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Electronic Detection of Weak Spectrum Lines

by

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I. INTRODUCTION

Spectroscopic data can be recorded either photographically or photoelectrically. The photographic recording method yields a two-dimensional picture, one dimension more than the photoelectric recording, and is time-integrating. Because of this feature, the sensitivity of the photographic plate makes it difficult to be compared with the sensitivity of a photomultiplier. For limited applications, the photomultiplier offers a clear advantage; however, for extended applications, weak lines can only be detected photographically. Therefore, the ideal detection device should incorporate both a time-integrating circuit and a photomultiplier. Such a device would combine the response linearity of the photocathode and the time-integrating feature of the photographic emulsion.

Since the output of a photomultiplier is a convenient electrical signal, the limitation for amplification is imposed by the noise of the photocathode and related electronic components. A time-integrating circuit for the photomultiplier would, therefore, be advantageous only if this circuit is able to suppress the noise.

In the following sections, two different photoelectric methods for recording spectroscopic data are discussed and compared. The first method utilizes a digital electronic system (Enhancetron) containing a 1024 location memory capable of excellent line profile reproduction. The second method utilizes an analog electronic system where the line profile is displayed on a dual-beam oscilloscope capable of recognizing weak signals.

Along with the ability to detect weak spectrum lines, the ideal method must be capable of reproducing the exact shape of the profile lines detected. To better analyze the digital method as to its reproduction quality, it is also compared with the photographic method.

II. DIGITAL METHOD

The Enhancetron used in the digital method contains a 1024 location memory and employs ferrite cores. Each location is capable of storing a twelve-place binary number. A block diagram indicating pertinent elements of the Enhancetron is shown in Figure 1.

The switch indicated in Figure 1 is an electronic unit which causes the memory to be scanned. In the basic mode, scanning proceeds at the rate of 3×10^{-5} sec per location. Scanning is started by a trigger signal derived from the system under study. In this case, the trigger is the electrical output of a photocell attached to the optical scanning system of the spectrometer. Scanning begins with memory location No. 1 and proceeds to location No. 1024. A second trigger signal initiates a second scan in the same manner.

Consider that the trigger signal has just been received. The switch activates the integrator and the incoming signal is integrated for 3×10^{-5} sec. A charge proportional to the integral of the signal is then stored on an output capacitor.

At the same time, the voltage selector supplies a reference voltage. This voltage is chosen by a complicated procedure from among 256 voltage levels available.

At the end of the 3×10^{-5}-sec integration period, the voltage on the integration capacitor is compared with the reference voltage. If the former is greater, one count is added to the memory location and subtracted if smaller.

The switch then delivers a pulse which resets the integrator to zero and moves the input to memory location No. 2. It also causes the voltage selector to deliver a new reference voltage to the comparator.

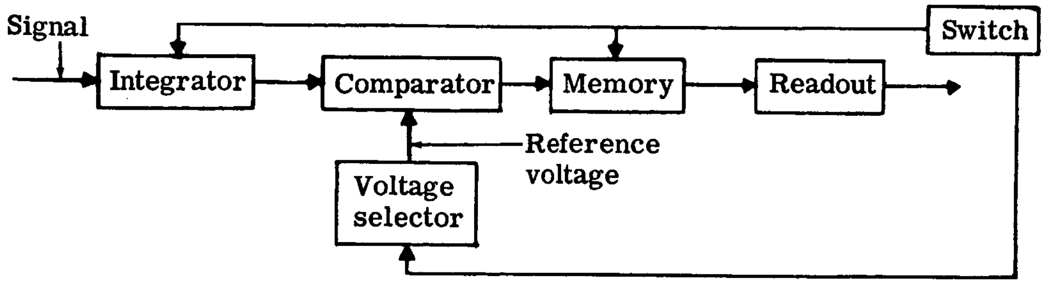


Figure 1. Block diagram indicating pertinent elements of an Enhancetron containing a 1024 location memory.

A procedure for location No. 2 is performed which is identical with that performed for location No. 1. The process continues until all 1024 locations in the memory have been covered.

The readout section contains a 256 voltage-level source. The exact voltage level is determined by reading eight bits from the corresponding memory location. The memory is scanned and this device turns the binary information read from the various locations into voltage levels.

Even though the memory stores 12 bits, the readout reads only eight bits. Just which eight bits are read is determined by the "Display Scale" setting. If the switch is in the "1" position, the first eight bits are read and if in the "16" position, the last eight bits are read.

During the time that a signal is being fed to the Enhancetron, the voltage selector supplies a different reference voltage to the comparator for each successive scan and point until all 256 voltage levels (both positive and negative) have been supplied. After starting over, this causes the memory location to provide accurate information regarding the magnitude of the input signal. To determine this, consider the reference voltage to be zero at all times. If the input signal is at the 100-v level, the system will add 356 counts to the memory location for both the positive and negative voltage levels. It will also add a total of 512 counts as long as the input signal is positive. If the input signal becomes negative, the system will subtract 512 counts.

Consider next a case where the reference level is changed. If the input level is 100 v, the system will add 356 counts to the memory location and subtract 156 counts. Thus, the count stored in the memory location reflects the magnitude of the input signal.

The Enhancetron is noted to provide scanning times from 3×10^{-2} sec to slightly more than 30 min. For a scanning time of 3×10^{-2} sec, the switch steps to a new memory location at the beginning of each scanning period of 3×10^{-5} sec. For other scanning times, the switch steps the memory every second, fourth, eighth, etc, scanning period. This keeps the integrator integrating for 3×10^{-5} sec regardless of the total scanning time.

If at a point in the scan there is no real signal, the count in the memory location will build up according to the law governing random action. It will be on either side of zero with equal probability. In magnitude, it will be proportional to the square root of the running time—time measured from the initiation of the scanning action.

If at a point in the scan there is a real signal, the count in the memory location will build up according to the sum of the real response and the noise response. The former builds up in proportion to the first power of the running time while the latter is dependent on the square root of running time.

Consequently, a real signal will climb above the noise as the running time is increased. Since the number of scans can be extended without limit, it appears that the signal should be discoverable regardless of how small the signal-to-noise ratio. This would be true if the number of bits in each storage location were infinite. With a finite number of bits, the limit is reached when the noise itself overloads the storage location. The signal, however, must be discoverable before noise overloads the memory. At present, it is estimated to take 30 min for the noise alone to overload the memory.

Lastly, the level of the input signal must be slightly less than one volt peak-to-peak. Larger levels than this on noise peaks will result in slight recording errors while lower levels cause a low signal buildup. It is mandatory that the input signal be constantly monitored on an oscilloscope and the preamp gain adjusted to maintain this level. A pure sine wave, however, can be used to observe the action when this level requirement is disregarded.

Figure 2 shows the optical test schematic used to detect extremely weak photomultiplier signals. The entrance slit is illuminated by a W-ribbon lamp. The grating is in zero order position. It is adjusted so that the image of the entrance slit lies on the exit slit. The rotating prism sweeps the image of the entrance slit across the exit slit. The resulting signal assumes a triangular shape, provided both slits are adjusted to the same width. The intensity of the lamp is adjusted to render the signal easily visible, permitting the signal shape to be known. A typical signal is shown in Figure 3.

The intensity of the lamp is reduced in Figure 4 to a level where the signal is buried in the electronic noise.

Enhancement of the signal by the Enhancetron resulted in the traces of Figure 5. Parts a, b, c, and d of Figure 5 correspond to different "exposure times"—different integration times. When these photographs were taken, the intensity of the W-ribbon could no longer be detected with the naked eye. The entrance slit of the spectrometer was only 2 mm high and 5 μ wide. This is a valid indication that extremely weak signals can be detected using the Enhancetron.

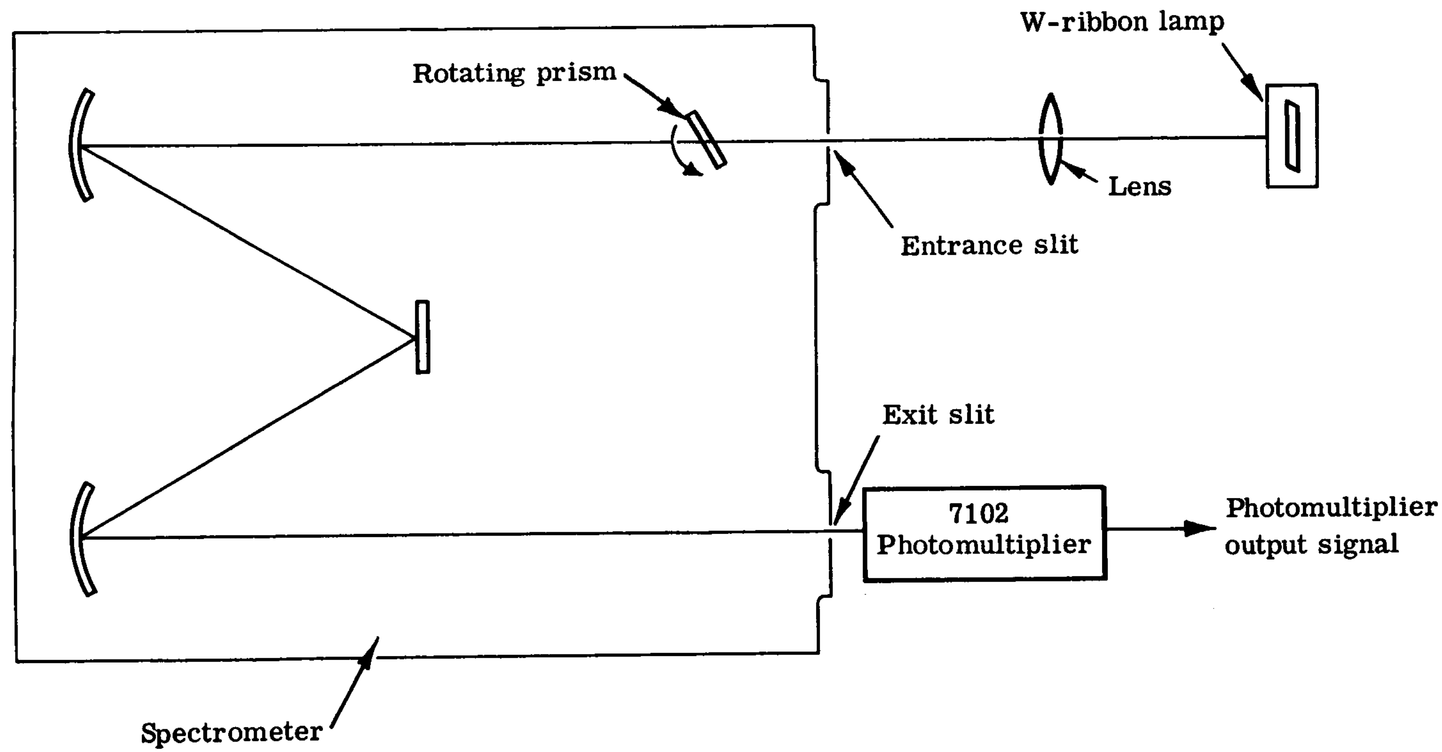


Figure 2. Optical test setup used to detect extremely weak photomultiplier signals.

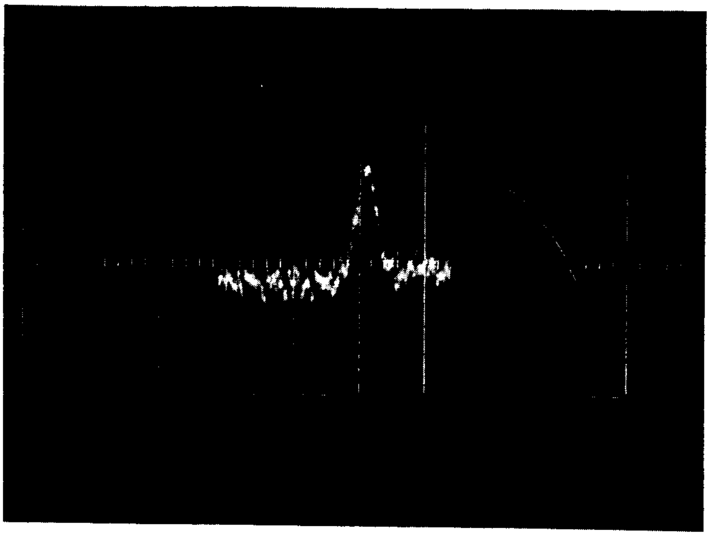


Figure 3. Intensity profile of a tungsten ribbon taken with a 7102 photomultiplier.

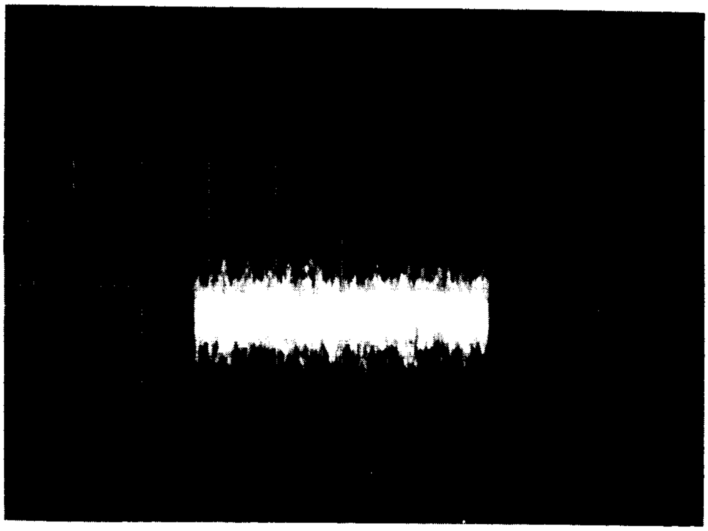
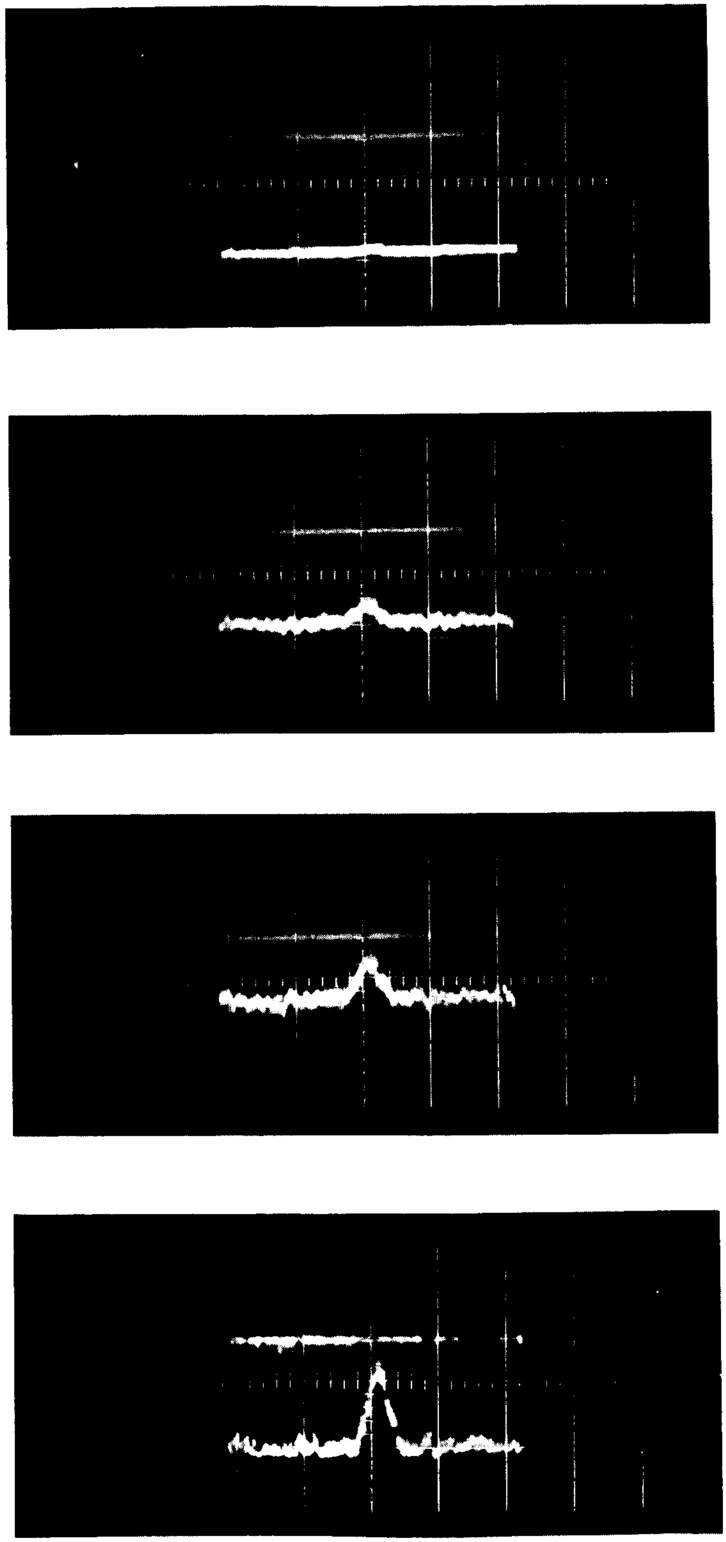


Figure 4. Intensity profile of a tungsten ribbon with the signal buried in noise.



a. 5 sec

b. 10 sec

c. 15 sec

d. 20 sec

Figure 5. Results of applying the Enhancetron to weak signals.

The technique was then applied to the argon spectrum lines 4333.56 and 4335.34. The grating was set for first order detection and the 7102 photomultiplier was replaced by the 1P28 photomultiplier. The intensity of the argon lamp was reduced by an aperture, so that the signal again was buried in noise. Figure 6 shows a single sweep oscilloscope photograph of the photomultiplier output. Figure 7 shows the same signal after enhancement with the Enhancetron. This demonstrates that the technique is applicable to spectroscopy. The intensity ratio of the two lines was not changed by the enhancement procedure.

One interesting fact is demonstrated in Figure 8. The content of the Enhancetron memory was printed twice to determine the reproducibility of an integrated signal. This double readout provided a means for determining what effect the noise from being integrated and from the readout section of the Enhancetron had on signal reproduction. As can be seen in Figure 8, the repetition is almost perfect.

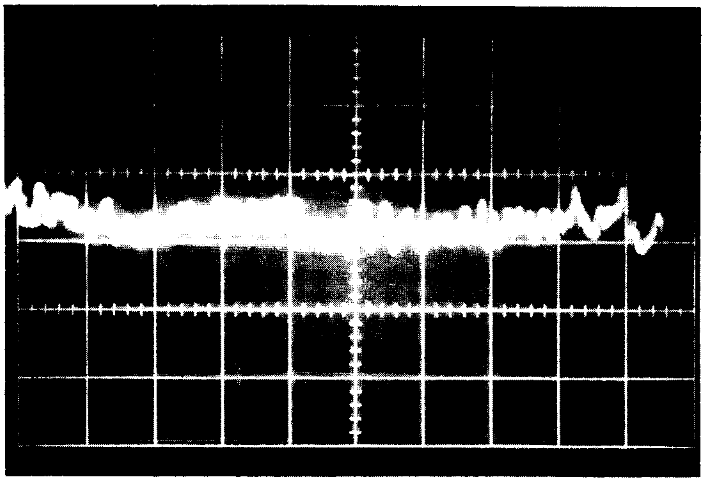


Figure 6. Single sweep oscilloscope trace of a 1P28 photomultiplier output signal buried in noise. (Argon lines 4333.56 and 4335.35Å).

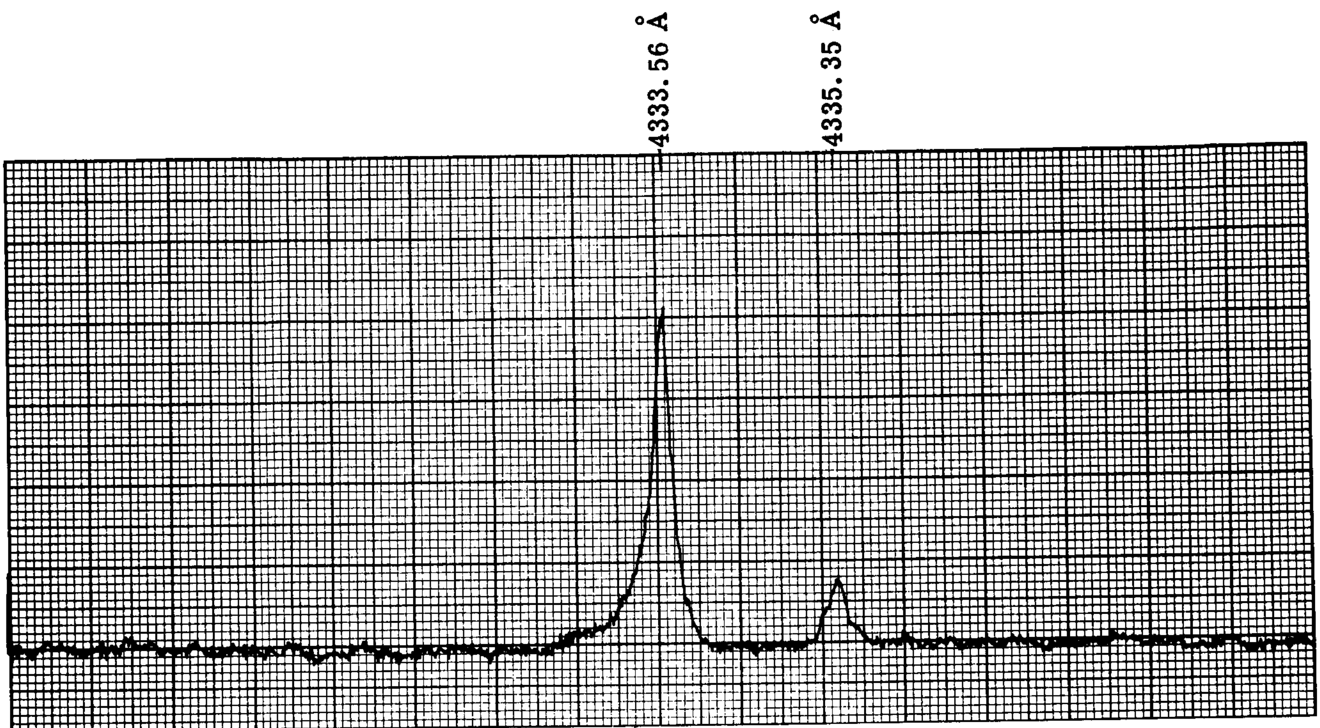


Figure 7. Signal of Figure 6 after integration with Enhancetron
(Argon lines 4333.56 and 4335.34Å).

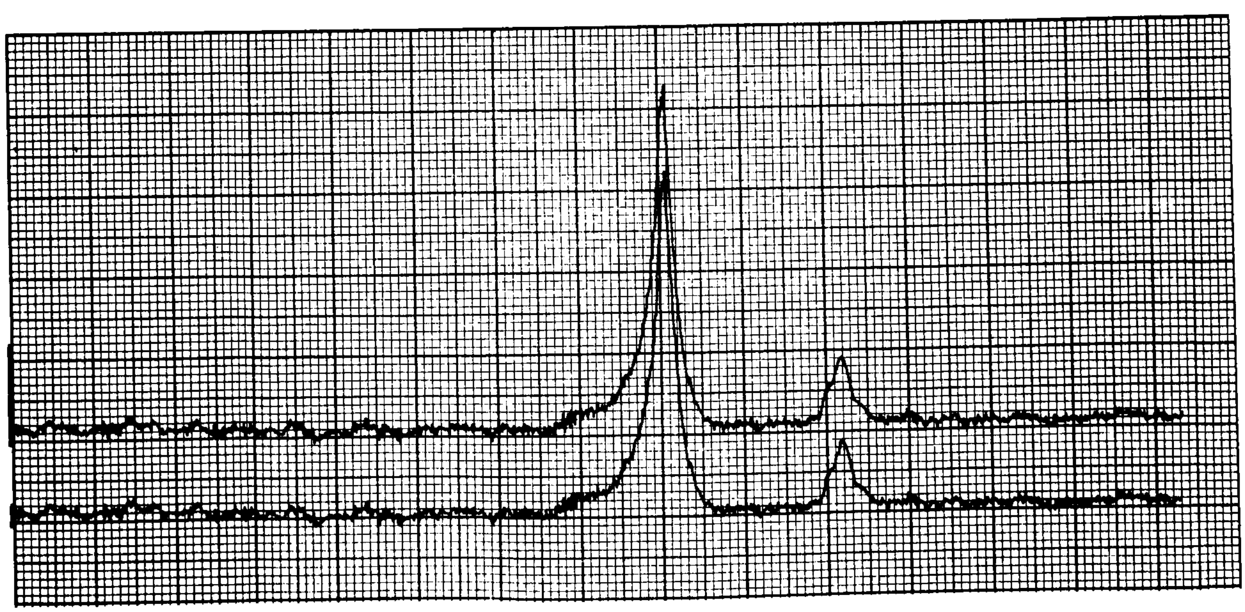


Figure 8. Repeatability test to determine accuracy of Enhancetron memory.
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III. ANALOG METHOD

The following paragraphs describe an electronic device which was developed at Allison and used until the Enhancetron became available. Since it produces traces comparable to those produced by the Enhancetron, it may be applied in cases where purchase of the Enhancetron cannot be justified. The instrumentation described herein uses components which are available in average laboratories.

Figure 9 is a block diagram of the analog system. The signals appearing at various points in the system are indicated in Figure 10. Line A of Figure 10 shows the real signal. Signal M corresponds to a prominent spectral line; signal N corresponds to a weak spectral line. Line B indicates how the weak signal can be rendered indiscernible by noise. Only the strong signal is noticeable. An operator using the conventional detection system would never recognize the weak signal.

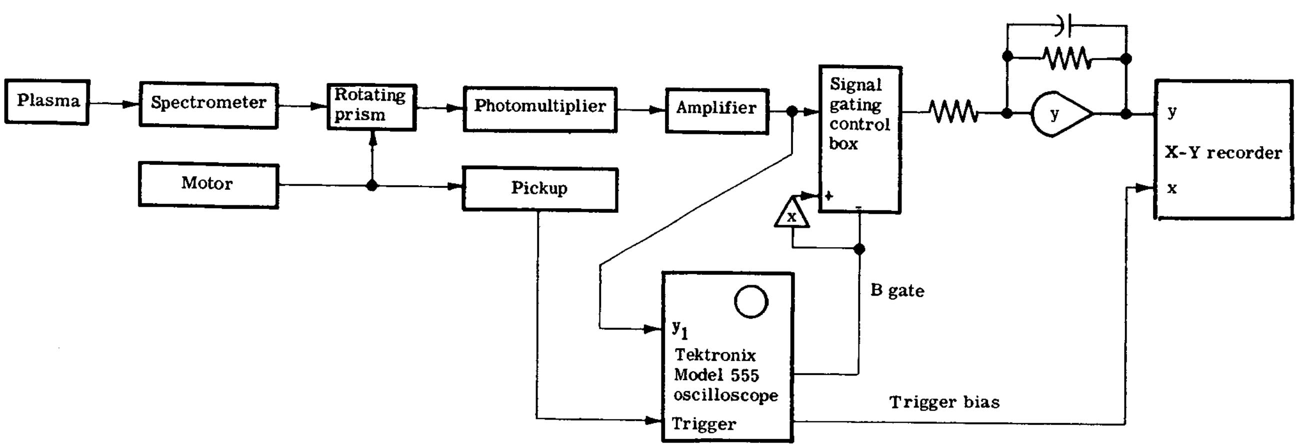


Figure 9. Special instrumentation used to detect weak repetitive signals.

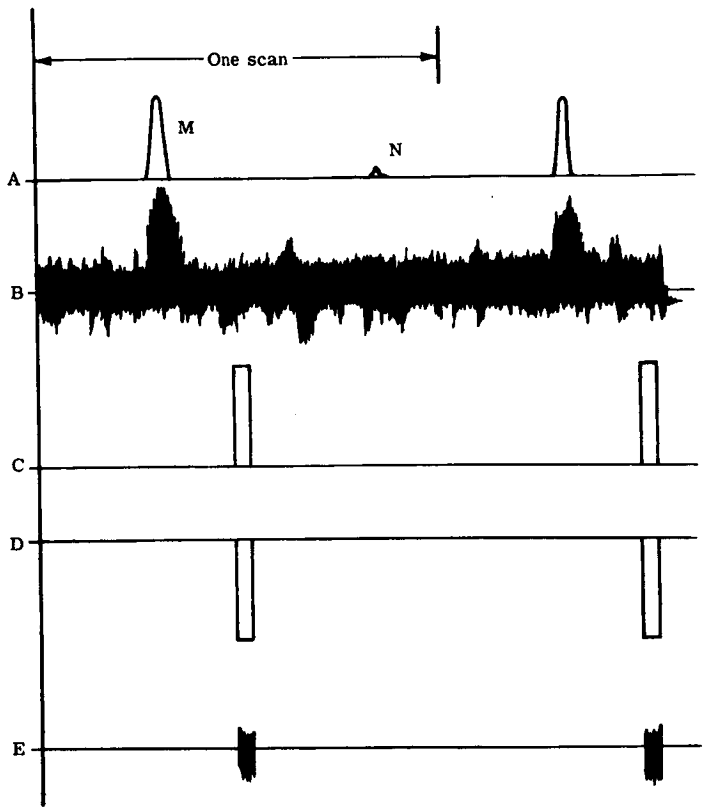


Figure 10. System signals.

The Tektronix Model 555 oscilloscope used is a dual-beam unit. An integral delay system in the oscilloscope permits the B beam to be delayed with respect to the A beam. Delay is accomplished by adjustment of a front panel potentiometer. The system permits a repetitive signal to be displayed on the A trace and any portion of this signal to be selected and displayed on the B trace. The potentiometer which fixes the delay delivers an output voltage which sets the triggering level of a sweep trigger tube. This voltage was taken from the oscilloscope and connected to the "x" channel of the x-y recorder.

Line C of Figure 10 indicates the gating signal for the B trace. The gate may be varied in width and may be positioned anywhere along the scan.

Line D shows the inverted gate obtained at the output of operational amplifier "x."

The circuit of the signal gating control box is shown in Figure 11. During the absence of a gating signal, the output signal from the box is clamped to zero. During the period of a gating signal, the input signal less the d-c component is carried through to the output terminal.

It was found desirable to incorporate a zeroing control into amplifier "x." This control was adjusted to bring the output of amplifier "x" to exactly the same level as the input during the absence of a gating signal. Absence of this control results in a gap between the two voltages or in an overlap and a consequent large circulating current through the two diodes.

Line E of Figure 10 shows the output of the signal gating control box. The noise burst of line E is an exact replica of the original signal. The noise burst feeds to operational amplifier "y" which is adapted to act as a low pass filter. It smoothes out the noise component and delivers the true signal at the output. When the signal gate is coincident with a buried signal, the output of amplifier "y" contains the signal plus noise.

The procedure for using the system is as follows:

1. Using the delay control potentiometer on the oscilloscope, search from left to right through one scan. The x-y recorder should move from left to right as the potentiometer is advanced.

2. Repeat the search from right to left. This may be done with pen up or down. The purpose of this search is to disclose any apparent signals due to amplifier drift.

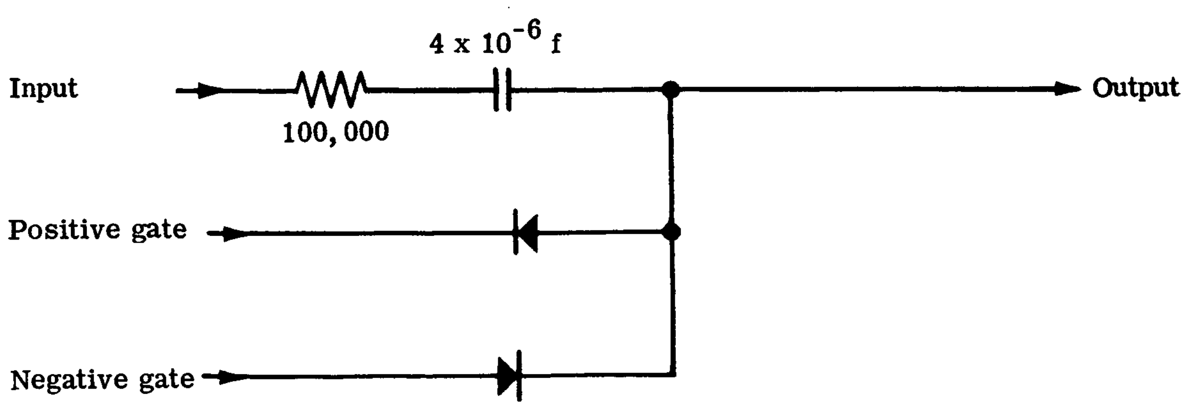


Figure 11. Signal gating control box schematic diagram.

Study of the system indicates that the base line appearing in line B of Figure 10 represents the average of all noise plus all true signals in the output of the photomultiplier. Consequently, the presence of a large true signal (or signals) causes an apparent shift in the base line at the output of operational amplifier "y." No so-called d-c restoration is provided. Because of these characteristics of the system, signals cannot be detected by adjusting the mirror to one position and leaving it there—causing just one small portion of the spectrum to be fed continuously to the photomultiplier. A scanning technique must be used. The output signal at one point of the spectrum must be compared with the output at other portions.

Some judgment on the part of the operator is required in selecting the time constant for the filter associated with operational amplifier "y." If the time constant is too small, the noise output of the amplifier becomes excessive, but the search for signals can be very rapid. If the time constant is too great, noise output is greatly reduced and very weak signals can be detected, but search time must be greatly extended. The extended search time gives rise to troubles from amplifier drift. The question soon arises whether a shift in the output trace is due to a true signal or to drift.

The width of the gate signal should generally be about the same as the width of the true signal being sought. Wider gates tend to smooth the noise but may fail to indicate weak signals. More narrow gates reveal the weak signals but accentuate the noise.

The time required to locate signals can be reduced by reducing the width of scan. However, width of scan should be about five times the width of the spectral line sought. It is well to bear in mind that the limit in time reduction is fixed by the signal-to-noise ratio. As the signal becomes weaker, more time must be allowed for a positive identification.

IV. COMPARISON OF DIGITAL METHOD WITH THE ANALOG AND PHOTOGRAPHIC METHODS

COMPARISON OF DIGITAL AND ANALOG METHODS

The digital method was compared with the analog method using the test schematic shown in Figure 12. The noise generator of the test device was set at a low frequency noise and the oscillator was set at 100 cps. The network of "ra," "rb," and "rc" permitted the two signals to be mixed in any proportions.

Potentiometer "pa" at the output of the power amplifier permitted the input to the Enhancetron to be adjusted to a proper level—generally adjusted to provide about one noise peak/sec above 1 v. The filter time constant was varied by changing capacitor "ca."

Initial tests employed signals for which the signal-to-noise ratio was high. For subsequent tests, it was progressively lower. Performance of the two systems was then compared for each level.

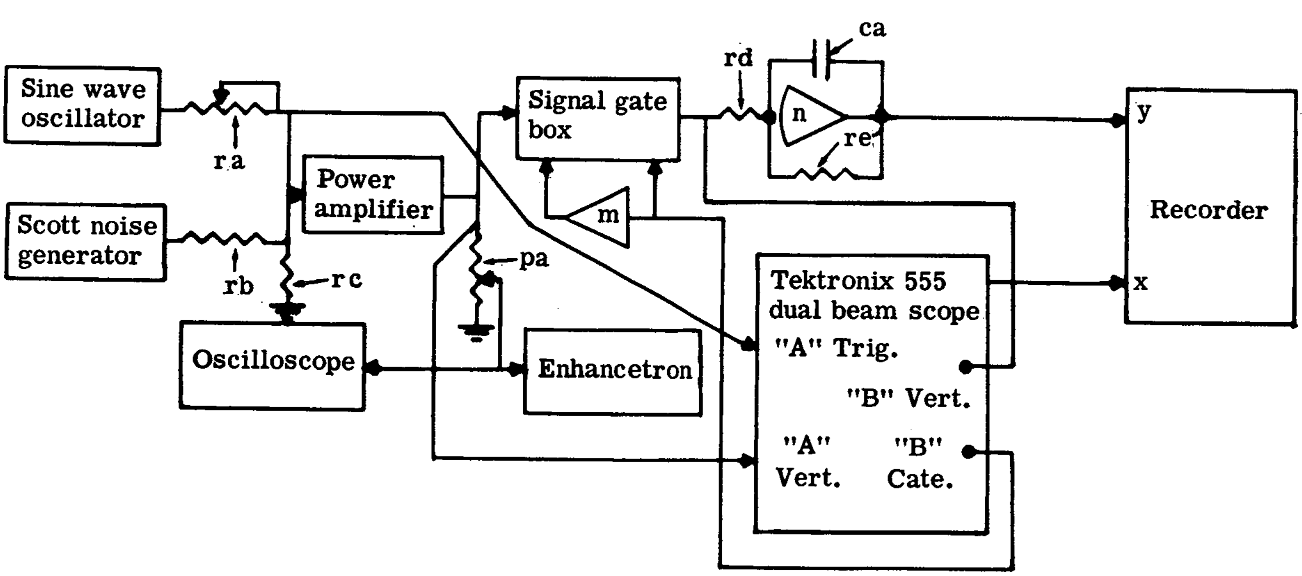


Figure 12. Instrumentation used to compare the digital and analog methods for detecting weak spectrum lines.

Two oscilloscope traces are shown in Figure 13, and the test results are presented in Table I.

Table I.

Comparison of digital and analog signal detection systems.

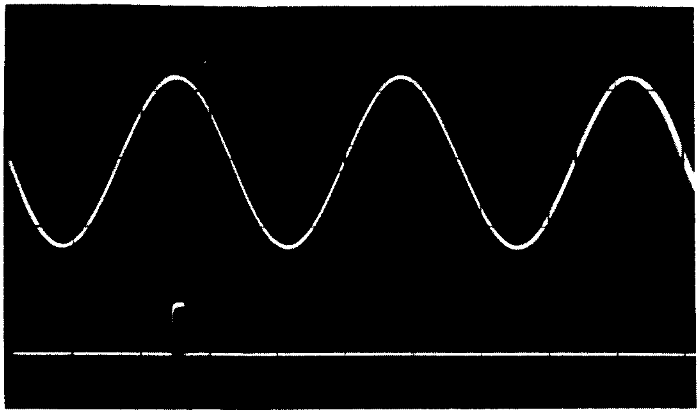
Test No.	Method	Test time (sec)	Input
1	Enhancetron	40	Pure sine wave—100 cps
2	Analog	60	Pure sine wave—0.3-sec time constant
3	Analog	90	Signal barely visible in noise (see trace No. 2 of Figure 13)
4	Enhancetron	600	Signal barely visible in noise (see trace No. 2 of Figure 13)
5	Enhancetron	600	Sine wave signal reduced by one order of magnitude from that used in Test No. 3
6	Analog	300	Same as Test No. 5 except noise reduced to zero (10-sec time constant)
7	Analog	1000	Same as Test No. 5, noise reinserted.

Oscilloscope trace No. 1 shown in Figure 13 shows the sine wave input in the upper trace. The lower trace shows the gated input to the filter. The gate width is about one tenth of a sine wave cycle. It is probably a good rule to make the gate width about a tenth of the width of the item under study.

Trace No. 2 shows the noise-plus-signal used in Tests No. 3 and 4 of Table I. The gated pulse appears slightly displaced to the right. This is due to improper alignment of the horizontal sweeps for the two traces.

Recording No. 1 of Figure 14 indicates the presence of noise. This is believed due to the recorder. The principle on which the Enhancetron operates, however, indicates that some noise should always be present in its output.

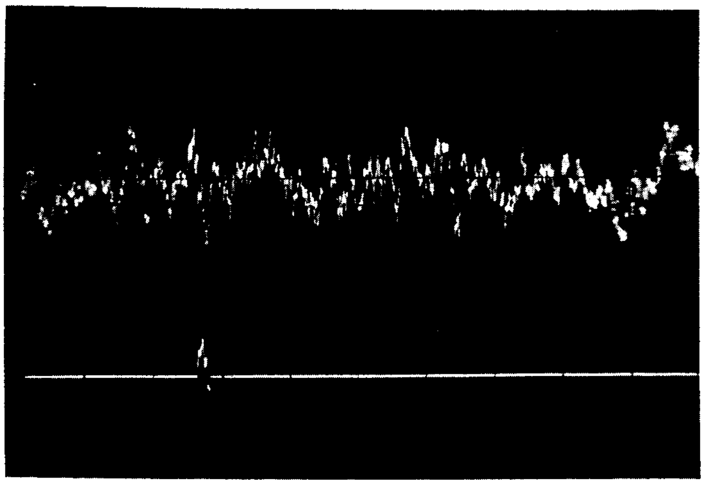
Recording No. 2 of Figure 14 indicates that the filter (analog) system operates equally well. It is noted that 60 sec were taken to make the traverse—traverse was by hand-turning of a Helipot. Constant rate was desired but hardly obtained. The time constant of 0.3 sec causes no apparent lag in the trace.



Trace No. 1

Sine wave input to filter system.

Gated sine wave input to filter proper.



Trace No. 2

Sine wave plus overriding noise.

Gated signal into filter proper.

Figure 13. Oscilloscope traces comparing the digital and analog methods.

Recording No. 3 of Figure 14 indicates that a sine wave barely discernible in noise may be drawn out well in 90 sec using the filter system.

Recording No. 4 of Figure 14 indicates that the Enhancetron in 600 sec can do as well in this particular case as the filter. Consequently, for signals barely covered with noise, the filter appears better. In both cases, the signal-to-noise ratio has been raised far above that of the original signal displayed in trace No. 2 of Figure 13.

Recording No. 5 of Figure 14 indicates that the Enhancetron does very well in extracting a weak signal from noise.

Recording No. 6 of Figure 14 was run from right to left and the Helipot was turned faster. The time constant of 10 sec causes the amplitude and phase to be a function of rate of turning. As the scan moved to the left, the amplitude continuously reduces. This test without noise serves to check for drift in the filter amplifier and other possible disturbances. The amplifier, however, appears stable.

Recording No. 7 of Figure 14 was obtained with the same sine wave signal input used to obtain recording No. 5. The added noise, however, indicates that the performance of the filter system is not as good as the performance of the Enhancetron—even when the scanning time is doubled for the filter. The reason for this reduction in analog performance probably lies in the filter operational amplifier. Drift in the filter amplifier will show up as a signal in the output. Such drift could cause the apparent errors in the trace. However, the discrepancies could be due to noise alone. It is highly probable that, in a refined version of the filter, chopper-stabilized amplifiers should be used—similar to those used in an analog computer. Since the Enhancetron is a digital device, it is not affected by the drift problems.

The conclusion drawn from this comparison indicates that the digital system provides a better system for detecting weak signals than the analog system. The analog system, however, was a better device for handling large signal-to-noise ratios. It was also determined during the comparison that for extended use of the analog system, a motor-driven Helipot was required to move its memory gate.

COMPARISON OF DIGITAL AND PHOTOGRAPHIC METHODS

For an identical spectrographic setup, signals were obtained from the Enhancetron at exposure times up to 1 hr when no traces could be detected on the photoplates (Kodak NI, fresh developer

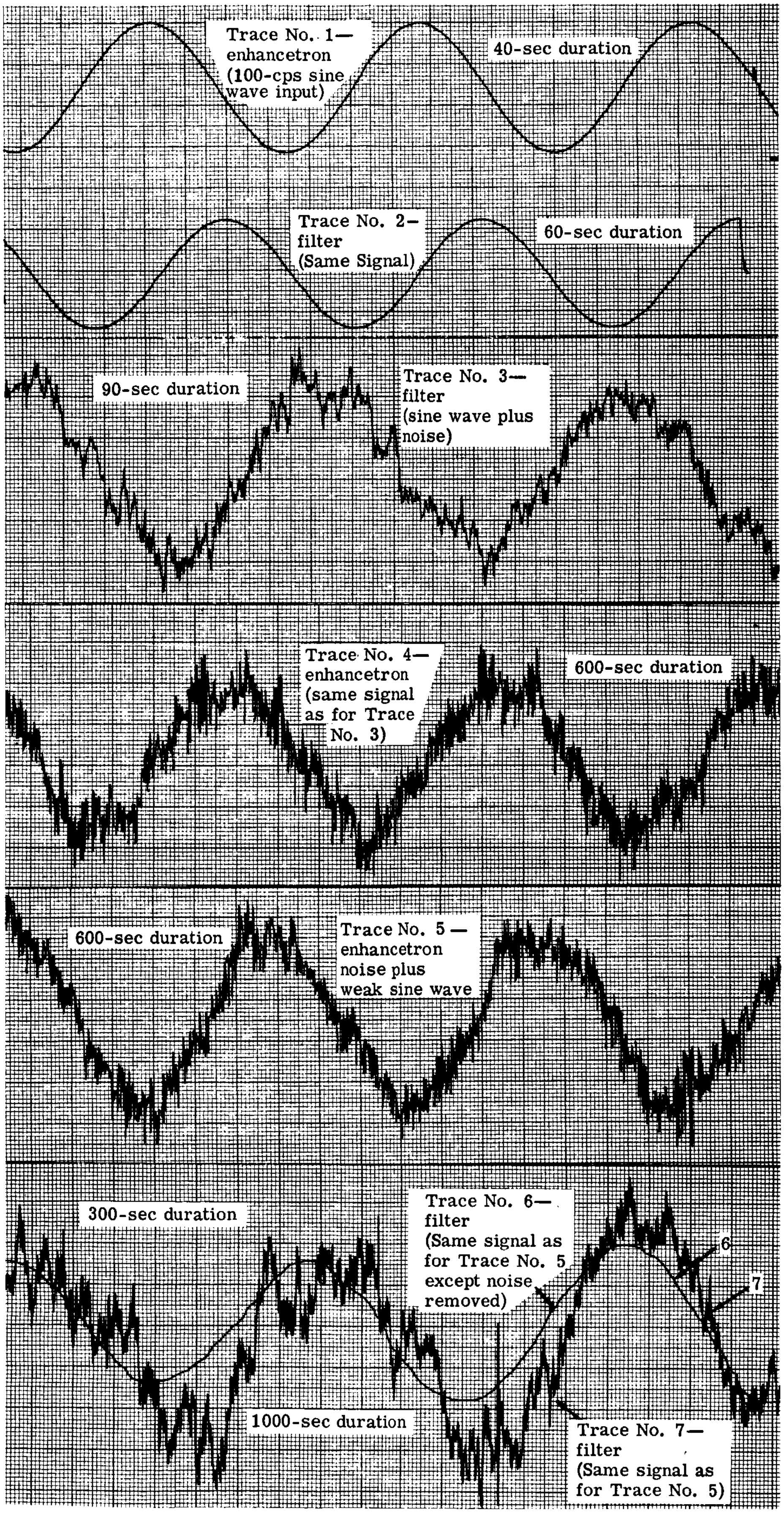


Figure 14. Recorder traces comparing the digital and analog methods.

D19, and 5 min developing time). Figures 15 and 16 show the results of such measurements. Signals I and II come out of the noise after approximately 3 and 12 sec exposure time and rise in proportion to the exposure time. The noise rises as the square root of time, so that after approximately 2 min, signal I is approximately ten times stronger than the noise. At 5 min, the signal is 30 times stronger, etc. The signals on the photoplates at the same wavelengths reach the noise level at approximately 15 and 1000 sec exposure time. The measurements were made with the image of the light source (a tungsten ribbon lamp at 2140°K) being swept (by means of a vibrating mirror) across the entrance slit (400 μ wide, 15 mm high) of an Ebert 3.4-m spectrograph. In the focal plane of the spectrograph, two 400-μ exit slits were mounted at λ = 7065 and 4026 Å. Photomultipliers were positioned behind the slits. Such a setup can be used to obtain arc profiles photoelectrically. To obtain the photographic curves, the multipliers were replaced by photoplates.

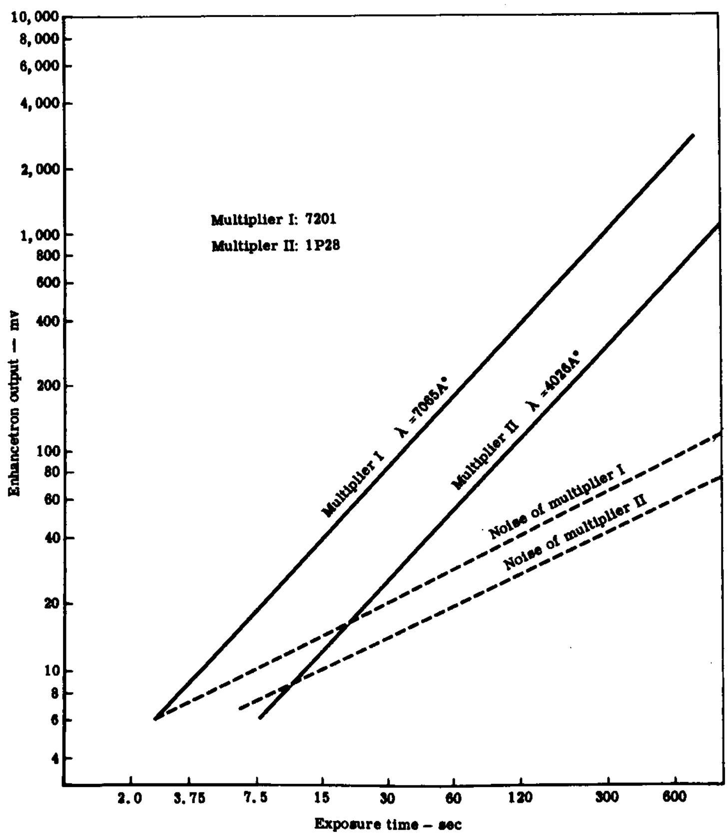


Figure 15. Multiplier output response curves.

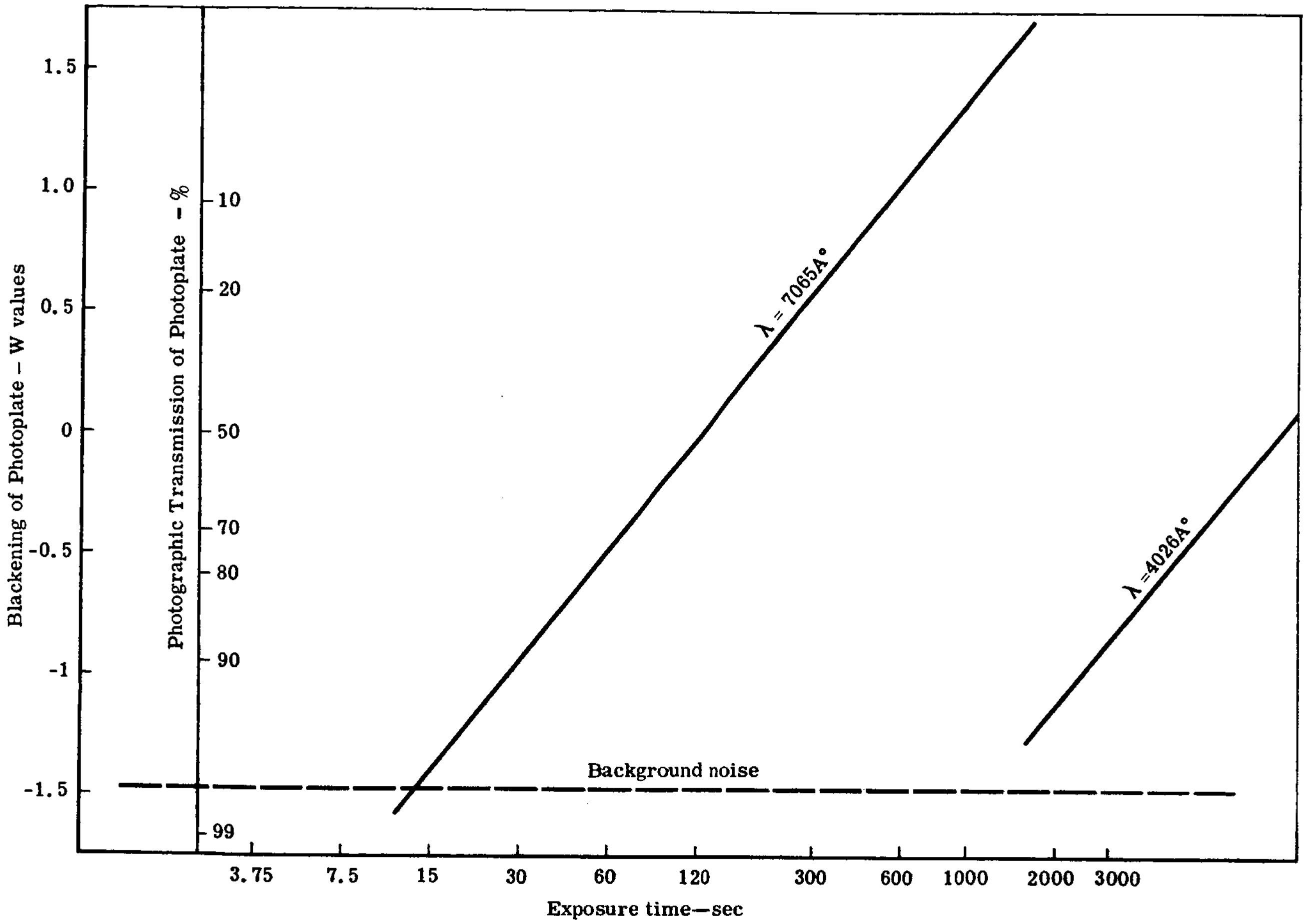


Figure 16. Tungsten values vs exposure times for two wavelengths of light.

In other tests, the Enhancetron proved capable of not only detecting very weak lines, but also their true line shape.

A line doublet with lines 0.4 Å apart was selected (mercury lines at 3662.87 and 3663.27 Å). The intensity of the lines is sufficient that the lines can be easily observed. The optical arrangement was the same as shown in Figure 2. Since the spectrograph could not completely resolve the line pair, the resultant line had a very distinctive shape. The intensity was then reduced until the signal height was of the same order of magnitude as the noise level. The oscilloscope trace of the line pair is shown in Figure 17. The signal shown in Figure 18 was enhanced in the Enhancetron and displayed on an x-y recorder. The resultant signal is shown in Figure 18. The trace obtained is (within the error of measurement) identical with the curve of the spectrograph at full intensity.

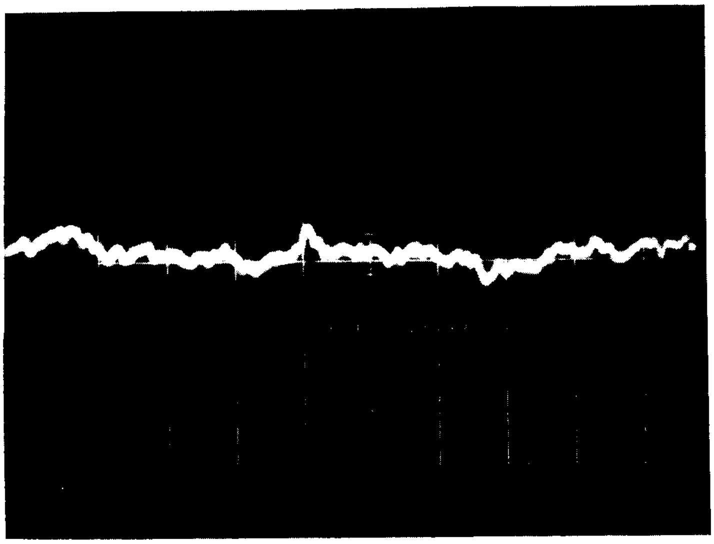


Figure 17. Signal output of photomultiplier.

Mercury lines—3662.87 (50)
3663.27 (500)

Spex 0.75 meter

Czery-Turner spectrometer

Slit width—10 microns

Slit height—2 mm

Scanning time—0.038 sec for 1024 points

Excitation—low pressure mercury arc

The stronger line (3663.27 Å) is electronically saturated and appears at a reduced height. This is done intentionally, since otherwise the 3662.87 Å line would be only a small pip on the larger one.

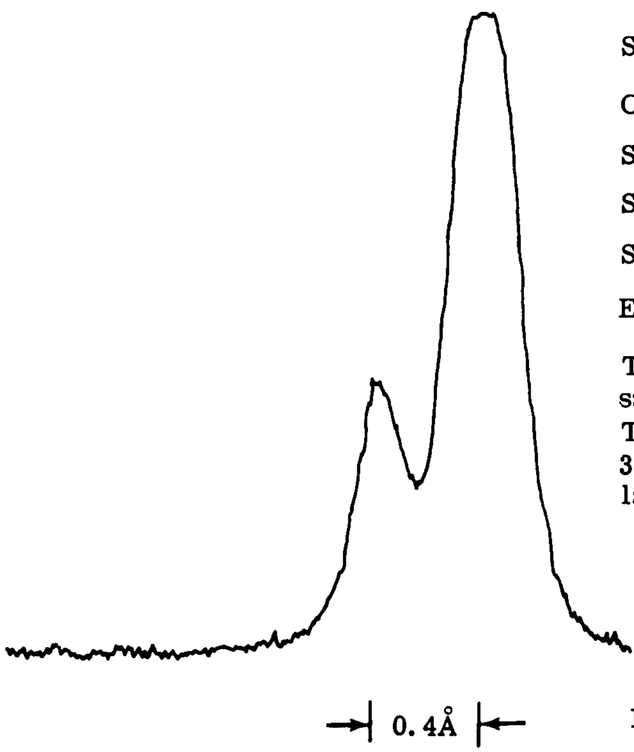


Figure 18. Signal of Figure 17 after integration with Enchancetron.

V. CONCLUSION

Both the digital and analog systems are not only capable of detecting and reproducing weak spectrum lines but also those lines buried in noise. When compared with the photographic system, both systems perform adequately. However, by improving their electronic design, the digital and analog systems can be improved to surpass the performance now attained with the photographic system.