TWO-DIMENSIONAL IMAGING OF THE FUNDAMENTAL ROTATION-VIBRATION CARBON MONOXIDE LINES AT 4.67µm

By

Claude Plymate
5150 South Bryce Avenue
Tucson, Arizona USA 85746-9531
plymate@noao.edu

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ABSTRACT

The discovery of the 4.67\textmu m carbon monoxide fundamental rotation-vibration emission line spectrum above the solar photosphere conflicts with classical models of the upper solar atmosphere. The emission lines indicate a brightness temperature as low as 3500K at an elevation where the temperature minimum had previously been estimated at \(~4400K. Modern models of the upper solar atmosphere assume a thin thermally-bifurcated atmospheric layer to reconcile the contradictory temperature minimums. The new Image Stabilizer system was utilized along with the infrared spectrograph at the McMath-Pierce Solar Telescope to produce 2-dimensional spectroheliogram images of the carbon monoxide emission layer. Results are presented which indicate that the strongest of the lines extend to roughly 500 km (0.7 arcseconds) above the solar limb. The data also suggest that the carbon monoxide density decreases with increasing elevation. Although the Image Stabilizer canceled image motion in the axis parallel to the solar limb, seeing still distorts and degrades the limb image. Frame selection techniques were used to construct images from the best seeing spectral frames resulting in 2-dimensional images approaching 1 arcsecond resolution during times of good seeing. The images clearly show both bright and dark features are present and can be mapped in the above-limb emission. The structures seen support a thermally bifurcated model of the solar atmosphere.
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1. INTRODUCTION

1.1 Background

Traditional models of the solar atmosphere were based upon one-dimensional plane-parallel hydrostatic calculations with the Sun being comprised of homogeneous layers. Anyone who has ever looked at the Sun knows that its outer atmosphere is anything but uniform. Still, these simple models have been remarkably successful at reproducing many of the global characteristics of stellar atmospheres. The one-dimensional models predict a sudden temperature drop due to radiative cooling above the photosphere, reaching a temperature minimum of ~ 4400K at an altitude of around 500 km (Uitenbroek 2000). Above the temperature minimum, mechanical heating begins to dominate, pushing the temperature upward through the chromosphere. The temperature rise through the chromosphere is gradual, moderated by the progressive ionization of hydrogen (Ayres 1998). The chromospheric heating is a consequence of compression due to the transition of solar oscillation pressure waves through the chromosphere. This picture of the upper solar atmosphere fits well with the observed line profiles of Ca II and Mg II lines in the visible solar spectrum (Ayres & Rabin 1996).

Infrared (IR) observations began to indicate that the actual solar atmosphere isn’t quite as simple as the models predict. The now-decommissioned horizontal spectrograph at the McMath Solar Telescope (now the McMath-Pierce Solar Telescope, McMP) was used to measure the center-to-limb variability of the fundamental rotation-vibration lines of carbon monoxide (CO) at 4.67µm. The depth of the strongest CO lines in the band showed a brightness temperature of 3500K (Noyes & Hall 1972). Fourier Transform Spectra of the CO bands confirmed the anomalously low brightness temperature in the strongest line cores to be less than 4000K. It was suggested that a way of reconciling the observations was to assume that the chromosphere was thermally inhomogeneous, containing large “cool” clouds of CO interspersed with compact zones of hot magnetic flux tubes (Ayres, Testerman & Brault 1986). This “thermally bifurcated” model of the upper solar atmosphere assumes that CO exists in a radiative-equilibrium temperature held low by cooling from optically thin emission in the CO bands themselves (Ayres 1994).

Most of the rotation-vibration CO lines in the solar spectrum are obscured by the terrestrial atmosphere. The lines around 4.67µm are a notable exception (Uitenbroek 2000). The anomalously cool layer just above the solar photosphere has only been able to be seen in these CO lines. “Few species have the required sensitivity to cool temperatures and [are] strong enough to thermalize in the middle chromosphere.” (Ayres 1994) This limits studies of the very cool CO layer to the rotation-vibration CO lines at 4.67µm (2143 cm⁻¹). This has led some to begin using the term “COmosphere” for this region of the solar atmosphere (Wiedemann et al. 1994).

Advancements made in observations of the 4.67µm CO lines have been inexorably tied to instrumental improvements on the McMP. The reason behind this is quite simple; the McMP is currently the only large-aperture solar telescope capable of observations in the
thermal IR. The McMP is unique among large solar telescopes in that it utilizes an all-reflecting unobstructed optical design; most solar telescopes make use of at least some transmitting optics in their optical paths that are opaque in the IR. The McMP main spectrograph was upgraded in 1992 to include computer control and the very large IR diffraction grating salvaged from the horizontal spectrograph used by Noyes and Hall in 1972. Tests of the new system discovered that the IR CO lines go into emission above the limb (Solanki et al. 1994). These measurements indicated a brightness temperature in the line cores of between 3600 and 3900K up to an altitude of ~0.4 arcseconds above the limb. Above that height the CO emission dropped off but not as quickly as the continuum. This directly demonstrated that cool gas exists well above the altitude where conventional models place the chromospheric temperature minimum (Ayres & Rabin 1996).

Later that same year, a companion instrument to the upgraded spectrograph came online - the Near Infrared Magnetograph (NIM). The NIM allowed for 2-d IR spectral frames to be collected while the solar image was stepped across the slit. By stacking the successive frames into a data cube, spectroheliogram images of the solar surface could be produced at any desired wavelength between 1 to 5$\mu$m (assuming the availability of an appropriate order-sorting filter).

The availability of the NIM generated a flurry of studies of the 4.67$\mu$m CO lines in the solar atmosphere. These studies focused primarily on mapping the intensity distribution of the CO lines over regions of the solar surface. Uitenbroek et al. (1994) used the new system to image both quiet and active regions. They found that sunspot umbrae and penumbrae selectively strengthen the CO lines. Their limb measurements indicated that the 3-2 R14 line ($2142.7$ cm$^{-1}$) extended above the continuum limb by approximately 0.5 arcseconds (360 km). Ayres & Rabin (1996) also used the IR spectrograph to image CO. They found that the outer atmosphere’s thermal and velocity fluctuations are connected to p-mode oscillations. However, being that the “chromosphere is thought to be heated at least partly by acoustic energy deposition, it is remarkable that the CO layers show so little evidence for disruption by large-amplitude disturbances” (Ayres & Rabin 1996). They proposed that the predominance of the acoustic energy passes through the CO layer without substantially heating it. They also measured the CO limb extensions to be around 0.6 arcseconds for the strongest lines, down to about 0.3 arcseconds for the weakest lines. Several models were proposed to begin to account for the new observations.

An annular solar eclipse was observed in 1994 with the McMP spectrograph and the NIM IR array camera to measure the off-limb intensity profile of the CO lines at 4.67$\mu$m (Clark et al. 1994). An eclipse provides an almost ideal opportunity for exploring this thin region atop the photosphere. During an eclipse, the Moon acts as a moving occulting disk, free from the seeing produced in the Earth’s atmosphere. The vertical intensity profile of the CO emission lines can be measured by taking a time series of spectral observations at the solar limb while the lunar disk passes through the field. The lunar limb will progressively cover the lower solar atmosphere leaving ever less of the higher up CO emission exposed. The intensity profile of the emission can be determined by correlating the line intensity with the elapsed time from the Moon’s crossing of the solar
IR continuum limb. This technique can produce measurements that are independent of seeing and even telescope aperture! The spatial resolution is, in theory, limited only by the knowledge of the relative speed of the lunar limb in relation to the Sun’s and by the spatial blurring of the Moon’s motion during each exposure. The eclipse observations by Clark et al. (1994) achieved an effective spatial resolution of 0.1 arcseconds. The height of the strong vibration-rotation CO 3-2 R14 line was measured to be $0.56 \pm 0.04$ arcseconds.

Unfortunately, solar eclipses cannot be scheduled at will, occurring infrequently at the whim of nature. They are “one-shot” events; if missed because of weather or instrumental failure, the data are irretrievably lost. Also, all eclipses are not created equally. Only total or annular eclipses where the solar and lunar limbs cross parallel to each other are truly unaffected by seeing. In a partial eclipse, an inclination angle exists between the limbs that will impose some height measurement confusion due to seeing motion along the limb proportional to the magnitude of the inclination and seeing.

A consensus appeared to be emerging at this point that at least a two-temperature, “thermal bifurcated” atmospheric model is necessary to account for all the observations. Current observations have not differentiated between many of the bifurcation models. Many questions are yet to be resolved. What are the temperature profiles of the hot and cool regions? How high do they truly extend and how do they vary with height? How much of the disk is covered by cool CO regions versus hot areas? Advancements in technology and techniques need to continue to be developed to help more accurately probe this layer of the solar atmosphere to better distinguish between the various models being proposed.

1.2 Project Goals and Approach

The aim of this project is to investigate techniques to map the 2-dimensional distribution of the 4.67 $\mu$m CO rotation-vibration lines above the solar limb utilizing a new prototype image stabilization system that has very recently become available. The goal is to produce spectroheliograms of the CO line emissions above the limb. The spectroheliogram images of the CO emission are used to measure the emission lines’ intensity drop with height. The 2-d images are examined for indications of CO intensity variation in the axis along the limb. Measuring emission variation parallel to the solar limb could be a useful technique for investigating the density distribution in the “COmosphere”. This might be helpful in eventually determining the amount of area taken up by the hot (>4400K) atmosphere between the cool (<3700K) CO regions.

Typically, the spectrograph slit is placed perpendicularly across the solar limb when measuring line heights. In this project, the slit is oriented parallel to the limb. The prototype Image Stabilizer is used to accurately step the slit across the limb. Several spectral frames are collected at each step position across the limb and frame selection techniques are utilized to determine the best seeing frames at each step. The best seeing frames are assembled into spectroheliograms of both the solar continuum and of the CO line emission. The continuum ‘grams can then be used to subtract the bright solar disk
from the CO gram revealing the above limb emission. It is hoped that by orienting the slit parallel to the limb, the typical problems caused by light scattering into the spectrograph from the portion of the slit illuminated by the bright solar disk will be eliminated. Once the slit moves above the limb, the only light entering the spectrograph should be from the emission lines. Intensity cuts across the middle of the spectroheliograms are used to compare the data to results from previous CO limb studies.

2. INSTRUMENTATION

2.1 Image Stabilizer

The Image Stabilizer system is a temporary test bed platform for a fast tip-tilt mirror (Figure 1) that is the first stage in an adaptive optics (AO) system being developed for the McMP. The AO system is expected to deliver diffraction-limited images in the IR, red of 2.3 µm, to the focal plane instrumentation of the McMP. The tip-tilt stage is used in the AO system to correct for overall image motion while a deformable mirror corrects for higher order distortions. Keller et al. (2002) recently reported on the development and first-light observations with the AO system. The Image Stabilizer bench was used to test the tip-tilt mirror and to develop the image correlation and servo software. Once functional, the Image Stabilizer bench became available to users of the telescope for scientific observations. It is expected that the AO system will begin to be made available for scientific observations in the first half of 2003.

On the current Image Stabilizer bench, the telescope image plane is placed above the stabilizer. The stabilized focal plane image is then re-formed onto the spectrograph input slit. Below the telescope image plane, a pick-off mirror diverts the telescope’s vertical beam horizontally onto a concave collimating mirror. The collimator forms a telescope pupil image on the tip-tilt mirror. The flat tip-tilt mirror sends the beam back to a second concave re-imaging mirror whose focal length is matched to the collimator. The re-
imaging mirror re-forms the telescope image without changing the image scale or focal ratio. A 98% reflecting beamsplitter is used to divert the horizontal beam from the re-imaging mirror downward to the spectrograph slit. The other two percent of the light that passes through the beamsplitter is imaged by a high-speed CCD.

The CCD is a $256^2$ pixel array camera from Dalsa Engineering that samples the telescope image at about 500 frames/second. A Pentium III-based PC running Linux retrieves each image frame and compares it to the previous frame to determine the image shift in the elapsed time between them. The computer then sends an error signal to the tip-tilt mirror’s piezoelectric actuators to correct for the shift.

The Image Stabilizer software has three modes of operation. One mode divides the CCD into four quadrants and compares the average intensity in each quadrant. This mode is used for locking onto and guiding on sunspots. Another mode uses correlation tracking techniques for guiding on weak intensity variations across quiet regions on the disk. The third mode is used for image stabilization of the solar limb and is the mode that was used for this study.

The limb stabilizer mode divides the CCD frame into three strips (horizontal or vertical). The telescope is driven to place the solar limb in the center strip. This places the bright solar surface in one of the side strips and the dark sky in the other. The computer determines the direction and magnitude of the error signal to be sent to the tip-tilt mirror by comparing the signal intensity averaged over the center (limb) strip with the average of the bright Sun and dark sky strips. The width and position of the center limb strip is user adjustable. In practice, the width is varied depending on the seeing conditions (narrower during good seeing, wider in times of poor seeing). The position of the center strip can be moved in single CCD pixel increments to allow the limb to be moved under software control. The ability to scan the limb was central in the design of this study.

2.2 Telescope

Five days (05 - 09 August 2002) were allocated to this project on the National Solar Observatory’s McMath-Pierce solar telescope at Kitt Peak. The McMP uses a 2-meter heliostat to supply the solar beam to a 1.5-m f/50 imaging mirror. An off-axis 3rd mirror is used to direct the beam downward into the observing room. The telescope’s 4-decade old unobstructed all-reflecting design makes it uniquely suited for IR investigations of the Sun.

2.3 Spectrograph

The telescope’s main “work horse” instrument continues to be its vertical spectrograph. The spectrograph was originally built along with the telescope in the early 1960s and upgraded for IR studies three decades later. It utilizes an all-reflecting Czerny-Turner optical system with two large diffraction gratings – one for the visible spectrum and the other for the IR. The entire 13.7-m focal length optical tank rotates to compensate for the diurnal rotation of the image induced by the heliostat optical arrangement. This long
optical path gives the spectrograph a very high theoretical resolving power of up to \( \frac{\lambda}{\Delta \lambda} = 1.1 \times 10^5 \) in 2\textsuperscript{nd} order. In practice, the resolving power is found to be significantly lower, from \( 9 \times 10^4 \) (Uitenbroek et al. 1994) to as low as half that value (Ayres & Rabin 1996).

2.4 IR Array Camera

This project used the IR array, transfer optics, and read out electronics from the NIM. The NIM’s polarization optics were not included, transforming the system into an IR spectroheliograph, sometimes referred to as the IR Imaging Spectrometer (IRIS). The IR camera is a commercial 256\(^2\) indium-antimonide (InSB) array produced by Amber Engineering in 1992. This is housed in a 10-inch diameter nitrogen-cooled dewar from IR Labs. The integration times are relatively short, typically 30 – 300 ms. The short integrations mean that the array doesn’t require cooling to liquid helium temperature. Instead, the dewar is cooled with solid nitrogen (~58K), which is about 20\(^\circ\) colder than liquid nitrogen and is far less expensive than helium.

Figure 2. The McMP Vertical Spectrograph. Above are mounted the Image Stabilizer and electronics. The Image Stabilizer and IR array terminals are set on the spectrograph table. The IR array control and read out electronics are strapped to the spectrograph side.

The technique for cooling to solid nitrogen temperature involves first filling the dewar’s two flasks with liquid nitrogen. Once the dewar reaches liquid nitrogen temperature, the
pressure in the inner flask is lowered using a vacuum pump. The liquid nitrogen freezes out once its pressure drops below its triple-point pressure at ~100 torr. The outer “jacket” flask is left at liquid nitrogen temperature to minimize the thermal load on the solid nitrogen.

The IR camera’s read out electronics and control computer are mounted in a standard electronics rack on wheels that is strapped to the side of the spectrograph and rides with the spectrograph as it rotates through the day (Figure 2). The data collection and instrument control is handled by an early 1990s era Apple Macintosh Quadra 950. The data are stored in standard FITS format.

There are two filter wheels inside of the dewar at cryogenic temperature. This allows bandpass filters to be selected that cut the thermal emission beyond their bandpass from outside the dewar, yet are not significant thermal sources themselves.

3. OBSERVATIONS

3.1 Set Up and Alignment

The first two scheduled observing days (August 5 and 6, 2002) were cloudy. This down time was used to set up, collimate and focus the instrumentation. There were enough breaks in the clouds on the 6th to align and focus the various optics.

The Image Stabilizer was mounted on a table platform above the spectrograph. The telescope focus was moved to the top of the Image Stabilizer, which was adjusted to reform the telescope image plane on the spectrograph slit. The Image Stabilizer optics were then aligned so that the beam from the telescope remained collimated to the spectrograph. The telescope focus was translated up and down above the Image Stabilizer until the re-focused image on the spectrograph slit appeared as sharp as possible by eye. Finding the best focus is normally done during times of good seeing. The typical approach is to try to find where the focus begins to noticeably deteriorate in each direction and to “split the difference” between those two limits. The very long (87m) and slow (F/50) optical system of the McMP gives the telescope a large region (several mm) over which a good focus is found.

The transfer optics that couples the InSb dewar to the spectrograph were mounted and focused. The transfer optics demagnify the output of the spectrograph by a factor of 2 to suit the pixel size of the InSb array. They also form a telescope pupil image at the input to the dewar where a cryogenic aperture stop is mounted. The cold stop masks off-axis thermal emission from reaching the array.

Aligning and focusing the transfer optics and array involves replacing the spectrograph input slit with a circular aperture. The diffraction grating angle is rotated to zero order so that it forms an image of the input aperture at the spectrograph exit and is re-imaged onto the array. The transfer optics are adjusted so that the exiting solar beam passes through
the center of each optic and the dewar’s cold stop. The appropriate bandpass filter is selected with the dewar’s internal filter wheel. A 255nm-wide filter centered at 4196nm (4.196µm) was selected. A resolution target is placed at the input aperture and the array is translated fore and aft for best focus. The transfer optics are not achromatic and so the bandpass filter must be in the optical path while focusing the dewar. The spectrograph slit is reinstalled and the dewar is rotated about the optical axis to align the slit image with the array’s pixel columns.

The grating was rotated to center the CO lines on the array. Second order was selected to put the grating angle as close as possible to the grating’s blaze angle.

3.2 Slit Width

A 205µm wide slit was selected. Originally, a 160µm slit was to be used. A width of 160µm corresponds to about 0.38 arcsecond on the sky. (The McMP image scale is known to be 2.37 arcseconds/mm.) A 0.38 arcsec width would properly sample the 0.78 arcsecond diffraction limit of a 1.5-m telescope at 4.67µm.

\[
\text{Diff. Lim} = 1.22 \left( \frac{\lambda}{D} \right) = 1.22 \left( \frac{4.67 \times 10^{-6}}{1.5} \right) = 3.80 \times 10^{-6} \text{ Rad} = 0.78 \text{arcsec}
\]

Test exposures showed that integration times of about 400 ms were necessary using the 160µm slit. This was felt to be excessively long and so the wider slit was used. The 205µm slit projects a width of 0.49 arcsec but reduces integration times to 300 ms. Using a wider slit was felt to be a reasonable compromise to gain the shorter integration time. The effect of declination angle on the projected heliostat aperture was not considered during the selection of the slit width (see section 4.1 - Effective Telescope Aperture). Coincidentally, the heliostat under filled the telescope imaging mirror, degrading the diffraction limit to 0.93 arcseconds, making the 205µm slit a reasonable selection.

3.3 Transfer Optics

The transfer optics serve two functions. First, they fold the vertical beam exiting the spectrograph to conveniently feed the horizontally-looking InSb array dewar. Secondly, they reformat the 2-d spectra exiting the spectrograph for the InSb array. The transfer optics can be configured in several ways. They can be set up to demagnify the spectrograph beam by a factor of two. Two cylindrical lenses can be added which add another factor of two demagnification to one axis. The cylindrical optics are normally used to demagnify the spatial axis (along the slit) to better match the array pixel size to the telescope resolution.

The length of the projected slit onto the array was measured to be 46.6 arcseconds (see Section 4.2 – Image Scales). The cylindrical optics would have doubled this to about 93 arcseconds. The width of the arc of the solar limb across 93 arcsec would be about 1.14 arcseconds wide - well above the diffraction limit of the telescope. The 46.6 arcsec slit
length produced by the symmetric optics (without cylinders) images a solar limb arc only about 0.29 arcsec wide – well below the telescope’s diffraction limit. The complication of dealing with a large limb arc along the slit outweighed the concern of over sampling the spatial axis. The simpler symmetric optics were selected for the observations.

The solar radius is listed in the 2002 Astronomical Almanac as 15’ 47.8” (Nautical Almanac Office 2000).

\[ R_{\text{Sun}} = 15’ \ 47.8” = 947.8” \]

Let \( L_{\text{slit}} \) = Length of slit in arcseconds

Simple geometry shows that the width of the arc of the limb across the slit is:

\[ \text{Arc width} = R_{\text{Sun}} - \left[ R_{\text{Sun}}^2 - \left( \frac{L_{\text{slit}}}{2} \right)^2 \right]^{1/2} \]

If \( L_{\text{slit}} = 93.0 \) arcsec then \( \text{arc width} = 1.14 \) arcsec

If \( L_{\text{slit}} = 46.6 \) arcsec then \( \text{arc width} = 0.29 \) arcsec

3.4 White Light on Array

An unfortunate incident occurred while attempting to focus the array. The filter wheel was instructed to move to the 4.196\( \mu \)m bandpass filter. The filter wheel position switch failed, causing the wheel to mistakenly move to an open position (no filtering at all). This allowed white light to be imaged onto the array. Visible light falling on a cold InSb array has the unfortunate effect of saturating that region of the array and leaving it blind. The resulting blind area is shown in Figure 3. The image is of the half covered, out of focus spectrograph alignment aperture and a starburst resolution target. The only way to revive the dead area is to allow the array to warm back up. This would have meant losing at least two observing days. Since the burned-in aperture image only affected the right side of the array, the CO lines were carefully placed to the left of the blinded region for the observations (Figure 3).

3.5 The Clouds Parted

The weather on August 7 was a bit more promising with large breaks in the cloud cover. The dewar was topped with liquid nitrogen and the vacuum pump attached to the inner nitrogen flask at around 6am MST (13:00 UT). It takes about an hour to cool the array from liquid to solid nitrogen temperature.

The clouds parted at around 7am (14:00 UT), long enough to finish alignment of the IR array to the spectrograph slit and take a scale image with the Image Stabilizer so that its image scale could be determined. A transparent millimeter rule was placed at the focus of the Image Stabilizer and a frame from its CCD was stored.
Figure 3. Burned-in image of spectrograph alignment aperture on InSb array. The deep CO spectral lines (left) are positioned to avoid blinded region (right).

The spatial image scale along the spectrograph slit was also measured later in the day. Calibrated width obscurations were imaged by placing a scale in the telescope focal plane along the slit and collecting a spectral frame. The scale is a metal plate whose edge is cut into a square wave-like pattern of 5mm on a side, producing 5mm wide slots every centimeter.

The interest of this study was to concentrate on the CO distribution in the “quiet Sun” which is representative of most of the disk. The observing plan was to take most of the limb scans across the pole regions. This should avoid magnetic activity regions that might be present along the east or west limbs.

The spectrograph was rotated to align the slit with the telescope east-west axis in preparation for scanning the slit across the solar north and south poles. This was determined by running the limb of the Sun in hour angle and rotating the spectrograph until the solar limb remained tangential along the extended slit line. The solar P-angle for the day was found in the Astronomical Almanac (Nautical Almanac Office 2000) to be $+13.3^\circ$. The spectrograph was rotated counter-clockwise by $13.3^\circ$ to offset the slit orientation from the telescope east-west axis, to solar coordinates. The rotation distance was determined from the spectrograph’s rotation encoder display. The spectrograph rotation clock drive was then switched on to maintain the slit orientation as the telescope’s image rotated through the day.

The solar image was moved until the south polar limb was as parallel as possible to the slit as viewed on the Image Stabilizer camera. The image was then moved to place the slit just inside of the limb, the integration time was set to 300 ms and the Image Stabilizer servo loop was engaged. The first observing sequence was then started. A total of 35 slit positions were recorded across the limb. Ten spectral frames were taken at each slit position. The Image Stabilizer’s limb window was then stepped in software by one pixel,
moving the slit to its next limb position, before the next set of frames was taken. This created a scan of 35 slit positions, each of 10 frames, across the solar limb.

Following the observing sequence a set 10 of dark frames were taken. For darks, all the observing conditions are left the same as for the observing sequence with the exception that the input slit shutter is closed.

A sequence of flat-fields was collected next. Flat-fielding of solar data tends to be a bit more involved than for stellar astronomy. No artificial black body source has been found that does a good job of reproducing the extremely bright solar IR continuum. Several techniques have been developed for flat-fielding solar data. Most use the Sun, either directly or indirectly, as the flat-fielding source. The flat-fielding technique used here has come to be known as spatial-spectral flats. The diffraction grating is rocked back and forth under computer control through a relatively clean region of the solar spectrum while the solar image is randomly moved over the spectrograph input slit. Many frames are recorded and combined to average out both spectral and spatial features producing a clean flat-field image. One hundred spectral frames were taken. During the data collection the grating was rocked between 2142.2 cm\(^{-1}\) (4.668\(\mu\)m) and 2144.5 cm\(^{-1}\) (4.663\(\mu\)m) and the solar image was moved about, carefully avoiding Sunspot regions. The speed of the grating was set at 20% of maximum. This was felt to be a reasonable compromise between speed to blur spectral features and how often the grating stopped to reverse direction at the ends of the wavelength scan.

Two more sequences of observations, darks, and flats were collected that day before the observing conditions deteriorated. The second sequence was taken across the solar north pole. The third was taken above a sunspot (AR0057) conveniently located just inside of the west limb. The spectrograph was rotated 90° to align the slit with the west limb.

Three additional limb scans were collected the following day, 08 August 2002. The procedure used was very similar to the previous day’s. Two scans were taken across the Sun’s south pole and one across the north pole. The seeing then became too poor to continue this program. The rest of that day and the next the telescope was used to service other observing programs that were less dependent on good seeing conditions. A total of 6 limb scans were collected for this program (Table 1).

<table>
<thead>
<tr>
<th>Date</th>
<th>Scan</th>
<th>Time</th>
<th>Position</th>
<th>Steps</th>
<th>Frames/step</th>
<th>Darks</th>
<th>Flats</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 Aug 01</td>
<td>16:00 UT</td>
<td>South Limb</td>
<td>35</td>
<td>10</td>
<td>10</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>7 Aug 02</td>
<td>17:03 UT</td>
<td>North Limb</td>
<td>30</td>
<td>10</td>
<td>30</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>7 Aug 03</td>
<td>17:49 UT</td>
<td>West Limb</td>
<td>40</td>
<td>10</td>
<td>30</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>8 Aug 01</td>
<td>14:43 UT</td>
<td>South Limb</td>
<td>35</td>
<td>10</td>
<td>--</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>8 Aug 02</td>
<td>15:03 UT</td>
<td>South Limb</td>
<td>35</td>
<td>10</td>
<td>20</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>8 Aug 03</td>
<td>16:16 UT</td>
<td>North Limb</td>
<td>35</td>
<td>10</td>
<td>--</td>
<td>---</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Summary of the limb scans obtained.
4. ANALYSIS AND DISCUSSION

4.1 Effective Telescope Aperture

The McMP is listed as a 1.5-m telescope. This is due to the 1.5-m diameter of the #2 imaging mirror. It wasn’t appreciated until well into the data reduction that this view of the telescope aperture is overly simplistic. The effective aperture of the telescope changes depending on the observed declination and orientation. The projected north-south heliostat image will under fill the telescope’s imaging mirror when observing at high declination angles.

The McMP telescope is oriented such that the imaging mirror looks up an inclined optical tunnel pointing toward the north celestial pole. The heliostat is mounted at the top of the optical tunnel and tips back to reflect the solar beam down the tunnel. To look at the celestial equator, \( \delta = 0^\circ \), the heliostat would tip back by \( 45^\circ \). The heliostat angle with respect to the optical tunnel is \( \frac{1}{2} \) the declination (\( \delta \)) angle plus the \( 45^\circ \) to the celestial equator.

\[
\text{Heliostat Angle} = \frac{90^\circ + \delta}{2}
\]

The projected diameter of the heliostat in the north-south axis is thus not the mirror’s 2-m diameter but the diameter multiplied by the cosine of the heliostat angle (Figure 4).

\[
\text{Heliostat Projected Height} = 2 \cos \left( \frac{90^\circ + \delta}{2} \right)
\]

An equation was derived that describes the effective telescope aperture when observing at any declination and angle (\( \alpha \)) in degrees from terrestrial north coordinates.

\[
A_{\text{eff}} = 2 \left[ \cos \left( \frac{90^\circ + \delta}{2} \right) \left( 1 - \tan^2 \alpha \right) + \tan^2 \alpha \right]^{1/2}
\]

This equation is only valid when the heliostat beam under fills the imaging mirror and the calculated effective aperture is less than 1.5-m. This will occur whenever the heliostat is pointed to a declination angle north of \( -7.2^\circ \). The Sun’s declination is greater than \( -7.2^\circ \) between 02 March and 12 October (Nautical Almanac Office 2000). This effect should be taken into account whenever observing at the McMP between these dates. Observing at the poles, as was the case in this study, \( \alpha \approx 0 \) and the equation for the effective aperture simplifies to the projected height of the heliostat.

\[
A_{\text{eff}} = 2 \cos \left( \frac{90^\circ + \delta}{2} \right)
\]
The declination of the Sun was around $+16.25^\circ$ during the observations.

From the 2002 Astronomical Almanac (Nautical Almanac Office 2000):

- 07 Aug 02  $\delta = 16^\circ 31' 49.9'' = 16.53053^\circ$
- 08 Aug 02  $\delta = 16^\circ 15' 01.4'' = 16.25039^\circ$
- 08 Aug 02  $\delta = 15^\circ 57' 57.2'' = 15.96489^\circ$

$$\delta_{\text{Average}} = 16.24894^\circ \equiv 16.25^\circ$$

A declination of $+16.25^\circ$ results in an effective north-south aperture of just 1.2 meters.

$$A_{\text{eff}} = 2\cos\left(\frac{90 + 16.25}{2}\right) = 1.2 \text{ meters}$$

Calculating the diffraction limit of the telescope ($\Theta_{\text{min}}$) naively using the Rayleigh criterion for a 1.2-m circular aperture would indicate that the telescope resolution in the north-south axis was degraded to about 1 arcsecond. Using this same rationale, the east-west telescope aperture would remain 1.5-m with a resolution of 0.78 arcseconds.

$$\Theta_{\text{min}} = 1.22\left(\frac{\lambda}{D}\right) = 1.22\left(\frac{4.67 \times 10^{-6}}{1.2}\right) = 4.75 \times 10^{-5} \text{ Rad} = 0.98 \text{ arcsec}$$

However, the telescope aperture is not circular when the imaging mirror is under filled. The actual pupil shape becomes a 2-m major axis ellipse from the projection of the heliostat, which is truncated by the 1.5-m circular imaging mirror. The truncated ellipse begins to resemble a rectangular aperture at high declinations. The resolving limit for a rectangular aperture is the same as for the circular case but without the 1.22 multiplication factor. Assuming a rectangular pupil would result in a resolving limit of
0.80 arcseconds, about the same as the full 1.5-m circular aperture. The true diffraction limit must lie between these two values.

Calculating the diffraction pattern of this unusual aperture shape is non-trivial. Instead, it was determined by modeling the telescope using the optical modeling software ASAP from Breault Research Organization, Inc. ASAP was used to model the point spread function (PSF) for the telescope (Figure 5) at several different projected heliostat heights between the fully illuminated 1.5-m aperture, and the most extreme case of a projected heliostat height of 1.1-m that occurs at the highest solar declination of +23°. The Rayleigh criterion was determined by measuring the distance between the central peak and the first null point of the PSF (Table 2). A polynomial was found that fit the data.

\[ \Theta_{\text{min}} = 0.264(\text{Heliostat}_{\text{Minor Axis}})^2 - 1.23(\text{Heliostat}_{\text{Minor Axis}}) + 2.03 \]

<table>
<thead>
<tr>
<th>Projected Heliostat Height (Meters)</th>
<th>Rectangular Resolving Limit (Arcseconds)</th>
<th>McMP Resolving Limit (Arcseconds)</th>
<th>Circular Resolving Limit (Arcseconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>0.64</td>
<td>0.78</td>
<td>0.78</td>
</tr>
<tr>
<td>1.4</td>
<td>0.69</td>
<td>0.83</td>
<td>0.84</td>
</tr>
<tr>
<td>1.3</td>
<td>0.74</td>
<td>0.88</td>
<td>0.90</td>
</tr>
<tr>
<td>1.2</td>
<td>0.80</td>
<td>0.93</td>
<td>0.98</td>
</tr>
<tr>
<td>1.1</td>
<td>0.88</td>
<td>1.00</td>
<td>1.07</td>
</tr>
</tbody>
</table>

Table 2. Comparison of resolutions for a rectangular, circular and the McMP aperture.

ASAP shows that the telescope resolution actually improves somewhat in the east-west axis at high declinations. The foreshortened heliostat image causes the telescope pupil to appear more rectangular than circular (Figure 5). As the circular imaging mirror is progressively shadowed, the resolution drifts away from the circular resolving limit and toward the rectangular limit. Future programs that require maximum resolution should scan near the east-west axis to take advantage of this effect and to avoid the deteriorated resolution that occurs in the north-south axis.

Figure 5. Airy pattern formed by filled (right) and under filled (left) imaging mirror.
This is not the first time this effect has been overlooked. A review of recent journal articles of 4.67\(\mu \text{m}\) CO observations at the McMP did not reveal any mention of the degradation of the diffraction limit due to under filling the 1.5-meter imaging mirror. While reporting on observations taken on 05 October 1993, Uitenbroek et al. (1994) stated the diffraction limit of the telescope to be 0.77 arcseconds. The declination of the Sun on that date was around –4.88°. This would cause the effective aperture to actually be 1.47-m in the north-south axis, leading to a diffraction limit of 0.79 arcseconds. Ayres and Rabin (1996) stated the McMP diffraction limit to be 0.8 arcseconds for their observations of 22 – 24 March 1994. The solar declination passed through +1.5° during this run, degrading the effective aperture to 1.39-m and the diffraction limit to 0.83 arcseconds.

Admittedly these are trivial differences, however, Uitenbroek (2000) then quoted the telescope’s diffraction limit again as 0.8 arcseconds when reporting on observations taken on 06 May 1994. On that date, the Sun was at +16.6° causing the projected image of the heliostat onto the 1.5-m imaging mirror to be only 1.2-m in the north-south axis. The diffraction limit in that direction would have been 0.93 arcseconds. Ayres et al. (2002) appear to have propagated this same error when they also state the telescope’s diffraction limit to be 0.8 arcseconds for their observations of 13 – 17 April 2002. The solar declination during these dates was around +10.5°, degrading the diffraction limit to 0.89 arcseconds.

4.2 Image Scales

The image files from the prototype Image Stabilizer are not yet stored in any standard image format. They are simply raw data files made up of 32-bit integers. A short specialized program was written by the author to display and analyze these files. The program can export the cursor row and column to ASCII files for analysis. Figure 6 shows a screen shot of the program displaying the millimeter rule image and Figure 7 displays the plot of the vertical intensity cut across the CCD (the crosshair position).

The plot across the millimeter rule was used to calculate the image scale of the Image Stabilizer. The linear distance between pixels 17 and 239 was found to be 14 mm, giving 15.587 pixels/mm.

\[
\frac{(239 - 17 \text{ pixels})}{14 \text{ mm}} = 15.587 \text{ pixels/mm}
\]

The telescope image scale is known to be 2.37 arcsec/mm, producing an image scale on the Image Stabilizer of 6.69 pixels/arcsecond or 0.149 arcseconds/pixel. The image scale is important since the Image Stabilizer is used to shift the solar limb one pixel per step through a scan sequence. This then becomes the image scale perpendicular to the slit.

\[
\text{Image Scale} = \frac{(15.587 \text{ pix/mm})/(2.37 \text{ arcsec/mm})}{2.37 \text{ arcsec/mm}} = 6.69 \text{ pixels/arcsec}
\]

\[
= 6.69 \text{ steps/arcsec} \quad \text{(in the axis perpendicular to the slit)}.
\]
Figure 6. Image Stabilizer file display and analysis program.

Figure 7. Plot of the millimeter rule imaged by the Image Stabilizer.
A cut across the spatial axis of the 5mm slot scale image (Figure 8) placed across the slit was used to measure the spatial image scale along the slit.

The 50% intensity points of the 5mm slot intensity plot were interpolated. The distance between the descending plot lines is 130.96 pixels and 129.336 between the ascending. These distances average out to 130.141 pixels per 10 mm or 13.014 pixels/mm. Dividing this value by the telescope image scale of 2.37 arcseconds/mm results in the spatial image scale along the slit of 5.49 pixels/arcsecond.

<table>
<thead>
<tr>
<th>Pixel Values:</th>
<th>Descending</th>
<th>Ascending</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.147</td>
<td>87.938</td>
<td></td>
</tr>
<tr>
<td>150.93</td>
<td>217.274</td>
<td></td>
</tr>
<tr>
<td>Difference:</td>
<td>130.96</td>
<td>129.336</td>
</tr>
</tbody>
</table>

Ave (10 mm): 130.141 pixels
Ave per pixel: 13.014 pixels/mm  (Telescope image scale: 2.37 arcsec/mm)
Image Scale = 13.014/2.37 = 5.49 pixels/arcsecond  (in the axis parallel to the slit).

Figure 8. The 5mm slot scale across slit (left) and a vertical cut across frame (right).

4.3 Processing (dark & flat fielding)

Dark and flat field frames were taken for each of the 3 limb scans on the first run day, 7 August 2002. Only one set of darks and flats were collected on the second day, 8 August 2002, to save time since the seeing conditions appeared to be deteriorating. Darks and flats do not require good seeing.

The number of dark frames taken in each sequence is documented in Table 1. The darks from within each sequence were averaged to produce a single representative dark frame. Likewise, the flat field frames from each sequence were averaged to produce flat field frames of high signal-to-noise, free from spectral and spatial features to be used in the
data processing. The spectral frames are processed in a similar fashion to standard CCD images. Dark current frames are subtracted from both the raw data and flat field. The resulting flat is then divided from the dark-subtracted spectral image.

\[
\text{Spectral Frame}_{\text{Processed}} = \frac{\text{Spectral Frame}_{\text{raw}} - \text{Dark}_{\text{ave}}}{\text{Flat}_{\text{ave}} - \text{Dark}_{\text{ave}}}
\]

The software used for the dark and flat field processing was written by Marcel Bergman specifically to reduce data from the McMP IRIS and to process them into spectroheliograms. This code automates much of what would otherwise be the rather tedious process of dark subtractions and flat divides.

4.4 Frame selection

Once all of the spectral frames were processed, the true tedium of frame selection was undertaken. The best seeing frame from each position sequence was selected based on its average continuum value. It was assumed that the actual limb is sharper than the scan resolution. The frames that would produce the steepest limb profile in a spectroheliogram were presumed to represent the best seeing. Therefore, at step locations inside of the solar limb, the frames with the highest average continuum intensity must be the best seeing frames. Likewise, outside of the limb, the frames with the lowest average intensity levels are chosen as having the best seeing.

The point where the limb crossing occurred needed to be determined for each limb scan. This was found by creating spectroheliograms of the IR spectral continuum region between the CO lines and plotting the intensity roll-off across the limb at the center of the slit. A portion of the spectrum free from spectral lines needed to be found that could be used as the IR continuum. All 10 frames taken at each step position in the sequences were averaged together to create average step frames. Several spectral intensity plots were examined from each sequence to determine where the cleanest continuum resides. There are a total of 14 CO lines that have been identified within the spectral frame. For simplicity only the three strongest are being considered in this study – the 2-1 R 6 line at 4.66752 µm, 3-2 R 14 at 4.66698 µm and 4-3 R 23 at 4.66647 µm. The best continuum was found to be the 11 pixel wide region between the 2-1 R6 and 3-2 R14 CO lines (Figure 9). The deep line on the left side of the spectra is a terrestrial water line. The water line is unusually deep since the observations were taken during the humid summer monsoon season.

<table>
<thead>
<tr>
<th>CO Line</th>
<th>Wavenumber (cm(^{-1}))</th>
<th>Wavelength (µm)</th>
<th>Wavelength (nm)</th>
<th>Pixel</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1 R 6</td>
<td>2142.467</td>
<td>4.6675165</td>
<td>4667.5165</td>
<td>72.7</td>
</tr>
<tr>
<td>3-2 R 14</td>
<td>2142.714</td>
<td>4.6669784</td>
<td>4666.9784</td>
<td>100.6</td>
</tr>
<tr>
<td>4-3 R 23</td>
<td>2142.946</td>
<td>4.6664732</td>
<td>4666.4732</td>
<td>126.5</td>
</tr>
</tbody>
</table>

Table 3. CO line center wavelengths
The spectral width and dispersion of the frames were determined by comparing the wavelengths of the center of the three lines to their wavenumbers (Table 3) from the online version of “An Atlas of the Solar Spectrum in the Infrared from 1850 to 9000 cm\(^{-1}\) (1.1 to 5.4 \(\mu\)m)” (Livingston & Wallace 1990). The spectral frames were found to be 2.246 cm\(^{-1}\) (4.892 x 10\(^{-3}\) \(\mu\)m) wide with a dispersion of 8.944 x 10\(^{-3}\) cm\(^{-1}\)/pixel (1.947 x 10\(^{-2}\) nm/pixel).

Figure 9. CO Spectrum showing spectral lines and continuum region.

<table>
<thead>
<tr>
<th>Date</th>
<th>Scan # Position</th>
<th>Continuum Column #’s</th>
<th>Limb Crossing (50% Point) Between Pixels:</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-Aug-02</td>
<td>Scan01 South Limb</td>
<td>81 – 91</td>
<td>11 - 12</td>
</tr>
<tr>
<td></td>
<td>Scan02 North Limb</td>
<td>81 – 91</td>
<td>16 - 15</td>
</tr>
<tr>
<td></td>
<td>Scan03 West Limb</td>
<td>80 – 90</td>
<td>24 - 25</td>
</tr>
<tr>
<td>8-Aug-02</td>
<td>Scan01 South Limb</td>
<td>83 – 93</td>
<td>17 - 18</td>
</tr>
<tr>
<td></td>
<td>Scan02 South Limb</td>
<td>83 – 93</td>
<td>14 - 15</td>
</tr>
<tr>
<td></td>
<td>Scan03 North Limb</td>
<td>85 – 95</td>
<td>15 – 14</td>
</tr>
</tbody>
</table>

Table 4. “Clean” continuum columns and limb crossing positions.
Dr. Bergman’s program was used to produce spectroheliograms of each of the 11 columns from each limb scan. The 11 spectroheliograms were then averaged to generate an image of the average IR continuum limb. The intensity across the center of the limb image (the average of rows 120 – 129) was plotted and fit to a 6th order polynomial to reveal the limb intensity profile (Figure 10). The 50% point of each curve was taken to represent the actual limb crossing for that scan. The results are summarized in Table 4.

Figure 10. Averaged IR limb profile, 07 Aug 2002 scan 08, fit to 6th order polynomial.

The next step in the frame selection process was to determine the average continuum intensity for every spectral frame recorded. This was done in a somewhat roundabout fashion since the Bergman code can average in 1-dimension only. The program expects a series of 2-d spectra taken in sequential positions. This 3-dimensional data cube (spatial axis by spectral axis by position) is transformed into a sequence of 2-dimensional spatial (spatial along slit by position) images stacked by wavelength.

Figure 11. A portion of the frame selection spreadsheet for 07 Aug 02, Scan 01.
In the case of 10 spectral frames taken at each scan step, the 3-dimensions are spatial (along the slit) by spectral by time (at the same position). The spectroheliogram processing, in this situation, produces spatial-time grams stacked by wavelength. The 11 spatial-time grams corresponding to the continuum wavelength range are averaged to produce a single spatial-time gram. The Bergman code is then used to average - collapse the spatial axis - leaving a single dimensional graph showing the average intensity of continuum area (spectral and spatial) for each of the 10 frames. The continuum values were exported to a spreadsheet where the best seeing frame from each scan step was determined (Figure 11). The selected frames were assembled to produce new scan sequences for further processing.

Comparing the limb profile plots of the averaged spectroheliograms to grams from the frame-selected frames show only a modest improvement in seeing – evidenced by the increased slope of the best fit curve. This indicates that the Image Stabilizer is doing a good job of holding the limb motionless during the 10 frames taken at each step.

Figure 12. Limb profiles every 20 rows, fit to 6th order polynomial, 08 Aug 2002, scan 2

To check the consistency of the polynomial fit across the limb image, intensity plots were generated from every 20 rows along the slit and plotted together (Figure 12). All of the fitted limb profile plots have very similar slopes. This shows that the fitted curve can be relied upon as a repeatable method for accurately determining the limb crossing point. The position of each limb-crossing curve in Figure 12 consistently shifts to the left with
increasing row number. This position shift of each consecutive curve is caused by the spectrograph slit not being perfectly aligned with the solar limb. The arc of the limb can also be seen in the changing separation. The first curves from the top of the slit are bunched together on the right. The separation then increases with increasing row number towards the bottom of the slit. The consistency of the position of the limb crossing curves indicates that the limb crossing point measurements appear to be reliable down to a resolution of well below 0.1 arcsecond.

4.5 A Model Of The Solar Limb

A model of the solar limb was constructed to compare with the spatial resolution of the IR continuum achieved in the solar limb scans. The limb model began by representing the actual solar limb with a sharp (zero width) edge. Each point along the sharp limb was then spread over a Gaussian curve whose FWHM points were set equal to the calculated 0.93 arcsecond diffraction limit of the telescope. Each point was further blurred by averaging over a half arcsecond (±0.25 arcseconds) to account for the ½ arcsecond wide spectrograph slit. Lastly, each point was spread over another Gaussian arbitrarily set to 1 arcsecond meant to represent seeing. The IR continuum data points from the center of the slit of the frame-selected scans are plotted over the simple theoretical limb model (Figure 13). The intensity profiles across the limb created from spectroheliograms were made from the average of the 11 pixel wide continuum window. The limb profiles are the average of the 3 rows (rows 123 - 125) that cross the center of the slit. The data were normalized and the pixel values were converted to height in arcseconds by multiplying by the Image Stabilizer image scale of 6.69 arcseconds/pixel. The data were shifted so that their 50% point crossings overlap. The sign was changed on the height scale of the scans that began above the limb so that their slopes are in the same direction as the scans that started on the disk.

The plot shows that the model does a rather good job of reproducing the limb profiles from the real data. Variable seeing conditions are clearly evident by comparing the spread in how closely the data approach the diffraction limit curve. The 08 August 2002, Scan 01 plot, in particular follows the theoretical limit quite closely. The seeing was obviously quite good during that scan. The seeing appears to have deteriorated fairly quickly that day. Taken less than 2 hours later, Scan 03 shows a significantly shallower slope. Since the setup did not change between the scans, the difference can only be due to a change in seeing conditions.

The current setup using the McMP telescope and the Image Stabilizer at four and a half microns in the IR can apparently approach diffraction-limited resolution during times of excellent seeing. It is gratifying to see the system work this well. The completion of the full AO system for the McMP will not improve on the resolution during the best seeing conditions. AO will allow the diffraction limit to be reached during more varied seeing and will eliminate the requirement for frame selection. A newer generation, higher sensitivity IR imager would permit shorter integrations than the 300 ms exposures used for this project. This would be less affected by seeing fluctuations during the “shutter open” time, but again would approach the same resolving limit, just more often. To truly
freeze seeing under typical seeing conditions would require integrations around ¼ of the 300 ms used here (Keller et al. 2002). Only the development of a larger aperture IR solar telescope, which is likely a decade away, will significantly improve the ultimate resolution.

Figure 13. A model of the solar limb plus the frame-selected IR continuum data.

4.6 Slit Center Limb Profiles

Limb profile data from the three strong CO lines were prepared in the same manner as were the continuum limb profiles (see section 4.5 - A Model Of The Solar Limb) except that only 3 columns in the core of each line were averaged instead of the 11 pixel wide “clean continuum”. The continuum intensities were subtracted point-by-point from the CO line intensities and plotted.

The plots of the CO minus continuum data consistently show a sharp intensity rise with height above the solar limb followed by a slower decline. The plots, though quite noisy, suggest a somewhat saw-tooth like shape. It is assumed that the noise, which appears as large excursions in the intensity plots, are the result of seeing fluctuations and are not real features of the CO. Each plot shows a different peak intensity; this might be indicative of actual density variations in the CO at differing locations above the limb. This is consistent with Solanki et al. (1994) who reported that the cores of the CO lines stay at a constant intensity to about 0.4 arcseconds above the sharp continuum drop. Above ~0.4 arcseconds, they found the CO cores begin to drop off, but more slowly than the IR continuum. Figure 14 shows an example of the difference plot from the 08 August 2002 Scan 02 data.
The fast initial rise in the difference plots is to be expected due to the sharpness of the IR continuum limb. The slower roll-off of the CO above the limb says something about the density distribution with height of the CO. This also indicates that the vertical CO structure is at least partially resolved. Again, the plots suggest a saw-tooth like intensity plot with a very fast rise followed by a slower, somewhat linear-looking drop.

### 4.7 A Model of the CO Minus Continuum Limb Profile

Two models of the intensity variation when viewed tangentially to the limb and stepped progressively in height were produced for two different CO layers. One model assumes the CO layer maintains a constant density up to its maximum altitude. The other assumes that CO decreases in a linear fashion with height above the solar continuum. A simplified approach was taken by dividing the diminishing CO emission into 10 layers, each of a uniform density and thickness equal to the Image Stabilizer step size (~0.15 arcseconds). The two models were plotted together on the same scale (Figure 15). The two plots have distinctly different appearances. The uniform density plot (top, blue) begins dropping slowly near the continuum and turns more sharply downward near the top of the CO layer. The decreasing density model (bottom, red) falls more rapidly above the continuum before leveling out as the intensity approaches zero at the top of the CO layer. Varying the how much the density changes between steps changes the steepness of the intensity drop, but the overall appearance remains.
A third model was tried in which each step’s density was some fraction of the step below. This model has a similar look to the linearly decreasing density model in Figure 15. Its curve is a bit more extreme than the linear case, but would be difficult to differentiate without a very high signal-to-noise. It does seem clear, even with the high-noise plots here, that the constant density model does not resemble the CO limb profiles. This strongly suggests that the CO density does decline in some way with height above the solar continuum limb. Higher signal-to-noise would be required to be able to determine exactly how the density declines.

Table 5. Height above IR continuum of the CO lines’ 50% intensity point in arcseconds.

<table>
<thead>
<tr>
<th>Date</th>
<th>Scan</th>
<th>50% CO Line Height (arcsecs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-Aug-02</td>
<td>1</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.42</td>
</tr>
<tr>
<td>8-Aug-02</td>
<td>1</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.38</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>0.43 (312 km) 0.45 (326 km) 0.44 (319 km)</td>
</tr>
</tbody>
</table>
Measurements by Ayres & Rabin (1996) found the CO limb extensions vary between about 0.6 and 0.3 arcseconds depending on the line strength. Table 5 summarizes the height measurements for the three CO lines for each of the six limb scans and Figure 16 is a graphical representation of the measurement from 08 August 2002, Scan 02.

These measurements assume that both the continuum and CO layer have a sharp cut-off point. Since the CO minus continuum profiles show that the CO intensity falls more gradually than does the continuum, this technique would tend to under represent the CO height.

Figure 16. CO 50% intensity heights above the IR continuum.

4.9 2-D Imaging of the COmosphere

The prime motive of this study has been to develop techniques for producing high-resolution 2-d images of the CO emission layer. The NIM was not designed to allow scanning across the limb. Past studies using the NIM hardware (the IRIS) have been limited to producing spectroheliograms of the 4.67\(\mu\)m CO lines on the solar disk. Even if the original NIM hardware were modified to scan the limb, the results would be severely smeared by seeing motion during a long scan. The new Image Stabilizer overcomes this limitation by holding the limb stationary and translating the limb position on command so that very high spatial-resolution scans can be accomplished. The stabilizer only corrects for the motion across the limb. Seeing motion will still be present in the axis along the slit. The stabilizer cannot correct for blurring or distortions to the limb caused by seeing; these corrections are left for the future AO system.
The 3 CO lines are seen to behave essentially identically in the limb profiles (Figures 14 & 16). It was, therefore, felt that little would be lost by averaging the line centers together. Averaging the CO grams simplifies the project while increasing the signal-to-noise of the images. Continuum images are made from the same 11-pixel “clean continuum” window described above. CO line center images were produced from 3 columns at the core of each line. The averaged CO ‘grams show the CO distribution on the disk quite well. What is unclear in the CO images is where the lines transition from absorption into emission. To highlight the CO emission region, the CO image is scaled to the continuum intensity and the difference (CO – continuum) is displayed.

The spectroheliograms from all six scans are displayed in Figure 17. The images are arranged in a column for each scan, showing continuum, CO line center and their difference images. The images have been stretched in the horizontal axis, across the limb, to accentuate the detail within the thin COmosphere layer. Each image is 46.6 arcseconds in the axis parallel to the limb. All but scans 2 & 3 from 07 August 2002 are 5.23 arcseconds (35 Image Stabilizer steps) wide. The width of Scan 02 from 07 Aug. is 4.48 arcseconds (30 Stabilizer steps) and Scan 03 is 5.98 (40 steps).

The most prominent feature in the images are the vertical striations near the limb. These are apparently caused by seeing variations between spectral frames. The Image Stabilizer did its job of holding the averaged limb at the prescribed position for each frame. Distortion and blurring of the limb still occurs, resulting in the structures seen here. The effect clearly varies with seeing. Scans 03 from 07 August and 01 from 08 August show the least amount of striations indicating the best seeing. This is consistent with the graph of the IR continuum limb profiles (Figure 13) which also show that these scans were taken during good seeing conditions.

The arc of the solar disk and minor errors in alignment of the spectrograph slit to the limb are visible in the images. The width of the solar arc was calculated to be 0.29 arcseconds over the height of the frames. The image scale across the limb is 0.149 arcseconds/pixel making the limb arc ~2 pixels wide. It is a testament to the quality of the Image Stabilizer’s limb guiding ability that such small features are measurable.

The largest slit alignment error occurs in Scan 02 of 07 August. The difference in the limb crossing from the spectroheliogram top to bottom is about 6 pixels, or ~0.9 arcseconds. It is likely not a coincidence that the largest alignment error is associated with scans that appear to have been taken during poorer seeing conditions and is roughly equal to the magnitude of the seeing. The scans taken during good seeing have the best alignment. The slit was aligned to the limb image on the Image Stabilizer monitor “by eye”. Seeing may dictate the limit to this simple technique. If greater alignment precision is required, a more sophisticated technique may be required such as taking spectral frames and looking at the intensity variation along the slit. This would be a slow, tedious task with the current IR array system. A frame would need to be collected and stored before it could be called up and plotted using a separate software package like Dr. Bergman’s code.
Figure 17. Spectroheliograms of the IR continuums, CO line centers and their differences.
On-disk structures are seen in the CO line center images that are similar to those seen in previous studies (Ayres & Rabin 1996, Uitenbroek 2000). Unique to this study is the ability to show that structures exist and can be measured in the above limb emission. Non-uniformity in the COmosphere can be seen directly in the difference (CO minus continuum) spectroheliograms. The west limb image, 07August Scan 03, shows an extremely uniform CO layer. However, the south limb scans taken on 08 August (Scans 01 & 02) have several noticeable structures. A brightness enhancement extends through the CO layer in the upper quarter of Scan 01. At the center of Scan 02 is what looks to be a particularly dark void that seems to correspond with a dark lane on the disk that extends to the limb. This would seem to support the concept of a thermally-bifurcated atmosphere. The dark lane would correspond to a hot region that is above the dissociation temperature of CO. The ability to map the bifurcation areas could aid in differentiating between differing solar atmospheric models.

There are hints of several other smaller and/or fainter structures visible in the images. It is felt that these represent real variations in the CO emission and not artifacts of seeing since they extend over several scan steps. The vertical striations demonstrate that seeing-induced intensity variations don’t survive that long. The CO enhancement in the 08 August Scan 01 is roughly 20% above its surroundings (Figure 18) in intensity. It is roughly 2 arcseconds across (~1450 km) and extends vertically ~0.8 arcseconds (580 km). The void region on the 2nd scan of that day is ~1.8 arcseconds (1370 km) across.

The last scan, 08 August 2002 Scan 03, is significantly noisier than the others. Why this is so isn’t fully understood. It is possible that the dewars’ cryogens ran out and the InSb array began to warm. The array noise will increase as the temperature goes up.

![Chart Title](image)

Figure 18. Intensity variation across CO layer enhancement, 08 Aug. 2002 Scan 01.

The third scan of 07 August appears to have both the best seeing and least structure. These reasons make it the best choice for measuring the overall height of the CO
emission. The half power points of the rising and falling CO emission intensities were interpolated for every 10th pixel along the slit, 25 points total. The average height difference between the half power rise and fall points is 0.81 arcseconds (589 km) with a standard deviation of ±0.02 arcseconds (±13 km).

The averaged CO line center intensities were scaled to the IR continuum to maximize the contrast of CO structures. This technique should only be used for enhancing the contrast at the limb and not for determining the actual CO layer height as it will overestimate the thickness. By scaling the CO line center intensities to the continuum, the CO lines appear to go into emission as soon as the continuum intensity begins to drop. Subtracting the continuum from the raw CO data, as was done in section 4.8, “Measuring the CO Line Heights”, the CO will not be seen to transition into emission until the IR continuum drops below the CO line intensity.

Measuring the CO line height, the distance between the 50% rise and fall points, for Scan 03 of 07 August by subtracting the continuum data from unscaled (raw) CO data, results in a height of 0.69 arcseconds (498 km) with a standard deviation of ±0.04 arcseconds (±30 km). This is about 15% less than the height measured using data scaled to the continuum intensity.

Synthetic data were used to demonstrate the difference in apparent height between three methods of measuring the thickness of the CO layer (Figure 19). Synthetic data were created to reproduce the look of the IR limb profile (black plot). The synthetic CO intensity plot (red) is given a lower intensity (66%), a shallower slope, and is offset to the right compared to the IR continuum plot. The blue line represents the CO intensity curve scaled to the IR continuum. The dashed lines show the continuum intensity subtracted from the CO (dashed red) and the scaled CO (dashed blue) intensity plots. The black horizontal lines display the magnitude of the height estimated from the 50% intensity crossings of the three techniques. Notice that this model reproduces the characteristic fast rise followed by a slower decline in intensity seen in the non-scaled subtractions.

The model demonstrates that each of the three techniques for measuring CO emission heights give slightly different results. One can see from the graph how simply taking the difference between the continuum limb and the CO 50% intensity point under-represents the distance over which CO is in emission. Subtracting the continuum from the CO clearly overestimates the height. Taking the height difference between the rising and falling 50% points of the raw data with the continuum subtracted off appears to be the most realistic method for determining height.

The heights measured by averaging the difference between the unscaled (raw) CO line centers and continuum data at 25 locations (every 10 pixels) across the limb are summarized in Table 6. The final scan (08 August, Scan 03) was not included due to its high noise level. The standard deviations give an indication of how much seeing conditions distorted the limb during each scan. The future AO system should correct for distortions along the slit and decrease the standard deviation values.
The height estimates in Table 6 are roughly 0.1 arcsecond (73 km) above what has been reported in earlier studies. This is a somewhat frustrating result that isn’t fully understood. Perhaps the width of the slit is smearing the IR limb and CO profiles causing an overestimate of the CO layer thickness.

<table>
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<tr>
<th>Date</th>
<th>Scan</th>
<th>Steps</th>
<th>(Std. Dev)</th>
<th>Arcsec (Std Dev)</th>
<th>km</th>
<th>(Std Dev)</th>
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<td>4.03</td>
<td>±0.71</td>
<td>0.60 ±0.11</td>
<td>437</td>
<td>±77</td>
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<td>±2.01</td>
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<td>±218</td>
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<tr>
<td></td>
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<td>±0.27</td>
<td>0.69 ±0.04</td>
<td>498</td>
<td>±30</td>
</tr>
<tr>
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<td>01</td>
<td>4.67</td>
<td>±0.59</td>
<td>0.70 ±0.09</td>
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<td>±63</td>
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<tr>
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<td>±0.84</td>
<td>0.69 ±0.13</td>
<td>498</td>
<td>±91</td>
</tr>
</tbody>
</table>

Table 6. CO height measured between 50% points of unscaled CO – continuum data.

5. CONCLUSION

5.1 Image Stabilizer Offers Improved Technology

The 4.67µm fundamental rotation-vibration CO lines represent a unique probe into the anomalously cool region of the solar atmosphere above the photosphere. The depth of the strongest CO lines have been recognized as indicating a brightness temperature well below that of the traditionally accepted temperature minimum of ~4500K. Since the
discovery of the CO lines in the solar IR spectrum, the details of this atmospheric region have been elusive and driven by technological advances. Center-to-limb variability studies were done in the early 1970’s using the McMP horizontal spectrograph which led to the realization that the CO line depth indicated a brightness temperature of ~3500K in the region just above the photosphere (Noyes & Hall 1972). The discovery that the 4.67\(\mu\)m CO lines go into emission above the limb of the Sun had to wait for the upgrading of the McMP main spectrograph in the early 1990’s (Solanki et al. 1994). The 256\(^2\) IR array camera and the completion of the NIM allowed astronomers to explore the CO’s 2-dimensional distribution on the solar disk. This study continues the technological advancement in the study of the 4.67\(\mu\)m fundamental rotation-vibration CO lines by incorporating the recently completed Image Stabilizer into the NIM system to allow 2-d spectroheliograms of the CO emission above the limb to be collected with spatial resolutions approaching the telescope diffraction limit.

5.2 Results

The emission height of the strong fundamental rotation-vibration CO at 4.67\(\mu\)m were measured to be roughly around 0.7 arcseconds or ~500 km. This is a bit larger than has been found by other researchers by about 0.1 arcsecond. This discrepancy isn’t fully understood but may be a result of spatial smearing across the ~0.5 arcsecond wide slit or due to the measurement techniques used. The techniques used by others in determining the height should be carefully examined to ensure their compatibility with the technique used here. In this study, the height was determined as the distance between the half power points of the CO line center emission. The IR continuum was subtracted from the CO intensity so that only the CO emission remained.

The cross-limb profile of the CO emission (continuum subtracted) intensities shows a sharp rise followed by a more gradual decline. Simulations show that this saw-tooth like profile suggests that the COmosphere density is not uniform but declines with altitude. The simulation shows that a uniform density CO layer would have a rather different looking profile, starting off relatively level and turning more sharply downward near the top of the layer.

Two-dimensional images of the CO emission layer were produced. Spectroheliograms of the on-disk CO line center intensities were scaled to the on-disk continuum. The continuum grams were subtracted from the CO line center images resulting in spectroheliograms that accentuate the emission region and displays any intensity variation in the cool CO layer.

The CO images were successful in clearly demonstrating that structures can be mapped in the above limb emission. Both intensity enhancements and “voids” were found. At least one “void” appeared to be associated with a dark lane in the CO that started on the disk and extended to the limb. The non-uniformities in the above limb CO emission are consistent with the thermally bifurcated models of the upper solar atmosphere. The ability to map the scale and intensity variation in the CO emission structures may be useful in distinguishing between the various proposed models. It is hoped that this
technique for imaging the COmosphere will continue to be developed and will be found to be an important tool for mapping the density distribution of CO above the solar limb.

5.3 Lessons Learned

Mistakes were made and lessons were learned as a result of this study. A hardware problem with a filter wheel’s position switch led to the InSb array being flooded with visible light, causing a section of the array to be unusable during the observations. The geometry of the heliostat optical system creates a non-circular telescope pupil when observing at declination angles above $-7.2^\circ$. The projected height of the heliostat under filled the imaging mirror producing an effective aperture of only 1.2-m in the north-south axis. The telescope diffraction limit was likewise degraded to 0.93 arcseconds in the north-south axis. This fact was not realized until well after the observations were taken and as a result, all but one of the limb scan observations were taken in the north-south direction. Future observations should avoid these pitfalls.

5.4 Future Improvements

It is hoped that this project represents another step in the continuing process of probing the cool atmospheric layer above the solar photosphere. As a result of this project, it has been realized that there are several obvious and some not so obvious improvements to both the hardware and techniques used that can be made to better image the 4.67\(\mu\)m CO emission.

The spectrograph slit was simply aligned “by eye” using the Image Stabilizer display. An accurate alignment could be assured by taking test ‘grams. Plotting the intensity variation along the slit axis, parallel to the limb, quickly shows any misalignment as a slope across the plot. Similarly, a quantitative test for best telescope focus could be performed by placing the slit across the limb. Measuring the width of the cross-limb profile plot would give a direct indication of focus quality. The best focus could be found by moving the focus in small increments and measuring the limb profile until the steepest profile is found.

Observers should be aware of how under filling the telescope imaging mirror can degrade the effective diffraction limit. When the Sun’s declination is above $-7.2^\circ$, programs that require maximum resolution should limit their scans to the east-west axis.

A new InSb array should become available at the McMP in the first half of 2003. The new array will be a lower noise 1024\(^2\) pixel array with faster readout electronics. This will be a major upgrade to the facility. The new low noise array will be able to take much longer integrations before becoming saturated by its own thermal emission. This will allow a narrower slit to be used while still achieving an adequate signal-to-noise. The use of a narrower slit may be the solution to why the CO height appears to be overestimated by $\sim$0.1 arcsecond in this study.
The McMP AO system is another major facility upgrade that is expected in 2003. AO should eliminate the need for the time-consuming process of frame selection. Under most seeing conditions, the AO should deliver stable diffraction-limited IR images to the spectrograph. Highest quality spectroheliograms, free from the striations and other distorting effects of seeing evident in this project, should be able to be produced in single scans. It is also expected that the AO system will be able to interface to the new InSb array to automate the scanning process that is currently done manually.

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