PRINCETON UNIVERSITY

RECENT DEVELOPMENTS AND APPLICATIONS OF THE SEC VIDICON FOR ASTRONOMY

by

Paul Zucchino and John L. Lowrance

Princeton University Observatory

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INTRODUCTION

The engineering development of the SEC vidicon as an astronomical sensor has continued at Princeton University Observatory in parallel with its operational use. One scientific application was the six hour exposure of the Quasar PHL-957 at the Coudé spectrograph of the 200-inch Hale telescope. The developmental effort includes both the enhancement of the basic attributes that make the SEC an appropriate sensor, namely: high quantum efficiency, low threshold, and long integration; as well as work to broaden its scientific usefulness, such as the development of a MgF_2 photocathode window for vacuum ultraviolet sensitivity, and a permanent magnet focus design for thermal compatibility with proposed large space telescopes. Additional details on the characteristics of the SEC tube are discussed, as well as plans to make a larger and higher resolution version.

Physical Description of the Present Tube Design

Figure 1 is a photograph of the present tube. It is 17 inches (43cm) in overall length and 3 inches (76mm) in diameter in the image section region. The active photocathode area is a one inch (25mm) square determined by the one inch square active area of the SEC target structure at the other end of the image section, 5 inches (13cm) behind the photocathode.

The entire tube including the image section is magnetically focused by immersion in an 80 gauss axial magnetic field. The use of a magnetically focused image section is required to maintain the high MTF (Modulation Transfer Function) over the image format and to have a plane photocathode geometry which is practically essential for fabrication of ultraviolet transmitting photocathode windows and for compatibility with most optical systems.

A significant milestone that was reached this year in the development of the sensor for astronomical applications in space, was the successful fitting of an ultraviolet transmitting photocathode window to the tube.

Lithium Fluoride will transmit down to 1050Å. Unfortunately, its transmission is seriously degraded by bombardment by energetic particles. Magnesium Fluoride will transmit down to 1150Å, and is much less susceptible to irradiation. It is also more resistent to scratches and less hydroscopic than Lithium Fluoride.

Accordingly Magnesium Fluoride (MgF_2) was selected for the sensor window. The thermal expansion coefficient of MgF_2 is considerably different from that of glass and special techniques were developed to seal the window to the tube. Gold foil is cemented to the MgF_2 window with a frit glass. The gold foil is then electron beam welded to a Kovar flange which is subsequently welded to a mating Kovar flange on the tube. Kovar closely matches the thermal expansion coefficient of glass.

The photocathode is a bi-alkali which exhibits high quantum efficiency from 5000Å into the far ultraviolet. Net Quantum efficiencies of 15 percent have been obtained at 1235Å. Red response is sacrificed to reduce the internal background in the tube. Cesium used to improve red sensitivity also results in enhanced dark emission from the photocathode and enhanced field emission from the walls of the image section.

A practical requirement for sensors to be used for space astronomy is that they be sufficiently rugged to withstand the launch environment. The current tube design (WX-31718) has been tested by exposure to thermal and mechanical shocks, acceleration, and vibration levels, consistent with sounding rocket and orbital spacecraft launch environments. The tube has proven to be sufficiently rugged to withstand launch stress without degradation, provided that high frequency vibration levels in the 100 Hz to 2000 Hz range are kept below 5g rms by means of vibration absorbing mounting methods.

SCIENTIFIC OBSERVING PROGRAMS

The first application of the SEC vidicon to a scientific observation program at Princeton was made by Taylor[2] who used the sensor to integrate spectra obtained with a half meter Ebert-Faste spectrograph with a dispersion of 3.5A^{o}/mm at the photocathode of the tube. The instrument was used both on the 36-inch reflector at Princeton and the 60 inch telescope at Mt. Wilson.

The next scientific application was the colaboration of Morton and Oke[1] in obtaining a high dispersion spectrum of the radio quiet quasar PHL-957 with the Coude spectrograph of the 200-inch Hale telescope. The spectrum from 4270 to 4495Å with 0.75Å resolution was obtained in a six hour exposure on this object which has a visual magnitude of 16.6. The spectrograph slit width imaged on the photocathode was 75 microns. The SEC vidicon used for that observation had a MTF response of 85% at that element size. Accordingly the observed resolution was that of the spectrograph determined by slit width without significant broadening by the TV system.

The faint luminosity of the object and high spectrograph dispersion resulted in a photoelectron count rate of 1.4 photoelectrons per minute per slit width resolution element in average regions of the spectrum. The exposure time of slightly over six hours (375 minutes) yielded about 525 photoelectron events per typical spectral resolution element. The TV tube image section background amounted to 295 photoelectrons per element. The resulting signal to noise ratio was 18 in regions of the spectrum of typical intensity.

It should be noted that the only significant noise contribution from the TV system to an observation of this type is the image section background. If the tube background had been zero during the six hour exposure, the typical signal to noise ratio would have been 25 instead of 18. Expressed in background photoelectrons per cm^2 per sec the tube photocathode dark count was 100 cm^{-2} sec^{-1}.

Figure 2 is a digitized television image of the spectrum obtained of PHL-957. Figure 3 is the corresponding reduced data spectrum. The analog video obtained during readout is digitized to permit effective data reduction and photometric calibration of the television signal. These data reduction procedures have been described elsewhere.[1,2,3,4]

Crane of Princeton has used the SEC vidicon system to do photometry of galaxies. He made detailed calibration measurements of the photometric characteristics of the tube. The calibration data and methods are also used for other applications of the tube such as the above discussed spectroscopy. Crane has shown that the sensor can be calibrated photometrically with a precision of two percent.[3]

Figure 6 and 7 are digitized television images obtained by Crane, and Figure 5 is a computer printed display of a digitized image. Figure 4 is a copy of a portion of the Palomar Sky Survey plate showing the galaxies in the central portion of the Abell cluster 1367 that were observed. All the television images discussed here were obtained on the 36-inch reflector at the Kitt Peak National Observatory.

Figure 5, the computer page printout, was made from the sum of two 2.5 minute TV exposures on the double galaxy NGC 3845. NGC 3845 is the object indicated by the uppermost arrow in Figure 4. The printed symbols in Fig. 5 correspond to intensity level changes of 0.05 of the sky background level. The double galaxy structure can be clearly discerned in Fig. 5 although it had been lost through overexposure in the Sky Survey. The faint spot close to the double galaxy at the "two o'clock" position in Figure 4, shows up clearly in the page printout of Figure 5.

Figure 6 is a digitized television image obtained in a single two minute exposure on the galaxies NGC 3841 and 3842 which are indicated by the middle and bottom arrows on Fig. 4. The small intense mark to the far right of 3842 in Figure 6 is a hole in the SEC target.

Figure 7 is a digitized television image obtained by stacking eight separate exposures of the same objects as Fig. 6. The total exposure was 17 minutes. Note that the outer regions of NGC 3842 are more readily seen with the increase in total photoelectrons accummulated. The stacking program employed to process the data for Fig. 7 translated the digital images so that the objects registered from frame to frame. Since the objects were on slightly different regions of the SEC target for the various exposures, the target hole noted in Fig. 6 shows up scattered about in Fig. 7. The use of slightly different target regions for successive exposures of the same object helps prevent build up of any coherent target grain noise when multiple frames are stacked to obtain greater photometric range. Crane observed that the relative noise in the summation of eight frames (Fig. 7) was reduced by the square root of eight when compared to the single frame exposure.

Laboratory results on multiple frame summing or stacking are discussed in a latter section of this paper.

PHOTOELECTRIC TRANSFER FUNCTION

The sensor's response to primary photoelectrons (pe) is shown in Fig. 8 along with the noise properties of the input photoelectron flux and of the preamplifer (PA). Fig. 8 has been normalized to an image element size of 36 by 48 microns on the photocathode.

The photocathode and target are in fact continuous surfaces, so the size and shape of an image element is determined by how the target is raster scanned by the reading electron beam and by the video bandwidth used in examining the video signal. Very small (less than 25 microns square) image elements are not advisable for quanatative work because of several related factors. One, the individual elements cannot be adequately resolved because of the drop in MTF at high spatial frequencies. Two, the SEC target storage capacity in photoelectrons per image element becomes too small for adequate photometry. And three, image abberations such as read beam pulling become significant as the scale of an individual image element becomes smaller.

The normalization employed in Fig. 8 corresponds to the actual operating format employed in the scientific observing programs reviewed in the previous section.

The 36 micron dimension is the pitch or line-to-line separation of the raster of readout scanning lines traced by the electron beam. The element dimensions are all referred to the photocathode although the dimensions on the SEC target are roughly the same since the image section magnification is nominally unity.

The 48 micron dimension is the element length along the scan lines and corresponds to the distance scanned by the reading electron beam in the time duration of one half cycle of video bandwidth.

The digitizing of the video signal is done at a sampling rate that results in 3.4 digital samples per cycle of video bandwidth. This sample rate is higher that the absolute minimum of 2 samples per cycle required by the Nyquist criteria for sampled data systems, but a margin is required to practically advoid aliasing effects and excessive digital filtering attenuation of the highest spatial frequencies in the data.[5] Accordingly, the length of a digitized image element, known as a pixel, referred to the photocathode is 28 microns. However, Fig. 8 and the discussion which follows is based on the analog image element size of 36 by 48 microns.

The small exposure noise threshold for the SEC vidicon depends upon the preamplifier noise performance expressed as the equivalent number of noise electrons per half cycle of bandwidth at the SEC target.[4] For the preamplifier and operating temperature used at Mt. Palomar during the PHL-957 observation, the preamplifier noise was 600 rms target electrons (Te), this value is plotted in Fig. 8. Since the target gain (G_T) for small exposures was 78, the preamplifier noise referred to the photocathode was 7.7 photoelectrons per image element. This means that an exposure of 8 photoelectrons per element would produce a readout signal just equal to the rms preamplifier noise. Correspondingly, an exposure of 60 photoelectrons per element would have a quantum noise just equal to the preamplifier noise. Therefore, for exposures that exceed 60 photoelectrons per element the dominant noise component is the statistical noise in the photoelectron flux itself. For example, for an exposure of 200 photoelectrons the quantum noise would be 14.1 pe, the preamplifier noise would 7.7 pe, and the total noise would be 16.1 pe or only 14 percent greater than the quantum noise. This is the basis for saying that for exposures above 60 pe per element, the sensor is quantum noise limited.

The target gain does not remain at its initial value as the exposure progresses as indicated by the curvature of the plot of target electrons in Fig. 8. Crane[3] has shown that, this characteristic can be calibrated, even for each region of the tube if necessary.

For the particular tube calibration shown in Fig. 8, the maximum practical exposure was 1730 pe per element because higher exposures caused excessive loss in incremental target gain. To observe objects or spectra requiring a greater maximum photoelectric capacity per picture element the procedure for stacking of separate exposures is followed.

Most SEC vidicons do not seem to have as sharp a decrease in gain with exposure as the tube whose calibration is shown in Fig. 8. In any case, its actual transfer function is both known and used for reducing TV data to intensities.

MODULATION TRANSFER FUNCTION

The most recent measurement of the MTF of the SEC vidicon is shown in Fig. 9. The high performance shown is the result of several factors. One, the tubes used by Princeton do not have a suppressor mesh nor is one needed for sequential exposure-then-read operation. Two, the tubes are of all magnetic focus design with an 80 gauss field and a magnetically focussed image section. And third, slow scan readout is used with consequent higher performance of the reading electron beam.

Since higher MTF response at the frequencies of interest is always advantageous, an analysis of the MTF determining elements of the present tube was done.

Pietrzyk[6] of Westinghouse has shown that the square wave MTF of the magnetically focussed image section exceeds 80 percent at 20 cycles/mm for photoelectrons of two volts maximum energy, and exceeds 95 percent for photoelectrons of one volt maximum energy. From this, one concludes that for operation with visible light the image section response is essentially ideal out to 20 cycles/mm, and for ultraviolet operation with bi-alkali photocathodes (where the maximum energy of most emitted photoelectrons does not exceed two volts) the image section MTF is better than 80 percent.

The maximum achievable first scan MTF with a dielectric storage target is related to the thickness of the storage layer in a manner known as the Krittman effect.[7] Fig. 10 shows the calculated Krittman effect responses for several values of idealized target thickness. The measured response of the SEC vidicon is also plotted on the same scale. Assuming perfect responses for the reading beam and for the image section the effective thickness of the SEC target would be six microns based on the comparison of measured tube response and the Krittman effect curves of Fig. 10. Although the actual thickness of the SEC target cannot be physically measured in a manner that would be meaningful for determining effective electrostatic storage layers thickness, an indirect measure of the target thickness can be inferred from a measurement of the electrical capacitance of the target layer. Such a measurement made on the same tube used for the measured MTF curve of Figs. 9 and 10 indicated an effective target thickness of 7.5 microns. Since that is thicker than the Krittman values of Fig. 10, one concludes that the target thickness determined by capacitance measurement do not directly correspond to the image storage thickness that determines the Krittman response. A more significant conclusion is that it is almost certain that the present tube MTF is almost completely limited by the thickness of the target. Fortunately, Westinghouse is soon to start producing higher capacitance and presumably thinner targets in future SEC tubes for Princeton.

STACKING OF FRAMES

The stacking or addition of successive exposures of the same object in order to extend the photometric range of the sensor is quite practical as demonstrated by Crane[3]. The television data in digital form is easily manipulated by means of digital computers.

Since stacking of frame raises the total photoelectrons observed on each image element, the statistical precision improves as the square root of the number of frames stacked. It was anticipated that this procedure would reveal target or photocathode fine structure or gain irregularities that are normally masked by the quantum noise in the photoelectron flux in single frame exposures.

An experiment to explore the limits of frame stacking was undertaken in which 36 exposures of the same test pattern were made with the SEC television camera. Each frame was digitized and computer summations were made of eleven and thirty six frames. The television images were in effect averaged on an element by element basis.

Fig. 11 shows the same single scan line of digitized video data taken from a single frame, the average of eleven frames, and the average of thirty six frames.

The noise in the lowest intensity (norminally zero intensity) portions of each line is primarily preamplifier readout noise and it is seen to decrease as the square root of the number of frames averaged.

The noise in the highest intensity (nominally 1200 photoelectrons per image element) portions of each line does not decrease as the square root of the number of frames stacked. Between one frame and eleven frames the noise decreased roughly two to one instead of 3.3 to one.

Comparing the first broad pulse of full intensity signal from the left in the one frame and in the eleven frame cases, one sees some structure in the pulse top. Extending the average to 36 frames, the full intensity noise does not seem to reduce at all in peak-to-peak amplitude, and one can find several regions of correlation in the structure of the full intensity traces between the eleven frame and the 36 frame data.

It is clear that the statistical noise has averaged down to the point where it is no longer visible among the fine target structure revealed by the stacking process.

Methods to avoid the limit imposed on the photometric precision one can obtain by stacking of frames are clearly required if one hopes to effectively stack more than about eight frames.

There are three methods of alleviating the problem.

The simplest, and for many purposes the most practical, is to intentionally use slightly different registrations between the image and the target structure for each exposure. Then the target structure noise, which in single frames is below the statistical image noise, will be averaged down in the same fashion as the image statistical noise. This requires registering the image data between frames prior to stacking. This will be practical with many images. Crane[3] had done this for the eight frame stacking of Fig. 7.

A second method, quite the opposite of the first, is to calibrate the tube with sufficient numbers of frames so that the resulting calibration library has sufficient photometric precision to serve as a means of calibrating out tube structure. This required extensive calibration in terms of the numbers of frames required, as well as precise registration of frames both for calibration and observational exposures. Efficient computer data handling is required to pursue this method.

A third solution, independent of, and possibly in addition to either of the foregoing, would be to improve the SEC vidicon target to reduce the grain structure. Some target changes are currently contemplated primarily to achieve higher photoelectric capacity and higher MTF. Perhaps grain characteristics can also be improved.

It should be pointed out that the requirement to stack frames only arises where more than about 2000 photoelectrons are to be gathered on any of the 350,000 picture elements usually available. Many astronomical observations do not even "fill" a one frame exposure. The six hour exposure time on the 200 inch Hale Telescope used on PHL 957 (Figures 2 and 3) could have been extended to 24 hours without filling the tube nor resorting to trailing the object along the slit jaws!

OPTICAL SCATTERING WITHIN IMAGE SECTION

Some high contrast photometric applications are quite sensitive to a source of error analogous to flare in a photographic camera, e.g. photometry of galaxies. A potential source of scattered image light in the SEC vidicon is the semi-transparent nature of the photocathode. A portion of the light flux imaged on the photocathode passes through the photocathode and falls upon the target structure five inches (13 cm) beyond. Since the target structure in standard SEC tube construction is quite optically reflective, a portion of the light flux that first passed through the photocathode will be reflected from the front surface of the target structure back to the photocathode causing an illumination induced background of questionable uniformity.

Westinghouse has coated the front surface of the target with fluffy black aluminum to serve as an optical absorber.

In a test for image section scattered light suggested by Wampler of the Lick Observatory a small central portion of the photocathode window is covered with a patch of opaque tape and the entire remaining active photosurface is then intensely illuminated. The distribution and amount of scattering of light to the shielded portion of the photocathode can then be evaluated.

Figure 12 shows oscilloscope traces of the resulting video signals obtained during such a test at Princeton. The upper and middle traces were obtained with a conventional tube without the black target coating, while the lower trace was obtained while testing a tube with the fluffy black coating.

The opaque test patch covered a 0.25 inch (6.3 mm) square near the center of the photocathode. The illuminated are was one inch (25 mm) square, the full active area. The area covered was about six percent of the active area while the balance of 94 percent was subjected to full and then, many times full, illumination.

The upper portion of Figure 12 shows the reference condition with nominal full scale illumination and signal output from the photocathode and essentially zero signal from under the patch.

The middle portion of Figure 12 shows the signal obtained with sixteen, forty, and one hundred fold overexposures of the uncovered photocathode area. The resulting scattered light background is seen to be uniformly distributed under the patch without any leaking or blooming evident near the edges of the patch. By comparison with the upper trace it is seen that a forty fold overexposure of 94 percent of the photocathode leads to a normal full scale signal in the covered test patch. So, one can say that the scattering is 2.5 percent of the total illumination over the bulk of the photocathode. Of course, in most practical observing situations the overexposed portions of the photosurface would be only a small fraction of the total area, not the 94 percent used in the test.

Although a reference condition is not shown for the bottom trace, it shows the test patch signal during a 100 fold overexposure of the tube with the coated target. The full scale signal level was equal to that obtained under the patch during the 100 fold overexposure. Therefore, the scattering fraction in the case of the tube with the black target coating is only 1 percent of the total illumination.

Since that is a factor of 2.5 lower than in the uncoated target case, and there appears to be no significant disadvantages associated with the black target coating, all future Princeton tubes will have the coating.

PERMANENT MAGNET FOCUS

The photocathode dark current and other background emissions within the image section are strongly influenced by temperature.[8] The maintenance of a low image section temperature of about -20°C is nearly essential to obtain very long exposures of several hours duration without significant background contamination.

For ground based work, various refrigeration schemes can be employed, but for future operation behind a diffraction limited orbital telescope it would be highly desirable, if not essential, to not dissipate the heat generated by an electromagnetic focus coil. This has led to the development of a permanent magnet assembly to provide the focus field for the television tube. The alternative of electrostatic focus is unacceptable because of lower MTF and geometric distortion. The 80-gauss focus field, when electromagnetically generated requires about 10 watts in a practical design for the 1 inch (25 mm) target tube. A 2" x 2" (50 x 50 mm) target tube would require approximately 60 watts.

Princeton has undertaken the development of a permanent magnet focus assembly. A schematic of the current design is shown in Figure 13. The 80-gauss field is generated by the two axially magnetized permanent magnets. The field is flattened by tapering the wall thickness of the inner cylinder connecting the two magnets. The return path through the outer shell minimizes the stray field. This stray field is an important consideration in space applications because of the moment generated from interaction with the earth's field and the resultant effect on the pointing stability of the satellite. Of course, it is also important to shield the image section from external magnetic field changes during an exposure. The outer shell also serves as an external field shield.

A prototype of the permanent magnet focus assembly of the configuration shown in Figure 13 is currently being evaluated at Princeton.

FUTURE PLANS

Princeton under NASA sponsorship plans to continue the development of the SEC vidicon (currently Westinghouse type WX-31718) in order to exploit its capabilities as both a ground based astronomical sensor and as a key component in future spacecraft observatories.

An SEC vidicon television camera is currently being built for Flight 9 of Stratoscope II, expected to occur in early 1973. This camera will replace the 70-mm film camera and is expected to increase the system sensitivity by at least two stellar magnitudes. This flight will also be a very good test of the television sensor's performance with a nearly diffraction limited telescope.

A second television camera is being built for a sounding rocket payload. The television camera will record the spectra from an objective grating echelle spectrograph. This payload will be launched in the summer of 1972.

The next phase in the image sensor development will be to incorporate a higher capacitance target in the tube. This is expected to increase the dynamic range and also improve the target MTF since the higher capacitance target should exhibit a lower effective thickness. Work will also be initiated to make a red sensitive version of the tube and still maintain the low internal background in the image section in the presence of Cesium.

For some applications, e.g. the proposed Large Space Telescope (LST), the total number of image elements available with the current tube is marginal. A program has recently been initiated to improve the total resolution of the image sensor, both by increasing the MTF in cycles per mm and also be enlarging the image area.

The first step will be to determine the feasibility of making a higher capacity SEC target that is 2 inches square (50 x 50 mm) and rugged enough to withstand the launch environment. Targets with a narrow support down the middle will be considered. An attractive alternative to the large diaphragm is a solid substrate target. In this case the target must be exposed and read out from the same side. Rotating the target 180° appears to be the best scheme and does appear feasible with proven techniques. With a solid substrate the target size is no longer limited by fragility but by the electron optics required to achieve a uniform high resolution scan by the electron reading beam.

A higher capacitance target is highly desirable to maintain the dynamic range in photoelectroncs per picture element as the picture elements are made physically smaller. It also appears necessary to make the KC1 layer thinner in order to improve the intrinsic resolution of the target in first scan readout, (see Figure 10). Fortunately higher capacitance targets can also be expected to be thinner.

The possibility of a large silicon target tube is also being explored. The main uncertainty here is, again, the manufacturability and ruggedness of the thin silicon diaphragm. Equally important is the question of target dark current, i.e., the period over which it can integrate.

It may be possible to develop a basic large tube that could take either the SEC or silicon diode target. The silicon targets are made by several manufacturers, including RCA and Texas Instruments.

ACKNOWLEDGMENTS

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FIGURE CAPTIONS

Fig. 1 Photograph of SEC vidicon (type WX-31718).

Fig. 2 Digitized TV image of spectrum of PHL-957.

Fig. 3 Processed spectrum of PHL-957.

Fig. 4 Portion of Palomar plate showing NGC 3845, 3841, and 3842.

Fig. 5 Page Printout of TV digitized image of NGC 3845.

Fig. 6 TV digital image, 2 minute exposure, NGC 3841 and 3842.

Fig. 7 Digital stacking of eight frames, total exposure 17 minutes, NGC 3841 and 3842.

Fig. 8 Photoelectric Transfer Function.

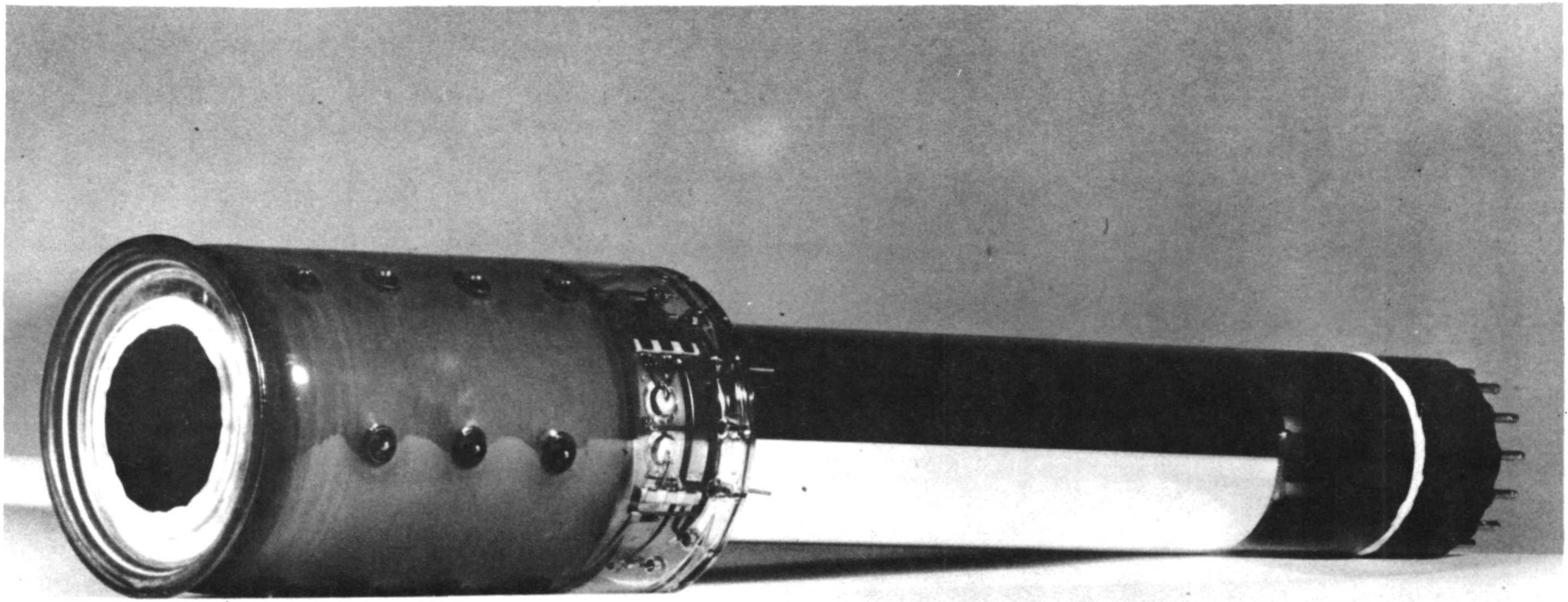
Fig. 9 Modulation Transfer Function.

Fig. 10 Krittman effect MTF's.

Fig. 11 Stacking of digitized TV data.

Fig. 12 Image section optical scattering data.

Fig. 13 Schematic - Permanent Magnet Focus Assembly.



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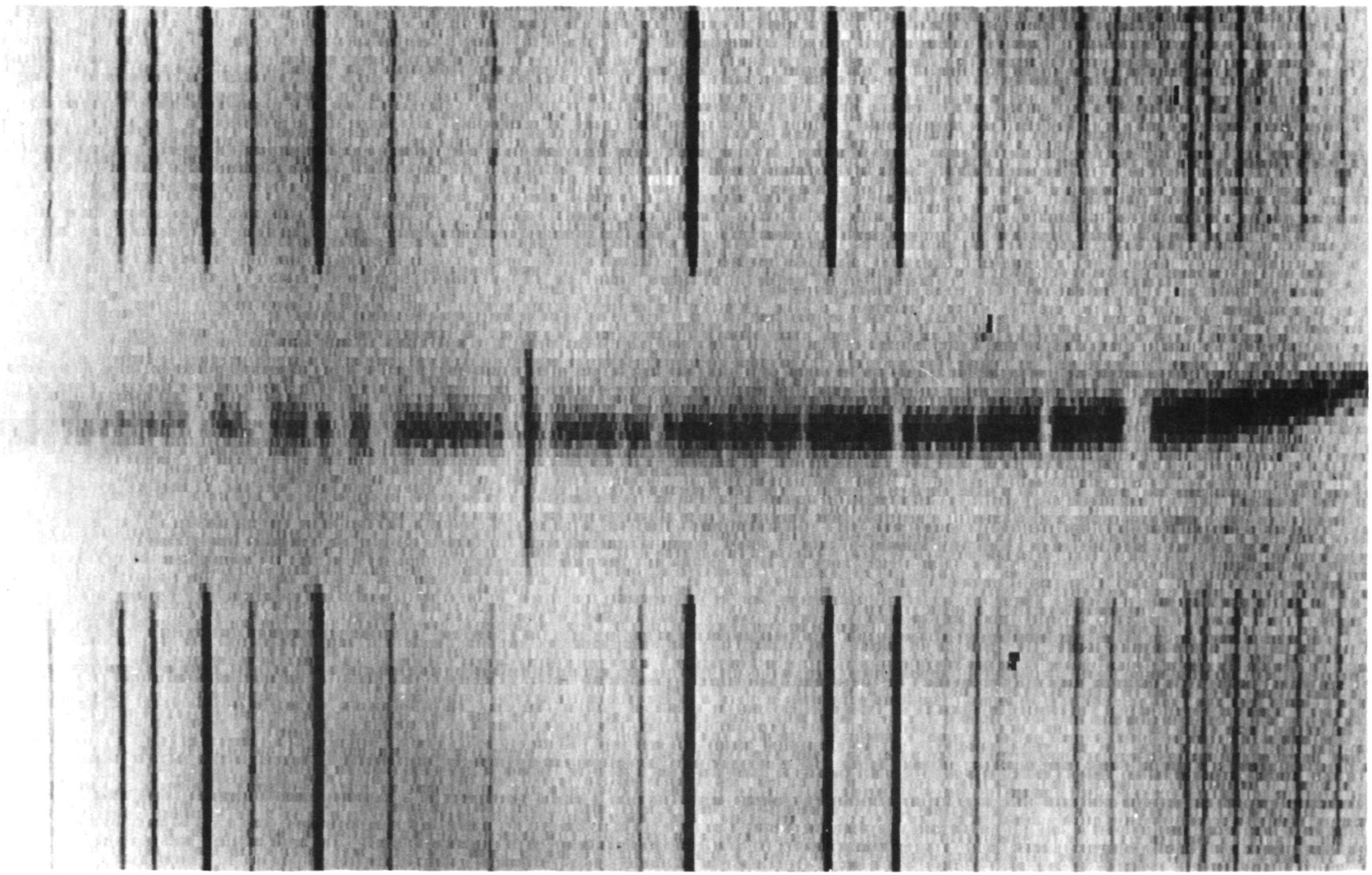


Fig. 2 Digitized TV image of spectrum of PHL-957.

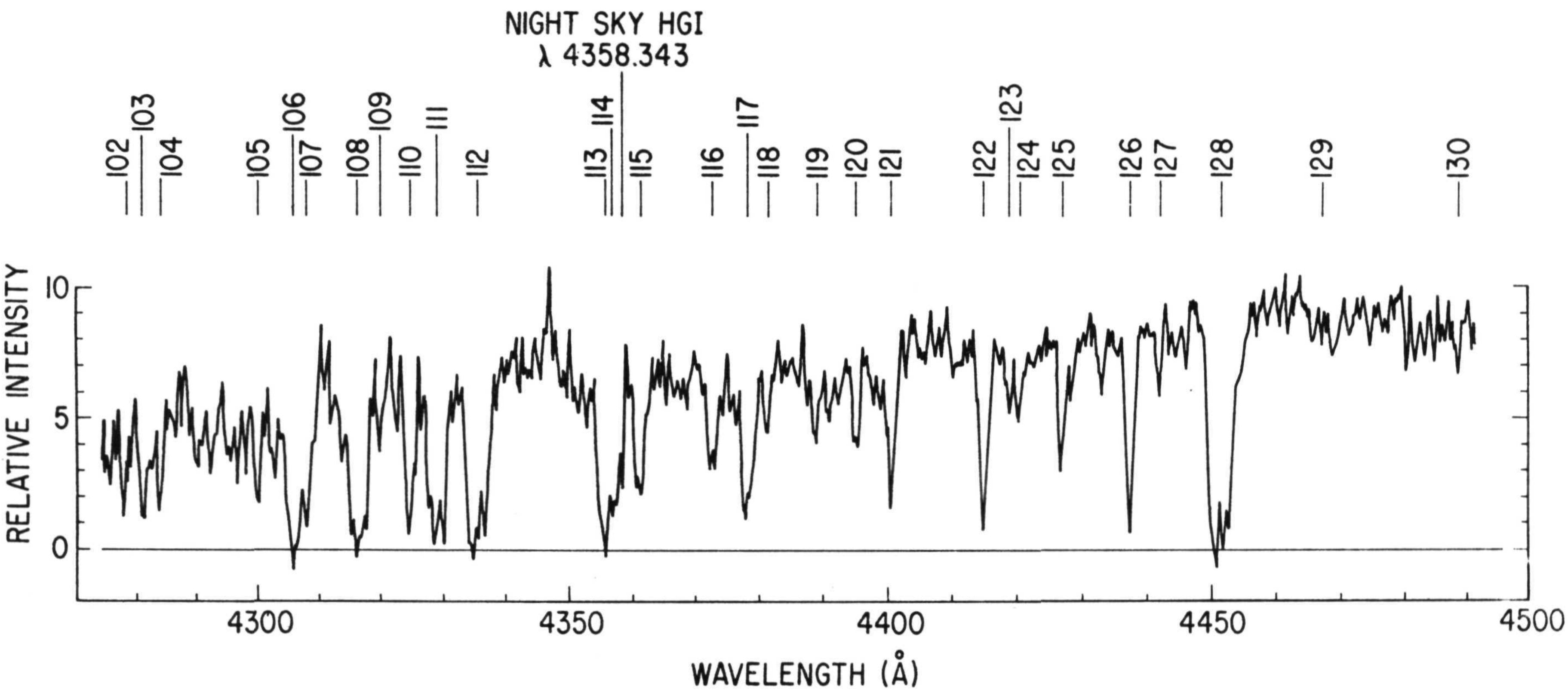


Fig. 3 Processed spectrum of PHL-957.

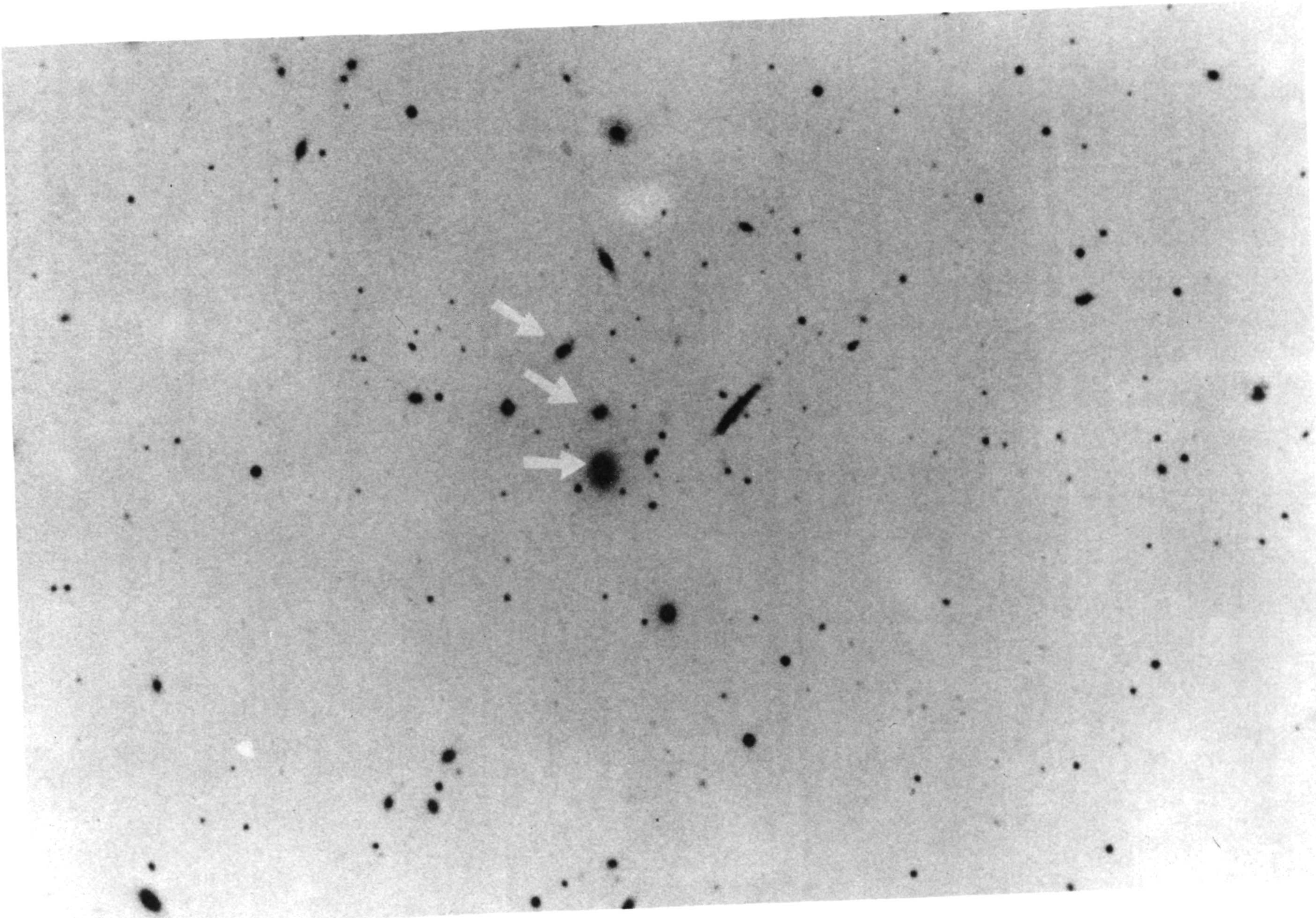


Fig. 4   Portion of Palomar plate showing NGC 3845, 3841, and 3842.

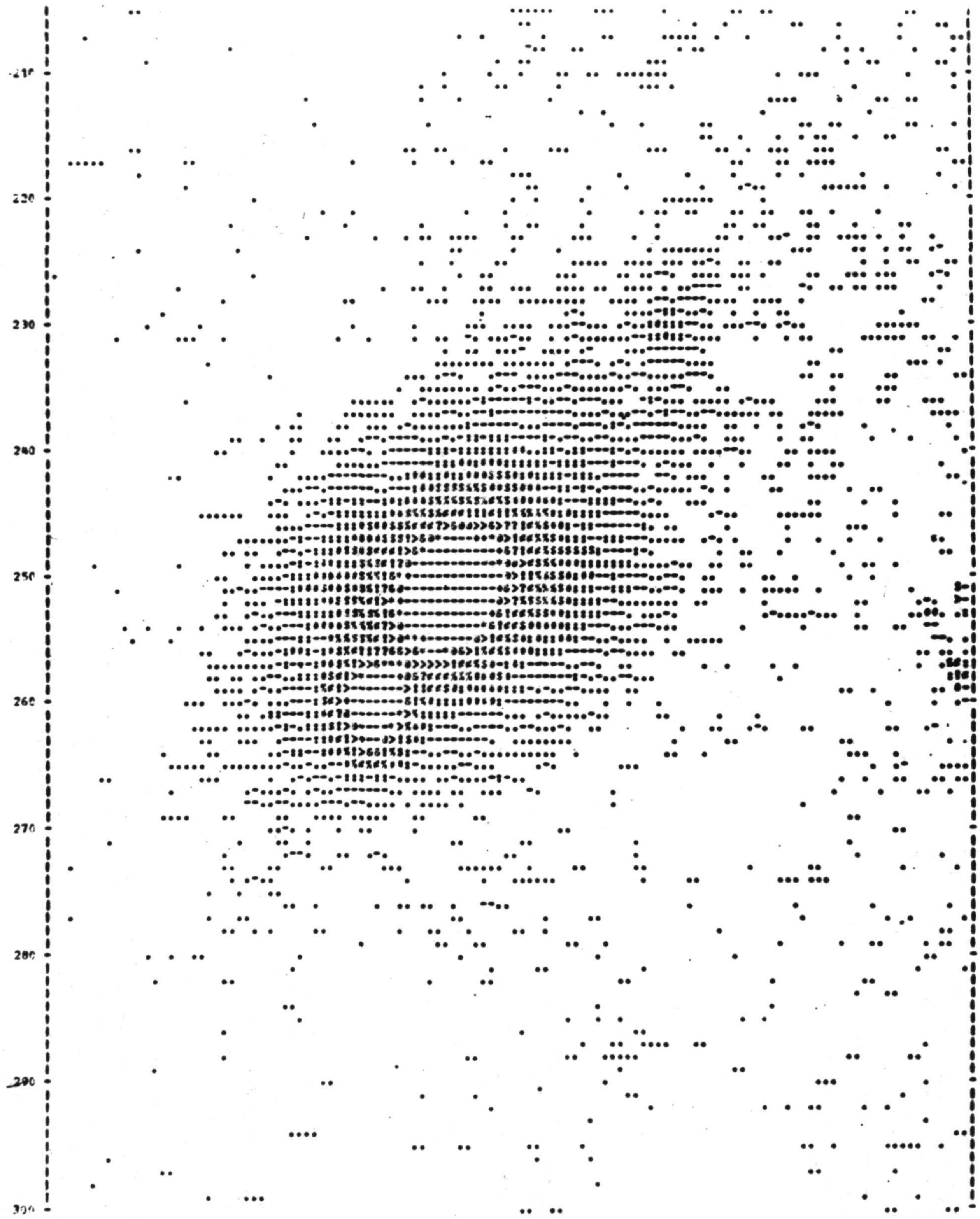


Fig. 5 Page Printout of TV digitized image of NGC 3845.

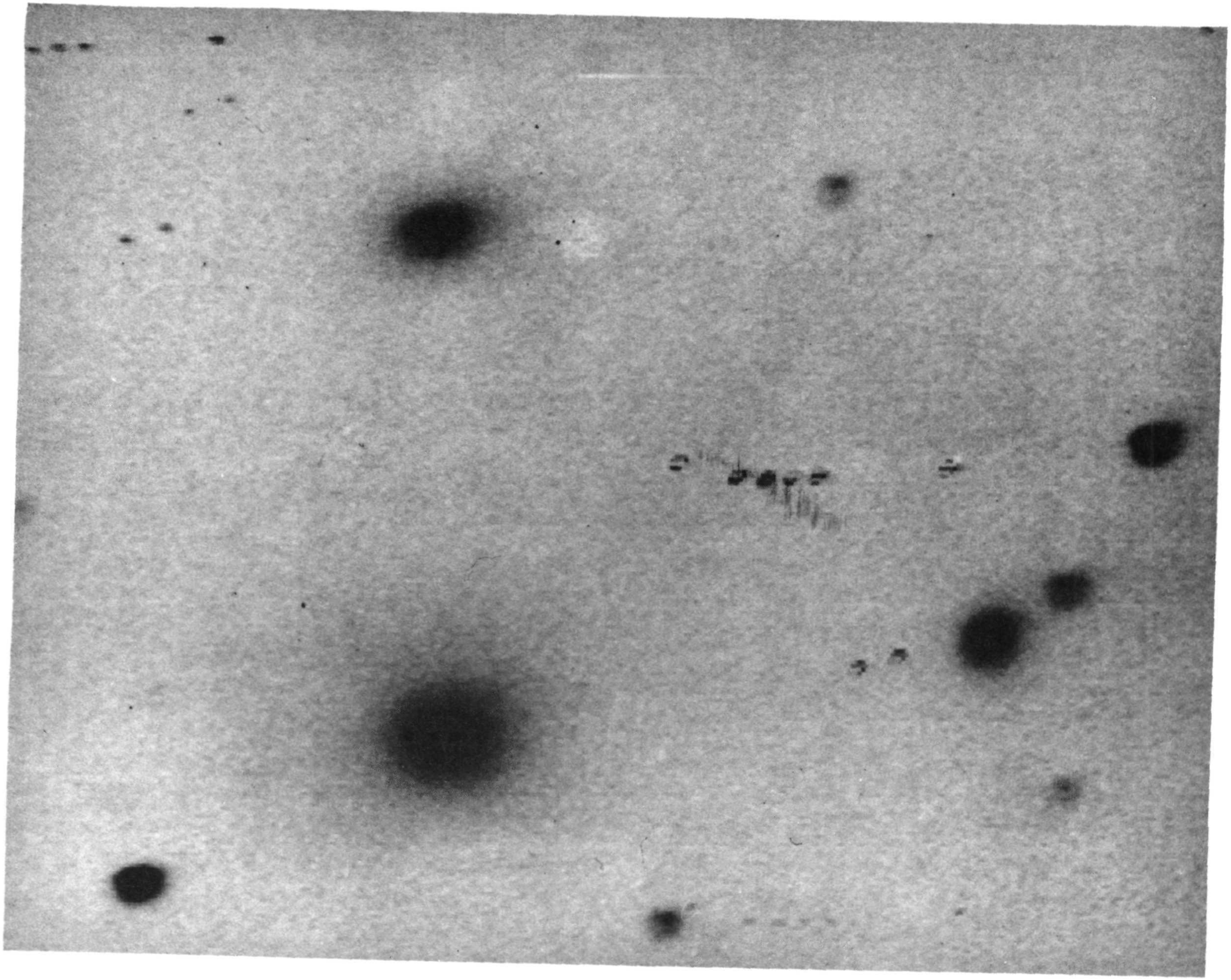


Fig. 7 Digital stacking of eight frames, total exposure 17 minutes, NGC 3841 and 3842.

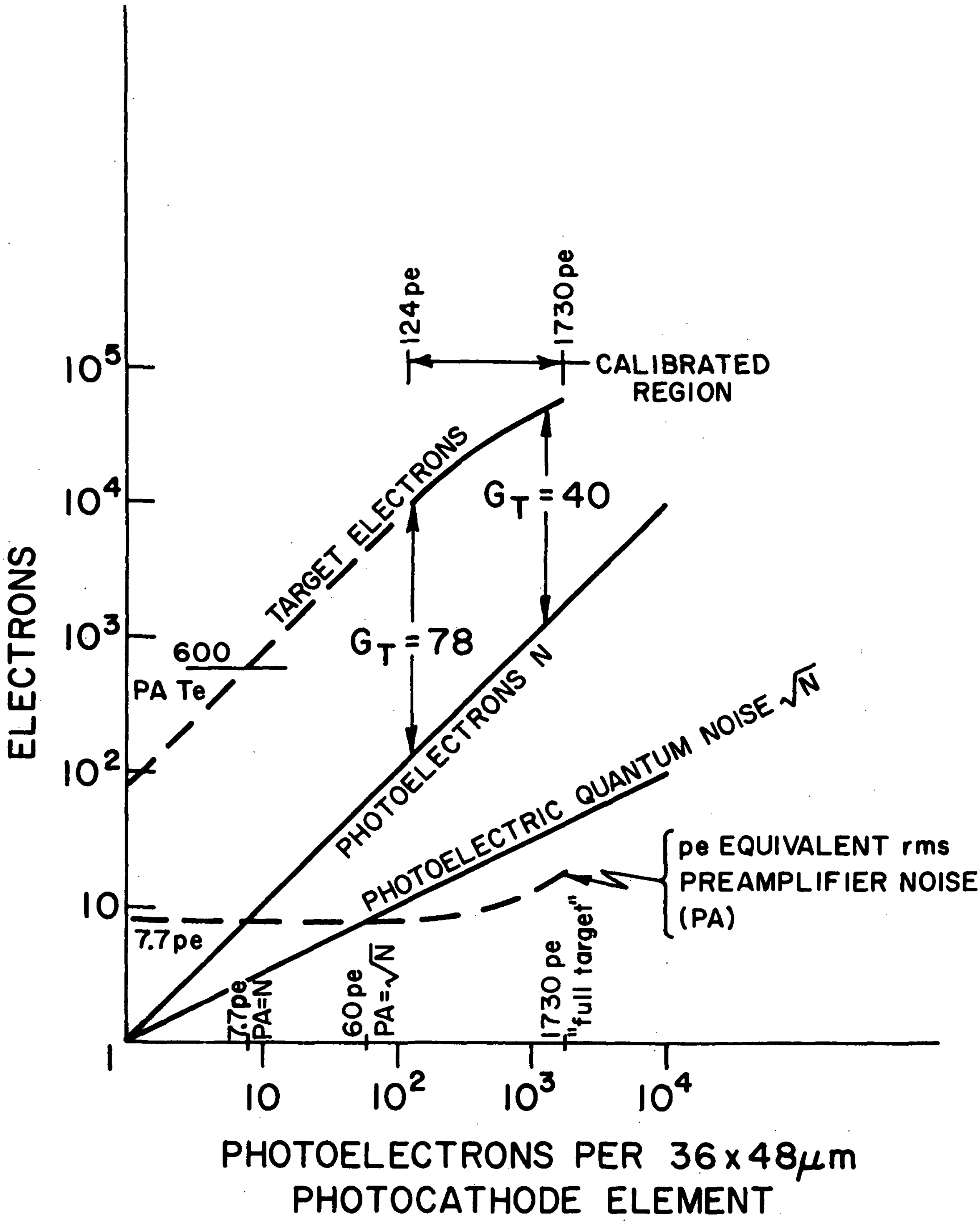


Fig. 8 Photoelectric Transfer Function.

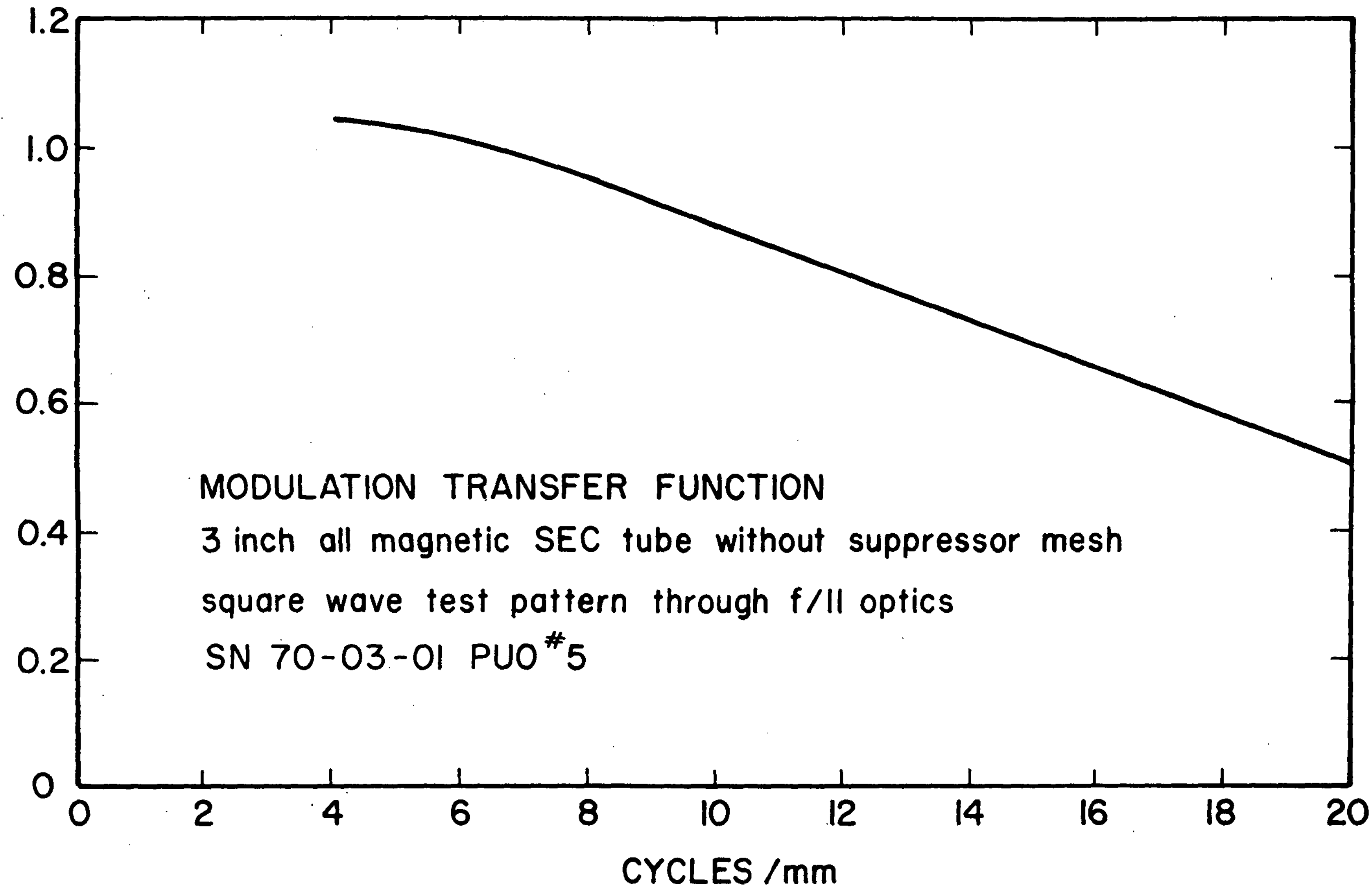


Fig. 9 Modulation Transfer Function.

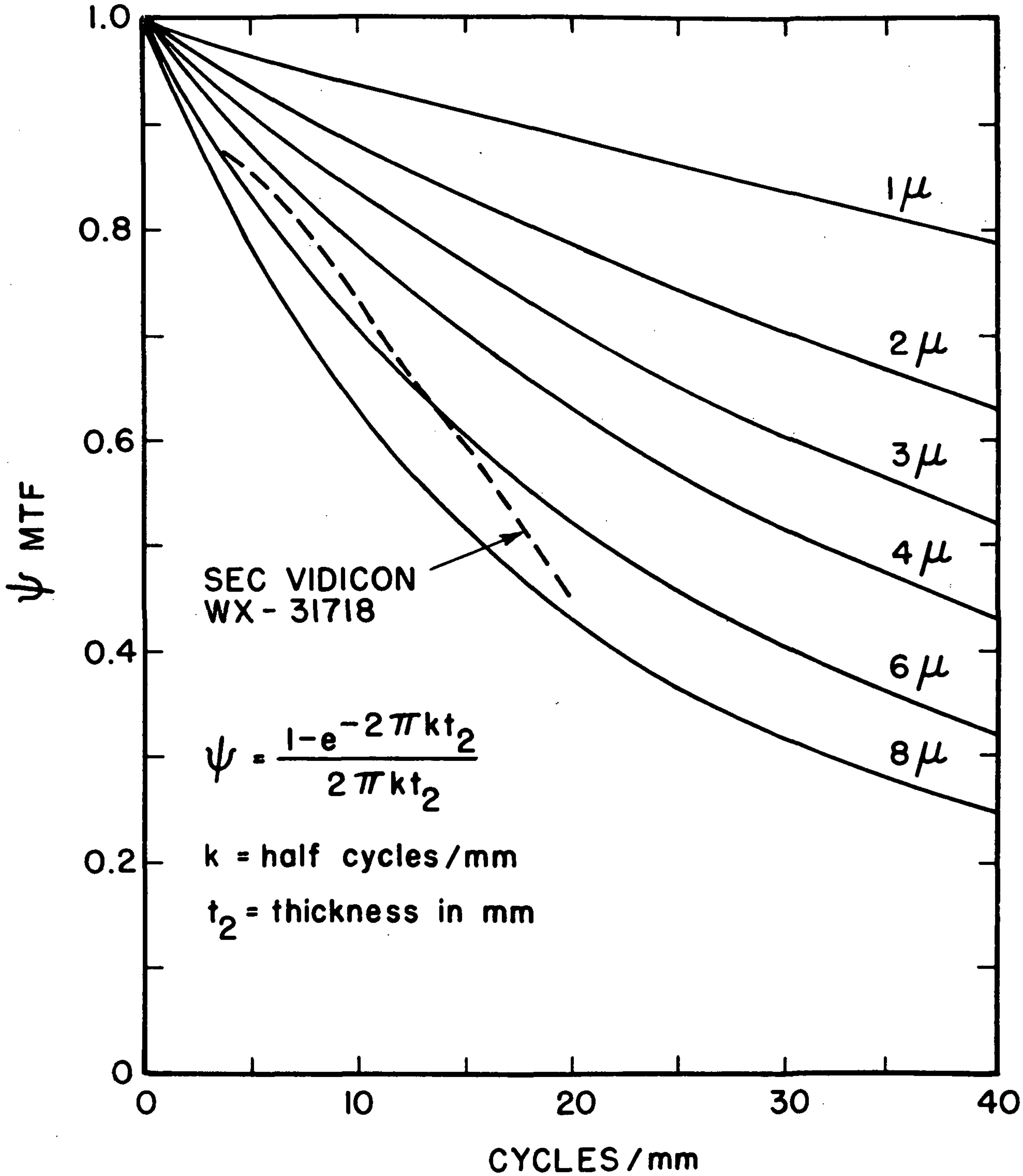


Fig. 10. Krittman effect MTF's.

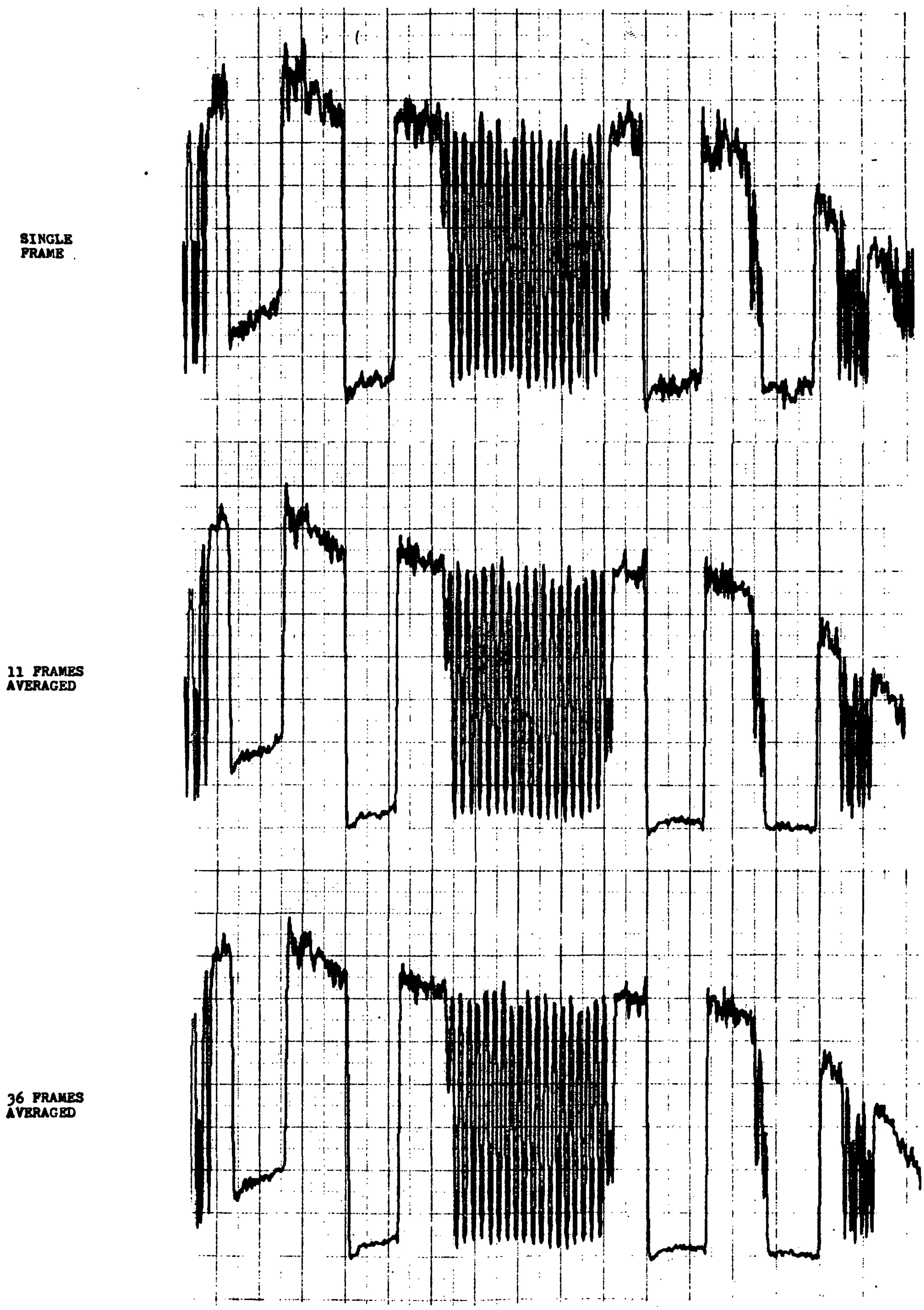
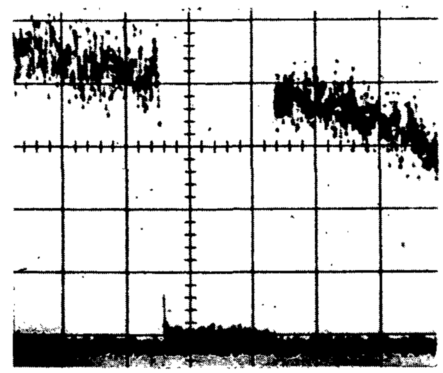


Fig. 11 Stacking of digitized TV data.

REFERENCE
EXPOSURE
WITH BLACK
PATCH ON P.C.

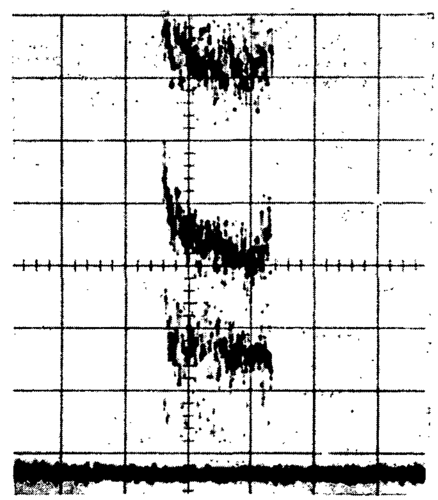


100 X

40 X

16 X

REFERENCE EXPOSURE



100 X
REFERENCE EXPOSURE
WITH BLACK ALUMINUM
TARGET COATING

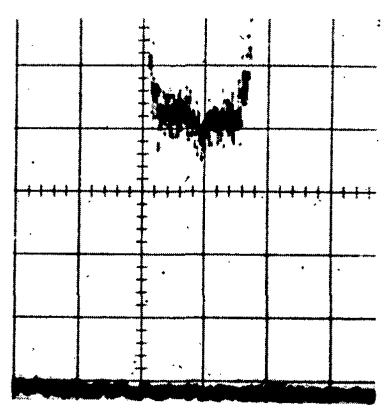
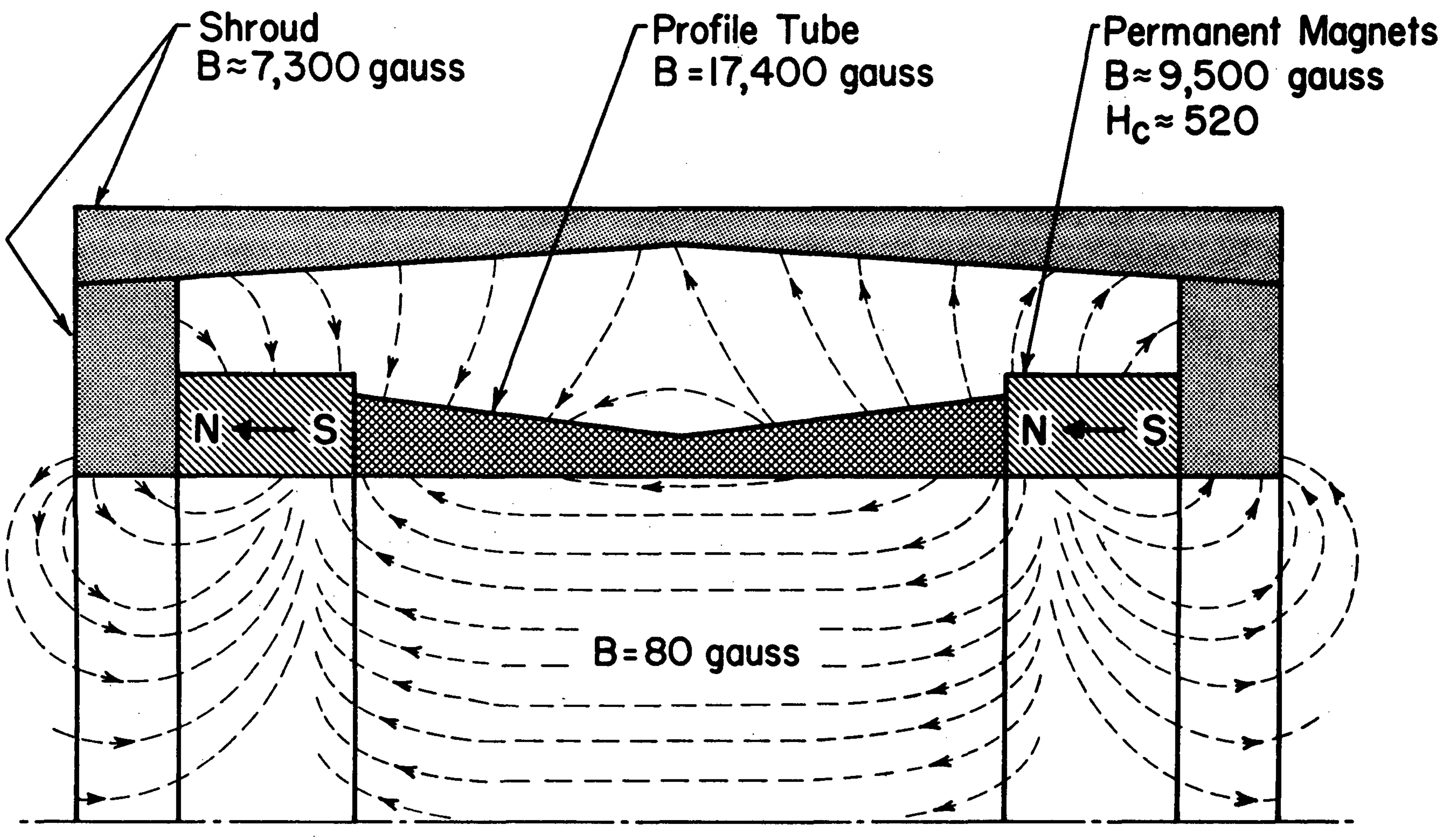


Fig. 12   Image section optical scattering data.



Thickness of profile tube is tapered such that the flux density (B) in the iron is constant having a value of 17,400 gauss. The magnetizing force (H) required to sustain this field is 80, thus producing an axial field of 80 gauss within the interior of the cylinder.

Fig. 13 Schematic-Permanent Magnet Focus Assembly.