DMD-Based Multi-Object Spectrograph Design and Wavelength Calibration

Dunlap Institute for Astronomy & Astrophysics
UNIVERSITY OF TORONTO

Matthew C. H. Leung
Supervisor: Dr. Shaojie Chen
Dunlap Institute for Astronomy & Astrophysics, University of Toronto

Royal Astronomical Society

1. INTRODUCTION

A multi-object spectrograph (MOS) is an instrument that can acquire the spectra of hundreds of astrophysical objects simultaneously, saving much on observing time. In the recent years, the **digital micromirror device (DMD)** has shown potential in becoming the central component of the MOS, being used as a programmable slit mask [1]. We have designed a seeing-limited DMD-based MOS covering a spectral range of **0.4-0.7 μm**, with a field of view (FOV) of **19.20' × 25.60'** and a spectral resolution of **1000**. We present the optical design of this DMD-MOS and a wavelength calibration procedure for hyperspectral data reduction.

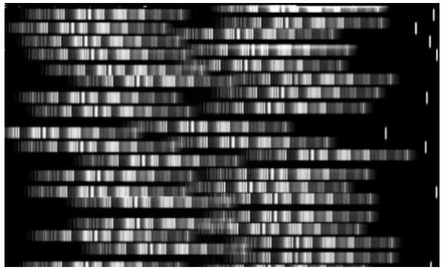


Figure 1 - Example of multi-object spectra from the Gemini Multi-Object Spectrograph (GMOS) (Original Image: Gemini Observatory)

2. DMD ADVANTAGES

Current MOS systems mainly use two different types of object selection systems:

1. Repositionable optical fibres (e.g. Subaru FMOS [2]), which take time to configure [3]
2. Custom-made slit masks (e.g. Gemini GMOS [4]), which are made ad hoc with high costs

A DMD can be used as a **generalizable slit mask** that can be quickly programmed. A DMD consists of an array of many tiny mirrors (13.70 μm pitch each), which can be individually programmed to tilt along an axis, ±12°, corresponding to an ON and an OFF configuration. DMDs have been used for commercial and industrial applications, and thus have **lower costs** and **proven reliability**.

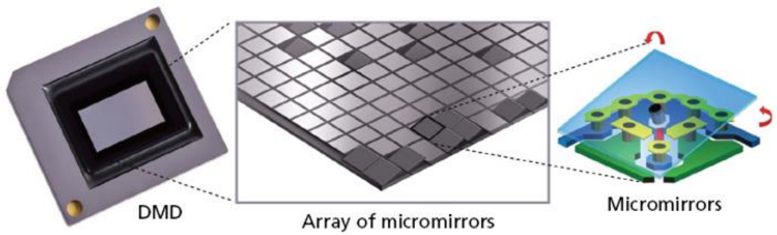


Figure 2 - Digital Micromirror Device (Original Image: LEDs Magazine)

3. DMD-MOS SYSTEM OVERVIEW

Incoming light from a telescope is focused onto the plane of the DMD. Micromirrors in the ON configuration act like slits in a conventional spectrograph, reflecting incoming light into a **spectral channel** to acquire the spectra of objects. Micromirrors in the OFF configuration reflect incoming light into a **camera channel** for standard imaging and object selection (fields acquisition). Since the camera channel is just a conventional imaging system, our research focus is on the spectral channel.

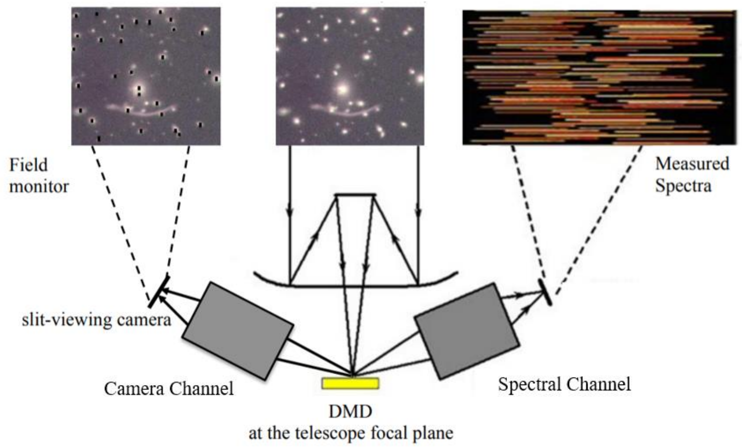


Figure 3 - DMD-MOS system layout (Original Image: Robberto et al., 2016 [5])

4. OPTICAL DESIGN

Our DMD-MOS employs **all-spherical refractive optics**. Light reflected by the micromirrors into the spectral channel pass through a collimator, and then is dispersed by a **volume phase holographic (VPH) grism**. The dispersed light is then focused by some camera optics onto an imaging detector.

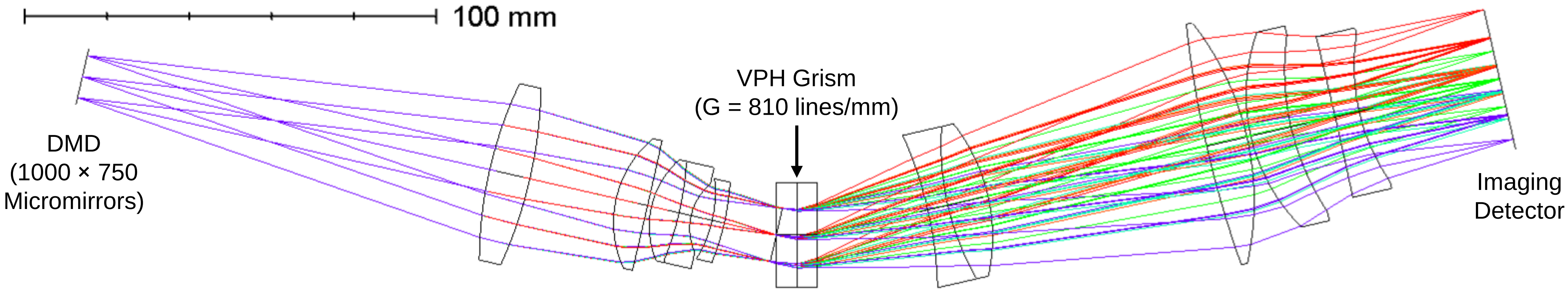


Figure 4 - DMD-MOS system diagram for the spectral channel, from DMD to image plane (detector)

5. OPTICAL PERFORMANCE

An analysis of the system was conducted, and the DMD-MOS meets the design requirements:

- RMS Spot Radii are less than 2× the pitch of a pixel (9 μm) (by Nyquist Theorem)
- Spectral resolution of the system >1000
- All rays within the FOV and with wavelength 0.4-0.7 μm will fall on detector; no rays clipped

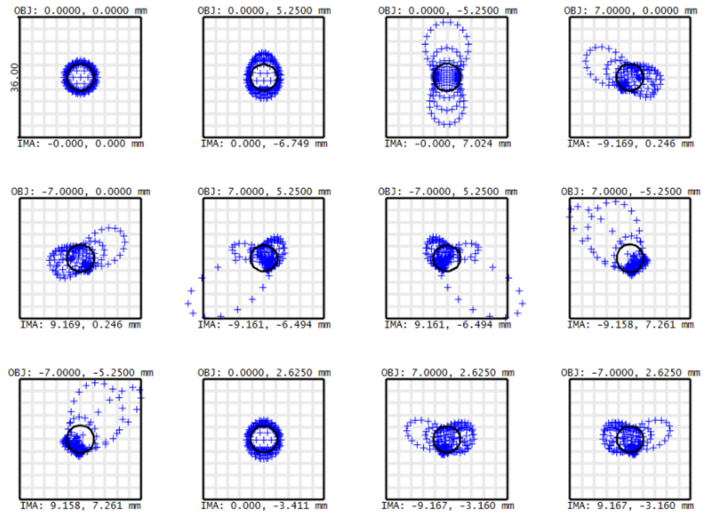


Figure 5 - Spot Diagrams of the DMD-MOS system, which can be used to determine RMS spot radius and optical performance; rays are from a variety of field positions on the DMD as indicated above each diagram, and are at centre wavelength $\lambda_c = 0.55$ μm; the black ring in each diagram is the airy disk

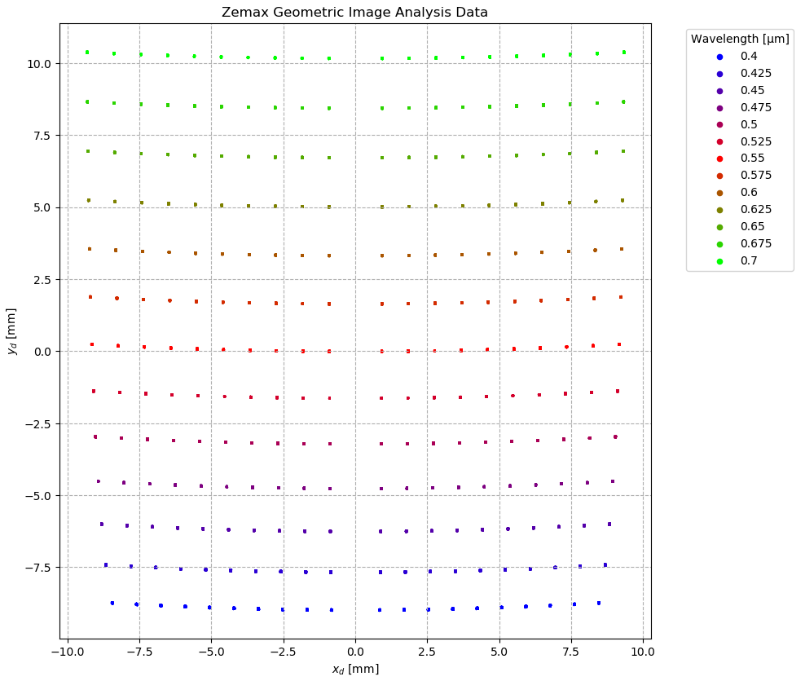
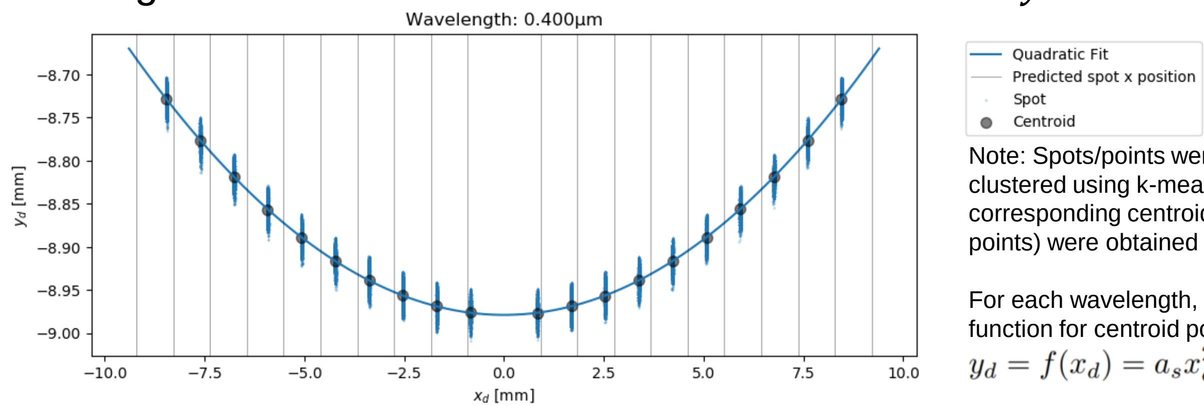


Figure 6 - Diagram of where rays land (spots/points) on the image plane, obtained by **launching 1 million rays** into the system, with the DMD having 20 ON micromirrors along its centreline; 13 different wavelengths were used for this Monte Carlo style simulation in Zemax OpticStudio (optical design software)

6. WAVELENGTH CALIBRATION FIT

Hyperspectral imaging systems have **smile distortion and keystone distortion** which need to be corrected. A wavelength fit was determined for this DMD-MOS system to map points from the DMD plane, (x, y), to corresponding points on the image plane (detector), (x_d, y_d), for some wavelength λ, using **simulated data** from Figure 6 in which DMD ON micromirrors were at $y = 0$.



Note: Spots/points were clustered using k-means, and corresponding centroids (grey points) were obtained

For each wavelength, fit a function for centroid positions:

$$y_d = f(x_d) = a_s x_d^2 + c_s$$

Figure 7 - Smile distortion at minimum wavelength $\lambda = 0.40$ μm, where distortion is greatest; note that smile distortion can be fitted with a **quadratic function**, with coefficients a_s and c_s that depend on λ

6. WAVELENGTH CALIBRATION FIT (Continued)

The **k-means clustering** algorithm was used to cluster points together corresponding to rays from the same micromirror. Given some point (x, y) with $y = 0$, λ, and the magnification of the spectrograph M_S: x_d and y_d can be found with the equations and constants below, with a **maximum error of 0.022 mm** at λ = 0.40 μm. Note that x and y are in units of mm and λ is in units of μm.

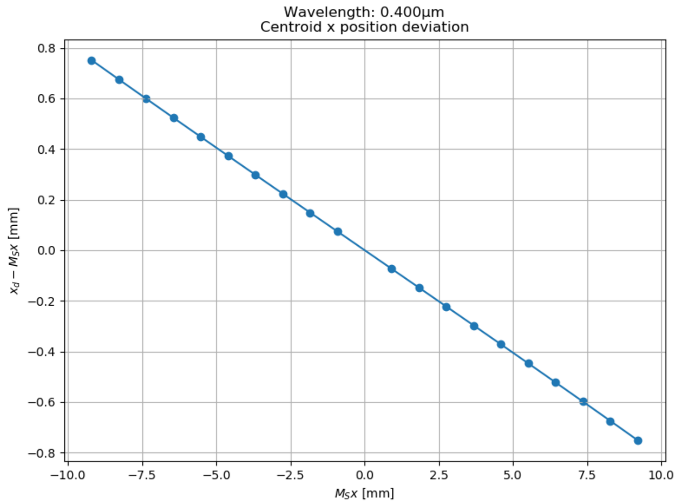
$$x_d = \left(\sum_{i=0}^{2} a_{ki}\lambda^i\right)(M_S x)^3 + \left(\left[\sum_{i=0}^{3} c_{ki}\lambda^i\right] + 1\right)(M_S x)$$

$$y_d = \left(\sum_{i=0}^{3} a_{si}\lambda^i\right)\left[\left(\sum_{i=0}^{2} a_{ki}\lambda^i\right)(M_S x)^3 + \left(\left[\sum_{i=0}^{3} c_{ki}\lambda^i\right] + 1\right)(M_S x)\right]^2 + \sum_{i=0}^{3} c_{si}\lambda^i$$

Distortion Type	Constant	Value
Smile	a_{s0}	0.00782671
	a_{s1}	-0.01890454
	a_{s2}	0.02581286
	a_{s3}	-0.01394186
	c_{s0}	-14.86248407
	c_{s1}	-35.79126845
	c_{s2}	158.05186215
	c_{s3}	-79.78971198

Distortion Type	Constant	Value
Keystone	a_{k0}	0.00007896
	a_{k1}	-0.00030339
	a_{k2}	0.00019631
	c_{k0}	-1.23198145
	c_{k1}	5.53880362
	c_{k2}	-8.34571333
	c_{k3}	4.25929110

Table 1 - Values of various constants in the above fit equations



For each wavelength, find a fit for the centroid "deviation":

$$g(x) \equiv x_d - (M_S x)$$

$$g(x) = a_k (M_S x)^3 + c_k (M_S x)$$

Figure 8 - Keystone distortion at minimum wavelength λ = 0.40 μm, where distortion is greatest; note that keystone distortion can be fitted with a **cubic function**, with coefficients a_k and c_k that depend on λ

7. CONCLUSION AND NEXT STEPS

We completed the optical design of this DMD-MOS and verified its performance with design constraints. A wavelength fit was determined for the case of $y = 0$, which we will generalize to the entire FOV ($y \neq 0$) next. A larger number of rays will be used for future simulations to reduce the error of the fit. After a generalized fit is determined, we hope to extend this fit procedure and DMD-MOS instrument to other applications, such as remote sensing. This DMD-MOS will be placed on a 16 inch telescope at the University of Toronto, and will be used as an exploratory study for future DMD-based MOS systems.

8. REFERENCES

[1] M. Robberto et al., "Applications of DMDs for astrophysical research," *Proc. SPIE* 7210, Emerging Digital Micromirror Device Based Systems and Applications, 72100A (13 February 2009).

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[3] A. Travinsky et al., "Evaluation of digital micromirror devices for use in space-based multiobject spectrometer application," *J. Astron. Telesc. Instrum. Syst.* 3(3) 035003 (17 August 2017).

[4] R. L. Davies et al., "GMOS: the GEMINI Multiple Object Spectrographs," *Proc. SPIE* 2871, Optical Telescopes of Today and Tomorrow (21 March 1997).

[5] M. Robberto et al, "SAMOS: a versatile multi-object-spectrograph for the GLAO system SAM at SOAR," *Proc. SPIE* 9908, Ground-based and Airborne Instrumentation for Astronomy VI, 99088V (9 August 2016).