DEVELOPMENT OF A HIGH PRECISION INFRARED DENSITOMETER SYSTEM

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DEVELOPMENT OF A HIGH PRECISION INFRARED DENSITOMETER SYSTEM

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ABSTRACT

DEVELOPMENT OF A HIGH PRECISION INFRARED DENSITOMETER SYSTEM

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A densitometer system to characterize high density, narrow band filters has been developed and put into operation. This system has the ability to measure filter density over a wide dynamic range and with high resolution. The theoretical requirements of the instrument are presented and a detailed description of all of the components is given. System operation is briefly described, followed by data that represents the optical density profile of several different filters. The overall performance of the system is evaluated and recommendations for future improvements are discussed.
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LIST OF SYMBOLS

\[ a = \text{grating groove spacing} \]
\[ A1-A4 = \text{auxiliary spectrometer mirrors} \]
\[ BLS = \text{bottom left slit} \]
\[ BRS = \text{bottom right slit} \]
\[ c = \text{speed of light} \]
\[ C = \text{first radiation constant} \]
\[ C_D = \text{junction capacitance} \]
\[ C1 = \text{spectrometer center mirror} \]
\[ d = \text{second radiation constant} \]
\[ D = \text{optical density} \]
\[ D^* = \text{detector figure of merit} \]
\[ E = \text{irradiance} \]
\[ GL = \text{left side diffraction grating} \]
\[ GR = \text{right side diffraction grating} \]
\[ h = \text{Planck's constant} \]
\[ i = \text{detector photocurrent} \]
\[ k = \text{Boltzmann's constant} \]
\[ l = \text{slit to mirror distance} \]
\[ L = \text{radiance} \]
\[ L1 = \text{spectrometer upper left mirror} \]
\[ L2 = \text{spectrometer lower left mirror} \]
\[ m = \text{number of monochromators} \]
M = radiant exitance
M1-M4 = spectrometer alignment mirrors
N = number of grooves on a diffraction grating
NEP = noise equivalent power
N_{\lambda} = number of photons per wavelength
P_{\lambda} = monochromatic incident optical power
q = elementary charge
R = reference scan signal level
R_D = detector shunt resistance
R_S = detector series resistance
R1 = spectrometer upper right mirror
R2 = spectrometer lower right mirror
s = slit width
S = sample scan signal level
T = temperature in degrees Kelvin
TLS = top left slit
TRS = top right slit
v = object distance
v' = image distance
w = grating width
\( \psi \) = grating blaze angle
\( \varepsilon \) = emissivity
\( \lambda \) = wavelength of light
\( \lambda_b \) = blaze wavelength
\( \Delta \lambda \) = spectral resolution
\( \Omega \) = solid angle
\( \eta \) = quantum efficiency
\( \sigma \) = Stefan-Boltzmann constant
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CHAPTER I

INTRODUCTION

Instrument Requirements

The densitometer has been built to substantially advance the state of the art in transmission measurements of infrared filters. Transmission measurements are made across a narrow band at any wavelength from 1 to 5 microns. The transmission levels greatly exceed the measurement capabilities of conventional equipment, which typically measure optical densities below 4, over a 2-3% bandwidth, at near infrared wavelengths. The measurement of a large attenuation factor requires a system with a correspondingly high signal to noise ratio. For example, to measure an optical density of 6, the optical power which must be available to the detector in the absence of a sample must be $10^6$ times greater than the noise level of the detector. Thus, the light source must have a high power output and the detector must have a low noise level. Since there is interest in measuring attenuation across the 1 to 5 micron region, both the light source and the detector must be broad
band. The major challenge is that the system must be capable of characterizing notch filters. These filters attenuate across only a narrow range \((d\lambda)\) which is much smaller than the wavelength \((\lambda)\) at which the measurement is made.

The difficulty in measuring high attenuation levels in a notch filter is related to the arbitrary wavelength requirement. Ideally, powerful narrow band light sources (lasers) would be used. Unfortunately, dye lasers do not have a spectral range which extends far into the infrared, and they have unstable outputs. Diode lasers are available in the wavelength region of interest; however, these are lacking in high power. The only practical light source which continuously covers the 1 to 5 micron region is an incandescent source, or hot filament. A thermal source of this type provides the requisite power across the region by emitting radiation at all wavelengths simultaneously. The broad band detector responds to each of these wavelengths. Thus, we need to measure the removal of energy across a narrow range as shown in Figure 1.

During the development of the densitometer, three different definitions of linewidth in a stop band filter were encountered. The linewidth definition is important because it establishes the basis on which both filter
Figure 1. Transmission Characteristics of a Narrow Band Filter. The spectrometer must eliminate the out-of-band radiation if a high optical density measurement is to be made.
fabrication and densitometer performance are evaluated. These three definitions are illustrated in Figure 2. The most common definition is the full width at 50% transmission, shown by position (c) in the figure. Some custom filters use this definition. It is useful in establishing the available throughput of a filter over a given spectral range; it is also a good definition for the pass band of a filter. The definition chosen for the densitometer corresponds to the region over which high attenuation occurs. The measured linewidth is taken as the spectral region between those points, which are down 3dB in optical density from the maximum density achieved by the filter (position (a) in Figure 2). This width determines the resolution needed to measure the full density of the filter.

The two definitions may vary by as much as a factor of 10, since even a perfectly made filter will have nearly a parabolic shape when plotted in terms of density (see Figure 2). This discrepancy is a characteristic of high density filters. The two definitions approach each other as the maximum density drops below 3. In recognition of this problem, one manufacturer created a third definition: the range between those points at which the optical density is half its maximum value (position (b) in Figure 2).
Figure 2. Ideal Shape for a High Density Filter. The arrows indicate the three different filter definitions in use. D is the filter density and \( \lambda \) is the wavelength. Definition a refers to a 3 dB drop in density. Definition b is the filter width where the density is one half of its maximum. Definition c is the linewidth for 50% transmission.
Intense broad band radiation at wavelengths other than the one at which the measurement is made must not reach the detector. These wavelengths will contribute a noise signal which will swamp the density measurement. Stray light must typically be reduced by a factor of roughly $10^9$, while keeping as much light as possible at the signal wavelength. This calls for a pass band filter to be placed in the optical train with the notch filter producing the situation (shown in Figure 3). Thus the instrument filter must have a continuously tuneable pass band wavelength and reject stray light by a factor of $10^9$. The only practical means of meeting these strenuous requirements is to use a high-resolution grating spectrometer as the instrument filter.

In summary, there are three critical components of the densitometer: an intense thermal source, a low-noise broad band detector, and a spectrometer with superior stray light rejection.

The densitometer must have resolution capabilities which correspond to the chosen linewidth definition, (the region 3dB down from the maximum density). Since very narrow notch filters can be made, high resolution is essential. The capability of the densitometer to characterize filters cannot be given without specifying the resolution and the density obtained.
Figure 3. Spectral Filtering Required for the Densitometer. The densitometer must act as a narrow pass band filter in order to characterize high density interference filters.
CHAPTER II

THEORY

Theoretical Requirements

The main components of the densitometer are the source, entrance and exit optics, spectrometer, and detector. The performance of these components is set by basic physical laws; this chapter presents those laws.

Source Radiation Theory

The output of a thermal source is governed by fundamental blackbody radiation laws and depends on the emissivity of the source, operating temperature, effective emission area, wavelength in question, and solid angle subtended by the collection optics.

A blackbody is an ideal body of uniform temperature that perfectly absorbs all incident radiation. A blackbody is also a perfect thermal radiator in that all nonblackbody thermal radiators in equilibrium at the same temperature as their blackbody counterparts emit less radiant flux than the
blackbody. The radiant flux of a nonblackbody thermal radiator is determined by the material characteristics of its surface and temperature. In the case of a blackbody, radiant flux is determined by temperature only. The radiance of a blackbody, which describes the differential angular dependence of the flux density, is the same in all directions.

The total radiation output of a blackbody source scales as the fourth power of the absolute temperature according to the Stefan-Boltzmann Law

\[ M(T) = \sigma T^4, \quad (2-1) \]

where \( M(T) \) is the radiant exitance, \( \sigma = 5.67032 \times 10^{-8} \text{W/m}^2\text{-K}^4 \), and \( T \) is the temperature in degrees Kelvin. For greybody sources, a scaling constant, \( \varepsilon \) (emissivity) is introduced to the law. An ideal blackbody has an emissivity of 1. All greybodies, by definition, have an emissivity of less than 1. The SiC element used in the densitometer has an emissivity of 0.9, which is about as high as can be obtained without a special cavity design.

The spectral distribution of blackbody radiation is described by the Planck Radiation Law. In terms of spectral radiant exitance, the law is

\[ P(\lambda) = \frac{2\pi\sigma c^3}{(\lambda^5 \cdot \exp(c/\lambda kT) - 1)} \]

\[ P(\lambda) \quad \text{ergs/s/cm}^2\text{-A} \]

where \( P(\lambda) \) is the spectral radiant exitance, \( c \) is the speed of light, and \( k \) is the Boltzmann constant. This law describes the distribution of energy per unit area and wavelength in blackbody radiation. The Planck function gives the probability distribution of radiant energy per unit wavelength interval, which is a fundamental concept in the study of radiation properties.
\[ M(\lambda, T) = \frac{c}{e^{\frac{e^d}{\lambda T}} - 1} \text{ W/m}^3, \quad (2-2) \]

where the first radiation constant is \( C = \frac{2\pi hc^2}{2} = 3.745 \times 10^{-16} \text{ W m}^2 \) and the second radiation constant is \( d = \frac{hc}{k} = 1.439 \times 10^{-3} \text{ mK} \). Similarly, the spectral radiance of a blackbody is given by \( \text{W/m}^3\text{sr} \):

\[ L = \frac{M}{\pi} \quad \text{W/m}^3\text{sr}. \quad (2-3) \]

Graphs of \( L \) as a function of body temperature are shown in Figure 4\textsuperscript{1}. It is desirable to operate the source at as high a temperature as possible. The maximum operating temperature of a thermal source is limited by the point at which the element either burns up, sublimes, or disintegrates. The SiC source is designed to operate at 1800 K and is typically run at 2100 K. In the densitometer it is sometimes run at 2300 K and could be run for brief periods of time at 2500 K. These temperatures are as high as can practically be achieved for a thermal source operating in air. Increasing the source operating temperature to 2500 K or 3000 K would only improve the instrument performance, respectively, by factors of 2 and 5 dB. Thus, the only way to maximize the source output is to increase its effective area and/or the collection solid angle. However, these parameters are set, respectively, by the detector and the spectrometer, as will be shown later. It can be concluded that, in the absence of laser
Figure 4. Spectral Radiance of a Blackbody Source. Spectral radiance is plotted as a function of wavelength for different blackbody temperatures. Output power in the 1 to 5 micron region is limited using a thermal source.
sources to cover the spectral range, the SiC element used in the densitometer system provides as much light as physically practical. The element gives the greatest output power in the 1 to 2 micron region while significantly less power is emitted in the 3 to 5 micron region.

**Radiation in an Optical System**

For an optical system, a variety of quantitative parameters can be used to describe the amount of radiation present. The flux density at a surface is the measure of radiant power $W$ falling on an area $A$. It is given by

$$E = \frac{W}{A}. \quad (2-4)$$

This quantity, referred to as irradiance, may be applied to a radiating surface, the power crossing an imaginary surface in space, or the power falling on an actual surface. A geometrical description of irradiance is shown in Figure 5a.

Unfortunately, irradiance tells us nothing about the angular spread of the incident power. Consider the power $dW$ incident at an angle $\theta$ to the normal of the surface and contained in a solid angle $d\Omega$ (see Figure 5b).
\[ E = \frac{W}{A} \]

(a)

\[ L_\theta = \frac{dW}{A \cos \theta \, d\Omega} \]

(b)

Figure 5. The Definitions of (a) Irradiance (E) and (b) Radiance L.
The radiance, $L$, is defined as the power per unit projected area per unit solid angle $\Omega$,

$$L = \frac{dW}{A \cos(\theta) d\Omega} \ (\text{W}/\text{m}^2 \text{sr}) .$$

(2-5)

Again, radiance may be applied to a real or imaginary surface. Radiance is a more useful quantity than irradiance in the context of optical systems because it has the same value throughout the system as long as power is not lost from the beam by absorption or scattering. Constant radiance is a consequence of constant throughput$^3$, defined as the product of the cross sectional area $A$ of the light beam and the solid angle delimiting it. Figure 6 shows this for a simple lens system. The linear magnification, $m$, is given by

$$m = \frac{v'}{v} ,$$

(2-6)

where $v$ is the object distance and $v'$ is the image distance (Figure 6). The ratio of the image area to the object area can then be expressed as

$$A' / A = \left(\frac{v'}{v}\right)^2 .$$

(2-7)

Similarly,
\[
\frac{\Omega'}{\Omega} = \left( \frac{v}{v'} \right)^2.
\]  

(2-8)

Therefore, the throughput is

\[
A\Omega = A'\Omega'.
\]  

(2-9)

If \( U \) is defined as the total power input to the system, then, from the equation above for \( L \), with \( A \) and \( A' \) normal to the optic axis, \( U = LA\Omega \). Thus if \( U \) is conserved then \( L' = L \). Conservation of radiance is a fundamental limit of an optical system: this cannot be overemphasized. In reality, losses due to absorption and scattering further limit system throughput. Conservation of radiance seems to indicate that an optical system is limited by its slowest element. This refers to components that have relatively small collection solid angles. In the case of the densitometer, this is the spectrometer.
Figure 6. The Conservation of Throughput for a Simple Lens System \( A \Omega = A' \Omega' \).
Spectrometer Theory

The important parameters for the spectrometer are its' resolution and stray light rejection. Resolution is dependent on the diffraction gratings in the instrument; the development of this is provided in Appendix A. The stray light rejection parameter depends on the entrance slit width and the slit-to-mirror distance according to the relation

\[ \text{SLR} = (l/s)^m, \]  

(2-10)

where \( l \) is the slit-to-mirror distance and \( s \) is the slit width. The variable \( m \) represents the number of monochromators in the system. The instrument used is a double monochromator, specially designed to act like a triple monochromator in terms of its stray light rejection capabilities. Thus, for the densitometer system, \( m \) will have a value of 3.
The resolution, $R$, of an optical instrument measures its ability to separate adjacent spectral lines. It is generally defined by

$$R = \frac{\lambda}{\Delta \lambda},$$

(2-11)

where $\Delta \lambda$ is the difference in wavelength between two equal intensity spectral lines that are barely separated.

Two peaks are considered resolved if the distance between them is at least such that the maximum of one falls at the first minimum of the other. This is called the Rayleigh criterion. The angular half-width of the diffracted image is

$$d \theta = \frac{\lambda}{w \cos \beta},$$

(2-12)

where $w$ is the width of the entire grating and $\beta$ is the angle of the diffracted beam. By differentiating the grating equation (A-3) with respect to $\beta$ and $\lambda$, one obtains

$$\cos \beta d \beta = \frac{(kd\lambda)}{a},$$

(2-13)
where \( a \) is the distance between the centers of two grooves and \( k \) is an integer constant referred to as the order. Two wavelengths are separated if \( d\beta = d\theta \)

\[
\frac{\lambda}{w\cos\beta} = \frac{kd\lambda}{a\cos\beta} .
\]  

(2-14)

This yields

\[
\frac{\lambda}{d\lambda} = kw/a = kN ,
\]

(2-15)

where \( N \) is the total number of grooves on the grating. Resolution can also be expressed in terms of the original grating equation,

\[
R = a/\lambda * (\sin\alpha + \sin\beta) * N ,
\]

(2-16)

or

\[
R = w/\lambda * (\sin\alpha + \sin\beta) .
\]

(2-17)

It can be concluded that the resolution depends on the width of the grating, the working angle conditions, and the wavelength.
The spectrometer must provide the required stray light rejection capability and preserve optical throughput. To achieve high stray light rejection, the spectrometer must be large and/or consist of staged units. Maximizing optical throughput requires fast optics and/or large slit widths. Ideally, a low-loss, maximum stray light rejection spectrometer would be custom-engineered and built. Since funds were limited, a commercially available instrument with superior stray-light rejection was selected. Unfortunately, all commercial spectrometers of this type use slow optics. These spectrometers are long, and use collection optics with a diameter much smaller than their length. This results in instrument throughput being sacrificed.

**Detector Theory**

A solid-state photovoltaic detector serves as the signal detection device for the densitometer. Photovoltaic detectors use a p-n junction to convert radiant power directly into an electric current. If a sufficiently energetic photon is absorbed near the junction, it produces an electron-hole pair which, in turn causes current to flow. In the photovoltaic mode, no external biasing is required. Maintaining a zero-volt bias on the detector will obtain
high sensitivity performance. The generated photocurrent is given by:

\[ i = \eta q N_\lambda , \quad (2-18) \]

where \( \eta \) is the quantum efficiency, (i.e., the number of excess carriers produced per absorbed photon), \( q \) is the electronic charge, and \( N_\lambda \) is the number of photons of wavelength \( \lambda \) absorbed in the semiconductor per unit time. \( N_\lambda \), also referred to as the photon absorption rate, is related to the absorbed monochromatic incident optical power, \( P_\lambda \), by:

\[ N_\lambda = (P_\lambda \cdot \lambda)/hc , \quad (2-19) \]

where \( \lambda \) is the wavelength of the incident light, \( h \) is Planck's constant, and \( c \) is the speed of light. Thus the photocurrent may be written as:

\[ i = (\eta q P_\lambda \lambda)/hc . \quad (2-20) \]

In most standard photovoltaic detectors, this photocurrent is converted to a voltage which serves as the output signal. The output voltage is obtained by multiplying the photocurrent by the impedance of the detector circuit. The impedance includes the detector shunt resistance, any series
resistance, and the junction capacitance as shown in Figure 7.

The resulting signal does not consist of only the voltage generated by the incident photon. Background radiation from other wavelengths causes an additional DC current to flow. This background current is proportional to the area of the detector. The shot noise depicted in the figure arises from this current and the signal current.
Figure 7. Basic Circuit of a Photovoltaic Detector. Incident photons cause a current to flow. The effective impedance of the circuit is a combination of $R_s$, $R_o$, and $C_D$. 
The importance of the background component depends on the size of the signal current. If the signal current is much larger than the background and the signal irradiance is uniform, an improved signal-to-noise ratio is obtained using a large detector. This occurs because the signal level is proportional to the detector area while the noise is proportional to the square root of the area. However, when the signal irradiance is focused down to a small spot (as in the case of the densitometer), it is advisable to make the detector area as small as the focused spot. By making the detector small and using a focused beam, a high signal-to-noise ratio is obtained.

Photovoltaic detectors are characterized by their sensitivity and intrinsic noise level. The parameter \( D^* \) is generally used to compare different types of detectors. \( D^* \) is defined as the signal-to-noise ratio at a particular electrical frequency in a 1 Hz bandwidth when 1 watt of radiant power is incident on a 1 cm\(^2\) active area detector. Given sufficient gain by using an amplifier, the higher the \( D^* \) value, the better the detector. \( D^* \) is given by

\[
D^* (\text{cmHz}^{1/2} \text{W}^{-1}) = \frac{\{\text{active area (cm}^2\}\}^{1/2}}{\text{NEP (W/Hz}^{1/2}\})}.
\]

(2-21)
The term NEP in Equation 2-21 stands for noise equivalent power. This is the radiant power that produces a signal-to-noise ratio of 1 at the detector output. It is defined with respect to a particular chopping frequency, wavelength, and unit effective noise bandwidth,

\[
\text{NEP}(\lambda) = \frac{\text{Noise (A/Hz}^{1/2})}{\text{Responsivity (\lambda) (A/W)}}
\]

where the responsivity is defined as the detector photocurrent (or voltage) output per unit incident radiant power at a particular wavelength.

The \(D^*\) value of a solid-state detector, an inherent property of the detector material, is wavelength dependent. Performance in a given spectral region can be enhanced by selecting the most appropriate semiconducting detector material for that region. An Indium Antimonide detector was selected to cover the 1.5 to 5 micron region. This detector has especially good performance in the 3 to 5 micron region. A Germanium detector was selected to cover the 0.9 to 1.4 micron region. Both detectors are made by EG&G Judson. Curves of \(D^*\) versus wavelength the detectors are shown in Figures 8 and 9. The two different curves in Figure 8 show \(D^*\) for InSb using two different fields of view.
Figure 8. $D^*$ as a Function of Wavelength for InSb Detectors as Specified by EG&G Judson.
Figure 9. $D^*$ as a Function of Wavelength for Ge Detectors as Specified by EG&G Judson.
The higher curve is for a 60-degree field of view while the lower curve is for a 180-degree field of view. The three different curves in Figure 9 for Ge show \( D^* \) for different operating temperatures. The Ge detector is very valuable at the short wavelength end of this region where the performance of the InSb detector falls off rapidly.

The noise level of the detector depends on the material used and the detector area. The detector noise level can be minimized by making the detection area as small as possible, provided the detector is background noise limited. Using a small detector places demands on the optical system which must image the light source onto the detector area. Realistic constraints on the optical system limit the size of a detector. Therefore, once the detector material and element size have been selected, the minimum noise level of the detector is fixed. Detection noise is not the only noise component that will corrupt the desired signal. Additional noise due to amplifiers, stray light, and vibrations will contribute to the base noise level of the system.
CHAPTER III

DESIGN

Design Overview

The densitometer system incorporates a variety of innovative design features. In this chapter, a general overview of the system design will be presented, the special features will be discussed, and a detailed description of all the components will be presented.

Densitometer Design

A block diagram of the densitometer system is provided in Figure 10. The system consists of a hot filament light source (LS), input optical train, chopper (C), fixed and variable attenuators (A), spectrometer (U-1000), exit optical train, and photodiode detector (D) connected to a lock-in amplifier (LOCK-IN). A computer (Z-200) is used for signal processing and much of the system control. The input optical train is divided into two arms: one which
Figure 10. Block Diagram of the Densitometer. Chopped light beams travel through the system and are measured using an infrared detector.
can be considered a sample arm and the other a reference arm. Each arm can potentially contain both fixed and variable attenuators as needed. The variable attenuators are adjustable mechanical slits and have a flat optical response from 1 to 9 microns. Generally, the fixed attenuators follow a similar response beyond 1.2 microns. A sample (S) may be placed in either arm, but for the sake of consistency samples are usually placed in the same arm. A symmetric light chopper, located close to the light source, modulates the output of each arm.

The system can be operated using one or both arms. The one-arm method involves making a direct comparison between signal levels with the sample in and out of one arm. This method makes it simple to characterize the density profile of a sample over a wide wavelength region. One-arm operation has been used the most while two-arm operation is still in the developmental stages. Two-arm operation involves a more indirect comparison. The two arms can be set so that the optical signals passing through each arm are equal. The sample is then placed in one arm and the attenuation of the reference arm is adjusted by a known amount until the two signals are again equal. The density of the sample at the wavelength at which the measurement was made is taken as the increase in density of the reference arm. The accuracy of the measurement depends on the effort to calibrate the fixed and variable attenuators. This
method, a null measurement technique, may produce more accurate results than the one-arm method. The fixed attenuators are neutral density filters with densities of 0.5 to 4.0. The variable attenuators can reduce signal level by a factor of 100. Thus, a dynamic range of 6 decades is available.

The raw data sent to the computer from the detector is stored and then manipulated to characterize the filter. The final result is an optical density spectrum that displays optical density as a function of wavelength for each filter.

**Optical Layout**

A sketch of the optical layout is presented in Figure 11. This sketch divides the system into six regions to show where the optical components are located. Radiation from the broad band Nernst source is collected by two off-axis parabolic mirrors and passed through two independent arms of the system (a). The image of the source is rotated 90 degrees using a pair of flat mirrors in each arm (b). The beams are then alternately blocked using a rotating chopper blade (c). Along this region of the optical path each arm can be equipped with both neutral density filters and a variable slit (not pictured). These components serve as fixed and variable attenuators respectively.
Figure 11. Optical Train of the Densitometer. The system is designed as a radiometer with independent sources in each arm of the instrument. The spectrometer is located at the detector end of the system to filter out as much background light as possible.
beams are then focused onto the entrance slit of the spectrometer using a pair of flat mirrors, a pair of off-axis parabolic mirrors, and a reflecting prism (d). The spectrometer disperses the incident beams, and the resulting narrow band light leaves the spectrometer via the exit slit. The exiting light is collected and focused by an off-axis parabolic mirror, which also directs the beam to a flat mirror (e). The beam is reflected off this flat mirror to an off-axis parabolic mirror that demagnifies the beam onto the active area of the photodetector (f). To preserve high throughput, it is imperative that the beams be properly centered on all the mirrors so that no vignetting occurs.

Special Features

The hot filament used in the densitometer is a Nernst glower. Its maximum output power is obtained by running the SiC element very hot, from 2100 to 2400 K. These temperatures, well above the glower design temperature of 1800 K, are only invoked to analyze very dense filters. Operating the glower at such high temperatures greatly reduces its operating lifetime. However, the advantage of increased output power, especially in the 1 to 1.5 micron region, is worth the risk. The electrical resistance of the SiC element falls off as its temperature increases. To maintain stable light output
and prevent thermal runaway, an elaborate control circuit and special power supply were designed$^5$.

A one-meter-long Jobin-Yvon U-1000 double monochromator is used as the dispersing instrument. Because of its unusual design this spectrometer has the stray light rejection capability of a triple monochromator of similar size. It also has excellent tracking performance.

The optical train was developed to minimize losses in the input optics. The division of light into a sample and reference beam is accomplished without the use of high loss beam splitters: this improves throughput by 6 dB. Off-axis parabolic mirrors, rather than spherical mirrors, are used to collect and focus the light. This improves the image preservation capabilities of the system, allowing more light to pass through the various limiting stops in the system. No lenses are used in any part of the system; this eliminates chromatic aberration, minimizes absorption losses, and reduces background emission. This also allows a single set of optics to be used at any wavelength from the ultraviolet to the far infrared with the exception of the diffraction gratings in the spectrometer. The mirrors in the exit optics train are gold-coated to minimize losses in the infrared, particularly in the 1 to 1.5 micron region. These mirrors can be replaced with aluminum-coated ones to allow for operation in the visible region.
Eliminating beam splitters in the system optics requires that the reference and sample beams be adjacent rather than superimposed at the entrance to the spectrometer and at the detector face. While the design of the spectrometer is well-suited for this, a standard detector face is not. A rectangular 1mm-x-4mm element is used in the InSb detector rather than a more conventional 2mm diameter element to match the detector to the input optics. For the Ge detector, a standard 5mm diameter element is used.

The Nernst glower had to be mounted vertically to prevent sagging at high temperatures; however, the spectrometer has horizontal slits. This is a total mismatch of the spectrometer to the light source. The problem was corrected by using a pair of flat mirrors in each arm of the input optics to rotate the image of the glower 90 degrees. This requires that the Nernst glower and the collection optics be mounted on a platform above the main optical table.

The densitometer uses two types of attenuators to make measurements: fixed and variable. The variable attenuators are adjustable slits which make null measurements possible. The slits are suitable for operation at any wavelength from ultraviolet to the far infrared. The slits have a dynamic range of 20 dB. Fixed attenuators with optical densities up to 4 are available to supplement the variable attenuators.
They can be used to extend the dynamic range of the variable attenuators to cover high optical densities. The choice between variable slits and neutral density filters provides redundancy and the ability to check for consistent measurements.

The system includes a Zenith-48 microcomputer with 650 K of memory and a 40M hard drive. Custom-made software acquires and processes the raw data. Software is also in place to operate the variable slits and the spectrometer.

The spectrometer is mounted on a separate framework from the main optics table where much of the input optics are located. The three-level optical layout allows all the optics to be mounted close to their platform levels, giving the system stability. All the optics have rugged mounts which have been machined so that the settings can be locked to reduce drift.

**Details of the Optical Train**

The setup used to collect and direct the light emitted from the Nernst glower towards the spectrometer is shown in Figures 12 and 13. The Nernst glower sits on an elevated platform and is contained in an aluminum housing. This housing has three apertures cut in it.
Figure 12. Side View of the Nernst Platform. Light from the glower is collected by off-axis parabolic mirrors. The image of the glower is then rotated 90 degrees using a pair of flat mirrors in each arm.
Figure 13. Parabolic and Flat Mirrors on the Nernst Platform. It is imperative that the off-axis parabolic mirrors be positioned one focal length away from the Nernst glower and at the correct angle.
The rear aperture is used in the control circuitry. The light emitted through the other two apertures is the source radiation for the two arms of the system. In each arm, the light is collected by an off-axis parabolic mirror, then reflected to a tilted flat mirror as described in Figure 12. The off-axis parabolic mirrors must be one focal length away from the glower and tilted at the proper angle to capture the maximum amount of light. A closer view of the components on the elevated platform is given in Figure 13. From the tilted flat mirrors, the beams are sent to the main optics table and reflected from a second pair of flat mirrors. These two pairs of flat mirrors rotate the image of the Nernst glower from its original vertical position to a horizontal one. This aligns the image of the vertical source with the horizontal slits of the spectrometer. After being reflected by the flat mirrors below the platform, the beams pass through the chopper blade and travel down to the optical components in front of the entrance slit. In the space between the chopper blade and the remaining input optics (about 1 m) the variable slit attenuators and neutral density filters can be installed for doing null measurements.

The collimated beams from each collection arm are independently focused and imaged at separate points on the entrance slit using the last set of flat and parabolic mirrors, along with a reflecting prism, as shown in
Figure 14. Since the spectrometer has horizontal slits, the resolution of the instrument is retained. The geometry of this last group of input optics is extremely tight due to the one-inch diameter of the incident collimated light beams and the need to preserve throughput. A sketch displaying this tight geometry is provided in Figure 15. Many iterations are necessary when initially positioning the mirrors to avoid vignetting the beams (see Appendix C). The mounts for the flat mirrors are made small to account for the tight geometry.

The spectrometer has an f-number of 8 and is equipped with square mirrors so that the resulting beam profile matches the shape of the gratings as closely as possible. The corresponding collection solid angle is square. The solid angle of the input optics is circular. This is an obvious geometrical mismatch between the spectrometer and the input optics. The manner in which the input beam fills the first spectrometer mirror affects the performance of the instrument. The three situations of interest are shown in Figure 16. If the solid angle of the input optics projected upon the first spectrometer mirror circumscribes the square mirror (C1), the throughput of the system will be maximized. However, if the circle corresponding to the input optics is inscribed by the first
Figure 14. Parabolic and Flat Mirrors Near the Entrance Slit of the Spectrometer. Again, proper positioning of the off-axis parabolic mirrors is extremely important.
Figure 15. Entrance Slit Reflection Geometry. Obtaining such a configuration without any vignetting is essential to maximum throughput.
Figure 16. Match Between the Solid Angles Subtended by the Input Optics and the Spectrometer. Circle C1 corresponds to maximum throughput. C3 corresponds to the system design.
spectrometer mirror, stray light rejection will be maximized (C3), while reasonably good throughput is preserved. The f/7.3 parabolic mirrors that are used correspond to a circle between these two limits (C2). This reduces maximum throughput by 10%.

The layout of the spectrometer is shown in Figure 17. Light enters the instrument through the top left slit (TLS) and exits via the top right slit (TRS). The spectrometer consists of two parallel monochromators that are arranged for vertical scans of the gratings. All the slits on the spectrometer are horizontal and have independent width and aperture controls. A section between the two monochromators (consisting of four flat mirrors and a spherical mirror) enhances the rejection capability of the instrument. The design of this spectrometer gives it the stray light rejection capability of a standard triple monochromator, but with improved reliability and throughput.

Light entering the spectrometer through the TLS is sent to the first grating (GL), then transferred to the second monochromator setup using a series of mirrors. The light then encounters the second diffraction grating (GR) and is reflected out of the spectrometer through the TRS.
Figure 17. Mirror Configuration in the Spectrometer. The five mirrors between the two monochromators enhance stray light rejection.
The exit optics of the densitometer are shown in Figure 18. The light exiting the spectrometer is collected by an off-axis parabolic mirror and focused onto a flat mirror. This flat mirror directs the beams to the final off-axis parabolic mirror which demagnifies the beams onto the detector.

The detected signal results from a demagnified image of the Nernst element. The image is demagnified to minimize the size of the detector area, which helps reduce noise. The signal is then amplified and sent to a lock-in amplifier, which is tuned to the chopping frequency. The lock-in amplifier output signal and the wavelength at which the measurement is made are fed into the computer.

Using two sets of mirrors to collect the light from the Nernst source, rather than using beam splitters to divide the light into two beams, improves the light output of the system by a factor of 6 dB. Each arm receives light from a separate area on the Nernst element: so the sources are independent for each arm. The use of baffling between the arms eliminates any crosstalk between the beams. The use of independent light sources eliminates secondary systematic errors. If beam splitters were used to obtain the two separate beams, crosstalk could occur. This would result from any back reflections and beam coupling induced by the beam splitters.
Figure 18. Exit Optics and the Detector. The image of the two independent sources is preserved in size through all of the intermediate transfer optics. It is demagnified on to the active area of the photodetector.
The Nernst glower light source is an intense infrared source which may be electrically heated to high temperatures directly in air. Since it does not require any kind of protective atmosphere, the only radiation that is absorbed is done so by the surrounding air. This provides a continuous emission spectrum useful for diagnostic testing.

The glower uses a SiC element (rod) which is a non-conductor when cold, but becomes an excellent conductor when preheated to its "ignition" temperature. It has a negative resistance characteristic that requires special control considerations. Negative resistance refers to its marked decrease in resistance with an increase in temperature\(^6\).

The entire Nernst glower assembly consists of a controller, Nernst element and preheater assembly, and an optical housing. The Nernst Glower Controller and the optical housing were UDRI-designed and-constructed\(^5\). The work was completed by J. Michael Aulds in the Electronic and Computer Development Laboratory. The replaceable Nernst elements (Model #242B1033-3) and preheater assembly (Model #242D120) were purchased from Artcor. The company has since been restructured and these components are now available through Therm-Tech.
The above components work together to ignite the Nernst element and provide stable output radiation. The preheater assembly starts the Nernst glower by radiant heating in about ten minutes, then it is automatically turned off. When the element is activated, it has an effective active area 1.4-mm wide and 6-mm high. The controller monitors the light output using a phototransistor. The controller display can be set to show the phototransistor output in volts, the current passing through the element, or the voltage across the element.

The main components of the Nernst electronics are the preheater, driver, controller, and display. Operation of these devices is described below.

Preheater

The preheater consists of a pair of high resistance wires mounted close to the element. It is started by the pushbutton switch on the front of the electronics package. The switch is latched; the output of this latch turns on a solid-state relay, the relay powers a step-down transformer that energizes the preheaters to about 12 to 14 volts. A light emitting diode (LED) is driven from the transformer as an indicator that the preheaters are on. The preheaters will automatically turn off in two ways. The first occurs if the Nernst glower conducts enough current (about 400 ma).
to indicate normal operation is taking place. The preheaters will also turn off if a problem prevents the current from exceeding the threshold. A timer will turn off the preheaters after about ten minutes. The power setpoint must be set above midscale for the Nernst element to start conducting. The resistance of the Nernst element drops to about 90 ohms after it begins conducting.

**Driver**

The Nernst driver consists of four transistors in a bridge arrangement. Current runs through the two arms of the bridge in two separate half-cycle patterns. The logic generates a two-phase, nonoverlapping clock from a free running oscillator. These drive opposite arms of the bridge; thus the current through the Nernst element reverses about 1,000 times per second.

**Controller**

The light output is sensed by a phototransistor with a second phototransistor used to temperature compensate the active transistor. The difference in current between the two transistors (light current/dark current) is amplified and used as the control signal. This is summed with the setpoint (opposite polarity) and integrated to control the PNP pass transistor which controls voltage to the bridge
(voltage can range from 0 to 60 volts). For stability, the setpoint is derived from a 10-volt reference supply. Loop-gain and loop-dampening adjustments can be made. Adjustments are also provided for maximum and minimum setpoint trim, and a maximum current through the Nernst.

**Display**

The display will show either the output of the phototransistor amplifier in volts or the electrical power input to the Nernst element in watts. The power is computed by multiplying the current through the Nernst by the voltage across the element. The voltage is divided down to a suitable voltage for the analog multiplier. The other input is from a current sense resistor.

After a warmup time of about 20 minutes, the optical output power of the Nernst element at temperatures below 2100 K at any wavelength is stable to one part in a thousand. The lifetime of one element is directly affected by the power at which it is operated. The higher the typical operating power settings, the shorter the lifetime will be. The normal lifetime of a Nernst element operating at a setpoint of 40 Watts is over 2,000 hours and 200 starts.
Optics Specifications

All the mirrors in the densitometer system (excluding the spectrometer mirrors) are gold-coated to maximize the throughput of the system. Gold coating is preferred over aluminum because the reflectivity is higher in the typical operating wavelength region. It is especially vital to optimize the optics at the low wavelength end because source power is limited at typical operating temperatures. Throughput could be further improved by gold-coating the mirrors inside the spectrometer.

Concave off-axis parabolic mirrors were chosen for the system because of their ability to produce a highly collimated light beam from a point source at the focus position. Conversely, the mirrors are capable of focusing incident collimated light, parallel to the axis of revolution, down to a corrected point image along that axis. Concave spherical mirrors operate in a similar manner but they form imperfect point images in collimated light: therefore they cannot form perfectly collimated beams from a point source.

The off-axis parabolic mirrors in the densitometer were purchased as stock items from Space Optics Research Labs. They have an f-number of 7.3, which is near that of the spectrometer’s 8. The clear aperture is 2.3 cm and the
apparent focal length is 16.8 cm. The off-axis angle of the mirrors is 36 degrees. The only exception is the last mirror in the optical path, which is used to image light onto the detector; it has an f-number of 1 and an apparent focal length of 2.3 cm.

The seven external flat mirrors in the system are 5 cm in diameter. They are used to direct light through the system and perform a key image rotation. A gold-coated 60-degree prism located directly in front of the entrance slit directs the beams into the spectrometer.

**Spectrometer Specifications**

The one-meter-long, F/8 Jobin-Yvon U-1000 spectrometer is designed for spectroscopic applications requiring high resolution and extreme stray light rejection. The components of the spectrometer were shown earlier in Figure 17. The instrument consists of two identical monochromators in an additive mount equipped with diffraction gratings. Each monochromator has an asymmetric Czerny-Turner mounting equipped with two horizontal slits which can be independently set at widths of up to 3 mm. The two flat mirrors in each monochromator are 4 in. square and aluminum-coated. The two gratings are mounted and rotate on a single shaft which is parallel to the grating grooves. The gratings are rotated by a cosecant bar driving scheme
that is computer-controlled. The gratings are 110 x 110 mm$^2$ and can be replaced so that a variety of wavelength regions may be studied using this instrument.

The double monochromator design requires that light be transmitted from the first monochromator to the second. The exit slit (BLS) of the first monochromator is imaged on the entrance slit (BRS) of the second monochromator by means of a concave mirror. The optical path of the transferred light is defined by flat mirrors A1-A4 and a 500-mm focal length concave mirror C1.

The resolution and stray light rejection specifications of the instrument depend on the gratings. For use in the one micron region, a pair of Milton-Roy gratings were purchased. The gratings have the following specifications:

* groove density: 600 grooves / mm
* ruled area: 102 x 102 mm$^2$
* Blaze wavelength: 1 micron
* blaze angle: 17.45 degrees
* efficiency at 1 micron: 84 %.
The gratings used in the three-micron region were purchased from Jbon-Yvon Optical Systems and have the following specifications:

* groove density: 300 grooves/ mm
* ruled area: 102 x 102 mm²
* blaze wavelength: 3 microns
* blaze angle: 26.75 degrees
* efficiency at 3 microns: proprietary information

The alignment of this instrument is a major task. Complete alignment procedures for the spectrometer and densitometer optics are given in Appendix C.

**Variable Attenuators**

The variable attenuators for the null measurement technique are pairs of precision slits. They provide a flat response from the ultraviolet to the far infrared. The slits are complex electro-mechanical devices which are computer-controlled. One of the variable slits is shown in Figure 19. The slit is operated by driving a wedge between the two movable shutters (stainless steel razor blades) of the aperture.
Figure 19. Electro-Mechanical Components of a Variable Slit. A stepper motor drives the wedge between the blades to vary the aperture size. Two LVDTs monitor the blade spacing.
A high resolution stepper motor drives the assembly. Eighty-turns-per-inch miniature ball slides, which provide precision linear translation, drive the wedge to push open the shutters. The shutters are mounted on these ball slides. The stepper motor and controller/power supply were purchased from Slo-Syn Electronics. The motor is capable of 200 steps per revolution and the controller is capable of 10,000 steps per second. This combination provides 1.6 microns of travel per step. Given that the wedge half-angle is 32.2 degrees, each shutter will open approximately one micron per step.

Linear Variable Differential Transducers (LVDTs) are used as the position feedback devices for both slits. Two LVDTs are mounted on each slit to monitor the spacing between the shutters. The LVDTs require a 12-V power supply; in return, they provide a DC output voltage of ± 5 volts proportional to the displacement of the movable shutter. They have a 0.01% repeatability over their one inch of travel even though their linearity falls off at either extreme end. Linearity is not a vital concern since the only requirement is the ability to repeat a position.

The LVDT voltage readings are sent to the computer via a 16-bit analog to digital converter. The converter divides the ± 5 V analog LVDT readings into 65,536 increments of 153 µV each. Computer software is used to monitor these
voltage levels. Additional software controls the stepper motor, making it possible to repeat an LVDT position to within 0.0001 V.

In addition to the variable slits neutral density filters are available. These filters are conveniently mounted in a wheel, allowing for easy installation and removal from an input beam. The filters have densities of 0.5 to 4 and a relatively flat response for wavelengths greater than one micron.

**Chopper**

The chopper in the densitometer system is located after the second set of flat mirrors near the source, as indicated in Figure 12. The chopper has a diameter of 255 mm and is equipped with a shroud and translational ports for each arm of the system. The movable ports are used to position the beams for maximum throughput. They are necessary because the two beams are not parallel. The shroud was designed to reduce the air drag caused by the rather large blade. The blade and housing, custom designed by UDRI, are driven/controlled by a standard HMS 220 Light Beam Chopper controller. The chopper is always operated at
around 150 Hz and is used as the reference for the lock-in amplifier.

**Photovoltaic Detectors**

A photovoltaic detector converts incident optical radiation into an electric current or voltage that is the output signal. A standard figure-of-merit for photodetectors is their specific detectivity, or $D^*$ value. This parameter depends on the area of the detector, the noise level, and the responsivity of the detector.

Two different detectors were used in the densitometer system. A Ge detector was used in the lower wavelength region from 0.8 to 1.8 microns. An InSb detector was used for the longer region, from about 2 to 5 microns. The $D^*$ values of these two detectors as a function of wavelength were shown in Figures 8 and 9.

The Ge detector is a J16D series from EG&G Judson. It is liquid-nitrogen cooled, which provides significant performance improvements. It is mounted in a sideview metal dewar and has an active area diameter of 5 mm.

The InSb detector is a J10D series, also from EG&G Judson. It is cooled and mounted in the same manner as the Ge detector. It has an active area of 1.0 mm x 4.0 mm;
this rectangular shape was specially designed for the densitometer. It allows the two adjacent beams to be incident on the detector face while keeping the surface area to a minimum. A 200 nV noise level is present when either detector is used.

**Lock-In Amplifier**

The lock-in amplifier used in the densitometer system is an EG&G Model 5209. Its features include a wide sensitivity range, a variety of available filters, several time constant settings, digital displays for the output signal and tuning frequency, and provisions for computer interface.

The lock-in amplifier uses a signal modulated at a reference frequency as input. In this case, the chopper blade frequency is employed. The signal is then amplified and applied to a phase-sensitive detector operating at the reference frequency. Because of frequency drift effects of the phase-sensitive detector, the result is an output signal that includes a value representing the amplitude of the signal of interest as well as ac components that may be due to noise and interference. The noise can then be reduced by an arbitrary amount using filters.
The lock-in amplifier/chopper blade combination is especially useful for monitoring weak signals. The photodetectors are inherently noisy and completely eliminating stray light is impossible. The rejection of spurious frequencies that come about due to these effects can be improved by increasing the time constant of the measurement. The final output signal is sent directly to the computer. The appropriate settings for the lock-in parameters are provided in Appendix B. The noise level of the detected signal at the lock-in amplifier input can be minimized to about 200 nV.

Computer

The densitometer is controlled through the DENOS computer program, written by Dr. John Loomis of the UDRI Applied Physics Division. This software provides a user interface for system control. All primary functions are displayed in a menu across the top of the monitor. Functions include controlling the spectrometer, controlling the variable slits, making wavelength scans, and manipulating data files. Appendix B provides a detailed description of software implementation.

The monochromator controller is interfaced to the computer through a serial port. Each function of the controller is performed by reading or writing a series of
bytes to the controller. The position or wavelength setting of the monochromator is determined by the orientation of the grating. The absolute position of the grating is not sensed, only relative changes in the stepper drive are recorded.

When power is applied to the monochromator or after any manual adjustment of the grating position, the absolute position of the monochromator must be sent to the controller via the serial interface. This is done through another subroutine. Thereafter, the computer may set the target position and command the controller to step to that position. A configuration file records the absolute position of the monochromator while DENOS is inactive. When DENOS is executed, it reads the configuration file and restores the absolute position to the controller.

During a scan, the signal level recorded by the lock-in amplifier is fed directly to the computer. At each point in the scan, the signal level is monitored for a period of time (delay time) and then time averaged to yield one signal level at a given wavelength. This signal level/wavelength pair is one data point in the scan output file. The complete scanning process is described in Appendix B.
The variable slit controller uses a digital output interface card to send pulses to the stepper motors to control slit width. The true value of the slit width is sensed by the two LVDT sensors on each slit. The analog signal from these sensors is read through an A/D converter and displayed on the monitor.
CHAPTER IV

EXPERIMENTAL RESULTS

Measuring Optical Density

As previously noted in the Introduction, existing instruments can only measure (at most) an optical density of 4 in the infrared region of the spectrum. These instruments also have limited resolution and can only determine filter width up to 2% to 3% of the wavelength of maximum density. The densitometer described here is capable of measuring optical densities approaching 6 in the infrared, with a resolving capability of less than 1% of the wavelength of maximum density. The system is capable of operating in two different modes. The one-arm technique is the most studied and is well established. The two-arm method, or null measurement, was used on one filter to see if improved accuracy in the density measurement could be obtained.
Filter Characterization Using the One-Arm Method

Several different filters were characterized using the densitometer system. In the one-arm method, wavelength scans are made with the filter in and out of the system. An optical density spectral profile is then generated using the formula

$$D = \log \left( \frac{R}{S} \right)$$

where D is the optical density, R is the reference scan (sample out) signal level, and S is the sample scan (sample in) signal level. A density value is thus obtained for each point at which the spectrometer stops to sample the signal level during a scan.

Two features are of interest when analyzing the filter spectra: shape of the filter, and magnitude of the optical density. The ideal filter shape is given in Figure 2 of Chapter II. Major and minor flaws in the shape can be detected using the densitometer. Discovery of these flaws is a valuable piece of information for the manufacturers of high density filters.

Another feature of interest is the magnitude of the optical density. The system was designed to measure optical density well beyond the capability of existing systems. The
width of the filters is defined at points 3 dB down from the maximum density point. This definition corresponds to a 0.3 drop on the optical density versus wavelength spectra in the next section. All density spectra have been normalized relative to the maximum optical density.

**Filter Density Spectra**

The density spectrum of Filter 1 is shown in Figure 20. This is a high quality filter that closely follows the ideal rugate spectral shape. The filter also has a very high density of about 5.2 at its maximum. The location of the 3 dB points is well within the resolution of the instrument. The points are 0.3% and 0.4% away from the wavelength of the highest density. This spectrum displays all the outstanding capabilities of the densitometer.

The density spectra of Filter 2 are shown in Figures 21 and 22. The first scan was over a wide wavelength region; the lock-in amplifier was set for high signal levels so it would not overload. Consequently, when the scan reached the dense part of the filter, the signal level dropped to the detection limit of the amplifier. This is shown by the flat part of the spectrum in Figure 21. The filter density was not constant over this range. The straight line on the plot was created as a flag in the software to indicate the signal was too small to detect with the sensitivity used.
Figure 22 is a scan of this flat region using a higher sensitivity on the lock-in. Though it is noisy, this scan shows the maximum filter density to be about 5.0. Combining the information from Figures 21 and 22, it can be seen that this filter has a flat region of high density and does not follow the ideal shape. This shape is probably due to noise problems with the instrument; the true density is likely higher.

The density spectra of Filter 3 are shown in Figures 23 and 24. Figure 23 is a broad band scan displaying the maximum density at about 1.8. Figure 24 is a narrow scan concentrating on the high density region. The maximum density wavelength was obtained from this more accurate spectrum, which is shifted some from the broad band scan. This shift is probably due to an error in the delay time of the scan (see Appendix B). Figure 24 indicates that the filter has a good shape with 3 dB points at 0.8% of the maximum wavelength.

Filter 4 has a profile similar to that of Filter 3 (see Figures 25 and 26). The difference in the maximum density value in each figure (3.6 versus 3.95) is due to the lock-in sensitivity. The lock-in is unable to precisely measure the signal level in the most dense region of the filter during the broad band scans. Figure 26 gives the more accurate value because the lock-in was set to measure smaller
signals. This figure also displays the good shape of the filter, with the 3 dB points at 1% of the maximum wavelength.

The two flaws in Filter 5 are visible in Figures 27 and 28. The lower wavelength flaw was isolated in the narrow scan of Figure 28. The maximum density near the flaw is about 2.6. The flaw causes density to drop to almost 2.0. The 3 dB points measured from the top of the flaw on either side indicate positions of 0.5% on the lower side and 0.2% on the high wavelength side. This spectrum displays the ability of the densitometer to uncover notch flaws in filters. As with Filter 3, the shift in wavelength between the two scans is probably due to insufficient delay time on the broad scan.

Filter 6 is of relatively low density but has an interesting profile. The broad band scan in Figure 29 shows the uneven shape which is then magnified in Figure 30. The lower wavelength peak is a flaw in the filter. When a high resolution scan of the maximum density region was completed (Figure 31) this part of the filter displayed a smooth shape. The density was only 1.4 and the 3 dB points were at 0.4% and 0.5%, respectively, for the low and high wavelengths.
Filter 7 is a wide band filter of relatively high density. The density spectrum is shown in Figure 32. It has a maximum density of 4.0 and an asymmetric shape. The lower wavelength 3 dB point is at 5.3%; the higher one is at 2.2%.

Filter 8 is another high density wide band filter. The spectra for this filter have been normalized to the center wavelength of the maximum density region. The broad band density spectrum is shown in Figure 33. The most dense region appears flat due to the flag in the software. The narrow band spectrum of Figure 34 covers the maximum density region. The sharp peaks are present due to noise problems with the instrument: thus actual density may be slightly higher. The maximum density is estimated to be about 4.25 with the 3 dB points located at 1% on either side of the maximum.
Figure 20. Density Spectrum of Filter 1.
Figure 21. Wide Band Density Spectrum of Filter 2.
Figure 22. Narrow Band Density Spectrum of Filter 2.
Figure 23. Wide Band Density Spectrum of Filter 3.
Figure 24. Narrow Band Density Spectrum of Filter 3.
Figure 25. Wide Band Density Spectrum of Filter 4.
Figure 26. Narrow Band Density Spectrum of Filter 4.
Figure 27. Wide Band Density Spectrum of Filter 5.
Figure 28. Narrow Band Density Spectrum of Filter 5.
Figure 29. Wide Band Density Spectrum of Filter 6.
Figure 30. Narrow Band Density Spectrum of Filter 6.
Figure 31. Spectrum of Region of Highest Density for Filter 6.
Figure 32. Wide Band Density Spectrum of Filter 7.
Figure 33. Wide Band Density Spectrum of Filter 8.
Figure 34. Narrow Band Density Spectrum of Filter 8.
Null measurements are completed by "matching" a measured quantity to a well-known reference such that the difference between the two is essentially zero. Hence, the unknown quantity is provided by the known reference that it matches.

Null measurements are typically employed when large signal levels are present. This method allows much of the noise that is proportional to the amplitude of a signal to be greatly reduced. In the case of the densitometer, signals are measured over a wide dynamic range. The null measurement is used to remeasure the lower density regions of the narrow band filters that were originally characterized using the one-arm method. Calibrated variable slit attenuators and neutral density filters (ND) are used as the known reference. With the potential of improved precision, the null technique may yield a better profile of the filter shape. The method can also be used as a point-by-point check to the one-arm scanning method.

Null measurement operation involves measuring the signal level with the sample positioned in one arm, then comparing it to a signal of known attenuation in the other arm. The beams never strike the detector simultaneously during this procedure. The comparison is made by measuring
the output signal of each arm individually. The complete
description of how to operate the system using the null
measurement is given in Appendix B. The basic equation used
to obtain the density of the unknown filter at one
wavelength is

\[
\text{filter density} = \text{change in the non-sample arm slit density} +
\]
\[
\text{the density of any ND filters present.}
\]

The change in the non-sample arm slit density is obtained
using a calibration curve that shows attenuation as a
function of LVDT signal. This curve is presented in Figure
35. The density of the ND filters is also from a
calibration curve; however, the curves of the ND filters
have a much flatter profile which makes them easier to use.
A typical density spectrum of a neutral density filter is
shown in Figure 36. The density calibration curves are read
manually and summed to yield the filter density.

The null measurement was completed on the side bands of
Filter 8 from the previous section. Several points on each
side of the maximum density region were examined. A
comparison between the density values obtained using the
one-arm method and the null technique are given in
Figures 37 and 38. These figures indicate an agreement
between the one-arm method and the null technique. The two
methods generally agree to ±0.05 in the less dense region of
the filter. Near the most dense region, the agreement drops to about ±0.2. This disagreement is due to uncertainty in the calibration and errors inherent to reading the calibration curves.
Figure 35. Calibration Curve of Density vs. LVDT voltage.
Figure 36. A Typical Neutral Density Filter Spectrum.
Figure 37. Comparison of Null Measurement to One-Arm Technique for the Lower Wavelength Side of Filter 8.
Figure 38. Comparison of Null Measurement to One-Arm Technique for the Higher Wavelength Side of Filter 8.
CHAPTER V

DISCUSSION

Evaluation of Instrument

The densitometer can characterize filters with maximum optical densities up to 5.2. By achieving a density of 5, the system has shown the ability to detect signals over a dynamic range of 50 dB. Using the 3 dB density drop-off as the definition of linewidth, the densitometer has shown the ability to characterize filters with linewidths of less than 1%. The system successfully measures the maximum density and shape of the filters studied. It also has the ability to detect flaws in filter design.

Reliability

The densitometer has several features that contribute to its reliability. The source, entrance and exit optics, spectrometer, and detector all provide stable, high-performance operation that will be discussed.
The high temperature Nernst element meets the wide wavelength requirement of the densitometer. It provides enough broad band optical power to characterize most filters without having to be driven very hard. When called upon to operate at maximum output to characterize very dense filters, the glower has repeatedly met the challenge. Granted, lifetime is reduced but this is expected. The power supply and control circuitry provide very stable output. Under normal operating conditions, the glower output is stable to one part in a thousand.

The gold-coated entrance and exit optics perform very well. These mirrors, along with the spectrometer, image the light transversing the system to the active area of the detector with minimal losses. All the off-axis parabolic mirrors provide well-collimated beams with minimal aberration when they are properly aligned. The optics are very stable due to their mounts. All the mirrors are on rugged mounts that have provisions for fine adjustment as needed. Further stability is provided by mounting the mirrors close to their respective platform levels. Major realignment is not usually needed, but daily "tweaking" to achieve maximum signal is necessary.

Reliability is also a strong feature of the spectrometer. The U-1000 has shown excellent tracking over
six diffraction orders for both argon (514 nm) and helium-neon (632.8 nm) lasers. The shape of the filters has been reproduced in repeated scans, again showing the excellent tracking of the instrument. The only disappointment is the manufacturers' claim that the gratings can easily be changed with minimal realignment. This was found to be untrue; extensive alignment work was needed each time the gratings were changed (see Appendix C).

The two detectors and the supporting electronics worked well consistently over the wide dynamic range. Previous studies indicated that the detectors were linear over the range in question and no severe problems were encountered experimentally. However, the Ge detector has a less than satisfying gain and could be improved. The liquid nitrogen level in the detectors had to be checked every 4 hours or so, and the batteries in the pre-amplifier had to be changed about every 10 days.
CHAPTER VI

CONCLUSION

The densitometer has shown it is capable of performing the task for which it was designed. The system is capable of characterizing narrow band filters over a wide dynamic range in the infrared region of the spectrum. A filter can be analyzed for maximum density, overall lineshape, and any flaws that may be present. Several filters have been examined and characterized by the system.

All the densitometer components are very reliable; thus, once the densitometer is aligned it can be operated a long time with minimal maintenance. The system is operating at a state-of-the-art level that can only be improved with additional funding and effort.

Recommendations

A variety of improvements could be made to the current densitometer system. Throughput could be improved by recoating not only all the external mirrors, but the
spectrometer mirrors as well. Also, a cover should be built to contain the entire system. This will improve stray light rejection and reduce the large amount of dust that rapidly accumulates on and around the optical components. If work is to continue in the 3 micron region, it is recommended that new gratings be purchased since the current ones have large scratches on the edges. For continued work in the 1 micron region, the possibility of obtaining a new detector or an improved amplification technique should be investigated because the current setup has a relatively low gain.

Since the smallest detectable signal is partially limited by electronic noise, a market investigation should be conducted to see if lower noise components could be obtained. The two primary devices to investigate are the chopper motor drive and lock-in amplifier. The present chopper motor has to work very hard to operate at the 150 Hz rate required for experimental work. A smoother running, and quieter motor would improve small signal detection capability. The scenario for a new lock-in amplifier is similar. If a quieter amplifier with many of the same features as the current lock-in is available, it should be purchased. The major noise contributor appears to be stray light reaching the detector. Though it is not understood how this light gets through the system, it is believed that adding more baffling would reduce the problem.
If the null measurement technique is to be pursued further, several system upgrades must be fulfilled. To achieve more accurate attenuation values for the variable slits, a computerized calibration scheme should be implemented. The tedious initial process of measuring attenuation as a function of slit width must still be performed; however, accuracy will be improved by adding software that can interpolate an attenuation value for a given slit width based on the original calibration data. Additional software is also needed to operate both slits simultaneously. This will greatly reduce the time required to complete a null measurement. Also, additional neutral density filters must be purchased. The filters that are currently available for the system do not have a flat response over the entire wavelength region. This would not be a big issue except that the anomalies occur in wavelength regions where many of the filters have their highest optical density.

The one-arm method could be improved by reducing the distance between the source and the spectrometer. Moving the platform closer to the spectrometer would reduce beam expansion and widen the dynamic range. This would be useful in characterizing very dense filters, but would also eliminate the null measurement capability.
Beyond introducing new equipment and software, other steps can be taken to ensure the system is operating at state-of-the-art level. The most crucial and demanding concern is optical alignment. The input optics need to be adjusted on practically a daily basis to keep the signal level maximized. The spectrometer optics do not need to be adjusted as frequently, but good initial alignment for a given pair of gratings is essential for good results. When the gratings are changed, complete realignment for the spectrometer is necessary. Care should be taken to minimize dust and dirt in the lab. Routinely cleaning the optics table, the platforms for the system, and the inside of the spectrometer with a cloth and some alcohol or acetone helps reduce the problem. Also, occasionally mopping the floor never hurts. When data is being taken, stray light and any movement in the lab should be kept to a minimum. This reduces the chance of unwanted radiation contributing to the signal level.
APPENDIX A

Diffraction Grating Theory

A diffraction grating consists of a large number of close, equally spaced "grooves" on a plane or concave surface. In a spectrometer, collimated light from a slit set parallel to the grooves is reflected or transmitted by the periodic structure formed by the grooves. The grooves can be considered as behaving like a large number of coherent sources.

For any given wavelength of light, the secondary wavelets from the grooves interfere constructively at certain angles and destructively at others. Maxima of intensity appear in the output plane (exit slit) at angles corresponding to the interference maxima. Figure 39 shows a plane wave incident at an angle \( \alpha \) on a reflection grating with groove spacing \( a \). The path difference between contributions from adjacent grooves to a wave diffracted at angle \( \beta \) is

\[ \Delta = I_2 \overline{H} + I_2 \overline{K} = a(\sin \alpha + \sin \beta) \]  

(A-1)
Figure 39. Geometry of a Diffraction Grating. $\alpha$ is the angle of the incident light with respect to the grating normal. Similarly, $\beta$ is the angle of the diffracted light. The groove spacing is $a$. 
Constructive interference phenomena will be observed in the directions where $\Delta = k\lambda$ ($k$ being a positive or negative integer). In that case

$$\Delta = a(\sin \alpha + \sin \beta) = k\lambda$$  \hspace{1cm} (A-2)

This formula gives, for each $\alpha$, all the possible values of $\beta$, where a maximum of intensity for wavelength $\lambda$ are found (one maximum for each value of $k$). The grating equation may be rewritten as

$$\sin \alpha + \sin \beta = k\lambda/a.$$  \hspace{1cm} (A-3)

This formula shows that for light at a fixed incident angle, $\beta$ depends on $\lambda$. The result is that light is dispersed by the grating. For each possible value of $k$ a spectrum is obtained. In the special case of $k = 0$, the grating does not act as a dispersing element, it simply reflects all the incident light as a flat mirror would.

A given wavelength $\lambda$ can have several maxima at different values of $\beta$, corresponding to different orders $k$. The complete spectrum of a source is repeated, and the long wavelength end of one order may well overlap the short wavelength end of another. For example, the second order of 600 nm falls in the same position as the first
order of 1200 nm. For this reason, cutoff filters are often employed when systems are operated at long wavelengths.

Most gratings today are blazed: that is, the groove is shaped to concentrate a large fraction of the incident light into diffraction at a particular angle. The principle is illustrated in Figure 40. The preferred direction is that corresponding to specular reflection from the "step" of each groove. If the step is inclined at angle $\psi$ to the surface of the grating, and $N$ and $N'$ are, respectively, the normals to the grating and the step, then

$$\alpha - \psi = -\beta + \psi . \quad (A-4)$$

$\beta$ is negative because it is on the opposite side of $N$ than $\alpha$. Therefore, $\psi = (\alpha + \beta)/2$. Combining this with the grating equation results in

$$k\lambda_b = 2\sin\alpha \cos(\alpha - \psi) \quad (A-5)$$

where $\lambda_b$ is the blaze wavelength. Blazing allows the grating efficiency to be high over an appreciable range from the optimum wavelength. It typically falls to half maximum at about $2/3 \lambda_b$ on one side and $3/2 \lambda_b$ on the other. The grating is, of course, also blazed for the second order of $\lambda_b/2$ and so on. It is possible to achieve a peak efficiency of about 80%$^2$. The efficiency is defined as the ratio of
energy diffracted by the grating at wavelength $\lambda_b$ in an order of interest to the energy reflected by a flat mirror under the same working conditions.
Figure 40. Geometry of a Blazed Grating. $N$ and $N'$ are the normals to the grating and to the step, respectively. The blaze wavelength corresponds to specular reflection from the step.
APPENDIX B

Densitometer Operation

Starting up the densitometer system involves turning on the Nernst glower, preparing the detector, and turning on all the supporting electronics. A step-by-step procedure for operating the densitometer is given below.

Nernst Glower

Before turning the glower on, remove all dust bags covering mirrors near the glower.

Turn on the power switch, located at the bottom right corner of the controller face.

Turn the set point control knob one complete turn.

Press the preheat button.

Monitor the current by selecting "Nernst Current" on the LED display. The current should gradually increase over about 5 to 10 minutes and stabilize around 850 mA.

If the preheat light goes out without producing such an increase in current, press it again; this should cause current to flow.
Once the glower has stabilized, the set point dial can be adjusted to vary the output current of the glower. The operating range is from 500 to 1500 mA. The current should NEVER exceed 1500 mA.

The glower should be turned off gradually. Take about one minute to slowly reduce the current to zero. Allow the controller to sit for a few seconds, then shut off the power.

Once the glower off, it must not be started for at least 35 minutes. This allows it sufficient time to cool down.

Be careful when adjusting optics or working anywhere near the glower housing on the platform--it is very hot.

**Detector Preparation**

The detector must be cooled with liquid nitrogen so it can be operated. Liquid nitrogen can be poured into the detector by inserting a funnel in the top and slowly pouring it in. Be sure all of the mirrors in the vicinity of the detector are covered with a cloth or a plastic bag when pouring the nitrogen in to the dewar. Slowly pour the nitrogen into the detector until it is full. After some initial boiling off, the detector will fill. It is full when nitrogen spills out onto the top of the detector.
The housing for the mirror/detector combination can now be put in place. The detector can then be connected to the pre-amplifier through the hole in the top of the housing. The pre-amplifier should always be off when making connections to the detector or to the lock-in. The pre-amplifier sits on top of the housing during operation.

Be sure that both the detector and the pre-amplifier are grounded to the optics table. The detector can be grounded by a connection to the metal surface on its backside. The pre-amplifier can be grounded by a connection to its case.

The BNC cable from the detector is connected to the input of the pre-amplifier. Another BNC line runs from the output of the pre-amplifier to the lock-in input, channel A. The pre-amplifier can be turned on only when no bright lights are on in the room. This prevents damage to the amplifier.

All the remaining components now need to be turned on. Turn on the spectrometer control by flipping both green switches so they are lit.

Also turn on the chopper blade, lock-in amplifier, and pre-amplifier.

The chopper blade has to be connected to the lock-in through the TTL input. It is normally operated at around 150 Hz.
When the chopper blade is first installed, it must be positioned for maximum throughput. The aperture height on the chopper is fixed so some slight adjustment of mirrors in the entrance optics may be required. Horizontal positioning of the chopper can be set by moving the translation stage to optimize the signal.

The lock-in amplifier measures the signal it receives from the detector/pre-amplifier combination. The measured signal is fed into the computer. The parameters of the lock-in should be set as described in the noise section below. The amplitude (sensitivity) and time constant can be varied depending on signal strength. Longer time constants should be used for smaller signals.

The last component to be turned on is the computer, which controls the data taking process. Numerous parameters regarding the lock-in amplifier, the spectrometer, and the data to be collected can be selected by the operator to measure transmission (signal) as a function of wavelength. Data collecting procedures along with a description of the software will be presented in detail in the following sections.
To measure the optical density of a sample, a signal versus wavelength profile of the sample has to be made with the sample in the system. A blackbody reference profile with the sample out of the system also has to be made during the same data-taking session and under the same conditions to serve as a comparison to the sample profile. Always make the reference scan first in case the system has to be shut down. The reference scan has parameters similar to those in the survey scan described below except they may cover larger wavelength regions (0.5 to 1 micron). The following parameters cover the information needed to document a scan.

* The current setting of the Nernst controller.
* The slit widths of the four spectrometer slits.
* The wavelength region of the scan.
* The number of data points taken.
* The delay time for sampling the signal at each point.
* The signal scale on the lock-in amplifier.
* The time constant for the lock-in amplifier.

Two typical types of scans are taken when a sample is analyzed. First, a survey scan is taken over a broad wavelength region to locate the low transmission region. Typical survey scans cover about 0.5 microns, use slit
widths of 1.5 mm, include 100 data points, have a delay time of 10 seconds, and use a lock-in time constant of 3 seconds. This scan can be used to start "homing in" on the high density region of the sample. Successive scans are made, each covering a smaller wavelength region. As the scanning region is narrowed, the number of data points taken decreases and the delay time and time constant increase. This approach is used to integrate out as much noise as possible while still being able to complete a scan in a reasonable time (30 minutes). A typical scan which pinpoints the high density region covers only .01-.02 microns, includes 30 data points, has a delay time of 30 seconds, and has a lock-in time constant of 10 seconds. Scans made between the survey and pinpointing scans can have any number of points and time scales as required to locate the low transmission region. The only requirement is that the delay time is always at least twice that of the lock-in time constant. This gives the system time to accurately measure the signal level at each point without having the previous signal value influence the measurement.

A density measurement is made by comparing the reference scan made with the sample out to one made with the sample in. The formula for optical density is log (signal with sample out/signal with sample in).
Generally, the samples being studied are very dense over a narrow bandwidth. To measure such high densities, good stray light rejection, small signal detection capabilities, and strong signals with the sample removed are necessary. By varying the spectrometer slit widths and experimenting with band pass filters, the system can be set in a configuration which is optimum for each individual sample studied. Narrowing the slits below 1.5 mm improves the stray light rejection at the expense of loss of signal. For slit widths of 1 mm or less and in the final analysis of any sample, it is recommended that the Nernst glower be operated at full power (1500 mA). By performing a set of scans at various slit widths there may be one setting that consistently produces a higher density measurement than the others. However, this is not always the case.

The motivation for putting a band pass filter in the system comes from the fact that a good narrow band filter will pass light over only a narrow wavelength region and attenuate all other wavelengths. There is a need then for a band pass filter which has a pass band over the same region as the high density region of a sample. Given the wide variety of samples to be studied and budget limitations, this technique was attempted on only some of the samples. The band pass filter is placed in the exit optics of the system as close to the detector housing as possible. The filter has to be positioned for maximum throughput. This is
done with the sample removed and the spectrometer set at a wavelength in the pass region of the filter. By adjusting the height and translating the filter, a position can be reached where the signal is a maximum. Observations should be made to be sure that the filter is in the path of the last parabolic mirror, not completely off to one side, and not intercepting the incident beam at all. The same method of taking reference, survey, and pinpointing scans is then followed. The spectrometer slit widths can be varied as well. These scans again may or may not provide improved density measurements.

Noise

A key to the success of this system is the ability to measure very small signals on the order of tens of nanovolts. To do this, all forms of detectable noise must be minimized. Extensive work was done for this purpose. In terms of light rejection, detector housing along with extensive baffling and keeping the room very dark served to keep this problem as small as possible. Grounding the detector, pre-amplifier, and optics table greatly reduced much of the electronic noise. The lock-in amplifier contributes to the electronic noise as well. By varying the numerous parameters of the lock-in the noise has been minimized to \( \pm 200 \) nV. The lock-in settings to accomplish this are as follows:
Sensitivity: Channel A with FLOAT
Filters: LP mode and MAN set frequency
Tuning: REF and Hz
Reference: TTL input
Time Constant: 100 sec
Slope: 12 dB
Dyn Res: HI RES
Display: Signal

All the scans made should be completed with the lock-in on these settings. The time constant value may be changed.

Data Acquisition and Spectrometer Control

The computer is used to scan the spectrometer and collect signal data. The software program called DENOS carries out all the required routines in the following manner. After turning the computer on type the following commands:

adready
then type
denos.
This places the operator in the main menu where there are four options. SCAN (F1) is the subprogram used for data acquisition. ISA (F2) is a subprogram which moves the spectrometer gratings without taking data. SLIT (F3) is
Before taking data, a working knowledge of spectrometer operation is needed. The menu choice ISA (F2) is thus treated first.

**Menu Option ISA (F2)**

This section of the software allows the spectrometer to be scanned over a wide range of wavelengths without taking any data. It also sets parameters so the spectrometer and data acquisition software are properly scaled with respect to each other. The F1 and F2 buttons when pressed simply move the spectrometer forward or reverse by the number of Angstroms indicated by the "increment" line. This number can be changed by moving the cursor down to it with the mouse or the arrow keys. The "current position" line should show the same reading as the dial on the spectrometer. If it does not, the CALIB (F3), selection must be invoked. After pressing F3, the operator is posed a question by the screen regarding continuation. If the "current position" reading does not need to be changed, type n to return to the ISA screen. If it does need to be changed, press and hold the shift key then type y. The screen then prompts the operator to enter the dial reading of the spectrometer. This must be done accurately to avoid data errors. If the
zeroth order position of the spectrometer is not at precisely 0.0 on the dial display then the computer has to be told a lie. The zeroth order position has to be defined as 0.0 on the computer. For example, if the zeroth order position was really at 10A the computer would have to be calibrated such that it reads 0.0A when the actual spectrometer dial display is 10A. Hence, the computer display and the spectrometer dial will read different wavelengths. Once the calibration is set, all data acquisition should be based on the computer wavelengths.

The grating factor is a wavelength conversion parameter dependent upon the blaze wavelength of the gratings in the spectrometer. It serves to make the software compatible for data taking with different sets of gratings in the system. Gratings blazed at 1 micron require a grating factor of 3.0. A blaze of 3 microns requires a grating factor of 2.0.

The speed setting should be left at 5. If an error is made when scanning the spectrometer, the only way to stop the scan is to press the Esc key on the computer several times. This may effect the spectrometer calibration, so the wavelength reading must be checked.
Scanning Options and Generating a Plot

The scan menu contains routines for data collection and manipulation. The scan (F1) option is used to set the parameters of a data taking scan. Options F1 through F6 are used for data file manipulation. The procedure for data collection and manipulation is completed as follows.

Pressing the F1 key moves the cursor to the "Wavelength Scan" box on the screen. A title for the scan should be typed in on the first line. The "start" and "finish" settings indicate the wavelength region to be scanned in microns. The "# of steps" setting indicates the number of data points that will be taken over the wavelength region. The "delay" setting displays how many seconds the spectrometer will sit at each data point while the signal level is sampled. All these numbers can be edited using the arrow and number keys on the main keyboard. Once all the parameters are set, press the F1 key to start the scan. Be sure all other components of the system are ready to go before starting the scan. When the F1 key is pressed, the spectrometer will automatically go to the start position regardless of its current location. A scan may be aborted by pressing the Esc key several times. The scan is complete when "ready for scan" reappears on the screen. All
completed and aborted scans are automatically saved to a data file named "denos.dat".

All scans can be classified into two groups: reference scans or sample scans. Reference scans are the blackbody response of the system with no sample in place. Sample scans are acquired with a sample in the system. Both types of scans are initially plotted using the F3 menu option. When the F3 key is pressed, three plotting subcommands appear on the screen: F9 (raw), F2 (plot again), and F1 (print). Option F9 sets up a plot of signal versus wavelength on the screen. The upper and lower limits of the graph can be set in the red region at the top of the screen using the number keys and the RETURN key. The horizontal axis is the wavelength in microns; the vertical axis is the signal level in millivolts. Press the F2 key (plot again) to remake and edit the plot as much as necessary. Press the F1 key (print) to send the plot to the plotter for a hard copy.

The two other plot subcommands are O.D. and ratio. These commands require two scans as input. The computer uses one scan as a reference and the other as a sample to complete the desired manipulation. The ratio command divides the sample scan signal profile by the reference scan. The O. D. command uses the two files to generate an
optical density plot. The operation is completed using the formula
\[
D = -\log_{10}(R/S),
\]
where \(R\) is the reference signal level at a given wavelength and \(S\) is the corresponding sample signal level. The O.D. and ratio plots can be edited in the same way as the raw plot described above.

At issue now is whether scans are designated as reference or sample scans. When a scan is completed, it automatically appears in the sample window in the upper, right corner of the screen. Successive scans replace previous ones in this window and they are accumulated in the data file in chronological order. Any completed scan in the data file can be used as a sample or a reference scan. A file can be placed in the sample window by using the F5 and F6 keys to locate the desired file. To designate a scan as a reference scan press the F4 (REF) key. Three reference subcommands then appear on the screen: F8 (set), F9 (apply), and F7 (on/off). Option F8 moves the file in the sample window to the reference window at the lower right corner of the screen. This scan is thus set as a reference. The reference scan may then be applied to any other scan to generate ratio and/or optical density plots. This is accomplished by positioning the desired scan in the sample
window, then hitting the F9 (apply) key. The F7 (on/off) key removes files from the reference window. The reference can also be changed by following the above procedure and overwriting the initial scan in the reference window. The entire data manipulation menu can be exited by pressing the Esc (done) key.

As previously mentioned, all collected scans accumulate in chronological order. This is a convenient way to store the data because it allows a blackbody reference scan to be grouped with several corresponding sample scans in one large data file. The chronology of data can be "reset" by closing the current collective file and renaming it. The data is automatically stored in a file named "denos.dat". To rename this file so it is not overwritten, press the F4 button twice to exit the data acquisition system, then type the command: rename denos.dat (any filename). This creates a new file with all of the raw data. To access the data in this file type denos filename. This returns to the basic operating system with the requested file present for any manipulation.

Outside the operating system the data can be displayed in table form by typing the command: type filename. The screen will display the data points giving the wavelength followed by the signal level at that wavelength immediately to the right of it. This will continue for all the scans in the
collective file. It is recommended that once data starts to accumulate on the hard drive, it also be saved to floppy disks as a backup should the hard drive fail.

**Null Measurement**

The null measurement technique employs all the available features of the densitometer system to make an optical density measurement at one particular wavelength. The steps for completing a null measurement follow.

The spectrometer should be set at the desired wavelength and the glower current must be set so the signal can be detected with the sample in place. Next, a "completely open" position must be defined for each variable slit. The slits should be opened wide to maximize the signal, but the slit width has to be restricted to the linear operation region of the LVDTs. Once these settings are established, the signal value of each arm should be measured. These open positions will serve as references when the slits are closed to produce the desired attenuation effects. Before putting the sample under test into the system, both arms of the densitometer must be of equal intensity. This is accomplished by closing the variable slit in the strong arm until the two beams are equal. Record the LVDT reading for the strong arm slit position where this occurs. The sample is then placed in the
stronger arm and the signal level recorded. After blocking the stronger arm, the other arm is attenuated until the detected signal matches that of the stronger arm with the sample in place. This attenuation is completed by using the variable slit and the neutral density filter wheel in the weak arm. The two attenuators are used in combination to acquire the matched signal.

Since the density of the ND filters is known and a calibration curve exists for the attenuation of the variable slits, the density of the sample can be determined. The quantities that need to be measured are the LVDT reading for the weak arm slit and which neutral density filter(s) is being used. The LVDT value that the strong arm slit has to be set at to make the two arms equal is unimportant, but getting the two arms to have equal signal values initially is essential. The density change caused by the variable slit in the weak arm can be determined from the calibration curve (density vs. LVDT value) for the slit. The curve is used by noting the difference in the LVDT values between the defined open position and the match position and obtaining
the corresponding density change. The density of the filter is then given by

\[ \text{filter density} = \text{weak slit density change} + \text{ND filter density}. \quad (4-2) \]

The null technique uses both arms of the system and eliminates the need to constantly move the sample in and out. The accuracy of the measurement depends on the consistency and accuracy of the slit calibration curves along with the neutral density filters. The curves are not dependent on the glower power or wavelength. The neutral density filters generally have the same density over a narrow band region; this is very useful in completing the null measurement on a narrow band filter. The graphs of density versus LVDT voltage are currently interpolated manually. This greatly reduces the accuracy of the present null technique. In future endeavors, a computer algorithm could be used to interpolate slit calibration curves and improve the accuracy of the measurement.
APPENDIX C

OPTICAL ALIGNMENT

SPECTROMETER OPTICS

The spectrometer used in the densitometer system is a Jobin-Yvon U-1000. There are two gratings and nine mirrors inside the housing which direct light through five slits as it propagates through the spectrometer. To clearly communicate alignment procedures, each mirror and slit in the spectrometer has been labeled in the enclosed figures.

Figure 41 defines all the slits and lower mirrors on the auxiliary base. The light from the input optics enters the spectrometer via TLS (entrance slit) and leaves the system through TRS (exit slit). TLS and BLS are the top and bottom slits on the left side of the spectrometer, while TRS and BRS are the corresponding slits on the right side. The center slit between BLS and BRS allows light to pass between the two arms of the spectrometer. It is not adjustable in any way and is not given a label. Mirrors A1 through A4 are
located in front of the lower slits and are numbered from left to right.

Figure 42 displays how light propagates through the spectrometer. Consider the case of light entering through TLS. The light strikes the upper flat mirror L1 and is then reflected to the grating (GL). Light reflected off the grating travels to mirror L2 located below L1 on the back of the spectrometer. The beam then returns to the front of the spectrometer where it passes through BLS and is reflected off mirrors A1 and A2. A2 directs the light through the center slit where it is reflected by the center mirror C1 and redirected back out the center slit. The beam is then directed through BRS by mirrors A3 and A4. This light again travels to the back of the spectrometer where it is reflected by mirror R2. The reflected light strikes the GR and returns to the back of the spectrometer where it is reflected by upper mirror R1. The reflected beam passes through TRS and exits the spectrometer.

**Spectrometer Alignment Phase 1**

In this first step of the alignment procedure, two laser beams are used to roughly position the large interior
Figure 41. Front View of the Spectrometer. All four slits have independent width and aperture adjustments.
Figure 42. Mirror Configuration in the Spectrometer. The five mirrors between the two monochromators enhance stray light rejection.
mirrors and the diffraction gratings. The setup uses an argon and a He-Ne laser and four flat mirrors as shown in Figure 43. Mirrors M1-M4 should be flat mirrors mounted with both horizontal and vertical tilt controls. Using these mirrors it is possible to center the argon and He-Ne laser beams on the entrance slits (TLS and TRS) and on the top rear mirrors (L1 and R1). Use M2 for TRS and M3 for TLS. Be sure the spectrometer is set at the zero position on the display. This is a two-person operation.

**STEP 1**

Vertically center the beams on the slits. Use vertical controls on M2 and M3. Hold an index card behind the slit and adjust the mirror until the brightest spot is obtained. Do this for both slits.

**STEP 2**

Horizontally center the beams on the slits. A plumb line is an essential tool. Use horizontal controls on M2 and M3. Carefully locate the center of the slit. Drop the line directly in front of the slit housing, centered on the slit and motionless. Center the beam by adjusting the mirror until the beam is bisected by the line. Do this for both slits.
Figure 43. Spectrometer Alignment Phase I. Two different color lasers are used to align the spectrometer mirrors.
STEP 3  Vertically center the beams on rear mirrors L1 and R1. Use M4 for L1 and M1 for R1.

NEVER TOUCH ANY OF THE MIRROR SURFACES IN THE SPECTROMETER!

These mirrors are 4" x 4" so the vertical center is 2" from the top or bottom.

Use the vertical control on M4 or M1 to roughly center the beam.

Carefully measure the beam position with a clear ruler.

Continue this trial and error method until the beam is centered.

STEP 4  Horizontally center the beams on L1 and R1.

Use the horizontal control on M4 for L1 and M1 for R1.

Center the plumb line on the rear mirror.

Be sure the weight on the line does not come in contact with the mirror.

Center the beams using the mirror controls by the same method described for the slits.

At this point the work done on the slits is probably lost. The only way to center the beams on the slits and the mirrors is to continuously go back and forth between the two places until the beam is in the right place. (Repeat steps 1 through 4).
Once the beams are centered on the slits and the rear mirrors, the next step is to propagate the beams through the spectrometer. The objective is to superimpose the two beams on the center of the center mirror (C1). Also, the beams must exit the spectrometer through the center of the top slit on the side opposite of where they entered.

**STEP 5** Center the beams on the lower slits. The screws on the back of mirrors L2 and R2 can be used to tilt these mirrors horizontally and vertically about a fixed pivot point. The vertical center can be located by narrowing the lower slits (BRS and BLS) until they are almost closed. The beams can be centered one at a time using L2 for BLS and R2 for RLS.

Viewing the lower slit from inside the spectrometer, use the vertical control screw to center the beam on the slit. The beam should be at least faintly visible. If it cannot be seen directly on the slit, carefully hold a strip of index card against the slit to view the beam. Horizontal centering requires that the slits be opened wide and the special viewing mirror be used. Remove the cover on the auxiliary base of the spectrometer and
place the viewing mirror in front of the lower slit being worked on. Position the viewing mirror such that the image of the slit can be clearly seen by an observer crouching next to the spectrometer.

Have the observer hold a plumb line down through the center of the slit. The beam will be centered when it is bisected by the line. Another person should adjust the horizontal screw control on the lower mirror until the observer sees the beam is centered by looking at the slit image in the viewing mirror. Complete this procedure for both lower slits.

At this point the beams are independently centered on their entrance slits, rear mirrors, and lower slits. Now, they will be brought together by centering them on mirror C1.
STEP 6
Center the beams on Cl.
Mirrors A1 and A4 are used to center the beams on Cl. With an Allen wrench, the set screws on the back of these mirrors can be turned to tilt the mirrors. Adjust these screws until both beams are centered on Cl.
Locating the center of this mirror is very awkward. The plumb line is still the best method for horizontal centering. Vertical centering depends on using a clear ruler placed as close to the mirror as possible. Always be very careful not to touch the mirrors when using these alignment tools.
The beams should now be superimposed on each other at the center of Cl.

STEP 7
Center the beams on exit slits TLS and TRS.
The tilt of mirror Cl can be adjusted by using the dial located on the back of the spectrometer.
Adjust the mirror so the beams exit the spectrometer through the slit opposite to the one they entered. (Look for the argon beam outside TLS and for the He-Ne beam outside TRS.)
Steps 6 and 7 are iterative; numerous repetitions are required for success. Again, a plumb line centered on the exit slits should be used to center the beams.

Spectrometer Alignment Phase 2

This phase of the alignment procedure involves using light from a pair of mercury lamps to align the spectrometer gratings over a large wavelength region.

Initial Setup

The left arm of the spectrometer should have a mercury lamp, variable aperture, and two lenses placed in front of the entrance slit as shown in Figure 44. By sending a laser beam through the center of the top right slit and the center of rear mirror R1, the optic axis of the spectrometer can be defined. This laser beam can be used as a guide to center the optical components in the left arm.

Position all the optical components including the source so they are vertically centered on the exiting laser beam. Start with a very wide aperture. To center the lenses, observe the back reflections off the lens surfaces. When the lenses are centered on the beam, the reflections
Figure 44. Spectrometer Alignment Phase II. A mercury lamp is used to align the diffraction gratings in the spectrometer.
will overlap the incident beam. Hence, only one spot will be observed when the lenses are centered.

Translate the two lenses to obtain a sharp image of the source on the inner jaws of the entrance slit. Light entering the slit has to fill the top rear mirror and the grating in the left arm of the spectrometer. Adjust the position and diameter of the variable aperture so the beam of light is centered on the rear mirror and the grating. The beam should also fill both the mirror and the grating on the left side of the spectrometer. The same configuration must be obtained for the right side components. Unfortunately, the convenience of having a laser beam as a guide is lost. The entire centering process has to be completed on the observer's best judgment. The key to good alignment here is to avoid compensating errors such as tilted lenses and not placing the source in direct line of the entrance slit.

Once the mercury lamps are in place, align the spectrometer at various diffraction orders of the mercury light.
<table>
<thead>
<tr>
<th>Diffraction Order</th>
<th>Spectrometer Setting (Å)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.0</td>
</tr>
<tr>
<td>1</td>
<td>910.1</td>
</tr>
<tr>
<td>2</td>
<td>1820.2</td>
</tr>
<tr>
<td>3</td>
<td>2730.3</td>
</tr>
<tr>
<td>4</td>
<td>3640.5</td>
</tr>
<tr>
<td>5</td>
<td>4550.5</td>
</tr>
<tr>
<td>6</td>
<td>5460.7</td>
</tr>
</tbody>
</table>

First, determine the dial readings at which each one of the slits is completely closed. This is necessary for alignment purposes because data must be taken with various combinations of slit widths to locate positions of maximum brightness.

To locate the zero position of each slit, illuminate each with a bright light source placed directly in front of it. The mercury lamps can be used for the top slits while a good flashlight or gooseneck lamp can be positioned as close as possible to the front of the lower slits as a light source.

With your head inside the spectrometer, view each slit and rotate the barrel control on each one until no light is seen exiting the slit. Record the zero position of each slit.
The BRS cannot be determined this way because it is physically impossible for an observer to view this slit from inside the spectrometer. Use a tilted mirror placed in the right arm of the spectrometer to view the slit from above and locate the position at which no light exits the slit.

**Locating Positions of Maximum Brightness**

The positions of maximum brightness are located for each lamp independently. While using the left side lamp be sure to block the right side one and vice versa.

The spectrometer can be scanned by computer or by the manual joystick control. It is recommended that the joystick be used only to scan small regions (10A or less). The computer can be used to scan from order to order. Since a backlash problem is present in the drive controller the spectrometer can be scanned in only one direction. For example, if the 8A to 12A region was to be scanned several times, the spectrometer can be scanned directly from 8A to 12A. However, it cannot then be moved from 12A to 8A with good results. The proper procedure is to scan the spectrometer back to about 3A (to remove backlash) and then proceed to scan the desired region.

Starting with zeroth order and using only the left side mercury lamp, locate the grating position for maximum
throughput of each slit. This can be accomplished by opening all the slits wide (>2mm) and then gradually narrowing the slit under investigation. This will require several scans in the vicinity of zeroth order. Be sure to follow the proper method to avoid backlash problems. The viewing mirror can be used to locate maxima for the lower slits while an index card can be used for the top right slit.

If the position of maximum throughput is the same for all four slits to within 0.2A then the spectrometer can be considered aligned in zeroth order. If this is not the case, further adjustments of the spectrometer mirrors are needed. Mirrors L2 and R2 can be adjusted in an iterative manner until a combination is obtained which results in maximum throughput for each slit occurring at roughly the same position.

Now scan the spectrometer through the six other diffraction orders to locate the maximum throughput of each slit in each order. Just record these positions, do not make any mirror adjustments. In the sixth order position, the spectrometer gratings can be adjusted. The special wrench can be used to change the tilt of the gratings. Tilt the gratings such that the maximum throughput positions for each slit are close to 5460.7A. Once this is completed, bring the spectrometer back to zeroth order and recheck the alignment. Undoubtedly, things will have changed for the
worse. The lower mirrors have to be adjusted again to get all the slits in agreement. The spectrometer then can be taken to third order to see how the adjustments hold up. Move the spectrometer to sixth order and check everything again. Adjust the gratings as necessary. This tedious process will have to be repeated over and over again until the positions of maximum throughput are the same to within .2A for all slits in zeroth, sixth, and at least two other orders.

The zeroth order position need not be 0.0 on the spectrometer. Similarly, the maximums do not need to be exactly what they are in the table. The important thing is that the separation between orders is consistent. The separation between orders should be 910.1A.

A couple other procedures can be used to help align the spectrometer. Tape can be used to partially cover the upper slits so that only a few millimeters in the center of the slit allow light to pass through. This eliminates non-uniformity in the light incident on the lower slits. Also, the sine bar driving mechanism which moves the gratings can be adjusted. By changing the length of the bar, throughput maximum can be set at a desired wavelength (e.g., 5460.7A). This sine bar drive is located in the spectrometer in the space below the wavelength display. The adjustment is difficult and extremely sensitive. It is recommended that it
only be attempted as a "last chance" procedure. Adjustments to the sine bar drive should be made only with direct consultation with the manufacturer (Instruments SA).

EXTERNAL OPTICS

A series of flat mirrors and off-axis parabolic mirrors are used to direct light from a Nernst glower into the spectrometer. The beam exiting the spectrometer is then directed to the detector face by three more mirrors. The signal generated by the beam incident on the detector is the output of the system.

Installing the External Optics of the Densitometer

Rough positioning of the optical components can be accomplished by following the photographs. All this installation can be done with the Nernst element off and the chopper blade out of the system. Start with the elevated platform. Please note that these mirrors are GOLD-COATED; touching their surfaces in any way
will result in PERMANENT DAMAGE. The complete optical path of the densitometer is outlined in Figure 45 and described below.

The Nernst element and detector, two off-axis parabolic mirrors, and two flat mirrors are placed on the platform. Figures 46 through 48 display how these components are positioned relative to one another. These components form the two arms of the densitometer system. Light emitted from the element strikes the two parabolic mirrors which focus and redirect the beams onto the two tilted flat mirrors. The beams are then directed to two more tilted flat mirrors placed directly below the two openings in the platform (see Figure 46). These mirrors direct the beams to the entrance optics in front of the spectrometer on the platform. Before reaching the entrance platform the beams will pass through the chopper blade and the variable slits. These two components are installed after the alignment procedure has been completed.

Figures 46 and 49 show how the chopper blade fits into the system and its proper orientation. Figure 50 displays the electro-mechanical components of the variable slit while Figure 51 simply shows the front face of the slit. When these components are installed they have to be centered on
Figure 45. Optical Train of the Densitometer. The system is designed as a radiometer with independent sources in each arm of the instrument. The spectrometer is located at the detector end of the system to filter out as much background light as possible.
Figure 46. Side View of the Nernst Platform. Light from the glower is collected by off-axis parabolic mirrors. The image of the glower is then rotated 90 degrees using a pair of flat mirrors in each arm.
Figure 47. Top View of the Nernst Platform. The beams travel to the main optics table through two apertures in the platform.
Figure 48. Parabolic and Flat Mirrors on the Nernst Platform. It is imperative that the off-axis parabolic mirrors be positioned one focal length away from the Nernst glower and at the correct angle.
Figure 49. The Chopper Blade. The housing for the blade has two movable windows on each side.
Figure 50. Electro-mechanical Components of a Variable Slit. A stepper motor drives the wedge between the blades to vary the aperture size. Two LVDTs monitor the blade spacing.
Figure 51. The Front Face of a Variable Slit. The entire face is anodized black in order to minimize stray reflections.
the beams propagating from the tilted flat mirrors below the Nernst platform to the entrance optics directly in front of the spectrometer.

Upon arriving at the entrance platform, the beams strike two flat mirrors which are tilted transverse to the incident beams. These mirrors redirect the beams to two off-axis parabolic mirrors. The parabolic mirrors then focus the two beams onto two sides of a prism which is directly in front of the entrance slit. These components are shown in Figure 52. The prism reflects the beams into the spectrometer. The beams propagate through the spectrometer until they reach the exit slit (TRS) and leave the spectrometer. The beams then arrive at the exit optics of the system. The exiting beams encounter another parabolic mirror placed directly in front of and about 14 cm away from, the exit slit. This mirror focuses the beams on a flat mirror located back on the platform just to the right of the exit slit. This flat mirror reflects the beams to a short focal length parabolic mirror which focuses the beams onto the detector.
Figure 52. Parabolic and Flat Mirrors Near the Entrance Slit of the Spectrometer. Again, proper positioning of the off-axis parabolic mirrors is extremely important.
Alignment of Entrance Optics for Densitometer

All the mirrors in the optical train located before the entrance to the spectrometer are aligned using two sources. The light from the Nernst element can be used to align the system. Also, a He-Ne laser can be sent into the spectrometer through the exit slit for alignment purposes. Consider first the alignment procedure using the Nernst element.

Install the element on the platform. Be sure the detector is directly in line with the rear aperture on the element housing. Measure how high off the platform the element is. The first two parabolic mirrors must be centered at this height, 6.6 in. away from the element at a 36 degree angle with respect to the normal of the mirror barrel. Light from the Nernst element must fill these mirrors completely. The light should also be centered on the mirrors. These mirrors have to project the beams to the center of the tilted flats on the platform.

Since the flat mirrors are mounted such that they cannot be translated or have their height altered, all adjustments are dependent on the freedom of the parabolic mirrors. A combination of translating the base plate, slightly tilting the parabolic mirror, and rotating the entire mirror mount should allow the distance and angle
conditions to be met. The micrometer-type controls on the parabolic mounts are used to control the horizontal and vertical tilt of the mirror. They are relatively fine adjustments and cannot be expected to produce any change more than a few centimeters in the position of the reflected beam. These tilt controls are used to center the beam on the tilted flat mirrors. This again is a trial-and-error process involving rotation and translation of the mirror as well. The end result should have light from the Nernst element striking the parabolic mirrors 6.6 in. away at a 36-degree angle such that the light is centered on these mirrors and then reflected to the center of the tilted flat mirror. Next, the beams have to be centered on the flat mirrors below the platform. The position of the beams beneath the platform depends on the tilt (left and right) of the tilted flat mirrors. These mirrors should not be tilted at a large angle. In fact, the beam leaving one of these tilted flats should be as close to vertical as possible.

The mirrors below the platform should be directly in line with the beams coming from the platform. Most likely, the mounts will restrict the position of the lower flat mirrors. This will inhibit your ability to center the beams on the lower flat mirrors without changing some of the previous work. The mirrors on the platform may be tilted SLIGHTLY to
center the beams on the lower flats. After doing this, ensure that the light coming from the parabolic mirrors is arriving in the proper position at the upper flat mirrors.

Besides centering the lower flat mirrors on the beams, they must also be at the correct height. The center of the lower flat mirrors has to be at the same height as the entrance slit (TLS) of the spectrometer. Light from the lower flat mirrors has to propagate down to the remainder of the entrance optics and remain at a constant height. The micrometer controls on the back of the lower flat mirrors can be used to center the two beams on the flat mirrors in front of the entrance slit. The two beams need not be parallel as they travel towards the next set of flat mirrors, just at the same height. The flats in front of the entrance slit have to be positioned in combination with the off-axis parabolic mirrors to yield two focused unvignetted beams at the prism faces directly in front of the entrance slit.

The flat mirrors must be angled so that the light reflected off them goes to the parabolic mirrors. The beams have to fill the parabolic mirrors and be centered on them. The parabolic mirrors in turn must be 6.6 in. away from the entrance slit. The angle between the light coming from the flats and the light going to the prism has to be roughly 36 degrees. The next step is to locate the optimum position of
the prism. The prism must be positioned so that light from each arm of the densitometer is incident on the corresponding angled sides of the prism. The prism then has to redirect the beams through the entrance slit and to the top left mirror of the spectrometer. To avoid the loss of signal, both beams need to be centered on this mirror and then propagate through the spectrometer with minimal attenuation.

Before discussing the alignment of the exit optics, it should be noted that a laser beam can be used to reverse-align the entrance optics. A He-Ne laser beam sent into the spectrometer through the top right slit in conjunction with the two Nernst element beams can be used to obtain the optimum alignment. The laser beam, of course, must be centered on the top right slit and all the mirrors in the spectrometer to be useful. Thus, we need some control over the position of the beam. If two flat mirrors with both horizontal and vertical tilt control are used, the beam can be properly positioned. The tilt controls on the mirror further away from the spectrometer can be used to adjust the vertical and horizontal position of the laser beam on the top right slit. The plumb line method must be reapplied as well. The tilt controls on the mirror closest to the spectrometer can be used to center the beam on the top rear mirror. Translation of this mirror allows the beam to be positioned in either arm of the entrance optics. After the laser beam is propagating straight through the spectrometer,
it can be used as a good reference in a step-by-step alignment. Since the laser beam can only be in one arm of the entrance optics at a time, the alignment has to be completed one arm at a time. All this alignment should not require large adjustments.

Translate the laser beam to each face of the prism. Slight adjustment of the tilt of the prism base allows for the height of the laser beam at the first parabolic mirror in each arm to be the same. This height must match the height of the entrance slit. The beam should not rise or fall as it exits the spectrometer. The laser beam should also propagate away from the prism to the parabolic mirrors at the same angle for each arm. As usual the laser beam must be centered on the parabolic mirrors.

The horizontal tilt control on the back of the parabolic mirrors can be used to position the laser beam on the flat mirrors in front of the entrance slit. The beam should be positioned about 1/2 in. from the near edge of the flat mirror and stay at the same height as for the parabolic mirror.

The beams can now can be sent down to the flat mirrors below the Nernst platform. When the beam is in each arm, the two beams need not be parallel in the horizontal plane. However, the beam height at all four flat mirrors has to be
the same. Using the tilt control on the parabolic mirrors and very small adjustments of the tilt controls of the flat mirrors in front of the spectrometer, center the beams on the flats below the platform.

Next, use the tilt controls on the flat mirrors below the platform to center the laser beam on the parabolic mirrors near the Nernst element. The beams must be left "as is" to properly reflect all the Nernst light they receive; therefore it is not important that the beams be centered on the flat mirrors located on the platform. The position of these parabolic mirrors is critical: a large change in their current position should be unnecessary and is discouraged. Remember, these mirrors should already be the correct distance and angular geometry required by the system.

The last step in the reverse-alignment process is to use the tilt controls on the parabolic mirrors to position the laser beam directly on the Nernst element. So now each arm should be "reverse-aligned" when the laser beam is present. At this point the laser beam and light from the Nernst element should map out the same optical path in each arm. The Nernst beam and the laser beam should be concentric. Any further adjustments to the system should just be minor
"tweeks". Our use of the system has allowed us to determine which mirrors have dominant control over certain regions of the optical path. These adjustments are given below:

Small tilt adjustments of the parabolic mirror on the platform are useful in centering the Nernst beams on the tilted flats below the platform. The tilted flats in turn can be tilted slightly to center the beams on the parabolic mirrors near the spectrometer. Experience has shown that once the flat mirrors in front of the entrance slit are roughly positioned they should not be disturbed. Tilting these parabolic mirrors then may be done to optimally position the beams on the prism.

These three adjustments are performed on a daily basis once the densitometer is operational to ensure the detector is receiving the maximum possible signal.

Alignment of the Exit Optics for the Densitometer

Proper positioning of the exit optics required the use of a different light source; a Fiber-Lite high-intensity lamp with 1/8-in. diameter fiber was used. The fiber light was placed inside the spectrometer and a lens was used to focus the light on the lower left slit of the spectrometer. A diagram of the exit optics is provided in Figure 53.
Figure 53. Exit Optics and the Detector. The image of the two independent sources is preserved in size through all of the intermediate transfer optics. It is demagnified on to the active area of the photodetector.
The lens used for focusing should be positioned so that the ratio of its diameter to the distance it is away from the lower slit is about 8. This matches the f-number of the spectrometer. With an index card and a plumb line to observe the beam of light at the exit slit, the lens should be positioned such that the light leaving the spectrometer is centered on the exit slit. Proper focusing of the beam should fill the rear mirrors and gratings with light. The light leaving the spectrometer should come out straight with minimal deviation horizontally or vertically. The spectrometer gratings should be set at the defined zeroth order position.

The exiting beam must be centered on the parabolic mirror placed directly in front of the exit slit. The parabolic mirror must be located about 6.6 in. away from the next flat mirror to focus the beam onto the flat. The parabolic mirror is positioned by first centering the beam on it and then translating the parabolic mirror until a sharply focused beam appears on the flat mirror next to the exit slit. Small adjustments of the tilt controls on the parabolic can be used to center the beam on the flat mirror to ensure maximum throughput.

Now, the short focal length parabolic mirror must be placed in the path of the beam to receive the parallel light reflected by the flat mirror. This mirror cannot be too
close to the flat mirror, because some space is needed to install the housing which covers this mirror and the detector. Space is also needed in case of a need to introduce a band pass filter to the system. The mirror is about 12 in. away in the original system but it can be closer.

Exact positioning of this last parabolic mirror requires that the reflected beam be focused onto the detector. Efforts must be made to configure the mirror/detector combination so that no light is lost and the beam is normally incident on the detector face. All the micrometer tilt controls along with the translation stage on the last mirror can be used to focus the beam sharply onto the center of the detecting region.

The fiber light can now be removed and the system can be illuminated with the light from the Nernst element. The entire system should now be aligned. In the future, if the detector is changed, only the last parabolic mirror should be adjusted in combination with the new detector to achieve a good focus. The fiber light must be put into the system again to make this adjustment.
BIBLIOGRAPHY


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