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DATA CONDITIONING AND DISPLAY FOR APOLLO PRELAUNCH CHECKOUT

MULTI-PARAMETER MONITORING DISPLAY

PREPARED FOR:

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WASHINGTON, D. C.

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DATA CONDITIONING AND DISPLAY FOR APOLLO PRELAUNCH CHECKOUT

Multi-Parameter Monitoring Display

by:

Richard D. Pepler

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Submitted to:

Office of Manned Space Flight
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Attention: Chief, Checkout Apollo Test

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The writer accepts responsibility for the inadequacies of this report, but wishes to acknowledge the invaluable contributions of his colleagues. Most of the key ideas expressed herein resulted from discussions with colleagues who were working on related tasks of the NASA project (Contract No. NASw 1363), and in particular, with Mr. Joseph G. Wohl, who was Program Director.

SUMMARY

The objective of the work reported in this technical memorandum was to design formats for monitoring multiple parameters on CRT displays. We aimed to develop graphic displays that would enable viewers to see intuitively patterns in measurement data, or changes in patterns, that they might miss if the data were presented in alphanumeric formats.

Any display format acts in a manner somewhat analogous to a filter; it makes some aspect of the data more visible and hides other aspects. An engineer needs to be able to select which measurement parameters he wants to look at and to specify what information about each parameter he wants displayed and in what format.

We reviewed current knowledge relevant to graphical display design, and used different principles to design six formats differing in data transformations and display coding: Bar Histogram, Contour Histogram, Density Bar Graph, Strip Chart Formats of Raw Data, Moving Estimates of the Mean and Moving Estimates of the Standard Deviation of the data.

The interpretability of the different CRT display formats was evaluated using streams of simulated data with specified characteristics that we generated on our in-house computer. Six judges independently viewed displays of the simulated data in each of the six formats, and ranked the formats according to their value for detecting three kinds of disturbance to the data; a step change in the mean, a ramp change in the mean, and a change from a single to a bimodal distribution. Every judge viewed the equivalent of fifteen updates of a CRT display in each format for every disturbance.

The differences among the summed rank values given by the six judges to the formats were found to be statistically highly significant and could not have been due to chance.

The Strip Chart Format of a moving estimate of the mean was the best. Then the Bar Histogram, Strip Chart Format of the raw data, Contour Histogram, Density Bar Graph, and Strip Chart Format of

moving estimate of the standard deviation were ranked next in that order. For detecting a change from a single to a bimodal distribution the Strip Chart Format of the moving estimate of the mean and the Bar Histogram were again ranked first and second, respectively. But in this case the Strip Chart Format of the moving standard deviation was judged to be better than the Strip Chart Format of the raw data values.

The Histogram and Density Bar Graph Formats were based on a temporary store of one hundred most recent data samples and were updated every ten new data samples. In contrast, the Strip Chart Formats of the moving estimates of the mean and standard deviation were based successively on the ten most recent data samples and recomputed every new sample. An evaluation was undertaken of the additional programming effort required to expand the Saturn V display capability to provide the equivalent of the formats developed in this study. The presentation of moving estimates of the mean and standard deviation of test measurements would require minimal additional programming, while the provision of temporary storage for generating up to twenty Histogram and Bar Graph Formats simultaneously would require approximately 70 man-weeks programming effort, and the addition of a 4000 words memory module to the DDP 224 computer system.

I. INTRODUCTION

Prelaunch checkout engineers need to monitor data from many test points simultaneously. They need multiple sources of information to obtain as complete an understanding as possible of the performance of their systems under test conditions. They must verify the performance and status of their systems and strive to detect any unusual responses to the test stimuli that might possibly indicate an impending failure. Test data from individual support systems (e.g., propellant loading) are recorded and displayed currently at many separate consoles and racks, and even in different rooms of the launch complex. Test data from each space vehicle system are also supplied to many separate displays on several racks or consoles for each system. But the Apollo/Saturn test engineers are also provided with CRT displays on which they can call up data from many previously specified test points. These CRT displays provide engneers with a valuable capability for monitoring measurement data from multiple test points at a single location.

The CRT displays present instantaneous values of sampled measurement data in alphanumeric tabular formats and have an appearance somewhat similar to arrays of multiple digital readout devices. Unfortunately, rapidly changing values in the right-hand column of such digital displays provide indications of changing values that are difficult to interpret. This difficulty is probably due mainly to the burden that changing digital values impose on a viewer's short-term memory, if he is to derive information on rate of change, changes in rate of change, or even on direction of change in measurement values. Consequently, if the ACE-S/C and Saturn V CRT displays present data in only tabular formats they are likely to be used in practice more after the fashion of warning displays (that blink when a parameter exceeds some "red-line" value) than as continuous monitor aids to help detect and interpret any ususual states or conditions that are beginning to develop.

The objective of the present task was to design formats for CRT displays that will help an engineer detect quickly any systematic changes in the values of any two to six selected measurement parameters more or less as they occur, and observe any changes in relationships among the selected parameters during tests.

Our approach to this problem was to explore the feasibility of designing displays that organize and transform measurement data into easily understood graphical representations or data "pictures." Different principles were used to design these graphic displays, so that we could explore and evaluate the effect of different data transformations and display coding on the interpretability of the displays.

The second section of this report reviews knowledge relevant to graphical display design: the literature on human perception of graphic patterns, human engineering design guides, and current practice in designing displays, panels and consoles. This review of background knowledge on display design forms the basis for our present approach to CRT format design that is described in Section III. Section IV describes the new display concepts and their demonstration and evaluation as aids in detecting anomalous data and new relationships among measurement parameters. The data processing implications of providing these new graphic display capabilities with the ACE-S/C and the Saturn V display systems are considered in Section V. Our conclusions and recommendations constitute Section VI.

II. RELEVANT KNOWLEDGE

Man has the ability to organize his visual world into objects and forms that differ along a great many dimensions of sensation, e.g., color, brightness orientation, size, texture, shape, etc. He has always a natural tendency to attempt to structure his field of view into shapes or patterns against a more uniform background, and in this way to identify or give some meaning to his visual surroundings. Man's ability to recognize patterns and relationships is an aspect of perception that is little understood, and consequently is an ability that man finds most difficult to simulate with computer systems. Graphic representations of measurement data attempt to encode information in ways which will enable viewers to perceive intuitively relationships and patterns in the underlying data, that they might miss if the data were encoded alphanumerically.

The literature on visual pattern and shape perception was reviewed in the hope of extracting principles that could be used to design data displays. Much of this research has been theoretically oriented and directed towards testing general theories of perception and memory [5]. Investigators have used a variety of shapes and patterns to explore the effects of variously degraded viewing conditions on pattern detection, discrimination, identification, recognition or reproduction.

Surprisingly little attention has been paid to defining and quantifying the shapes or patterns used in these studies [1]. Findings based on one set of stimulus material can rarely be generalized to a broader selection of different shapes or patterns. One reason for the lack of general measures or terms to define shapes or patterns is that shape is not a single stimulus dimension; it is multi-dimensional, and the number of dimensions needed to describe a shape are not constant but increase with the complexity of the figure. Complexity, figural symmetry, rotation, and compactness are characteristics of patterns that have been reliably related to perceptual performance [3]. Many unique stimulus conditions and different tasks have been used in research on the perception of patterns, but evidence shows repeatedly under a variety of circumstances that observers have a remarkable ability to detect a pattern or discriminate among several patterns despite severely degraded viewing conditions, distortions and/or the presence of irrelevant stimuli [13]. Discrimination between similar but different component forms in a complex pattern is accomplished most reliably when the forms differ in brightness. The orientation of the lines in the component figures is the most powerful single geometric aspect that enables an observer to discriminate between them [2].

Findings from visual perception research have been used and interpreted in various human engineering design handbooks (7, 12) as guidelines for the design of symbolic and pictorial displays, e.g., warning indicators, meters, recorders, flight instruments and CRT radar displays. Such guidelines tend to be written in terms of individual electromechanical scalar and digital display devices or CRT displays used for detection and tracking tasks. On the other hand, guidelines for arranging individual displays on a panel to facilitate check reading for abnormal values or relationships among several parameters can be used as guidelines also for formatting measurement data from several sources on a single CRT display.

For example, the handbooks recommend that meters be arranged in rows in such a way that all their pointers are horizontal when all the measurement values are normal. A viewer scans naturally and easily across the array of meters and can immediately detect any pointer that is not horizontal.

The recommended arrangement of meters creates a compound display in which measurement values are in effect coded by the orientations of line segments arranged to form a single horizontal line. A non-normal value causes a change in orientation of a line segment that contrasts with the uniform orientation of the other line segments. To follow the general guidelines of the handbook recommendation, formats for CRT displays should encode and arrange measurement values so that normal readings constitute a uniform pattern of symbols against which the symbol for an unusual value will stand out in sharp contrast.

The usual meter type display provides a viewer not only with a clear indication of the instantaneous readings of some measure, but indications of the direction and rate of change in measurement values. Meters provide an opportunity for viewers to discriminate between normal patterns of movement of the pointers and any unusual movement or sequence of movements. A meter type display is a rich source of information that provides indications of both instantaneous and derivative measurement values (9). By paying close attention to the movements of a meter needle an engineer can learn a great deal about the characteristic variations in continuous measurement values or the characteristics of a sampled data stream. Pen recorders also provide a rich source of information (like a meter), but in a permanent form that can be viewed contemporaneously, and at any subsequent time.

The fact that Apollo/Saturn prelaunch checkout engineers require that data displayed in CRT page formats should also be presented on meters and recorders emphasizes the relatively greater reliance they now place on these latter devices for obtaining as complete a picture as possible of the state and performance of their systems.

Before CRT displays can become equally rich sources of information about system performance measures, they need to be capable of providing either selectively or simultaneously:

1. Simple pattern indications of normal measurement values.

2. Direct indications of the normal variability of each measurement parameter.

3. Sensitive indicators of when and how the mean of a data stream is shifting.

4. Direct representations of changing relationships among the parameters selected for display.

The approach described in the next section outlines a rationale for the new display format concepts that we have developed in an attempt to provide the capabilities listed above.

III. APPROACH

Displays of test data are not necessary to an engineer if he knows in advance the exact characteristics of the data streams he is monitoring and of the disturbances he is interested in detecting. He can select a statistical method for sampling the data and for testing differences between the samples that will detect and identify disturbances to the data stream more effectively than he can by looking at displays of the data (11). But the power of such statistical tests depends on their specificity or appropriateness to the data sampled. Rarely does an Apollo/Saturn prelaunch checkout engineer have such exact knowledge about his data before testing.

Usually, a test engineer has only a general idea of the characteristics of the test data and of the probable or critical types of disturbance that he might have to detect. In these circumstances an engineer needs on opportunity to learn all he can about the characteristics of the data he is collecting. He should therefore be able to monitor the test data on displays that are rich in information; this means that he should have a capability for looking at the data displayed in a number of different formats. Any display format and coding method acts in a manner somewhat analogous to a filter; it renders some aspects of displayed data more "visible" and tends to hide other aspects or information. At different times, or for different data streams, an engineer may want to see the shape of the distribution of a sample of data, its mode and range, have an estimate of its mean and variance, or see how certain parameters of the data change in relation to each other, to similar parameters of other data streams, and also over time. Certain formats display these different kinds of information more effectively than others.

In order that our new display format concepts shall provide an "on-line" monitoring capability, we have assumed that they are based on regularly updated samples of the data stream held temporarily in storage for a uniform length of time. As new data enter the temporary store an equal number of the oldest data samples leave it on a "first in, first out" basis. The temporary store of data samples can be thought of as an open ended "pipeline" into which new data flows at one end and old data flows out at the same rate at the other end.

Data in the "pipeline" can be manipulated and displayed in a variety of ways, for example, coded and displayed directly as a series of values plotted against time, rearranged into an ordered series of values and displayed as indicators spaced on a linear measurement scale, counted by class intervals and displayed as a frequency histogram, or processed to obtain changing estimates of the data's mean, variance, other statistical moments or time derivatives.

The size of the temporary data store and the proportion of data samples updated at one time should be determined in relation to the rate at which each test point is sampled. We say this on the assumption that the sample rate authorized for each test point was based on prior knowledge of the probable variability in the data from that point. If a test measurement parameter of a system were stable, it might for example be assigned a sample rate of one per second. In this case, the temporary storage of data necessary for generating a meaningful display might be as small as twenty samples. On the other hand, for data from a test point with a sample rate of 10 or 100 per second, the temporary store might have to be as long as 100 to 200 samples respectively to achieve a reasonably stable picture of the data stream. In the one sample per second case, we should have a completely new set of data in the "pipeline" every 20 seconds, and in the second sample, either every 10 or 2 seconds.

A basic concept underlying our approach to designing formats that will enrich the Apollo/Saturn prelaunch checkout systems' CRT displays is that an engineer should have the capability of selecting what measurement parameters he wishes to look at, and of specifying what information about each parameter he wants displayed and in what format.

IV. MEASUREMENT DATA DISPLAY FORMATS

A. General

An engineer will be interested mainly in three kinds of information from each test point: (1) trends in the data over time, (2) correlations between the data from two or more parameters, and (3) the frequency distribution of measurement values within each data stream. Further, an engineer may want to see trends not only in the data samples, but also in their moving averages and moving variances as these are computed successively, and perhaps, also the density distribution of the first derivative of the values as well as of the values themselves. The utility of derivative information for comprehending the physical process underlying the recorded test data are discussed in a companion report [11].

The formats that we considered are all position coded and scalar in the sense that the values or numbers of raw or processed data samples are displayed as the positions of points or lines in relation to a scaled vertical and/or horizontal axis. Although we did not have the capability for generating display formats that make use of brightness coding, we have also explored conceptually the merits of a format that uses the variable brightness of each datum point as an indication of the length of time it has been in the temporary store. With this additional coding dimension it is possible, for example, to add "time" information to the data points arranged in an ordered series of measurement values. This concept of a "fading trace" bar graph format, in which measurement indications lose their brightness with time, is among the formats described.

The concept of a selective display capability by which an engineer can call up six or so parameters for simultaneous viewing constrains, to some degree, our freedom in formatting the displays of each individual data stream. One constraint is that the same information about each of the signal data streams should be presented in the same format. Formats that relate data from each source to a vertical scale (e.g., density bar graph) should be arranged side by side on the CRT screen so that comparisons among them can be made with a horizontal scanning (eye) movement. Scales should have low values at the bottom and high values at the top of the screen. The perception of the relative values of each parameter in these displays involves an appreciation of the relative "heights" of indications on each scale. Relationships among parameters can be checked most easily if their vertical scales are chosen and adjusted so that "normal" values on each scale are aligned horizontally across the screen. Finally, it may prove desirable to align the upper and lower no-go limits with the top and bottom of the CRT screen and to view the indications as vertical "meters" for close-to-limit indications.

Formats that graph the distribution of values in each of several data streams should present the graphs one above the other so that the modes of each distribution of values are approximately aligned vertically. In such a format the measurement class intervals are on the horizontal axes. Perception of detail is most accurate when the eye scans from left to right [6] probably as a result of well-established reading habits, and information is extracted from histograms better when the bars or columns of frequency values are drawn vertically than horizontally [10]. Engineers are accustomed to reading multipen recorders which display the values of several parameters as the positions of traces to either side of time lines running the length of the recording paper.

These recorders are usually mounted so that the time axis is vertical, the pens are at the top of the display and move horizontally from left to right. The time trace of a strip chart format that we propose for the CRT display should also run from top to bottom of the screen with the measurement scales running from left to right. The most recent values that enter the pipeline are read at the top of the display and the oldest at the bottom, i.e., new values appear at the top of the display, progress down the screen and disappear at the bottom. Comparisons between different parameters in a strip chart format are made by scanning the display horizontally.

B. Format Concepts

We have explored the value of the following formats for detecting and identifying various kinds of disturbances in different data streams:

1. Frequency histograms (plotted as vertical bars and contours).

2. Strip charts of raw data, moving means and moving standard deviations.

3. Density bar graphs.

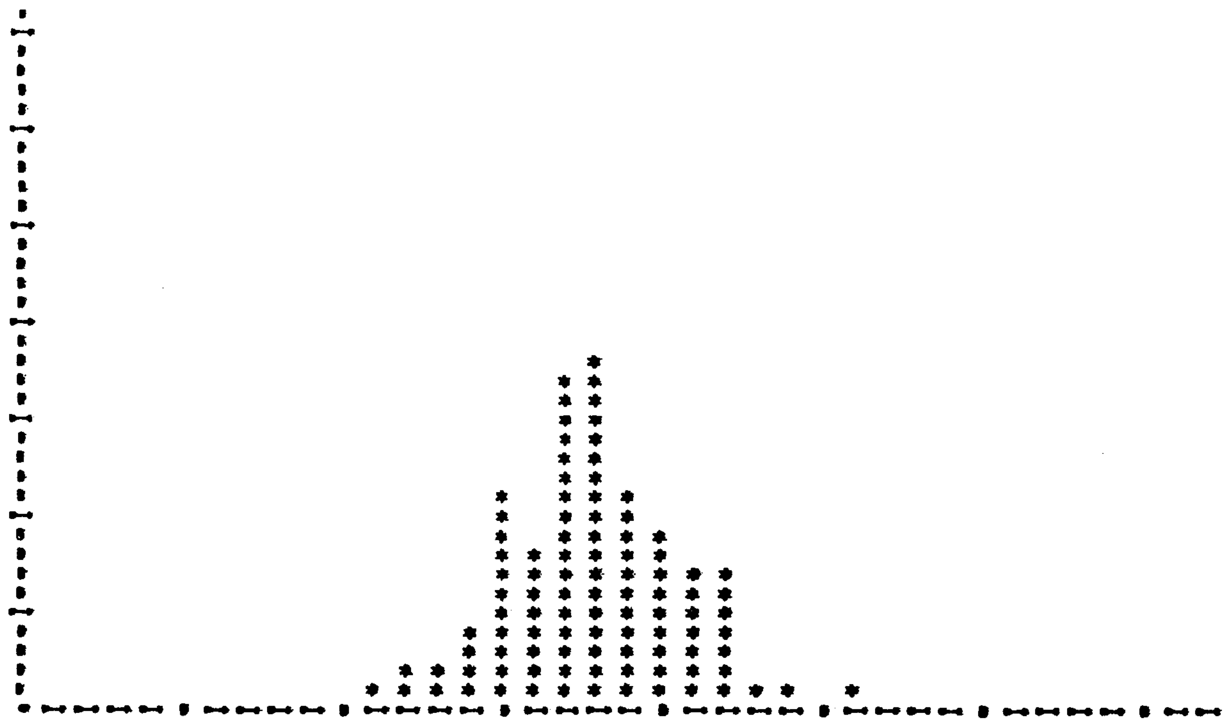
4. Fading trace bar graphs.

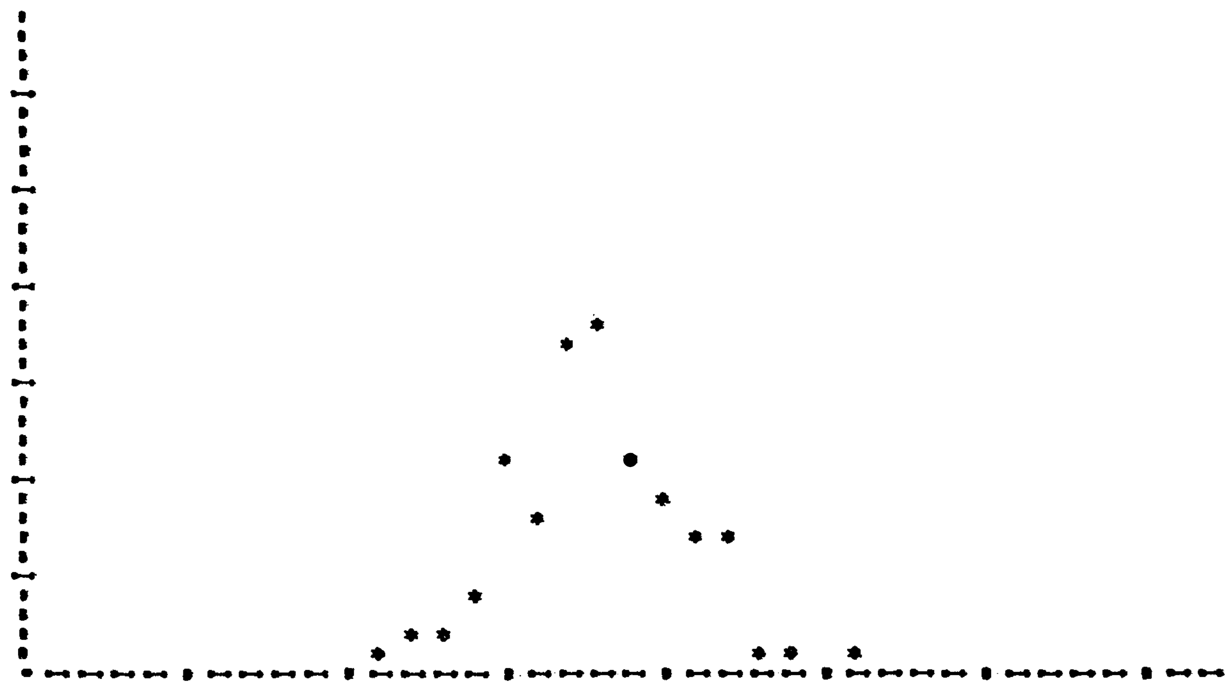
1. Frequency Histogram

Measurement values are encoded as positions in reference to a horizontal scale that is gradated in values representing the limits of successive classes of values. All values falling between two adjacent interval marks on the scale are plotted vertically one above the other over the center of the class interval. The number of measurement values falling in each class interval is read from a vertical scale. Since indications of measurement values falling in each class interval are plotted one above the other, the number of values in each class is read against the vertical scale as the height of the indications above the horizontal axis. The frequency distribution of measurement values in a data stream (when plotted as a histogram) can be perceived as the shape or outline formed by the heights of the columns of indications above the horizontal axis. The mode and range of the distribution are immediately apparent from the maximum height and the extreme class interval values of the histogram. Changes in a stream of data being monitored can be perceived as a change in the shape of the histogram. The histogram format can show either all the data points in each class interval or only the final values in each interval. The former is referred to as a bar type histogram, the latter as a contour histogram. Figure 1 shows the histogram plots of 100 samples of data from a simulated source with a mean value of 28, and a standard deviation of 0.6667 units.

2. Strip Chart

Successive data samples are displayed as the positions of indications in relation to a horizontal scale of measurement values and to a vertical time scale that indicates their "age." As a new value appears at the top of the display, all values are displaced down the screen one unit on the time scale and the oldest value at the bottom disappears. The effect is to paint a time trace of successive samples of measurement values. In addition to plotting individual data samples as these occur, this display format can also present changing statistics of the data stream, such as moving means and standard deviations. The degree of "smoothing" achieved with these statistics depends on the numbers of samples on which the successive computations of each statistic are based. Figures 2 and 3 illustrate the strip chart format. Figure 2 shows the simulated data that are plotted as histograms in Figure 1; Figure 3 charts moving estimates of the mean and the standard deviation of the same data. The estimates of the mean and standard deviation are based on successive samples of 10 data points.





1 - B

Figure 1. Computer printout: One hundred examples of simulated measurement data in (A) Bar Histogram and (B) Contour Histogram formats

TIME PLOT FOR RUN 1

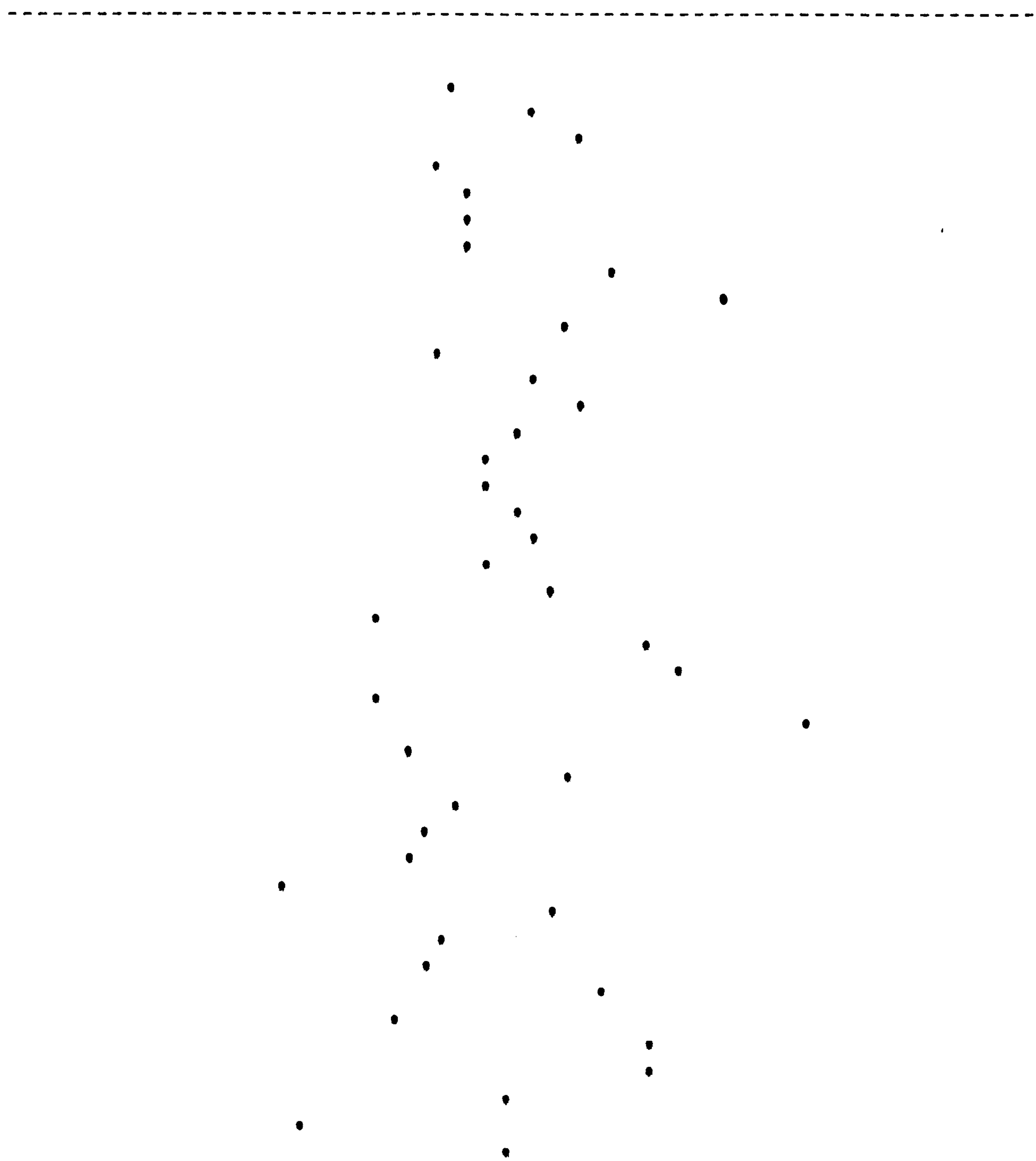


Figure 2. Computer printout: Samples of simulated measurement data in Strip Chart format (see derivative data in Figure 3)

TIME PLOT FOR RUN 1

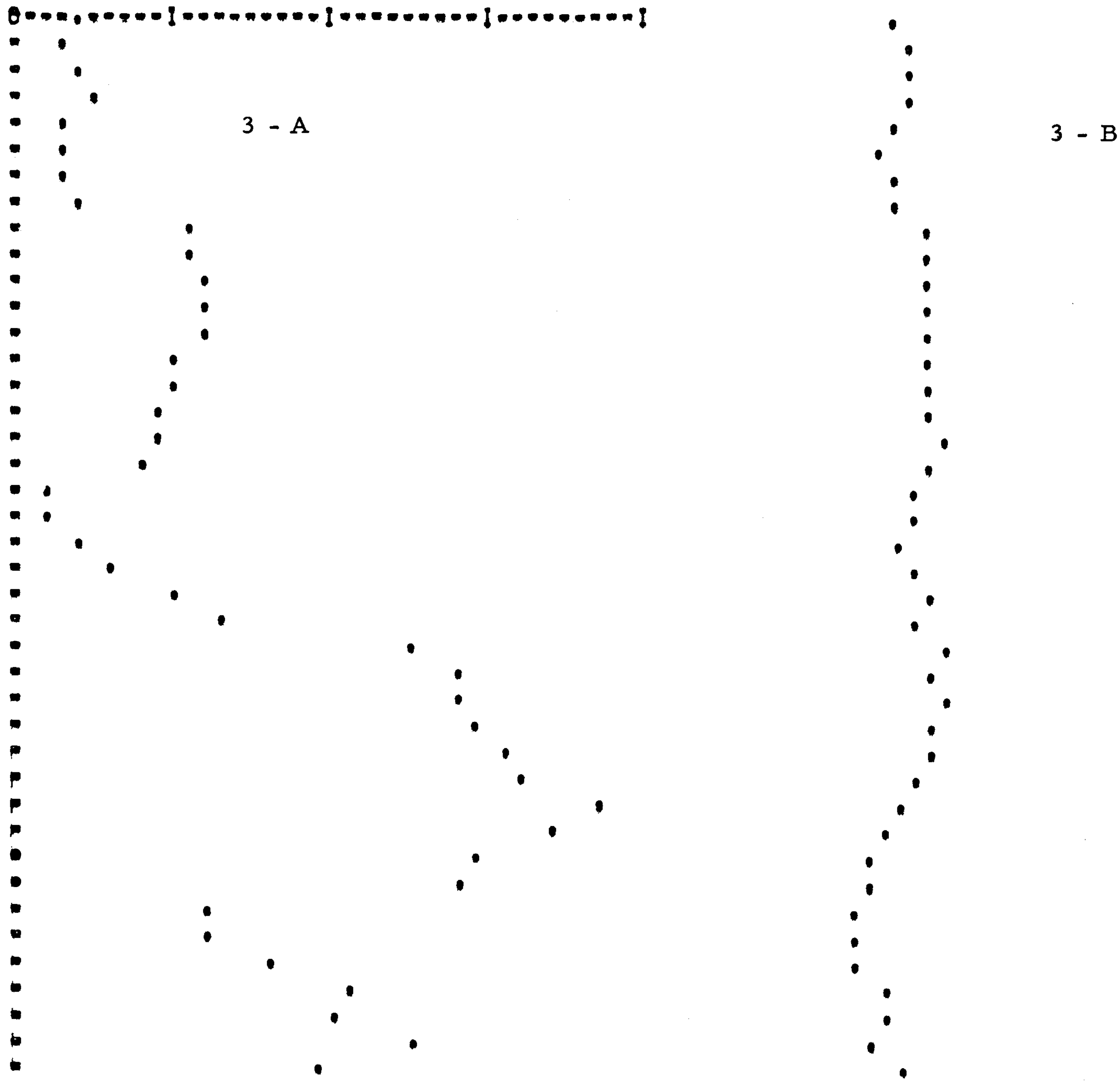


Figure 3. Composite computer printout: Moving estimates of (A) the standard deviation, and (B) the mean of samples of simulated measurement data (see raw data in Figure 2). Estimates are based on successive samples of ten data points.

3. Density Bar Graph

The samples of data in the "pipeline" are displayed as the positions of indications on vertically oriented scales of measurement values. An interval size is selected for each scale such that the data points are distributed over approximately at least one-third of a scale. The range of the data in the "pipeline" is immediately apparent. The modal values can be judged reasonably accurately as the center of the part(s) of the scale about which most indications are clustering. On a CRT display parts of a scale about which many indications are clustered will appear denser than parts of the scale with few indications. If the data stream has a normal distribution, the mode will be at the center of the densest part of the scale. Figure 4 reproduces a number of density bar graphs of successive up-dates of the 100 data points in a simulated "pipeline" store. Each horizontal bar (three short lines) indicates that data with the indicated value are present in the "pipeline." A bar gives no indication of how many samples there are with this one value.

4. Fading Trace Bar Graph

This format is a variant of the Density Bar Graph, but includes an additional display dimension. The measurement value indications of the data are related to a vertical scale as in the previous format, but they are also "tagged" with an indication of the "age" in the pipeline. New values are indicated on the CRT with maximum brightness but the brightness level of all indications decreases with time. Brightness and time are related logarithmically in that brightness decreases most rapidly at first and progressively less for each older datum in the pipeline. Where this additional coding dimension is available, an engineer, monitoring data during an automated test, should be able to detect very rapidly whether the new data were still drawn from the same population of values as before or from a new population.

C. Demonstration and Evaluation

We had hoped to use records of data from actual prelaunch checkout tests in our experimental evaluations of the interpretability of the different CRT display formats. This was not possible; and so we used instead our in-house computer to generate streams of simulated data with specified means, variances and disturbances.

We used two random number generators to produce two streams of data values distributed normally about a mean value of 28. One stream

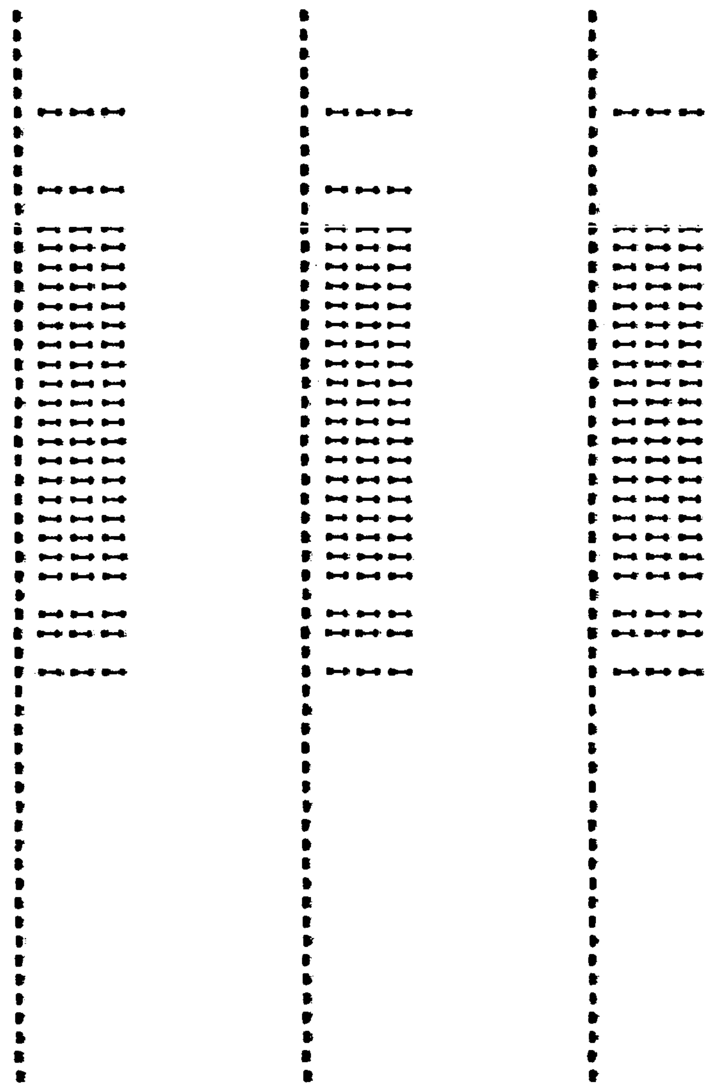


Figure 4. Computer printout: Density Bar Graph format presentations of one hundred samples of data; each successive presentation includes ten new samples of data.

of values (Stream A) had a standard deviation of 0.66, the other (Stream B) had a standard deviation of 1.33. We also generated four classes of disturbances: step changes in the mean (equal to two and three standard deviations);ramp changes in the mean of differing slopes (equal to 0.2 and 0.6 standard deviation increments to the mean for each updating of the data in the simulated "pipeline"); changes in the distribution of data entering the "pipeline" from normal to rectangular, log normal and bimodal; and changes in the variance of the data stream (Stream A to B and Stream B to A).

We assumed for the purpose of our simulation that the data streams were from a test point that was being sampled at a rate of ten times per second. We selected a "pipeline" length of one hundred data samples, and assumed a display update rate of once per second. This meant that in order to simulate on our printer, the successive updates of the CRT display every second, we produced successive plots of the data in the "pipeline" for every ten new data samples that entered it. This meant that a step change in the mean of the data stream took ten plots or simulated CRT frames to be completely represented (i.e., to replace all samples from the former data stream with samples from the new data stream). Each new histogram or bar graph was printed on a separate page. The scale factors for the printouts were selected so that the histogram of data Stream B (with the 1.33 standard deviation) occupied two thirds of the horizontal axis, so that the values on the horizontal axis ranged from 24 to 36 units, and the density bar graph for the same data occupied the lower two thirds of a vertical scale. The strip chart formats for the sample data values, the moving mean and moving variance values of the data presented in the other format displays were plotted separately and continuously. An open rectangular mask representing the CRT screen and scaled to permit a viewer to see 100 data points had to be moved over the plot to simulate a changing trace on a CRT display. The horizontal scale for the strip chart format was varied so that the raw data samples and the mean and variance values occupied approximately one third of the scale range.

We evaluated the interpretability of the different formats by having six judges independently view displays of simulated data (Stream A) in each of six formats, and rank the formats according to their value for detecting each of three kinds of disturbance to the data stream. A step change in the mean of 1.333 units, a ramp change that increased the mean 0.1333 units every ten samples, and a change from a single to a bimodal distribution, with half the data having a new mode of 30, and half the old mode of 28.

These three disturbances were selected from among a total of eight, which we generated in the sample data from our computer, because they were judged to be the more difficult to detect. Preliminary evaluations indicated that the relative difficulty of detecting these three disturbances (under the conditions of our simulation) enabled viewers to rank the six formats most confidently. With more obvious disturbances to the data, viewers could not rank the formats in relative value. The disturbances were presented in counter-balanced sequences to alternate judges, and every judge was presented the formats in different sequences (according to prepared random series of numbers 1 to 6).

Every judge viewed the equivalent of 15 updates of a CRT display, i.e., 250 data points, in each format for every disturbance. Each judge looked at all six formats twice before ranking them according to the ease in detecting a disturbance to the data stream. (In the case of the change from a single to a bimodal distribution only four formats were used.) The judges viewed only one data stream at a time. We assumed that the relative values of the formats for detecting disturbances would be independent of the number of streams of data displayed. The changes in the appearance of the bar histogram format presentations resulting from a step change in the mean of the data stream by two standard deviations (i.e., by 1.333 units) are shown in Figure 5. The first, third, and fifth updates of the display following the change are reproduced. The same data are shown also in density bar graph format in Figure 6.

The rankings that the judges gave the formats for detecting each disturbance are listed in Table 1, as well as the sums of ranks for each format, and an overall rank based on these summed ranks. The differences among the summed ranks for the formats were tested for statistical significance (by the use of Friedman's two-way analysis of variance for ranked data). In every case the differences were highly significant and could not have been due to chance. Table 1 shows that for detecting either a step change or a ramp change in the mean of a data stream the strip chart format of a moving estimate of the mean was the best, and the strip chart format of a moving estimate of the standard deviation was the worst. The bar histogram and the strip chart of the raw data values were second and third, and contour histogram and density bar graph fourth and fifth in that order, although the difference between the summed ranks of the last two formats for detecting a step change in the means was very small.

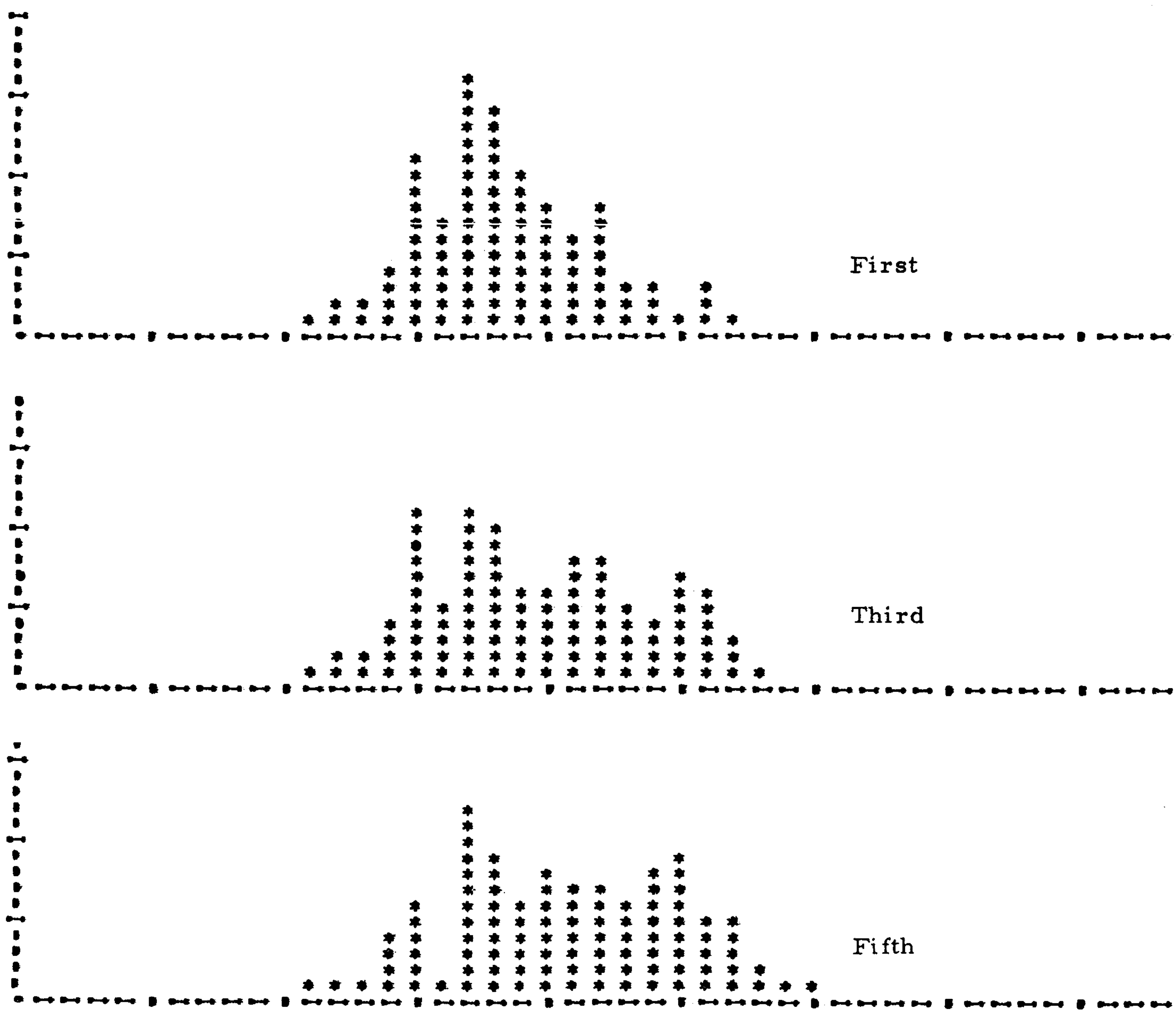


Figure 5. Examples of the first, third and fifth "updates" of data in a Bar Histogram format following a step change in the mean of the data stream.

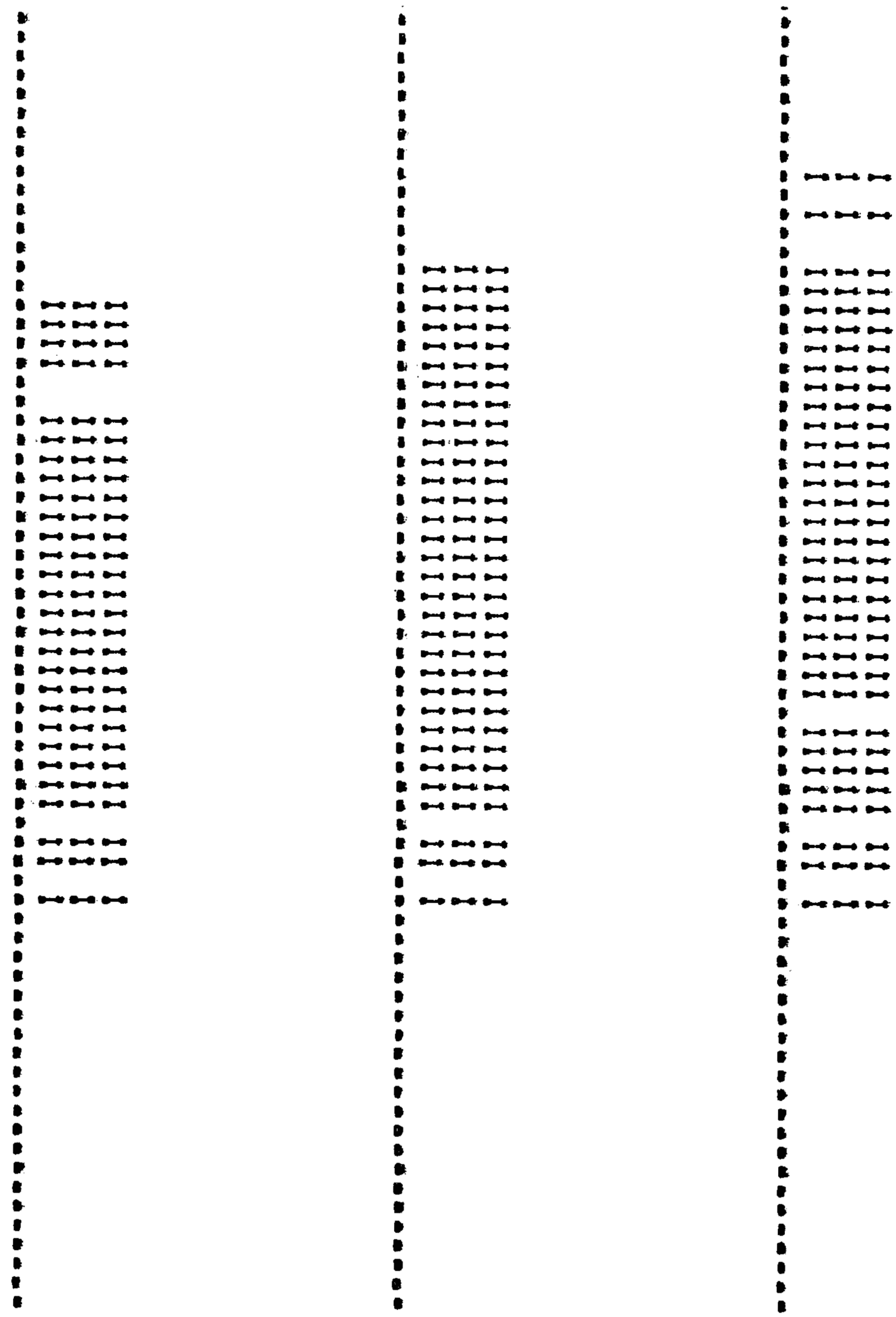


Figure 6. Examples of the first, third and fifth "updates" of data in a Density Bar Graph format following a step change in the mean of the data stream.

Table 1. Ranks of each format for detecting disturbances to a simulated data stream.

Type of Disturbance	Judge No.	Formats: Bar Histogram	Contour Histogram	Density Bar Graph	Strip Chart(s) X	$\bar{X}$	σ
A. Step Change in Mean	1	2	3	5	4	1	6
	2	3	4.5	4.5	2	1	6
	3	2	3	6	4	1	5
	4	4	5	3	1	2	6
	5	3	4	5	2	1	6
	6	1	5	2	4	3	6
		15	24.5	25.5	17	9	35
		(2)	(4)	(5)	(3)	(1)	(6)*
B. Ramp Change in Mean	1	2	4	5	3	1	6
	2	3	4	5	2	1	6
	3	2	4	6	5	1	3
	4	4	5	3	2	1	6
	5	2	1	6	3	4	5
	6	2	5	4	3	1	6
		15	23	29	18	9	32
		(2)	(4)	(5)	(3)	(1)	(6)*
C. Single to Bimodal Change in Distribution	1	3	-	-	4	1	2
	2	4	-	-	2.5	1	2.5
	3	2	-	-	4	3	1
	4	1	-	-	3	2	4
	5	3	-	-	4	2	1
	6	1	-	-	3	2	4
		14			20.5	11	14.5
		(2)			(4)	(1)	(3)*

*The numbers in parentheses are the rank values of the summed rank values of all six judges.

The strip chart of a moving estimate of the mean and the bar histogram were again ranked first and second for detecting a change from a single to a bimodal distribution. But in this case, the strip chart format of the moving standard deviation was judged a more sensitive index than the strip chart format of the raw data values.

D. Discussion

The fact that our judges found the strip chart format of a moving estimate of the mean the best format for detecting a change in mean is not surprising. It provides a direct index of the parameter of the data stream that was changed. A new estimate of the mean of the data was generated and displayed in the strip chart format for every new data sample. In our simulation, since the estimate of the mean was based on successive samples of ten data points, about three samples of data from the new stream were needed to produce a perceptible change from the estimates of the mean when all the data were drawn from the original stream. Assuming a sample rate of 10 per second, a change such as this should be detected with this format in about 0. 3 second. In general, the size of a perceptible change in the estimated mean with each new datum depends upon the number of points used to compute the estimate, the variability of the data stream, the size of the disturbance to the mean of the data stream, the size of the display screen and the scale factors of the two axes in the format.

In contrast, the histogram and density bar graph formats were based on the temporary storage of one hundred most recent data samples and were updated every ten new data samples. Consequently, if we assume that one third of the displayed data had to be new in order that a small disturbance be detected, thirty new samples would be needed to produce a clearly perceptible change to the histogram or density bar graph formats. Given a ten per second sample rate and a one second display update rate, we would expect to detect such a disturbance in three seconds with a histogram format. Clearly, the above comparison between the derived times for detection with the histogram and strip chart formats is valid only for the conditions in our simulation, and for an assumed threshold of detectability that is a constant ratio of new to old data irrespective of format. The latter assumption is clearly not true with regard to the relative interpretability of the bar histogram, the contour histogram and the density bar graph formats. However, the comparison does point up the relative sensitivity of a strip chart recording of a moving estimate of the mean (based on ten data points) to changes in mean values of the data stream as compared to a histogram format (based on 100 data points).

The usual arithmetic technique employed in obtaining the moving estimate of the mean turns out to be rather wasteful of working computer storage when compared to the so-called "Exponentially-Mapped-Past" or EMP estimate [8]. This is explained in detail in a companion report [11] and will not be discussed further here. Suffice it to say that the EMP technique requires essentially no historical storage (pipeline), operates on the last data point only, and may be fed directly into the existing time plot display capability of the Saturn V Display System (see Section V , Data Processing Implications).

The bar histogram format was ranked above the strip chart format presentation of raw data values. This is probably because the histogram format orders the data into clearly defined class intervals, so that new data falling into previously empty or little filled intervals are easily perceived. On the other hand, new extreme values on the strip chart plot are difficult to discriminate as a result of the irregular horizontal spacing between successive points and irregular vertical spacing between extreme points.

In principle, a well-designed density bar graph format should have a similar advantage as the histogram format over the strip chart plot of raw data points. But in our evaluation it ranked below the raw data plot, mainly we think, because of the poor quality of our simulation of a density format CRT display.

The quality of our simulated contour histogram format display could also be criticized, since it might be better described as a skeleton histogram format. Only the highest point in each filled class interval was displayed. In the absence of a line connecting adjacent points, the histogram outline was sometimes ambiguous. However, this skeleton contour is the only plotting capability of the current ACE-S/C CRT display system.

The strip chart format of a moving estimate of the standard deviation was judged the worst format for detecting the changes in mean that we simulated. The variability in the estimates prior to the disturbances to the mean was quite pronounced. This suggests that for the simulated data streams a base of ten samples was too small on which to compute a stable estimate of the standard deviation of the data stream. Under these conditions, the increase in the estimate of the standard deviation, that occurred with a shift in the mean of the data to a higher value, could not be easily detected. However, when the standard deviation of the data stream increased, with the change to a bimodal distribution (as might occur in practice with the sudden introduction of noise), the plot of the moving estimate of the standard deviation was judged to be better than the plot of the raw data points for detecting the change.

We were unable to simulate the fading trace bar graph format, but it would seem to combine the good features of the density bar graph with an indication of the temporal sequence of the data points. It is a display potentially rich in information, and should be a powerful aid to an engineer monitoring data sampled at high rates.

Although limited by the lack of a CRT display, our simulation of the suggested formats for data monitoring demonstrated the significance of display format design for detecting different types of disturbance. It also enabled us to evaluate the relative effectiveness of six formats and to identify critical format design and data transformation requirements of more effective prelaunch checkout CRT displays.

V. DATA PROCESSING IMPLICATIONS

A. Summary

The purpose of this section is to determine the data processing requirements for the data conditioning and display formatting techniques already described, within the environment of the Saturn V DDP 224 Display System. It should be noted that the plotting of raw data as a moving time plot can already be done on the Saturn V Display System. Similarly, the plotting of an EMP estimate of the mean requires only trivial amount of storage and instructions beyond that already available.

We assume the availability of test results from up to ten separate data streams via "pipeline" storage of up to 200 sample points. The estimated memory required is:

Data Storage (10 pipelines at 200 points) plus working storage	2, 900 words
Program Storage	3, 100 words
Total	6, 000 words
Total - if 100-point pipelines are used	4, 800 words

An effective programming rate of 10 instructions per day has been allowed(4) plus an additional eight man-weeks for integration with the DDP 224 Display System for an estimated 70 man-weeks of programmer/ analyst effort.

Based upon the current status of available memory in the DDP 224 Display System, the incorporation of the high-speed monitoring program would require the addition of another module (4, 096 words) of high-speed memory.

In summary the hardware, memory, and programming implications of incorporating the high-speed monitoring program into the DDP-224 Display System are estimated as follows:

- Hardware: one additional module (4,096 words) and a function select switch on the display console

- Memory Utilized: 6,000 words

- Programming Effort: 70 man-weeks

By way of contrast, incorporation of EMP estimates of the mean (i.e., moving average) for 10 variables requires no additional hardware, less than 100 words of storage, and a few days of programming and debugging effort.

B. Program Design Considerations

1. General

The High-Speed Monitoring Display Program (HSMDP) is designed to operate under the control of the existing DDP 224 Display System software. The DDP 224 Display System has two major functions: (1) to react to data and commands which the test engineer enters via the display console keyboard and console control deck, and (2) to display information from test programs that are running, or have been completed, in the RCA 110A. The HSMDP is dependent upon both of these functions. It must have available, in series, 200 sample readings from the equipment under test. The initiation of the test and the return of the test results is a "command" function and must be accomplished by the DDP 224 Display System. The 200 sample points are stored in what is referred to as a pipeline so that as test results are brought in, they are moved through the pipeline. When the 201st test result arrives, the 1st test result is pushed out. The HSMDP allows a maximum of 10 such pipelines for operational use. (This number could, of course, be expanded at the expense of 200 words of high-speed storage for each additional pipeline; or, the pipeline length could be reduced to 100 sample points and 20 pipelines could be accommodated with the storage originally allocated for 10 pipelines of 200 sample points.)

The sampling rate will be irrelevant to the HSMDP since it adopts the philosophy of freezing the pipeline at the time a display request is fully validated. This is necessary because the DDP 224 Display System may interrupt the HSMDP computation for a higher priority display and the data in the original pipeline would change and possibly cause an invalid display if it were not frozen.

The HSMDP, operating under the control of the DDP 224 Display System, will utilize the Console Input Analysis Routine and will accomplish its displays via the Display Output Routine.

2. Functional Program Description

The High-Speed Monitoring Display Program is capable of performing all operations on both raw and derivative data. The first derivative is approximated simply by taking the difference between successive samples and dividing by Δt, then using the resultant data stream in all computations. This option is exercisable on demand and while it is being exercised for a given display from one console, another test engineer may be using the same data in its raw form at another console.

There are three basic types of display formats which may be accommodated by the HSMDP:

- Density Bar Graph
- Frequency Histogram
- Scatter Plot

Up to ten density bar graphs (or histograms) may be simultaneously displayed.

The functional flow for creating these displays is shown in Figures 7a, b, c. The "Function Select" portion is shown merely to indicate that a switch must be allowed to notify the DDP 224 Display System that the HSMDP is desired. It is not anticipated that this operation will require additional high-speed memory, but it will require additional analysis and test to insure that it has been properly debugged and is not adversely affecting the other functions. (The time estimate for this has been included in the integration estimate under "Programming Requirements".) Upon receipt of the request the Console Input Analysis Routine of the DDP 224 Display System would notify the test engineer at the requesting console that the HSM mode has been selected and that he will be required to furnish data and display specifications. (The memory required for the status display has been included in the HSMDP storage requirement.) Once the mode has been selected, the test engineer continues by depressing the "Execute" control switch.

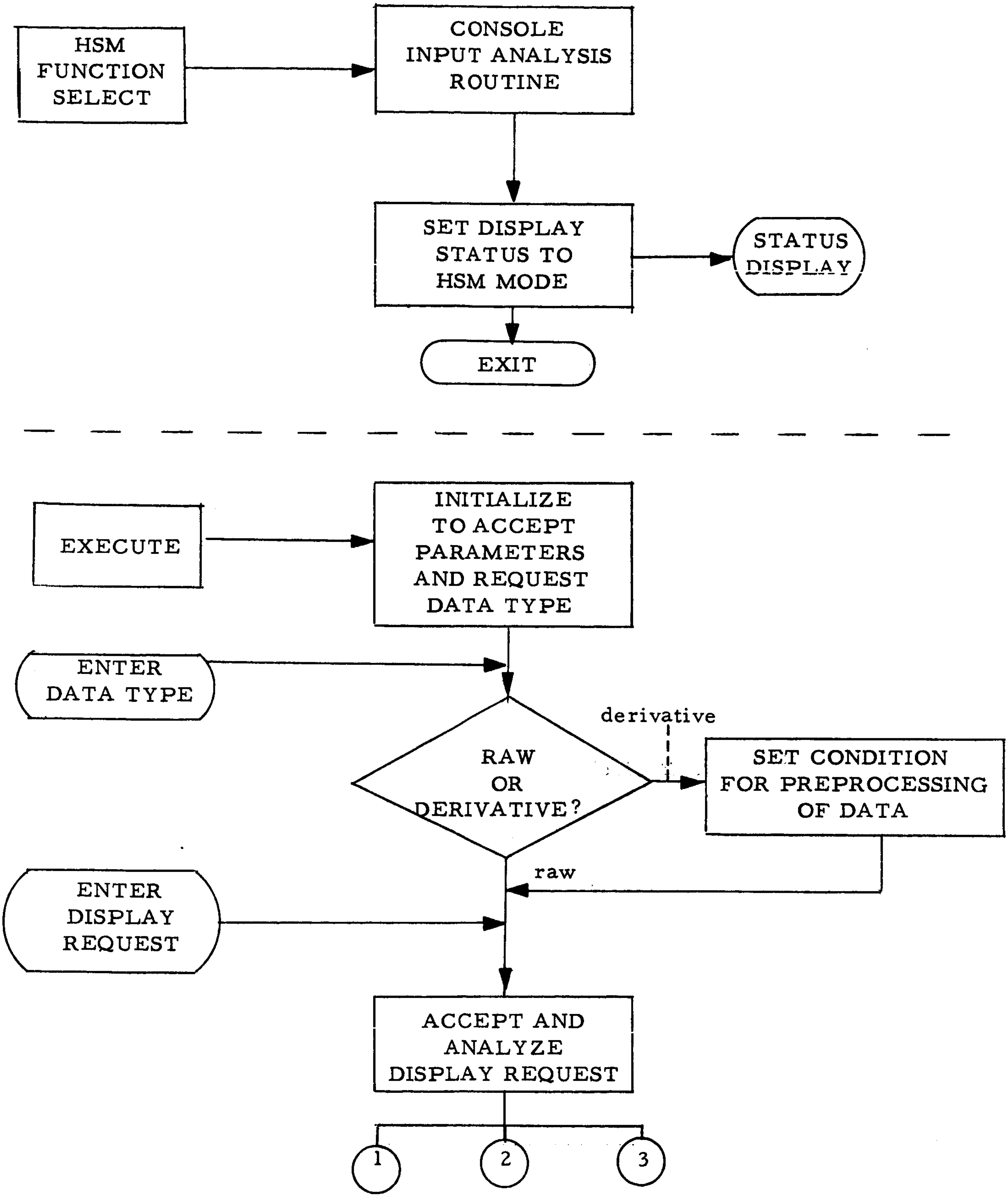
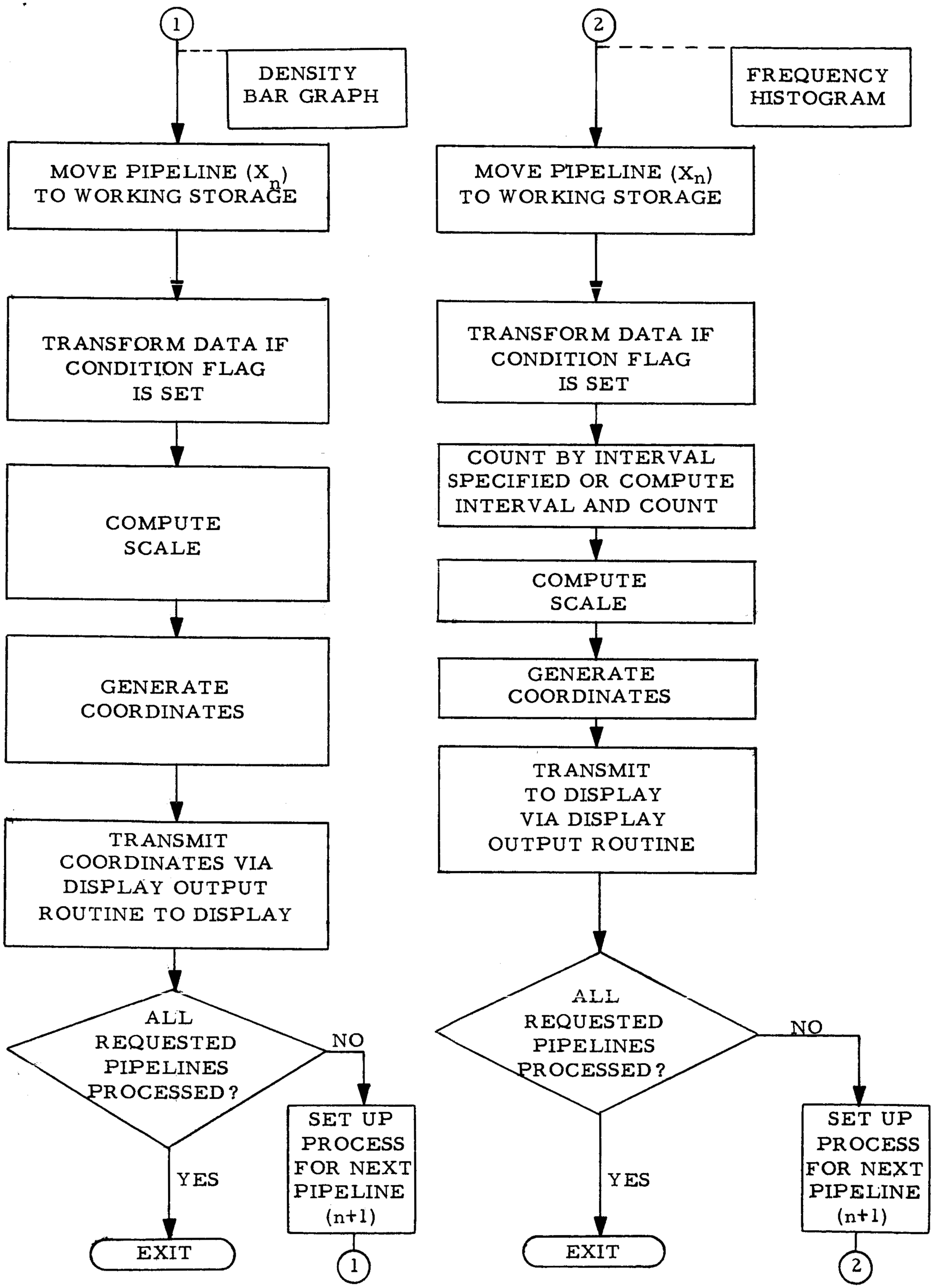


Figure 7a. High-Speed Monitoring Display Program. flow chart



1
DENSITY BAR GRAPH
MOVE PIPELINE (X_n) TO WORKING STORAGE
TRANSFORM DATA IF CONDITION FLAG IS SET
COMPUTE SCALE
GENERATE COORDINATES
TRANSMIT COORDINATES VIA DISPLAY OUTPUT ROUTINE TO DISPLAY
ALL REQUESTED PIPELINES PROCESSED?
NO
SET UP PROCESS FOR NEXT PIPELINE (n+1)
1
YES
EXIT
2
FREQUENCY HISTOGRAM
MOVE PIPELINE (X_n) TO WORKING STORAGE
TRANSFORM DATA IF CONDITION FLAG IS SET
COUNT BY INTERVAL SPECIFIED OR COMPUTE INTERVAL AND COUNT
COMPUTE SCALE
GENERATE COORDINATES
TRANSMIT TO DISPLAY VIA DISPLAY OUTPUT ROUTINE
ALL REQUESTED PIPELINES PROCESSED?
NO
SET UP PROCESS FOR NEXT PIPELINE (n+1)
2
YES
EXIT

Figure 7b.

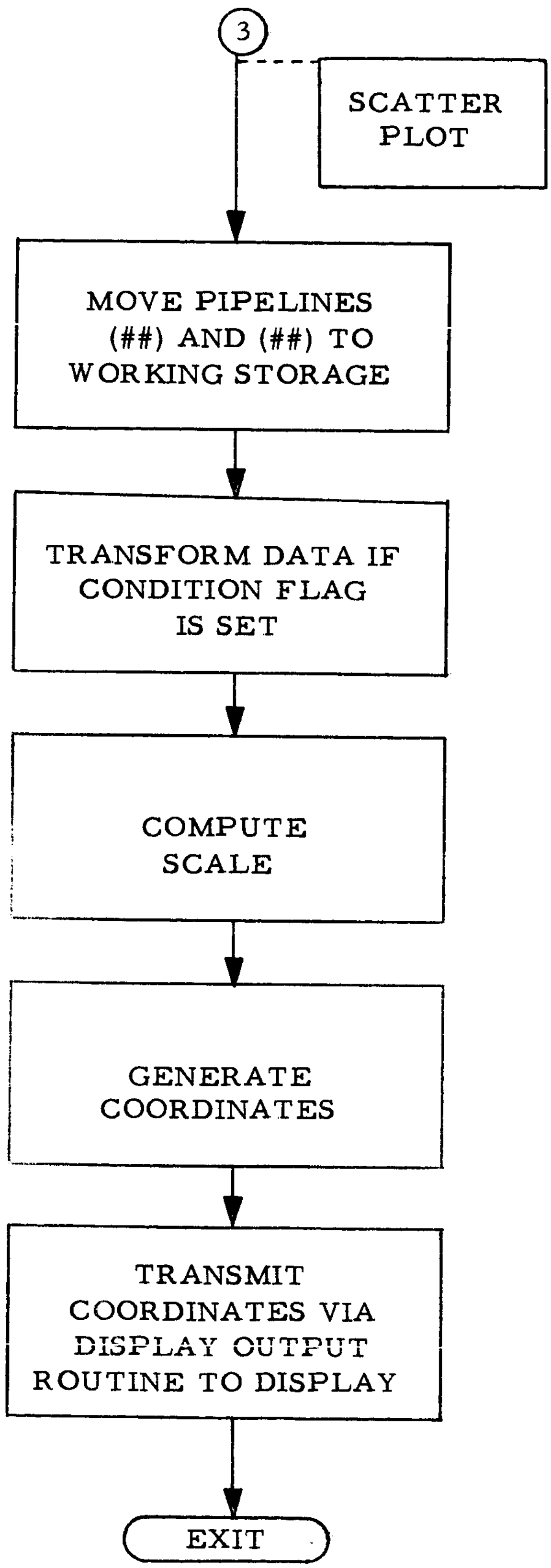

3
SCATTER PLOT
MOVE PIPELINES (##) AND (##) TO WORKING STORAGE
TRANSFORM DATA IF CONDITION FLAG IS SET
COMPUTE SCALE
GENERATE COORDINATES
TRANSMIT COORDINATES VIA DISPLAY OUTPUT ROUTINE TO DISPLAY
EXIT

Figure 7c.

Upon receipt of the execute signal the DDP 224 Display System relinquishes control (at the next appropriate time interval) to the HSMDP which has the responsibility for requesting, receiving, and analyzing the input parameters.

The first request is to determine the nature of the data to be used in generating the display, i.e., raw or transformed data. The program will accept "R" or "T" for the designation. The next request is for the display specifications. Display specifications may be entered as follows:

DENSITY BAR GRAPHS*	PIPELINE ##, ##..
HISTOGRAMS*	PIPELINE ##, ## .. INTERVAL (x)
SCATTER PLOT	PIPELINES ##, ##

The analysis portion of the HSMDP will validate the request. The entire words need not be typed out but that portion of the word up to the first space must be identical to the spelling listed above, e.g., DEN B GRAPH or D B G would be valid requests for Density Bar Graphs.

The pipeline number may be 01, 02, ... 10 in the initial version of the HSMDP. Each number is associated with an internal table showing the source of the sampled data. The internal table may be altered before tests to allow for sampling of other data streams.

The interval to be counted for the generation of a histogram may be specified by the test engineer; however, if it is omitted, the program will compute an appropriate interval compatible with the range of the samples included in the pipeline and the display area of the console display.

The analysis routine will, after validation of all input parameters, set the appropriate data condition (raw or derivative) in the routine required and transfer to that routine for the remainder of the display generation. Since this routine will be executed while tests are in progress, it will be susceptible to interruption by the DDP 224 Display System control module at any time. Therefore, provision is made for freezing pipeline contents

*Up to 10 may be displayed simultaneously, with individual scaling.

at the time the request is validated. The freezing is accomplished by moving the data from the affected pipeline to working storage.

The specific functions performed by each display generation routine and the order in which they are performed are specified in the flow chart (Figure 7) and are not reiterated here.

3. High-Speed Memory Considerations

Each sample point will require one word of DDP 224 high-speed memory storage. Therefore, the initial allowance of 10 pipelines of 200 sample points each requires 2,000 words of memory. There is also a working storage requirement of two pipelines (400 words) to allow for transformation of the data. The utilization of working storage also guarantees pipeline freezing in the event that higher priority system interrupts prevent the display routine from completing its computations between sample readings. There are additional working storage requirements for tables (to associate the pipeline number to internal storage and for communications tables to communicate with the test engineer during request entry) which are estimated at 500 words for a total of 2,900 words of non-program storage requirements. (If the pipeline was limited to 100 sample points, this requirement would be 1,700 words.)

It is estimated that the initialization and input analysis routine will require 600 words of program storage and that each of the 5 routines will require an average of 500 words of program storage for an estimated total program storage requirement of 3,100 words.

4. Programming Requirements

Based upon an effective programming rate of 10 instructions per day,[4] and an estimated 3,100 words of program instructions, the required programming effort is approximately 62 man-weeks for the HSMDP proper. In addition, since this program must be integrated with the DDP 224 Display System and will require the communications with the RCA 110A computer to fill the pipeline, it is estimated that 8 man-weeks will be required to establish and test the necessary controls and modifications to the overall system package.

5. Internal Execution Time

Internal execution time is, of course, a function of the complexity of the particular display request and the options exercised. If we exclude the time required for the test engineer to format and enter his request, the effective execution time for processing of a single pipeline of data and forwarding the coordinates to the Display Output Routine of the DDP 224 Display System is estimated at less than 200 milliseconds for raw data and 300 milliseconds for transformed data. The time factor could be reduced to approximately 150 milliseconds and 250 milliseconds, respectively, for pipelines of 100 sample points as opposed to 200 sample points. In both cases, when multiple pipelines are being processed, the time factor should be multiplied by the number of pipelines being processed. These estimates are based upon the DDP 224 instruction execution rate of 260, 000 operations per second.*

*Computer Control Company, Framingham, Mass. DDP 224 General Purpose Digital Computer, April 1964.

VI. CONCLUSIONS AND RECOMMENDATIONS

The work reported in this memorandum and in a separate companion study[11] have both explored the possibility of several methods for transforming and formatting measurement data, so that an engineer will be able to obtain the information he needs most readily. Our intent has been to provide formats for CRT displays that will present more aspects of test data than is possible with the current tabular formats. The companion study[11] was concerned primarily with formats to display the maximum information possible about a single measurement parameter.

The present study was concerned to develop formats that could be used to display data simultaneously from a number of test points on a single CRT screen. Our evaluation procedure used only one data stream at a time, however, and was based on the assumption that the interpretability of the formats was independent of the number of parameters displayed simultaneously.

This study has demonstrated that the ease with which viewers of graphically encoded measurement data can detect a change in the mean or in the distribution of data depends to a considerable degree on how the data is transformed and formatted for display.

We found that a Strip Chart Format of a moving estimate of the mean and a Bar Histogram Format of a changing store of the most recent 100 data samples were the best of the six formats, that we tested, for detecting a change in a simulated data stream. The moving estimate of the mean provides the earliest indication of a change to the mean of the data, although the Histogram Format gives more information about the distribution of the data samples.

The Contour Histogram, that plots only the "height" of the data count in each measurement class interval, is more difficult to interpret than the Bar Graph Histogram. The outline shape of the Contour Histogram is sometimes ambiguous, and consequently, perception of a change in shape can be difficult.

The length of the temporary store or "pipeline" of data that is used for the Histogram and Density Bar Graph Formats, the number of data samples upon which moving estimates of the mean and standard deviation are based, and the scales on the scalar axes of all the formats are factors that determine display interpretability in relation to the variability in the measurement data. Consequently, we recommend that a test engineer should have the opportunity to set and to change the above display format factors, so that he can empirically derive the best compromise between display stability and display sensitivity for his particular streams of data with their unique characteristics.

A Density Bar Graph is potentially an efficient format for monitoring a number of measurement parameters simultaneously on a single CRT display. We would strongly recommend that it should be given a more thorough evaluation than we were able to provide. This evaluation should include both a constant brightness Density Bar Graph and a variable brightness or fading trace Bar Graph Format.

An analysis of the data processing implications of the display format concepts that we have explored shows that a flexible display system, which a test engineer can use to view a selection of data from critical test points in different formats, can be implemented at reasonable cost. Approximately 70 man-weeks of programming time and the addition of 4000 words of memory would be required to provide the Saturn V DDP 224 System with twenty pipelines, each capable of storing 100 most recent data samples. The programming required to provide moving estimates of statistical variables in Strip Chart Formats was judged to be negligible.

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DARIEN, CONNECTICUT 06821

One Parkland Drive
Area Code 203 655-3971
In N.Y.C., WYandotte 3-2464

Executive Offices
System Sciences Division
Management Research & Consulting Division

NEW YORK, NEW YORK 10017

200 Park Avenue
Area Code 212 661-2160

Management Research & Consulting Division

WASHINGTON, D.C. 20007

1050 Thirty-First Street, N.W.
Area Code 202 333-0100

System Sciences Division

SANTA MONICA, CALIFORNIA 90404

1454 Cloverfield Boulevard
Area Code 213 393-0166

Western Division

MANHATTAN, KANSAS 66503

200 Research Drive
Area Code 913 JEfferson 9-3565

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