Subpixel Scatter in Digital Micromirror Devices

Kenneth D. Fourspring, Zoran Ninkov, John P. Kerekes
Chester F. Carlson Center for Imaging Science Rochester Institute of Technology
54 Lomb Memorial Drive Rochester, NY 14623-5604;

ABSTRACT

The DMD™ (Digital Micromirror Device) has become an integral part of the instrumentation for many applications. Prior characterization of this device has been focused on its use in DLP™ (TI Digital Light Processing) projector applications where a collimated wavefront impinges on the DMD. The results of such investigations are not applicable to using DMDs at the focal plane of an optical system where it is used as a slit mask (e.g. in a multi-object spectrometer). In order to study the DMD scattering function in this second case, a subpixel spot scanning system has been assembled. The scattered light collected from this system allowed a subpixel scattering function to be determined for the DMD when illuminated by a converging beam.

Keywords: Digital Micromirror Device, multi-object spectrometer, stray light

1. INTRODUCTION

In many applications, investigators are interested in collecting full spectral information at many spatial locations within the field of view that the optics provides. For example, astronomers would like to simultaneously obtain spectral information on as many stars as possible within the telescope’s field of view. To this end, two general instrument approaches have been developed. The first method involves machining a specific slit mask for the field of interest that is placed at the focal plane of the system. Only light at specific locations passes 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.

Initial measurements to assess the utility of Digital Micromirror Device for use as a slit mask in astronomy were encouraging. This led to the development of RITMOS (Rochester Institute of Technology Multi Object Spectrometer). Central to RITMOS operation is a DMD that permits the collection of many spectra simultaneously. The focal plane of the telescope at which RITMOS is to be used was re-imaged using relay optics operating at f/8.5 onto a DMD. The target selection process occurs at this intermediate focal plane. An Offner relay with two fold mirrors re-images the DMD onto a peltier cooled CCD that records the image. The light not deflected into to the imaging channel instead is reflected into the RITMOS spectral channel. In the spectral channel, the light travels through a collimator operating at f/7.62, through a stop, and then is dispersed by a 1200 grating. This light is then re-imaged using f/3.35 optics onto a second CCD that records the spectra. A spectrum can be determined for each of the slit positions selected by the DMD. The spectral side of the RITMOS was designed to operate from 390 nm to 490 nm with a spectral resolution of 0.703 Å for a two mirror wide slit.

Recently there has been interest in using multi-object spectrometers in applications beyond the field of astronomy. A feasibility study has been initiated at RIT to generate an end-to-end model of a vehicle tracking system and determine expected performance when using the RITMOS instrument. To achieve this DIRSIG, a software package developed at RIT was used to generate synthetic Earth scenes. This package is capable of generating hyperspectral image cubes of a synthetic scene data and can propagate this radiation to the aperture of a sensor. This software model was used to generate synthetic input imagery. This input data is then convolved with the system parameters of RITMOS to determine expected performance.

Further author information: (Send correspondence to Kenneth D. Fourspring) : E-mail: kdf5036@rit.edu

Emerging Digital Micromirror Device Based Systems and Applications II, edited by Michael R. Douglass, Larry J. Hornbeck,
Proc. of SPIE Vol. 7596, 75960J · © 2010 SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.843702

Proc. of SPIE Vol. 7596  75960J-1

Downloaded from SPIE Digital Library on 26 Apr 2010 to 129.21.58.33. Terms of Use: http://spiedl.org/terms
Characterizing RITMOS optical properties are essential to building back-end models and making sensor performance predictions. In particular, no information was available on the scattering properties of the DMD when used at a focal plane of an optical system to describe the aggregate light adjacent micromirrors scatter into a target’s spectrum. This parameter is key to determining signal-to-noise and threshold detection limits. To quantify this parameter, an apparatus was assembled to measure the stray light function for a single micromirror. Additionally, a physical model is being developed to explain the scattering results. A combination of two different software packages is utilized to generate the model. The software package Rhino7 was used to build the cad geometry, and Photon Engineering’s FRED8 ray tracing package will be utilized to perform the ray tracing. These results will be reported in a subsequent paper.

There is a fundamental difference in DMD utilization in the RITMOS instrument and in a DLP® projector. In the projector application, a collimated wavefront, or flood illumination, impinges onto the DMD at twice the DMD tip angle (in the case of the DMD used in RITMOS 20° off axis). This light is then either reflected directly through the cover glass (the on state), or the mirrors are tilted 10° in the opposite direction and the light is sent to a light trap (off state). The image formation in a DLP® projector occurs at the DMD and the smallest image feature reproduced is one micromirror. In RITMOS, the light falling on the DMD comes from a relay lens and a converging wavefront is focused onto the DMD. The smallest image that can be formed is a function of the foreoptics spot size. Generally one would set up the system so that the foreoptics spot size would correspond to a 2x2 array of micromirrors, to avoid issues with differences in reflectivity as a function of subpixel position.

The RITMOS used a Texas Instruments DMD that has an 848x600 array of micromirrors, which tilt ±10° relative to the optical axis. This micromirror array’s pitch is 17μm. An individual mirror is 16μm across and adjacent mirrors are separated by a gap of a 1μm. In addition, the central micromirror hole or via was measured to be about 4μmx4μm. An image of several micromirrors can be seen in Figure 7. The mirrors tip along the diagonal, making diamond shaped pixels. Newer mirror designs utilize a ±12° design and have higher ON-OFF state contrast ratios. An instrument was assembled to make scattering studies applicable to the case where the DMD resides at the focal plane.

2. SOURCES OF STRAY LIGHT IN DMDS

Scattering by rough surfaces can be a significant source of stray light. There are two general regimes for scatter from rough surfaces. Scattering by object size on the order of the wavelength of light used is referred to as Mie scattering, and scattering by particles much smaller than the wavelength of light is referred to as Raleigh scattering. In a DMD, the inherent surface roughness of the aluminum would result in Raleigh scatter, which contributes to the diffuse scatter component. This type of scatter is wavelength dependent, because the roughness remains constant while the illumination wavelength changes.

The initial effort at a scattering model indicated the main sources of DMD scatter as primarily:

- the via located in the center of the mirror
- the edges of the mirror
- multiple scatter events that occur underneath the mirror that propagate into the field of view of the detector
- the protective window that is placed above the DMD in the optical path (an external source of scatter).

Most external sources of scatter will propagate light in a non-critical direction (i.e. not toward the detectors). These non-critical stray light sources are simply losses in the optical throughput of the system.

3. DESIGN OF STRAY LIGHT MEASUREMENT SYSTEM

An experimental apparatus was realized to measure stray light for a DMD as used in the RITMOS instrument. Several experimental setups were investigated prior to the present design, which yields the most useful information. In the current incarnation, a novel scanner was designed to project a subpixel spot onto the DMD. The system was designed so that it mimics the way light is focused onto the DMD in the RITMOS system.
Figure 1. A laser source was focused through a lens onto a micromirror array. The speckle pattern was then reflected onto a screen and imaged.

Figure 2. The spectrum of the tungsten light source is shown in black (labeled N in the legend). The spectrum of the B, V, R, and I Bessell filters is convolved with the white light spectrum and shown here. This data was measured by using a Ocean Optics USB2000 spectrometer.

3.1 Light Source

A laser was initially thought to be an ideal light source, because of its high power and the availability of optics optimized for laser light. A HeNe laser was initially used as a light source. A Keplerian style beam expander was built and the light was focused onto the DMD array. A screen was placed approximately a meter away from the DMD. An image of the screen was then taken using a digital camera. It was determined that it would be very difficult to use a laser source due to speckle patterns caused by random interference of the beam with itself (Figure 1 A). Additionally Figure 1 A illustrates an x-shaped pattern surrounding the central lobe. This stray light is likely due to light scattering off the edges of a mirror. In view of these problems a tungsten filament source was chosen that has a wider spectral output and can be easily filtered so as to characterize the spectral characteristics of scattered light.

An Oriel Q-series tungsten filament source was used with a f/1.0 collimator lens assembly (PN#60076). This housing also contained a rear reflector to refocus the light, improving throughput. A 25μm pinhole was then used to further spatially filter the light source. An optically stabilized power supply provided power to the 100W bulb, which was the maximum rated power for this particular light source enclosure. The filament was aligned to the collimator by putting a laser through the collimator lens (Figure 3). Additionally, an enclosure
was built on top of the light source collimator assembly so that light from the heat vents would not reach the micromirror array. Care was taken to make the enclosure large enough so that there was enough room for the lamp to cool sufficiently. Before taking any measurements, the light source was turned on for a period of time and allowed to thermally stabilize. The light source was rated to have an RMS stability of 0.5%. Figure 2 shows the spectrum of the tungsten light source convolved with the Bessell filters used to make estimates of the scattering at different wavelengths.\(^9\)

3.2 Spot-Projection Lens

Next, an optical system had to be designed to take the light from the light source and project it onto the micromirror array, just as a point source would be imaged onto the micromirror array. The pinhole was then set up to be imaged onto the micromirror array by placing the pinhole at an object to image ratio of 5:1, giving a minification factor of 5. The spot size should be approximately 5\(\mu m\) in diameter on the micromirror array. Moving further away than this does not create a smaller spot due to the diffraction limit of the spot-projecting lens. The lens used to project the spot was a Thorlabs AC254-075-A-ML. It was a \(f/6.0\) achromat made from BK7 and SF5. It was essentially a diffraction limited optic, and its \(f/#\) was close to that of the RITMOS relay optics. The expected spot size was modeled using the OSLO package.\(^10\) The lens model was imported into OSLO and the lens was verified to be diffraction limited (Figure 4). Several spectral bands were simulated as well to verify that the lens was chromatically corrected. The spot size calculated by OSLO was compared to the diffraction limited spot size modeled by a circular aperture and the squared magnitude of \(J_1\) bessel function. The relative aperture size of the spot-projection lens was the limiting factor for creating a smaller spot.

3.3 Spot-Imaging Setup

A microscope was set up to image this individual spot and determine the subpixel position relative to the micromirror being tested. A Mitutoyo 0.14 NA 5x NIR Infinity corrected microscope objective was used to image the spot. The lens tube used was a Navitar zoom 6000 series coupled to a Prosilica GC-1380 camera with a 2/3" sensor array. This camera enabled one to focus the spot onto the DMD and determine the relative position of the spot on the DMD. The total system magnification ranged from 3.48x to 22.86x. The microscope had a working distance of approximately 34\(\mu m\) and a resolving power of 2\(\mu m\).

3.4 Stage Selection

Next a method was required to move the spot across the micromirror. A two axis DC motor Physiks Instrumente stage was used as the raster scan stage to move the mirrors across the spot. It was determined to be simpler to translate the micromirror array rather than the spot projection lens and light source. The stage has a resolution of 0.06\(\mu m\) and a repeatability of 2\(\mu m\). This resolution was sufficient for examining micromirrors. The acceleration, ramp rates, and velocity were optimized to give the best stage repeatability results.
Figure 4. The Point Spread Function of the Lens used to create the subpixel spot. The calculated spot size as a function of wavelength for the Thorlabs AC254-075-A-ML.

3.5 Scatter-Collecting Camera

To collect the scatter, a camera with a large dynamic range was required. Also, a macro lens was required so that enough light could be collected and focused onto the sensor. A cooled Photometrics CE-350 CCD camera was chosen to collect the scattered light. This scatter-collecting camera utilized a back-thinned SITe SI502AB back-side illuminated CCD. The CCD had an RMS read noise of approximately 8 electrons and a full well capacity of approximately 300,000 electrons, so it was very suitable for performing low light level scatter measurements. The macro lens used to capture the stray light was a Micro-Nikkor 60 mm f/2.8. It had a 39.7° FOV and was operated at a 1:1 magnification. The stray light was collected at f/11, to enable the shutter to be open for a longer period of time and minimize the effect of shutter jitter.

3.6 Additions to the Experimental Setup

Several additional items were included in the final experimental setup. To enable viewing of the spot at the specular angle, a fold mirror periscope system was developed. This enabled the spot to be projected onto the DMD by the spot projection lens and simultaneously imaged by the microscope objective. A fold mirror system was prototyped in the ray tracing package FRED to determine the size of the mirrors required, and to ensure that all of the proper working distances would be maintained (Figure 5). Figure 5 shows two views of the experimental apparatus. A half-silvered mirror and an Ocean Optics USB2000 spectrometer were also added after the filter wheel and pinhole to monitor light source power. All of the elements of the apparatus are labeled in Figure 5 in the as follows:

- A. the Oriel Q-series light source,
- B. the Oriel collimator assembly and pinhole,
- C. the first fold mirror in the periscope system,
- D. the Thorlabs spot projection lens,
- E. the second fold mirror in the periscope system,
- F. the DMD assembly mounted to a rotation stage,
- G. the Mitutoyo microscope objective,
- H. the Navitar lens tube,
- I. the spot-imaging camera,
- J. the Nikon macro lens,
- K. the scatter-collecting camera.
3.7 Focusing and Aligning the Optical Components

A laser was used to coarsely align all optical components. However, a more accurate procedure had to be performed to focus the two cameras and spot-projection lens onto the DMD. To align the spot-imaging camera, the pinhole was removed from the light source, so that a large flood illumination was focused onto the DMD. This made it possible to use short integration times with the spot-imaging camera. After this, the spot-imaging camera was translated so that the large spot was centered in the FOV of the array. A histogram was used to aid in finding and focusing the spot. All of the mirrors were then turned toward the spot-imaging camera. The camera was then focused so that the relative edge response was greatest in the center of the field of view of the spot camera. The relative edge response was calculated by applying an edge detector to the image, setting a threshold and grouping several sets of columns on the image. The columns with the highest relative edge response were in the best focus. Since this camera was imaging at 20 degrees off axis and the microscope had a large numerical aperture, it had a very limited depth of field (about 14μm). Due to this constraint, it was very important to obtain the best possible focus of the projected spot in the center of the field of view.

To focus the spot onto the mirrors, the mirrors were moved to their flat state. An iris was used to stop down the beam at the pinhole location. The focus was adjusted on the spot projection lens while monitoring the continuous video feed of the spot-imaging camera. After the approximate focus was found the iris was replaced with a pinhole. Next the spot-projection lens’ micrometer position was recorded and a pseudo-random spot scan was performed to randomly step the stage in x and y. The stage was stepped in a random fashion to avoid the problem of having the spot illuminating the region between two mirrors or within the via. These images were averaged together so that all of the non-uniformities of the DMD were averaged out. This process was repeated through focus of the spot projection lens. At each focus position the FWHM was found for the spot.
and this value was recorded. The FWHM size was then plotted versus focus and a minimum position was found. This was found to be the best method of minimizing the spot on the DMD (Figure 6). The procedure to focus the scatter-collecting camera was very similar to the procedure for focusing the microscope lens.

3.8 Data Collection

A raster scan was conducted across the micromirror array by moving the DMD across the projected spot. Scanning was always performed in a single direction to avoid hysteresis issues with the stage. The scanning region was 68μm by 40μm, which resulted in 140 data locations. Four different mirror positions or cases were examined as shown in Figure 7. The spot-imaging camera observed the inverse slit that the scatter camera recorded.

The motion order was very important for collecting co-aligned scatter data. The mirrors were moved to their four positions (Figure 7) at each stage position. Images were obtained from both cameras simultaneously at each case. The spot-imaging camera was used to determine the current position and the scatter camera to collect the radiometric data. Several frames were co-added on the spot-imaging camera to improve the image recorded of the spot on the micromirrors. Exposure times were set by moving to the nominal location in the center of the pixel and choosing an exposure time that was approximately 75% of the camera’s full well capacity.

An automated method was designed to determine which DMD micromirror was being illuminated. This enabled the four different mask patterns to be determined automatically. The automated method first stepped through the rows on the DMD to find the highest change in flux on the scatter-collecting camera. The process was repeated for the DMD columns within the previously found row. Once the DMD row and column were found, the slit or mask patterns were programmed into the DMD controller. The spot was then centered by viewing the image on the spot-imaging camera. To improve signal to noise ratio on the pixels receiving lower flux, the scatter-collecting camera was binned into 3x3 pixels around the maximum pixel. When the system was aligned properly, the majority of the light illuminated a single detector element on the scatter-collecting camera.

3.9 Data Analysis

Two important parameters are required to characterize scatter in DMD: $I_R$ and $I_S$. $I_R$ is the reflected light from a single micromirror and $I_S$ is the scattered light by the micromirror array. To determine the difference in reflectivity as a function of subpixel position, the following equations were derived from the four mirror states as shown in Figure 7:
Case 1. All of the mirrors are facing the scatter-collecting camera, so the light recorded by the scattering camera is 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 of the 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 (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).

\[ \text{Case}_1 = I_R + I_{RA} + I_S \]  

\[ \text{Case}_2 = I_S \]  

\[ \text{Case}_3 = I_{RA} + I_S \]  

\[ \text{Case}_4 = I_R + I_S \]  

\[ \text{Contrast} = \frac{I_R}{I_S} \]  

Figure 7. The Rhino software package was used to generate the above renderings of four different mask patterns. The scatter camera would be positioned above and to the left of the micromirror and the spot-imaging camera would be positioned to the right side.
The unprocessed data can be seen in Figure 8. General insight was gathered from the raw data. Case 1 shows the maximum response was obtained on a periodic structure at the same pitch as the micromirror array. This indicates that the spot was likely much smaller than a single micromirror element. Case 2 shows the scattered light. The scattered light was much greater around the edges of the pixel. Note that the pitch of the peaks for case 2 is doubled suggesting greater scatter at the edges of micromirror pixels. These equations were be solved to find the \( I_R \) and \( I_S \) at each position. To achieve this, a matrix was set up and a Gaussian elimination method was used to back out the reflectance and stray light values. After these were determined, a ratio can be taken to determine the ratio of reflected light to the ratio of stray or scattered light at each position within a DMD pixel. Figure 9 shows the resulting data at three different spectral bandpasses as defined by the Bessell filters whose transmission are seen in Figure 2.9 The orientation of the mirrors was obvious when viewing the contour plot. These initial measurements indicate there is a variation in scatter with spot position on the individual DMD mirror (Figure 9). These data were not compensated for the portion of the spot that is off the edge of the mirror. Future analysis will use the imagery from the spot-imaging camera to determine the amount of light that is off the mirror for normalization purposes.

Additionally the scatter data were viewed as a function of distance from the center pixel on the scatter CCD array (see Figure 10). These results will be further interpreted to determine the degree of spectral contamination by adjacent mirrors as a function of wavelength. When the illuminating spot is in the center of the micromirror, higher reflectance values are measured at the center pixel on the scatter-collecting camera. Additionally, there is less scatter at distances further from the center pixel on the scatter-collecting camera when the spot illuminates the center of the pixel. The edge measurements have lower \( I_R \) values and also change less as a function of distance. This indicates that when the illuminating spot is closer to a mirror’s edge, more scatter occurs. There are not only intensity differences between the mirror’s values, but additionally differences in shape of the curves. In the future, images will be co-added to help boost the signal of the pixels at greater distances from the center pixel. Additional data points without performing on camera binning will be collected to confirm these trends.
Figure 9. This shows the results of applying equations 1, 2, 3 and 4. Equation 5 was then applied to all of the data points and the contrast ratio results are plotted here. The data on the top and bottom are the same, just viewed in three dimensions.

While taking the experimental measurements, an additional stray light path was discovered as shown in Figure 11 A. Depending on the wavelength of illumination, a ghost image was present approximately 1800 μm away on the specular reflection of the micromirror. Assuming that the glass thickness is 2500 μm the ghost image was predicted in the vicinity of this location. This scatter path was not a significant problem in the typical DMD projector application, because the case where this would occur is when the pixel would be in the off state. This becomes an important parameter in both the spectral and imaging channel of the RITMOS. In the imaging channel, this effect simply degrades the image quality. For the spectral channel, it poses a different problem. Since the location of the slit or micromirror determines the center of the spectrum, this ghost image will essentially be a second slit in a different row. This effect causes low-level spectral contamination. Further optical modeling suggests that this was primarily a function of the quality of the protective window’s antireflection coating. Producing a high-quality antireflection coating optimized for the spectral region of the multi-object spectrometer is very important.

4. SUMMARY AND FUTURE WORK

Several methods have been developed to experimentally measure the stray light from a digital micromirror device used at the focal plane of a multi-object spectrometer. The contrast ratios are generally much lower than the ratios given in the projector applications due to differences in DMD utilization and the definition of contrast. Software modeling will be repeated on newer generation DMD devices to predict new contrast ratios. The trends derived from the DMD scatter measurements can be simplified to a two-dimensional kernel enabling a simple back-end scattering model for the RITMOS system. Further measurements with finer stepping of the stage are required to generate an accurate kernel. This kernel is now being incorporated into a complete optical scattering model to enable modeling of RITMOS for target identification and tracking.
Figure 10. The radial scatter plotted from the center pixel on the scatter CCD array. The four plots are for different color filters, and within each plot there are several data points for positions within a micromirror.

Figure 11. An important scatter path is shown here which is caused by multiple reflections within the cover glass window. (a) Is a sketch that illustrates the light bouncing off of the mirror, going through the first interface of the glass, but then being internally reflected by the glass. The light is then internally reflected again. (b) An image from the scatter-collecting camera showing the ghost image.
ACKNOWLEDGMENTS

This material is based on research sponsored by the Air Force Office of Scientific Research (AFOSR) under agreement number FA9550-08-1-0028 (AFOSR-BAA-2007-08). The U.S. Government is authorized to reproduce and distribute reprints for Governmental purposes notwithstanding any copyright notation thereon.

REFERENCES


