Scattered Light in a DMD based Multi-Object Spectrometer

Kenneth D. Fourspring, Zoran Ninkov, John P. Kerekes,

Chester F. Carlson Center for Imaging Science; Rochester Institute of Technology
Rochester Institute of Technology, 54 Lomb Memorial Drive, Rochester, NY, United States;

ABSTRACT

The DMD (Digital Micromirror Device) has an important future in both ground and space based multi-object spectrometers. A series of laboratory measurements have been performed to determine the scattered light properties of a DMD. The DMD under test had a 17 μm pitch and 1 μm gap between adjacent mirrors. Prior characterization of this device has focused on its use in DLP (TI Digital Light Processing) projector applications in which a whole pixel is illuminated by a uniform collimated source. The purpose of performing these measurements is to determine the limiting signal to noise ratio when utilizing the DMD as a slit mask in a spectrometer. The DMD pixel was determined to scatter more around the pixel edge and central via, indicating the importance of matching the telescope point spread function to the DMD. Also, the generation of DMD tested here was determined to have a significant mirror curvature. A maximum contrast ratio was determined at several wavelengths. Further measurements are underway on a newer generation DMD device, which has a smaller mirror pitch and likely different scatter characteristics. A previously constructed instrument, RITMOS (RIT Multi-Object Spectrometer) will be used to validate these scatter models and signal to noise ratio predications through imaging a star field.

Keywords: Digital Micromirror Device, Multi-object Spectrometer, Scattered Light

1. INTRODUCTION

Astronomers are interested in collecting full spectral information at many spatial locations within the telescope field of view. To this end, two general instrument approaches have been developed. The first involves machining a specific slit mask for the field of interest that is placed at the focal plane of the system and only light at specific locations pass through to the spectrometer. Each mask is unique both to the field to be observed and to the telescope at which it is to be used. This method is employed in the GMOS instrument. The second approach involves locating fiber inputs at locations on the focal plane corresponding to targets of interest in the field of view. The output ends of these fibers are aligned along an input slit to a spectrometer. Disadvantages of this approach include difficulty in the initial alignment, time to place fibers for each change of field, coupling efficiency and centroiding of the target within the fiber. Prior measurements to assess the utility of Texas Instruments Digital Micromirror Device (DMD) for use as a slit mask in astronomy were encouraging. This led to the development of the RIT multi-object spectrometer (RITMOS). RITMOS utilized an 848x600 array of 17 μm mirrors to collect many spectra simultaneously. This particular DMD tilted ± 10° and had 1 μm gaps between adjacent mirror edges. The current configuration of RITMOS was designed to be mounted at the primary focal plane of the University of Rochester’s 24” f/13.8 Mees Telescope. Light from the telescope first encounters a set of relay optics (operating at f/8.85). These optics were designed to match the telescope plate scale to the minimum slit size, a 2x2 array of mirrors. The DMD is illuminated at normal incidence at a secondary focal plane rather than by a collimated beam 20° off axis as in a projector. To select targets, all of the mirrors are turned towards the imaging side of the instrument. An Offner relay re-images the DMD onto a cooled CCD. The image from this CCD is used to select target stars. Next the corresponding mirrors are turned towards the spectral channel. In the spectral channel, the light passes through a 3 element collimator (operating at f/7.62). Then, a 1200 l/mm transmission grating that disperses the light and it is re-imaged it using an f/3.35 optic onto a second CCD that records the spectra. The spectral side throughput is approximately 11%. Only one target can be selected per row on the CCD so as to avoid overlapping spectra. RITMOS was designed to operate from 3900-4900 Å and has a spectral resolution of 0.703Å for a two mirror wide slit. Figure 1 shows a drawing of the RITMOS’s optical path. The limiting factor for SNR in any spectrometer is stray light, and for RITMOS a good understanding of scattered light from a DMD is not available.
2. EXPERIMENT

An experimental apparatus was designed to project a sub-pixel spot on to a single DMD micromirror. The DMD was mounted on a high precision translational stage so the spot could be position at multiple positions on the DMD mirror. An optically stabilized tungsten filament light source was collimated and a pin hole was used to spatially filter this light. A filter wheel was placed in front of the source so the spectral effects could be investigated. The pin hole was then reimaged onto the DMD array by a diffraction limited lens operating at f/7 to mimic the illumination conditions in RITMOS. The light was then captured by two separate cameras. One camera system was used to collect the scattered light with a macro lens. The second camera utilized a long working distance microscope objective to image the spot at 22x magnification. This optical setup enabled the extraction of stray light information.

2.1 Experimental Order

The lamp was allowed to stabilize for a period of several hours prior to collecting data. To determine which DMD mirror was illuminated, a sequence of row and column patterns were sent to the mirrors. Then the four DMD slit patterns were generated (see the top portion of figure 3 to for an illustration of the mirror patterns. The stage moved to the lower right corner of the array region to be tested. An initial fast scan was performed using the open filter and mirror pattern four to verify that the correct sub array was scanned. A dark image with the CCD shutter closed was then taken at the start of the experiment. Sixty-four dark images were co-added to generate a master dark offset frame. The spot was then raster scanned across the DMD. At each spot location, the mirrors were stepped through 4 different mask patterns and then the filter wheel was moved to each of the 5 filter positions. Twenty measurements (5 filters and 4 mirror patterns) were therefore taken at each position during the micromirror scan. The Bessel filter set was chosen because it is widely utilized for astronomical photometry measurements. An open (designated N in all of the Figures and plots), B, V, R, and I filters were used. The scans sampled 25x25 spatial locations with 2 μm steps increments for a total scan area of 50x50 μm. After the scan was completed, a second set of dark images were taken and a quick post scan was done to verify that the stage and camera were operating correctly.

2.2 Scatter collecting Camera

To accurately characterize the scatter, a high dynamic range camera and macro lens was used. A cooled Photometrics CE-350 CCD camera was chosen to collect the scattered light. This scatter-collecting camera utilized a back-thinned SITE SI502AB backside illuminated CCD. The CCD had an RMS read noise of approximately 8 electrons and a full well capacity of 300,000 electrons. The macro lens used was a Micro-Nikkor 60 mm f/2.8. It had a 39.7° FOV and was operated at a 1:1 magnification.
Figure 2 The photos above illustrate the experimental apparatus used for the data collection. The left image shows the scatter collecting camera (A) and the spot imaging camera (B). The central image shows the tight proximity of the two camera systems and fold mirrors that are required to project the spot and simultaneously image it with the two cameras. Finally, the right image shows the source (C), filter wheel (D) location and (E) the DMD array on a translation stage. Also the complete camera system was enclosed to minimize the amount of ambient light that would contaminate scatter measurements. The optical table pictured above is a 4’x6’ table.

Initial measurements were plagued by noise in the CCD images, including the dark frames. The noise pattern was periodic with the 40 kHz readout rate of the CCD electronics. Since the pattern appeared approximately every 6 to 7 pixels, this meant that the noise source’s frequency was 7 kHz. It was found that the noise correlated with the optical power supply being in close proximity to the CCD liquid cooling lines. It appears that AC noise from the optical power supply was coupling into the CCD liquid cooling fluid (a water-glycol mixture). A grounded foil shield was placed between the optical power supply and the other electronics eliminating further problems.

3. DATA ANALYSIS AND RESULTS

3.1 Scattered Light Analysis

Four different mirror slit patterns were generated to extract two important parameters: \( I_s \) (scattered light) and \( I_R \) (specular reflected light). The following equations assume that the scattered light component is the same from all mirrors regardless of the mirror state. The top box of Figure 3 illustrates a visual representation of the micromirror slit patterns.

- Case 1. All mirrors are facing the scatter-collecting camera, so the light recorded by the scattering camera was the sum of the reflected light from the center mirror, the reflected light from the adjacent mirrors and the scattered light from all mirrors (Equation 1).

- Case 2. All mirrors are away from the scatter-collecting camera, so only the scattered light is collected by the scatter-collecting camera (Equation 2).

- Case 3. One mirror is turned away from the scatter collecting camera. Therefore the camera collects the reflected light from the adjacent mirrors and the scattered light from all of the mirrors (Equation 3).

- Case 4. Only the central mirror is facing the scatter collection camera. Therefore the camera records the reflected light from a single mirror plus the scattered light from all mirrors (Equation 4). \( I_{RA} \) is the reflected light from adjacent mirrors in the array.

\[
\begin{align*}
\text{Case}_1 &= I_R + I_{RA} + I_s \\
\text{Case}_2 &= I_s \\
\text{Case}_3 &= I_{RA} + I_s \\
\text{Case}_4 &= I_R + I_s \\
I_R &= \text{Case}_1 - \text{Case}_3 \quad \text{or} \quad I_R = \text{Case}_4 - \text{Case}_2
\end{align*}
\]
The scattered light analysis was processed by subtracting the co-averaged dark frame from each image taken in each of the filter and DMD mirror states. A 40x40 sub-array was recorded to speed up camera readout and data analysis. The maximum value from each scatter collecting CCD image was found. Then these values were then placed together for each spot position to build up a 25x25 pixel scan image. These scan images cover a spatial area of 50 by 50 µm, so several DMD mirrors are seen in each image. The scatter collecting camera’s maximum pixel was taken from each of the scatter measurements. In the blue, there appears to be a lower fill factor. This is because the parts of the mirror near the edges are cupped up and reflect less light to the scatter collecting camera. The images for case one show structure that is periodic at the same pitch of the micromirrors. Case 2 all of the mirrors are turned away, showing scattered light from all of the mirrors. There is a great deal of scattered light at the edges of the mirrors and in the central region of each mirror near the via. Case 3 shows the absence of one mirror and case 4 shows the reflected and scattered light for a single micromirror. There is also a bright spot on one side of each mirror and this is likely due to the fact that the mirrors are curved, and the camera is capturing the specular reflection at this point. It appears as though there is a square region missing in each of the mirrors and it is also apparent that the scattered light is wavelength dependent. From these plots one can derive the reflected light and scattered light for a single micromirror (Equation 5). By solving for the \( I_R \) and \( I_S \) the contrast value (Contrast = \( I_R/I_S \)) for each position in the micromirror can be determined. Integrating these values over a complete micromirror can gives a single pixel contrast ratio analogous to a SNR. This is the maximum contrast ratio possible from a DMD based MOS instrument with this generation of DMD is shown in table 1.

Table 1 The maximum integrated contrast values (\( I_R/I_S \)) for each spectral filter (B, V, R, I, N) used.

<table>
<thead>
<tr>
<th>Filter</th>
<th>Contrast Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>273</td>
</tr>
<tr>
<td>V</td>
<td>305</td>
</tr>
<tr>
<td>R</td>
<td>318</td>
</tr>
<tr>
<td>I</td>
<td>106</td>
</tr>
<tr>
<td>N</td>
<td>287</td>
</tr>
</tbody>
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3.2 Mirror Curvature

Flatness and surface roughness are two of the key parameters which determine the amount of scattered light scattered light. The DMD mirrors are made in a semiconductor process, and thin film properties become very important. The DMDs are packaged at TI with a transparent window ahead of the DMD for protection. The window was removed from a non-functioning DMD of the same model as the DMD under test. A Veeco Wyko NT9000 white light interferometer was used to examine the surface relief of these mirrors. These interferometer measurements enabled the mirror curvature to be extracted. Figure 4 shows the variation in mirror height measured. It can be seen that the mirror edge is 0.25 µm higher than the region around the via at the mirror center. Also the profile is symmetric around the mirror and not a function of the axis that the mirrors tip on. Our initial thought was that this might be the result of the mirrors hitting a hard stop when they are tilted. However, this is not the case as the stop is not located at the mirror edge but rather closer to the underlying hinge structure in this generation of DMDs. Since the mirrors are 16 µm across this implies that the radius of mirror curvature is approximately 257 µm. This number will be one of the parameters used in to tailor the stray light model in a software simulation to be performed. Also notice that there appears to be a square region to each of the mirrors which is flat. This is likely the same square pattern that was seen in the spot scan data which for the B, V, and R filtered data. Figure 4 was also rotated so that the mirrors would be the same orientation as the other measurements presented in this paper.

An alternative approach to characterize the mirror flatness was also investigated. For each of the scans, case 4 was considered. In each of the scatter camera’s images, the row and column centroid are computed. At each location in the scan, the movement of the centroid across the scatter collecting CCD was plotted as shown by the arrows in Figure 5 and 6. This method of plotting the data enabled one to view where the spot was being imaged on the scatter collecting camera (Figure 5). Two cut-lines were made through this plot, one in the vertical direction and on the horizontal direction. The vertical cutline should be flat if there is no curvature, because this is the direction parallel to the hinge. The mirrors only tip across the row direction in the scan, so a dip in the plot should be seen there. In figure 5, there is curvature in both the x and y direction for the blue case. Figure 6 shows the same data plotted for the I filter. It can be seen that there is very little curvature in the vertical cutline. This is likely due to the fact that the spot is bigger in the I band and therefore the curvature is averaged out.
Figure 3. In the top boxes, the four mirror slit patterns are shown. The central mirror pictured in each of the slit patterns is the mirror under test. The remaining mirrors in the array are set to the same state as all of the outside mirrors. Case 1, all mirrors are positioned toward the scatter collecting camera, Case 2 All mirrors are placed away from the scatter collecting camera. Case 3 one mirror is turned away from the scatter collecting camera. Case 4 only one mirror is turned towards the scatter collecting camera. The labeling along the vertical axis indicated the different filter used in each of the four mirror cases.
Figure 4 The image above is a interferometric surface height image of a 3x3 array of DMDs. The mirror edges are outlined. The orientation of the hinge is also outlined in a white overlay. The mirrors bow up around the edges at approximately 0.25 μm. Note the central via and lighter areas in between the mirrors.

Figure 5 The plot on the left shows case four overlaid by a vector plot. The arrows indicate the direction that the centroid translates on the CCD during the spot scan. The plot on the right shows the two different cutlines through the spot scan data. This data is shown for the B filter.
3.2 Micromirror Self Shadowing (MSS)

Micromirror self shadowing, is the change in illumination caused when part of the incident beam of light is blocked by the edge of an adjacent mirror. Therefore, a fraction of the reflected cone of light is also blocked by the adjacent mirror. The self shadowing does not become an important factor until illumination angles become faster than f/3 for the 10° tip DMD. Since the spot projection lens only illuminates the mirrors at f/7 and the RITMOS relay optics only illuminate the mirrors at f/8 MSS is not a significant factor. However, mirror curvature may change this limit and will be further investigated.

3.3 Sources of Scatter

There are many different material parameters that can cause light to be scattered in a non-specular direction. Scattering by rough surfaces is significant source of stray light. Surface micro-roughness, material defects, and dirty or contaminated surfaces can all cause a material to be optically rough. In a DMD, the inherent surface roughness of the aluminum will contribute to diffuse scatter. This type of scatter is wavelength dependent, because the roughness remains constant while the illumination wavelength changes.

Our initial efforts at composing a scattering model for the DMD indicated the main sources of DMD scatter are:

- the via located in the center of the mirror
- the edges of the mirror
- mirror curvature
- multiple scatter events that occur underneath the mirror that propagate into the field of view of the detector

4 SOFTWARE MODELING

The spot size was measured by imaging the spot by facing the spot directly on the imaging high magnification camera. A technique was also developed to optimize the focus. To characterize the spot during the scans, a series of images were taken as the stage was stepped randomly. The spot imaging camera was set up 20° off axis and at each stage position an image was saved. Theses images were averaged together. The focus was changed on the spot projection lens and the scan was repeated until a minimum FWHM was found. The size was verified by averaging the spot-imaging images from case 2. The FWHM of the spot at all of the wavelengths used was approximately 2 µm or less. This is not actually the real spot size of the spot, this is the spot imaged on the micromirror array, so it is the spot plus the scattered light. FRED7, a non sequential ray tracing package was used to model the spot size of the lens. Figure 7 shows the spot as a function of wavelength as simulated in FRED. These simulated results agree well with the experimental values. Differences are likely due to micromirror scattered light in the spot images.
The Harvy-Shack scatter model is commonly used for modeling stray light on polished aluminum surfaces. It is a linear shift invariant function. Equation 6 shows the Harvy-Shack model formulation. The $b_0$ is a scaling parameter to ensure the BSDF is integrates to less than 1 for a 100% scattering surface. The BSDF (Bi-directional scatter distribution function) describes the reflectance of light. $B$ is the sin of the illumination angle, and $B_0$ is the sin of the specular angle. $L$ describes where the specular roll-off knee occurs in radians and $S$ is the slope for large $B-B_0$ values. A future paper will parameterize these values of the Harvy-Shack model to model the micromirrors within FRED.

$$BSDF = b_0 \left(1 + \frac{(B - B_0)^2}{L^2}\right)^{\frac{S}{2}}$$  \hspace{1cm} (6)

The experimental apparatus as described earlier was modeled in the FRED software package. An image of the experimental apparatus in FRED is shown in Figure 8. The fold mirror setup was prototyped in FRED prior to building it to ensure that there would not be any vignetting of the scatter collecting camera system. The fold mirror system was used rather than a direct illumination path, because it was not possible to illuminate the mirrors and image them at the proper $\pm 20^\circ$ with both camera systems. Partial vignetting of the spot imaging system occurred, but since this system was only used for determining where the spot was, (no radiometric scatter measurements were derived from this system), this was not an issue.

Figure 7 The spot size as a function of filter used is shown above for the data collected by the spot imaging camera (left). The spot size impinging on to the micromirror was predicted using the FRED software package (right).

Figure 8 The experimental apparatus shown in the FRED software package. The A rays show the incoming wavefront. The B rays show the light reflecting from micromirrors towards the spot-imaging camera. The C rays show the light being reflected into the scatter collecting camera.
CONCLUSION

A methodology to measure the stray light from a DMD as utilized in a multi-object spectrometer has been described. The main sources of scatter were the mirror edges, layers underneath the mirror and the central via within the mirror. The individual mirrors on the DMD tested had significant curvature (i.e. they are not flat). The form of the scattered light was dependent on the illuminating light. The scattered light appears to be more diffuse in the blue band than in the red region of the spectrum. A contrast ratio was determined for a single micromirror at different wavelengths. Future work will parameterize the software model by performing additional scattered light simulations. In addition, measurements on a newer DMD are underway to understand their scatter phenomenon.

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