NOISE MEASUREMENTS IN
LASER MICRODENSITOMETRY

by

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1972
STATEMENT BY AUTHOR

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ABSTRACT

A laser microdensitometer prototype was constructed at the Optical Sciences Center in order to study noise effects in film when scanned with small shaped spots on the order of 3 μm in diameter. The films included in this study were Kodak Plus-X Aerographic Film 5401, Kodak High Definition Aerial Film 1414, and Kodak High Definition Aerial Film 3404.

The evaluation of noise during scanning includes the determination of noise as a function of scanner defocus and density level as well as an investigation of the Wiener spectrum (noise power spectrum). This study indicates that the peloid particles imbedded in the backing of some thin base films have a significant effect on the output of a scanning system utilizing coherent radiation due to the phase perturbations introduced into the wave front as it passes through the material.

It has been shown that the noise power spectrum is an effective tool to be utilized in system analysis. Through Fourier techniques the presence of a faulty analog-to-digital converter was discovered which added artifacts to the power spectrum output from the system. The presence of the converter artifacts does not seriously effect the validity of the granularity data collected. The Wiener spectrum data, however, were inconclusive due to the poor statistics utilized.
CHAPTER 1

INTRODUCTION

The evaluation of imagery on photographic materials requires the measurement of transmission or density as a function of distance along the image. High quality optical systems and photo-sensitive materials with resolving power on the order of 600 cy/mm or greater require that the measuring device be such that the pertinent information may be extracted from the imagery without undue degradation from the recording system. This requires that the area of the scanning spot of the microphotometric system be much smaller than the finest detail of interest.

Various devices, referred to as microdensitometers, have been designed for this purpose and the optical arrangements have been documented in the literature.\textsuperscript{1-4} Most of these devices utilize an incoherent source of radiation with a condensing system to image a small spot of radiation on the sample. The condensing system is essentially a Kohler illumination system with a compound microscope substituted for the usual microscope condenser system.

The spot of radiation on the sample is imaged onto a limiting aperture, referred to as the postslit, by another microscope system. The radiation is then transferred to a photomultiplier tube by a condenser system. If the irradiated area of the sample, as projected on the postslit, is much larger than the postslit itself then deleterious
effects are introduced primarily due to the flare light introduced into the collecting optics.\textsuperscript{2,4} This results in degradation of scan information where large density differences are present in the scanning field. If, however, the irradiating spot is reduced by means of a preslit so that the spot on the image is only slightly larger than the postslit projection, then much of the scattered radiation is reduced with improvements appearing in the output of the system. There is a limit to the amount of reduction permissible before the coherence of the radiation is modified introducing nonlinearities into the system.\textsuperscript{4,5}

In addition to the difficulties introduced by the effects of partial coherence there are many other problems associated with high quality microdensitometer systems.\textsuperscript{2} These include the temporal stability of the radiation source and the spatial uniformity of the radiation in the scanning plane. The electronics of the system present numerous problems many of which may be reduced by utilizing slow scanning rates.

Extremely low radiation levels tend to decrease the signal-to-noise ratio, reducing informational accuracy, in most present systems designed to scan with slit or spot areas on the order of 500 $\mu$m$^2$ or less. In addition to the coherence problems introduced by small scanning apertures, the radiation (flux) levels are usually quite low (on the order of nanowatts) and electronic noise becomes significant especially at higher density levels. In many systems the noise level limits the density or the minimum area of the scanning spot that may be utilized. The electronic noise mentioned here is not to be confused with the grain noise, or granularity, associated with the random grain structure of the photographic material.
The ability of the system to maintain focus over the area of the sample to be scanned presents further difficulties. Maintenance of the focal position within ±1 µm is desirable when using measuring objectives with a numerical aperture of 0.3 while ±2 µm is required for a 0.65 numerical aperture (assuming image detail on the order of 5 µm or greater). The effect of defocus is to change the radiation distribution and projected aperture size on the sample reducing the quality of the system and hence degrading the information obtained from the imagery.

The silver photographic image is made up of an inhomogeneous arrangement of silver particulates in a gelatin or other suspending medium. When this type of image is scanned with a small aperture, the random variations, or noise, in the density will be apparent in addition to the desired information, or signal. If the signal-to-noise ratio is much greater than unity, the signal may be extracted without major difficulty. The noise in photographic material, or granularity, is defined in the literature as "...the spatial variation of density which is observed when numerous readings are made with a densitometer having a sufficiently small aperture (usually on the order of microns)."6

In order to determine a single number which might describe the noise levels of different materials, investigators have developed various techniques.6-11 The noise is usually assumed to approach a Gaussian or normal distribution about a mean value. Hence, the variability of density about the mean may be characterized by the standard deviation, σ(Î¬), termed the R.M.S. granularity. This is an accepted measure of photographic grain noise used by the industry today. However, this
value is a function of density, the area of the scanning aperture, the type of emulsion, and development chemistry. An over simplified model has been developed to show the relationship between granularity, the ratio of the mean grain area to the area of the scanning aperture, \( a/A \), and the average density of the material, \( \bar{D} \), and is given by a relatively simple extension of the Nutting equation: \(^\text{12}\)

\[
\sigma(\bar{D}) = 0.66(a/A)^{\frac{1}{2}} \bar{D}^{\frac{1}{2}}.
\]  

\( (1) \)

It can be seen from Figure 1 that as the area of the scanning aperture approaches the order of magnitude of the mean grain area the granularity, \( \sigma(\bar{D}) \), becomes quite large. Hence, if this model holds for small scanning apertures it is obvious that only films with very small density fluctuations (i.e., small mean grain areas) could be scanned such that the signal may be readily extracted. This presents no great problem since such films have inherently high information storage capabilities and are the type of materials that require exceptionally small scanning spots for image evaluation.

With the previous points in mind, a scanning system has been developed which is an attempt to negate some of the problems encountered in the usual incoherent microdensitometers. Spot sizes on the order of a few micrometers in diameter have been utilized but measurements have been limited to the determination of noise.

A continuous wave laser is an ideal source for such small spot microdensitometry. \(^\text{13}\) The single wavefront nature permits the attainment of shaped small spots on the order of 3 \( \mu \text{m} \) or less with extremely high energy densities. The coherent nature of the radiation in the laser
Figure 1. Relationship between Granularity and Density for Various Ratios of Mean Grain Area to Scanning Aperture Area.
microdensitometer may cause differences in the granularity and image structure data compared to an incoherent microdensitometer.

Numerous problems may be anticipated in view of the fact that the scanning spot consists of coherent radiation. The extensive temporal coherence of the source will allow for the creation of interference fringes between the front and rear surfaces of the film as well as between the film surfaces and the optics, if the system is not properly constructed. Furthermore, due to the temporal coherence one would anticipate considerable differences in the out of focus images when considering a similar condition with an incoherent system.

A further point that bears mention is that a hologram is really an out of focus image. One may anticipate that what is observed in the coherent microdensitometer may be described as a hologram of the grain structure inherent in the photographic material.

Since a coherent system transfers radiation with the optics in a manner considerably different than an incoherent system, it is obvious that the collection optics should have a significant effect on the output of the system. If there are no optics interposed between the film sample and the sensor, which must collect all radiation exiting from the film, there is no possibility of introducing nonlinearities into the system.
CHAPTER 2

BASIC OPTICAL SYSTEM

A prototype laser microdensitometer has been developed at the Optical Sciences Center as a segment of this thesis work in order to study the noise problems associated with coherent microdensitometry. The basic system, shown schematically in Figure 2, is constructed on a Beck lathe bed optical bench.

A helium-neon laser (Spectra Physics Model #133) with a rated power output of 1 mw is used in this system. The laser has better than 1% long term stability after a one-half hour warm-up period. In addition, no detectable high frequency components are present in this laser up to 1000 hz (higher frequencies were not tested).

A 10X microscope is used as a beam diverger in conjunction with a pinhole spatial filter. This filter eliminates all but the central order of the diverger output. Hence, the output of the diverger-filter combination, which overfills the entrance pupil of the following microscope objective, is a beam of coherent radiation with approximately a Gaussian intensity distribution.

A pair of high quality, flat field, achromatic 10X microscope objectives were chosen for the purpose of imaging a scanning spot on the sample and transferring the radiation to the photomultiplier tube. The objectives were designed for use with a cover glass and for a tube
Figure 2. Optical Schematic for the Laser Microdensitometer.
length of 160 mm. Though cover glasses were not used, all work was done at the designed tube length. A star test was performed on 10X objectives at a tube length of 160 mm, without cover glasses. This indicated that no significant aberrations were introduced under the above conditions.

The entrance pupil of the illuminating objective is overfilled with a Gaussian shaped beam such that approximately 50% of the beam diameter is utilized. This results in a relatively flat intensity distribution at the entrance pupil. The illuminating objective then forms an image which is similar in profile to an Airy disc. One would anticipate an Airy disc only if the entrance pupil is uniformly filled and if the imaging objective is diffraction limited (without aberrations). The image formed by the illuminating objective did approach an Airy disc in that no aberrations were noticeably present (in the star test) while the distribution of radiation was radially symmetric. This image is the spot of radiation used in scanning the photographic material. Approximately 84% of the energy in this spot lies within the first dark ring with radius, \( R \), given by

\[
R = \frac{0.61 \, \lambda}{n \sin u}
\]  

(2)

where \( \lambda \) is the wavelength of radiation being used and \( n \sin u \) is the numerical aperture of the illuminating objective. In this case the calculated spot size radius should be 1.54 \( \mu m \) while a measured radius of 1.8 \( \mu m \) is obtained with the laser microdensitometer.

The scanning spot size was estimated by moving a blackened knife edge through the scanning spot and recording the output. The levels of the recorded output at 10% above the minimum, and 10% below the maximum
were chosen as including the majority of the energy in the scanning spot. The diameter of the scanning spot was then estimated from the linear distance between these two levels.

The film carrier was designed for this particular application to assure that the film sample could be held relatively flat over sample distances of 4 or 5 mm. The design of the carrier without the use of a cover glass reduces the problems of inter-reflections, dirt, and inhomogeneity of the glass. With the film laying on the carrier, the two clamps are placed on the sample and the thumb screws slowly drawn tight with a clamping action taking place. In addition to the clamping action, the film is pulled taut over the opening in the carrier.

This film carrier is mounted on a translation module (Kinamatic Series TT-110, Ardel Instrument Company, Inc.) such that the sample is moved through and perpendicular to the optical axis of the system. One revolution of the micrometer drives the translation module 0.025 inches. The translation module is coupled to a 20 RPM Bristol motor for scanning the sample at a rate of 212 μm per second. A flexible coupling, made of tygon tubing, is utilized between the motor and the micrometer drive of the translation module.

The illuminating and collecting objectives are maintained in their same relative positions with the best focus of the illuminating objective being imaged onto an opal glass in front of an RCA 1P21 photomultiplier tube (PMT). The dynode circuit for the 1P21 is one designed for low electronic noise (see Appendix A). The PMT is operated at approximately 750 v utilizing a regulated DC power supply (Power Designs Pacific, Model #2K-10). This operating voltage is the lowest level at
which the PMT responds properly in terms of linearity (Appendix A).

Operating at the lowest voltage level possible assures that a minimum
of electronic noise will be introduced into the output of the PMT.
Even utilizing the PMT in this low gain fashion requires the use of
neutral density filters in front of the beam diverger to attenuate the
radiation and avoid saturating the photocathode of the PMT.

The output of the PMT is read as a voltage drop over a wire
wound resistor in parallel with a capacitor. The capacitor acts as a
filter with a half-power point at approximately 900 Hz. (See Appendix
A for evaluation of the electronic filter.) This is well above the fre­
cuencies of interest which are, at most, on the order of 200 Hz. Hence,
the filter does not degrade the information in the system but does elim­
inate higher frequency noise due to the electronics, the PMT, and, pos­
sibly, the laser.

The dynode resistor chain used with this IP21 is one designed
for low electronic noise. This, in addition to the electronic filter and
the low operating voltage of the PMT, assured low electronic noise from
the PMT which was not measurable on a sensitive oscilloscope.

The voltage drop across the load resistor of the PMT (which is
proportional to the sample transmission) is taken in analog form by the
Hewlett-Packard 5480A Signal Analyzer, converted into digital data and
stored in the 5480A. The 5480A is a storage oscilloscope designed for
looking at signals buried in noise. The capabilities of this system,
however, are not utilized in this work. The signal analyzer was chosen
for data collection purposes since it has an effective analog-to-digital
converter and digital storage system which may be interfaced with a
computer. The information, once stored digitally, may be displayed on the oscilloscope for visual evaluation before further data processing is undertaken. The system is capable of storing up to 1000 data points which may be collected at a rate of 2 points per second or as rapidly as 100 points per millisecond.

The laser microdensitometer system is not bandwidth limited by the 5480A which has a bandwidth of 50 Khz. The 5480A sample integration time is 1.2 ms with an analog-to-digital conversion resolution of 9 bits. At the scanning rates encountered in this work, the sample moves a total distance of 0.25 \( \mu \text{m} \) during this sample integration time.

The digital stored information is taken, on command, from the 5480A to the memory of the 2115A computer. The Hewlett-Packard 5481A utilizes a direct interface between the 2115A and the 5480A with software available to perform some operations on the data or to transfer the data to magnetic tape for further processing. In this situation the data was transferred directly to EDP tape for analysis using the University Computer Center's CDC 6400 system.
CHAPTER 3

DISCUSSION

The system described in the previous chapter was developed such that the problems discussed in Chapter 1 would be minimized or, ideally, eliminated. In most instances the problems encountered in normal microdensitometry have been eliminated in the laser microdensitometer system.

One major difficulty in microdensitometry is that partial coherence complicates the mathematical analysis of a system when an incoherent source is utilized with small illuminating apertures. Further problems are encountered when the collecting objective is used to image the sample onto the PMT (or an opal glass). Weingartner and Grimes have suggested that the nonlinearities due to imaging with partial or pure coherent radiation may be eliminated by collecting all of the transmitted radiation. The use of a laser source simplifies the mathematical analysis but may introduce other problems which, at this time, have not been investigated. Included among the possible difficulties are the effects of optical path variations in the photographic emulsion due to variations in refractive index, swelling of the emulsion, or variations in emulsion thickness in film manufacture.

Flare light in the optical system is usually a major difficulty in precise measurements. This light is introduced due to reflections between optical elements and reflections from the perimeter of the
optical system. The magnitude of the flare light is dependent, among other factors, upon the amount of sample that is illuminated. Ideally only the area of interest should be illuminated, but this is difficult to accomplish in most conventional systems while at the same time assuring that the illuminated area is aligned with the sampling aperture. In the laser microdensitometer system this problem is reduced due to the configuration chosen for the illuminating-collecting system.

The illuminating objective images a point source of coherent radiation into a diffraction limited pattern similar in structure to an Airy disc. This radiation distribution may be determined theoretically. Since approximately 84% of the incident radiation falls within the central area of the diffraction pattern, very little radiation is available for scatter from extraneous imagery. In fact, the remaining 16% of the energy is spread over a relatively large area of the sample imagery. The average energy density in the first bright ring is approximately 10% of that in the central portion, while the average energy density in the first four rings is 2.4% of that in the central portion. Hence, the amount of radiation that is scattered due to illuminating more than the desired area is at least an order of magnitude less than that in the area to be measured. This is the equivalent of increasing the illuminated area by 15% over the desired sample size area. An increased area of this magnitude would make alignment of the conventional postslit and preslit system quite difficult.

The temporal stability of the laser in use is better than 1% at the frequencies of interest over a long term period. This could be eliminated as a factor in system error by using a system which could
continuously monitor the output of the laser while sampling the output
of the system with a differential amplifier. In most cases 1% stability is much better than incoherent systems can offer unless a dual beam
comparison system is utilized.

In incoherent systems the radiation levels are such that it is
difficult to measure higher density regions of the photographic materi-
al without introducing significant electronic noise. The laser micro-
densitometer was conceived initially as a way to overcome this problem,
in addition to being able to produce extremely small spot sizes. Using
a 1 mw laser, the problem is not the lack of radiation but rather an
excess of radiation. The measured output of this laser was actually
1.95 mw. Due to the overfilling of the illuminating objective, approxi-
mately 1 mw is obtained at the sample plane. This gives an energy den-
sity of 143 watts/mm$^2$ when the scanning spot is 3 μm in diameter. This
high energy density, even with the low red sensitivity of the 1P21 PMT
requires the use of neutral density filters which are placed before the
beam expander. The advantage of such high energy densities is that the
PMT may be operated at its lowest gain reducing the amount of electronic
noise introduced into the output signal. In fact, it is possible to use
solid state detectors in place of the PMT further reducing the bulk of
the microdensitometer while increasing its reliability. During this
investigation a neutral density filter of approximately 1.0 density was
utilized while scanning samples with densities on the order of 1.40.

The high energy densities available in the scanning spot may
lead to deformation of the sample being scanned. While bleaching of a
blue dye image was noted in some color imagery, no significant
deformation was noted in black and white silver images. This problem should be further studied possibly utilizing an interference microscope to quantitate the amplitude as well as the phase deformations which may occur with high energy density scanning spots.

A major difficulty in microphotometric work is to assure that the sample stays in the focal plane. This positioning is quite critical and can seriously modify the intensity distribution in the scanning spot. This immediately degrades the information obtained and acts somewhat like a spatial filter eliminating the higher frequencies while modulating the lower frequencies.

It may be noted that the tolerances on focus mentioned in Chapter 1 appear rather stringent. In order to maintain a tolerance of \( \pm 1\frac{1}{2} \) \( \mu \)m, the question must be asked as to where one wishes to focus the system. For instance, Kodak 1414 film has a base thickness of approximately 37 \( \mu \)m, a dye backing of approximately 6 \( \mu \)m, and an emulsion thickness of 6 \( \mu \)m. It has been shown that the image depth below the surface of the emulsion can depend on the development time and the exposure levels.\(^7\) Hence, it would be important to maintain one constant focal plane but at what level in the emulsion should this plane be located? This question has not been answered in this paper or in the literature, to the knowledge of the writer.

Due to the size of the scanning spot and the nature of coherent radiation, it is quite easy to visually locate the approximate best focus. The use of monochromatic radiation does not create problems due to the sensitivity difference between the human eye and the PMT as would
be expected using an incoherent broad band source. In addition, chromatic aberrations of the objectives play no part in the image forming role.

The system focus of the laser microdensitometer is set electronically by selecting the position in which the grain noise is maximum. The sample holder is aligned so that the best focus is maintained ±5 μm over at least 3 mm of sample.

The present configuration of the system does have a limited dynamic range (2 decades). If the range is exceeded it is necessary to add or subtract neutral density filtration and recalibrate the system. The short dynamic range may be overcome by the use of a comparison (differential amplifier) solid state system or the utilization of a wide dynamic range photometer as recently described in the literature. The limited range of the present photometer system did not hinder the type of measurements made for this evaluation.
CHAPTER 4

DATA MANIPULATION

The micrometer translation stage is utilized to transport the sample material through the optical path of the system at a constant rate of 212 \( \mu \text{m/second} \). A total of 1000 sample points are collected and used for the calculation of the transmission and standard deviation (noise). These 1000 sample points are taken over 2.12 mm of the film specimen.

In order to vary the focal position, while maintaining the relative positions of the illuminating and collecting objectives, the film sample is moved along the optical axis of the system (Figure 3). The emulsion side of the film is maintained toward the source at all times.

With the film in the negative focal position, the focus of the beam is to the right of the sample. As the film is moved toward focus, the diffraction point image first impinges on the backing of the material. The spot then moves through the base and finally falls on the silver grained portion of the film.

When the film is scanned at various focal positions, it is effectively being scanned with different sized illuminating spots. In addition, the energy distribution in these spots varies as a function of focal position and, possibly, as a function of other aberrations present.
Figure 3. Film position relative to scanning spot.
in the illuminating objective. The relationship between defocus and theoretical spot diameter may be ascertained from Table 1.

**TABLE 1.**

<table>
<thead>
<tr>
<th>Defocus (µm)</th>
<th>Diameter (µm)</th>
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<tr>
<td>0</td>
<td>3.0</td>
</tr>
<tr>
<td>50</td>
<td>28.0</td>
</tr>
<tr>
<td>100</td>
<td>53.0</td>
</tr>
<tr>
<td>160</td>
<td>83.0</td>
</tr>
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The 1000 data points are stored digitally in the 5480A and displayed on the scope. This permits an immediate evaluation of the data, visually, to assure that obvious defects were not present in the sample area. Defocus, variation in average transmission with film position and large fluctuations in transmission due to dirt or scratches on the sample were causes for rejecting a data set. If the data set appeared to be satisfactory, the digitally stored information was then dumped to magnetic tape, utilizing the 2115A computer system, for further analysis on the University Computer Center's CDC 6400 system.

The 6400 computer was used to reformat the data points into transmission values and compute the average transmission and standard deviation in terms of transmission utilizing all 1000 data points per data set. In addition, the RMS noise (the standard deviation divided by the average transmission) was determined for each focal position.
Since the short form (32 Fortran statements) of the Fast Fourier Transform (FFT) was utilized to determine the power spectrum as a function of focal position, only 512 data points were utilized for each data set. This limitation (use of $2^n$ data points) is set by the subroutine FFT.

Prior to transforming the data, the average transmission was subtracted from each data point in order to remove the DC level. The FFT was then performed and the modulus of the data in transform space was determined. This information was then plotted as the power spectrum of the noise associated with the film and scanning system.
CHAPTER 5

SCANNING EFFECTS

Various effects, not found in incoherent microdensitometry, were noted while scanning silver halide photographic material using the laser microdensitometer. Incoherent microdensitometers might produce a chart recorder output, while scanning an evenly exposed piece of photographic material, that would resemble Figure 4. This output is in fact the result of scanning Kodak High Definition Aerial Film 1414 (Emulsion Number 3-2-1-1) on estar ultrathin base with the laser microdensitometer focused on the silver grain structure. (The film was processed in Versamat Type C chemistry at 80° F. at 3 fpm with only one processing rack.) Note that the variations around the average transmission appear to be normally distributed and may be assumed to be Gaussian allowing the application of Gaussian statistical parameters to describe the distribution.

It is quite apparent, however, that the chart recorder output shown in Figure 5 is considerably different than that in Figure 4. Likewise, it is apparent that the normal statistical parameters, i.e., mean and standard deviation, will not satisfactorily describe the noise, or deviation, present in this output. This output is from the same sample as before but with the laser microdensitometer focused on the backing of the material. This noise component is primarily due to the phase variations present in the backing of this particular material.
Figure 4. Chart Recorder Output with System Focused on Silver Grain Structure.

Figure 5. Chart Recorder Output with System Focused on Pelloid Particles.
These two noise components may be found in other photographic materials, especially in the thin or ultrathin base category. The pellloid particles, the primary contributor to the second noise component, are plastic particles approximately 2 to 5 \( \mu m \) in diameter embedded in the gelatin backing of the film. Data Corporation scanned 3414, a similar material with the pellloid backing, utilizing a 1.12 \( \mu m \) diameter spot in an incoherent microdensitometer and found that "tests indicate no contributions to granularity from the pellloid backing of this film sample."\(^{18}\)

The coherence of the laser microdensitometer makes this device sensitive to optical path differences and refractive index variations in the material being scanned. As long as the collection apparatus utilizes an optical system these phase variations will have a significant effect on the output of the scanning system. These variations produce phase perturbations in the wavefront as it passes through the material resulting in a nonlinear system in terms of intensity measurements as long as the collection optics are utilized.

The noise due to the pellloid backing has a significant effect on the total noise at all focal positions. The noise as a function of defocus (Figure 6) shows the effect of the pellloid backing on 1414 (developed in D-19 developer). The cross section of the photographic material, in the upper part of the figure, indicates the thickness of the various components prior to processing as specified by the manufacturer. It is apparent that the separation of the two noise peaks corresponds to the separation of the emulsion and the pellloid backing. A similar sample in which the backing was removed after processing indicates a lower
Figure 6. Noise as a Function of Defocus for Samples with and without the Pelloyd Backing.
noise level from the silver grain component in addition to decreased noise at all focal positions. It is possible that the second peak, due to the pellloid material, could be eliminated by collecting all of the radiation exiting from the film.
CHAPTER 6

NOISE AS A FUNCTION OF DEFOCUS

Even though the standard deviation about the average transmission may not be an adequate measure of the noise, as noted previously, it will be used to indicate the effect of defocus on the RMS noise for the selected photographic materials.

The effect of focal position and density on the noise levels of 1414 film (Versamat processed) scanned on the laser microdensitometer is shown in Figure 7. The noise peak on the right is due to the photographic (silver) grains of the material. The left peak is due to the pellloid backing of 1414.

The pellloid peak is apparent at all density levels including the base-plus-fog level. In fact, it is greater than the silver grain noise peaks for densities below 0.85.

A maximum noise value of 0.18 is noted with this sample for the silver grain noise at a density of 1.53. The separation of all peaks is similar to the separation of the emulsion and backing, i.e., approximately 37.0 μm.

Kodak High Definition Aerial Film 3404, Estar Thin Base (Emulsion Number 446-2-20), is similar in image forming structure to 1414 (Figure 8). This film has a base thickness of 62 μm. The backing utilizes pellloid particles. The noise vs. defocus plots indicate that the
Figure 7. Noise as a Function of Defocus at Various Density Levels for 1414 Film.

Figure 8. Noise as a Function of Defocus at Various Density Levels for 3404 Film.
peaks are now separated by the base thickness of 62 μm with a noise maximum of 0.20 for a density of 1.54. It is interesting to note that there is a noise peak for the silver grains even at the base-plus-fog level of this material. This may be attributed to the fact that the film was near its expiration date and the fog level was slightly higher than normal for this material.

Kodak Plus-X Aerographic Film, Type 5401, on a 130 μm acetate butyrate base (Emulsion Number 288-39-3-68) produces much higher noise levels as suggested previously in Figure 1. (Note the scale change for $\sigma_T/T$ in Figure 9.) It is now apparent that the noise levels due to the silver grain structure are much higher, due to the larger grain size, while the peak due to the pelloid noise is not present. (Pelloid particles are not used in the manufacturing of Type 5401 film.) The noise level differences between 5401 and 1414 would be anticipated in view of the grain size differences.

Transmission noise, $\sigma_T/T$, may be related to granularity, $\sigma(\overline{D})$, by the relationship

$$
\sigma(\overline{D}) = 0.434 \frac{\sigma_T}{T} \left[ 1 + \frac{1}{12} \left( \frac{\sigma_T}{T} \right)^2 + \frac{1}{80} \left( \frac{\sigma_T}{T} \right)^4 + \ldots \right]. \tag{3}
$$

This relationship may be reduced, if the higher order terms can be disregarded, to

$$
\sigma(\overline{D}) = 0.434 \frac{\sigma_T}{T}. \tag{4}
$$

In this case $\sigma_T/T$ must be small.\textsuperscript{6,19} We can thus see that the noise we measure as a function of transmission is proportional to the granularity. Furthermore, we can now work back through Equation 1, knowing the
Figure 9. Noise as a Function of Defocus at Various Density Levels for 5401 Film.
RMS granularity, and determine the ratio of the mean grain area to the area of the scanning aperture. For 1414 the ratio is 0.011 while for 5401 a value of 0.405 is obtained. This now allows us to determine the approximate diameter of the average silver grains in each emulsion assuming that the scanning spot is 3.6 μm in diameter and that the silver grain projected profiles are approximately circular. We find that for 1414 and 5401 the respective silver grain diameters are 1.14 μm and 2.3 μm. Since the values for such parameters are not published by the manufacturer it is necessary to go one step further and determine the resolution from the above information. This may be described by the reciprocal of twice the average grain diameter, multiplied by the Kell factor (approximately 0.7).\textsuperscript{20}

The resolution for 5401 as determined in the above manner is 155 cy/mm compared with the published values of 112-115 cy/mm. The resolution of 1414 (determined) is 970 cy/mm compared to Kodak's published values of 630 cy/mm. This discrepancy could be caused by estimating the scanning spot size smaller than it actually is, or an error in density measurements. The error is approximately the same for both materials indicating that this is a systems problem, or that the approximations and assumptions made are incorrect. In working the above argument in reverse, one finds that the spot size should be approximately 1.6 times larger than that measured to obtain the resolution specified by the manufacturer. However, resolution is measured according to the ANSI standard which requires that the resolution be subjectively specified by an individual while viewing the target, as imaged on the film under test, through a microscope. These values, as published by Kodak, are known to
be quite conservative. A factor of 1.5 to 2.0 discrepancy between published and experimental values would not be considered uncommon by many users of these photographic materials.

In plotting $\sigma_T/T$ as a function of density for the film grain peaks, we see that the characteristics are quite similar for both 1414 and 3404 as would be anticipated (Figure 10). It may also be interesting to note that the $\sigma_T/T$ values are proportional to the square root of the density as indicated by Equation 1. The curve for 5401 is considerably different in magnitude than for 1414 and 3404 but it too is proportional to the square root of the density. The noise levels are extremely high for 5401 and would indicate that one should anticipate considerable difficulty in extracting a signal from this material with such a small scanning spot. One more interesting point is that the noise curves (Figures 7-9) are relatively symmetrical about each peak.

In most microdensitometers the Callier's Q factor is of importance due to the geometry of the radiation collecting systems. It is quite interesting to note that the ANSI Diffuse density as measured on a MacBeth TD 402 densitometer compares rather well to the laser microdensitometer densities for flashed photographic materials (Figure 11). The densities for both the materials with the pelloid backing, and the 5401 without pelloid, are comparable to the diffuse densities. Normally, those densities measured with an incoherent microdensitometer are considerably higher than those measured with the ANSI diffuse geometry, especially in the higher density ranges (2.0 and above). The results shown here would not normally have been anticipated.
Figure 10. Noise as a Function of Density at the Best Silver Grain Focus.
Figure 11. Laser Microdensitometer Densities vs. ANSI Diffuse Densities for Three Films.
The close agreement between the diffuse densities and laser microdensities tends to be a difficult problem to explain. In incoherent systems the scatter of radiation by the filamentary nature of the silver image results in a reduced amount of energy being collected by the optics on the pick-up side of the sample. One would anticipate that this effect would be present in a coherent system with further loss of energy (to the collection optics) due to the phase perturbations introduced by the photographic material. However, in the coherent system it appears that most of the energy is diffracted into a small cone angle by the sample which is consequently picked up by the collection optics. Similarly, the photographic material does not diffract the incident radiation significantly when there is no high frequency image information present, such as in a holographic plate.
CHAPTER 7

COMPARISON OF RESULTS

From Selwyn's granularity law we know that "G" should be constant.\(^{21}\) Hence, the granularity, \(\sigma(\bar{D})\), decreases with increasing area of the scanning aperture so that it is proportional to \((1/A)^{1/2}\). Selwyn's granularity law is given by

\[
G = (2A)^{1/2} \sigma(\bar{D}).
\]  

This relation is based on the assumption that the area of the scanning aperture is large compared to the area of the silver grains. Approximations allow us to estimate \(\sigma(\bar{D})\) from \(\sigma_T/T\) values (see equation 2) and hence, determine Selwyn's granularity, \(G\). A comparison can now be made between the Selwyn's granularity value for the experimental data and that data published by the industry.

In comparing the values in Table 2, one must be careful not to overlook the assumptions that have been made, and the system differences. Primarily, the laser microdensitometer utilizes a coherent course of a single wavelength with a scanning spot approximately 3 \(\mu m\) in diameter. The values of Kodak granularity as shown in Table 2 were originally collected with a 48 \(\mu m\) diameter scanning spot with films developed in D-19. In addition, Kodak's data is for an incoherent, broad band source.
The information supplied by Data Corporation is for data collected utilizing what Data Corporation claims is a 1.12 μm scanning spot and a broad band incoherent source on a material similar to 1414. However, since the theory of the formation of the micro-spot, the optical system, and the geometry of the system have not been described in the literature it is difficult, if not impossible, to compare the results supplied by Data Corporation with those supplied by Kodak and those developed from the laser microdensitometer.

The only conclusion that may readily be drawn from Table 2 is that Selwyn's law does not hold for a system utilizing an extremely small spot for scanning and a coherent source. Further work would have to be carried out to determine if an extension of Selwyn's law may satisfactorily describe the granularity in the situation when the area of the grain approaches the area of the scanning aperture.

Table 2.

<table>
<thead>
<tr>
<th>SELWYN'S GRANULARITY G</th>
<th>.434 σ_T/T</th>
<th>Kodak</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1414</td>
<td>0.354</td>
<td>0.543</td>
<td>---</td>
</tr>
<tr>
<td>3404</td>
<td>0.344</td>
<td>0.585</td>
<td>---</td>
</tr>
<tr>
<td>5401</td>
<td>1.780</td>
<td>2.050</td>
<td>---</td>
</tr>
</tbody>
</table>
CHAPTER 8

WIENER SPECTRUM OR NOISE POWER SPECTRUM

The use of the concept of granularity to describe noise in photographic material is limited in its applicability in view of systems analysis utilizing frequency dependent functions. As mentioned previously (see page 22), the mean and standard deviation (RMS granularity) cannot be used to describe a distribution which is not Gaussian (normal) in nature.

In 1955, R. Clark Jones suggested the use of the noise power spectrum, sometimes referred to as the Wiener spectrum, to describe the fluctuations in transmission or density of photographic materials.\textsuperscript{22} His technique, utilizing a wave analyzer to perform a Fourier analysis on the output signal of a scanning microphotometer, was soon followed by that of Hans J. Zweig utilizing a correlation approach.\textsuperscript{10,23,24}

The RMS granularity, noise power spectrum, and the correlation approach contain similar information in that the noise power spectrum and the autocorrelation function are a Fourier transform pair and \( \sigma^2(D) \) is the area under the power spectrum curve, or the value of the ordinate of the autocovariance function for zero separation. The relationship between \( \sigma(D) \) and the size of the scanning aperture can be shown to yield sufficient information to derive the autocovariance function.\textsuperscript{25}

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Of the above techniques the power spectrum approach yields to a simpler development especially when the analysis of granularity must be carried step-wise through an imaging system. Under this approach one may combine the components through multiplication rather than by the method of convolution. Furthermore, under certain conditions, the modulation transfer function of the system may be estimated from the noise power spectrum of the system output.26

Various techniques, both analog and digital, for experimentally determining the noise power spectrum of photographic materials have been described in the literature.22,26-28 In addition, many theoretical papers including experimental verification have been published.10,23,24,29 The most comprehensive treatise concerning the measurement of the power spectrum using both analog and digital techniques is presented by Blackman and Tukey.30 They cover, in depth, the problems associated with spectrum measurement including aliasing, transformation, variability, prewhitening, rejection filtering, measurements at low frequencies, and a detailed section on planning for measurement. For the sake of brevity the reader will be referred to this publication for the mechanics of noise spectrum measurement.

It is a basic premise of Fourier analysis that the power spectrum of an impulse function is flat. Furthermore, it may be assumed, depending on the parameters of the scanning aperture and grain size, that photographic grain is merely a superposition of impulse functions. Consequently the power spectrum of photographic granularity should be flat, limited only by the modulation transfer function of the scanning aperture and the electronics of the data recording system. As the grain
size increases, however, the power spectrum may show a considerable
decrease at spatial frequencies on the order of the reciprocal of the
grain diameter. Due to the random distribution of the particle sizes in
the photographic image structure, the prediction of the fall-off of the
spectrum due to finite grain size is rather difficult. For scanning
systems with large apertures, or poor systems MTF's, the combination of
the transfer function and the roll-off due to the finite size of the
silver particulates may cause quite rapid deterioration of the power
spectrum with increasing frequency. With a small scanning aperture and
very fine grained photographic material, the spectrum should be relatively
flat even at high frequencies. One should be aware that in most cases
the noise power spectrum displayed in the literature is normally the
noise power spectrum weighted by the MTF of the scanning system.

The use of the terms "noise power spectrum" and "Wiener spectrum"
have elicited comments from most workers in the field as to the appropriateness of their usage. In communications theory where the quantities being described are voltage and current, the observables of physical interest are often signal power and power fluctuation. This is the only situation under which the term "power spectrum" may be used, according to some purists. Since the quantities of interest in the photographic situation are density and granularity, it is argued, one must not think in terms of "power" since the observables of physical interest are not $D^2$ and $\sigma^2 (D)$. The ambiguity exists since one normally measures the density and granularity in terms of voltages as output from a microphotometer. However, the quantities of interest are not power and power
fluctuation and care must be taken to assure that the interpretation of the output is correct.

The Wiener spectrum (noise power spectrum) is given by

\[ W(\xi) = \lim_{X \to \infty} \frac{1}{X} \left| \int_{-X/2}^{X/2} t(x) e^{-j2\pi \xi x} dx \right|^2 \]

(6)

where \( x \) is the spatial variable, \( \xi \) is the frequency variable in cy/mm, and \( t(x) \) is the transmission, or density, of the sample as measured by the microphotometer along the distance \( X \). This function is valid only if \( t(x) \) is a random, stationary process. In addition, since the Wiener spectrum is a measure of a two dimensional distribution, made with a two dimensional aperture in the scanning system, care must be taken in a rigorous development of the theory. For a complete development of the Wiener spectrum the reader is referred to the work of R. Clark Jones. It is often noted that an infinitely narrow slit must be used to determine the Wiener spectrum, but the error made using a slit of finite length may be determined theoretically.

In order to determine the Wiener spectrum of the various photographic materials utilizing the laser microdensitometer, 512 data points (out of the 1000 collected for granularity determinations) were selected. The average transmission was subtracted to eliminate the zero order component in the spectrum. If this is not accomplished satisfactorily, as during the initial analysis of data for this work, the magnitude of the zero order component (DC) will be such that the high frequency information is scaled out of significance.
After subtraction of the average transmission, the Fast Fourier Transform was used to determine the real and imaginary parts of the data transform. Finally, the sum of the squares of the real and imaginary components was determined, and the array was normalized to the maximum value of the array of data points.

Many difficulties were encountered in determining the power spectrum, most of which, in retrospect, were due to the lack of insight. After the average value is subtracted from the transmission information, one would suspect that the zero order component should disappear. This would surely be true if an infinitely large sample were taken to assure that the average was indeed correct. Any residual DC component present in the data transmitted to the FFT will be emphasized in the final plot since the array is normalized to the maximum value, which is normally the first data point, representing the zero order. Consequently, the first data point in the spectrum array was set to zero prior to scaling and plotting.

Another associated problem is that of a variation in the average transmission level across the sample length. If there is any variation this tends to introduce low frequency components into the scanned data and consequently into the Wiener spectrum. In this particular work there was no apparent difficulty with this problem since the sample length for 1000 data points was only 2.12 mm and the density variations over that length were negligible.

Initially it was assumed that 1024 data points would allow better statistics than 512 in determining the spectrum. For this reason the 1000 data points were used with the additional 24 being set to zero.
This was assumed, especially in the fine grained photographic materials, to have little effect on the data. However, the spectra indicated the presence of the 24 zeroes quite significantly by modulating the spectral data with a \((\sin x/x)^2\) function. The function naturally displayed characteristics related to the width of the 24 zero data points. Hence, it is apparent that when working with the noise spectra in which there are only weak frequency components, extreme care must be taken to assure that the data is not contaminated with unwanted frequency detail. Likewise, such an evaluation of an instrument, i.e., the output of a device with white noise input, may give the experimenter extensive insight into his system and its limitations.

Another problem encountered in the power spectrum measurement was due to the nature of the analog-to-digital converter in the 5480A Signal Analyzer. The problem is probably due to a defective stage in the analog-to-digital converter which does not convert the fine incremental differences correctly, tending to assign the same value to a series of data points around a central value. Figure 12 shows the power spectrum of a typical sample of 1414 film. This data has been smoothed with a five point Gaussian moving average filter prior to plotting. The scanning system was defocused approximately 50 μm when this data was taken. In all the samples collected, including those for various density levels and other film types, the peaks present in Figure 12 were evident. Upon close examination it was apparent that these peaks were occurring at approximately 4 cy/mm and integer multiples thereof. This frequency could not be related to any periodic function in the system including rotational frequency of the scanning drive motor, or the
Figure 12. Typical Power Spectrum Curve Using Gaussian Smoothing.
scanning stage motion. Furthermore, the 4 cy/mm periodicity occurred in films with and without pellloid backing, at base-plus-fog levels as well as at higher densities, and on materials of various thicknesses.

The 5481A system was completely evaluated prior to use utilizing various wave forms including square waves, sine waves, and noise generated by an electronic noise generator. This data was carried completely through the data analysis process including calculations and plotting on the 6400 computer system. Absolutely no indications of this periodicity existed during this phase of the evaluation. However, the first photographic material scanned immediately after this evaluation (and a pilot run prior to this evaluation) indicated periodicity.

In order to determine if the periodicity noted was real and if data averaging would have any effect it would have been preferable to rescan the sample many times and average the Wiener spectrum output from each scan. Due to the difficulties in assuring exact focal positioning in rescans it was decided to use another approach. In this approach 10 groups of 512 data points, with the groups selected at random from the 1000 data points of one scan, were used to generate the Wiener spectrums which were then averaged. The average spectrum was then plotted, without the five point Gaussian smoothing function, with the 4 cy/mm periodicity becoming more apparent (Figure 13). This indicated that the periodicity indeed exists in the data but still did not specify the origin of the periodic signal.

Professor R. R. Shannon then suggested that the periodicity may be introduced by clumping of data, or dropping of data points and compression of data. To investigate this possibility, a ramp function,
Figure 13. Typical Power Spectrum Curve Using Grouped Averaging.
generated by the 5480A, was used as input to the system. This function varies 1 v peak-to-peak with the voltage being proportional to the distance along the abscissa of the scope face. On examination of the plot on the scope face it was obvious that the trace was not a straight line. Upon evaluation of data from the scope face, printed out on the teletype, one could readily see that from 6 to 8 data points were exactly the same value, then an increment in value occurred with another 6 to 8 data points being of the incremented value. This process repeated itself over the entire 1000 data points with the incremental value being exactly the same over one 1000 data point group. This test was also performed utilizing a signal generator to assure that the waveform generated by the 5480A was not faulty.

Furthermore, this grouping of data was not constant. The magnitude of the increments varied from scan to scan with some scans displaying an almost smooth, straight line while others appeared obviously stepped on the scope face. Upon critically reviewing some previously recorded noise data it became apparent that the analyzer preferentially recorded certain values. This did not occur for a rapidly changing waveform such as a sine wave. However, once aware of the problem it was possible to choose the sine wave such that these artifacts were apparent.

Since this artifact has been introduced into the data used for generating the granularity information previously presented, the question of validity of the data arises. The granularity data would be considered invalid if the periodic components added enough information to the area under the power spectrum curve to make a significant error in $\sigma^2 (D)$. In comparing the location of the peaks in Figure 13 with those in Figure 12
it is apparent that those peaks due to the periodic component in the data
are significant, but that the area under each peak, down to the average
level of the spectrum curve, is not significant when compared to the total
area under the spectrum curve. This may not necessarily be true when a
considerable amount of defocus is present and most of the high frequency
components have been filtered out by the MTF of the scanning system.
In this case the periodicity may add significant information to the pow­
er spectrum curve. This, in fact, may explain the cause of the $\sigma_T/T$ vs.
defocus curves (Figures 6-9) leveling out and appearing to take on a
constant value for greater amounts of defocus. However, it is the opin­
ion of this writer that the error introduced by the periodic components,
near focus, is not significant.

The power spectrums (Wiener spectrums) for 5401 and 1414 films
at best focus indicate a relatively flat spectrum (Figures 14 and 15).
These and the remaining plots have been smoothed with a five point
Gaussian moving average filter with 256 data points between 0 and
240 cy/mm. The flat spectrum is what one would expect for 1414 based
on the argument of superposition of impulse functions representing the
photographic grain structure. One would not expect the flat spectrum
out to 240 cy/mm for 5401 film considering that its resolution is on the
order of 115 cy/mm. A roll-off should occur near 200 cy/mm but is not
obvious from this plot. The lack of agreement for this spectrum with
theory may be due to the poor statistics utilized in determining the
5401 Wiener spectrum, or may be associated with the coherent nature of
the optical system.
Figure 14. Relatively Flat Power Spectrum for Type 5401 Film at Best Focus. (Density = 0.95)

Figure 15. Relatively Flat Power Spectrum for Type 1414 Film at Best Focus. (Density = 1.14)
The power spectrum of 5401 at the base-plus-fog level (Figure 16) again indicates a relatively flat power spectrum out to 240 cy/mm. The 1414 material at the base-plus-fog level (Figure 17) starts to indicate a roll-off of the spectrum which can be attributed to a difference in film structure and not to modulation by the optical scanning system. It may be suggested that the information present at the lower frequencies in the 1414 sample is due to the presence of the pelloid particles which are 2 to 5 μm in diameter and widely dispersed in the backing of the material. The effect of the pelloid particles on the scanning system output may be seen in Figure 6.

The significance of the pelloid particles on the power spectrum may be seen in a comparison of Figures 18 and 19. In these figures the focus is such that the pelloid material is at best focus for the 1414 material with the 5401 scans being made at the same focal position. In 5401 one can see the roll-off typical of defocus in the scanning system. However, in the 1414 case the low frequency components are much more pronounced, especially in the 40 to 80 cy/mm range. This again appears to suggest that the pelloid particles do add significantly to the power spectrum in the lower frequency areas.

In order to prove, or disprove, the above assertions concerning the effect of the pelloid particles on the Wiener spectrum of 1414 film it would be necessary to improve the statistics of the data analysis. In addition, the flat spectrum of 5401 material should be investigated to determine if this may be caused by inhomogeneities in the base of the photographic material or is associated with some other phenomena of a coherent laser scanning system with coarse grained films. It would be
Figure 16. Relatively Flat Power Spectrum for Type 5401 Film at Best Focus. (Density = Base Plus Fog)

Figure 17. Power Spectrum for Type 1414 Film at Best Focus. (Density = Base Plus Fog)
Figure 18. Power Spectrum for Type 5401 Film with System Focused 60 μm into Base Material. (Density = 0.95)

Figure 19. Power Spectrum of Type 1414 Film with System Focused on Pelloid Particles. (Density = 1.14)
suggested that data collection and averaging should follow the techniques in Blackman and Tukey. This would require an extremely long string of data points. Several data sets should be utilized to calculate the spectrum with averaging of the final Wiener spectrum using a minimum of 10 sets of data. Since one major problem in this work was assuring the same focal position for repeated scans at better than ±10 μm, it is suggested that a device similar to that used by Celio could be utilized, along with analog and digital techniques to determine the Wiener spectrum.
CHAPTER 9

SUMMARY

A prototype laser microdensitometer has been developed at the Optical Sciences Center in order to study the noise problems associated with coherent microdensitometry. This device has been utilized, in conjunction with digitizing equipment, to determine the granularity as a function of defocus for three types of photographic materials. In addition, the Wiener spectrum (noise power spectrum) has been determined from this same data utilizing digital techniques.

The granularity data indicated the presence of pellloid particles in the backing of the thin base photographic materials. These particles significantly added to the noise level of the scanned output. At low density levels the RMS noise from the pellloid particles was greater than the granularity due to the silver grain structure of the materials. Possible indications of the presence of these particles appeared in the Wiener spectrum data.

Most of the Wiener spectrum data was relatively inconclusive due to the poor statistics utilized. Furthermore, artifacts were found to be present in the data from the analog-to-digital converter which added information to the Wiener spectrum curve. The utilization of the noise power spectrum to evaluate the experimental system, including the hardware and software, proved invaluable in pointing out problems which would
normally go undetected and possibly negate the results of evaluation work using such equipment.

The artifacts introduced by the analog-to-digital converter did not appear when the system was utilized to measure the power spectrum of strong signals. When this same system was forced to determine the spectral content of a pure noise signal, the magnitude of the artifacts became significant and quite apparent in the power spectrum output.

Since the RMS noise level is approxiamtely an order of magnitude greater with the laser microdensitometer than with the device utilized by Eastman Kodak for similar determinations when scanning coarse grained films (e.g., Plus X) it will be necessary to restrict the use of the laser microdensitometer to fine grained, high resolution materials. In most cases the scanning spot size of approximately 3 μm would be much smaller than needed for relatively coarse grained materials. In the case of high resolution, fine grained materials, the 3 μm spot would prove beneficial and a reduction to smaller spot sizes, either by using higher numerical aperture objectives or shorter wavelengths of radiation would be quite valuable. Since small spot sizes are feasible with high energy densities, it may be possible to utilize solid state collection devices in place of the costly photomultiplier tubes. Further study would be necessary to determine if excessively high energy densitites may cause deformation of the imagery either on the micro-image level or in the macro-image structure.

The high noise levels are lower than the Selwyn granularity relationship would predict. This variation (on the order of 60%) indicates that the Selwyn law does not hold for either the purely coherent
case, or for the case where grain size approaches the order of magnitude of the scanning spot size. This study was not conclusive in determining the cause for departing from the Selwyn relationship.

Finally, the relationship between the laser microdensitometer densities and those densities measured according to the American National Standards Institute method for visual diffuse density is of interest. Normally, there is close agreement at the lower densities while the microdensitometer values are expected to become much greater at higher densities. This study indicates that, utilizing the specified system, the densities determined using the laser microdensitometer are quite similar to those determined utilizing the ANSI visual diffuse readings.

In conclusion, the major points derived from this study are:
1) the effect of the pelloid particles on the noise levels; 2) the fact that the Selwyn granularity relationship does not hold and predicts noise levels higher than observed; 3) the close relationship between the densities measured on the laser microdensitometer and those measured using ANSI diffuse visual techniques; 4) the fact that the noise levels are proportional to the square root of the densities; and 5) the utilization of the power spectra for determination of the system integrity. The results of this study indicate that further work is justified in the application of the laser microdensitometer to image analysis.
APPENDIX A

ELECTRONICS

The photomultiplier tube and associated electronics comprise an important part of the system utilized in these measurements. Unless the characteristics of this segment of the system are well defined, the results of such a study would be meaningless.

In this particular system an RCA 1P21 photomultiplier tube (PMT) is used as the sensor. The 1P21 is mounted inside of an aluminum tube to provide shielding with a small port directly in front of the photosensitive surface. This port is covered with a piece of Kodak opal glass.

The dynode chain for the 1P21 (Figure A1) is designed for low noise operation. All resistors in the chain are high quality wire wound resistors including the load resistor, $R_4$. The high voltage is supplied to the PMT by a Power Designs Pacific Model 2K-10 high voltage power supply.

The linearity of the system, including the 5480A Signal Analyzer, was measured with various voltages applied to the PMT. In order to vary the radiation falling on the PMT, a polarizing filter was placed between the beam expander and the opal glass in front of the PMT. The Spectra-Physics, Model 133 (TEM$_{00}$, linearly polarized), was used for the source. (This is the same laser utilized for a source in the laser microdensitometer.) As the polarizer is rotated one would expect the intensity to
vary proportionally to \( \cos^2 \theta \) where \( \theta \) is the angle between the transmission axis of the polarizer and the instantaneous electric field vector. The system linearity was found to be quite good (within 2\%) for over two decades. The range over which the system proved to be linear did not vary for higher voltage levels up to 1000 \( v \) being limited primarily by the electronics in the signal analyzer. In this study it was desirable to operate the PMT at the minimum voltage which would assure linearity while maintaining the electronic noise at a minimum level. Hence, during the experimental work with the laser microdensitometer it was necessary to operate the PMT at 750 \( v \) and to select the sensitivity range so that all values of the noise to be recorded in each scan fell within the 2 decade linear range. In the latter case, it was possible to utilize neutral density filters to place the output level at the appropriate voltage for the scope sensitivity setting. (These filters were placed between the laser and the beam expander as required during the study.)

The frequency response of the system is quite important in order to assure that none of the information desired is being filtered out by the electronics. The capacitor in the PMT circuit serves as a filter passing only lower frequency components of the signal. A calculation of the circuit response indicates a roll-off as shown in Figure A2 (solid line). In order to verify that this was the response of the entire circuit, a simple test was made. A light emitting diode (LED), Monsanto type MV2, was driven by a Wavetek Model 116 wave generator. The LED has a rise time on the order of a few nanoseconds when a square pulse is applied, with the light output in the green region of the spectrum \((0.56 \pm 0.02 \ \mu m)\). This radiation was applied to the system directly
Figure A1. Schematic for Dynode Chain Used with RCA 1P21 Photomultiplier Tube.

Figure A2. Theoretical and Experimental Response vs. Frequency for System Electronics.
in front of the opal glass. The intensity of the light was adjusted so that the PMT could be operated at the 750 volt level.

The response of the PMT and associated electronics (without the 5480A) to the LED was displayed on an oscilloscope. The peak-to-peak levels were measured at various frequencies and normalized to the modulation at 1 Hz. The results are indicated in Figure A2 (broken line). The agreement between the theoretical and experimental results appears to be rather good. The higher response level from the experimental data may be attributed to the higher harmonics present in the square wave, since we are measuring the square wave response as compared to the calculated sine wave response. It is apparent from Figure A2 that the half power points fall at about 900 Hz. (Note that in Figure A2 the normalized peak-to-peak voltage response is plotted and not the power response.) Hence, the electronics could not degrade the desired information, considering the low scan rates utilized in this work, but would filter out any higher frequency electronic noise present.
REFERENCES


