THE APPLICATION OF DIGITAL TECHNIQUES TO THE OPTIMIZATION OF PLATE EXPOSURE TIME IN STELLAR SPECTROSCOPY

by

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DEPARTMENT OF ELECTRICAL ENGINEERING
In Partial Fulfillment of the Requirements For the Degree of
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THE UNIVERSITY OF ARIZONA

1968
STATEMENT BY AUTHOR

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SIGNED: Neil F. Sullivan

APPROVAL BY THESIS DIRECTOR

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Associate Professor of Electrical Engineering

May 6, 1968
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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF ILLUSTRATIONS</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>vii</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>viii</td>
</tr>
<tr>
<td>CHAPTER I INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Types of Spectrographs</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Variable Factors in Spectroscopy</td>
<td>3</td>
</tr>
<tr>
<td>1.3 General Description of the System</td>
<td>8</td>
</tr>
<tr>
<td>II SYSTEM SPECIFICATIONS AND REQUIREMENTS</td>
<td>10</td>
</tr>
<tr>
<td>2.1 Design Goals</td>
<td>10</td>
</tr>
<tr>
<td>2.2 Optical Design Considerations</td>
<td>11</td>
</tr>
<tr>
<td>2.3 Determination of Signal Level Range</td>
<td>16</td>
</tr>
<tr>
<td>2.4 Photodetectors</td>
<td>19</td>
</tr>
<tr>
<td>2.5 Choice of Design Philosophy</td>
<td>28</td>
</tr>
<tr>
<td>III SYSTEM DESCRIPTION</td>
<td>32</td>
</tr>
<tr>
<td>3.1 Overall System Concept</td>
<td>32</td>
</tr>
<tr>
<td>3.2 Theoretical Signal Analysis</td>
<td>35</td>
</tr>
<tr>
<td>3.3 Signal Processing</td>
<td>40</td>
</tr>
<tr>
<td>3.4 Information Storage and Display</td>
<td>48</td>
</tr>
<tr>
<td>IV CONCLUSIONS</td>
<td>51</td>
</tr>
<tr>
<td>4.1 Laboratory Test Results</td>
<td>51</td>
</tr>
<tr>
<td>4.2 Performance Results</td>
<td>55</td>
</tr>
<tr>
<td>4.3 Further Developments in Progress</td>
<td>59</td>
</tr>
<tr>
<td>APPENDIX A DESCRIPTION OF THE PULSE AMPLIFIER</td>
<td>63</td>
</tr>
<tr>
<td>LIST OF REFERENCES</td>
<td>71</td>
</tr>
<tr>
<td>FIGURE</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
</tr>
<tr>
<td>1.1</td>
<td>2</td>
</tr>
<tr>
<td>1.2</td>
<td>4</td>
</tr>
<tr>
<td>1.3</td>
<td>5</td>
</tr>
<tr>
<td>2.1</td>
<td>22</td>
</tr>
<tr>
<td>2.2</td>
<td>23</td>
</tr>
<tr>
<td>2.3</td>
<td>27</td>
</tr>
<tr>
<td>2.4</td>
<td>30</td>
</tr>
<tr>
<td>3.1</td>
<td>33</td>
</tr>
<tr>
<td>3.2</td>
<td>36</td>
</tr>
<tr>
<td>3.3</td>
<td>41</td>
</tr>
<tr>
<td>3.4</td>
<td>43</td>
</tr>
<tr>
<td>3.5</td>
<td>45</td>
</tr>
<tr>
<td>3.6</td>
<td>50</td>
</tr>
<tr>
<td>4.1</td>
<td>53</td>
</tr>
<tr>
<td>4.2</td>
<td>54</td>
</tr>
<tr>
<td>4.3</td>
<td>56</td>
</tr>
<tr>
<td>4.4</td>
<td>58</td>
</tr>
<tr>
<td>A-1</td>
<td>65</td>
</tr>
<tr>
<td>A-2</td>
<td>67</td>
</tr>
</tbody>
</table>
FIGURE Page

A-3 Bistable Tunnel-Diode Counter .................. 69
A-4 One-Shot and Line Driver ......................... 70
LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Factors Contributing to Optical System Losses</td>
<td>18</td>
</tr>
<tr>
<td>2.</td>
<td>Photon Rates and Equivalent Power Input for</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Various Source Brightnesses (36&quot; telescope)</td>
<td>20</td>
</tr>
</tbody>
</table>
ABSTRACT

The photoelectric exposure meter described in this thesis was designed to monitor a small fraction of the light passing through an astronomical spectrograph, and to provide a continuous indication of the integral value of the light flux being monitored as measured from some reference time determined by the operator. Since the sample comprises a fixed percentage of the total flux passing through the instrument, the displayed information is directly related to the total flux incident on the photographic plate used for recording the data. Thus the operator may optimize the exposure in spite of time variations in the light flux value due to external conditions.

After evaluation of the system constraints, a digital approach was selected. The system was designed to have a relatively wide linear dynamic range, and particular attention was given to the optical design considerations from the viewpoint of obtaining good imaging, and also source-detector spectral matching. The various parameters and properties of photomultiplier tubes were investigated.

Evaluation tests of the photoelectric exposure meter described have been carried out on the 36" Cassegrain spectrograph and on the 84" Coudé spectrograph at the Kitt Peak National Observatory. The results indicate that the system requirements have been met.
CHAPTER I

INTRODUCTION

1.1 Types of Spectrographs

Since the discovery of the absorption or dark line spectrum in the Solar spectrum in 1814 by von Fraunhofer, and the laboratory investigations of Kirchoff in 1859 which revealed that the features of any spectrum are governed by the temperature, pressure, and chemical composition of the source of the radiation, stellar spectroscopy has developed into a major branch of astronomy.

Through refinements in both instruments and techniques, major contributions in astronomy and astrophysics have been made possible as a result of spectroscopic studies of stellar objects. The chemical composition, temperature, rotational velocity, and radial velocity are a few of the physical parameters of stars which can be determined on the basis of spectroscopic analysis of the light from a star.

Spectrographs used in astronomy today fall into two general categories. First, there is the Cassegrain spectrograph which is so named because it operates at the Cassegrain focus of the telescope. A photograph showing a Cassegrain spectrograph attached to a 36-inch telescope is presented in Figure 1.1. This type of spectrograph is a relatively low resolution instrument and is used primarily for spectral classification work and radial velocity determinations.
Figure 1.1  Cassegrain Spectrograph on 36-inch Telescope
The other type of instrument is the Coudé spectrograph. Coudé spectrographs remain stationary with respect to the telescope, are physically rather large, and have high resolution capabilities. Due to their size, they are rather expensive, and are usually only incorporated into the design of large telescopes. Figure 1.2 shows a cross-sectional view of the Coudé system at the 84-inch telescope on Kitt Peak. The details of the spectrograph are shown in the drawing of Figure 1.3. This type of spectrograph is needed for studies of relative abundances of elements in stars, in rotational velocity determinations, and in other programs where high resolution is necessary.

Both types of instruments have been highly developed in terms of efficiency and resolution through advances in optical techniques and the development of high-precision diffraction gratings.

In spite of the advances made in spectrograph development, the astronomer is still faced with the problem of judging when to terminate an exposure once it has been initiated. The spectrogram which is overexposed or underexposed represents a waste of instrument time and observer time. This thesis treats the development of a photoelectric exposure meter for use with astronomical spectrographs. Different techniques are considered, and a design philosophy is chosen which best meets the system requirements.

1.2 Variable Factors in Spectroscopy

There are numerous factors which influence the integrated light flux incident upon the photographic plate which records the spectrum over any given time period (Hiltner 1962, pp. 5-16). The astronomer
Figure 1.2  Coude Spectrograph at 84-inch Telescope
Figure 1.3  Details of 84-inch Coudé Spectrograph
must be aware of these factors, particularly those which are time-dependent with periods of the order of the total exposure time, and he must be able to quantitatively assess their effect on the duration of the exposure. All of the factors listed below have a bearing on the quality, contrast, and ultimate usefulness of the final data in the form of the photographic plate.

The most significant factors influencing the time duration of the plate exposure time are:

1) The source brightness, which can vary by factors of about 10,000 to 1 for various sources in routine work and by greater amounts in some not infrequent instances.

2) The optical parameters of the spectrograph such as the dispersion of the grating and the quality and cleanliness of the various optical elements in the system.

3) "Seeing" or the smearing and dancing of telescopic images caused by refractive deflection of starlight as it passes through turbulent strata in the Earth's lower atmosphere. "Seeing" is a limiting factor in determining what fraction of a stellar image can be squeezed through the slit of a spectrograph.

4) Scintillation or amplitude modulation of the starlight caused by turbulent strata very high in the Earth's atmosphere. This is commonly observed on crisp, clear nights as a "twinkling" of the stars in the eyes of the casual observer.

5) Atmospheric extinction which is an absorption-scattering phenomenon that has wavelength and air-mass dependency.
air-mass is the distance to the top of the atmosphere at the zenith). At sea level the extinction amounts to approximately 15% at $\lambda = 5500$ Angstroms if the air is very clear. It rises steeply in the blue and ultraviolet regions becoming greater than 90% at wavelengths less than 3000 Angstroms. In the infrared regions the transmission characteristics of the atmosphere become very irregular.

6) Dust, haze, and man-made pollutants carried to moderately high levels by vertical currents and spread over vast areas by winds.

7) Meteorological factors in the form of clouds ranging from thin veils of ice crystals at high altitudes to fuzzy lumps of cumulus in the lower portion of the atmosphere.

The experienced observer can do remarkably well in timing his exposures by "educated guesswork" except in the face of factors 6 and 7 above. The observer who lacks in experience with a particular instrument at a given site might have difficulties due to most of the above factors.

The above factors provided a justification and impetus for the design and construction of an "exposure meter" (which will hereafter be referred to as EM) to take the guesswork out of the problem of timing the photographic plate exposure in stellar spectroscopy.

While the EM concept is not new, this approach is unique in that it departs from the usual approach of treating the output signal of a photomultiplier tube as an analog quantity (Warren and Argyle, 1956).
1.3 General Description of the System

The light from a star whose spectral characteristics are of interest is gathered by the telescope and imaged at the entrance aperture, or slit, of the spectrograph. The light proceeds from the slit to a collimator mirror which converts the diverging rays of light into a bundle of parallel rays and directs the bundle onto a diffraction grating. The diffraction grating separates the light into an orderly spectrum which is quantitatively described by classical diffraction theory. Light reflected from the grating is imaged on a photographic emulsion which is deposited on a glass plate.

The final data record in stellar spectroscopy is the developed photographic plate which carries the image of the stellar spectrum. A suitable data record might be broadly defined as a plate with background density and line detail that is suitable to the purposes of the investigator. These characteristics are directly related to the time integral of the light flux incident upon the photographic emulsion, and the light flux is subject to all the previously mentioned disturbing influences.

In order to obtain a suitable data record in spite of the variables described within the previous section, the observer must have a quantitative knowledge of the total light flux incident on the photographic emulsion from the time that the exposure was begun. This can be accomplished by constructing a system which removes a representative sample of light from the spectrograph, and processes the sample in such a way as to provide the observer with an indication of the amount of
light which has passed through the system. The general system description can be formulated, in basic terms, as one which requires the following components:

1. a light sampling scheme
2. an energy conversion device to convert light energy to electrical energy
3. a signal processing and integrating capability
4. an indicator or information display unit
CHAPTER II

SYSTEM SPECIFICATIONS AND REQUIREMENTS

2.1 Design Goals

The design goals which were established in the initial stages of the device development are as follows:

1. The EM should provide the spectrograph operator with a visual indication of the integrated light flux through the instrument as measured from some reference time that is established when the exposure is initiated.

2. The device should be relatively easy to operate in the sense that it should not burden the spectroscopist by requiring some complex pre-use alignment or by requiring readjustment during the course of an exposure.

3. Approximately five percent of the light passing through the spectrograph slit would be available for use by the EM.

4. It was desirable to determine the correct exposure time with this device to within ± five percent. This means, for example, that if the plate exposure should theoretically take one hour, then the EM should indicate to the observer that the plate exposure is completed within fifty-seven to sixty-three min. after the exposure began (also see 3.2).

5. The EM should be capable of dealing with exposure times ranging from several minutes to many hours. It can be readily appreciated that integrations of low signal levels over long
time periods will require precautions to minimize drift and offset errors.

6. The device should function reliably in the operational environment of the telescope dome where the temperatures range from 10 degrees F. to around 75 degrees F. depending on the season of the year.

7. The range of light intensities that will be encountered in normal usage would be from visual magnitudes 2 to 12 which represents a range of 10,000 to 1 in light intensity.

8. While cooling of the photodetection device is the normally accepted procedure for reducing dark current in photoelectric photometry, cooling was to be avoided in this device if at all possible in order to minimize preparational requirements and servicing during use. This essentially goes along with a previously mentioned goal of minimizing the operational complexities of the device.

9. The system must be immune to electrical noise transients caused by large motors, and by relays switching heavy currents in the telescope building.

The above requirements provided the foundation upon which the design of the EM was based.

2.2 Optical Design Considerations

In searching for an appropriate approach to be followed in a problem such as the one at hand, one very often sees a pattern emerging
which emphasizes certain general considerations which are important factors in the design problem, regardless of the specific solution chosen. Such was the case in the design of the optical portion of the EM, and for this reason a discussion of the optical design considerations is felt to be in order.

First of all, inherent in the process of producing a spectrogram is the scanning of the stellar image along the length of the spectrograph slit in order to produce a widened image, or one which is more than just a narrow line whose intensity varies with wavelength. The result of scanning the image back and forth along the length of the spectrograph slit is a superposition of narrow lines which result in a broadened image with individual wavelength features much more readily identifiable. However, in sampling the light beam, this motion can cause some undesirable effects if it is neglected in the optical design formulation. The most obvious effect would be the possible variations in the total light passing through the system due to the beam being obstructed by some structural member in the system as it moves back and forth, or because of the beam being partially outside of the light gathering capabilities of the optical elements during a portion of the image excursion along the slit. A more subtle effect is due to the fact that the sensitive area of photo-electric conversion devices does not generally possess a uniform sensitivity as a function of position. Thus, if a light image were allowed to assume different positions on the photosensitive surface, the output signal would show variations although the light intensity remained constant. The information conveyed would then be false with the amount of error being a
function of the non-uniformity of the surface and the amount of motion that the image underwent.

Even in those systems where there is no motion involved, close attention must be paid to the behavior and nature of the light beam, both before and after sampling. One approach which is practical, and which was followed by the author in this project effort, is to draw the entire system to scale and to then lay out the edge rays of the light beam through the system to ascertain that no undesired stops or obstructions exist. Image motion can be minimized or eliminated through the selection of a proper entrance aperture for the system and the use of suitable optical imaging techniques.

Another factor which must be borne in mind is that the sensitive surfaces of photo devices have a graininess due to the finite size of the constituent elements. If one reduces the size of the image too greatly, the output signal may become too noisy due to this graininess. By investigating the properties of the photodevice in question, and forming the image so that image detail is averaged over many elemental photosensitive areas, this effect can be avoided.

There are several techniques for obtaining a sample from a beam of light. They can be classified generally as follows:

1. area ratio sampling
2. time ratio sampling
3. beam splitting

Area ratio sampling consists of inserting a reflecting surface in the beam normally with the plane of the surface making a 45° angle with the
direction of the beam whose area bears some fixed ratio to the total beam area, thus determining the amount of light removed from the beam. This is generally compatible with systems having reasonable sized beam diameters. Miniscule beams would be difficult to deal with in this fashion. Time ratio sampling is carried out by inserting a reflecting surface in the beam at some periodic interval which intercepts the entire beam. The amount of light removed from the beam is determined by the ratio of the time in versus the time out over one period of the process. Beam splitting is done with optical elements which generally intercept the entire beam, divert a fixed amount out for sampling, absorb a certain fraction and pass the remainder. Beam splitters can alter the characteristics of the light through the system by selective filtering and refraction effects. Thus one must carefully examine the requirements of a particular system before making a choice on the sampling method to be used.

Last, but not least, is the consideration of spectral matching. Any optical detection system may be considered as consisting of the source, the optical elements such as lens, prisms, and filters which can alter the intensity and wavelength characteristics of the input power, and the photon detector, the sensitivity of which is wavelength dependent. In the extreme case, one could image a system with a given flux input $P$, measured in watts for which the output, $I$, of a linear detector (usually a current or voltage) was zero. The explanation, of course, would require that the spectral passband (or bandwidth) of the optical system, or the detector, or some composite of both, was outside
the spectral distribution of the source radiant energy. Normally one would construct an optical system and select a detector on the basis of maximizing the ratio \( I/P \). Two fundamental and defining relationships are (Eberhardt, 1966)

\[
P = W_p \int_0^\infty \omega_\lambda d\lambda \text{ watts} \tag{2.1}
\]

\[
I = S_p W_p \int_0^\infty \sigma_\lambda \omega_\lambda d\lambda \text{ watts} \tag{2.2}
\]

\( W_p \) = peak spectral density of input flux in watts/meter

\( \omega_\lambda \) = normalized relative spectral distribution of input flux as a function of wavelength \( \lambda \), in meters

\( S_p \) = peak response of detector to monochromatic input radiation

\( \sigma_\lambda \) = normalized relative spectral response of the detector

\[
\frac{I}{P} = S_p \int_0^\infty \frac{\sigma_\lambda \omega_\lambda d\lambda}{\omega_\lambda d\lambda} = S_p \alpha(\omega_\lambda \sigma_\lambda) \tag{2.3}
\]

The integral ratio, \( \alpha \), is the ratio of the bandpass region common to both spectral distributions to the bandpass of the input or source radiation. In the problem of spectroscopic work, the source distribution factor \( \omega_\lambda \) as well as the photographic emulsion responsivity \( \sigma_\lambda \) are variables. Fortunately, the most interesting sources from a spectrographic viewpoint lie in the wavelengths 3500Å - 7000Å, and types of photo-emulsions and photo-detectors exist which have good responsivity over this range. When certain wavelength regions are investigated over
this rather wide range by using wavelength selective emulsions and filters, one must be capable of duplicating the optical passband in the sampling system to maintain a reasonable relationship between the light flux to the photographic emulsion and the sample to the exposure meter system.

2.3 Determination of Signal Level Range

A factor very pertinent to the final selection of a photosensitive detector is the range of light levels that the system will be subjected to. This information is also essential to making use of theoretical techniques in system analysis for predicting performance under various conditions.

In astronomy, a commonly used parameter in discussing relative luminosities of various stellar sources is the term "stellar magnitude." If $l_m$ is the luminosity of a star of magnitude $m$, and $l_0$ is the luminosity of a star of magnitude zero, then in general,

$$\frac{l_m}{l_0} = (2.512)^{-m}$$  \hspace{1cm} (2.4)

The visual magnitude of a star corresponds to the monochromatic flux at $\lambda 5465$. For a star of apparent magnitude 0.0, the flux at $\lambda 5465$ is $6.45 \times 10^3$ quanta/in.$^2$/sec/A (Hiltner 1962, p. 284). For a star of magnitude 2.0 which is the maximum intensity specified, the flux is approximately $1 \times 10^3$ quanta/in.$^2$/sec/A. Assume a bandwidth of 3000A (4000A - 7000A passband) and a 36" telescope. The photon rate at the input to the system for a star of magnitude 2.0 would be about $3 \times 10^9$
quanta/sec. For a star of magnitude 12.0, the input rate would be $3 \times 10^5$ quanta/sec. These rates represent the approximate number of photons, within an order of magnitude, which would be intercepted by a 36-inch diameter telescope aimed at some source with the specified visual magnitude.

The rates mentioned are modified by the optical system. Optical elements introduce losses and also the conversion efficiency of the detector is usually low in photoelectric devices.

In Table 1 we find a list of the factors which alternate the light as it passes through the EM optical system. This information allows a determination of the approximate photon rates at the input to the photosensitive detector.

The total transmission factor from the input of the system to the detector input can be expressed as

$$T_0 = \prod_{n=1}^{n=k} T_n = (.80)(.85)^2(.40)(.05)(.90)^2(.20) \leq 0.001 \quad (2.5)$$

Therefore, for a star with $m_v = 2.0$, the photon rate at the input to the detector is approximately $3 \times 10^6$ quanta per second, and for a star with $m_v = 12.0$, the photon rate is approximately $3 \times 10^2$ quanta per second. These figures will be useful in later design considerations. The power input to the detector corresponding to these photon rates can be easily calculated using the relation $E = \frac{hc}{\lambda}$, and assuming a mean wavelength of the incident photons of 5465A as follows:

$$\text{energy/photon} = 6.62 \times 10^{-34} \times \frac{3 \times 10^8}{5.465 \times 10^{-7}} = 3.6 \times 10^{-19} \text{ joule/photon} \quad (2.6)$$
TABLE 1. Factors Contributing to Optical System Losses

<table>
<thead>
<tr>
<th>Source of Light Loss</th>
<th>Percent Loss</th>
<th>Percent Transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Secondary mirror shadow</td>
<td>0.20</td>
<td>0.80</td>
</tr>
<tr>
<td>Primary mirror surface</td>
<td>0.15</td>
<td>0.85</td>
</tr>
<tr>
<td>Secondary mirror surface</td>
<td>0.15</td>
<td>0.85</td>
</tr>
<tr>
<td>Spectrograph slit loss</td>
<td>0.60</td>
<td>0.40</td>
</tr>
<tr>
<td>Light pickoff</td>
<td>0.95</td>
<td>0.05</td>
</tr>
<tr>
<td>Lens No. 1</td>
<td>0.10</td>
<td>0.90</td>
</tr>
<tr>
<td>Lens No. 2</td>
<td>0.10</td>
<td>0.90</td>
</tr>
<tr>
<td>Blue matching filter</td>
<td>0.80</td>
<td>0.20</td>
</tr>
</tbody>
</table>
therefore, for $m_v$ 2.0, the detector power input is given by

$$P_{in} = 3 \times 10^6 \frac{\text{quanta}}{\text{second}} \times 3.6 \times 10^{-19} \frac{\text{joule}}{\text{photon}} \approx 10^{-12} \text{ watt} \quad (2.7)$$

and for $m_v$ 12.0, the detector power input is given by

$$P_{in} = 3 \times 10^2 \frac{\text{quanta}}{\text{second}} \times 3.6 \times 10^{-19} \frac{\text{joule}}{\text{photon}} \approx 10^{-16} \text{ watt} \quad (2.8)$$

A tabulation of photon rates and corresponding values of equivalent power input for source brightnesses with visual magnitudes in the range of 2.0 to 12.0 is presented in Table 2. The tabulations are based on a 36-inch collecting aperture.

2.4 Photodetectors

There are several types of devices which convert input light energy in the form of an incident photon flux into an electrical output signal. Among these devices are included the vacuum photodiode, the photomultiplier, and the solid-state photoconductive devices such as the photodiodes and phototransistors. The latter is essentially a photodiode and a transistor preamplifier formed as an integral unit.

At the present time, the photoconductive devices do not offer a practical solution to low light level work except in a laboratory type environment where cryogenic temperatures are more readily attainable for purposes of overcoming the rather high noise levels associated with these devices at room temperatures.

For astronomical research the most commonly used energy detector is the photomultiplier tube (Hiltner, 1962, pp. 126-156). This detector
TABLE 2. Photon Rates and Equivalent Power Input for Various Source Brightnesses (36" telescope)

<table>
<thead>
<tr>
<th>Visual Magnitude $m_v$</th>
<th>Photon Rate at Detector (photons/sec.)</th>
<th>Detector Equivalent Power Input (watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>$3.0 \times 10^6$</td>
<td>$1.1 \times 10^{-12}$</td>
</tr>
<tr>
<td>3.0</td>
<td>$1.2 \times 10^6$</td>
<td>$4.4 \times 10^{-13}$</td>
</tr>
<tr>
<td>4.0</td>
<td>$4.8 \times 10^5$</td>
<td>$1.7 \times 10^{-13}$</td>
</tr>
<tr>
<td>5.0</td>
<td>$1.9 \times 10^5$</td>
<td>$6.9 \times 10^{-14}$</td>
</tr>
<tr>
<td>6.0</td>
<td>$7.6 \times 10^4$</td>
<td>$2.7 \times 10^{-14}$</td>
</tr>
<tr>
<td>7.0</td>
<td>$3.0 \times 10^4$</td>
<td>$1.1 \times 10^{-14}$</td>
</tr>
<tr>
<td>8.0</td>
<td>$1.2 \times 10^4$</td>
<td>$4.4 \times 10^{-15}$</td>
</tr>
<tr>
<td>9.0</td>
<td>$4.8 \times 10^3$</td>
<td>$1.7 \times 10^{-15}$</td>
</tr>
<tr>
<td>10.0</td>
<td>$1.9 \times 10^3$</td>
<td>$6.9 \times 10^{-16}$</td>
</tr>
<tr>
<td>11.0</td>
<td>$7.6 \times 10^2$</td>
<td>$2.7 \times 10^{-16}$</td>
</tr>
<tr>
<td>12.0</td>
<td>$3.0 \times 10^2$</td>
<td>$1.1 \times 10^{-16}$</td>
</tr>
</tbody>
</table>
offers the advantage of built in amplification by using the principle of secondary electron emission. This amplification is essential because of the low signal levels normally encountered. The dark noise in photomultipliers can be reduced to acceptable levels by cooling to dry ice temperature (Baicker 1960, p. 79).

The photomultiplier tube may be characterized as a high gain, low noise transducer which converts light energy to an electron current. A typical pictorial representation of a PM is shown in Figure 2.1. The electron current is the result of three basic electron emission processes: thermionic, secondary and photoelectric. Thermionic emission originates largely at the photocathode, and the thermionically emitted electrons undergo amplification through the dynode chain in the same manner as does the signal. The thermionic component is a noise component and degrades the signal-to-noise ratio of the system. The statistical nature of the photo-electric and secondary emission processes also contribute noise currents, but at room temperature these are normally small compared to the thermionic noise (Eberhardt, 1959). The photomultiplier tube operates on the following basic principle: Light passing through the optical system falls on the multiplier photocathode causing it to emit free electrons. Each incident photon has a probability, \( P \), of causing a photo-electron to be emitted from the photocathode. \( P \) is frequently referred to as the quantum efficiency, and is dependent upon the wavelength of the incident photons and the photocathode material. A typical response curve illustrating this is shown in Figure 2.2. The photoelectrons are
Figure 2.1  Pictorial Diagram of Photomultiplier Showing Voltage Divider Chain
Figure 2.2  LP21 Spectral Sensitivity Characteristics
electrostatically focused to strike a secondary emission stage called a dynode. More electrons are produced by the secondary emission process, and these are accelerated and focused to strike a succeeding dynode. The process is repeated until the electrons are collected at a final stage, called the anode, where the output signal is an electron current proportional to the light signal incident upon the photocathode. The electron acceleration and electrostatic focusing between dynode pairs is due to the potential difference created by the chain of dynode resistors which establish the dynode voltage values.

The electron cloud is spread out by variations in transit time through the multiplier section arising from the different energies and directions of the secondary electrons. In spite of the transit time spread caused by these factors, typical frequency response measurements on 1P21 tubes have shown bandwidths in excess of 100 megahertz. Independent pulse measurements showing rise times of less than 1 nanosecond have substantiated these bandwidth measurements (Engstrom, 1963). The transit-time delay, which is the delay time between the arrival of a photon at the photocathode and the appearance of an electrical pulse at the anode, is normally longer than the pulse rise time. This factor, however, is normally not important in most applications.

If one wants to utilize the wide bandwidth characteristics of the photomultiplier, the output circuit must be designed with care. The total anode interelectrode capacitance of a 1P21 type tube is approximately 6pf. If one maintains the input capacitance of the following amplifier stage low and limits the length of the interconnecting
coaxial cable, which normally adds several pf. per foot of length, a
total capacitance at the anode of about 20 or 25 pf. might represent
a typical load. Therefore, to maintain a time constant of one nano-
second in the output circuit, the equivalent load resistance in the
anode circuit should be on the order of 50 ohms.

The linearity of photomultipliers has been shown to be ex-
tremely good over wide ranges of light input. The maximum deviation
from linearity for the 1P21 has been measured at <3% for anode currents
ranging from $10^{-11}$ to $10^{-3}$ amperes. In addition, the gain of the photo-
multiplier is essentially independent of temperature over the normal
operating ranges. The photocathode responsivity is also quite stable
with temperature except that they often exhibit a slight increase in
sensitivity at the long wavelength threshold with increasing tempera-
ture. The most significant thermal effect associated with photomulti-
pliers lies in the temperature dependence of the thermionic emission.
Cooling the tube to dry ice temperature (-60° C) results in a reduc-
tion in dark current by a factor of about 100 in the case of the 1P21
tube (Zworykin and Ramberg, 1949, p. 150).

In using photomultipliers, one should also be aware of the fact
that the sensitivity of the photocathode surface varies from point-to-
point, and that external magnetic fields can also affect the sensitivity
through defocusing effects. Suitable magnetic shielding can minimize,
if not eliminate, the latter. Good optical imaging can reduce the ef-
facts of sensitivity due to image position. Maximum sensitivity is
generally found to lie in the central portion of the photocathode
geometry. Stable power supplies should always be used since a 1% change in supply voltage can result in a 5% to 10% change in gain in the photomultiplier. A typical gain versus supply voltage characteristic is shown in Figure 2.3.

One final important consideration worthy of discussion before leaving this section is the nature of the signal at the anode of the photomultiplier. For each photoelectron emitted at the photocathode, approximately $10^6$ electrons arrive at the anode in a burst, with a time spread due to transit time effects. The bursts of anode pulses overlap, and, due to time constants of the anode output circuit and associated amplifier input circuit, the net result is a continuous, but fluctuating, output current. The magnitude of this anode current can be expressed as (Engstrom, 1963)

$$I_a = \int_0^\infty P(\lambda)S(\lambda)d\lambda \text{ amperes} \quad (2.9)$$

where

- $P(\lambda) = \text{input power in watts as a function of } \lambda$
- $S(\lambda) = \text{photodetector sensitivity in amperes/watt as a function of } \lambda$
- $I_a = \text{anode current in amperes}$

A more practical expression can be written if one can characterize the input flux as $N$ photons per second. In that case:

$$I_a = NP\mu e \text{ amperes} \quad (2.10)$$

where

- $N = \text{input photon rate}$
- $P = \text{mean value of quantum efficiency}$
- $\mu = \text{multiplier gain factor}$
- $e = \text{charge on the electron} = 1.6 \times 10^{-19} \text{ coulomb}$
Figure 2.3 Current Gain Characteristic of 1P21
This dc anode current will have a noise component given by the relation
(Eberhardt, 1960)

\[ i_n^2 = 2e\mu I_a \Delta f \]  

(2.11)

which is the basic shot noise expression where

- \( e \) = charge on electron = \( 1.6\times10^{-19} \) coulomb
- \( \mu \) = current amplification factor of multiplier
- \( k \) = multiplier noise factor = \( \frac{\sigma}{\sigma - 1} \) where \( \sigma = \text{gain/stage} \)
- \( I_a \) = dc anode current
- \( \Delta f \) = bandwidth of system

Another viewpoint is to regard each burst of electrons arriving at the anode as a pulse with total charge \( Q = ne \) where \( n \) is the number of electrons in each burst. If the anode circuit has a total capacitance \( C \), a voltage pulse of peak value \( V = \frac{Q}{C} \) will appear each time a burst of electrons arrives due to a photoelectron being emitted at the photocathode. The voltage pulse will have a fast rise time (approximately equal to the transit time spread) and will decay exponentially with a time constant equal to \( RC \), the anode circuit time constant. Thus the output signal of a photomultiplier may be regarded as a dc current or as a pulse train.

2.5 Choice of Design Philosophy

At this point we have a set of design goals, a range of signal intensities which must be dealt with, and a reasonable idea about the type of energy detector that is required.

Since cooling of the detector is not desirable in this case, the dark current due to thermionic emission will constitute a problem.
One approach to its solution would be to use a differential amplifier-integrator configuration with a bucking signal applied to one input and the detector signal applied to the other. With no light input to the system, the bucking signal could be adjusted to null out the dark current effects at the signal input. The strong temperature dependence of the thermionic emission might well be a source of trouble during long integration times where the temperature might vary and introduce errors.

An alternate solution is to use a synchronous detection scheme. This approach is often used in dealing with low signal levels or in cases where the signal is buried in noise. The block diagram of a conventional synchronous detection system with a few additional components is shown in Figure 2.4. The input light signal is mechanically modulated prior to being detected and converted into an electrical signal. It is then amplified by a bandpass type amplifier which is sensitive to the Kth harmonic of the modulated signal (usually K=1). This signal is applied to a phase-sensitive detector and the detector output is smoothed by a simple RC type low pass filter. In this type of system the output of the low pass filter is always zero when there is no light signal at the system input and the dark current is not processed by the integrator and subsequent circuitry. If a light signal is present, the output of the low pass filter will be at some level related to the light intensity and the integrator will integrate the signal until the Schmitt trigger circuit fires, resetting the integrator and sending a pulse to a digital counter. This system was constructed
Figure 2.4 Block Diagram of Synchronous Detector System
in the laboratory and was found to work reasonably well until subjected to environmental temperature conditions and long integration time tests at low light levels. The dc drifts and offsets caused errors, and attempts to eliminate them were not successful. These problems also inspired further thought along the lines of alternate solutions.

Fortuitously, Mr. Warren Ball of our laboratory had recently designed, constructed, and successfully tested a stable wideband amplifier with a built-in discriminator and scalar capability (see Appendix A). The unit was designed for use in photoelectric photometry applications. It was reasoned that if the signal of interest in this problem could be converted to a digital form by treating the photomultiplier output signal as a pulse train, then the problems related to drift, dc offsets, wide temperature variations, and long integration times could be solved in one simple package. It was at this point that a choice was made to pursue the digital approach and the analog work was abandoned. The synchronous detection scheme was retained as a necessary part of the system, however, as dark current effects are present whether one regards the output of the photomultiplier tube as a dc current or as a pulse.
CHAPTER III

SYSTEM DESCRIPTION

3.1 Overall System Concept

Having considered alternative approaches to the task of providing an accurate measure of the integrated light flux through the astronomical spectrograph for purposes of optimizing the plate exposure, a digital approach has been selected. A synchronous detection system is utilized in order to eliminate the effects of photomultiplier dark current which is mainly caused by thermionic emission. Long integration times required for low light level inputs are readily handled with digital circuits without degradation of the output signal due to drifts or offsets in the electronics which are common to the analog counterpart of this type of system.

The overall block diagram of the digital exposure meter is shown in Figure 3.1. A description of its operation is as follows. The light sample extracted from the main light beam is mechanically modulated by a chopper disc driven by an 1800 RPM synchronous 2-phase motor with phaselock capability within ±5 electrical degrees. Alternately transparent and opaque sections of the chopper cause the modulation by periodically interrupting the optical path. The modulated light flux is then imaged on the high gain photomultiplier tube which converts the input photons to current pulses. An RCA type 1P21 photomultiplier tube was used in the first unit constructed.
Figure 3.1 Digital Mode Exposure Meter
Output pulses from the photomultiplier are routed to a wideband direct coupled pulse amplifier (see Appendix A for details) which includes a threshold discriminator, a scale of thirty-two counter and a pulse shaper circuit. The counter may be bypassed if desired. The discriminator is set to eliminate amplifier shot noise and electrical interference generated in the local environment. The output signal pulses are transmitted through coaxial cables to a module which houses signal processing electronics. The electronics consists of gating circuits, logic for performing the gating, a reversible or bi-directional binary coded decimal counter with display, and circuits for detecting a selected count in the counter. When the selected count is reached, an alarm, consisting of an audio tone and an indicator lamp, is triggered. The signal pulse train is applied to the reversible counter clock line through a gate which is operated synchronously with the chopper drive. Each gating interval is of fixed duration, determined by a precision oscillator and countdown circuit. The forward and reverse control signals to the counter are also synchronized with the modulated light signals. The synchronization is such that when the light flux is incident on the photomultiplier tube, the pulses are gated to the clock line and the forward control line of the reversible counter is activated, causing an accumulation of the pulses. The signal during this portion of the cycle contains a photon induced signal component and a dark signal component. When the light flux is blocked by the chopper, the dark current pulses from the photomultiplier are gated onto the clock line for precisely the same interval as was
allowed for the photon-induced accumulation. However, the reverse control line of the counter is now activated, and the dark noise is subtracted from the contents of the counter. In this manner, the dark current is balanced out, and the counter stores a quantity directly related to the photon rate.

A diagram showing the timing of the various events described above is given in Figure 3.2. With zero light signal into the system, the counter averages around zero with deviations from the zero value caused by statistical fluctuations in the dark current. The next section will discuss the signal analysis in more detail.

3.2 Theoretical Signal Analysis

At this point, an analysis will be developed for the purpose of determining the ability of the system to meet certain of the design goals. While bearing in mind that we are dealing with approximate values, we seek a result which will indicate the general feasibility of the approach.

We begin by defining the set of variables with which we will be working. Let:

\[ r_s = \text{average signal rate at the input to the bi-directional counter in counts per second.} \]

\[ r_n = \text{average noise rate due to dark current at the input to the bi-directional counter in counts per second.} \]

\[ \gamma = \frac{T}{t} = \text{ratio of length of gated sample interval to length of one complete chopper cycle.} \]
Figure 3.2 Timing of Signal Processing
In some time interval $T \gg t$, assuming a Poisson-distributed arrival of photon induced counts (Tusting, Kerns, and Knudsen 1962), the mean value of the signal count, $S$, gated into the bi-directional counter should be

$$s = r_s \gamma T \text{ counts} \quad (3.1)$$

with an expected deviation

$$\sigma_s = (r_s \gamma T)^{1/2} \quad (3.2)$$

In the same interval, $T$, the noise, $N$, gated into the bi-directional counter should be

$$N = r_n \gamma T - r_n \gamma T = 0 \quad (3.3)$$

with an expected deviation

$$\sigma_n = (2r_n \gamma T)^{1/2} \quad (3.4)$$

The value of $N = 0$ results from the counter being gated in an accumulative mode for the first half interval, and in a subtractive mode for the second half interval. Note that the deviations, or "noise", in $N$ are additive.

After some integration time, $T$, the contents of the counter should be

$$C = S \pm \sigma_T \quad \text{where } S \text{ is defined above} \quad (3.5)$$

and $\sigma_T$ is the vector sum of $\sigma_s$ and $\sigma_n$, that is

$$\sigma_T = \sqrt{\sigma_s^2 + \sigma_n^2} = (r_s \gamma T + 2r_n \gamma T)^{1/2} \quad (3.6)$$

That the total deviation in the count can be expressed in this way is due to the assumed statistical independence of the two components. The signal deviation, $\sigma_s$, originates in the processes external to the detector, while the noise deviation, $\sigma_n$ originates in the thermionic emission processes within the photomultiplier tube.
One of the design goals is to keep the error in the information conveyed to the astronomer to a value less than \pm 5 percent. This can be expressed as

\[
C = S \pm 0.05 S
\]  \hspace{1cm} (3.7)

Comparing this with value of C derived earlier, we see that

\[
0.05 S = \sigma_t = (r_s \gamma T + 2r_n \gamma T)^{1/2}
\]

or

\[
0.05 = \frac{\sigma_t}{S} = \frac{(r_s \gamma T + 2r_n \gamma T)^{1/2}}{r_s \gamma T} \hspace{1cm} (3.9)
\]

which is the expression for the system error. The inverse of this expression is the better known signal-to-noise ratio of the system,

\[
\frac{S}{N} = \frac{S}{\sigma_t} = \frac{r_s \gamma T}{(r_s \gamma T + 2r_n \gamma T)^{1/2}} \hspace{1cm} (3.10)
\]

For any reasonable number of counts in an interval (say 100 or more) the Poisson distribution approaches the Gaussian normal distribution. The \pm 1\sigma value of the error expression has a confidence factor (probability) of approximately 0.68. That is, the probability that the signal will have a mean value \(S \pm \sigma_t\) is 0.68. Let us impose a more rigid restriction on the error at this time by requiring the 5 percent error limit to have a confidence factor of 0.95 which corresponds to a \pm 2\sigma interval under the normal distribution. This reduces the error constant from 0.05 to 0.025.

Having derived the error expression for the system and using the error limit specified in the design goals, we can test the system...
performance by the following approach.

1. Plot the average spectrographic plate exposure time as a function of source brightness from empirically derived data provided by experienced spectroscopists.

2. Solve the error expression derived in this section for the integration time, $T$, required to limit the system error to $\leq 5$ percent with a confidence factor of 0.98 for various average signal rates corresponding to different source brightnesses.

3. Plot the theoretically derived integration time, or exposure time, on the graph with the empirically derived data.

The system error criterion will be met as long as the integration time required to meet the error limit is less than the empirical value of the integration time at any given value of source brightness over the range of operation specified in the design goals ($2.0 \leq m_v \leq 12.0$).

The photomultiplier tube used in the exposure meter had an average dark current pulse rate of 1500 counts per second at room temperature. The value of $\eta$ for this system is $\eta = 0.468$. Using these constants in the error expression and solving for $T$, the theoretical integration time required to meet the error specification, we obtain

$$T^* = \frac{(r_s + 2r_n)^{1/2}}{r_s \eta^{1/2}(0.025)} = \frac{58.5 (r_s + 3000)^{1/2}}{r_s}$$

(3.11)

An example will be worked for the case of $m_v = 12.0$ corresponding to a photon rate at the input to the photomultiplier of 300 photons/second (see Table 2). The photomultiplier quantum efficiency over the optical
passband of interest is about 12 percent according to the manufacturer’s data curves. This means we have a value of $r_s$ of $0.12(300) = 36$ counts/second to use in the above expression. Solving for $T$ yields a value of 8800 seconds which is less than the approximate 12000 seconds which is required to obtain a spectrogram of a source with $m_v = 12.0$. Figure 3.3, is a plot of the results of this analysis. It shows the empirical spectrogram exposure time for source brightnesses over the range of interest, and the plot of the integration time required by the EM system to insure that the information displayed is within the specified error limits with a confidence level of 0.98. Since the curves do not cross, and the theoretical curve lies to the left of the other, we can conclude that the exposure meter error will always be less than the limit values and our performance criteria can be met.

3.3 Signal Processing

The light signal which the EM uses is obtained in the following manner. A pellicle, which is a thin organic film with very good optical properties, is placed in the main beam of the spectrograph between the slit jaw and the collimating mirror. It is placed at a 45 degree angle with respect to the optical axis, intercepts the entire beam, and reflects about 6 percent of the light out of the beam to the EM system. An optical transfer system consisting of a lens pair forms a reduced image of the slit on the photocathode surface. Star motion is the slit as seen in the image plane is minimal because of the 10:1 reduction factor used. The maximum slit length is 1.0 inch and this entire length is seldom used, so the total image excursion on the photocathode surface is usually on the order of 0.050 inch.
Figure 3.3 Results of Signal Analysis
A filter holder which accommodates up to four colored filters for spectral matching purposes is incorporated in a mechanical configuration which houses the light chopper assembly and the photomultiplier tube. The Pulse amplifier is attached to this configuration but is readily removable. The entire optical system is shown in Figure 3.4.

After the light has passed through the spectral matching filter, it is modulated by the mechanical chopper assembly on a 50 percent on, 50 percent off basis, and finally the modulated light strikes the photocathode. For the 12 percent quantum efficiency mentioned earlier, on the average about 12 photoelectrons are released for every 100 incident photons. These are amplified by the secondary emission process in the photomultiplier tube, and the resultant average voltage pulse appearing at the anode is given by $\overline{V} = \frac{\overline{Q}}{C}$ where $\overline{Q}$ is the average charge per pulse, and $C$ is the total anode circuit capacitance including cables and amplifier input. For a multiplier gain of $10^6$ and $C = 25$ pf, $\overline{V} = 6.4$ millivolts. The anode circuit resistance is matched at 100 ohms into the pulse amplifier so that the anode circuit time constant is equal to 2.5 nanoseconds.

The voltage pulse appearing at the anode is fed to the dc coupled wideband amplifier (BW = 25 MHz), which has a fixed gain of 60 db. An amplitude discriminator biases off dynode noise pulses which will have amplitude less than the pulses originating from the photocathode and also rejects noise originating in the external environment inducing voltages less than the signal voltage at the input of the amplifier. Amplifier shot noise is also eliminated by the discriminator.
Figure 3.4 Exposure Meter Light Signal Pickoff
action. A fast five stage binary counter, which can be by-passed, follows the discriminator, and the final stage of the amplifier is a one-shot driver which feeds a 1 microsecond pulse to a transformer-coupled output stage providing a push-pull, balanced to ground, output signal. For random pulse rates higher than about 0.1 MHz, the modulo-32 counter is utilized to prevent dropping pulses at the one-shot due to its one microsecond pulse period.

A pair of 93 ohm coaxial cables transfer the signal from the pulse amplifier output over a distance of about 20 feet to a module which gates the pulses into the bi-directional counter in a synchronous manner where they are accumulated. The receiving end of the pair of transmission lines consists of a matched transformer which converts the push-pull signal back to a single-ended signal. It is then re-shaped and amplified by a line receiver before being gated into the counter.

The gating circuitry for the system is shown in Figure 3.5. The letters within the circles identify signals shown in Figure 3.2. The line voltage driving the synchronous motor is stepped down to 6.3 volts and its zero crossing is detected by the Schmitt trigger circuit. The output is inverted from the input, and the circuit has individual threshold and hysteresis adjustments. Two inverters following the zero crossing detector provide the bi-directional counter control signals which are exactly out of phase. During the half cycle that the reference signal is positive, the Reverse Inhibit control signal to the counter is at a logical "1" and the Forward Inhibit control signal is
Figure 3.5 Counter Control and Input Signal Gating
at logical "0". During the second half cycle of the reference signal, the control signals are in the opposite state. The counter control signals, therefore, alternately gate the counter between the accumulative and subtractive modes in synchronism with the reference signal.

When the light beam is modulated by the synchronously driven chopper, there is a small amount of time varying phase shift between the chopper driven rotor and the electrical driving signal. If the pulse signal resulting from the modulated light were gated to the counter clock line in synchronism with the Forward Inhibit and Reverse Inhibit signals, the phase excursions of the chopper rotor would cause the signal pulses to overlap the intervals around the zero crossing points. This would allow signals from the two separate timing intervals to be intermixed in the counter.

A blanking scheme has been devised to eliminate the possible mixing of modulated signal pulses around the zero-crossing point. The effect is illustrated in Figure 3.2 where the counter clock gate output is delayed with respect to the zero-crossing occurrences and is of duration $T < \frac{t}{2}$, thereby precluding signal interval mixing.

The blanking is accomplished in the following manner: assume the binary control counter consisting of four toggle type flip-flops was completely reset. The bi-directional counter clock gate is disabled by the AND-gate driven inverter, and the control counter input gate is disabled by the OR-gate driven inverter pair. On the next reference input zero crossing detected by the Schmitt trigger, the inverter following that circuit will undergo a logic transition which
triggers the one-shot for either logic transition, i.e., one-to-zero or zero-to-one. The two millisecond pulse from the OR-gate starts the control counter by qualifying the input clock gate, allowing the 2 KHz clock signal to enter the binary chain of flip-flops. After the second pulse, one input to the AND-gate driven by the  Q outputs of the flip-flops is no longer qualified. This enables the signal gate for the bi-directional counter, gating the signal to the counter clock line. The bi-directional counter will count in the direction dictated by the logic states on the inhibit lines. The bi-directional counter clock gate was enabled one clock-time or 0.5 milliseconds after the zero-crossing of the reference occurred, so a blanking at zero-crossing is achieved.

The one-shot signal is gone after 2 milliseconds, but the input gate to the control counter will be enabled by one of the counter  Q outputs through the OR-gate until the counter recycles after 16 inputs, which corresponds to 8 milliseconds in time. At this time the bi-directional counter clock gate is disabled, as is the control counter clock, until the next zero-crossing of the reference occurs. At such time the process just described is repeated.

In summary, with the reference signal being the 60 cycle line, zero-crossings occur every 8.33 milliseconds. At this instant, the control counter is started and it will count for 8.0 milliseconds. One-half millisecond after the control counter starts, the bi-directional counter clock gate is enabled, and signal pulses are allowed to clock the counter. When the control counter turns over at the count of 16, the gates are disabled until the next zero-crossing occurrence.
3.4 Information Storage and Display

The gating electronics described in the previous section on signal processing allows the signal pulses to be accumulated while the average dark current pulses are cancelled out. A bi-directional, or reversible counter is utilized for information storage. The counter consists of six 1-2-4-8 binary-coded-decimal decades wired to respond to directional control signals, called gating signals. The counter clock is the signal pulse train after blanking has occurred. The counter is either incremented or decremented at the clock rate depending on which control line is activated. Points A, B, and D on Figure 3.5 correspond to the signal points under consideration.

The binary-coded-decimal outputs from each counter decade are wired to commercial decoder-driver modules which activate decimal display tubes. Six decimal digits representing the contents of the counter at any given time are displayed on the front panel for the operator. The counter is reset at the beginning of each exposure by grounding all true outputs on the counter with a push-button control from the front panel. A modular power supply provides the 200 volt power for the display tubes.

Since the observer is often busy with other tasks, provision has been made to cause an alarm to be triggered when any preselected count has been reached by the counter. Selection is by decimal coded switch setting. Decoding logic based on diode matrix techniques (Millman and Taub, 1965, pp. 349-352) converts the outputs of each counter decade to ten-line decimal form. A decimal coded switch
selects the desired count from each decade and the six switch outputs form the input to a logical and gate. When the preset count is reached, the gate is qualified and an alarm, consisting of an audio tone and an indicator lamp, is triggered. This indicates to the observer that the preset count, which represents the correct plate exposure, has been reached, and he terminates the exposure by closing the shutter on the spectrograph. A block diagram of the decoding and alarm circuitry is shown in Figure 3.6.
Figure 3.6  Counter Decoding and Alarm
4.1 Laboratory Test Results

The digital exposure meter was constructed using discrete circuit elements. A negative logic convention was used with zero volts representing a logic "0" and negative six volts representing a logic "1". The logic functions were implemented with AND, OR, and Inverter circuits which comprise the standard complement of the Electronic Research Laboratory logic family.

Bench tests were made in the laboratory to check out the gating functions, counter performance, decoding logic and the alarm circuitry. Previous temperature tests had qualified all the standard ERL logic circuits over a wider temperature range than anticipated in the operational environment of this instrument. Also, the pulse amplifier had been qualified over the temperature range of 0 degrees C. to 50 degrees C. The pulse amplifier is discussed in greater detail in Appendix A.

Drift tests were made in the laboratory to check the capability of the system to average out the dark current from the photomultiplier tube, and to ascertain that the noise fluctuations, $\sigma_n$, remained within the limits derived in Section 3.2. The unit was set up in the dark room in the laboratory, and the dark current pulses from a photomultiplier were amplified and shaped by the pulse amplifier operated with the
discriminator bias level set to a nominal dial value of 2.0 and the scale of thirty-two counter by-passed. The results of the drift tests are summarized in Figure 4.1 which indicates the capability of the system to average out the photomultiplier tube dark noise and to contain the error within the predicted statistical limits, namely \( \pm 2\sigma_n \)

where \( \sigma_n = (2\gamma T)^{1/2} \) as developed in an earlier section.

In order to better understand the nature of photomultiplier output signals as pulses rather than as a continuous analog current, several other tests were made at this time. One set of measurements was made to determine the functional relationship between the dark current pulse rate and the pulse amplifier discriminator setting with the photomultiplier anode voltage as a parameter. The results of this test are shown in Figure 4.2 for anode voltages of 1000 volts and 1100 volts. A general conclusion that can be made as a result of this test is that for the RCA 1P21 type photomultiplier, most of the dark current pulses are of low amplitude and the majority can be eliminated by proper choice of the discriminator bias level.

The final test on the system was concerned with investigating the combined effects of anode voltage and discriminator bias setting on the system performance. With the system set up in the dark room of the laboratory, a source of low light intensity was created using a constant current source, an incandescent lamp and optical attenuating filters. For an arbitrary constant low light level, \( I_1 \), count rates as a function of discriminator setting were measured with the anode voltage as a parameter as in the previous test. This test was then
Figure 4.1 Exposure Meter Drift Test Results
Figure 4.2  Dark Pulse Rate vs. Discriminator Bias
repeated for another arbitrary low light level, $I_2$, where $I_2$ was less than $I_1$. The results of these tests are presented in Figures 4.3a and 4.3b. Analysis of this test data brings out some interesting points. The plateau of the curves in both instances represents the fact that all the photons from the source which are passing through the collecting optics are being counted with due regard to photomultiplier quantum efficiency effects. Notice that at lower anode voltages, maximum collection does not take place, even for low values of discriminator bias. For a given bias level setting, the collection efficiency increases with increasing anode voltage. However, so does the noise as is shown in Figure 4.2. It turned out that a bias setting greater than 0.8 was necessary to eliminate pulse amplifier shot noise and that external noise in the telescope dome areas was bothersome up to bias settings of 1.5. These factors determine the lower limit of the discriminator setting. The upper bound is set by the maximum allowable anode voltage for the particular photomultiplier tube being investigated. In arriving at a set of usable parameters, consideration must be given to the relations between collection efficiency, discriminator setting, external noise, thermionic tube noise and high voltage setting. It becomes apparent that the operating parameters cannot be arbitrarily chosen.

4.2 **Performance Results**

The digital mode exposure meter has been in use with the Casse-grain spectrograph on the Kitt Peak 36-inch telescope for more than a
Figure 4.3  Test Results Relating Relative Signal Rate and Discriminator Dial Setting
year. It has withstood the full range of operating environments en­countered through the seasons during this period.

The performance of the device has been satisfactory in every respect, and it has met the design objectives which were outlined in a previous section. A comparison of spectrograms taken with and without the aid of the EM is presented in Figure 4.4. These spectrograms were taken by experienced observers, and the comparison is made primarily to demonstrate the uniformity of density in a series of exposures on different sources when the observer is guided by the EM. The spectra in Figure 4.4 (a) were taken without using the EM, and although they are usable, one can see a wide variation in the density of the con­tinuum, or background, in the series of exposures on the plate. In contrast, the series of spectra shown in Figure 4.4 (b) have a reason­ably uniform continuum density. In reduction of the data and in com­paring stellar spectra for classification purposes, a uniform continuum density is desirable as it reduces the time required for the process.

As a matter of clarification, each plate has a series of narrow spectra on it. Each spectrum is from a different source and each is separated by a comparison spectrum generated by a laboratory discharge lamp. The spectrograph normally incorporates two or three comparison sources, the most common being Fe, Ne, and A sources. These provide wavelength calibration lines for adjacent unknown spectra. After each exposure, the photographic plate is physically displaced a known amount by means of a micrometer-driven lead screw on the plate holder.

What can not be demonstrated in this paper is the fact that the successful performance of the EM has contributed to an increased
(a) Obtained without Exposure Meter

(b) Obtained with Exposure Meter

Figure 4.4  Comparison of Spectrograms
efficiency in the observational efforts, and in telescope usage. Observers now use the spectrograph under sky conditions which would previously have precluded observational work. When variable sky conditions prevail, guessing the exposure time with sufficient accuracy to produce good spectra is usually quite impossible. Another contribution has been in the fact that relatively inexperienced observers can obtain the same quality of exposures as more experienced observers. Underexposing or overexposing the plate resulting in wasted observer effort and telescope time has been virtually eliminated.

The performance of the EM was such as to warrant requests for additional units to be used on other spectrographs at Kitt Peak, and at the Cerro Tololo Observatory in Chile, which is also operated by the Association of Universities for Research in Astronomy.

4.3 Further Developments in Progress

In planning the construction of additional units, consideration was given to the question of how the first model could be improved, and how it could be made adaptable to the Coudé-type of Spectrograph. Several interesting points were brought to light as a result of this review.

Improved performance in terms of signal statistics can be had by reducing the dark current pulse rate, and by increasing the quantum efficiency of the detector. Recent years have provided an ever increasing amount of developmental effort in the field of photomultiplier tubes. In seeking to improve the system from this point of view, it was found that the newly developed line of photomultipliers manufactured
by the ITT Industrial Laboratories in Fort Wayne, Indiana, were particularly suitable for this application (Eberhardt, 1964). The model FW130 photomultiplier manufactured by ITT was chosen for use in EM units now under construction. It has a lower dark current pulse rate than the 1P21 by a factor of 10 to 15, which results in an improvement in the signal-to-noise ratio by a factor of 3 to 4. This is achieved primarily by a reduction in the effective photocathode area. The 1P21 photocathode area is felt by many to be unnecessarily large. In addition, the FW130 has a spectral responsivity which extends further into the red region of the spectrum, providing wider source-detector spectral matching capability.

Another very important feature of the FW130 which will be used to great advantage in the newer EM configurations is the fact that the unique image-forming electron lens system which provides the small effective photocathode area is deflectable by the addition of a magnetic deflection yoke externally at the neck of the tube. The need for a motor-driven light chopper will be eliminated by this feature and the light beam will be electronically modulated by a square-wave drive signal applied to the deflection yoke. This feature will eliminate the danger of vibration-induced distortions of the spectra.

The new units will be implemented with integrated circuit diode-transistor logic of the NAND-type which uses a position logic convention. The commercial logic function boards manufactured by the Data Technology Corporation of Mountain View, California, are now stocked by our laboratory, and used in the construction of digital
systems. A time-sampling system utilizing the same gating philosophy for dark current elimination has been constructed for use with the Coude spectrograph at the 84-inch telescope. It was felt that the pellicle pickoff system might introduce spectral line profile distortion in the high-resolution Coude instrument. Therefore, instead of removing a fixed, small percentage of the light on a continuous basis and modulating it with a chopper, time-sampling was attempted. A small mirror was attached to the shaft of a stepper motor. The motor steps the mirror into the beam in three steps of 15 degrees each. The mirror samples the beam for 100 milliseconds and then is reversed and backed out to a rest position. A 100 millisecond sample is taken at 5 second intervals resulting in about 2 percent of the light being removed from the beam. After the mirror returns to the rest position, the counter is gated in the reverse mode and the photomultiplier dark current pulses are subtracted from the count accumulated while the mirror was intercepting the beam. The gate duration in this case is 100 milliseconds as before. This system is now operating, and providing successful plate exposure guidance at the 84-inch telescope.

Finally, a provision suggested by Mr. Don Trumbo is being planned which will automatically trail the star along the slit of the spectrograph to achieve the image-broadening necessary to evaluate the spectrum. Normally this is done by the observer through manual push-button actions. When the star image is placed in a certain position on the slit, and the telescope drive rate is held constant at the rate corresponding to the angular rate of the star on the celestial sphere,
the image remains fixed with respect to the slit. Any displacement along the length of the slit, which is oriented in the East-West direction, is obtained through a variation in the basic telescope drive rate. Increasing the drive rate above the sidereal rate will cause the telescope to move faster than the star and the image will appear to move along the spectrograph slit from West to East. Reducing the drive rate causes the star to move at a higher rate than the telescope and the image appears to drift from East to West along the slit.

The trailing would be accomplished by using rate multiplication techniques to multiply the exposure meter input rate by some constant factor $< 1$ selected by the observer, and electronically adding the result to the basic telescope drive rate.
APPENDIX A

DESCRIPTION OF THE PULSE AMPLIFIER

The unit which has been referred to as the pulse amplifier is actually comprised of four separate sections incorporated into one integral assembly. The sections are the pulse amplifier proper, the threshold detector or discriminator, an optional scale of 32 counter, and the output driver stage. Each of these sections will be discussed separately in the paragraphs which follow, and salient features will be pointed out.

The pulse amplifier section is shown schematically in Figure A-1. It consists of three stages of d.c. coupled doublets with a.c. feedback between the output emitter and the input base connections. The second and third stage feedback circuits have clamp diodes to prevent large amplitude pulses from saturating either stage. The amplifier stages are R-C coupled with the input bias for each stage being derived from the previous output stage through the 4.7K ohm resistors which provide d.c. coupling between stages. Overall amplifier stabilization is obtained by the d.c. feedback loop between the output and the input. Transistor bias levels were chosen to provide a high gain-bandwidth product. Low-noise resistors were used exclusively in the first doublet stage and the power supply was decoupled at each stage by means of a pi-section filter.

The amplifier is intended to be used with d.c. source resistances exceeding 50K ohms. Capacitive coupling would be required for
Figure A-1  Pulse Amplifier Section
operation with lower source resistances. In the application under consideration, the source consists of a photomultiplier tube which is a nearly perfect current source. The current gain of the amplifier is 450 and the voltage gain is approximately 2500. The rise time of the amplifier is approximately 10 nanoseconds. Its input impedance is 100 ohms.

The threshold detector used in the pulse amplifier consists of a tunnel-diode monostable circuit which is shown in Figure A-2. The bias voltage is established by the 500 ohm potentiometer paralleled by the 6.8 volt zener diode. The 1.0 mfd capacitor filters potentiometer noise while the L-C pi configuration prevents high frequency noise triggering via the power supply.

The voltage across the tunnel-diode is fixed by the voltage divider action of the 1K ohm and 47 ohm resistors in series. The equivalent circuit at this point establishes the d.c. load line and bias point for the circuit. The IN3717 is a 2 ma. diode.

The input pulse is capacitively coupled into the 560 ohm series input resistor from the final amplifier stage. The output is capacitively coupled to either the scale of 32 counter or the output stage directly, depending on the selector switch setting. The back-diode speeds up the recovery of the circuit after triggering by decoupling the threshold detector from the following stage, thereby reducing the loading on the detector circuit.

The scale of 32 counter, which is an integral part of the pulse amplifier module, consists of five series-connected bistable
Figure A-2   Tunnel-Diode Threshold Detector
tunnel-diode stages. Two of the five identical circuits are shown in Figure A-3. The counter is non-resettable, and operates in the toggle-mode from the input pulse train. The circuit responds to positive trigger pulses generated in the preceding threshold detector stage.

In this type of circuit, only one of the two tunnel-diodes in each stage can be in the "on" state at any given moment. This condition is assured by the supply voltage being limited to a value less than that which would support both being on simultaneously. Each input trigger pulse then causes the circuit to change state.

The output circuit consists of a one-shot circuit driving a cutoff transformer-coupled output stage which is operated push-pull into 93 ohm coaxial cables. The push-pull mode is used because of the noise environment in operating locations. The driver stage supplies an output pulse of approximately 2.5 volts amplitude. The output pulse width varies slightly, depending on the repetition rate. It is approximately 0.6 microseconds in duration at a repetition rate of one megacycle. Figure A-4 shows the output circuit configuration consisting of the one-shot and line-driver.
Figure A-3  Bistable Tunnel-Diode Counter
Figure A-4  One-Shot and Line Driver
LIST OF REFERENCES


