The integration of a heliostat with the UTMSL 5-meter spectrometric system: the v(1)+2v(2) band of atmospheric nitrous oxide

John Stewart Hager

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To the Graduate Council:

I am submitting herewith a thesis written by John Stewart Hager entitled "The integration of a heliostat with the UTMSL 5-meter spectrometric system : the v(1)+2v(2) band of atmospheric nitrous oxide." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Physics.

W. E. Bass, Major Professor

We have read this thesis and recommend its acceptance:

Stephen J. Daunt, Thomas Handler

Accepted for the Council: Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)
To the Graduate Council:

I am submitting herewith a thesis written by John Stewart Hager Jr. entitled "The Integration of a Heliostat with the UTMSL 5-meter Spectrometric System; The \( \nu_1 + 2\nu_2 \) Band of Atmospheric Nitrous Oxide." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements of a degree of Master of Science, with a major in Physics.

W. E. Blass, Major Professor

We have read this thesis and recommend its acceptance:

S. J. Davis

Accepted for the Council

Associate Vice Chancellor and
Dean of The Graduate School
The Integration of a Heliostat with the UTMSL 5-meter Spectrometric System; The $\nu_1+2\nu_2$ Band of Atmospheric Nitrous Oxide.

A Thesis Presented for the
Master of Science Degree
The University of Tennessee, Knoxville

John Stewart Hager Jr.
August 1995
Acknowledgments

I would like to thank a number of individuals who have been a great deal of help in accomplishing the task of integrating a heliostat with the 5-meter spectrometer. I would particularly like to thank Dr. W. E. Blass, for his faith in me and his guidance. I would also like to thank Dr. Stephen J. Daunt for his help and Dr. Thomas Handler for serving on my committee.

I would like to thank Larry Jennings and Allen Ewing for their immense help in getting the programming and electronics updated, Frankie Brannon for starting the project before I arrived in the group. Gerald McElyea and others in the laboratory were indispensable in practical aspects of lab work. I deeply appreciate all their help.

Finally, I would like to thank Yolla my wife, my mother and father for their patience and understanding during my graduate years at the University of Tennessee.
Abstract

The integration of a heliostat with the 5-meter Littrow spectrometric system at the University of Tennessee Molecular Systems Laboratory opens up new research possibilities. Environmental and solar studies are but a few prospects.

This is a two-part study. The first part deals with the integration of a heliostat with the 5-meter Littrow spectrometric system at the University of Tennessee Molecular Systems Laboratory. The second part deals with an application to the $v_1+2v_2$ combination band of $\text{N}_2\text{O}$ in the earth’s atmosphere. Atmospheric nitrous oxide was chosen as an example of the type of data that can be collected with the heliostat.

The main part of the work involves the designing and building of a heliostat and the optical components that enabled the sun’s radiation to be analyzed by the 5-meter Littrow spectrometric system.
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1. Introduction

Initial project

The project to integrate the 5-meter Littrow spectrometer to a heliostat was initiated in 1987 through a Research Incentive Grant to the Department of Physics by the University of Tennessee. The University of Tennessee Molecular Systems Laboratory 5-meter Littrow spectrometer is the outcome of a long term project initiated by Professor Norman Gailar who developed the original optical design of the spectrometer. The spectrometer was originally designed to have two beams in the sample section in order to have two experiments functioning at the same time (Fig. 3.2). The sun’s radiation is brought into the second beam in the sample section. This allows the taking of spectra of the sun’s and earth’s atmosphere. The carbon rod source can still be used in the first beam as a way to calibrate the spectrometer or to take infrared absorption data of molecules, as the spectrometer was originally designed.

A heliostat or sun tracker is placed on the roof of the physics building. This instrument directs the sun’s radiation to a fixed mirror, so the Sun’s radiation can be reflected down a four story high optical conduit to 5-meter Littrow spectrometer. Through a series of optics, radiation is brought into the second
beam of the spectrometer (Fig. 3.2). The new optics of the second beam were kept as close as possible to the original design.

The spectrometer was the subject of extensive study by Donald Jennings in 1974 (Jennings, 1974). There have also been modifications since 1974 that enable the system to achieve more closely its theoretical resolution limit. These changes are discussed by Dakhil (Dakhil, 1983). In order to connect the spectrometer with the heliostat, a 10 inch diameter optical pipe or conduit that goes from the roof of the fourth floor of the physics building down to the Molecular Systems Laboratory has been constructed. Also, modifications have been made to the second beam of the spectrometer to bring the sun's radiation in and through the spectrometer.
2. Heliostat

Introduction

In many types of astronomical research, it is desirable to have the measuring instrument stand still. In order for the instrument to stand still you must reflect the radiation of the astronomical object into the instrument, by a moving mirror. A heliostat is such a device, and it tracks the sun. At UTMSL two types of heliostats are used. Coelostat is used in the summer months, because the sun is above the celestial equator. A mirror is rotated around and mounted parallel to the polar axis. It makes one rotation every 48 hours. The siderostat is used in the winter months. A mirror makes one rotation every 24 hours, and the radiation is reflected along the polar axis. The heliostat is place on top of the fourth floor roof of the physics building. The radiation is bought down a four story high optical conduit to 5-meter Littrow spectrometer.
Path of the sun

Introduction

The path of the sun is not only important in the design and placement of a heliostat, but it is also important to the length of the path that the sun's radiation takes through the atmosphere. The angles and time of the sun's path can be calculated by series.

Angles

The difference between the ecliptic plane and the equatorial plane of the earth is 23.5°. The solar declination is the angle between a line joining the centers of the sun and the earth to the equatorial plain. It ranges from 23.5° (summer solstice) to -23.5° (winter solstice). The Taylor series

\[
\delta = (0.006918 - 0.399912 \cos \Gamma + 0.070257 \sin \Gamma \\
-0.006758 \cos 2\Gamma + 0.000907 \sin 2\Gamma - 0.002697 \cos 3\Gamma \\
+0.00148 \sin 3\Gamma)(180/\pi)
\]
is used order to calculate the declination of the sun (Iqbal, 1983). Where

\[ \Gamma = 2\pi(d_n - 1)365 \]  \hspace{1cm} 2.2

and \( d_n \) are the days since January 1st.

Figure 2.1 shows the path of the sun relative to an observer on earth.

- \( \theta_z \) is the zenith angle.
- \( \alpha \) is the solar altitude, or solar elevation; \( \alpha = 90^\circ - \theta_z \).
- \( \omega \) is the hour angle, noon zero, morning positive and 15' equals one hour.
- \( \phi \) is the geographic latitude, in degrees, north positive
- \( \psi \) is the solar azimuth, in degrees, south zero, east positive
- \( \delta \) is the declination of the Sun

Using the daily declination of the Sun, the latitude of the Nielsen Physics Building \((35^\circ 57' 25'')\) and Figure 2.1, the angle of the sun’s highest point off the horizon for each day of the year \( (\alpha_{\text{max}}) \) is shown in Table 2.1
Celestial Sphere and the Sun's Coordinated Relative to an Observer on Earth.
Table 2.1
The Maximum Altitude of the Sun at the Nielsen Physics Building at the University of Tennessee.

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Table 2.1 is useful in the initial set up of a heliostat. The angle of the primary mirror is set by a plum bob apparatus. To set the angle of the primary mirror you position it at zero degrees azimuthal or noon LAT. This is when the sun is at its highest point. The plum bob is parallel the edge of the mirror. The angles that the plum bob makes with surface of the mirror should be the angles that are in Table 2.1

From Figure 2.1, the azimuthal angle and the angle of the sun’s altitude are related by

$$\cos \psi = \frac{(\sin \alpha \sin \phi - \sin \delta)}{\cos \alpha \cos \phi}. \quad 2.3$$

At sunrise, the angles are

$$\cos \psi = -\frac{\sin \delta}{\cos \phi}. \quad 2.4$$

The Solar Altitude angle,

$$\sin \alpha = \sin \delta \sin \phi + \cos \delta \cos \phi \cos \omega. \quad 2.5$$

At noon the angles are

$$\sin \alpha = \sin \delta \sin \phi + \cos \delta \cos \phi, \quad 2.6$$

therefore,

$$\alpha = 90^\circ - \phi + \delta. \quad 2.7$$
Solar radiation data are often recorded in terms of local apparent time (LAT). Using standard or daylight savings time proves to be inconvenient. The sun may not be at $\alpha_{\text{max}}$ when it is noon in standard or daylight savings time, but always when using LAT. This discrepancy is called the equation of time and is measured relative to a perfectly uniform terrestrial motion. The information base that is needed in solar observation, like temperature and wind velocity, are given in standard or daylight savings time. Therefore it is desirable to convert local time in to local apparent time or LAT. Again from (Iqbal, 1983), the equation of time is

$$E_t = (0.000075 + 0.001868 \cos \Gamma - 0.032077 \sin \Gamma$$
$$-0.014615 \cos 2\Gamma - 0.04089 \sin 2\Gamma)(229.18)$$

$E_t$ is represented in radians and the multiplier 229.18 converts it into minutes. The maximum error with this series is 0.0025 rad, equivalent to about 35 seconds. Local apparent time for a given standard time can now be calculated by the formula

Local apparent time = Local standard time + $4(L_n - L_r) + E_t$. 

2.9
\( L_s \) and \( L_e \) are standard longitude and local longitude respectfully. Standard longitude for the eastern time zone is 75° and the local longitude for the Nielsen Physics Building is (83° 55' 30" or 83.925°). The physics building is west of the standard longitude so the longitude correction is negative. The final equation for Local apparent time at the physics building is

\[
\text{Local apparent time} = \text{Local standard time} - 35.7 \text{minutes} + E_i \tag{2.10}
\]

The incremental value of \( \omega \) or hour angle (noon zero, morning positive and afternoon negative), is 15° per hour using LAT.

**Irradiance of the sun on a inclined surface**

Irradiance will indicate the rate of solar energy arriving at a surface per unit time and per unit area (Wm\(^{-2}\)). As the sun moves through the sky, the angle between it and the secondary mirror obviously changes. Therefore the amount of irradiance also changes. The smaller the angle the more surface of the tracking mirror is pointed towards the sun and therefore more area. This changes independently from the sun’s radiation going through different amounts of the earth’s atmosphere. The formula for calculating the irradiance is,
\[ \dot{i}_0 = \dot{i}_{sc} E_0 (\cos \beta \cos \theta_z + \sin \beta \sin \theta_z \cos (\psi - \gamma)), \]

where \(\dot{i}_{sc}\) is the solar constant and \(E_0\) is the eccentricity correction factor of the earth's orbit (Iqbal 1983).

**Coelostat**

The coelostat design is based on a telescope mount, the difference being, sending the sun's radiation to a fixed point. The coelostat is a tracking mechanism which includes a mirror that rotates around an axis that is lined up with the earth's polar axis, using a stepper motor to rotate the mirror. The rotating mirror has to remain parallel to the polar axis. Since, the sun sweeps out a great circle, then so does the coelostat. This means that the rotating mirror must be moved horizontal on a line in the same direction of the polar axis, in order to compensate for the declination of the sun. The secondary mirror would block the sun's radiation at around noon (LAT), near March 21 and September 21. This is because the normal of the rotating mirror is 54° to the polar axis, which is the same \(\alpha_{\text{max}}\) on March 21 and September 21. The sun's radiation would have to come in below the secondary mirror in late fall and early winter (Fig 2.2).
Figure 2.2
The Position of the Coelostat Primary Mirror
During Different Times of the Year.
Due to the limited space on the fourth floor roof it is not possible to place the rotating mirror far enough away from the secondary mirror for the Summer Solstice. The lowering of the secondary mirror will achieve the correct angles, but the heliostat becomes more complicated.

Although the coelostat works well in the summer months, the constant adjustment for the changing declination of the sun makes it impractical for a daily long-term tracking at UTMSL.

**Siderostat**

A siderostat is similar to the Kitt Peak McMath Solar Telescope (Pierce, 1964). The center of the rotating mirror and the center of the secondary mirror is aligned with the earth's polar axis. The rotating mirror sends the solar radiation down the polar axis. This way, the solar radiation is directed to a fixed point in the heavens. Due to the declination of the sun, the only thing that needs daily adjustment is the initial angle of the rotating mirror. The process is simplified by using Table 2.1. Since the declination of the sun changes minutely on an hourly basis, it is not necessary to adjust the declination of the rotating mirror during the day. The most the declination changes during any 24 hour period is 0.5°.
This maximum change occurs during the equinoxes. Since an average high resolution scan last about an hour, this is acceptable.

A siderostat has a disadvantage: the angle between incident and reflected light is generally greater than for the optimum position of the two mirrors of a coelostat, thus it is more sensitive to mirror figure and astigmatism.

Alignment

The alignment of the heliostat is more easily done at night. The alignment is done with helium-neon lasers. A tripod that sits on top of the fourth floor roof has a holder for a 0.8 mW helium-neon laser. Another laser is positioned just outside the exit slit of the grating monochrometer and the beam goes backward through the system. The procedure for aligning the heliostat is:

1. First, put a white sheet of paper, with a cross in the middle, on the mirror at the bottom of the conduit.
2. The alignment is made easier if you line up the returning grating laser with the center of the mirror at the bottom of the conduit first.
3. Go to the fourth floor roof and direct the laser to the center of the tracking mirror.

4. Center the laser on the secondary mirror, by adjusting the primary mirror.

5. Using binoculars and while looking at the laser beam’s reflection in the secondary mirror, align the laser dot with the cross on the paper, adjusting both the primary and secondary mirrors.

6. After removing the paper, place an aperture near the first focus between $M_{ib}'$ and $M_1'$ of Figure 3.2. There will be a magnified image of the aperture that can be seen with a pair of binoculars from the position of the mirror at the bottom of the optical conduit while looking at the top mirror of the periscope. Align the laser dot on the aperture using the mirror at the bottom of the optical conduit.

The dispersion of the lasers can be a problem. When the heliostat laser reaches the first focus, the laser dot is approximately 2 inches in diameter. That is why it is easier to do alignments at the foci of the optics.
3. The 5-Meter Littrow Spectrometer

Introduction

The University of Tennessee Molecular Systems Laboratory 5-meter Littrow spectrometer was the subject of extensive study by Don Jennings in his dissertation of 1974. There have also been modifications since 1974 that enable the system to achieve its theoretical resolution limit. These changes are discussed by Dakhil (Dakhil, 1983). The project to integrate the spectrometer to a heliostat was initiated in 1987 through a Research Incentive Grant to the Department of Physics by the University of Tennessee. In order to connect the spectrometer to the heliostat, a 10 inch diameter optical conduit that goes from the roof of the fourth floor of the physics building down to the Molecular Systems Laboratory has been constructed. Modifications have been made to the second beam of the 5-meter spectrometer's sample section to bring the sun's radiation in and through the spectrometer. Also, an upgrade to the controlling motor and re-wiring was implemented. The ray trace of the 5-meter spectrometer with the new optics are shown in Figure 3.1.
Figure 3.1 The 5-Meter Littrow Spectrometer Integrated with a Heliostat.
The spectrometer consists of four main sections:

1. The sample section (Fig. 3.2)
2. The prism predisperser section (Fig. 3.3)
3. The grating monochromator section (Fig. 3.4)
4. The detector section (Fig. 3.4)

There is a vacuum system for the 5-meter spectrometer. All the sections are connected to a vacuum manifold, which is coupled with to the pumping system. There are gate valves at all inter-section ports, between each section and the manifold, and between the pumping system and the manifold. There are also small air inlet valves on each section and on the manifold. The system presently functions on the air rather than vacuum for solar studies.

Since the sun’s radiation passes through the earth’s atmosphere it is not necessary to operate the system in vacuum. Some reasons one might consider to bring the spectrometer down to vacuum is to make is easy to calibrate and to keep the optics clean. It is difficult to keep the pump oil vapor and dust off the mirrors, especially the bottom periscope mirrors.
Figure 3.2 The Sample Section
Figure 3.3
The Prism Section
Figure 3.4

The Grating and Detector Sections
New interface and upgrades

Introduction

The 5-meter Littrow spectrometer was inactive for 5 years before the heliostat project was initiated. The original computer system and data acquisition system were replaced. The drive motors, wiring and control interfaces were also upgraded with new technology.

Data acquisition and control

The radiation from the heliostat is brought down through the sample section into the prism section. There, it is interrupted by the chopper at a rate of 1080 Hz and dispersed by the prism predisperser. After being doubly dispersed by the grating monochromator, the signal is detected and fed into a preamplifier. From there the signal goes to a lock-in amplifier and the reference signal comes directly from the chopper (Jennings, 1974; Dakhil, 1983). The amplified signal is then recorded digitally after sampling by an analog to digital (A/D) converter.
The PDP-11 computer acquisition and control system were replaced with an IBM compatible 386DX 25Mhz computer. This computer was fitted with an Alpha Products A-bus motherboard. Two A-Bus cards control the entire spectrometer. An Alpha Products DG-148 Digital I/O card is used for opening and closing the gate valves of the vacuum system. An Alpha Products SC-149 Smart Stepper Controller is used for governing all the stepper motors running the system. One data accusation card is used the Alpha Products FA-154 fast 12-bit A/D converter. It is used for sampling the amplified detector signal.

**Digital I/O**

The controls for the gate values were replaced with solid state units, so the gate values can be control by computer. The DG-148 card was chosen to control the gate values.

The DG-148 has three 8 bit I/O ports which may be configured for various modes of operation, input, latched output, strobed input or strobed output. The DG-148 opens and closes the seven gate valves.
**Stepper motor card**

The SC-149 card is supplemented with PD-123 power driver option. With the PD-123 a 5-amp/phase high torque stepper motor can be driven. Modifications were made to the PD-123 cards. Notable modifications included the removal of R5 and R6 resistors and the remote relocation of CR1, CR2, CR3 and CR4 LEDs. It should be noted that all grounds on the PD-123 are common. Leads to +5v are connected to the vacant R5 and R6. The schematics of the PD-123 card is in Figure 3.5

**Programs**

The A-bus system can be programmed through port calls using about any programming language. The decision was made initially to program in Visual Basic. A QuickBasic program that came with the SC-149 was divided up into different sub-routine to make up the Visual Basic program. This program has three main sub-routine; a main sub-routine, that controlled the buttons and the information that goes to the windows; a listening sub-routine that is a loop that constantly checks to see if the SC-149 has any information to communicate; a talking sub-routine that sends commands to the SC-149. All of these sub-routines are also controlled by different forms, buttons, slide bars and other sub-routines (See appendix A).
Fig 3.5 PD-123 Card
A QuickBasic program that came with the SC-149 was modified by the addition of a data acquisition sub-routine.

**Stepper motors**

The old servo type motors were replaced on the prism drive, both the entrance and exit slit drives, the course grating drive and on the grating arm drive. They were replaced with Superior Electronic stepper motor. Each motor rotates 1.8 degrees per step at a maximum step rate of 200 steps per second or one revolution per second. A stepper motor also drives the heliostat. The step rate for the coelostat is 16.6 steps/sec. The step rate for the siderostat is about 33.2 steps/sec, which is twice the coelostat step rate.

**New optics**

**Introduction**

The original design of the spectrometer has a second beam for running different experiments at the same time. The idea was to use the second beam to bring the radiation in from the heliostat. This way the sun’s radiation...
could not only be analyzed, but it could be used as a source in which you could put a gas cell in one of the focuses of the second beam. This way, analysis of infrared regions that are unaffected by atmospheric absorption can be scanned for a particular molecule. The main advantage is to use a 6000K black body source, the Sun, instead of a 2700K source, the carbon rod. The decision was made to bring the heliostat radiation in through the port hole 193 cm from the west side of the sample section optical table on the south side of the sample section. If the system is ever brought down to vacuum the steel cover of the port could be fitted with an infrared window. The window would only have to be approximately 5 cm in diameter, because it is near the first focus of the second beam. An infrared filter could be used as a window.

**Description of the new optics**

The heliostat brings the sun's radiation through a 10 inch diameter optical conduit to the laboratory. There it is picked off by a mirror at the bottom of the conduit and sent horizontally across the lab to a periscope. The bottom pick off mirror mount at the bottom of the optical conduit was designed to send the sun's radiation to any point in the lab. An optical table has been constructed that is on the south side of the sample section. The table holds a periscope, flat, and the first spherical mirror of the second beam. The periscope drops the beam 88.4 cm to the same level as the beam in the
sample tank (Fig. 3.6). The beam is then sent to a flat that in turn sends it to a 122 cm focal length spherical mirror. This mirror collects the sun’s energy at f/8. The beam is then sent to a flat that brings it to mirror \( M_i \). (See Figure 3.6).

**Second Beam**

The spectrometer was originally designed to use two beams simultaneously by switching between them. This feature was never implemented. The optics on the second beam reverses the optics of the first, starting after the 125 cm \( M_i \) mirror (Fig. 3.2) and moving all the way to the switching mirror. The original design used a system of three mirrors to obtain the radiation from the source to the second beam. In order to bring a collimated source into the second beam, matching the 125 cm \( M_i \) mirror and spatially matching the focal length of it and \( M_j \) is all that is needed (Fig. 3.2). The pupils, aberrations and focuses should all be approximately be the same as the original design. The differences are discussed later in this chapter.
Figure 3.6 New Optics
**Bottom Conduit Mirror**

The mirror at the bottom of the fourth story conduit has a 23.4 cm x 20 cm flat. The mirror mount can rotate and angled up and down in order to direct the radiation anywhere in the lab. It is design to be easily taken down and cleaned.

**New Optical table**

An 23x53 inch optical table was constructed. It has 3/8 inch threaded holes. They are 5 1/2 inches apart and are used for tie downs. The table stand is designed to sit on the main platform. The main platform of the spectrometer sits on six air baffles in order to absorb vibration. The new optical table holds the periscope, flat and the 122 cm focal length mirror.

**Periscope**

The periscope is designed to bring the center of the radiation over the detector tank and down 88.4 cm to the height of 23.7 cm above the optical table.
(Fig 3.6). The periscope is 50 inches tall and has a base 12 inches square.

**Spherical mirror**

The spherical mirror $M_1$ has 122 cm focal length and a diameter of 6 inches. It is the first focus of the new optics (Fig. 3.6).

**Switching mirror**

The switching mirror is on a linear drive axis. The drive axis is not threaded so there is nothing to strip out. The angle of the axis is perpendicular to the normal of the switching mirror. This keeps the errors down to a minimum (Fig. 3.2).

**Calculations**

The new optics and using the Sun as a source required new calculations of the optical characteristics of the 5-meter spectrometer. Pupils, aberrations and the curvature of the slit will cause degradation of the resolution. Calculations were made using the sun as a source instead of the carbon rod and new optics in the second beam instead of the original second beam design.
The first spherical mirror is $M_{ib'}$ (Fig 3.6). It is 6 inches in diameter, and its' focal length is 48 inches. The $f/#$, which is proportional to the inverse of the irradiance, is

$$f/# = f/d.$$  \hspace{1cm} (3.1)

(Hecht, 1987), where $d$ is the diameter and since the object is far away from the mirror $f$ is the focal length. $M_{ib'}$ collects the sun's radiation at $f/# = 8$.

**Pupils**

The diameter of $M_{ib'}$ is the first aperture stop or first exit pupil for the second beam. The aperture stop of the whole system is the grating itself. Since the grating is the most expensive element in the spectrometer, its size should be the limiting aperture in the spectrometric system. The entrance pupil of the whole spectrometer is the final image of the grating the mirror $M_{ib'}$ gives. That is, if the grating is the limiting aperture of the whole spectrometric
system. The intermediate pupils and the entrance pupils are shown in Table 3.1.

The table is fairly self explanatory. The ‘Dis. Between’ column is the distance between the mirror or object in the row above and the mirror or object in the row below. The ‘virtual’ column is the distance the virtual images are in front of the mirror on the same row. The ‘Real’ column is the distance the real images are in front of the mirror on the same row. The ‘Mag.’ is the magnification of the object.

In order for the grating to be completely filled with radiation, the real images of the grating, going backward through the optical system, must not be larger than the size of the beam at the point at which the real image is formed.

Note that almost all real images of the grating are very near the following mirror from the imaging mirror. The first real image formed by the parabola is at a collimated part of the beam. The other real images are small compared to the size of the beam.
Table 3.1
The Maximum Altitude of the Sun at the Nielsen Physics Building at the University of Tennessee.

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>5-meter</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100.00</td>
<td>500.00</td>
<td>475.00</td>
<td>-9500.00</td>
<td>20.00</td>
<td>574.55</td>
<td>406.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mirror #9</td>
<td>600.00</td>
<td></td>
<td>101.00</td>
<td>0.01</td>
<td>5.75</td>
<td>4.06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mirror #8</td>
<td>50.00</td>
<td>-1.00</td>
<td>100.00</td>
<td>0.98</td>
<td>-0.01</td>
<td>5.63</td>
<td>3.98</td>
<td></td>
</tr>
<tr>
<td>1/2 M Para</td>
<td>50.00</td>
<td>99.02</td>
<td>101.00</td>
<td>1.02</td>
<td>5.75</td>
<td>4.06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/2 M Para</td>
<td>50.00</td>
<td>99.00</td>
<td>101.02</td>
<td>1.02</td>
<td>5.86</td>
<td>4.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mirror #6</td>
<td>80.00</td>
<td>28.98</td>
<td>-45.44</td>
<td>-1.57</td>
<td>9.19</td>
<td>6.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mirror #5</td>
<td>149.55</td>
<td>403.63</td>
<td>237.57</td>
<td>0.59</td>
<td>5.41</td>
<td>3.83</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mirror #3'</td>
<td>200.25</td>
<td>114.03</td>
<td>-264.82</td>
<td>-2.32</td>
<td>12.57</td>
<td>8.88</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mirror #2'</td>
<td>197.55</td>
<td>451.82</td>
<td>351.03</td>
<td>-1.80</td>
<td>9.76</td>
<td>6.90</td>
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</tr>
<tr>
<td>mirror #1'</td>
<td>98.40</td>
<td>44.97</td>
<td>-82.80</td>
<td>-1.84</td>
<td>17.98</td>
<td>12.71</td>
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<tr>
<td>mirror #1b'</td>
<td>122.00</td>
<td>407.10</td>
<td>174.21</td>
<td>0.43</td>
<td>7.69</td>
<td>5.44</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The only marginal situation is the fourth real image of the grating. We use a collimated beam size of approximately 15 cm. The fourth pupil is imaged 237.57 cm off mirror $M_5'$ which is 88.02 cm in front of the focus of $M_5'$. The beam size goes from 15 cm at $M_5'$ to 1.1 cm at the focus. Instead of using 1.1 cm, we approximate the size of the sun’s image as a point. Then using similar triangles to compute the beam size at the fourth pupil, we will observe that the pupil is small enough to fit inside the beam. As follows, 7.5 cm is to 200 cm as $(\text{beam size}/2) \text{ cm}$ is to 88.02 cm. The beam size at the fourth pupil is $\approx 6.72$ cm. The diagonal of the image of the grating at the fourth pupil is 5.41 cm (table 2.1), which is smaller than the beam size.

Another marginal situation is the sixth pupil. The sixth pupil is 351.03 cm off $M_5'$. The beam diameter is 11.7 cm and the pupil diagonal is 9.76 cm, which is smaller than the beam size. The seventh or entrance pupil is 174.21 cm off $M_{10}'$, which is in the collimated part of the beam.
In order to calculate the curvature of the slits using the sun as a source, it is necessary to know the size of the sun’s image at the predisperser and monocrometer entrance slits. The sizes of the virtual and real images of the sun are calculated at every focus, including the slits, in Table 3.2.

Just as a window will cause a pin cushion distortion when you look through it at a skewed angle, the prism causes slit image distortion. The distortion of a straight slit is a parabola that curves toward the short wavelength side of the spectra.

This parabola can be approximated by an arc of a circle. Wadsworth-Littrow optical arrangement was implemented in the prism monochromator in 1977 (Dakhil, 1983). The slit image distortion depends on the angle of incidence on the prism and the focal length of the collimator. Both of these factors are invariant for a given prism in the predisperser using the Wadsworth-Littrow optical arrangement.
<table>
<thead>
<tr>
<th>FOCI</th>
<th>Objects</th>
<th>Distance Between Virtual and Real</th>
<th>Magnification</th>
<th>Diameter of Sun cm.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>122.00</td>
<td>1.40E+11</td>
<td>1.14</td>
<td>1.50E+13</td>
</tr>
<tr>
<td>mirror M1'</td>
<td>98.40</td>
<td>199.20</td>
<td>-0.98</td>
<td>1.11</td>
</tr>
<tr>
<td>mirror M2'</td>
<td>197.55</td>
<td>202.29</td>
<td>46.35</td>
<td>1.00</td>
</tr>
<tr>
<td>mirror M3'</td>
<td>200.25</td>
<td>8622.92</td>
<td>-41.65</td>
<td>1.10</td>
</tr>
<tr>
<td>mirror M4'</td>
<td>149.55</td>
<td>146.59</td>
<td>50.51</td>
<td>1.60</td>
</tr>
<tr>
<td>mirror M5'</td>
<td>80.00</td>
<td>7045.61</td>
<td>51.03</td>
<td>1.00</td>
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<tr>
<td>mirror M6'</td>
<td>50.00</td>
<td>2470.94</td>
<td>54.42</td>
<td>0.72</td>
</tr>
<tr>
<td>mirror M7'</td>
<td>50.00</td>
<td>2470.94</td>
<td>54.42</td>
<td>0.72</td>
</tr>
<tr>
<td>mirror M8'</td>
<td>50.00</td>
<td>2270.94</td>
<td>34.79</td>
<td>1.60</td>
</tr>
<tr>
<td>mirror M9'</td>
<td>100.00</td>
<td>2270.94</td>
<td>34.79</td>
<td>1.60</td>
</tr>
</tbody>
</table>
When the prism is set at minimum deviation, the formula for this circle is:

\[
  r_p = \frac{fn^2}{4(n^2 - 1)} \cot \theta_i
\]

where \( f \) is the focal length of the imaging optics, \( n \) is the index of refraction and \( \theta_i \) is the angle if incident on the prism. The index of refraction for the LiF prism at 2450 cm\(^{-1}\) is approximately 1.35. The angle of incidence is approximately 30° and the focal length of the imaging optics is 1 meter. The radius of curvature is 96 cm. The size of the sun’s image is only 0.64 cm at the entrance slit. So this curvature of the prism entrance slit is not of great concern.

The grating also distorts off-axis radiation. It curves the image of the entrance slit of the monochromator just like the prism but towards the longer wavelengths instead of the shorter. Figure 3.6 illustrates the final image of the entrance slit on the exit slit. The formula for calculating this shift is derived and discussed in Jenning’s dissertation (Jennings, 1974). The displacement of the top and bottom points of the entrance slit in a double pass monochromator is

\[
  \Delta x = (\alpha - \delta)^2 2 \tan \theta.
\]
where $\Delta x$ is the lateral displacement. The horizontal plane is defined by the collimator axis and the grating normal. The angle $\alpha$ is the angle which the incident and diffracted rays make with the horizontal plain. The angle $\delta$ is the angle that the center of inversion (the axis of the D-shaped mirror) makes with the horizontal plane. The angle $\theta$ is the angle that the grating normal makes with the collimator axis. Both the top and bottom points are displaced by the same amount in a double pass system.

The size of the sun's image at the entrance slit of the monochromator is 1.6 cm (Table 3.2). So $\Delta x$ at blaze or 65° is 44 mm. Since the diffraction limit of the slits is 110 mm at 2500 cm$^{-1}$. The lateral slit curvature effects the resolution negligibly.

*Data Acquisition Procedure*

The 5-meter spectrometer is controlled from a station on the north side. It contains the computer terminal, lock-in amplifier and stepper motors speed indicators.
Figure 3.7
Lateral Image Curvature of the Entrance Slit in the Focal Plain of the 5-meter Parabola.
The instrument functions which are controlled from this station are:

- Grating position drive
- Grating scan drive
- Prism position drive
- Slits widths drives
- Beam switching drive
- Vacuum system valves

These different apprentices and valves are discussed in Jenning’s dissertation (Jennings, 1974).

The procedure assumes that you are already on a prism order. The procedure for taking atmosphere spectra is as follows:

1. Run “5meter” program on the computer.
2. Power up stepper motor cards
3. Adjust declination and right ascension of primary heliostat mirror on roof.
4. Start heliostat and approximately align the Sun's radiation with the middle of the bottom conduit mirror.

5. Set speed of heliostat motor to 16.6 for coelostat configuration.

6. Turn on detector

7. Turn on chopper

8. Turn on lock-in amplifier

9. Adjust the speed to the heliostat to get the maximum signal on lock-in-amplifier read out.

10. Start grating drive.

11. Push 'q' to get out of SC-149 control mode

12. Push 't' to take data

13. Set sampling parameter

14. Name data file, after you name the data file and press return, the program will start taking data.

15. To stop taking data press 'q'

In order to rotate the prism to a specific order:

1. Rotate the prism until you see the red (920 nm) on the entrance slit of the monocrometer.

2. Take a prism profile by starting at the visible and scanning the infrared for about 20 minute at a motor speed of 200.
3. Print out the prism profile and scale the time on it.

4. Go back toward the visible and stop on the desired order by using the time scale.

Once the data had been taken, the programs to read and graph data were KaleidaGraph and Origin.
4. Experimental Observations

Introduction

Nitrous oxide was chosen as an example of the kind of data that can be taken with the heliostat. New problems and advantages of using the sun as a source instead of the carbon rod furnace, are discussed herein.

Nitrous Oxide

The nitrous oxide molecule is linear and asymmetric (NNO). The three fundamental bands are $v_1$ (1284.907 cm\(^{-1}\)), $v_2$ (558.767 cm\(^{-1}\)) and $v_3$ (2223.756 cm\(^{-1}\)). Since $v_1$ is approximately equal to $2v_2$ there is a strong Fermi resonance between the levels. The isotropic abundances are $^{14}\text{N}^{14}\text{N}^{16}\text{O}$ (99.043\%), $^{15}\text{N}^{14}\text{N}^{16}\text{O}$ and $^{14}\text{N}^{15}\text{N}^{16}\text{O}$ (0.358\%), $^{14}\text{N}^{14}\text{N}^{18}\text{O}$ (0.199\%), and $^{14}\text{N}^{14}\text{N}^{17}\text{O}$ (0.040\%) (Goody and Yung, 1989).

Nitrous Oxide has many natural sources. Hahn (1974-75) has estimated that the production of nitrous oxide by denitrifying bacteria in the soil is about 15
Mton $N_2O$ (N)/year, and the oceans are a net source of around 85 Mtons $N_2O$ (N)/year. But, there are man-made source of nitrous oxide. Measurements of the exhaust gases in the stacks of power plants burning coal and natural gas have shown high levels of nitrous oxide. Also, nylon production and man made fertilizers are a major source of nitrous oxide.

Nitrous oxide emanating from the troposphere is the major source of nitric oxide in the stratosphere through reaction (4.1),

$$N_2O + O(1^D) \rightarrow NO + NO$$ \hspace{1cm} 4.1

which then proceeds to catalytically destroy ozone by means of the cyclic reactions (4.2), (4.3),

$$NO + O_3 \rightarrow NO_2 + O_2$$ \hspace{1cm} 4.2

$$NO_2 + O \rightarrow NO + O_2$$ \hspace{1cm} 4.3

The amount of man made $N_2O$ is important not only as an indirect destroyer of ozone, but is itself a green house gas (Daunt et al, 1988).
Path length

The monochromatic transmittance $\tau_\nu$ at frequency $\nu$ governing the passage of IR radiation through a path length $Z$ along an inhomogeneous medium with pressure and temperature distributions $P(Z)$ and $T(Z)$, respectfully, is given by Beer's law in the form

$$\tau_\nu = \exp[-\int K_\nu(P,T)dU(Z)] \quad 4.4$$

where $K_\nu$ is the absorption coefficient and $U$ is the absorber amount (Goody and Yung, 1989). Once the integral in Eq. 4.4 is evaluated the formula is

$$\tau_\nu = \exp[-K_\nu(P,T)U(Z)] \quad 4.5$$

The absorber amount may be computed with the relation

$$U = M.R.(ppmv)\rho (g/m^3)Z(km) \quad 4.6$$
In order to see what the path change does to the transmittance, we just change Z in Eq. 4.6. The more the path or the more atmosphere that the radiation goes through the less the transmittance.

The amount of absorber that the sun's radiation goes through changes throughout the day. The path length is the largest at sunrise or sunset and is the shortest at noon.

An approximate method for calculating transmission is to divide the earth's atmosphere into layers. The troposphere and stratosphere contain the bulk of the atmospheric nitrous oxide. A good approximation would be to divide the atmosphere into 1-10 km region (troposphere) and a 10-40 km region (stratosphere). The amount of nitrous oxide varies in parts per million by volume between the troposphere and stratosphere. This is due to the disassociation of it in the stratosphere (see Eq. 4.1). The PPMV for the troposphere remains steady at 0.32. At about 11 km in altitude it drops to 0.315 and goes to .016 at 40 km. The pressure and density of the atmosphere drops by a factor of a 1000 at 40 km. Taking in account all the factors, 40 km is a good vertical or zenith path length in which to work.

The shortest path length of the UTMSL system occurs on the summer solstice. On the summer solstice the angle of the sun off the horizon at noon
LAT is 77.54° at UTMSL (Table 2.1). The path length is simply 40 km*csc(77.54°), which is 41 km. The longest path length is at sunrise and sunset on any day of the year. For a 40 km zenith path length it is 505 km.

The formula

\[
\text{Slant Path Length} = (\text{Zenith Path Length})(\csc \alpha) \tag{4.7}
\]

where \( \alpha \) is the altitude of the sun (Fig. 2.1), is fairly accurate for calculating path length (down to 30° for only a 0.25% error, it increases to 10% at 5°).

To illustrate what the change in path length does to the transmissions, two data set were taken on June 16th, 1995 of the \( \nu_1 + 2\nu_2 \) of nitrous oxide. The slant path lengths were calculated using a zenith path length of 40km and equation 2.5. The first data set was taken at approximately 10am LAT the second at noon LAT. The 10 am slant path length was 45.6 km and the noon path length was 41.0 km for a difference in path length of 4.6 km. Air masses can be calculated by integrating:

\[
m_{\text{air mass}} = \int M.R.(\text{ppmv})\rho(\text{g}/\text{m}^3)ds(\text{km}) \tag{4.8}
\]
Using Beer's law the ratio of the two different transmission are:

\[
\frac{\tau_v}{\tau_v} = \exp[-K_v(P,T)M.R.(ppmv)\rho(g/m^3)45.6km]
\]

\[
\tau_v = \exp[-K_v(P,T)M.R.(ppmv)\rho(g/m^3)41.0km]
\]

Of course there are temperture and pressure changes to consider. As the atmosphere warms up it also changes barometric pressure.

The change of the absorption due to a different slant path length is illustrated in Figure 4.1.

**Solar Prism Profiles**

The prism profile at particular angle of the grating is obtained by keeping the grating angle fixed and rotating the prism. This gives a profile of the signal intensity throughout the spectrum for that grating angle.
Figure 4.1
The Change in Transmission Due to a Change in the Slant Path Length.
When taking the prism profiles using the sun as a source, orders and groups of orders are absorb out. This is due to strong absorption bands that are close of major molecular constituents in the earth’s atmosphere. A typical prism profile was taken with the InSb detector, LiF prism and the grating at 65° (Fig. 4.2). The double pass grating equation

\[
\frac{1}{\lambda \text{ cm}^{-1}} = \frac{158n}{\sin \theta}
\]

where \( n \) is the order number, \( q \) is the grating angle and 158 is the grating constant. This equation was used to calculate the missing orders. The separation between each order at a 65° grating angle is 174.3 cm-1

Four main gaps are shown in Figure 4.2. The first gap absorbs out the 41-43 orders, ranging from 7147 - 7496 cm-1. The only significant contributor is water vapor. The second gap absorbs out the 30 and 31 order, which are 5230 cm-1 and 5404 cm-1 respectfully. The main contributors are water vapor and carbon dioxide. The third gap absorbs out the 19-22 orders, ranging from 3312 - 3835 cm-1. The main contributors are water vapor, carbon dioxide, nitrous oxide and HOCl. In this region it is possible that oil that has collected on the mirrors and oil on the detector element itself absorb out some radiation. In
Prism Profile with Grating at 65°

Figure 4.2
Missing Orders Due Mainly to H₂O and CO₂ in the Earth’s Atmosphere.
the past when the spectrometer was at vacuum, oil on the detector element was a problem. The fourth gap absorbs out the 13 order which is at 2266 cm⁻¹. The main contributors are carbon dioxide, nitrous oxide, carbon monoxide from the sun’s atmosphere and water vapor.

**Calibration**

In this work approximate calibrations are used on the 5-Meter. To find the large parallel bands of N₂O, that cover 60 cm⁻¹, it is not necessary to use exact calibration techniques of the 5-meter. A grating angle was approximated based on measurement using a 0.8 watt helium-neon laser. A more exact angle was found using methane as a calibration gas.

The wavelength of a helium-neon laser is 632.8 nm or 15,802.8 cm⁻¹. Table 4.1 is used to approximate the grating angle. The order with the most energy is the one that it closest to the blaze grating angle. Therefore the brightest laser dot is the 90th order, since it is closest to the blaze angle of the grating. This was confirmed using a protractor. The Table 4.1 uses the double-pass grating equation 4.10
Table 4.1

<table>
<thead>
<tr>
<th>Orders of a Helium-Neon Laser</th>
<th>86.0</th>
<th>87.0</th>
<th>88.0</th>
<th>89.0</th>
<th>90.0</th>
<th>91.0</th>
<th>92.0</th>
<th>93.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grating Angle</td>
<td>59.3</td>
<td>60.4</td>
<td>61.6</td>
<td>62.9</td>
<td>64.1</td>
<td>65.5</td>
<td>66.9</td>
<td>68.4</td>
</tr>
<tr>
<td>Separation cm⁻¹</td>
<td>183.8</td>
<td>181.6</td>
<td>179.6</td>
<td>177.6</td>
<td>175.6</td>
<td>173.7</td>
<td>171.8</td>
<td>169.9</td>
</tr>
<tr>
<td>22th order cm⁻¹</td>
<td>4042.6</td>
<td>3996.1</td>
<td>3950.7</td>
<td>3906.3</td>
<td>3862.9</td>
<td>3820.5</td>
<td>3778.9</td>
<td>3738.3</td>
</tr>
<tr>
<td>21th order cm⁻¹</td>
<td>3858.8</td>
<td>3814.5</td>
<td>3771.1</td>
<td>3728.8</td>
<td>3687.3</td>
<td>3646.8</td>
<td>3607.2</td>
<td>3568.4</td>
</tr>
<tr>
<td>20th order cm⁻¹</td>
<td>3675.1</td>
<td>3632.8</td>
<td>3591.5</td>
<td>3551.2</td>
<td>3511.7</td>
<td>3473.1</td>
<td>3435.4</td>
<td>3398.5</td>
</tr>
<tr>
<td>19th order cm⁻¹</td>
<td>3491.3</td>
<td>3451.2</td>
<td>3412.0</td>
<td>3373.6</td>
<td>3336.1</td>
<td>3299.5</td>
<td>3263.6</td>
<td>3228.5</td>
</tr>
<tr>
<td>18th order cm⁻¹</td>
<td>3307.6</td>
<td>3269.5</td>
<td>3232.4</td>
<td>3196.1</td>
<td>3160.6</td>
<td>3125.8</td>
<td>3091.9</td>
<td>3058.6</td>
</tr>
<tr>
<td>17th order cm⁻¹</td>
<td>3123.8</td>
<td>3087.9</td>
<td>3052.8</td>
<td>3018.5</td>
<td>2985.0</td>
<td>2952.2</td>
<td>2920.1</td>
<td>2888.7</td>
</tr>
<tr>
<td>16th order cm⁻¹</td>
<td>2940.1</td>
<td>2906.3</td>
<td>2873.2</td>
<td>2841.0</td>
<td>2809.4</td>
<td>2778.5</td>
<td>2748.3</td>
<td>2718.8</td>
</tr>
<tr>
<td>15th order cm⁻¹</td>
<td>2756.3</td>
<td>2724.6</td>
<td>2693.7</td>
<td>2663.4</td>
<td>2633.8</td>
<td>2604.9</td>
<td>2576.5</td>
<td>2548.8</td>
</tr>
<tr>
<td>14th order cm⁻¹</td>
<td>2572.5</td>
<td>2543.0</td>
<td>2514.1</td>
<td>2485.8</td>
<td>2458.2</td>
<td>2431.2</td>
<td>2404.8</td>
<td>2378.9</td>
</tr>
<tr>
<td>13th order cm⁻¹</td>
<td>2388.8</td>
<td>2361.3</td>
<td>2334.5</td>
<td>2308.3</td>
<td>2282.6</td>
<td>2257.5</td>
<td>2233.0</td>
<td>2209.0</td>
</tr>
<tr>
<td>12th order cm⁻¹</td>
<td>2205.0</td>
<td>2179.7</td>
<td>2154.9</td>
<td>2130.7</td>
<td>2107.0</td>
<td>2083.9</td>
<td>2061.2</td>
<td>2039.1</td>
</tr>
<tr>
<td>11th order cm⁻¹</td>
<td>2021.3</td>
<td>1998.1</td>
<td>1975.4</td>
<td>1953.2</td>
<td>1931.5</td>
<td>1910.2</td>
<td>1889.5</td>
<td>1869.1</td>
</tr>
</tbody>
</table>
The errors involved using the helium-neon laser are large do to the fact that you are just using the monocrometer section instead of the whole spectrometer. A more precise way of finding the grating angle is to use a calibration gas.

**Calibration gases**

Several calibration gas were used. Carbon monoxide was the calibration gas most used in the past when the 5-meter was run in vacuum. The problem using it now is water vapor and carbon dioxide absorb large amounts of energy at critical points in the carbon monoxide spectra. Nitrous oxide itself was used, but due to the similarity of the parallel bands, it was hard to identify specific regions of spectra.

The best calibration gas in this case is methane (CH₄). The band head in between 3010 cm⁻¹ and 3020 cm⁻¹ is relatively easy to pick out among the water vapor lines. Because the perpendicular Q-branches spread out, the farther away from the band head, it is simple to zero in on it.
The data from the calibration is in Figure 4.3. Figure 4.3 is the spectra of the laboratory air. Since, the path length is approximately 80 meters inside the 5-meter and methane composes $1.6 \times 10^{-4}$ percent of the earth’s troposphere (Goody and Young, 1989), methane lines are visible. Figure 4.3 is the same spectra only one with a 75 cm cell filled with 20 torr of methane in the beam. Notice the increase strength of the small methane lines and also the easily distinguished band head in Figure 4.3.

Also, the methane band head is at the middle of the 17th order if the grating is at 63.35°. Coincidentally, the middle of the $v_1 + 2v_2$ combination band of nitrous oxide is at the 14th order when the grating is at the same angle.
Figure 4.3
The Spectra of Methane at 3015 cm$^{-1}$ Band Head
Nitrous oxide is a linear rotor. The selection rules for a simultaneous rotational and vibrational transition are $\Delta J = \pm 1$. The Q-branch correspond to $\Delta J = 0$. It is allowed only when the molecule possesses angular momentum parallel to the internuclear axis. Since a linear rotor does not have a moment of inertia around the internuclear axis, there is no Q-branch. The R-branch of the $\nu_1 + 2\nu_2$ combination band corresponding to the $\Delta J = +1$ selection rule, is approximately between 2462 cm$^{-1}$ and 2500 cm$^{-1}$. The P-branch of the $\nu_1 + 2\nu_2$ combination band corresponding to the $\Delta J = -1$ selection rule, is approximately between 2425 cm$^{-1}$ and 2462 cm$^{-1}$.

The spectra of the $\nu_1 + 2\nu_2$ combination band of nitrous oxide taken with the 5-meter spectrometer at University of Tennessee Molecular Systems Laboratory is in Figure 4.4.
Atmospheric Nitrous Oxide at UTMSL

Figure 4.4
The $v_1+2v_2$ Band of Nitrous Oxide in the Earth's Atmosphere.
Solar lines

Several types of absorptions lines from the sun's atmosphere exist in the $\nu_1 + 2\nu_2 \text{N}_2\text{O}$ region of the infrared spectrum. The largest is the 4-5 electronic transition of hydrogen. It lies at 2467.73 cm$^{-1}$ (Carlsson and Rutten, 1994). Other lines include Silicon at 2449.1, 2457.1, 2457.8, 2466.6 and 2468.5 cm$^{-1}$; Iron at 2460.1 cm$^{-1}$; Calcium at 2463.2 cm$^{-1}$; and Sodium at 2472.62 cm$^{-1}$ (Livingston and Wallace, 1991).

Kitt Peak Spectra

The latest solar spectrum was downloaded from the argo.tuc.noao.edu anonymous ftp site. This spectra was taken with the 1-m Fourier Transform Spectrometer at the McMath solar telescope on Kitt Peak. The resolution is approximately $15 \times 10^3$ cm$^{-1}$. They have combined infrared solar spectra at different air masses to obtain a solar spectrum corrected for atmospheric absorption and an atmospheric spectrum with the solar features removed (Livingston and Wallace, 1991). The data from Kitt Peak is shown in Figure 4.4 and 4.5.
Figure 4.5
The $v_1+2v_2$ Band of $\text{N}_2\text{O}$ and Solar Spectra at Kitt Peak
Atmospheric Nitrous Oxide at UTMSL

Atmospheric Nitrous Oxide at Kitt Peak

Figure 4.6 Atmospheric Nitrous Oxide, at UTMSL and Kitt Peak
This data was used to confirm the data taken with the 5-meter. The large hydrogen electronic transition at 2467.7 cm\(^{-1}\) is the most obvious characteristic (Figure 4.5). All the solar lines in the \(\nu_1+2\nu_2\) region are identified on the solar spectra in Figure 4.5.

The resolution of the Kitt Peak data is 15 milli-wavenumbers. The resolution of the 5-meter spectrometer has been on the order of 10 milli-wavenumbers (Fig. 4.6). The larger FWHM of the UTMSL data can be attributed to several factors. One is pressure broadening.

Most all of the atmospheric nitrous oxide is in the troposphere. Kitt peak’s observatory is at 6900 ft in Arizona. UTMSL’s is at 900 ft. So, UTMSL is seeing pressure broadening at approximately 1 ATM. Kitt Peak sees it at 0.87 ATM.

Other factors are more concentrations of nitrous oxide in the Southeast as opposed to the Southwest and, the mis-alignment and large slit widths (500 \(\mu\)m) of the 5-meter spectrometer.
5. Discussion and Conclusion

The original design of the 5-meter Littrow Spectrometer was intended to increase the signal-to-noise ratio by making the exit slit image on the detector element as long as possible. This would fill the whole element with radiation thus enhancing signal to noise ratio of the 1960 era detectors which were not band width limited. The advances in detector technology have made this approach obsolete. Lock-in amplifiers, smaller band width limited detector elements and better electronics have greatly improved the signal-to-noise ratio. In order for the image of the carbon rod to be large the focal lengths of the mirrors in the system also have to be large. To get a reasonable f/#, since the focal lengths are large, the mirrors also have to be large. This also minimize off axis aberrations and the loss or marginal rays or vignetting. Today's technology the whole spectrometric system could be built on a much smaller scale.

A smaller scale could give you smaller f/#'s. There are advantages to having a smaller f/#. If we achieve a smaller f/# by shortening the focal lengths of the mirrors, we create a smaller image of the sun. We will have the same amount of radiation in the image. This will give us a smaller image at the entrance slit of the prism pre-dispenser and grating monochrometer. This in
turn reduces the slit image distortion relative to the wave length of the radiation.

The slit image distortion is the main limiting factor in the amount of grating passes that can be made. Before the heliostat, the intensity of the radiation of the carbon rod was a factor. Now that you increased the intensity by using the Sun as a source, additional grating passes are realistic. Smaller image size and increased source intensity would make a triple pass grating monochrometer system feasible. This would substantially increase the resolution of the 5-meter Spectrometric System.
References
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• Hecht, Eugene, *Optics*, Addison-Wesley, Reading, Massachusetts, 1987


• Jennings, Donald Edward, *The UTMSL 5-meter Littrow Spectrometer system; An Analysis of ν₂, CHD₃*, Dissertation at The University of Tennessee, 1974


Appendices
QuickBasic and Visual Basic 5-Meter Spectrometer data acquisition and control programs

QuickBasic data acquisition and control program ‘5METER’

- \( x = 2000 \)
- \( \text{CLS} \)
- \( \text{CLEAR 1000} \)
- \( ' \text{ clears buffer} \)
- \( P = 512 + 10 \)
- \( ' \text{ Port number} \)
- \( \text{LOCATE , , 1} \)
- \( = \text{INKEY$: COLOR (7)} \)
- \( ' \text{ looks for keyboard input then goes on.} \)
- \( \text{PRINT A$: : COLOR (15)} \)
- \( \text{GOSUB 510} \)
- \( \text{GOSUB 610} \)
- \( \text{GOTO 100} \)
- \( ' \text{ It goes through the 100-510-610-620-630 loop} \)
- \( ' \text{ until something has been typed form the keyboard.} \)
- \( \text{REM} \)
- \( \text{IF A$ = "" THEN RETURN} \)
- \( \text{IF A$ = "q" THEN GOTO 640} \)
- \( \text{FOR y = 1 TO LEN(A$)} \)
- \( \text{x = ASC(MID$(A$, y, 1))} \)
- \( ' \text{ reads a$ one letter at a time, and converts it to ASCII code.} \)
- \( \text{IF x = 33 OR x = 35 OR x = 36 THEN 550} \)
- \( ' \text{ emergency charaters- 33 or ! - stops everthing immediately, must reset} \)
- \( ' \text{ 35 or # - cancels current command line 36 or $ - Decelerated and stops} \)
- \( ' \text{ all motors.} \)
• IF INP(P + 1) > 127 THEN GOSUB 620: GOTO 540
• ' checks to see if the SC 159 has any thing to say. It usually sends out
• ' 95 and goes to 156 if it has someing to say. Remember GOSUB 620: GOTO 540
• ' is the THEN statement block
• OUT P, x: NEXT y: RETURN
• ' outputs ASCII code one letter at a time to the card
• IF (INP(P + 1) AND 2) = 0 THEN A$ = "e" + CHR$(13): GOSUB 500
• IF (INP(P + 1) AND 64) = 0 THEN PRINT CHR$(INP(P));
• z = INP(P + 1)
• FOR i = 1 TO 3: NEXT i
• RETURN

• P = 512
• PRINT
• PRINT
• PRINT
• PRINT "t) Take data"
• PRINT "r) Return to SC-149 Command Mode"
• PRINT "q) Quit to DOS"
• LINE INPUT "? "; f$
• PRINT
• IF f$ = "t" THEN
• GOTO 645
• ELSEIF f$ = "q" THEN
• GOTO 800
• ELSEIF f$ = "r" THEN
• GOTO 10
• ELSE
• GOTO 640
• END IF
• INPUT "Input sampling rate "; x
• LINE INPUT "Input prism file name "; c$
• = ".dat"
• = c$ + d$
• OPEN e$ FOR OUTPUT AS #1
• PRINT
• OUT P, 0: d = INP(P)
• H = INP(P + 1)
• L = INP(P)
• K = (L + (H * 256))
• PRINT USING "#####"; K
• WRITE #1, K
• PRINT
• FOR z = 0 TO x: NEXT z
• = INKEY$
• IF A$ = "q" THEN 750
• GOTO 720
• CLOSE #1
• GOTO 640
• END
Visual Basic control program

- Declare Function Inp Lib "inpout.dll" (ByVal Port%) As Integer
- Declare Sub out Lib "inpout.dll" (ByVal Port%, ByVal Value%)
- Dim s2(35), f2(35), y2(35), u(100), X(35), Y(35) As Double
- Global reply, step3, step4
- Global flag As String

Sub getcalfile (s2(), f2(), numinfi)
  Debug.Print numinfi;
  Rem Open "c:\cal.dta" For Input As #1
  Rem Input #1, numinfi
  Rem For conter = 1 To numinfi
  Rem Input #1, s2(conter), f2(conter)
  Rem Next conter
  Rem 235 Close #1
End Sub

Sub listening (flagal, reply)
  'Debug.Print "called by: "; flagal
  For mqe = 1 To 3000: Next mqe
  reply = ""
  937 If (Inp(522 + 1) And 64) = 0 Then
  reply = reply + Chr$(Inp(522))
  Else
  GoTo 938
  End If
  For mqe = 1 To 50: Next mqe
  GoTo 937
  938 If Right$(reply, 1) = Chr$(13) Then
  reply = Left$(reply, Len(reply) - 1)
  If flagal = 0 Then form1!receive.Text = reply

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If flagal = 1 Then  
form1!Text1.Text = Int(Val(reply) / 41#)  
helio!heliopos.Text = reply  
step3 = reply  
End If  
If flagal = 2 Then  
form1!Text2.Text = Int(Val(reply) / 41#)  
step4 = reply  
Rem tdlfrm!tdlposbox.Text = reply  
End If  
If flagal = 3 Then  
form1!Text3.Text = reply  
helio!heliospbox.Text = reply  
End If  
End If  
939 End Sub

Sub Main ()  
form1.Show 'Optionally, you can load and display a form.  
Rem For dlay = 1 To 10: Next dlay  
Call getcalfile(s2(), f2(), A)  
Rem Call SPLINE(s2(), f2(), A, 1E+30, 1E+30, y2())  
Do While DoEvents()  
ww = ww + 1  
If ww = 500 Then  
outptr$ = "pos3"  
' Debug.Print "from1"  
Call talking(outptr$)  
For mq = 1 To 1000: Next mq  
Call listening(1, resp)  
End If  
If ww = 1000 Then  
outptr$ = "sp3"  
Call talking(outptr$)  
For mq = 1 To 1000: Next mq  
' Debug.Print "from3"  
74
Call listening(3, resp)
End If
If ww = 1500 Then
outptr$ = "pos4"
Call talking(outptr$)
For mq = 1 To 1000: Next mq
'   Debug.Print "from2"
Call listening(2, resp)
Rem resp1 = Val(resp)
'   Debug.Print resp1, resp
Rem Call SPLINT(s2(), f2(), y2(), A, resp1, resp2)
Rem resp3 = Str$(resp2)
Rem form1!text3.Text = resp3
Rem tdlfrm!Text2.Text = resp3
ww = 0
End If
'Place idle-loop code here. These statements are processed
'whenever the system has free time
'Debug.Print "i'm in the idle loop " + r
'r = r + 1
' if r > 32000 Then r = 0
'let's listen to the sc149 since we are not doing anything
'Call listening(0)
Rem Call heliogetpos
Loop
End Sub

Sub SPLINT (XA(), YA(), Y2A(), N, X, Y)
KLO = 1
KHI = N
50200   If KHI - KLO > 1 Then
K = (KHI + KLO) / 2
If XA(K) > X Then
KHI = K
Else
KLO = K
End If
End Sub
• End If
• GoTo 50200
• End If
• H = XA(KHI) - XA(KLO)
• If H = 0# Then Exit Sub
• A = (XA(KHI) - X) / H
• B = (X - XA(KLO)) / H
• Y = A * YA(KLO) + B * YA(KHI)
• Y = Y + ((A ^ 3 - A) * Y2A(KLO) + (B ^ 3 - B) * Y2A(KHI)) * (H ^ 2) / 6#
• End Sub

Sub talking (motorcmd)
• 'Debug.Print "command received: "; motorcmd
• If motorcmd = "" Then 32001
• For mqe = 1 To 5000: Next mqe
• motorcmd = motorcmd + Chr$(13)
• For yyy = 1 To Len(motorcmd)
• For w = 1 To 3500: Next w: Rem Delay here
• xxx = Asc(Mid$(motorcmd, yyy, 1))
• 'Debug.Print x, Chr$(x)
• 551 out 522, xxx: Next yyy: GoTo 32001
• 32001 Rem ****** time to quit talking to sc149******
• End Sub
Appendix B

In order to integrate a heliostat with the 5-Meter spectrometer, detail drawings of the system were transferred to the Canvas 3.5.3b version of a drawing program. Through this software, I was able to try out new optical designs. Deneba software, Inc. of Miami, Florida manufactures Canvas. Canvas was also used to create detail drawings of new optical devices for the machine shop at the Neilsen Physics building. The following pages have most of those drawings.
Figure B.1
The 5-meter lltrow spectrometer, integrated with a heliostat.
Figure B.2
Prism section dimensioned
Figure B.3
Design for the flat mirror mount
Figure B.4
Bottom conduit mirror
Figure B.5
Design for the periscope
Figure B.6
Design of the optical table
Figure B.7
Design of the bottom conduit mirror holders
Figure B.8
Inside Suntracker Frame
Figure B.9
Outside sunshiner frame
Figure B.10
Heigth of the beams.
VITA

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