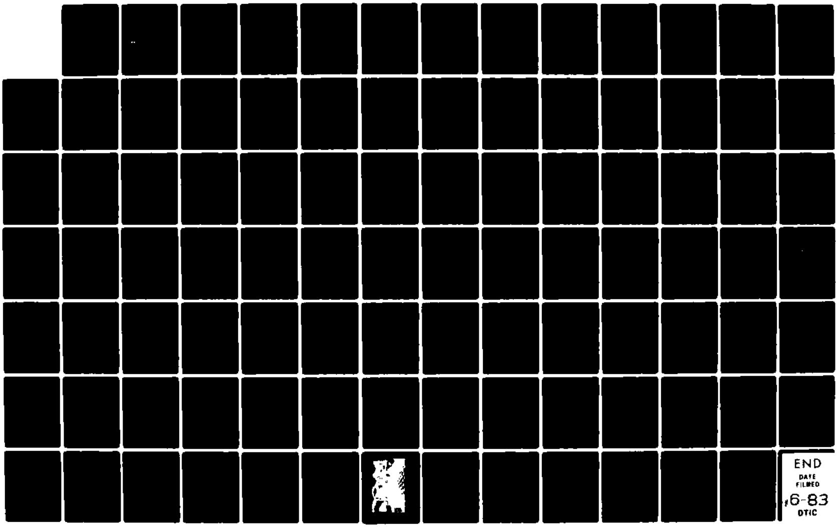
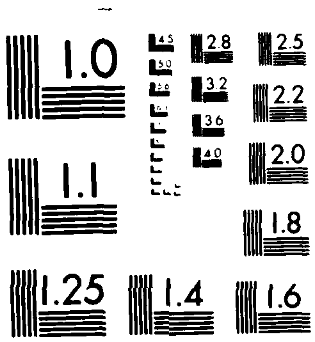
AD-A127 775 AUTOMATED INSTRUMENTATION SYSTEM VERIFICATION(U) AIR FORCE WEAPONS LAB KIRTLAND AFB NM J F SCHNEIDER APR 83 AFWL-TR-82-137 1/1

UNCLASSIFIED F/G 14/2 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

AFWL-TR-82-137

AFWL-TR-
82-137

AD A127775

AUTOMATED INSTRUMENTATION SYSTEM VERIFICATION

J. F. Schneider

April 1983

Final Report

Approved for public release; distribution unlimited.

DTIC FILE COPY

Prepared for

BALLISTIC MISSILE OFFICE
Norton AFB, CA 92409

AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base, NM 87117

83 05 03-002

This final report was prepared by the Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, under Job Order 672A0831. Josef F. Schneider (NTEO) was the Laboratory Project Officer-in-Charge.

This report has been reviewed and is approved for publication.

JOSEF F. SCHNEIDER
Project Officer

FOR THE COMMANDER

FRED L. HALLBERG
Maj, USAF
Chief, Test Operations Branch

JOHN H. STORM
Colonel, USAF
Chief, Civil Engrg Rsch Division

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFWL-TR-82-137	2. GOVT ACCESSION NO. AD A127775	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) AUTOMATED INSTRUMENTATION SYSTEM VERIFICATION		5. TYPE OF REPORT & PERIOD COVERED Final Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) J. F. Schneider		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Air Force Weapons Laboratory (NTEO) Kirtland Air Force Base, NM 87117		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 64312F/672A0831
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Weapons Laboratory (NTEO) Kirtland Air Force Base, NM 87117		12. REPORT DATE April 1983
		13. NUMBER OF PAGES 92
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Test Instrumentation
Data Acquisition System
Automatic Checkout
Linearity Measurement
Bandwidth Measurement
Dynamic Range Measurement

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A complete checkout of instrumentation channels from sensor connection to, and including, data reduction is achieved by measuring linearity, frequency response, and dynamic range simultaneously of as large a group of channels as is practical at one time. Inputs are a triangular wave signal and a noise signal. The checkout data are recorded in the same way as test data. A table that is ordered by recorder track and voltage controlled oscillator (VCO) center frequencies is produced in the course of the computer program to

DD FORM 1473, 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. ABSTRACT (Continued).

contain percent linearity, 3 dB bandwidth, percent deviation from standard bandwidth, dynamic range in decibels, and noise floor in millivolts (RMS) for every channel measured. Hardcopy plots of the nonlinearity deviations, the frequency response, and the noise floor spectrum can be produced during processing when requested. The computer program is friendly, the order of channel measurements can be completely arbitrary, repeated measurements replace the respective previous entries.

PREFACE

The impetus for the automation of instrumentation systems verification came from a request by the Air Force Ballistic Missile Office (BMO) to modernize all existing instrumentation vans and build new ones in order to provide a total capability of ultimately 1500 instrumentation channels. BMO required every van to be fully certified before deployment to various test sites. Based on earlier exploratory work aimed at automation, a proposal was submitted to BMO. The proposal was accepted. It was decided to perform the work inhouse.

The author wished to thank Lt Col Don Gage (BMO) for making this project possible; Mr. John Favour of the Boeing Company (TBC) for his constructive criticism; Captain Gary Shannon (AFWL/NTED) who presided over the effort as supervisor and as chairman of the Instrumentation Test Working Group (ITWG).

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (Concluded)

TABLES

I. INTRODUCTION

There is no doubt nor argument that the performance of an instrumentation system has to be verified from time to time. However, of concern is when, how often, to what extent, and by whom should verification be performed. Severe compromises must be made often with the frequency and extent of verifications required. The reasons compromises must be made are time constraints that do not permit all channels to be checked or even all of the checks necessary for characterization of one channel. It is unlikely that the time constraints will ease. Therefore, automation is the only answer to achieve complete characterization of instrumentation systems within reasonable time limits and with reasonable effort.

The automated procedure has to provide a complete checkout that can be performed (1) any time, in particular, after modifications and maintenance, or inplace whenever doubt about the proper operation of the system arises; (2) without undue interference with other, scheduled activities; (3) on all channels of the system rather than on selected ones; (4) with all tests on a channel that are necessary to fully describe its performance characteristics; (5) for the complete channel, i.e., including substantial cable length between transducer splice and recording device, or for selected parts of a channel, e.g., the recording van only; and (6) with the actual data playback and reduction equipment included.

This report describes the efforts and results of automating systems verification for the instrumentation equipment used in high explosives testing.

II. CHANNEL CHARACTERIZATION REQUIREMENTS

2.1 CHANNEL DEFINITION

An instrumentation channel, ideally includes everything that is necessary to sense the physical phenomenon and to acquire, condition, amplify, transmit, modulate, record, play back, demodulate, filter, and digitize the data and produce a plot.

In the practical world of verification measurements, the transducer has to be excluded from the channel because (1) it is practically impossible to apply a controlled stimulant to a transducer in situ with a waveform needed for the automated procedure (with the exception of noise floor measurement); (2) if only the van equipment is to be checked out it is an unreasonable effort, if not a useless enterprise to connect transducers to all channels of a van, since at this point, it is not even known which transducer will be connected for a particular test; and (3) the physical stimuli that are applied for the calibration of transducer curves are not normally in the form of the electrical stimuli that are to be applied to effect the automation of the verification requirement.

Therefore, for the purposes of the verification measurements, as described in this report, a channel is defined without the transducer at its front end. This then defines a "data channel," rather than an instrumentation channel.

Another useful definition is that of a "van channel" which is a shortened version of a data channel comprising only of the instrumentation van equipment plus the data reduction equipment. This definition is used for the van checkout. More often than not, all of the active elements of a data channel are in the instrumentation van. Vans have to be checked out before they are committed to the field, in between tests, and when they have been moved or modified.

Figure 1 shows these definitions for a conventional frequency modulation (FM) data acquisition system. The general purpose (GP) computer at the data reduction end (right end) is excluded from the data and van channel definitions because as soon as the data are in digital form, no degradation of the sort that requires the verification measurements can occur any more.

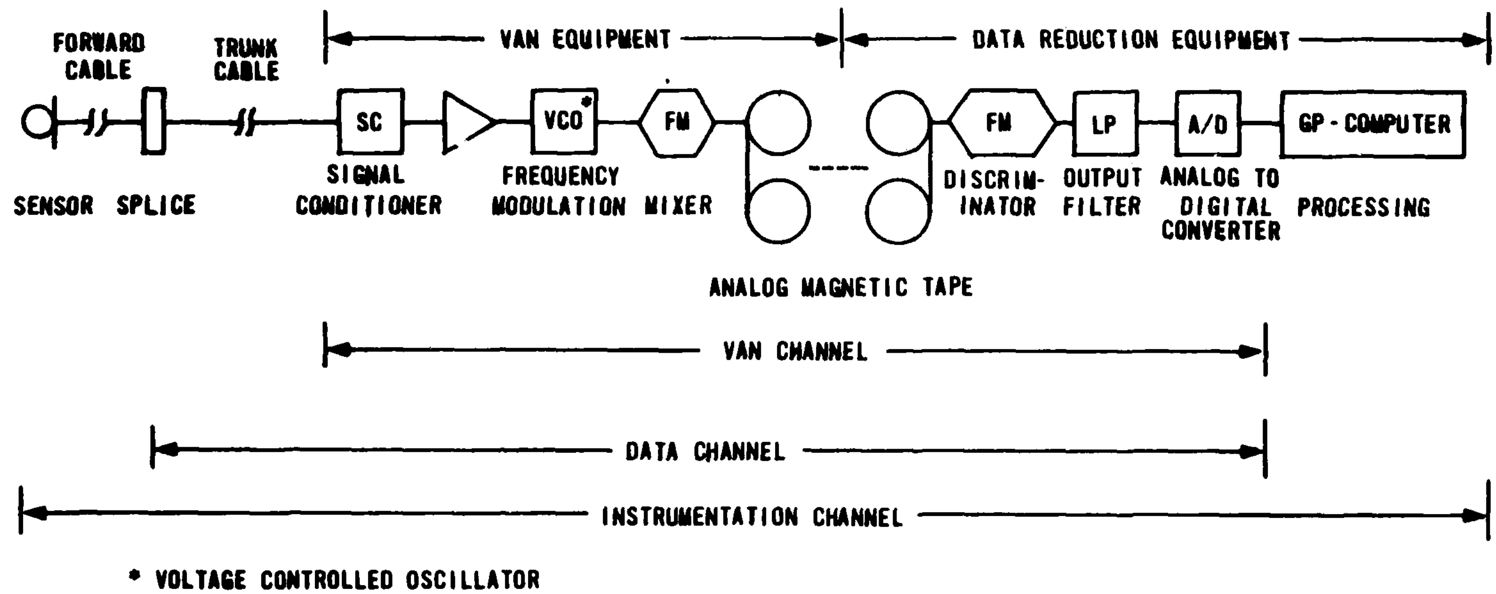


Figure 1. Channel definition for a conventional FM data acquisition system.

Other acquisition systems would need a modification of Figure 1, e.g., when signal conditioning and amplification are performed at the cable splice location or even at the transducer location. This does not, however, change the definitions. It only shifts certain elements from one definition (van channel) to another (data channel).

The checkout principles disclosed in this report also apply to other than FM instrumentation systems, with procedures adapted to peculiar designs. Figure 2 is an example of a digital acquisition system in the forward location. In a self-contained system (even the signal conditioners might be included), the checkout signals can be switched into the channel inputs by computer command, as is done in the Digital Acquisition of Remote Transients (DART) system used by AFWL's Civil Engineering Research Division (Refs. 1 and 2). A more conventional digital acquisition system for longer duration data is shown in Figure 3. It very much resembles the FM system and almost the same procedures can be applied.

2.2 TOOLS OF SYSTEM ANALYSIS

A data channel can be treated as a system whose characteristic modifies a signal on the way from the input to the output. Therefore, if the output of a system is to be predicted, all that needs to be known is the system characteristic or, as it is also called, the system response. It can be presented as a function in the time domain or in the frequency domain (Refs. 3, 4, and pp. 20-23 of 5). Since it is materially unimportant to know the details of the design of a system, it can be called a black box (Fig. 4). If the input to the system is available, its response can be obtained by measuring the output and relating it to the input. This can also be done to some sufficiency if the input is not available for the measurement but can be assumed. With the proper assumptions the frequency response of a data channel can thus be obtained (although not the phase response). That, however, is sufficient for the requirements of a bandwidth measurement on data channels.

The tool for the bandwidth measurement is the Fourier Transform (Ref. 6, p. 56) which transforms a time domain signal into a frequency domain signal, i.e., the amplitudes of data points within a time window are transformed into

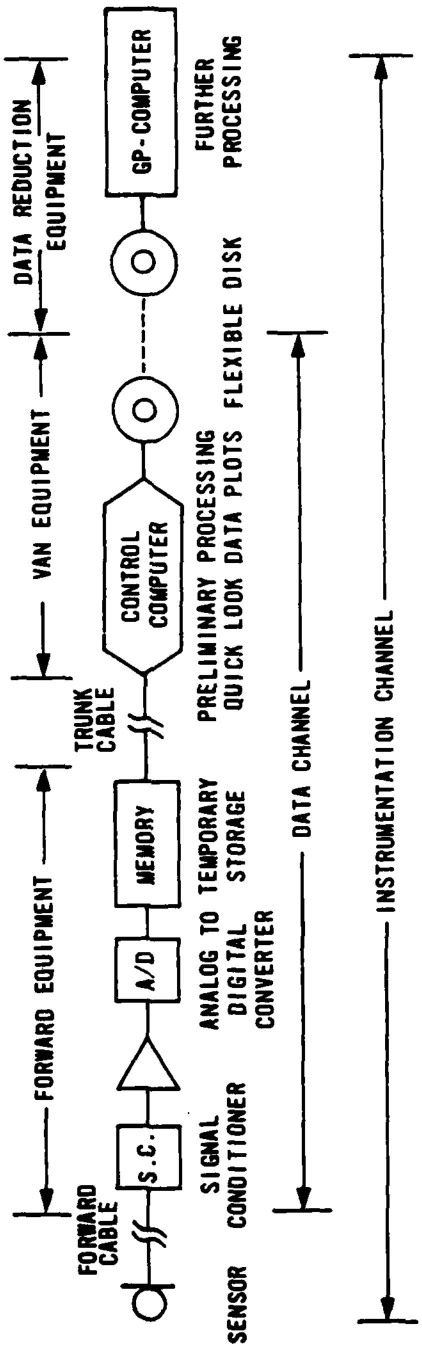
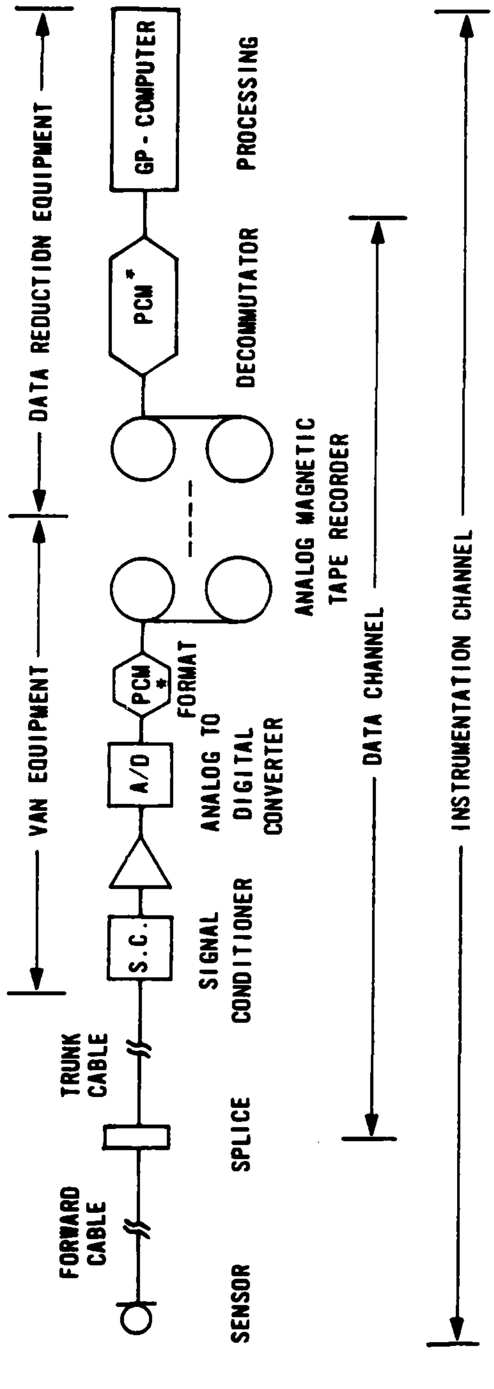


Figure 2. Channel definition for a forward digital data acquisition system.



* PULSE CODE MODULATION

Figure 3. Channel definition for a van-installed digital data acquisition system.

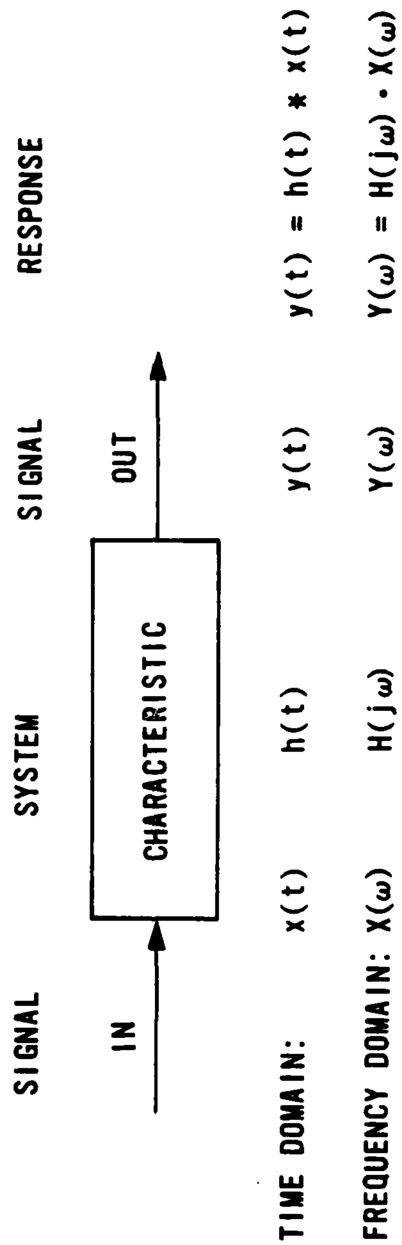


Figure 4. Black box concept.

amplitudes of frequency points within a frequency range. They are really the same data but with two different faces. So, a function f(t) is transformed into a function F (ω). The mathematical transform formula is introduced in Section 5.2.3, as are the input-output and response relations given in Figure 4.

The Fourier Transform is also used to produce the dynamic range measurement. The tool for the linearity measurement is the least square fit straight line which is in the time domain.

2.3 CHARACTERIZATION REQUIREMENTS

It should be kept in mind throughout this report that system verification testing assumes that the individual components of the system have been properly tested and set up for the system. Thus, the verification test is a quality assurance (Q.A.) tool. It is a coincidence that it also provides the properties of the instrumentation system that a customer needs to know for the analysis of his measurements. The channel characteristics that are necessary for verification of a data channel are: linearity, bandwidth, and dynamic range. These are the features that cannot be reduced below a certain equipment dependent minimum, therefore, they characterize the channel.

Common mode rejection ratio (CMRR), offset, and gain are also channel characteristics, but they are not included in the verification package. The latter two are secondary to the first three because offset and gain are installation dependent. Since offset is primarily a transducer and/or installation shortcoming that has nothing to do with the channel equipment proper and is therefore not existent when a van that is detached from an installation is checked out, it is not a characteristic of a van channel. This is the reason for its exclusion from the checkout package. The input amplifier offset is also excluded because the characteristic of a channel is zero offset, i.e., the regular channel set-up procedures have already removed the offset.

The gain of a data channel is determined by transducer sensitivity and the expected value of the measure and, therefore, it is not measured as a channel characteristic. This shall not diminish the importance of offset removal and proper gain setting. However, the offset does not have to be completely eliminated at the time of a test nor does the gain have to be known precisely. As a matter of fact, if both of them stay within certain (fairly wide) tolerances the system calibration procedure eliminates the effects of these deviations without degrading the data.

The CMRR is an amplifier characteristic which is important but, nevertheless, has so far been considered a secondary feature in the framework of van checkout. One reason might be that if the CMRR deteriorates, other amplifier characteristics will also show deterioration so that in the process of repairing these, the CMRR will be back within requirements. The checkout package could easily be extended to include CMRR if operational requirements for its automatic measurement should arise.

III. TRADITIONAL PROCEDURES

The necessity to measure data channel characteristics has not arrived just now, nor are the measurement principles hardly new. However, traditional procedures are slow, cumbersome, prone to error, and frayed with compromise. Therefore, there is a need for faster and more accurate measurements. The accuracy of any measurement can be improved by measuring more points along a curve, or by using a more elaborate setup with higher precision instruments, or by taking a large number of measurements of the same data for averaging. This translates into more workload and more compromise. Usually coverage is affected, e.g., only selected channels are checked or the system is checked only from the signal conditioner to the input of the tape recorder. The latter has been the rule for many years.

The linearity measurement is normally taken with known voltage steps as input and by measuring the output voltage for each step. A best straight line is then applied to find the percent of nonlinearity (Ref. 7) by drawing parallel boundaries of the points obtained and locating the reference line in the center between these boundaries. This exercise in geometry can be avoided by using end point linearity which generally yields less satisfying results (see also Section 5.1.2). Only at a few points (3 or 5) of the full amplitude range of the channel is the linearity normally measured with this procedure.

The bandwidth measurement suffers from similar shortcomings. A quick indication can be obtained by sweeping a signal generator through the frequency range of interest band by observing the output amplitude of the sine wave when it reaches 70 percent of the full-scale value at low frequencies. Although sufficient in many cases, this procedure lacks the necessary rigor for documentation. Higher accuracy is achieved by carefully measuring the input and output amplitude of selected sine waves. After drawing the frequency response curve thus obtained, the 3 dB point (i.e., the bandwidth) is determined by interpolation. Again, the bandwidth is normally measured with only a few points, maybe 5 or 7 in the frequency range.

The dynamic range measurement requires measuring the noise floor of a channel and relating it to the full amplitude range. However, this is difficult with FM multiplex systems, since as a rule, the measurement is taken at the voltage control oscillator (VCO) output. Therefore, these measurements are often not performed at all. Instead, the cable noise is measured in an installed system at the input to the van and called the channel noise.

So, these traditional procedures fall somewhat short of providing documented characterization of a data channel.

IV. AUTOMATION CONSIDERATIONS

4.1 RATIONALE

Automation can improve these areas tremendously. One area is the accuracy and completeness of the measurement. Another area is speedup of the procedures and transfer of the bulk of human labor to the computer. These improvements can easily be achieved with modern computers. The third area is the inclusion of the recording and data reduction equipment, and, where applicable, also of the forward equipment. The real payoff of automation has to be considered with all these areas in mind. If the system is already installed, the cable too can be included in the measurement. With that, the channel would be characterized as completely as possible. It should not be surprising that forward equipment and cable measurements are hardly, if ever, taken on a routine basis. If they have been taken in the past in a special effort and only on selected channels, their results were marginal, often inconclusive.

4.2 CONSIDERATION

Automation has to achieve several goals in order to be of value:

a. Measurement taking procedures should be as simple, unobtrusive, and requiring as little time and few hands to run as possible.

b. Evaluation of the measurements taken under item 1 should be done by data reduction personnel rather than by the instrumentation technicians. Thus, with the operator relieved of performing any writing down of measurements, meter readings, and of drawing curves, the possibility of human error should be greatly reduced and the overall operation speeded up considerably.

c. The final data should be tabulated in report-ready format, and sorted without regard to the sequence of the individual measurements. A plot of the resulting curves should be made available on request.

d. A large number of data points should be taken for each measurement to provide adequate precision and to describe the resulting characteristic curves in as much detail as necessary.

4.3 IMPLEMENTATION RESTRICTIONS

Complete automation cannot be accomplished for two reasons: one is that although it would be desirable to have switches in all the inputs (e.g., to a van or the forward amplifiers), it does not seem practical to consider them because signal quality could be jeopardized due to the nature of mechanical contacts or to offsets inherent in semiconductor devices. Therefore, the connection of an input to a test signal source must be made manually by paralleling inputs where they are easily accessible, e.g., at a barrier strip.

The other reason is that if a system has already been set up for a particular test configuration, the gains are different for different channels and so are the balancing offsets if the transducers are already installed. However, systems verification is more likely to be performed on van channels before the van has been incorporated into a setup and, therefore, these restrictions to automation of different gains and offsets do not apply. If a verification is to be done on installed systems, only selected groups of data channels can be checked under these restrictions.

4.4 BACKGROUND

As far back as 1973, a concept of automation of a Q.A. function was outlined in connection with the availability of the fast Fourier Transform (Ref. 3). No concrete proposal, however, had resulted from this because the requirement was not recognized at that time, nor was the organization ready to accept automation in the proposed form. However, some investigative work was done on the subject, especially on the automation of the linearity measurement (Ref. 8). Finally, when the necessity for automation was recognized and funds were provided, the effort described in this report was started.

V. APPROACH

5.1 LINEARITY MEASUREMENT

5.1.1 Input. The limited number of discrete voltage steps used for manual measurements are not good input for automated measurement systems because of the mechanisms needed to produce the steps and to keep the measuring device in synchronism with them. A staircase signal that results from these steps converges to a straight line if a large number, e.g., 256, of these steps are used. A straight line then is the ideal signal for dense linearity measurements. Present day signal generators can produce signals with nonlinearities of about 0.01 percent. A triangular wave is preferable to a repetitive ramp because of the high frequency components of the ramp during the flyback. Almost all function generators have a triangular signal, but a few also have a ramp signal.

The concept is based on putting a continuous signal at the input of a channel for as long as needed until the measurement is complete. This eliminates the necessity of designing a synchronizing link between the place and time the input is applied and the place and time the measurement is made. Thus, input and measurement do not have to be at the same location, nor, for that matter, at the same time. This brings the whole measurement as close to real data acquisition operation as is possible. If this input signal is simply adjusted so that it almost covers the full peak-to-peak amplitude range of the channel, it is not necessary for the voltage or, for that matter, the gain setting of the channel to be known because the measurement is taken at the output of the channel and is related to its full-scale range.

5.1.2 Definitions. Nonlinearity is generally defined as the deviation of a curve measured at the output of a system from a specified straight line (Ref. 7). Of the five straight-line specifications presented in Reference 7, three are normally used to characterize linearity.

5.1.2.1 End Point Linearity Straight Line. The line through the end of a set of measurements is the specified straight line for the end point linearity. This is shown in Figure 5. In this case of second-order nonlinearity, the resulting maximum deviation used for the linearity figure turns

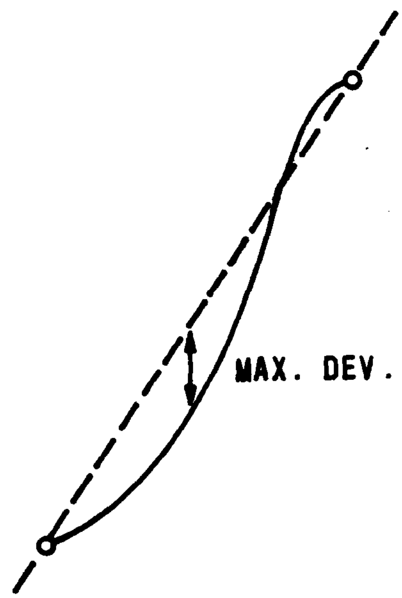


Figure 5. Definition of an end point linearity.

out to be about twice as high as one with a different reference line. There is only one advantage to this definition and that lies anchored in times past. Without a computer or calculator and only 5 to 11 measurements, the easiest way to arrive at a simple and fast result was to connect the two end points. This definition has not been chosen for the automated measurements.

5.1.2.2 Best Straight Line. The best straight line is a reference line specification that comes very close to the ideal. It is defined as the line that lies midway between two parallels that enclose all points of the measurement in such a way that their distance is a minimum (Fig. 6a). The reference line, however, is arrived at by geometrical construction rather than by an easily implemented algorithm. Although a computer exercise in analytical geometry could be imagined to produce this line, the construction is not satisfying. Suppose there is a measurement that is slightly off [a wild point (Fig. 6b)]. It could easily be thrown out by visual observation. But a computer algorithm has to include it for the lack of a wild point definition and a procedure of handling it. This could result in a grossly overstated nonlinearity figure.

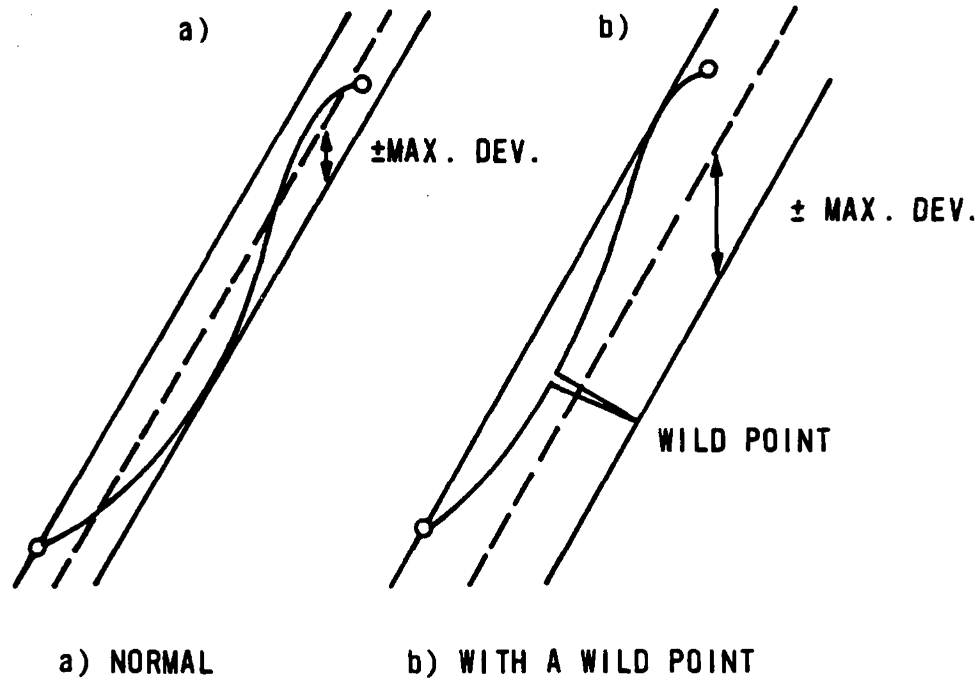


Figure 6. Best straight line.

5.1.2.3 Linear Fit Straight Line. The linear fit reference line is mathematically derived from the set of points of measurement by the least squares method. The least squares linear fit reference line is depicted in Figure 7 where a straight line is drawn through the same curve so that the sum of the squares of the distances of all measured points to this reference line is a minimum. This method provides the best fit no matter how arbitrary the set of points is. The maximum deviation from the reference line is used as the nonlinearity figure according to Reference 7. This also poses problems for measurements that have a wild point in the set. But since it is an official instrumentation definition, it is therefore used.

A more reasonable nonlinearity figure might be the rost-mean-square (rms) deviation of all points in the set. Then, although a wild point still has a certain influence on the positioning of the straight line, this influence diminishes as more and more points are used for the measurement. However, wild points are more a digital than an analog phenomenon and their

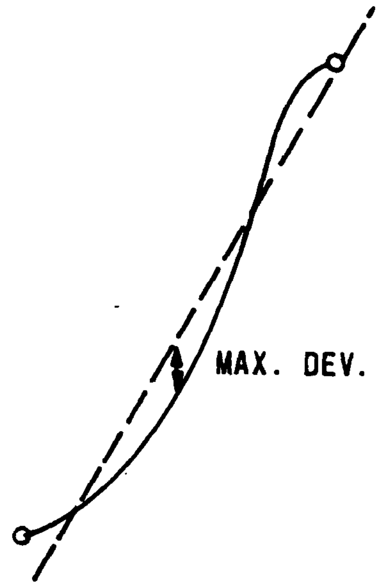


Figure 7. Definition of Linear fit (least squares method) straight line.

probability of occurrence in a controlled test setup is small. Furthermore, the averaging of the analog inputs and the smoothing of the digital output (see Section 6.1.3) decrease this probability to practically zero. For simple curves, the best straight line and the linear fit straight line approaches both yield very similar results, especially when the nonlinearities are in the low percentage area. However, the least squares method has been chosen for linearity measurements because it can easily be implemented on a computer in a straightforward manner.

5.1.3 Method. The least squares method has been around since 1794 when the then 17-yr old mathematician, C.F. Gauss, introduced it. The algorithm is described in many good books of mathematics (e.g., Ref. 9). The desired reference line is

$$f(x) = ax + b \tag{1}$$

and the function of the deviations $f_\Delta(x_i)$ of the data points y_i from this line is

$$f_\Delta\left(x_i\right) = f\left(x_i\right) - y_i = ax_i + b - y_i = v_i \tag{2}$$

The following sum must be a minimum in order to produce the best fit

$$S \equiv \sum_{i=1}^{n} v_i^2 = \sum_{i=1}^{n} \left(ax_i + b - y_i\right)^2 < \varepsilon \tag{3}$$

Slope a and offset b of the straight line to be fitted can be determined from this criterion. The partial derivatives of S with respect to a and b have to be zero for S to be a minimum.

Writing out the sum of Equation 3 yields

$$S = \left(ax_1 + b - y_1\right)^2 + \left(ax_2 + b - y_2\right)^2 + \ldots + \left(ax_n + b - y_n\right)^2 \tag{4}$$

Now

$$\frac{\partial S}{\partial a} = 0 \text{ and } \frac{\partial S}{\partial b} = 0 \text{ for a minimum of Equation 4}$$

$$\frac{\partial S}{\partial a} = 2\left(ax_1 + b - y_1\right) x_1 + 2\left(ax_2 + b - y_2\right)^2 x_2 + \ldots + 2\left(ax_n + b - y_n\right) x_n = 0 \tag{5}$$

$$\frac{\partial S}{\partial b} = 2\left(ax_1 + b - y_1\right) + 2\left(ax_2 + b - y_2\right) + \ldots + 2\left(ax_n + b - y_n\right) = 0 \tag{6}$$

Rearranging gives Equation 7 from Equation 6

$$nb + \left(\sum_{i=1}^{n} x_i\right) a = \sum_{i=1}^{n} y_i \tag{7}$$

and Equation 8 from Equation 5

$$\left(\sum_{i=1}^{n} x_i\right) b + \left(\sum_{i=1}^{n} x_i^2\right) a = \sum_{i=1}^{n} x_i y_i \tag{8}$$

The determinant of Equation 7 and 8 is

$$\Delta = n\left(\sum_{i=1}^{n} x_i^2\right) - \left(\sum_{i=1}^{n} x_i\right)^2 \tag{9}$$

With subdeterminants

$$\Delta_b = \left(\sum_{i=1}^{n} y_i\right)\left(\sum_{i=1}^{n} x_i^2\right) - \left(\sum_{i=1}^{n} x_i y_i\right)\left(\sum_{i=1}^{n} x_i\right) \tag{10}$$

$$\Delta_a = n\left(\sum_{i=1}^{n} x_i y_i\right) - \left(\sum_{i=1}^{n} x_i\right)\left(\sum_{i=1}^{n} y_i\right) \tag{11}$$

The solution is

$$a = \frac{\Delta a}{\Delta} \text{ and } b = \frac{\Delta b}{\Delta} \tag{12}$$

If an odd number of x_i's is chosen and if the coordinate system is put in the center of the ramp so the x_i's are symmetrical about the origin $\left(|-x_i| = |+x_i|\right)$ then $\Sigma x_i = 0$, and

$$a = \sum_{i=1}^{n} x_i y_i \sum_{i=1}^{n} x_i^2 \tag{13}$$

and

$$b = \frac{1}{n} \sum_{i=1}^{n} y_1 \tag{14}$$

Thus, the reference line is defined and the function of the deviations

$$f_\Delta\left(x_i\right) = \left(ax_i + b\right) - y_i = v_i \tag{15}$$

can be plotted. The single figure for nonlinearity that characterizes the channel is taken as the maximum deviation referenced to the peak to peak amplitude range

$$\mathrm{NONLIN} = \frac{\max |v_i|}{y_{pp}} \cdot 100\% \tag{16}$$

5.2 BANDWIDTH MEASUREMENT

5.2.1 Input. The traditional input for bandwidth measurements is a sine wave at a number of selected frequencies. Modern signal generators provide an automatically swept sine wave whose amplitude is kept sufficiently constant during the sweep so that it does not have to be measured separately, and the output measurements of the system can then be referenced to a constant. In order to make use of the swept input, a synchronized plotter or scope is necessary to produce the frequency response function.

An automated measurement has to be more general. A signal is needed that has all the information that is in a swept sine wave, and that is available, without the need for synchronization, on a continuous basis at least for as long as it takes to make the measurement. An impulse (Dirac function) is a signal that contains all frequencies from zero to an upper limit with equal amplitude (Ref. 6, pp. 66-67), i.e., its Fourier Transform

$$X(\omega) = \int_{-\infty}^{\infty} \delta(t) e^{-j\omega t} dt = 1 \tag{17}$$

An impulse is a discrete event in time and to be useful for bandwidth measurements again needs a synchronizing connection between the input signal and the output display. But, more prohibiting, an impulse $\delta(t)$ cannot physically be generated because it is thought of as a pulse having zero width and infinite amplitude, resulting in an area of 1, so in a way one could say

$$\lim_{T \to 0} \int_0^T \frac{1}{T} dt \to \delta(t) \qquad (18)$$

A visualization of this relationship is shown in Figure 8. There is no rigorous mathematical definition of $\delta(t)$ as a function, only as a functional (Ref. 5, p. 67ff). No signal generator can produce a function like that.

The only signal that meets the continuous availability requirements and contains all frequencies with the same amplitude is white noise. Its Fourier Transform yields a constant amplitude similar to Equation 17. With white

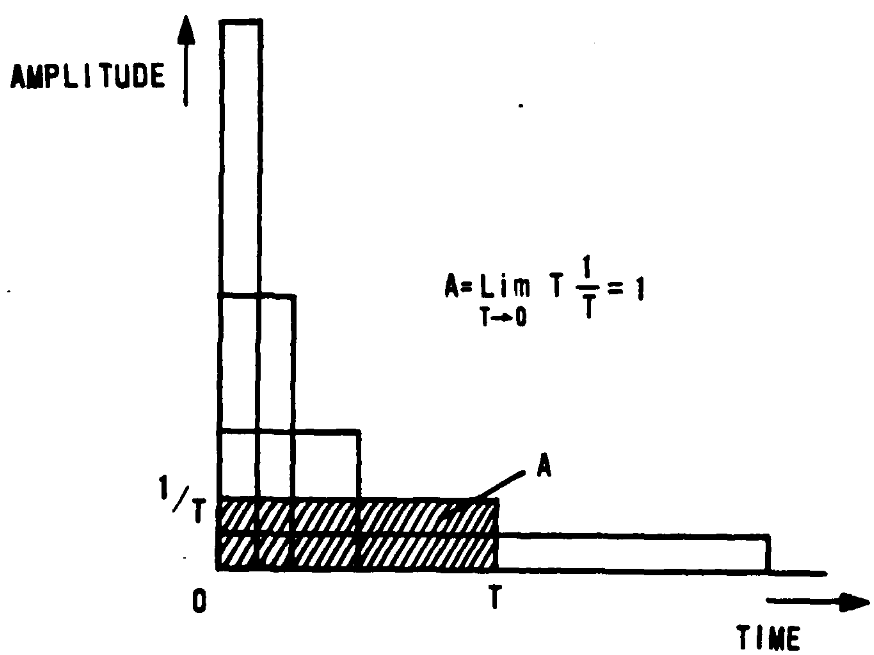


Figure 8. Limit concept for an impulse.

noise as input, the bandwidth measurements at the output of a system can be at a different place from where the input is applied. With the signal recorded, e.g., on magnetic tape, the measurement can also be made at a different time.

White noise as it will be used for the bandwidth measurement is a random signal (i.e., the amplitude of the signal of time $t + \Delta t$ cannot be predicted from its state at time t), whose average power is stationary, (i.e., the average power at time $t + \Delta t$ is the same as its average power at time t). The autocorrelation of this signal with average power I is

$$R(\tau) = \begin{Bmatrix} I \text{ for } \tau = \emptyset \\ \emptyset \text{ for } \tau \neq \emptyset \end{Bmatrix} = I\delta(\tau) \tag{19}$$

The power of a signal is its amplitude squared. Autocorrelation is a process of multiplying a signal by itself such that a copy of the signal that was taken at time t is shifted against the original from $t - \tau$ through t (where $\tau = 0$) to $t + \tau$ looking for the τ where the copy matches the original. Due to the unpredictability of future amplitudes, a white noise signal is so unique that a copy of it matches it in only one place, at $\tau = 0$, i.e., Equation 19 is obtained when the copy is positioned exactly in line with the original. Hence, and the result of autocorrelation of white noise is an impulse $\delta(\tau)$ with area I (Ref. 6, p. 303) which is also its average power. It follows then, in analogy to Equation 17 that the transform into the frequency domain yields

$$P(\omega) = \int_{-\infty}^{\infty} I\delta(t)e^{-j\omega t}dt \tag{20}$$

which is the power spectrum density, i.e., all frequencies (up to a low-pass limit) are present in the signal and all have the same amplitude (Ref. 6, pp. 303-304). Therefore, white noise is an input signal that fulfills all the requirements for automatic measurement of bandwidth.

5.2.2 <u>Definitions.</u> The bandwidth of a system with a low-pass characteristic is defined as the frequency at the one half power point of the power spectral density curve, or at the $1/\sqrt{2}$ point of the frequency response function which is the square root of the power spectral density. This point is commonly called the 3 dB point, the frequency at this point is also called the cutoff frequency (Ref. 5, pp 156-157).

The 3 dB value results from:

$$20 \log \frac{U_{out}}{U_{in}} = 20 \log \frac{1}{\sqrt{2}} = -3\text{dB} \tag{21}$$

The minus sign indicates that this is an attenuation. -3 dB says also that the output voltage is 70.7 percent of the input voltage to the system. The minus sign is often omitted. The dB scale definition in general is (see Ref. 10)

$$\text{dB} = 10 \log \frac{P_o}{P_i} = 10 \log \frac{U_o^2}{R} \cdot \frac{R}{U_i^2} = 20 \log \frac{U_o}{U_i} \tag{22}$$

This equation also shows how the voltage definition results from the power definition. To arrive at the scale for voltage measurements in dB, a certain value for U_i or P_i is defined as a reference, i.e., the dB scale reads zero at this point. Two, slightly different, dB scales are in use. One is based on 1 V as a reference and is denoted dBv (v for volt), the other is based on the power of 1 mW on 600 Ω as a reference, written dBm (m for milliwatt), which translates to a voltage level of 0.775 V for a zero on the dBm scale.

5.2.3 Method. Referring to Figure 4, the system characteristic can be obtained, in the frequency domain, by

$$H(j\omega) = \frac{Y(\omega)}{X(\omega)} \tag{23}$$

i.e., the transfer function $H(j\omega)$ is the ratio of the output signal transform

$$Y(\omega) = \int_{-\infty}^{\infty} y(t)e^{-j\omega t}dt \tag{24}$$

divided by the input signal transform $X(\omega)$. The magnitude of the (complex) transfer function

$$|H(\omega)| = \sqrt{R^2 + I^2} \tag{25}$$

is the frequency response curve. It can be obtained directly by squaring Equation 23 to get

$$H^2(j\omega) = \frac{|Y(\omega)|^2}{|X(\omega)|^2} = |H(\omega)|^2 \tag{26}$$

Now, if the input $X(\omega)$ is white noise with constant amplitude of all frequencies then $|X(\omega)|^2$ is also a constant. A low pass filter obtains a normalized transfer characteristic (value of 1 at d.c.), then the output to input ratio is multiplied with its inverse at d.c. thereby eliminating gain or loss of the device. Therefore, it is not necessary to know or to measure the input since it is a constant. The output spectrum can then be arbitrarily normalized by dividing it with its value at zero frequency. Finally, the square root is taken so that the system response now is, by eliminating the factor 2π, a normalized function of f

$$|H_n(f)| = \frac{Y(f)}{Y(0)} \tag{27}$$

Divided by $Y(0)$ (d.c. value) normalizes $|H(f)|$ to 1 at low frequencies. Because it is a ratio it has no dimension. Also the gain has been eliminated by normalization. The bandwidth finally is found at the 3 dB point or where the response curve is 0.707, i.e., output amplitude at the bandwidth frequency is down to 70.7 percent of the input amplitude. Figure 9 shows this ideal situation.

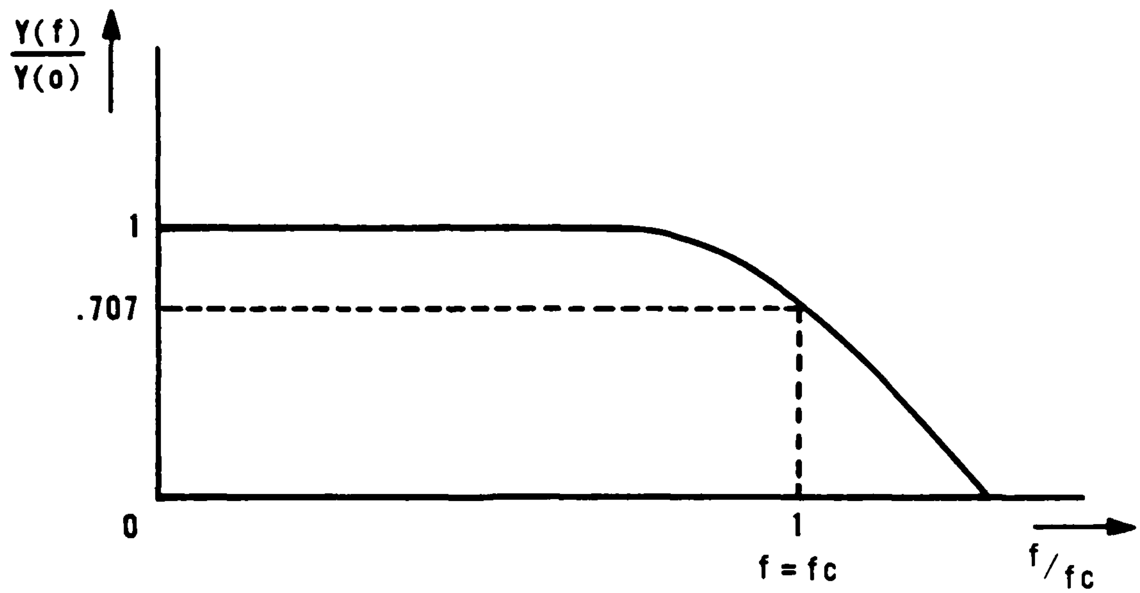


Figure 9. Ideal frequency response curve.

Unfortunately, this ideal situation is not obtainable without making certain manipulations. An unprocessed single sample output of a channel looks more like that shown in Figure 10. A random function like white noise can only be absolutely described by observing it for an infinite time and by looking at all frequencies with 0 Hz resolution. Since only limited observation time is available for a measurement and since a certain finite width of frequency resolution is necessary for obtainig a spectrum, a variance on the power spectrum density results as seen in Figure 10 (Ref. 11). The observation time can be increased by ensemble averaging a number of inputs which reduces the variance by a certain amount as shown for 50 input samples in Figure 11. (Ref. 8, p. 15). The remaining roughness, part of which is also due to shortcomings in the noise generator, has to be brutally smoothed out so that, in the end, an output results that is very close to the ideal curve in Figure 9. The smoothing is justified because it restores the ideal expectation which was lost due to limited observation time and limited observation bandwidth. The smoothing is necessary not just to produce the eye pleasing

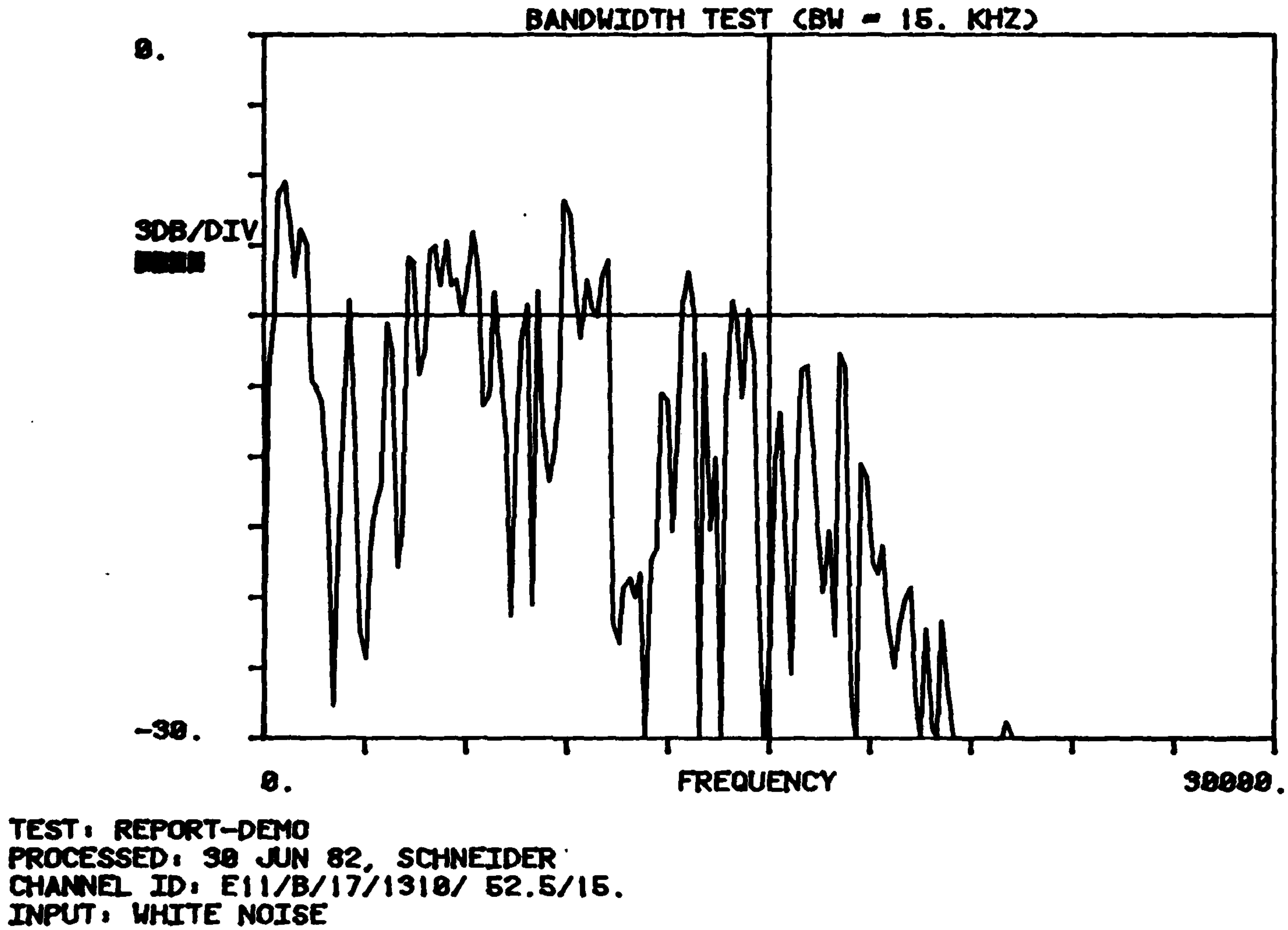


Figure 10. Real, unsmoothed frequency response curve produced with one input sample.

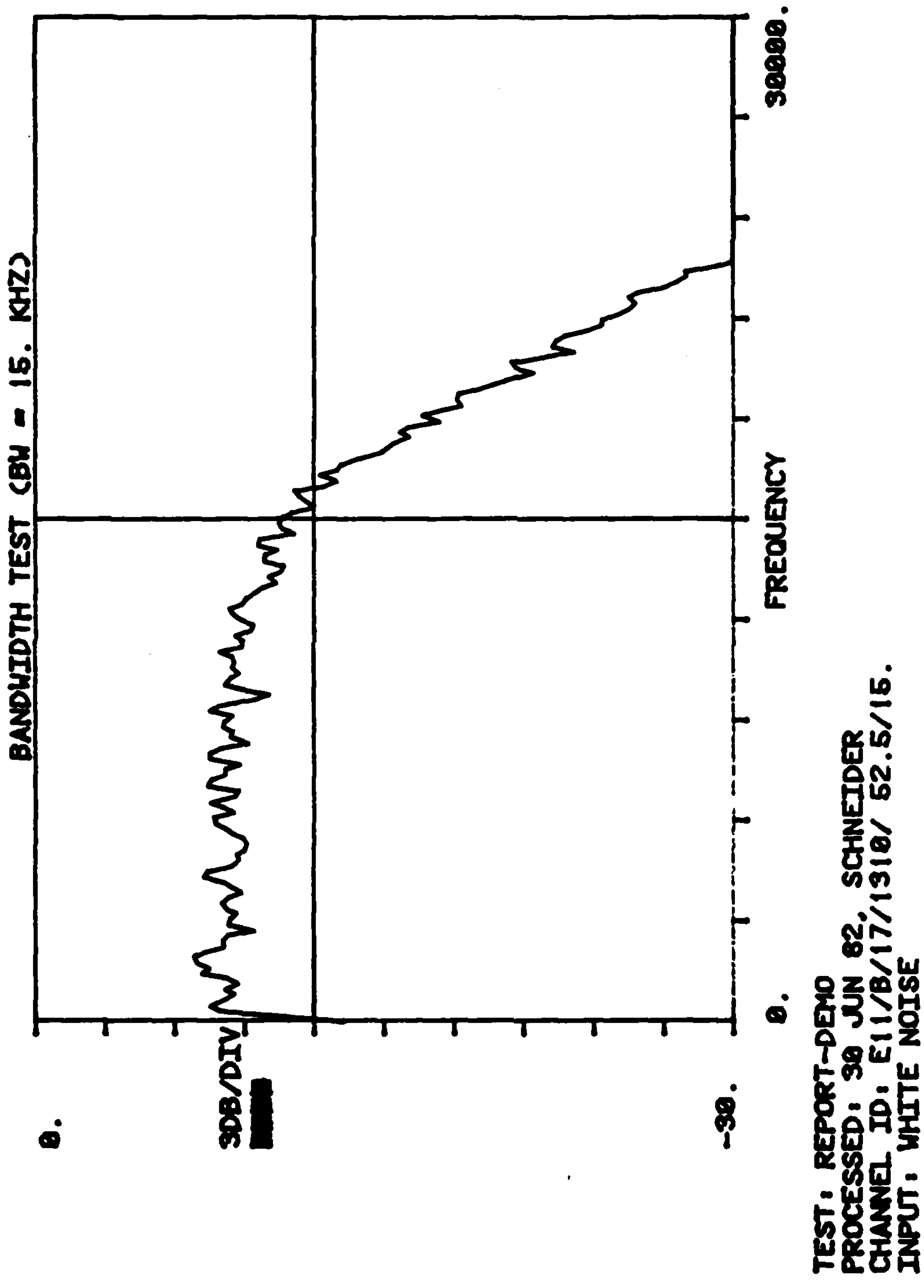


Figure 11. Real, unsmoothed frequency response curve produced with 50 input samples averaged.

ideal curve but also to find unambiguously the 3 dB point which is very difficult to obtain with the shape of the response curves of the Figures 10 and 11.

A simple box car-shaped running average was chosen (Ref. 12) for the smoothing algorithm. Its parameters (smoothing length and number of iterations) were arrived at empirically looking for minimum impact on frequency resolution and maximum smoothness of curve.

5.3 DYMANIC RANGE MEASUREMENT

5.3.1 Input. A defined input for the dynamic range or noise floor measurement is a short across the input of the channel. It has been observed, however, that leaving the input open does not change the results if the input terminals are in an environment that precludes an antenna effect. The quiescent transducer can be left connected to the input when an instrumentation system is measured in situ.

5.3.2 Definitions. A noise measurement has to be a true RMS measurement. Anything else is wrong. Often so-called RMS calibrated meters are simple rectifiers that measure some undefined level with some undefined time constant based on the calibration with a pure sine wave. The dial is then annnotated in RMS volts. A true RMS meter measures that average over a defined time constant of the power of a random signal and displays the square root thereof. So-called noise band measurements on oscilloscopes are very subjective and, therefore, mostly useless for comparison.

The dymanic range is the ratio of full scale amplitude range to noise floor value, expressed in dB (voltage definition)

$$\text{Dymanic Range} = 20 \log \frac{\text{F.S.}}{\text{noise}} \text{ [dB]} \tag{28}$$

For an honest measurement, full scale is not defined as the peak-to-peak (pp) d.c. range but rather as the RMS value of a sine wave whose peaks would be the d.c. peak values, e.g., a 20 V_{pp} d.c. range can accomodate a 7 V RMS sine wave.

An argument could be raised for the case of a transient whose RMS value is not as definable as it is for a continuous signal. If a d.c. full-scale reference is preferred in this case, the measured value based on the RMS full-scale reference has to be increased by 3 dB to obtain the new value. But that raises the question of also using a peak value for the noise floor amplitude. This would bring the actual dBs back to those obtained by the original definition (Eq. 28). The difficulty seems to be that for different transients with the same peak amplitudes, a different RMS value is measured depending on the waveshape while for random noise signals with the same RMS value the peak values are ill defined. Since it is not possible to provide for all eventualities, the RMS definition of the dynamic range seems useful and adequate.

5.3.3 Method. The objectives of the dynamic range measurement are not only to obtain a noise floor figure but also to display the frequency composition of the noise floor. Normally it is very difficult to detect sine wave components in a wideband signal on an oscilloscope, unless they are 60 Hz or otherwise dominant. Therefore, a frequency spectrum of the noise floor is provided via a fast Fourier transform (FFT) of the channel output (Refs. 13 and 14).

Generally, it is tacitly assumed that noise signals have a normal (Gaussian) amplitude distribution. Indeed, according to the central limit theorem (Ref. 15, p. 266), regardless of the shape of the individual distribution of the various uncorrelated noise sources that contribute to the final noise at the output of a system, the distribution of the output noise tends to the normal distribution. This is the justification for the assumption. The convenience of the normal distribution is that it needs only two values for a complete description, the mean and the standard deviation (Ref. 15, pp. 147 and 161). The mean is a d.c. value which is normally zero for noise and the standard deviation then is the true RMS value. Therefore, a true RMS measurement can completely characterize the noise signal.

If a periodic signal is added to the normal distributed noise signal, the RMS measurement is still true because the respective signal powers are added

$$RMS_{total} = \sqrt{P_N + P_S} \text{ [VOLT]} \tag{29}$$

Unfortunately, instrumentation channel noise always contains discrete frequencies, mostly 60 Hz and its harmonics but also higher frequencies in the 10 to 20 kHz range from switching power supplies, or some modulation products. If only one data sample is taken, the variance of the resulting spectrum is extremely high and the periodic components might not be too clearly visible. But when the spectrum is averaged over a number of samples, the variance goes down while the periodic components keep their original amplitudes. Therefore, information is gained by increasing observation time. This is shown in Figures 12 and 13. No smoothing is used here to keep the frequency resolution intact.

In cases where the channel noise floor approaches the data reduction system noise floor (rare, but possible), the power of a sample of the data reduction system noise floor spectrum is taken first and then subtracted from the power of the channel noise floor. While the time domain signal is random and never the same, the power spectrum of a random signal stays the same due to the stationarity property. Therefore, although the data reduction system noise floor sample is taken at one time and the channel noise floor sample at another, the power of the former can be subtracted from the power of the latter.

The measurement of the total power of the noise floor signal n(t) could be done in one of three ways (Ref. 8, p. 10):

a. In the time domain by averaging the power of sample of time T duration within a bandwidth from 0 to F Hz:

$$P = \frac{1}{T}\int_T n^2(t)dt \tag{30}$$

b. In the time domain by computing the autocorrelation of a sample of T duration and taking its value at $\tau = \emptyset$:

$$P = R(\emptyset) \tag{31}$$

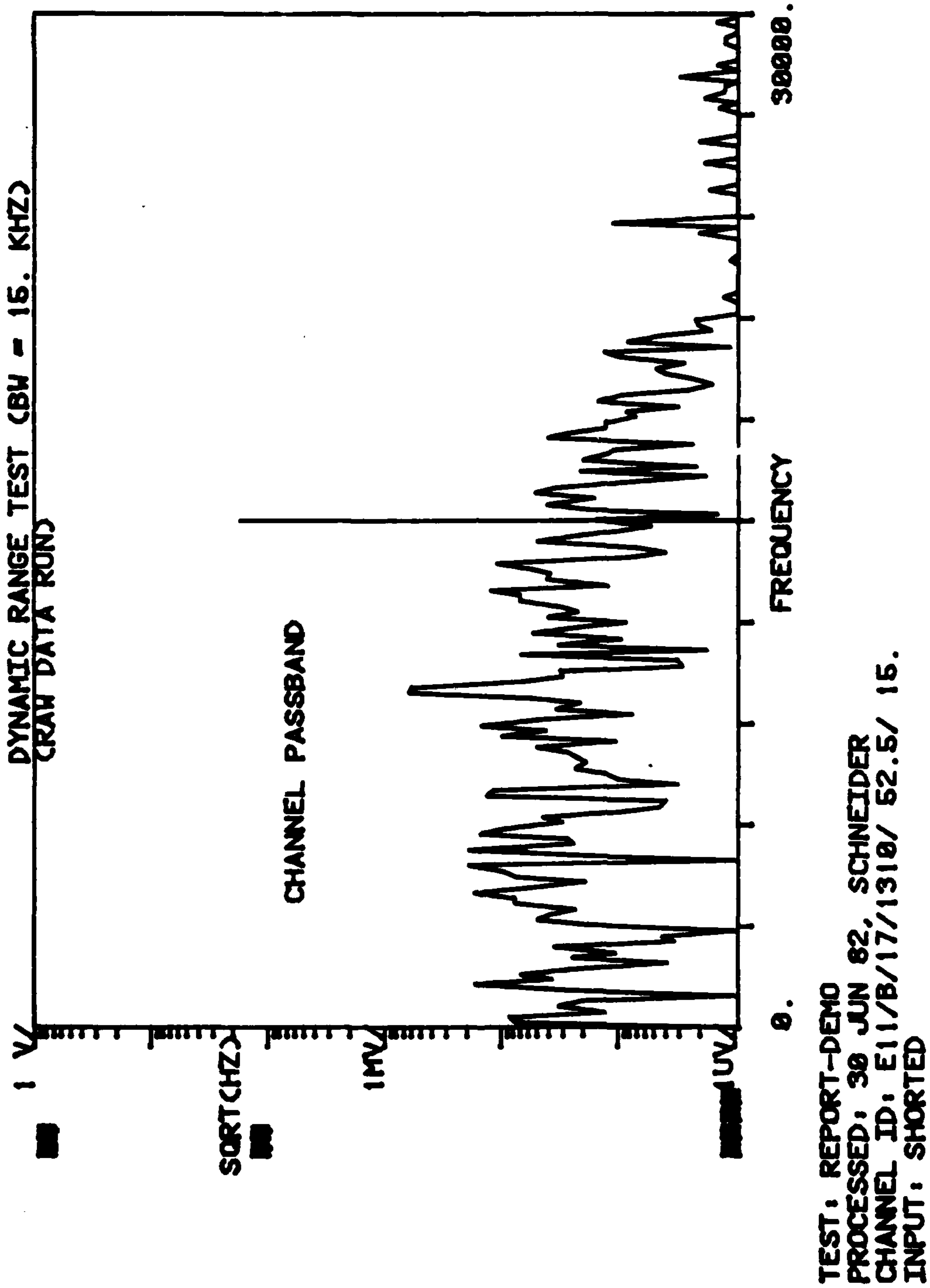


Figure 12. Noise floor spectrum produced with one input sample.

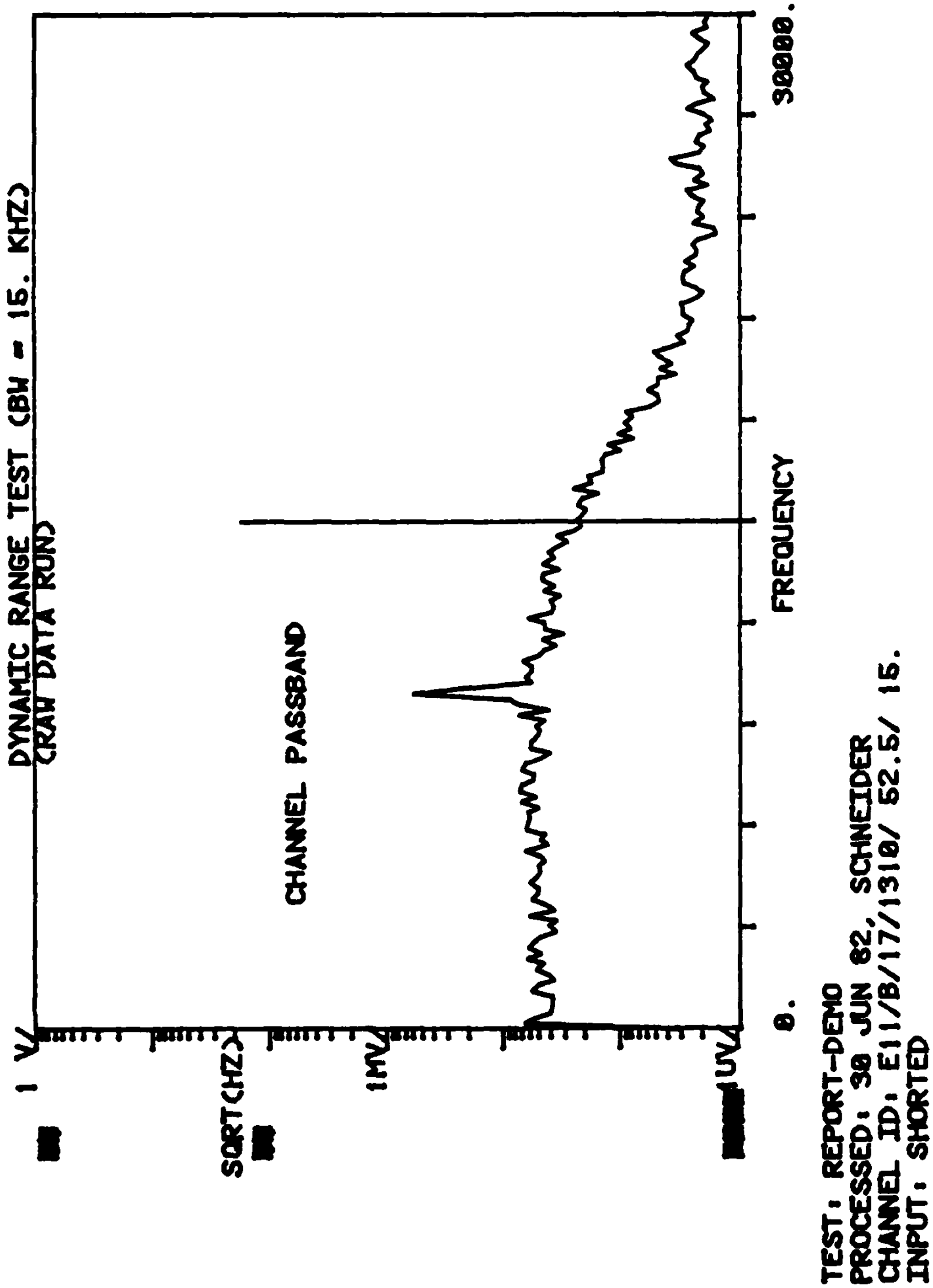


Figure 13. Noise floor spectrum produced with 50 input samples averaged.

c. In the frequency domain by integrating the power spectrum density p(f) that was obtained from a sample of T duration, over the frequency range from 0 to F:

$$P = \int_F p(f)\ df \tag{32}$$

The frequency domain approach has been chosen for the channel noise floor measurement because it also provides the noise floor spectrum.

VI. IMPLEMENTATION

6.1 LINEARITY MEASUREMENT

6.1.1 Input. Ideally, all imputs to a particular system, say a van, would be connected with one signal generator feeding one signal to all channels simultaneously. This can be done fairly easily with homogeneous vans like Van El (Ref. 16), when all gains are the same, but with different gains for different channels, like channels will have to be grouped and the groups handled sequentially. Simultaneous handling could be possible when more signal generators are used, or attenuators are used with one generator.

The input amplitude is adjusted so that the full amplitude range at the output of the channel is traversed by the triangular signal. This adjustment need not be to critical. If suffices when the peak-to-peak amplitude of the triangular signal covers at least 95 percent of the amplitude range.

The frequency of the triangular wave is chosen for negligible high frequency distortion. For reasons that will be explained in the next paragraph, certain selected frequencies have to be used in connection with the bandwidth of the channel. They are:

12.4 Hz for 0.5 kHz and above

31 Hz for 2 kHz and above

62 Hz for 5 kHz and above

124 Hz for 10 kHz and above

A frequency could be selected for the lowest bandwidth in the system and then used for all channels, but the lower frequencies need more processing time, than the higher ones. The respective data windows are 50, 20, 10, and 5 ms.

6.1.2 Recording. In order to properly include the recorder characteristics in the measurement, the recording should be done at operational tape speed. It must be done where channel bandwidth or FM multiplex bandwidth require it. Where this is not the case, a lower tape speed may be used, with subsequent gain in recording time, for linearity measurement only because a different tape speed does not materially affect the linearity characteristic of a channel. A 10.5-in reel with 4600 ft of tape plays a usable 7.5 min at 120 ips. It is imperative that a full tape be recorded to cut the rewind requirement in data reduction to a minimum.

6.1.3 Data Reduction. The channel output is adjusted to ± 1 V peak. The triangular wave is triggered into the data window at -0.8 V on the negative slope. This trigger level is a fixed feature of the equipment. The standardized (binary) sample rates combine with 256 data points desired in the window to produce the window times of 50, 20, 10, and 5 ms. In order to obtain optimum coverage of the upgoing ramp in these given windows with the -0.8 V trigger point, the triangular wave has to have the above mentioned frequencies. A typical input setup can be seen in Figure 14. The upright lines delineate the range within which the linearity processing is performed. They help the operator to see whether the available (recorded) signal can be used at all and whether the amplitude is properly adjusted. If it is not possible to put a straight line between the uprights, the measurement cannot be performed. The input frequencies that have been given provide the optimum results, but good linearity measurement can be made in the range between +3 percent and -8 percent of the optimum frequencies. These ranges are:

For 124 Hz from 114 - 128 Hz with bandwidth 10 kHz

For 62 Hz from 57 - 64 Hz with bandwidth 5 kHz

For 31 Hz from 28.5 - 32 Hz with bandwidth 2 kHz

For 12.4 Hz from 11.4 - 12.8 Hz with bandwidth 1 kHz

Exact power frequency harmonics should be avoided. The data reduction bandwidth is chosen for distoration-free passage of the triangle wave. It is not necessarily the channel bandwidth. However, the channel bandwidth should be at least as high (with one exception at 0.5 kHz).

The linearity signal is obtained from the channel output. Including data reduction in the channel, this is the discriminator output for multiplexed FM channels or the FM reproduce module output for one per track FM channels (the latter can also be played back through discriminators).

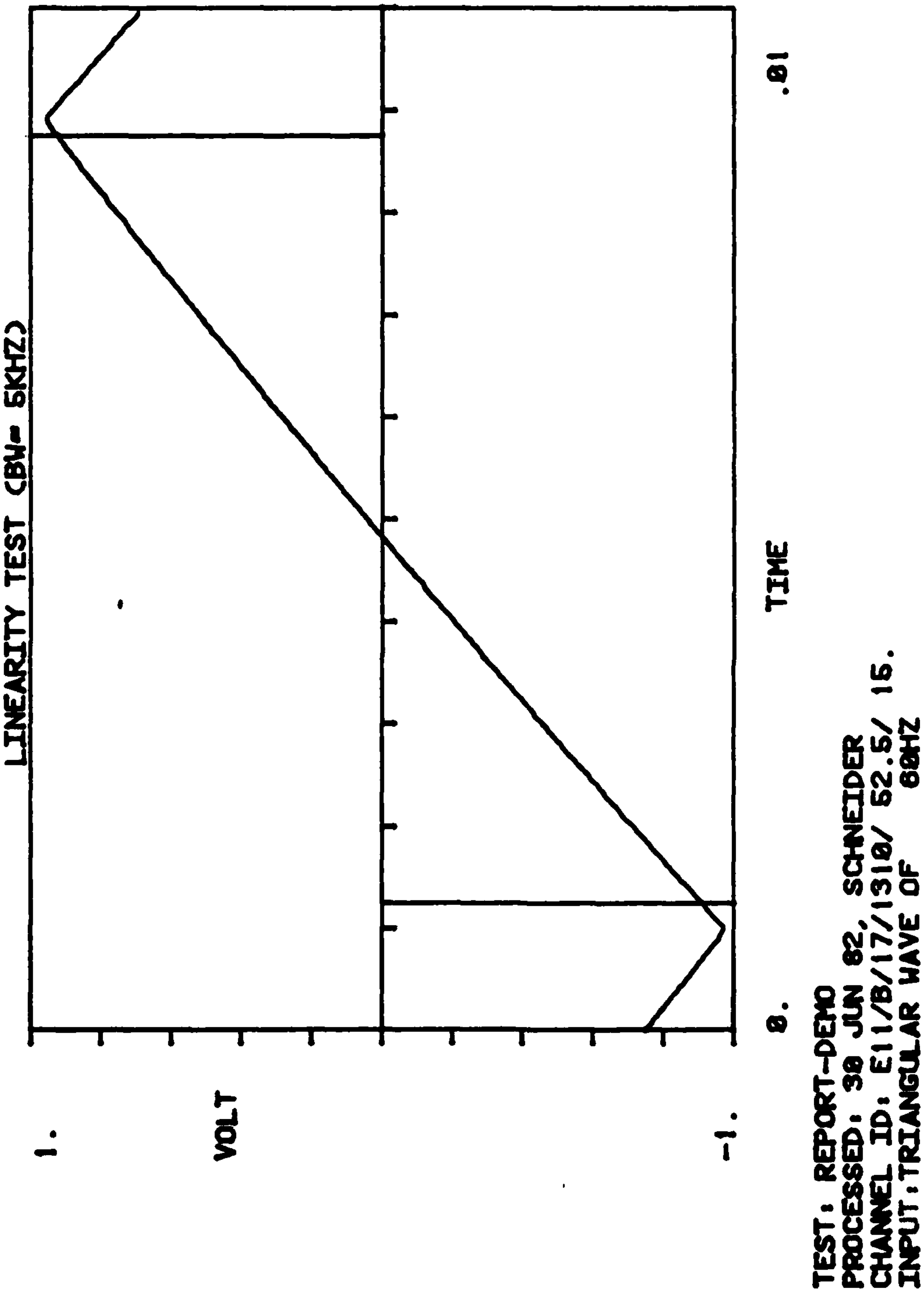


Figure 14. Linearity input signal setup.

Unfortunately, noise (random and 60 Hz) is ever present in certain amounts, e.g., a 0.4 percent of full-scale noise riding on the signal is not uncommon. This noise has nothing to do with nonlinearity but will show up as such in the result if the real nonlinearity is of the same order of magnitude. Because this noise is random, or, if periodic, not normally synchronous with the trigger, it can be reduced by averaging, e.g., 16 averages would bring the noise down by a factor of 4, or in the above example, to 0.1 percent of full scale. Empirically, 13 averages have been chosen as a compromise between noise reduction and processing time.

A separate input ahead of the averaging process can be taken and displayed for the purpose of setting up the proper levels and checking whether a valid measurement can be made (Figure 14). This input can be repeated as often as necessary until the setup is correct. Then 13 inputs are taken for the average which is used for the subsequent processing (see Section 5.1.3). The y_i components are the data points (or amplitudes) that are taken at the x_i points in the data window. Before Equation 15 is plotted, the computed nonlinearity curve is smoothed to remove sampling noise and other statistical roughness. The boxcar of the smoothing algorithm extends over five data points and the algorithm is applied once on the data.

The resulting nonlinearity curve is displayed together with identifying information (Fig. 15). The plot is normalized so that the horizontal centerline represents the computed straight (Eq. 1) and the curve represents the deviations therefrom (Eq. 15). The percent of maximum nonlinearity (Eq. 16) is printed on the plot. The horizontal axis of the display is calibrated in percent amplitude range. Lower and upper limits, corresponding to the uprights in Figure 14, are plotted so that there is no doubt about how much of the full range the measurement was taken. For routine measurements, the nonlinearity curve need not be displayed for every channel. Because it takes time, the display is normally suppressed and only the channel and test identification is printed together with the nonlinearity figure (Fig. 16). In case of doubt, the curve can still be displayed afterward.

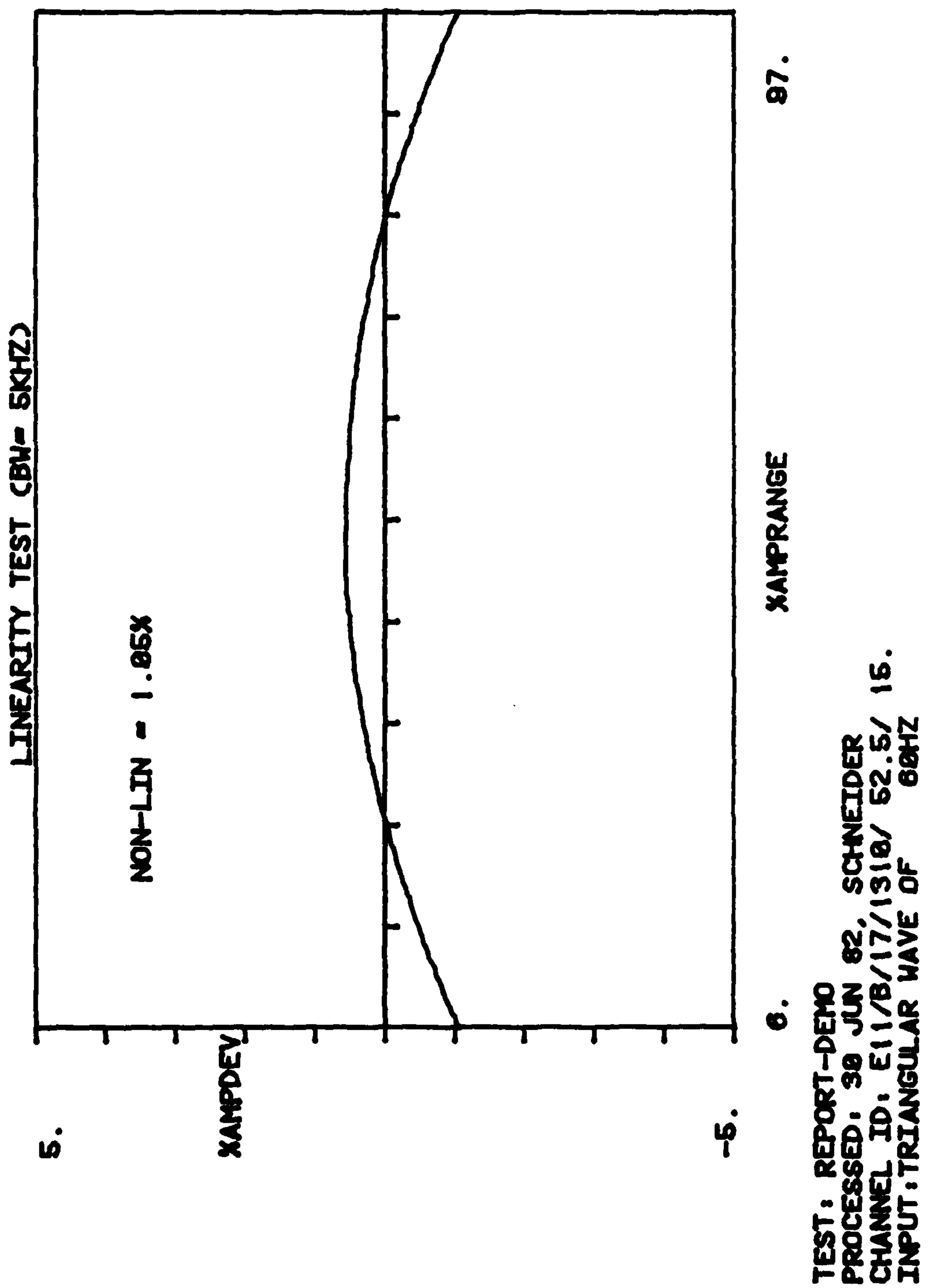


Figure 15. Nonlinearity output, curve plot.

LINEARITY TEST (BW= 5KHZ)

NON-LIN = 1.68%

TEST: REPORT-DEMO
PROCESSED: 30 JUN 82, SCHNEIDER
CHANNEL ID: E11/B/17/1310/ 52.5/ 15.
INPUT:TRIANGULAR WAVE OF 60HZ

SELECT NEXT OPERATION(S=HELP,OR:R,I,T,V,B,F,P,E):

Figure 16. Nonlinearity output, text only.

Further processing action is taken from a number of options:

a. The whole measurement can be repeated before anything is recorded on disk.

b. The last input data can be displayed if the validity of the input needs to be confirmed.

c. The tape recorder track is to be changed.

d. The VCO center frequency is to be changed.

e. Both the track and the VCO are to be changed.

f. The frequency of the input triangular wave is to be changed.

g. The table of accumulated measurement is to be printed.

h. The program can be exited.

The channel identification consists of tape recorder track number, VCO center frequency, ± deviation range, and lowpass cutoff frequency (11 in kilohertz). This identifier is printed in the table on each line followed by the result of the measurement, which here is the nonlinearity figure (Table 1). The header of the table consists of the instrumentation van designator Exx and the tape recorder letter (A,B....). The data from the channels that are recorded on one tape recorder are defined as the entity which is recorded on disk as a computer file. The file name contains the disk device the file is recorded on, the van designator, the tape recorder letter, and the function that is being measured, e.g., RK1:E05BLI says that this file is recorded on disk cartridge No. 1, containing the data of the channels that have been recorded in Van E5 on tape recorder B, and that it is a linearity measurement. This name is printed at the bottom of the table for easy correlation with the disk file directory. The file name is automatically compiled from the operator machine dialogue at the beginning of the program. Before any of the aforementioned options can be executed, the operator has to choose whether the channel just processed should be added to the file or not. Thus, each measurement can be saved as soon as it is available and no previous work can get lost due to a computer failure (e.g., power outage) except, maybe the last measurement.

TABLE 1. SAMPLE OF OPTIONAL NONLINEARITY TABLE OUTPUT.

CHECKOUT VAN E5 RECORDER B

CHANNEL ID TK/CFRQ/DEV/BW(KHZ)	LINEARITY NONLIN%	BANDWIDTH BW(KHZ)	BW-ERR%	DYN. RANGE S/N(DB)	MV(RMS)
11/ 48/ 2. / .5	.79				
12/ 48/ 2. / .5	.80				
9/ 48/ 2. / .5	.77				
8/ 48/ 2. / .5	.78				
6/ 48/ 2. / .5	.78				
5/ 48/ 2. / .5	.99				
3/ 48/ 2. / .5	.85				
1/ 48/ 2. / .5	.86				
1/ 320/ 16. / 4.	.39				
2/ 320/ 16. / 4.	.42				
3/ 320/ 16. / 4.	.38				
5/ 320/ 16. / 4.	.41				
7/ 320/ 16. / 4.	.43				
8/ 320/ 16. / 4.	.38				
9/ 320/ 16. / 4.	.46				
11/ 320/ 16. / 4.	.4				
12/ 320/ 16. / 4.	.46				
6/ 320/ 16. / 4.	.45				
1/ 64/ 4. / 1.	.45				
1/ 80/ 4. / 1.	.43				
1/ 128/ 8. / 2.	.54				
1/ 160/ 8. / 2.	.51				
1/ 256/ 16. / 4.	.54				
1/ 384/ 16. / 4.	.54				
1/ 768/ 32. / 8.	.48				
1/ 896/ 32. / 8.	.48				
1/1664/ 64. / 16.	.48				
1/1152/ 64. / 16.	.52				
1/ 512/ 32. / 8.	.50				
11/ 48/ 2. / .5	.50				
5/ 48/ 2. / .5	.53				
3/ 384/ 16. / 4.	.35				
8/ 512/ 32. / 8.	.30				
5/ 192/ 8. / 2.	.31				
6/ 512/ 32. / 16.	.33				
1/ 96/ 4. / 1.	.25				
11/ 160/ 8. / 2.	.49				
12/ 160/ 8. / 2.	.61				
7/ 384/ 16. / 4.	1.37				
7/ 384/ 16. / 4.	.76				

FILENAME= RK1:E05BLI

Before one can exit the program or change to a new van or a new recorder, the program prints a reminder that maybe the operator should print out the already accumulated results. When making changes in the channel identifier (ID), the ID of the channel just processed is displayed on the screen to avoid unnecessary and time consuming duplication or gaps in the channel sequence. A bad measurement that had already been recorded can be repeated later. It is added on the already established file. In the final result table (see Section 6.4), the measurements are sorted and later entries supercede earlier ones with the same ID. However, in the printout that is obtained within an individual function program, repeats appear in the sequence they were processed. The immediate repeat of a bad measurement can be seen in the last two entries of Table 1. Therefore, the operator can process the channels of a particular recorder in any sequence that suits him, he can at any time append to the file what has so far not been taken care of or what needed to be repeated. A file does not have to be completed in one session. It can be terminated any time and reopened again when processing continues.

In order to manipulate the files as just described, the file size has to be finite and defined. Although the size has been chosen big enough to accomodate normal processing needs, it is easily possible to reach this limit, when many repeats have to be made, or when all channels are used in one of the tighter packed vans. This eventuality is taken care of by opening an extension file when the computer signals that the basic file is full. The extension file has the same name except for the recorder letter for which one letter in the second half of the alphabet should be selected to avoid any ambiguity. The number of recorders per van will not exceed 12 in the foreseeable future.

6.2 BANDWIDTH MEASUREMENT

6.2.1 Input. Generally, the same holds here for the connection of the input signal as was described in Section 6.1.1. The RMS input amplitude of the white noise signal is adjusted to one-tenth of the value of the full peak-to-peak amplitude range, e.g., for 5 Vpp range at the input, the noise voltage would be 0.5 Vrms. This setting is not critical within -50 to +100 percent range. A higher setting than that would lead to clipping of some noise amplitudes which could distort the power spectrum somewhat. The bandwidth of the input noise signal should at least be the same as the bandwidth of the channel but not more than twice the channel bandwidth. If an adjustable filter is used, the ideal setting of the noise bandwidth is between 1.4 and 1.6 times the channel bandwidth. The measurement of the input voltage should be made at the filter output.

6.2.2 Recording. Recording is done in the same way as described in section 6.1.2. Here too the operational tape speed does not necessarily have to be used as long as the channel bandwidth is not affected. Again a full tape is to be recorded.

6.2.3 Data Reduction. The discriminator output is set for a full-scale range of ±10 V peak. If a tape recorder reproduce module is the output, a 10 times amplifier is used to obtain a ±10 V peak full-scale range. The operator enters van, recorder, and channel identification from which table and channel header are taken and the file name is constructed. An input sample can be displayed for set up and verification purposes. The size of the data window depends on the sample rate which is determined from the entered bandwidth of the channel. Table 2 shows the relationships. For example, if the channel bandwidth entered is more than 10 kHz but not more than 20 kHz, the samples will be taken at the rate of 81 920 per second. For all sample rates, 512 samples are taken per measurement. Thus, a data window of 6.25 ms is obtained in the example (Fig. 17).

The sample rates are basically calculated to be four times the bandwidth cutoff frequency. The next higher available value is then selected as actual rate (the decimals in the sample rates have to do with the binary dividers of two original clock frequencies in the data reduction equipment). The aliasing (Ref. 17) that still might be expected in the worst case is negligible for the purpose of finding the bandwidth of the channel. Figure 18 explains the aliasing effect under these conditions, i.e., channel bandwidth at the upper end of the range ($f_C = 1/2\ f_N$) and the noise signal not bandlimited. Assuming a 5-pole lowpass filter in the channel, the frequency response would be (ideally) -30 dB down at twice the cutoff frequency f_C, that is at f_N, the Nyquist frequency. The signal energy extending beyond this point is folded over back into the displayable spectrum area and added

TABLE 2. BANDWIDTH, SAMPLE RATE, AND DATA WINDOW FOR BANDWIDTH AND NOISE FLOOR MEASUREMENTS

Bandwidth kHz	Sample Rate kHz	Data Window ms
0.2	0.8192	626.0
> 0.2 - 0.25	1.024	500.0
> 0.25 - 0.4	1.6384	312.5
> 0.4 - 0.4	2.048	250.0
> 0.5 - 0.8	3.2768	156.25
> 0.8 - 1	4.096	125.0
> 1 - 2	8.192	62.5
> 2 - 2.5	10.24	50.0
> 2.5 - 4	16.384	31.25
> 4 - 5	20.48	25.0
> 5 - 8	32.768	15.625
> 8 - 10	40.96	12.5
> 10 - 20	81.92	6.25
> 20 - 25	102.4	5.0
> 25 - 50	204.8	2.5

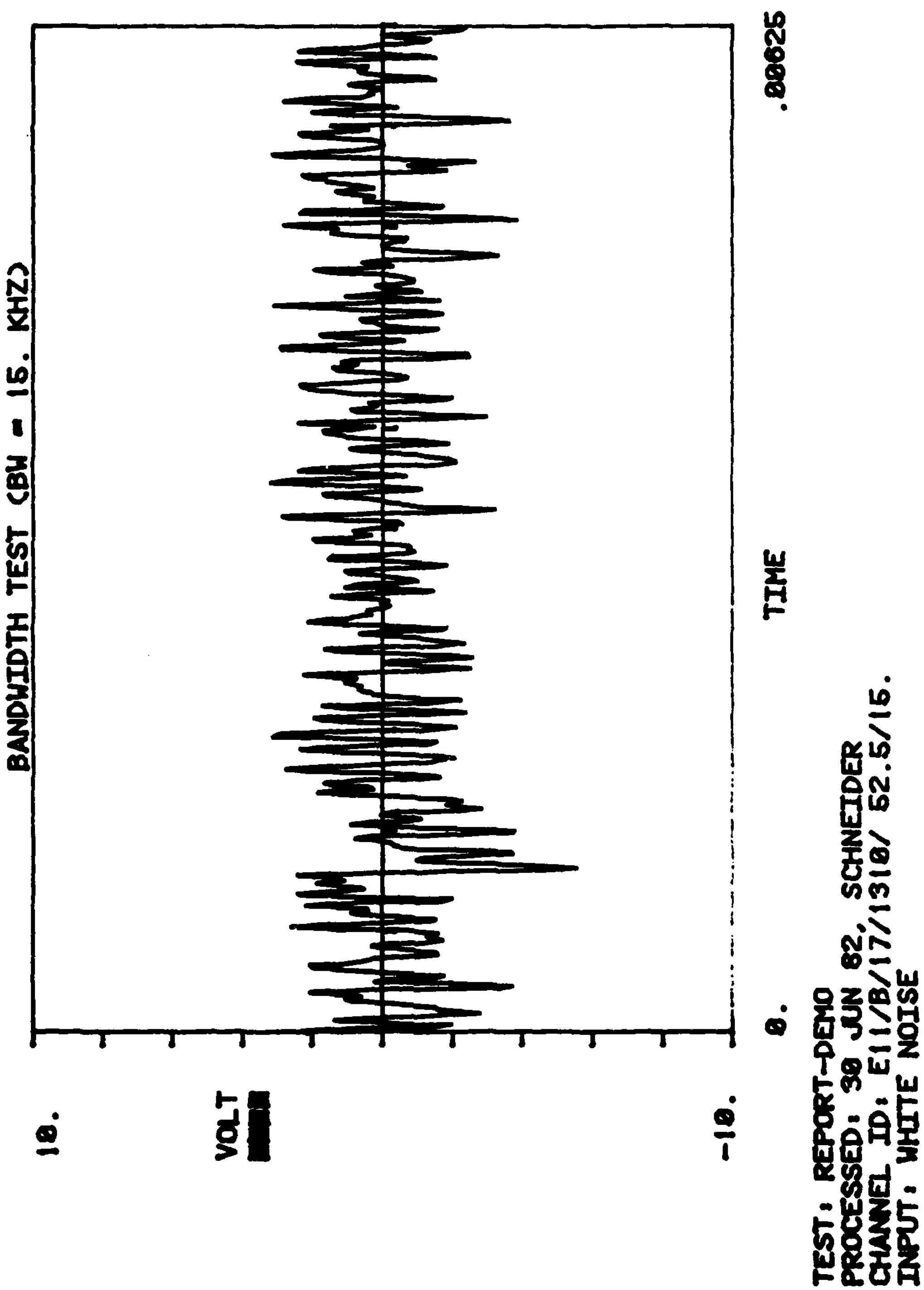


Figure 17. Bandwidth input signal setup.

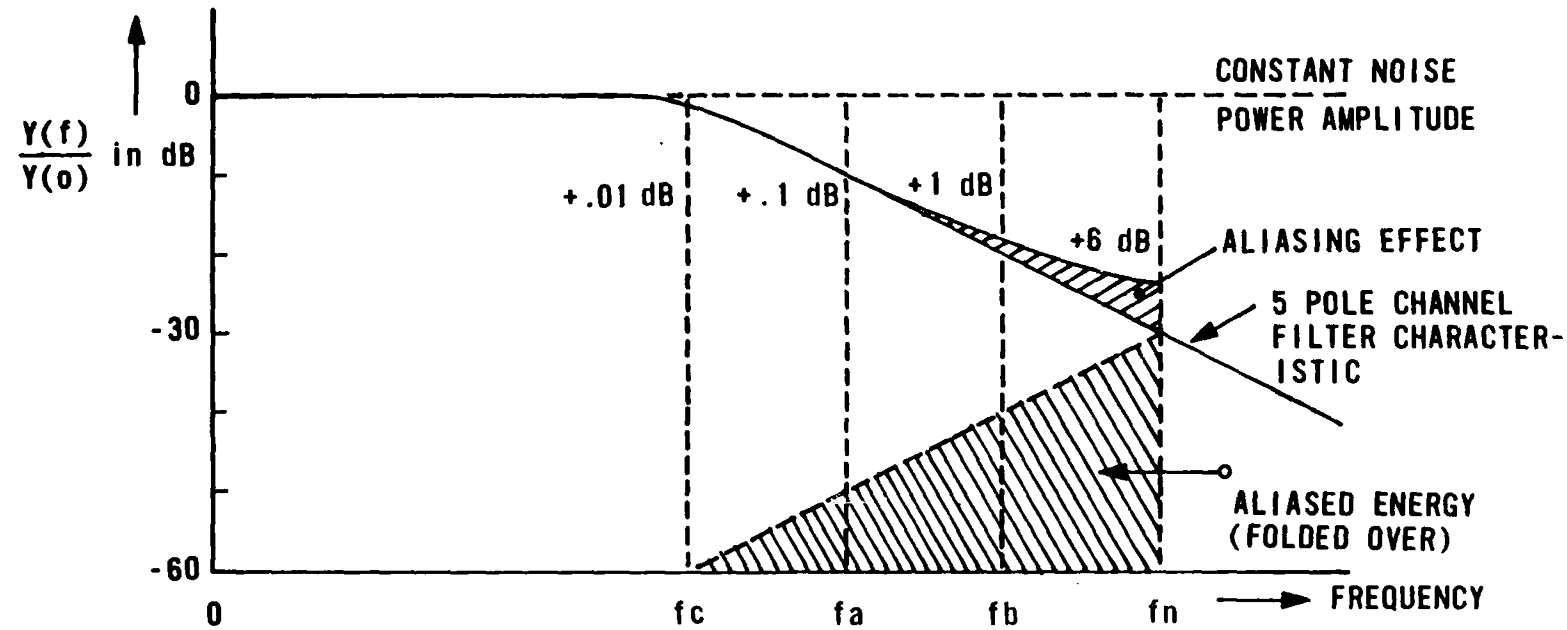


Figure 18. Aliasing effect with constant noise input signal amplitude.

to the signal already there. This aliasing effect produces a change in the frequency response curve of +6 dB at f_N, + 1 dB at f_b, + 0.1 dB at f_a and + 0.01 dB at f_c. The latter is the equivalent of 0.1 percent at the bandwidth determination point and therefore negligible. The -60 dB line in the figure has been defined as zero signal because it is only a 0.1 percent of full scale and therefore close enough to a pratical zero signal in a channel. This worst case aliasing has no material effect on the determination of the bandwidth cutoff frequency. If the noise signal is filtered at about 1.4 f_c with only a 3-pole lowpass filter, the aliasing effect is practically zero at f_c as shown in Figure 19.

The input is Fourier transformed to obtain the power spectrum. Fifty of these are averaged and the average is run 3 times through a smoothing process with a boxcar length of 13 data points. Because a frequency response function is a ratio of output over input (Eq. 23) and because the exact input voltage is not important nor is the gain to be measured, the response can be normalized to 1 at the low frequency end which corresponds to a ratio of 0 dB. Only the -3 dB line is specifically shown in the display (Fig. 20). The actual bandwidth is determined by looking for the first data point that reaches the -3 dB line. It is shown in the upper left half of the display. On the right side, the percent deviation of the actual from the expected bandwidth is printed. The legend on the display is the same as in the linearity case. The horizontal (frequency) axis is calibrated such that the expected bandwidth is always in the center of the plot, therefore, the full frequency range displayed is always twice the entered bandwidth. Thus, all the plots are normalized in both the horizontal and vertical axes so that any two can be overlaid for comparison no matter how different their bandwidth is or their input signal voltage.

The remaining operation of the program continues as described in Section 6.1.3 by selecting the options, putting the results on file, and printing the accumulated data.

6.3 DYNAMIC RANGE MEASUREMENT

6.3.1 Input. No input signal is applied, the channel inputs do not need to be connected in parallel, and the individual inputs are shortened or

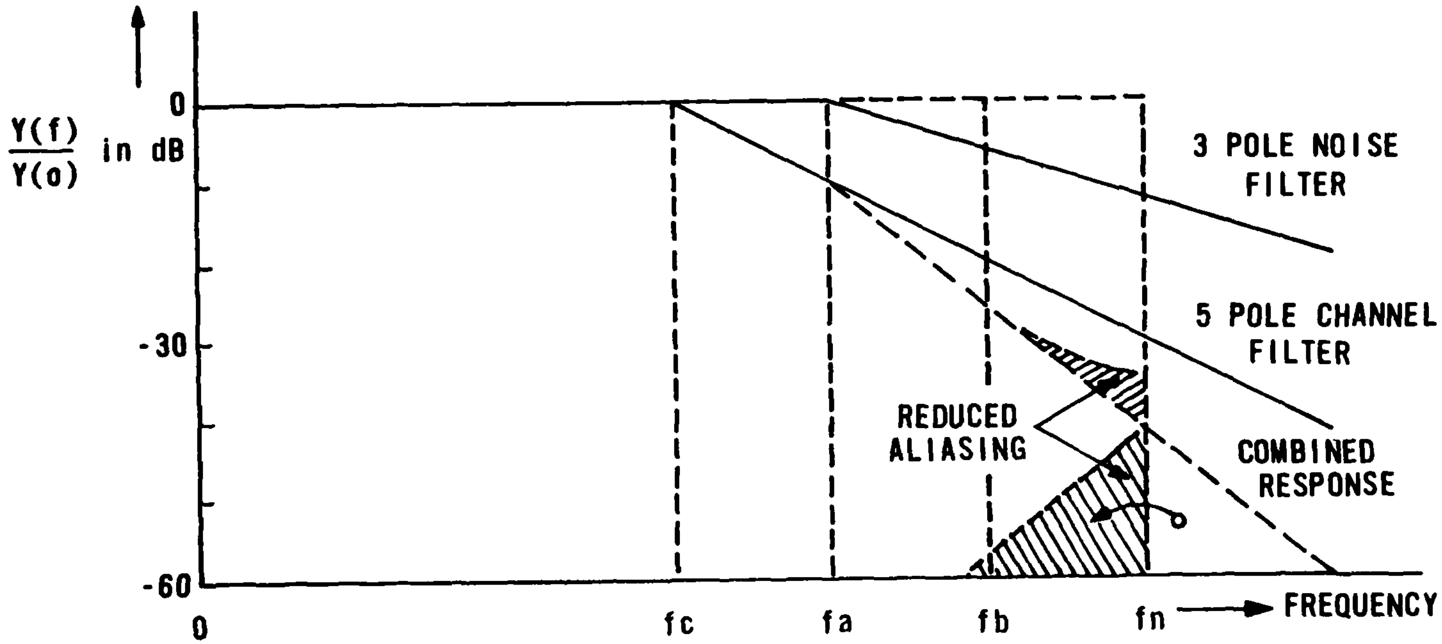


Figure 19. Aliasing effect with filtered noise input signal.

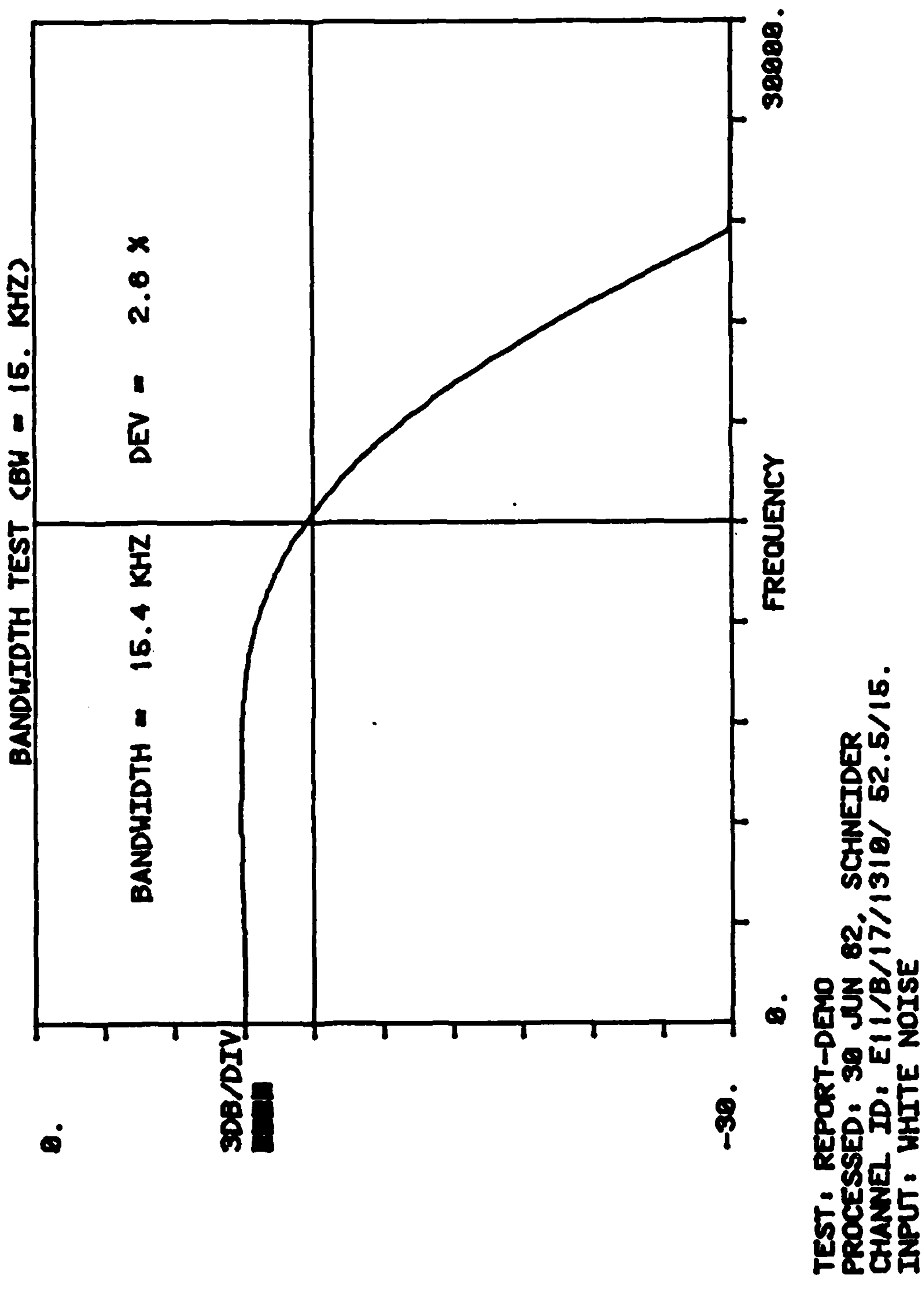


Figure 20. Frequency response curve output.

left open, if acceptable. If the inputs have been set up before for a bandwidth or linearity measurement, the inputs can be left connected and the short applied in lieu of the signal generator, unless groundloops are detected.

6.3.2 Recording. The recording is done in the same way as described in Section 6.1.2. However, it is important here that the operational tape speed be used because the noise characteristics of the tape recorder are different for different tape speeds.

6.3.3 Data Reduction. The discriminator output is set for a full scale range of ±10 V peak. If a tape recorder reproduce module is the output, a gain of 10 amplifier is used to obtain the same full-scale range. The operator enters the identifying parameters. An input sample can be displayed for set up and verification purposes. Sample rates and data windows are based on the bandwidth entered and are shown in Table 2. When the output spectrum is displayed, 512 input samples are taken per data window, and 50 data samples are averaged in the frequency domain for the autospectrum.

If a measurement system noise floor was taken before and its autospectrum was saved, the latter is now subtracted from the data autospectrum. Because of the statistical nature of the autospectrum of noise, it can happen that negative value result from the subtraction. This is avoided by forcing negative values to zero. Then the resulting autospectrum is integrated over the requested bandwidth which yields, after some calibration, the RMS value of the channel noise in millivolts. By referring it to the RMS full scale value (7 Vrms), the logarithmic value of dynamic range is obtained in dB. The autospectrum is then calibrated on a Vrms/$\sqrt{\text{Hz}}$ density scale and an average density value in the passband is calculated.

The display of the autospectrum of the noise floor spans twice the requested bandwidth and is normalized such that the requested bandwidth is always at the center. Dynamic range, millivolt noise and noise density values are printed on the display. The vertical axis is logarithmic over six decades from 1 V to 1 μV.

The remaining operation of the program continues as described in Section 6.1.3 by selecting options, recording results on file, and by printing the accumulated data.

Without the display, the resolution of the autospectrum is relaxed by using only 10 data samples for averaging with only 256 input samples each. The accuracy of the total noise value does not suffer but processing time is substantially reduced.

The correction of the measured noise by the measurement system noise to obtain the true channel noise can also be used in the routine measurement without the display. It loses its effectiveness above a signal-to-noise ratio (S/N) of 3. A substantial improvement of the measurement can be achieved below an S/N of 3. Figure 21 shows the results of a measurement without correction (which is annotated as a Raw Data Run on the plot). Noise has been added to the system for the purpose of demonstration. The system noise floor is shown in Figure 22 which is annotated as Correction Definition Run on the plot. It has to be requested as such when a correction is intented so it can be saved to be subtracted from as many subsequent data runs as it is valid for. A built-in provision prohibts a corrected run request from being executed if a correction definition run has not yet been done. The corrected data are presented as Corrected Data Run, as shown in Figure 23. The effect of correction can best be seen in the different millivolt noise values of Figures 21 and 23. The data in Figure 22 do not show the lowpass filter roll-off because the lowpass filter in the discriminator belongs to the channel, whereas what follows belongs to the measurement system.

6.4 TABLE OF RESULTS

The result table (Van Checkout Table) is produced from the individual function data tables (and their extensions, if any). In order to avoid confusion each entry is checked against the corresponding set of valid parameters, e.g., requesting a table of Van 6 performance will produce an error message because E6 does not exist. Equally, when the individual channel data are processed, invalid tape recorder tracks or VCO center frequencies are flagged with the subsequent option to skip this channel or to correct the

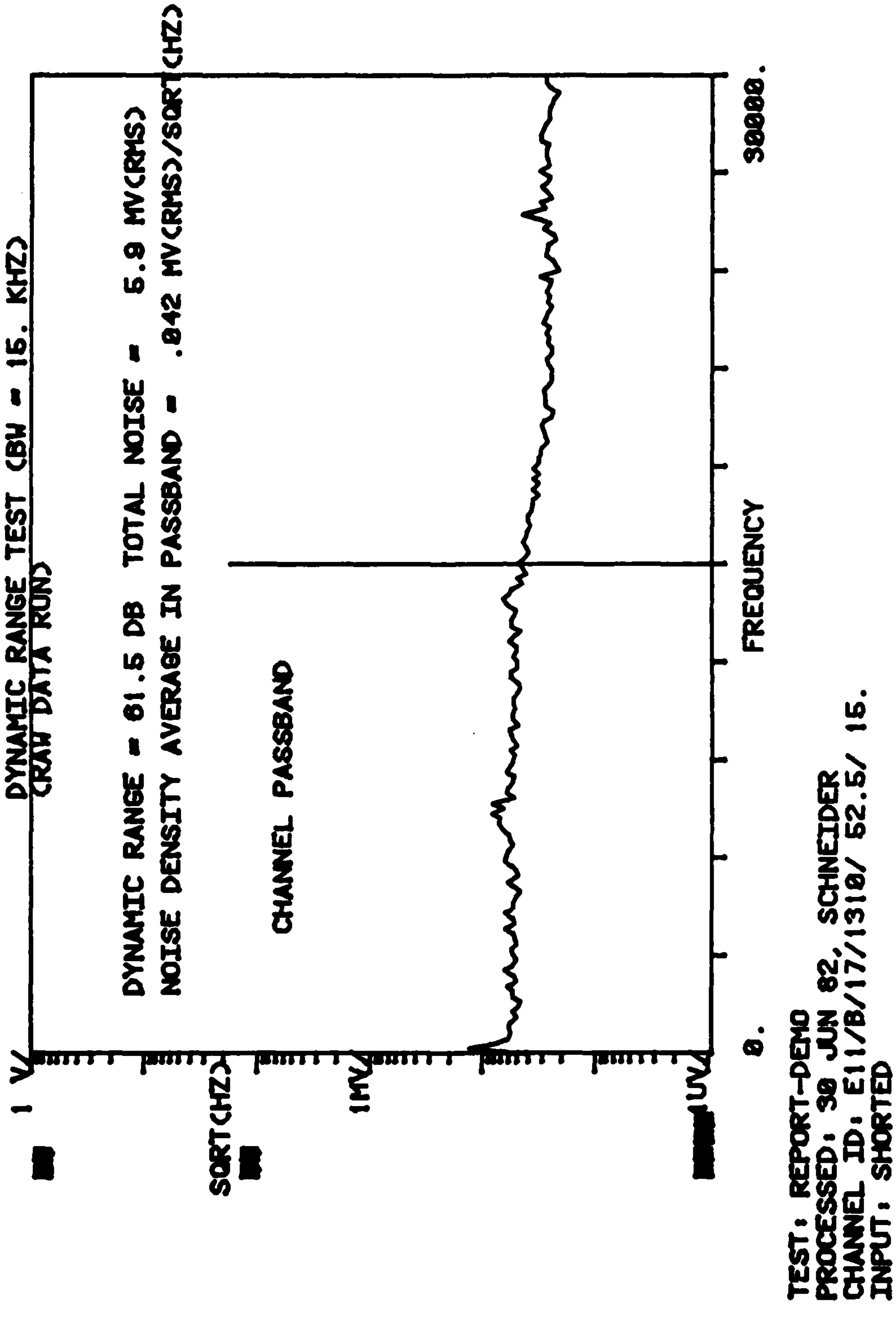


Figure 21. Raw data noise floor spectrum.

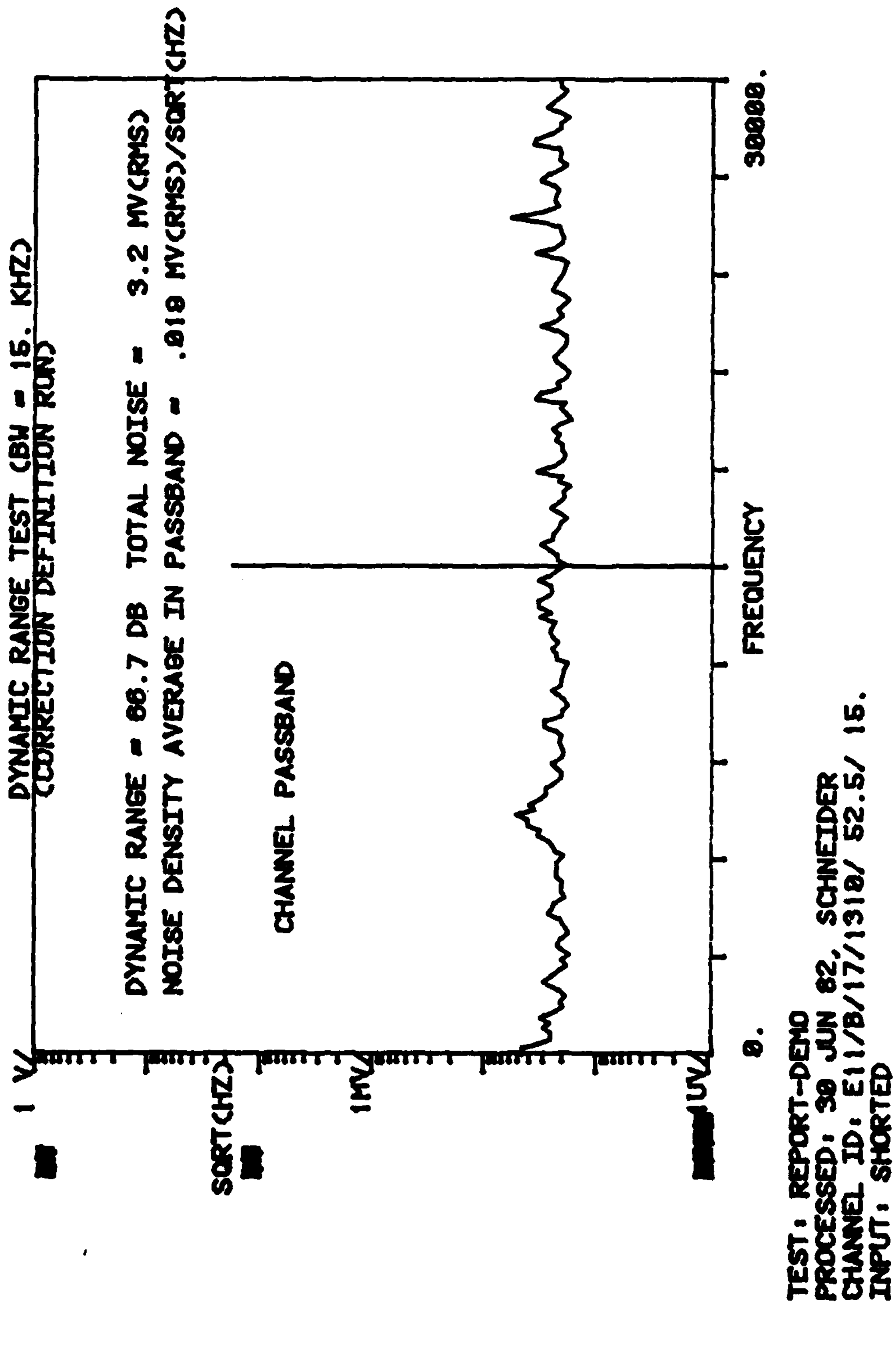


Figure 22. System noise floor spectrum for correction definition.

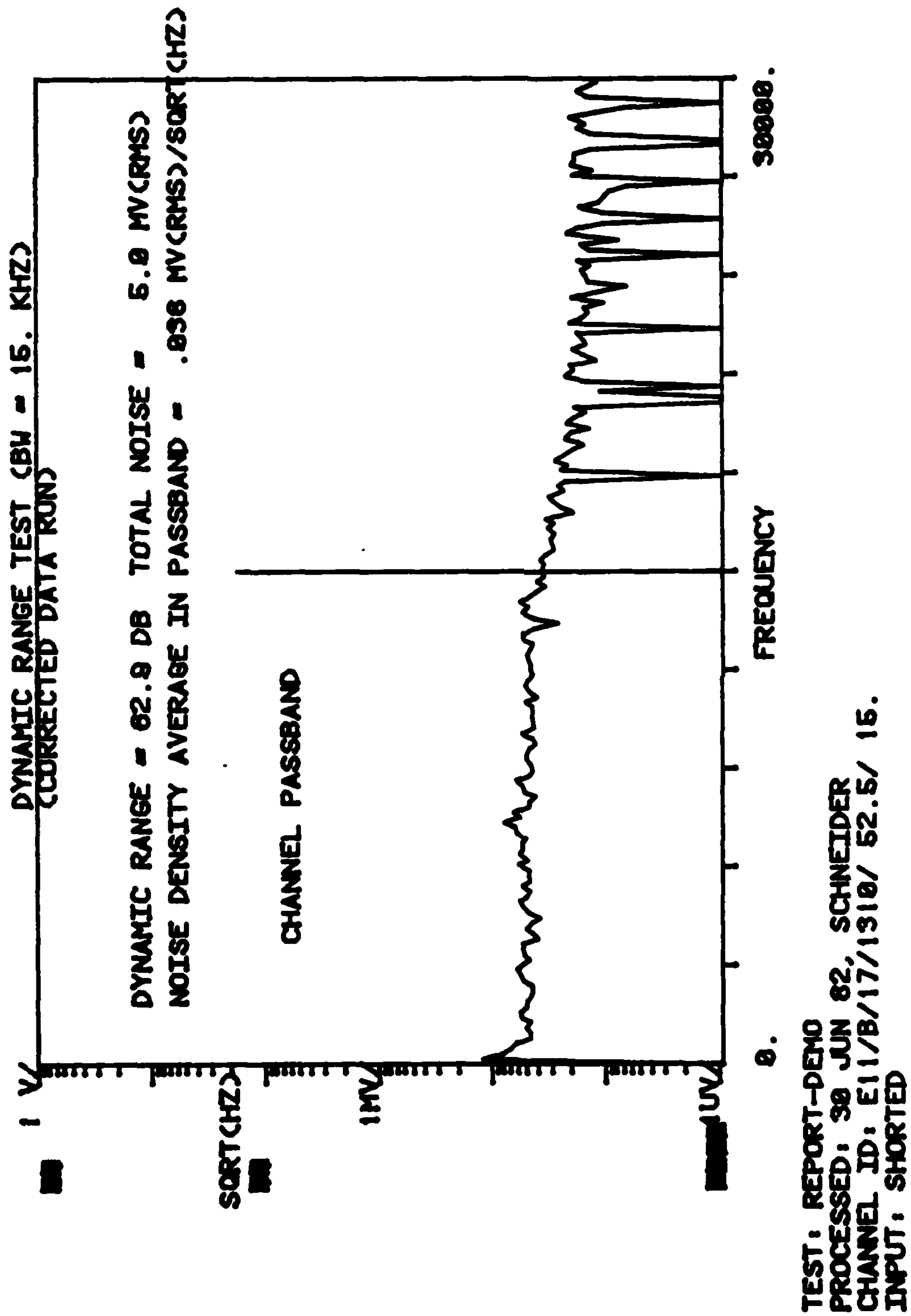


Figure 23. Corrected data noise floor spectrum.

track number or the center frequency in the channel ID, e.g., a center frequency of 384 kHz, although valid for Van E5, will be flagged when it appears among the data from Van E11 which does not have this frequency in its set. An interim set up of the result table provides a separate slot for each possible channel of a van. These slots are ordered by recorder track number and, within it, by VCO center frequencies, both in ascending sequence. The slots (rows in the table) are divided in columns for the entry of the channel ID and the data from the linearity, bandwidth, and dynamic range measurements, in that order. A channel ID is entered for every channel processed and the data are put into the proper column. If the same channel ID comes up again, its data is considered new data and the previously entered data in this slot and column are replaced by the new data considering them a correction of the old ones. A nonprocessed channel leaves an empty row in the designated position. A nonprocessed funtion of an otherwise processed channel is entered with the Zero in the respective column. An extension file, if properly announced as such, is processed in similar manner into the interim result table, losing its extension identity in the process.

Before the individual function file is processed into the interim result table, these raw data can be printed out on request as is, i.e., with all repetitions and in the same nonordered sequence as originally recorded. Tables 3 through 6 show samples of these individual fines for linearity, bandwidth, and dynamic range functions, the last one being an extension file to the dynamic range data.

The interim result table is processed into the final result table by compacting the data. This is done by pushing the channels down, thereby filling the empty slots. The final result table from the individual functions is shown in Table 7. Individual functions can also be presented in final, sorted, and compacted form as shown in Table 8 for the bandwidth data. The corrections that has been made for invalid track numbers and VCO frequencies are recorded back out into the individual data file so that when this file is used again, these numbers will be correct.

TABLE 3. TABLE OUTPUT OF NONLINEARITY DATA

CHECKOUT VAN E5 RECORDER B

CHANNEL ID TK/CFRQ/DEV/BW(KHZ)	LINEARITY NONLIN%	BANDWIDTH BW(KHZ)	BW-ERR%	DYN. RANGE S/N(DB)	MV(RMS)
11/ 48/ 2. / .5	.79				
12/ 48/ 2. / .5	.80				
9/ 48/ 2. / .5	.77				
8/ 48/ 2. / .5	.78				
6/ 48/ 2. / .5	.78				
5/ 48/ 2. / .5	.99				
3/ 48/ 2. / .5	.85				
1/ 48/ 2. / .5	.86				
1/ 320/ 16. / 4.	.39				
2/ 320/ 16. / 4.	.42				
3/ 320/ 16. / 4.	.38				
5/ 320/ 16. / 4.	.41				
7/ 320/ 16. / 4.	.43				
8/ 320/ 16. / 4.	.38				
9/ 320/ 16. / 4.	.46				
11/ 320/ 16. / 4.	.4				
12/ 320/ 16. / 4.	.46				
6/ 320/ 16. / 4.	.45				
1/ 64/ 4. / 1.	.45				
1/ 80/ 4. / 1.	.43				
1/ 128/ 8. / 2.	.54				
1/ 160/ 8. / 2.	.51				
1/ 256/ 16. / 4.	.54				
1/ 384/ 16. / 4.	.54				
1/ 768/ 32. / 8.	.48				
1/ 896/ 32. / 8.	.48				
1/1664/ 64. / 16.	.48				
1/1152/ 64. / 16.	.52				
1/ 512/ 32. / 8.	.50				
11/ 48/ 2. / .5	.50				
5/ 48/ 2. / .5	.53				
3/ 384/ 16. / 4.	.35				
8/ 512/ 32. / 8.	.30				
5/ 192/ 8. / 2.	.31				
6/ 512/ 32. / 16.	.33				
1/ 96/ 4. / 1.	.25				
11/ 160/ 8. / 2.	.49				
12/ 160/ 8. / 2	.61				
7/ 384/ 16. / 4.	1.37				
7/ 384/ 16. / 4.	.76				

TABLE 4. TABLE OUTPUT OF BANDWIDTH DATA

CHECKOUT VAN E5 RECORDER B

CHANNEL ID TK/CFRQ/DEV/BW(KHZ)	LINEARITY NONLIN%	BANDWIDTH BW(KHZ)	BW-ERR%	DYN. RANGE S/N(DB)	MV(RMS)
1/ 48/ 2. / .5		45	-8.8		
3/ 48/ 2. / .5		46	-8.0		
5/ 48/ 2. / .5		45	-8.8		
6/ 48/ 2. / .5		49	-1.6		
8/ 48/ 2. / .5		48	-3.2		
9/ 48/ 2. / .5		54	9.5		
11/ 48/ 2. / .5		49	-.8		
12/ 48/ 2. / .5		49	-.8		
9/ 48/ 2. / .5		51	3.1		
1/ 320/ 16. / 4.		3.55	-11.2		
3/ 320/ 16. / 4.		4.03	.7		
5/ 320/ 16. / 4.		3.96	-.8		
6/ 320/ 16. / 4.		4.03	.7		
7/ 320/ 16. / 4.		3.90	-2.4		
8/ 320/ 16. / 4.		3.84	-4.0		
9/ 320/ 16. / 4.		3.93	-1.6		
11/ 320/ 16. / 4.		3.90	-2.4		
12/ 320/ 16. / 4.		3.80	-4.8		
13/ 320/ 16. / 4.		3.90	-2.4		
1/ 64/ 4. / 1.		.99	-.8		
1/ 80/ 4. / 1.		1.	0.		
1/ 96/ 4. / 1.		1.	0.		
1/ 128/ 8. / 2.		1.88	-5.6		
1/ 160/ 8. / 2.		1.90	-4.8		
1/ 256/ 16. / 4.		4.09	2.3		
1/ 384/ 16. / 4.		4.09	2.3		
1/ 512/ 32. / 8.		8.	0.		
1/ 640/ 32. / 8.		8.06	.7		
1/ 768/ 32. / 8.		7.74	-3.2		
1/ 896/ 32. / 8.		7.80	-2.4		
1/1152/ 64. / 16.		15.59	-2.5		
1/1664/ 64. / 16.		15.59	-2.5		
3/ 384/ 16. / 4.		4.28	7.1		
7/ 384/ 16. / 4.		4.19	4.7		
8/ 512/ 32. / 8.		7.93	-.8		
5/ 192/ 8. / 2.		2.04	2.3		
6/ 512/ 32. / 16.		15.43	-3.5		
11/ 160/ 8. / 2.		2.08	3.9		
12/ 160/ 8. / 2.		2.09	4.7		

TABLE 5. TABLE OUTPUT OF DYNAMIC RANGE DATA

CHECKOUT VAN E5 RECORDER B

CHANNEL ID TK/CFRQ/DEV/BW(KHZ)	LINEARITY NONLIN%	BANDWIDTH BW(KHZ)	BW-ERR%	DYN. RANGE S/N(DB)	MV(RMS)
1/ 48/ 2. / .5				57.6	9.2
3/ 48/ 2. / .5				57.4	9.5
5/ 48/ 2. / .5				57.2	9.6
6/ 48/ 2. / .5				57.8	9.0
8/ 48/ 2. / .5				57.6	9.2
9/ 48/ 2. / .5				57.7	9.1
11/ 48/ 2. / .5				57.4	9.4
12/ 48/ 2. / .5				57.7	9.1
1/ 320/ 16. / 4.				49.3	24.1
3/ 320/ 16. / 4.				48.8	25.5
5/ 320/ 16. / 4.				48.6	26.2
6/ 320/ 16. / 4.				37.4	95.0
7/ 320/ 16. / 4.				49.3	24.1
8/ 320/ 16. / 4.				49.3	24.1
9/ 320/ 16. / 4.				48.3	27.1
11/ 320/ 16. / 4.				48.9	25.2
12/ 320/ 16. / 4.				49.1	24.5
13/ 320/ 16. / 4.				49.1	24.5
6/ 320/ 16. / 4.				48.6	26.0
1/ 64/ 4 / 1.				54.7	12.8
1/ 80/ 4. / 1.				54.5	13.2
1/ 96/ 4. / 1.				55.1	12.3
1/ 128/ 8. / 2.				51.4	18.8
1/ 160/ 8. / 2.				51.5	18.8
1/ 256/ 16. / 4.				48.9	25.2
1/ 384/ 16. / 4.				49.0	25.0
1/ 512/ 32. / 8.				49.3	24.0
1/ 640/ 32. / 8.				45.7	36.6
1/ 768/ 32. / 8.				45.6	36.7
1/ 896/ 32. / 8.				45.5	37.2
1/1152/ 64. / 16.				45.3	38.3
1/1664/ 64. / 16.				43.8	45.5
2/ 320/ 16. / 4.				49.4	23.8
3/ 384/ 16. / 4.				48.9	25.1
7/ 384/ 16. / 4.				48.6	26.2
5/ 192/ 8. / 2.				50.8	20.2
11/ 160/ 8. / 2.				51.0	19.8
12/ 160/ 8. / 2.				51.7	18.3
6/ 512/ 32. / 16.				42.6	52.2

TABLE 6. TABLE OUTPUT OF A DYNAMIC RANGE DATA EXTENSION FILE

CHECKOUT VAN E5 RECORDER Y

CHANNEL ID	LINEARITY	BANDWIDTH		DYN. RANGE	
TK/CFRQ/DEV/BW(KHZ)	NONLIN%	BW(KHZ)	BW-ERR%	S/N(DB)	MV(RMS)
8/1152/ 64. / 32.				63.7	4.5
9/1152/ 64. / 32.				64.0	4.4
8/1152/ 64. / 32.				41.4	59.6
9/1152/ 64. / 32.				41.2	61.1
14/ 256/ 16. / 4.				48.7	25.7

TABLE 7. RESULT TABLE OUTPUT FOR ALL FUNCTIONS

CHECKOUT VAN E5 RECORDER B

CHANNEL ID TK/CFRQ/DEV/BW(KHZ)	LINEARITY NONLIN%	BANDWIDTH BW(KHZ)	BW-ERR%	DYN. RANGE S/N(DB)	MV(RMS)
1/ 48/ 2. / .5	.86	.45	-8.8	57.6	9.2
1/ 64/ 4. / 1.	.45	99	-.8	54.7	12.8
1/ 80/ 4. / 1.	.43	1.	0.	54.5	13.2
1/ 96/ 4. / 1.	.25	1.	0.	55.1	12.3
1/ 128/ 8. / 2.	.54	1.88	-5.6	51.4	18.8
1/ 160/ 8. / 2.	.51	1.90	-4.8	51.5	18.8
1/ 256/ 16. / 4.	.54	4.09	2.3	48.9	25.2
1/ 320/ 16. / 4.	.39	3.55	-11.2	49.3	24.1
1/ 384/ 16. / 4.	.54	4.09	2.3	49.0	25.0
1/ 512/ 32. / 8.	.50	8.	0.	49.3	24.0
1/ 640/ 32. / 8.	0.	8.06	.7	45.7	36.6
1/ 768/ 32. / 8.	.48	7.74	-3.2	45.6	36.7
1/ 896/ 32. / 8.	.48	7.80	-2.4	45.5	37.2
1/1152/ 64. / 16.	.52	15.59	-2.5	45.3	38.3
1/1664/ 64. / 16.	.48	15.59	-2.5	43.8	45.5
2/ 320/ 16. / 4.	.42	0.	0.	49.4	23.8
3/ 48/ 2. / .5	.85	.46	-8.0	57.4	9.5
3/ 320/ 16. / 4.	.38	4.03	.7	48.8	25.5
3/ 384/ 16. / 4.	.35	4.28	7.1	48.9	25.1
5/ 48/ 2. / .5	.53	.45	-8.8	57.2	9.6
5/ 192/ 8. / 2.	.31	2.04	2.3	50.8	20.2
5/ 320/ 16. / 4.	.41	3.96	-.8	48.6	26.2
6/ 48/ 2. / .5	.78	.49	-1.6	57.8	9.0
6/ 320/ 16. / 4.	.45	4.03	.7	48.6	26.0
6/ 512/ 32. / 16.	.33	15.43	-3.5	42.6	52.2
7/ 320/ 16. / 4.	.43	3.90	-2.4	49.3	24.1
7/ 384/ 16. / 4.	.76	4.19	4.7	48.6	26.2
8/ 48/ 2. / .5	.78	.48	-3.2	57.6	9.2
8/ 320/ 16. / 4.	.38	3.84	-4.0	49.3	24.1
8/ 512/ 32. / 8.	.30	7.93	-.8	0.	0.
8/1152/ 64. / 32.	0.	0.	0.	41.4	59.6
9/ 48/ 2. / .5	.77	.51	3.1	57.7	9.1
9/ 320/ 16. / 4.	.46	3.93	-1.6	48.3	27.1
9/1152/ 64. / 32.	0.	0.	0.	41.2	61.1
11/ 48/ 2. / .5	.50	.49	-.8	57.4	9.4
11/ 160/ 8. / 2.	.49	2.08	3.9	51.0	19.8
11/ 320/ 16. / 4.	.4	3.90	-2.4	48.9	25.2
12/ 48/ 2. / .5	.80	.49	-.8	57.7	9.1
12/ 160/ 8. / 2.	.61	2.09	4.7	51.7	18.3
12/ 320/ 16. / 4.	.46	3.80	-4.8	49.1	24.5
13/ 320/ 16. / 4.	0.	3.90	-2.4	49.1	24.5
14/ 256/ 16. / 4.	0.	0.	0.	48.7	25.7

TABLE 8. RESULT TABLE OUTPUT FOR A SINGLE FUNCTION (BANDWIDTH DATA)

CHECKOUT VAN E5 RECORDER B

CHANNEL ID	LINEARITY	BANDWIDTH		DYN. RANGE	
TK/CFRQ/DEV/BW(KHZ)	NONLIN%	BW(KHZ)	BW-ERR%	S/N(DB)	MV(RMS)
1/ 48/ 2. / .5		.45	-8.8		
1/ 64/ 4. / 1.		99	-.8		
1/ 80/ 4. / 1.		1.	0.		
1/ 96/ 4. / 1.		1.	0.		
1/ 128/ 8. / 2.		1.88	-5.6		
1/ 160/ 8. / 2.		1.90	-4.8		
1/ 256/ 16. / 4.		4.09	2.3		
1/ 320/ 16. / 4.		3.55	-11.2		
1/ 384/ 16. / 4.		4.09	2.3		
1/ 512/ 32. / 8.		8.	0.		
1/ 640/ 32. / 8.		8.06	.7		
1/ 768/ 32. / 8.		7.74	-3.2		
1/ 896/ 32. / 8.		7.80	-2.4		
1/1152/ 64. / 16.		15.59	-2.5		
1/1664/ 64. / 16.		15.59	-2.5		
3/ 48/ 2. / .5		.46	-8.0		
3/ 320/ 16. / 4.		4.03	.7		
3/ 384/ 16. / 4.		4.28	7.1		
5/ 48/ 2. / .5		.45	-8.8		
5/ 192/ 8. / 2.		2.04	2.3		
5/ 320/ 16. / 4.		3.96	-.8		
6/ 48/ 2. / .5		.49	-1.6		
6/ 320/ 16. / 4.		4.03	.7		
6/ 512/ 32. / 16.		15.43	-3.5		
7/ 320/ 16. / 4.		3.90	-2.4		
7/ 384/ 16. / 4.		4.19	4.7		
8/ 48/ 2. / .5		.48	-3.2		
8/ 320/ 16. / 4.		3.84	-4.0		
8/ 512/ 32. / 8.		7.93	-.8		
9/ 48/ 2. / .5		.51	3.1		
9/ 320/ 16. / 4.		3.93	-1.6		
11/ 48/ 2. / .5		.49	-.8		
11/ 160/ 8. / 2.		2.08	3.9		
11/ 320/ 16. / 4.		3.90	-2.4		
12/ 48/ 2. / .5		.49	-.8		
12/ 160/ 8. / 2.		2.09	4.7		
12/ 320/ 16. / 4.		3.80	-4.8		
13/ 320/ 16. / 4.		3.90	-2.4		

VII. PROGRAM DESCRIPTION

7.1 GENERAL

Flow diagram (1) (Fig. 24) is common for all three individual function programs with exceptions noted on the diagram and in the following text. Flow diagram (2) (Figs. 25 through 27) consists of three different versions, one each for each function program. The differences are in the different data processing requirements. Flow diagram (3) (Fig. 28) is again common for all function programs with exceptions noted. The resulting table flow diagrams (4) through (6) (Figs. 29 through 31) are all different.

7.2 FLOW DIAGRAM (1)

Flow diagram (1) (Fig. 24) is common for all three function programs: Linearity (LIT), Bandwidth (BWT), and Dynamic Range (DRT) with one exception, the entering of the desired triangular wave input frequency which belongs to LIT only.

After starting, the program announces itself and does some initiations. The operator is asked to state which disk (hard or floppy) he wants to record the data on. The next question is whether the floppy disk driver (if used) and the printer driver had been loaded prior to starting the program (a requirement of the operating system). If this should not be the case, the program must be exited and the respective driver loaded in the operating system. Then the function program must be loaded again and started. If this question is not asked in the beginning, a fatal monitor error and computer halt will occur at the first reference to a peripheral whose driver is not available, only after valuable time had been spent in entering and acquiring data parameters. The procedure to follow in order to recover from the omission is printed on the screen in detail.

The event (test designation) is entered then with a maximum of 30 characters, as is the date and the operator (15 characters each). If the maximum length of the string is exceeded, an error message suggests to do the entry over again. After entering the van symbol and the recorder letter, the file name is complete and printed on the screen for a check. If wrong, the entries can be repeated. All entries are prompted in plain English.

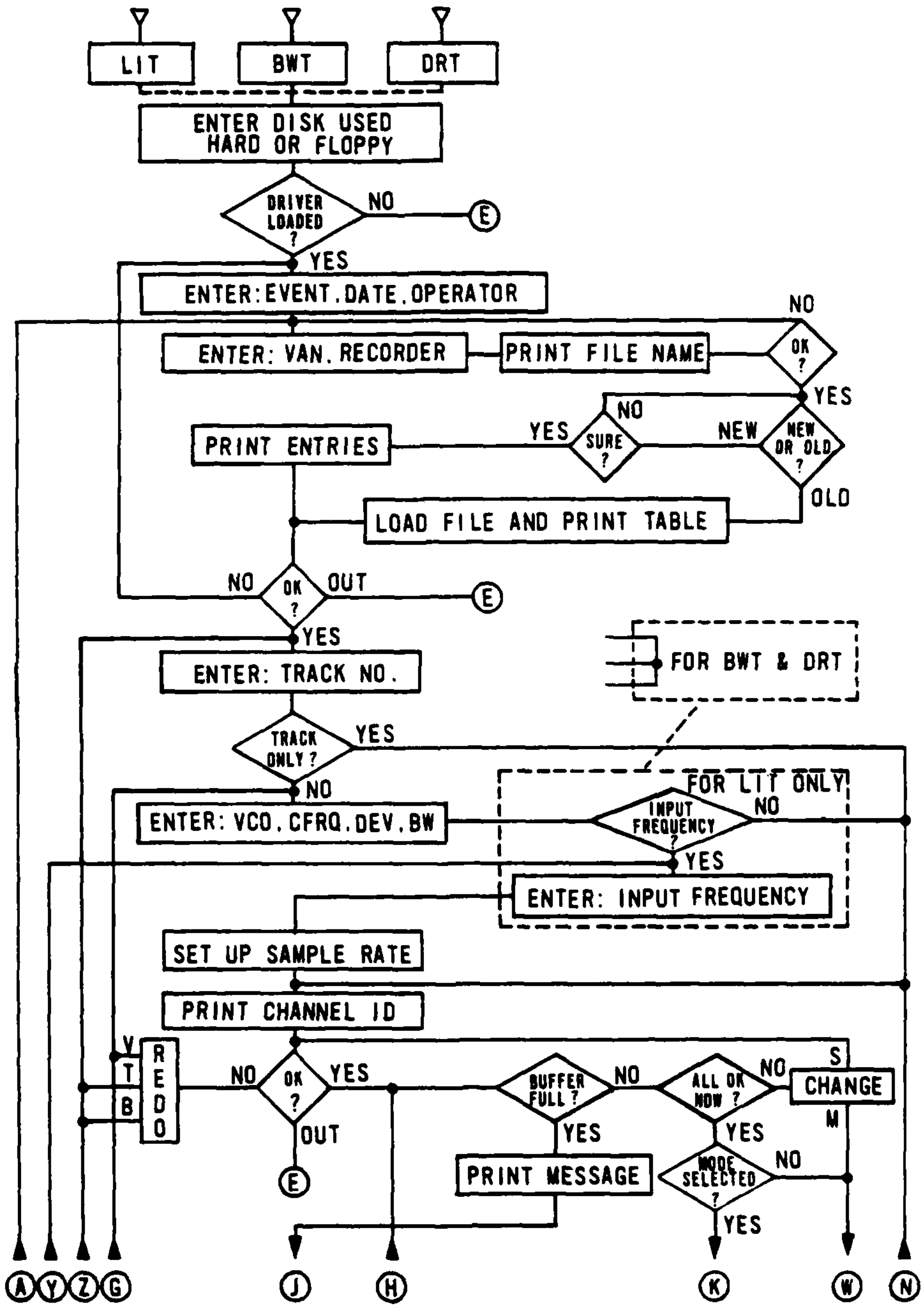


Figure 24. Flow diagram (1): LIT, BWT, DRT.

The next question asks whether the intended operation is a new one on this particular van and recorder or a continuation of a previous operation on them. If it is a new one, the operator is asked whether he is sure of it, because if he selects a new operation, any old file from a previous operation on the selected van and recorder will be overwritten and therefore lost. All entries are now printed on the screen for checking. If a continued operation was selected, the file from the previous operation is read from disk and the data table is printed on the screen. The test entries are then printed below the table.

Again, the operator is asked whether everything is OK so far; if not, all entries must be repeated. He can also exit the program here. If OK, the next entry is the recorder track number (TK) on which the data is located. If, in a repeat operation, only the track number was to be changed, the program skips over the remaining entry requirements. If not, the next entries are for the VCO center frequency (CFRQ), the ± deviation (DEV), and the channel bandwidth (BW), all in kHz. The LIT program requires one more, the desired triangular wave input frequency (in Hz). The latter will be skipped in a repeat operation unless specifically requested to be changed.

After all these parameters have been entered, the sample rate can be selected. It is determined by the input frequency in LIT, but by the bandwidth in BWT and DRT. Then the full channel ID is printed in the format TK/CFRQ/DEV/BW(KHZ), on the screen. Again, the OK question is asked. If not OK, the track number or the VCO entries or both can be redone, or a program can be exited. If OK, the file (buffer) is checked whether it is already full in which case a respective message is printed and, through line (J), the table from this file is printed on the screen or on the printer, if so desired. The following operation is either to enter an extension symbol for the recorder and start a new operation, or to take one of the options (for which a menu is printed on the screen) that are available after a full buffer, or, to exit the program. These options can be found in flow diagram (3), (Fig. 28).

If the buffer is not full, the final all OK now question is asked. If answered with NO, the selection of TK, VCO, or both can be changed (T,V,B in the diagram), or the display mode can be changed if it had been selected before (on a first run through, it is selected in the next step). If all is OK, the display mode selection is checked whether a mode has been chosen already. The result of this check can be found via lines (K) and (W) in the description for the respective function of flow diagram (2) (Figs. 25 through 27). Lines (A), (Y), (Z), (G), (H), and (N) (Figs. 25 through 27 bring actions back from following diagrams. Their meaning will be described there.

7.3 FLOW DIAGRAM (2)

7.3.1 Program LIT. If no display mode has been selected (line (W)) when this point in the program is reached, the operator is directed to select one (Fig. 25). Four modes can be chosen between displaying or not displaying input data and/or output function. With this selection entered or if a mode had been selected before (line (K)) a check is made to determine whether or not an input sample is to be displayed. If yes, a sample (only one, no averaging) is acquired and displayed. Before further action can be taken after an input display, a check is made to see whether or not option I (flow diagram (3), Fig. 28) is in force. If yes, the program branches directly back to the option selection through line (X) and prints an abbreviated form of the option menu on the bottom of the screen. If not, a smaller option selection is chosen that allows the program (1) to repeat the input (R), (2) to change the display mode for further processing (M), (3) to change the track number and VCO center frequency entries (S) (which is looped back to the respective entry points through line (N)), (4) to exit from the program (E) through line (U), or (5) to continue with the present setup (C). The program skips to this point directly when the input display selection is not made.

The number of inputs specified in the program is then acquired. They are accumulated and averaged in the time domain. The least squares fit calculations are performed, next the actual data are subtracted from the fitted straight line to obtain the percent nonlinearity curve, which is then smoothed for display, and the maximum nonlinearity figure is calculated. From here flow diagram (3) takes over through line (O). Line (Q) brings back from flow diagram (3) the request to redisplay the last input acquired.

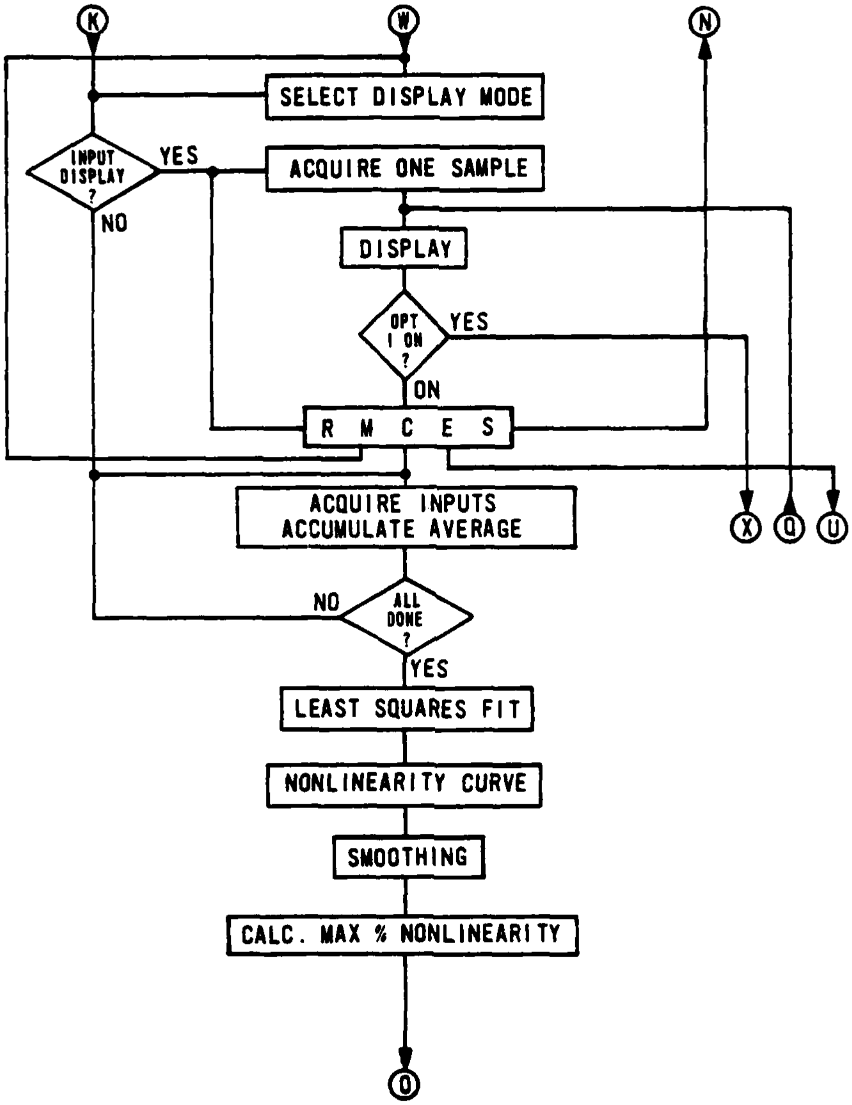


Figure 25. Flow diagram (2): LIT.

7.3.2 Program BWT. The beginning of flow diagram (2) (Fig. 26) down to the point of acquiring input is the same as for program LIT.

The inputs acquired for averaging are first transformed into the frequency domain by the FFT and then their autospectra are accumulated and averaged. Smoothing the resulting frequency response curve follows. Finally, the measured bandwidth and its percent deviation are calculated. The remaining part of the program is described in flow diagram (3).

7.3.3 Program DT. The option of subtracting the data reduction system noise floor from the measurement necessitates additional operator selections of particular runs, as is seen in Figure 27. Before a display mode can be selected, a check is made on the run status if the system is in the correction definition run (C). If yes, no change in display mode can be allowed because the subsequent corrected data run has to have the same number of data points as the correction definition run to make the subtraction work. Also, if initially a corrected data run (CD) should be requested, the operator is reminded that a C run has to be done first.

The actions around the input display are the same as in the other two diagrams (Figs. 25 and 26), but whereas in these, the program branches right into the input display after selection of a display mode, in DRT the further selection of a run has to be made. The program loops back through line (H) to the all OK question after run selection to allow the operator to correct one of the selections (display or run) if he hastely had made a wrong one. If a wrong run selection was made without recourse to correction at this point, the whole program would have to be continued down to the option selection before he can change the mode. The inputs are transformed into the frequency domain for processing where their autospectra are accumulated and averaged. In a C run, this average is saved so it can be subtracted later in any subsequent CD run. Ray data run (RD) requests are handled straight through. Finally, the RMS noise figure is calculated and the dynamic range (in dB) is produced, and the plot is calibrated in noise density (mV/√Hz).

7.4 FLOW DIAGRAM (3)

Figure 28 deicts the last part of these function programs which is common again to all three except where noted. After the processing steps, the

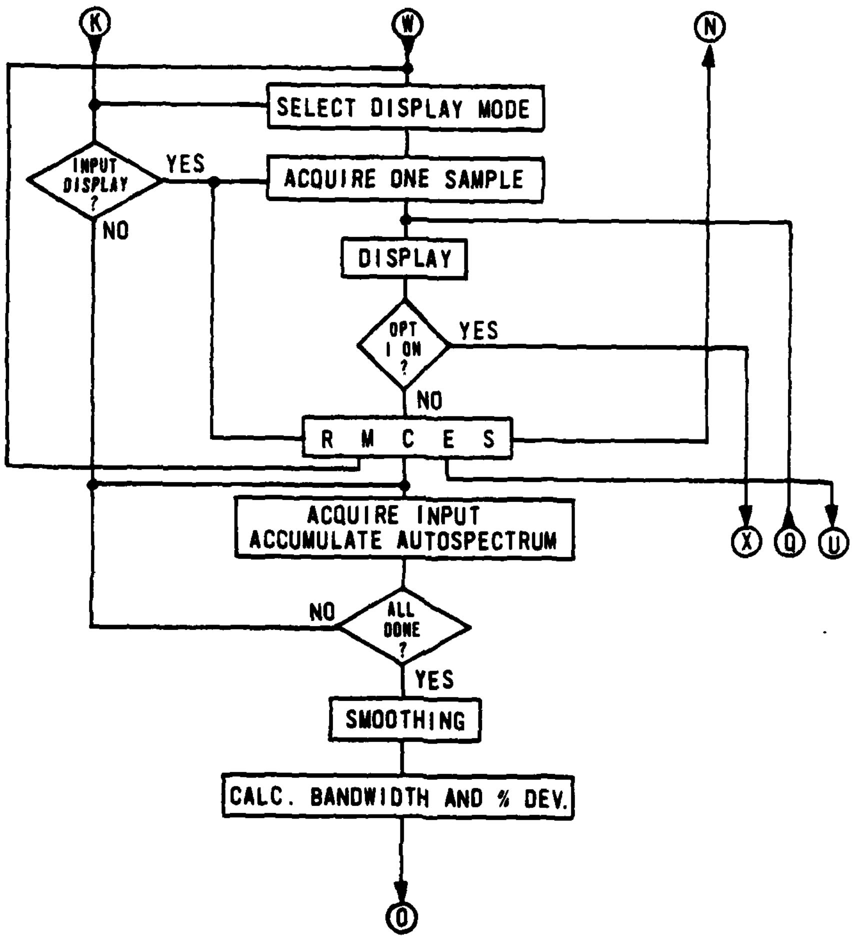


Figure 26. Flow diagram (3): BWT.

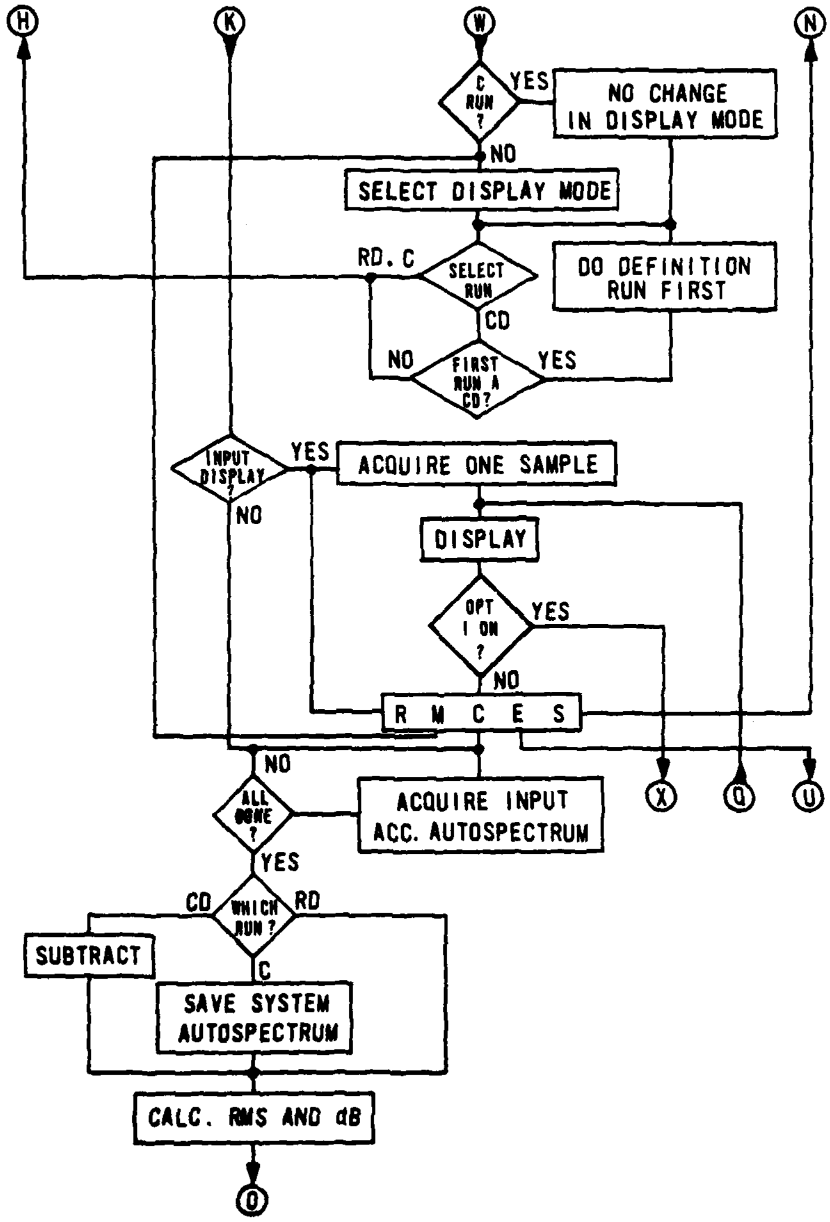


Figure 27. Flow diagram (4): DRT.

data enter through line (O) into this diagram. The channel ID and the calculated data values are entered in the table buffer which later is recorded as a file on disk. The resulting function is plotted now if output dislay mode was selected but the data with identifying information is printed on the screen whether display was selected or not. The table pointer reset flag is now cleared and an abbreviated menu of options for further operation is printed on the screen. In case one does not remember the menu items, typing S brings the full menu on the screen in long hand.

Option R (Repeat Input) goes back, through line (H) to flow diagram (1) (Fig. 24) and the all OK question. If the answer is to the all OK question yes, a new set of inputs is taken. The results of the previous operation are deleted by backspacing (resetting) the table pointer, unless it had been done before in which case the table pointer reset flag would be in the set position.

Option I (Display Last Input) returns, through line (Q), to the respective flow diagram (2) (Figs. 25 through 27) and display the last input sample of the set that was taken for averaging. After this display, the program returns, through line (X) to the options which are shown below the display on the botton of the screen.

All of the other items check first to determine whether or not the table printer reset flag is on. If not, the data are or are not recorded as requested on a disk file. If no recording is to be made, the table pointer is backspaced so that the next upcoming results write over the unwanted results from the previous option. In DRT it is necessary to know which type of run was made because the results from a C run do not go in the table, they are only used for correcting the test data. If the table pointer reset flag was set from a previous operation that proceeded through to the bottom of the diagram all the above is skipped. Before any detailed branching is done in Figure 24 in connection with options selected in Figure 28 the previous channel ID is printed on the screen. Option F is transmitted on line (Y), options T and B on line (Z), and option V on line (G).

Option F (Change Input Frequency) is used ony in program LIT and allows the operator to change the sample rate set up for a different triangular wave frequency.

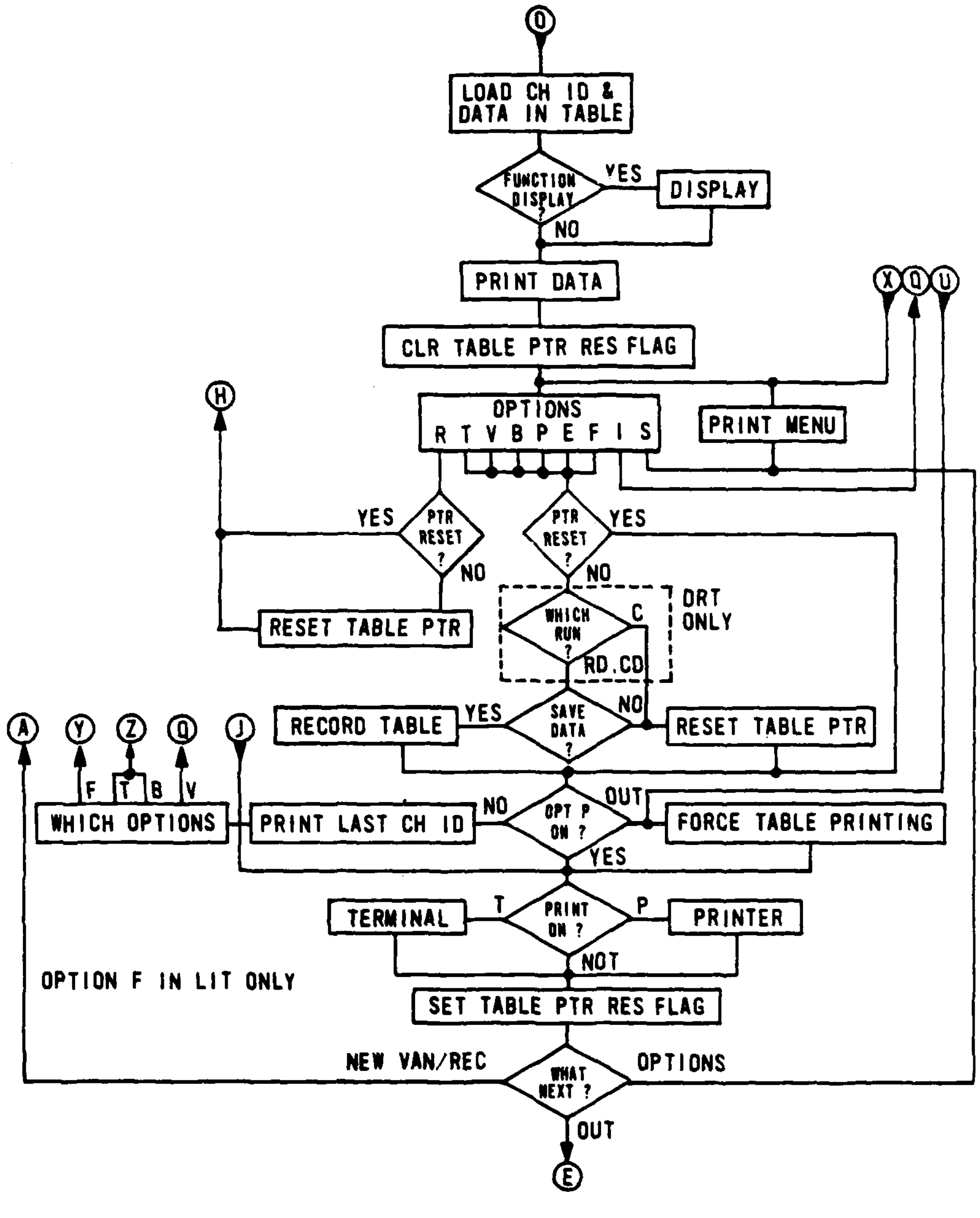


Figure 28. Flow diagram (5): LIT, BWT, DRT.

Option T (Change Track Number) and Option V (change VCO setup) allow to selectably change these, while option B (change both) loops back to the same place as option T and allows to change both, Track and VCO.

Option E is the exit from the program. Before he can exit, however, the operator is reminded that he better have the result table printed because he cannot do so any more after he has left the program.

Option P is the printing option. Both options P and E wind up at the question of where the table is to be printed, on the terminal (T), or on the printer (P). A no-print answer is also available. Then the table pointer reset flag is set and (1) another option can be selected or (2) a new van or recorder can be entered through line (A), or (3) the final exit can be made.

7.5 FLOW DIAGRAM FOR PRALL

PRALL is the program that sorts, merges, and compacts the data from the individual function files. Its flow diagram is in three parts, Figures 29 through 31. In flow diagram (4) (Fig. 29) the program starts by asking the operator to enter the type of disk (hard or floppy) from which the files have to be loaded. The next question is whether the printer driver or the floppy disk driver had been loaded. Then the desired van number is entered and a check is made on the legality of the entry. The recorder symbol is entered next whereupon the total number of tracks on the recorders in this van and all VCO center frequencies used on a track are set up for the later checking of illegal entries in the individual function tables. Table 9 lists all vans with the number of recorders, the number of tracks each, and the VCO center frequencies to be used. The program can print; in sorted, compact format; either each individual function table or the combined table. This selection has now to be made. If the combined table is selected (ALL), the individual function tables are processed in the sequence Linearity (LI), Bandwidth (BW), and Dynamic Range (DR), i.e., the linear table is processed first and then the program returns through line (G) with an automatic function change to BW and again to DR.

First, the filename for the selected function, as it is assembled from the entries, is printed for confirmation. The operator does not have to deal with the filename itself because it is derived from the type of the disk

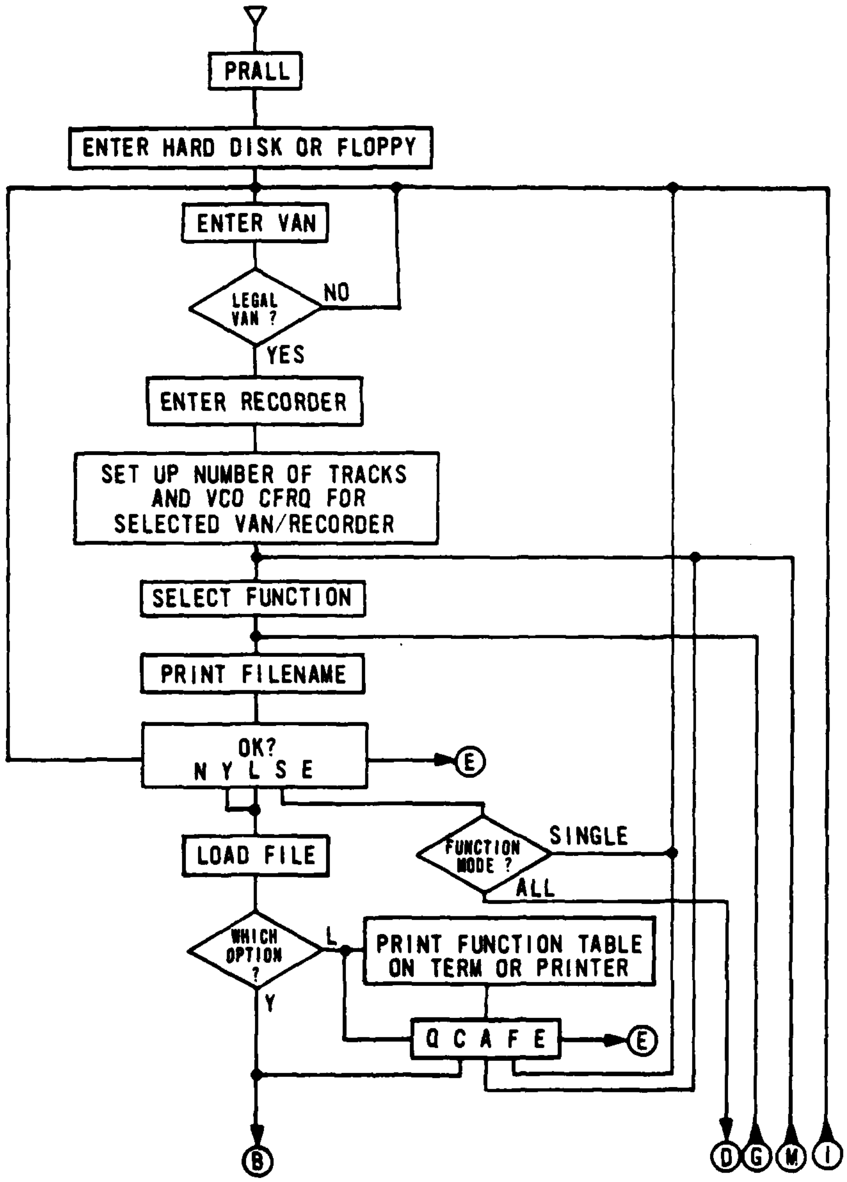


Figure 29. Flow diagram (6): PRALL.

TABLE 9. VAN CAPABILITY

Van	E1	E2	E5	E9	E11	E12
Recorders	2	2	2	4	2	8
Tracks/Recorder	28	28	14	28	14	32
VCOs/Track	8	5	17	1	11	1
Cen. Freq. (kHz)	76	200	48	54**	90	54**
	188	320	64	108**	160	108**
	300	440	80	216**	230	216**
	412	560	96	432**	300	432**
	524	680	128		370	
	636	1510*	160		500	
	748		192		640	
	860		256		780	
	1510*		320		920	
			384		1100	
			512		1310	
			640		1510*	
			768			
			896			
			1152			
			1408			
			1664			
			1975*			
Total Channels	448	280	476	112	308	256

*These are the tape speed compensation channels

**Center Frequencies availability depends on FM recorder system and on tape speed

Note: Regular tape speed is 120 ips, could be lower for E9 & E12 used, from the van and recorder tested, and from the function selected, but he can use this information to check the name against the disk file directory if he should run into trouble. To head off trouble, the operator can either confirm the filename (Y), redo it (N), or list it (L) on the terminal or the printer. Maybe he wants to skip (S) this file if e.g., ALL had been selected through line (D) but the BW file is not available, or he may exit (E) the program. If he skips when a single function was selected, the program assumes that he wants to enter a new filename and returns to the van entry.

With both Y and L selected, the file is loaded from disk into the input table. With L requested, the input function table is displayed on the terminal screen or printed by the printer. More decisions have to be made after this step. Q repeats the printing, e.g., if the table is displayed on the screen first, and if it is then decided that a hard copy is needed after all, the table can be printed by the printer. Option A requests a new function, Option F requests a new file name to be entered, E exits the program, and C continues it, meeting with the branch Y of precious decision.

Flow diagram (5) (Fig. 30) is the continuation of the program through line (B) where the sorting of the data from the input function table into the interim result table is begun. Before a line of data is sorted into the proper location, the track number is checked for legality. If it is illegal, the number is printed on the screen together with the VCO center frequency of this particular channel ID. For reference, the set of legal track numbers for this van and recorder is printed, whereupon the operator has the choice to skip this line of data or to change the illegal track number to a correct one. He can also exit here. After the track number is changed in the input table, a flag is set which is later used to record the change or changes in the input file. The program returns to the legality question which can now be answered with yes, unless another illegal number was entered making the change. The same procedure is used for the validity of the VCO center frequency. The reference set of legal frequencies for the entered van and recorder is printed for the operator so he can make the proper choice for a correction.

The program continues into flow diagram (6) (Fig. 31) through line (K). At this point, the channel ID should be legal and the channel data is entered

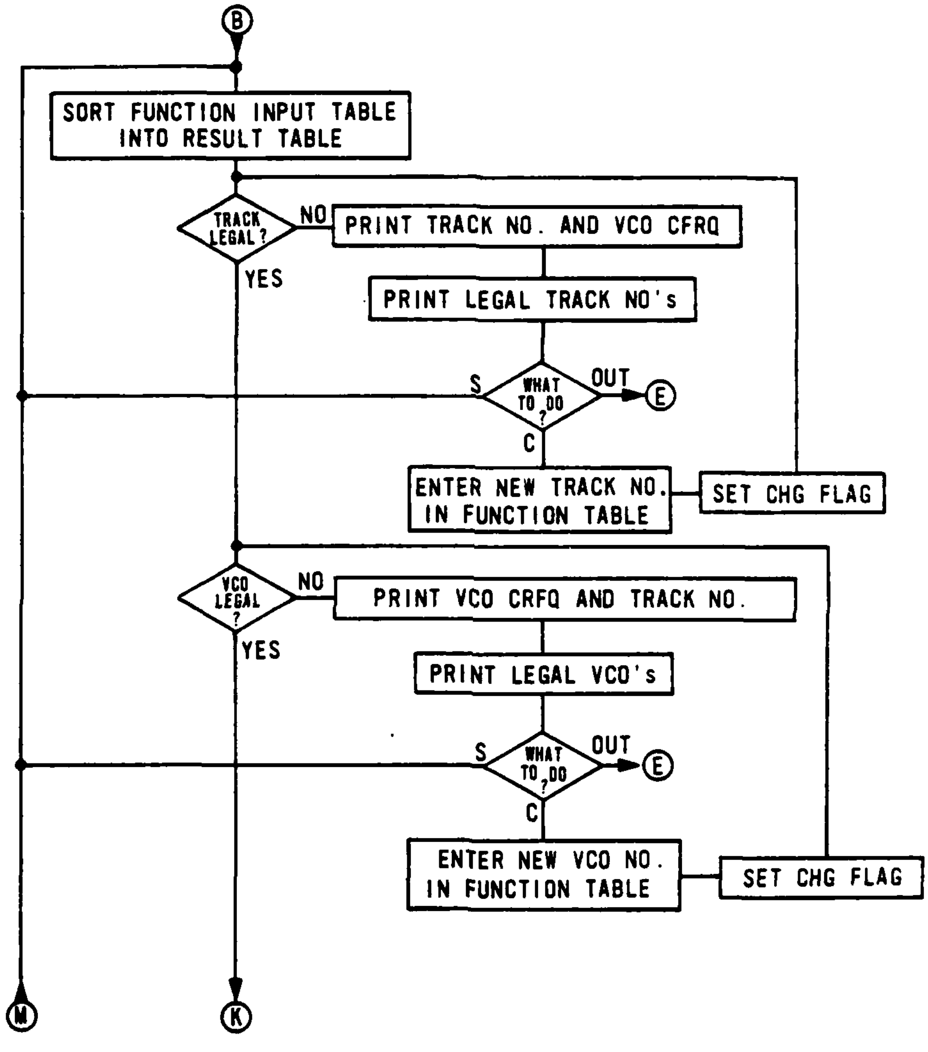


Figure 30. Flow diagram (7): PRALL.

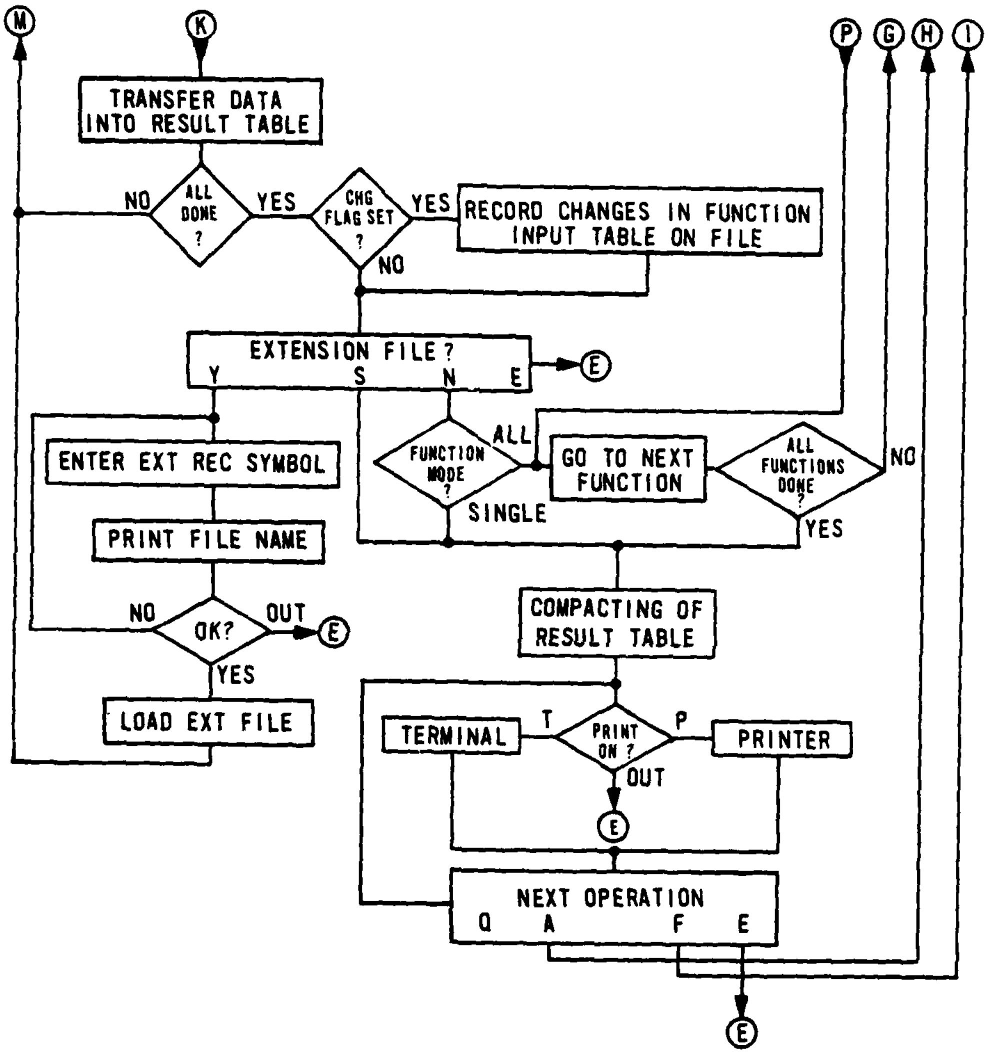


Figure 31. Flow diagram (8): PRALL.

in the interim result table in its proper slot. When the input table is exhausted, the change flag is checked. If there had been changes, they are now recorded automatically in the input file so that when this input file is used again, it will not be necesary to repeat the same corrections.

At this point, the question is asked whether there exists an extension file to the just processed input file. If there is (Y), the extension file recorder symbol is entered and the extension file name is printed and checked for correctness. If correct, the extension file is loaded and the sorting continues. The operator can also skip (S) any further sorting of remaining functions or he can exit (E). If there is no extension file (N), the program checks whether a single function or all functions were selected. In the single case, no further sorting is done, and in the all functions case the next function in line is selected. Before its input file can be loaded, a check is made whether the just processed function was the last one to be done, If it was, the compacting of the result table begins. When finished the table is printed out on either the terminal screen or the printer. The final choices for the operation of the program are to reprint (Q) the result table, to select another function input (A), to go to a different van and/or recorder (F), or to exit (E).

VIII. EQUIPMENT REQUIREMENT

8.1 INPUT SIGNAL

A good function generator with a triangular wave output should have less than 0.1 percent nonlinearity and a 10^{-5} or better short term (1 min) frequency stability. Sixty-Hz components should be down by 60 dB.

A noise generator should be able to set a bandwidth of at least twice, but not much more than four times, the channel bandwidth and a flat frequency spectrum (± 1 dB). It should have a RMS meter for measuring the voltage at the output of an attenuator and a 50 Ω output impedance.

8.2 DATA REDUCTION

Because data reduction is to be included in the measurement of a channel, a setup should be chosen that corresponds with the regular data reduction equipment if a separate system should be used for the checkout measurements. The tape recorder for playback should preferably be of the same manufacturer and model as the recorder for acquisition of the data in the van. Tunable discriminators should be used for the demodulation of FM multiplex signals. If the tests are played back through tape FM, amplifiers are needed to bring the signals up to the required levels. These amplifiers should have a 100 kHz bandwidth with linearity and stability requirements as were given for the function generator. An oscilloscope is useful for monitoring the signals before they enter the computer.

The computer should be fast minicomputer (to provide reasonable processing times), with an analog to digital converter front end. It should be able to run the TSL* software (Ref. 18) if the AFWL program package is to be used, should have 32 K memory space, two each hard and/or floppy disks, a line printer, and a cathode ray tube (CRT) terminal. A typical system is shown in Figure 32. At the left are the tape recorders followed by PCM and FM demoulation equipment, test equipment, amplifiers, and filters. In the corner is the monitor scope. The computer consists of the analog front end

*Registered Trademark of GenRad, Time/Data Division

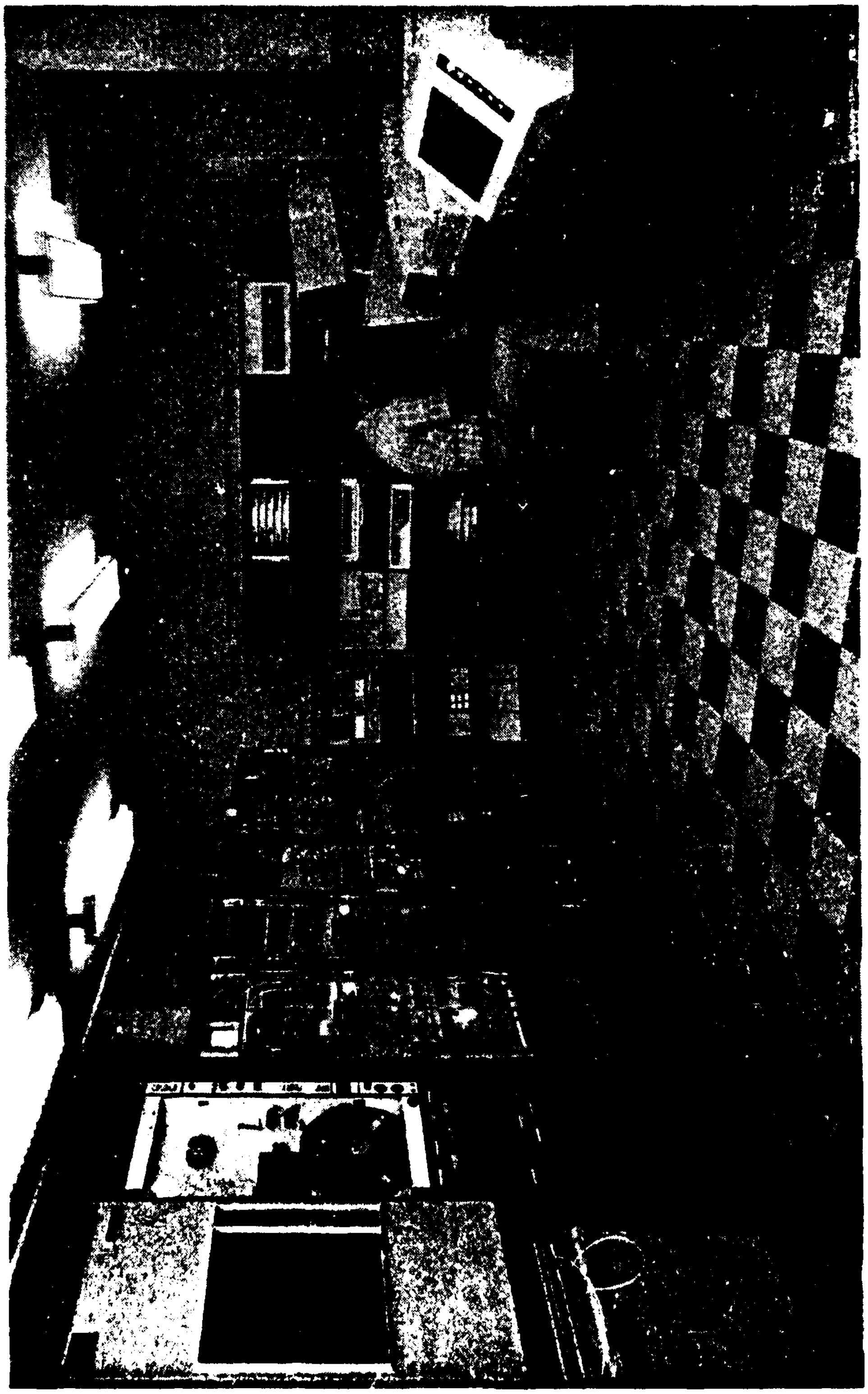


Figure 32. Typical data reduction equipment installation.

(with antialiasing filters), the central processing unit (CPU) and memory, two hard disks, and two floppy disks. Continuing on the right are the CRT terminal, a hard copier, a digital plotter, and a line printer.

IX. RESULTS AND CONCLUSIONS

9.1 RESULTS

The development version of this test package has been successfully used to check out four heavily modified vans with a total of almost 1200 channels. The channels that needed further attention were immediately spotted. The whole system can be run by trained field technicians. Reruns of particular tests on particular channels can always be made and the data added to the function file of the respective van and recorder. The package has also successfully been used to check out separate components (e.g., a VCO or an amplifier) in the laboratory, with the system in Figure 32.

The savings from using the verification system need special consideration. One cannot just compare the respective time of operation, although that is impressive enough, one also has to take into account the additional information and increased resolution that is provided by looking at 256 sample points for each measurement, or by producing the spectrum of the noise floor. Equally important is the additional coverage of all channel components by including in the measurement the tape recording and data reduction equipment.

In manual operation five points are normally taken for linearity and bandwidth measurements while one point is sufficient for a noise floor reading. Coverage extends from the van input to a frequency measurement at the input to but excluding the tape recorders. Even under these circumstances, the automated operation is in the average about 15 times faster than the manual operation, and the human factor is largely eliminated.

The development cost of the automated operation is personnel cost only. No extra equipment is needed that an organization with a requirement for automatic van checkout would not already have on the shelf. The engineering design and the development of the three function program package with the table printer program, and the report writing have consumed 450 engineering manhours.

The operational savings are based on the following: In manual operation two people spend about 10 to 15 min for one measurement, using about 5 points. The automatic operation estimate is based on a 300 channel van. It takes about 20 min to make the input connections with two people and another 10 min to record a full 10 1/2 in reel, this is a total of 30 min for 300 channels or 6 s per channel. Data reduction time is 35 to 45 s per channel including set up overhead. Again, two people are involved. That amounts to a total operating time of about 45 s per channel. Taking the short estimate of the manual operation (10 min per channel per function) and an average of 40 s per channel per function for the automatic operation a time improvement factor of 15 results. This amounts to a savings of 280 manhours every time a complete 3 function checkout of these 300 channels is made.

9.2 CONCLUSIONS

A method has been designed and a program package has been developed for the performance checkout of instrumentation channels by using the three functions linearity, bandwidth, and dynamic range as criteria. These methods are unconventional and provide a high degree of automation for volume processing of the test data. The program implements the methods in a fast processing design, and prints the results in a table that combines the data from the three functions in compacted form in a recorder track and VCO sorted sequence. The program could be modified to also include in the package common mode rejection ratio (CMRR) and offset measurements. The usefulness of the checkout system has been proven in actual applications.

X. FUTURE INSTRUMENTATION SYSTEMS

The traditional FM system, either multiplexed or one channel per recorder track, will be used for a long time to come. However, the move to digital acquisition systems will soon accelerate. The digital system DART that is described in References 1 and 2, is ready to be made operational. Some of the mechanics of the checkout package will not be applicable to these systems although the concept will stay the same. The checkout processing could be done either on the digital system's own computer if enough graphics capability is available or it can be done on the data reduction computer from a digital rather than an analog interface.

Test signals can, on command be switched into the inputs to the channels, as is already incorporated in the DART system. This indicates an even greater automation for these systems than was rationally feasible with the analog systems. The ideal situation where a function test is commanded by a keyboard entry on the digital system's controlling computer, and the data are evaluated without delay, resulting in a printed table of performance of all the channels in this system, is not far away. Incorporating these features in future digital systems will be much less costly than continuing with manual or even semiautomatic operation.

REFERENCES

1. Schneider, J. F., A Digital Acquisition System for Remote Transient Data, Report AFWL-DE-TN-78-001, Air Force Weapons Laboratory, Kirtland Air Force Base, New Mex, 1978.

2. Schneider, J. F., and Larson, A. L., "A PCM System for Forward Transient Data Acquisition," Proceedings of the 23rd International Instrumentation Symposium, ISA, pp. 525-530, 1977.

3. Schneider, J. F., Instrumentation System Analysis, AFWL-TR-73-186, Air Force Weapons Laboratory, Kirtland Air Force Base, New Mex, pp. 133-159, 1973.

4. Schneider, J. F., "Signal Analysis in Instrumentation," Proceedings of the 21st International Instrumentation Symposium, ISA, pp. 491-502, 1975.

5. Schwarz, R. J., and Friedland, B., Linear Systems, McGraw Hill, New York, 1965.

6. Papoulis, A., Signal Analysis, McGraw Hill, New York, p. 56 ff, 1977.

7. Standard ISA-S37.1, Electrical Transducer Nomenclature and Terminology, Instrument Society of America, pp. 8 and 11, 1969.

8. Schneider, J. F., Signal Analysis in Instrumentation, AFWL-DE-TN-78-004, Air Force Weapons Laboratory, Kirtland Air Force Base, New Mex, 1978.

9. Sokolnikoff, J. S., and Redhoffer, R. M., Mathematics of Physics and Modern Engineering, McGraw Hill, New York, pp. 673-675, 1966.

10. Reference Data for Radio Engineers, 5th Edition, pp. 3-13, 1968.

11. Otnes, R. K., and Enochson, L., Digital Time Series Analysis, Wiley, p. 206 ff, 1972.

12. Hamming, R. W., Digital Filters, Prentice Hall, pp. 28-32, 112-117, 1977.

13. Blackman, R. B., and Tukey, J. W., The Measurement of Power Spectra, Dover, 1958.

14. Cooley, J. W., and Tukey, J. W., "An Algorithm for the Machine Calculation of Complex Fourier Series," Math. Comput., Vol. 19, pp. 297-301, 1965.

15. Papoulis, A., Probability, Random Variables, and Stochastic Processes, McGraw Hill, New York, 1965.

16. Liebman, R. I., Data Acquisition Capability, AFWL-TR-82-114, Air Force Weapons Laboratory, Kirtland Air Force Base, New Mex, 1982.

./. Bendat, J. S., and Piersol, A. G., Measurement and Analysis of Random Data, Wiley, pp. 278-280, 1966.

18. Time Series Language, Progamming Manual, Time/Data Corp., 1974.

DAT

FILM