the CAOS terminal totally transparent to the user, who needs no knowledge of the detailed workings of the terminal or the software, both of which

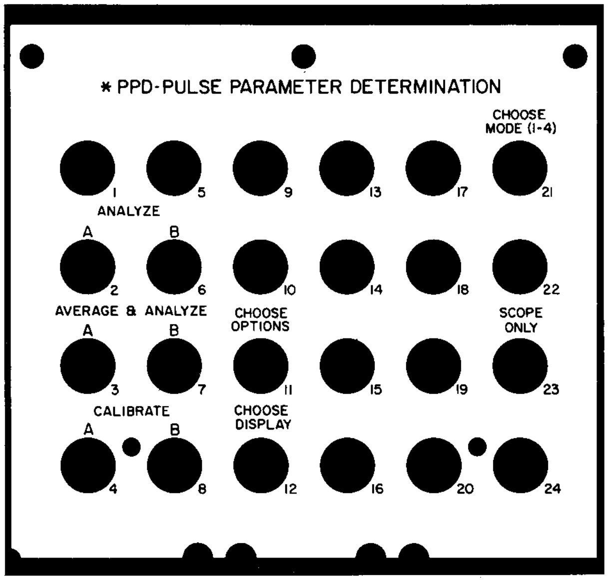
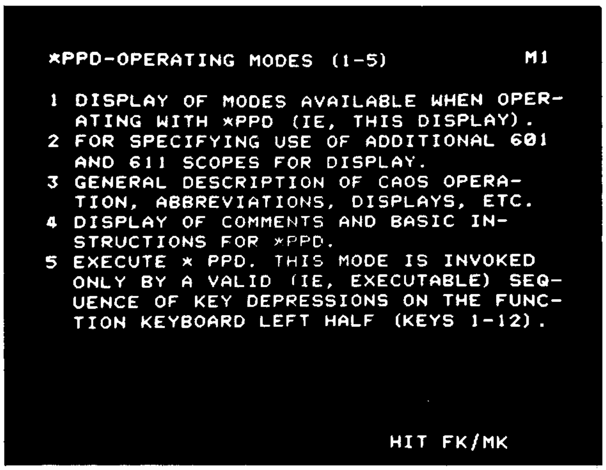


Figure 5 Function keyboard overlay card.

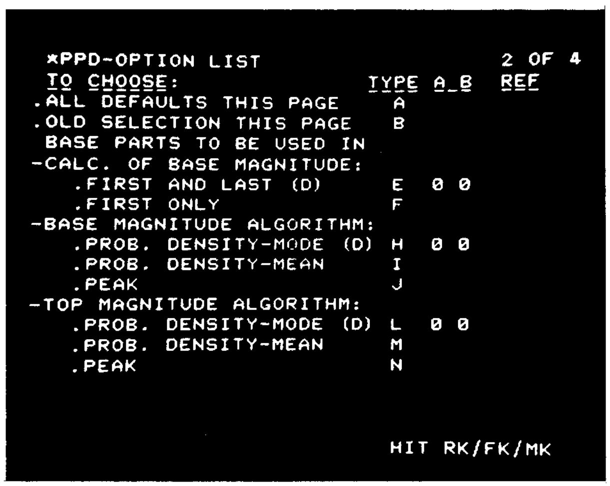
Figure 6 Mode 1 display.


*PPD-OPERATING MODES (1-5) M1

1 DISPLAY OF MODES AVAILABLE WHEN OPERATING WITH *PPD (IE, THIS DISPLAY).
2 FOR SPECIFYING USE OF ADDITIONAL 601 AND 611 SCOPES FOR DISPLAY.
3 GENERAL DESCRIPTION OF CAOS OPERATION, ABBREVIATIONS, DISPLAYS, ETC.
4 DISPLAY OF COMMENTS AND BASIC INSTRUCTIONS FOR *PPD.
5 EXECUTE * PPD. THIS MODE IS INVOKED ONLY BY A VALID (IE, EXECUTABLE) SEQUENCE OF KEY DEPRESSIONS ON THE FUNCTION KEYBOARD LEFT HALF (KEYS 1-12).

HIT FK/MK

Figure 7 Typical option list display.


*PPD-OPTION LIST 2 OF 4

TO CHOOSE:	TYPE	A B	REF
.ALL DEFAULTS THIS PAGE	A		
.OLD SELECTION THIS PAGE	B		
BASE PARTS TO BE USED IN			
-CALC. OF BASE MAGNITUDE:			
.FIRST AND LAST (D)	E	0 0	
.FIRST ONLY	F		
-BASE MAGNITUDE ALGORITHM:			
.PROB. DENSITY-MODE (D)	H	0 0	
.PROB. DENSITY-MEAN	I		
.PEAK	J		
-TOP MAGNITUDE ALGORITHM:			
.PROB. DENSITY-MODE (D)	L	0 0	
.PROB. DENSITY-MEAN	M		
.PEAK	N		

HIT RK/FK/MK

are completely masked. CAPS also minimizes core requirements since only it and the application routine associated with a single key must be present in the memory at any time. CAPS provides a high degree of interaction since:

- the sequence of operations is determined by the user's actuation of the function keyboard, and
- conversational features in CAPS, or in an application program, guide and prompt the user with instructional or diagnostic messages.

The CAOS library currently contains application programs for time-jitter correction, spectrum analysis, deconvolution and signal averaging in addition to the program for pulse parameter determination. New application programs, as required, may be written in FORTRAN and added to the library.

Pulse parameter determination program

The program for pulse parameter determination (PPD) is invoked by inserting the overlay card shown in Fig. 5 in the terminal. PPD makes extensive use of terminal displays, for example, when the operator depresses "Choose Mode" (key 21) and enters a "1" via the alphanumeric keyboard, the display shown in Fig. 6 results. Modes 1 through 4 comprise, in effect, an interactive instruction manual for the operation of PPD and the terminal itself. Space limitations preclude the presentation here of the 8 displays which these four modes contain. The operator, as a function of his familiarity with the PPD program and the terminal, may execute any or all of these modes or he may proceed directly to Mode 5, the PPD program proper. All displays have the following features in common with the display of Fig. 6:

- The top line always contains a page title and the mode and/or page numbers.
- The bottom line always contains abbreviated instructions for exiting from the page (i.e., in Fig. 6, "HIT FK/MK").

Mode 5, the PPD program proper, is executed with the 8 active keys on the left half of the function keyboard (see Fig. 5). Typical operation begins with:

1) execution of "Choose Display" (key 12) which provides an interactive control display through which the operator may format the display of results from the PPD program. The default (i.e., complete) display will be provided if no options are exercised.
2) execution of "Choose Options" (key 11) which provides interactive control displays through which the operator may exercise a number of data acquisition and analysis options. Again, default options are taken if the operator makes no specific choices.

Figure 7 shows a typical page of the PPD option list in which all default options are indicated by "(D)." By typing the specified alphabetic characters the operator may for either or both oscilloscope channels:

- select all default options on the page;
- retain his previous option selection;
- specify whether the determination of base magnitude shall be based on:
  a) both sections of the pulse waveform base, or
  b) that section of the base which precedes the first transition;
- specify whether the base (or top) magnitude shall be calculated as:
  a) the mode of its probability distribution,
  b) the mean of its probability distribution, or
  c) the peak magnitude of the pulse waveform.

Again, space limitations preclude showing the complete PPD option list which provides the following additional options:

- whether calibration of the sampling channel shall be
  a) continuous, or
  b) under manual control from the function keyboard;
- whether waveform averaging shall be
  a) continuous, or
  b) under manual control from the function keyboard (default);
- whether the pulse waveform analysis shall be based on:
  a) the entire waveform (default) or
  b) on a specified continuous portion of the waveform;
- whether the base magnitude shall be
  a) assumed to be zero (default);
  b) determined on an absolute basis, or
  c) assigned a specified value;
- whether the time origin shall be
  a) assumed to be zero (default), or
  b) assigned a specified value;
- whether the locations of the proximal, mesial, and distal lines shall be
  a) at 10%, 50% and 90%, respectively, of the pulse amplitude (default),
  b) at specified percentages of the pulse amplitude, or
  c) at specified magnitudes;
- whether the polarity of the pulse waveform shall be
  a) automatically determined by the program (default), or
  b) specified by the operator;
- whether attenuation external to the oscilloscope shall be assumed
  a) to be zero (default), or
  b) to be a specified value.

When the operator has completed executing the option list—an operation which can take negligible to significant time, depending on the number of default options which must be overridden—he executes the PPD program by depressing one of keys 2 through 4 or 6 through 8 (in Fig. 5) for each operation required. The operator may revert to conventional stand-alone oscilloscope operation at any time by depressing the "Scope Only" (key 23).

Examples of PPD operation

Space limitations preclude a comprehensive description of all modes of PPD operation with the sampling oscilloscope. The authors, instead, present a limited set of examples which illustrate PPD operation in general and indicate the degree of precision which can be achieved with CAOS. Throughout this section the discussion of numerical results is solely in terms of precision, that is, ". . . the degree of mutual agreement characteristic of independent measurements of a single quantity yielded by repeated applications of the [measurement] process under specified conditions . . . " [5].

Table 1 lists the hardware conditions and PPD software options for three types of test (A, B, and C) which were performed 9 times in a one-week period. Figures 8, 9 and 10 show the results of the first of these tests wherein:

- Figures 8(a), 9(a) and 10(a) show the pulse waveform data which were analyzed by the PPD program. Figures

Table 1 Test conditions and options.

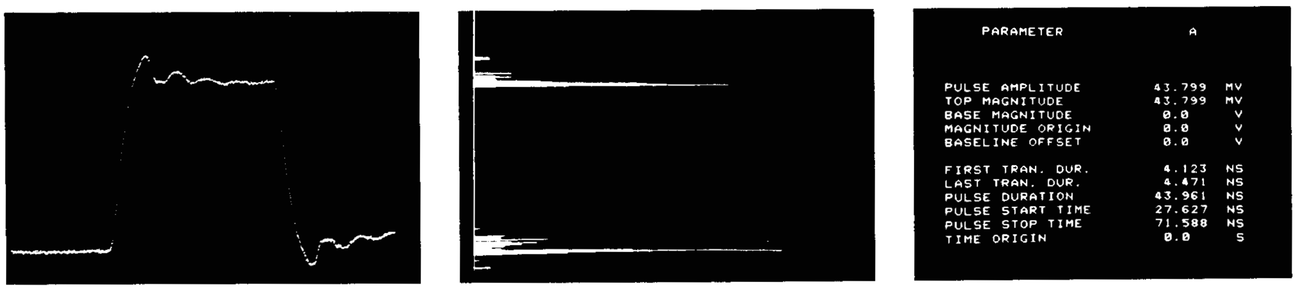
Type A (Fig. 8)	
Pulse source	Hewlett Packard Model 215A Pulse Generator
Repetition frequency	60 kHz
Pulse distorting circuit	Passive RLC network
Sampling head	Tektronix S-2 (75 psec)
Oscilloscope settings	
Vertical sensitivity	100 mV/cm
Horizontal sensitivity	10 nsec/cm
Number of sampling points	800
Triggering	External from pulse source
PPD operation	
Analyze A (key 2 in Fig. 5). All default options *except* that base magnitude and top magnitude were computed as the means of the probability density histograms.	
Type B (Fig. 9)	
Same as Type A, above, except:	
Vertical sensitivity—10 mV/cm. External attenuation of 20 dB (nominal) inserted between pulse distorting circuit and sampling head.	
Type C (Fig. 10)	
Same as Type B, above, except:	
PPD operation—Average and analyze A (key 3 in Fig. 5) with 10 digitizations of the waveform specified.	

(a) (b) (c)

Figure 8 (a) Pulse waveform, (b) probability distribution histograms, (c) calculated pulse parameters.

(a) (b) (c)

Figure 9 (a) Noisy pulse waveform (b) probability distribution histograms, (c) calculated pulse parameters.



(a) (b) (c)

Figure 10 (a) Averaged noisy pulse waveform, (b) probability distribution histograms, (c) calculated pulse parameters.

8(a) and 9(a) show the waveform data from one digitization; sampling noise at the 10 mV/cm sensitivity is evident in the latter. Figure 10(a) is the average of 10 digitized waveforms, each of which was similar to that shown in Fig. 9(a). Figures 8(b), 9(b) and 10(b) show the probability density histograms of the corresponding waveforms. For these figures the display routine adjusted the histogram data to provide a maximum horizontal deflection of 8 cm. The histograms, while exhibiting similar characteristics, are distinctly different, Fig. 9(b) being markedly different from the other two.

Figures 8(c), 9(c) and 10(c) show the calculated pulse parameter displays provided by PPD using the techniques, options, and algorithms described in previous sections. Note that, despite the differences between the waveform data and the significant differences between their histograms, the numerical results are in relatively close agreement.

Table 2 lists the salient results from Figs. 8(c), 9(c) and 10(c) and shows the variations (in percent of full scale) for all 9 executions of the three types of test described in Table 1. In Table 2 the extreme variations for each of the four major parameters are set in bold-face type. Long-term precisions of the order of $\pm 0.5\%$ of full scale, or better, are achieved throughout. As was

Table 2 Long term variations in indicated pulse parameters. Type A test arbitrarily taken as reference. Vertical full scale—800 mV; Horizontal full scale—100 nsec. Extreme variations for parameters are set in bold-face type.

Data for Run No. 1		*Variations in percent of full scale*								
		Run numbers								
		1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Pulse amplitude										
Type A	439.722 mV	...	+0.187	+0.250	+0.324	+0.450	+0.444	**+0.570**	+0.286	+0.273
Type B	437.370 mV*	**−0.294**	−0.123	−0.055	+0.105	+0.011	−0.134	+0.106	−0.178	−0.193
Type C	437.990 mV*	−0.217	+0.107	+0.121	+0.332	+0.160	+0.160	+0.366	+0.008	+0.241
First transition duration										
Type A	4.083 nsec	...	+0.063	−0.016	+0.049	+0.083	+0.048	+0.147	+0.038	+0.006
Type B	4.027 nsec	−0.056	+0.056	**−0.155**	+0.135	+0.043	−0.018	**+0.157**	+0.045	−0.088
Type C	4.123 nsec	+0.040	+0.062	−0.042	+0.038	+0.092	+0.006	+0.035	+0.121	+0.081
Last transition duration										
Type A	4.388 nsec	...	+0.038	+0.077	+0.013	+0.016	+0.141	+0.069	+0.046	+0.070
Type B	4.492 nsec	+0.104	**−0.099**	−0.062	+0.069	+0.003	+0.171	**+0.176**	+0.032	−0.090
Type C	4.471 nsec	+0.083	+0.077	+0.058	+0.059	+0.023	+0.157	+0.056	+0.085	+0.11
Pulse duration										
Type A	44.058 nsec	...	+0.182	+0.009	+0.036	−0.128	+0.045	−0.358	**+0.308**	+0.136
Type B	44.034 nsec	−0.024	+0.027	−0.170	+0.159	−0.272	+0.034	**−0.762**	−0.302	+0.078
Type C	43.961 nsec	−0.097	+0.063	−0.086	+0.021	−0.109	−0.064	−0.315	−0.251	+0.155

*Indicated data multiplied by 10.

Table 3 Short term variations in indicated pulse parameters. Statistics on 100 Type A tests. Vertical full scale—800 mV; horizontal full scale—100 nsec.

Pulse parameter	*Mean (in units shown)*	*Standard deviation (in units shown)*	*Standard deviation (in % of full scale)*
Pulse amplitude	445.974 mV	0.593 mV	0.0741
First transition duration	4.16860 nsec	0.03252 nsec	0.03252
Last transition duration	4.52299 nsec	0.03199 nsec	0.03199
Pulse duration	44.4658 nsec	0.0826 nsec	0.0826

expected, the Type B tests contribute a majority (6) of the extreme variations. Further, all nine runs, with the exception of run 7, were made after all equipment had been on for one-half to one hour. Run 7, which contributes 4 of the 8 extreme values in Table 2, was made after all equipment had been on for approximately six hours.

The results summarized in Table 2 indicated that the operation of CAOS (and all other hardware) under the PPD program was approaching a state of statistical control, insofar as precision was concerned. The sample sizes are of course, too small to warrant any firm conclusions.

Hence, an additional program was written which executed the Type A test 100 times and computed the mean values and standard deviations for the four major pulse parameters. The results are tabulated in Table 3.

The data in Tables 2 and 3, unfortunately, are only indicative of the precision that CAOS, or similar instruments, can bring to the pulse waveform measurement art. In all of the data presented variations from a variety of sources are combined. These sources of variation, in an estimated order of their contributions are:

1) the vertical and horizontal circuits of the sampling oscilloscope,

2) the pulse generator,
3) the A/D converter in the CAOS terminal,
4) the 20 dB attenuator,
5) the pulse distorting circuit, and
6) the interconnecting cables and connectors.

Variations due to items 3 through 6, above, are amenable to evaluation and control, but variations due to item 2, the pulse generator, are a formidable obstacle to final conclusions relative to the precision provided by CAOS.

Precision and accuracy

The discussion in the previous section considered precision only; some final comments on accuracy are in order. As Eisenhart concisely puts it, ". . . accuracy requires precision, but precision does not necessarily imply accuracy" [5]. The data presented in this paper demonstrate that CAOS and the PPD program provide precision pulse parameter determinations. But precision, valuable as it is as a prerequisite to accuracy, is only the first step. The second step from precision to accuracy is far from trivial, since it requires the development of a) pulse (or transition) generators and b) time mark generators whose characteristics are known to accuracies consistent with the precision CAOS provides.

As described elsewhere [1], the CAOS vertical calibration hardware provides dc calibration in the voltage (or vertical) axis of the oscilloscope. Useful as this feature is, it does not provide for determination of the transient response of the sampling channels. Sampling oscilloscopes with bandwidths in the 20 GHz region are currently available. Consequently, a pulse generator with a transition duration in the 5 to 10 psec range is required before an algorithm that compensates for oscilloscope frequency response can be included in CAOS software. Horizontal (i.e., sweep linearity) calibration of CAOS is, of course, possible with external oscillators or time mark generators of suitable accuracy.

Conclusions

The data presented in this paper—using pulse parameter determination as a vehicle—demonstrate the precision which can be realized by augmenting the sampling oscilloscope with appropriate digital processing. Since the CAOS hardware and procedures for acquiring waveform data are invariant, other digital processing algorithms that preserve and exploit the inherent system precision in other types of waveform analysis ensue. In addition to the program for pulse parameter determination, programs for spectrum analysis, convolution and deconvolution, digital filtering, and time jitter correction are available to the CAOS user. Programs for distortion analysis, circuit delay analysis, integration and others are envisioned and will be added as the need develops.

Digital systems for data acquisition, control, analysis and display are commonplace in industry and in laboratories. The oscilloscope, very probably, is the one instrument most used in the development of such systems. It is ironic that this versatile instrument itself is only now being given a degree of precision and greater versatility through automation of the type that CAOS provides.

Acknowledgments

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