An engineered design of a diffractive mask for high precision astrometry

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ABSTRACT

AutoCAD, Zemax Optic Studio 15, and Interactive Data Language (IDL) with the Proper Library are used to computationally model and test a diffractive mask (DiM) suitable for use in the Gemini Multi-Conjugate Adaptive Optics System (GeMS) on the Gemini South Telescope. Systematic errors in telescope imagery are produced when the light travels through the adaptive optics system of the telescope. DiM is a transparent, flat optic with a pattern of miniscule dots lithographically applied to it. It is added ahead of the adaptive optics system in the telescope in order to produce diffraction spots that will encode systematic errors in the optics after it. Once these errors are encoded, they can be corrected for. DiM will allow for more accurate measurements in astrometry and thus improve exoplanet detection. The mechanics and physical attributes of the DiM are modeled in AutoCAD. Zemax models the ray propagation of point sources of light through the telescope. IDL and Proper simulate the wavefront and image results of the telescope. Aberrations are added to the Zemax and IDL models to test how the diffraction spots from the DiM change in the final images. Based on the Zemax and IDL results, the diffraction spots are able to encode the systematic aberrations.

Keywords: diffractive, astrometry, AutoCAD, IDL, Zemax, adaptive optics, exoplanet

1. INTRODUCTION

One of the many ways of detecting exoplanets is via astrometry: precisely measuring the positions of stellar objects. In order to obtain the level of accuracy necessary for such a measurement from a ground-based telescope, an adaptive optics system is usually added to the telescope just after the pupil to correct for atmospherically-produced aberrations in the imagery. However, these adaptive optic systems can add in their own systematic errors to the final images due to imperfections in the lenses and mirrors[2]. A proposed way to correct this is to add a diffractive mask (DiM) just before the adaptive optics[1].

This DiM consists of a flat, transparent lens made of fused silica with a hexagonal pattern of opaque dots lithographically applied to its surface. If the telescope is centered on a bright star, the light coming through the DiM will diffract, producing diffraction spots that spread out to look like six evenly-spaced spikes emanating from the central star[3]. Since these diffraction spots are produced before the adaptive optic system but after the atmospheric aberrations, any errors in the diffraction spots result from errors in the optics the light passes through after the DiM. These errors can then be measured from the diffraction spots and corrected for in any image taken by the same telescope with the same adaptive optics system.

The DiM is designed to fit in the Gemini South Telescope in conjunction with the Gemini Multi-Conjugate Adaptive Optics System (GeMS). Three different methods are used to computationally test the validity and effectiveness of the DiM in the Gemini system. First, a 3D model of the DiM and its mounting components is designed in AutoCAD to simulate the mechanical components of the instrument. This model can be used to determine how the DiM will fit into

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the GeMS bench as there are very tight space constraints. It also gives a visual representation of the optic that the other modeling programs do not provide. This is the model that can be sent to manufacturers once production is ready to begin.

Next, the DiM is added to a current Zemax model of GeMS to analyze how rays of light will propagate through the system. It is important to make sure that adding the slim piece of glass that the DiM consists of does not cause too much distortion to the rays propagating through GeMS. Zemax is a program that models how rays propagate through a system and how a point source of light will change as it passes through the various lenses. In this simulation, an aberration is added to one of the mirrors in order to test if the aberrations will be present in the diffraction spots produced by the DiM.

Finally, a more in-depth and accurate model of GeMS and the DiM is created in Interactive Data Language (IDL) to simulate the on-sky results. The Proper Propagation Library functions are used to help create the simulation. The entire Gemini telescope and the GeMS bench is modeled in IDL with the DiM added in just before the GeMS optics begin. A single, central star is simulated to see the effects of adding both the DiM and an aberration to one of the mirrors in GeMS.

2. METHODS

2.1. AutoCAD

AutoCAD is a program used to create two-dimensional (2D) schematics and three-dimensional (3D) models of various product designs. In this case, it is used to create 3D models of the various DiM and mounting designs as well as 2D schematics of the DiM spot pattern and the mounting designs. A 3D DiM model and 2D spot pattern are created based on Proposal V9 and then modified to suit the specifications of GeMS and the mounting structures. Different options for mounting structures and translation stages are then modeled in AutoCAD with the DiM in place. Finally, a custom mounting structure is proposed for the GeMS DiM.

2.1.1. The Diffractive Mask

The proposed DiM has a diameter of 120 mm and a thickness of 3 mm, is composed of fused silica glass, and the diffraction spot pattern is lithographically applied as opaque dots on the surface. The dots are each 0.121 mm in diameter arranged in a regular hexagon pattern with hexagonal side length of 0.94 mm. To maintain a clear aperture of 120 mm, the final design of the GeMS DiM that is to be placed just after the first fold has a diameter of 127 mm and is 3 mm thick.

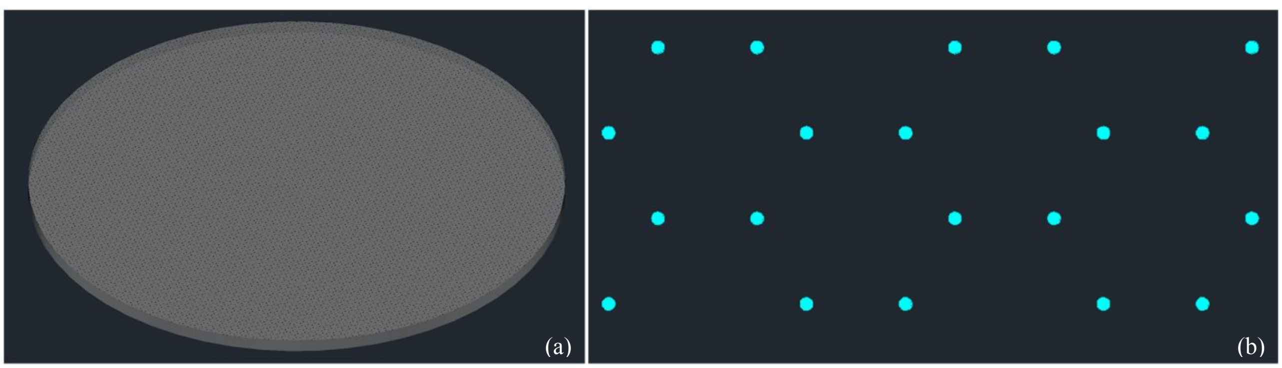

Figure 1: (a) 3D model of the 127 mm DiM. (b) The spot pattern.

The spot pattern is designed in AutoCAD using circles, the mirror tool, trimming, and hatching. First, one hexagon of circles is created and then mirrored to build a small portion of the full pattern. That portion is then mirrored to create a bigger portion. Each consecutively larger portion is mirrored until there is a 150 by 150 mm square of pattern. A 127 mm diameter circle is then placed in the center of the pattern. Any spots that overlap the edge of the larger circle are trimmed so that only the portion of the spot that is inside the large circle remains. The spots lying completely outside the circle are deleted. A solid hatch is applied to the inside of the spots. The glass portion of the DiM is modeled by a solid cylinder and the spot pattern is centered on the surface of the DiM.

2.1.2. The Mounting Structure

Various kinematic mounts and translation stages are imported into AutoCAD and assembled with the 127mm DiM and 6M screws in place. The mounts and stages are imported as .sat files and then converted into 3D drawings; the DiM is represented as a plain, solid cylinder without the spot pattern. Ultimately, the 127 mm (5 in) diameter of the DiM proves to be a limiting factor in finding a proper kinematic mount as most optical mounts are designed for 4 in diameter or a 6 in diameter, rarely in between. A possible solution is to use an adjustable mount but this would take up more space than necessary in the already spatially-confined GeMS bench and may not properly constrain the DiM. This leads to the necessity of a mount that fits the DiM as close to perfect as possible so either an exactly 127mm-diameter mount should be purchased or a custom mount needs to be designed.

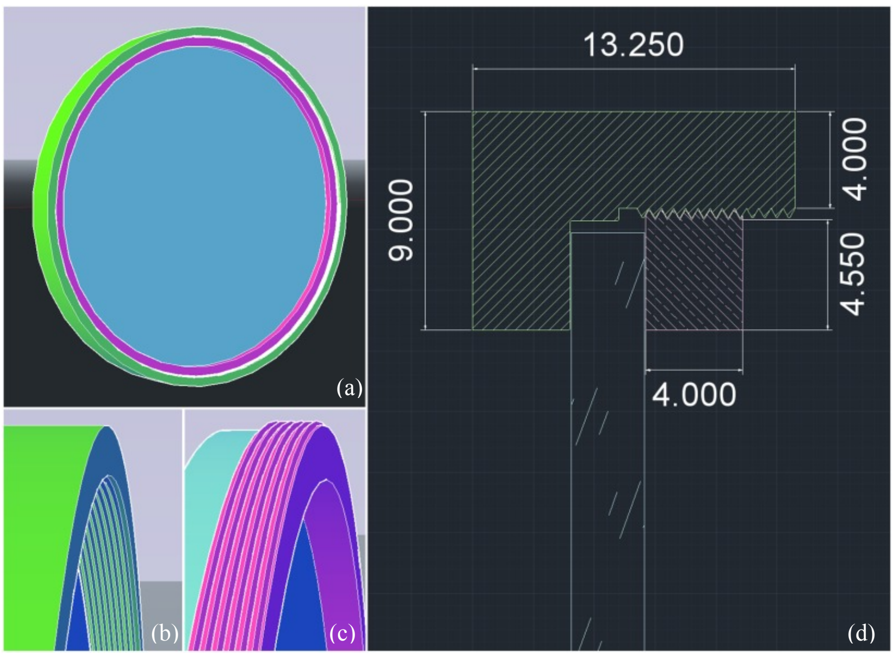

Figure 2: (a) A 3D model of the proposed custom mount. (b) The threaded mount. (c) The threaded retaining ring. (d) Schematic of the custom mount; dimensions in mm.

Figure 2 shows a portion of a possible custom mount for the DiM: a threaded retainer can be used to secure the DiM to the mount. Many of the other mounts use screws, clamps, or retaining rings to secure an optic. A retaining ring may be the best solution for the DiM because it allows for easy installation or removal of the optic. The retaining ring also has the quality of being adjustable to different thicknesses of optics and could accommodate an O-ring for centering of the DiM or adhesive to permanently secure the DiM to the mount[4]. Kinematic aspects still need to be added to the mount as well as a design for the base and the translation stage. The base can be deigned to work perfectly with a pre-purchased translation stage or can be designed to accommodate what a purchased translation stage may lack.

2.2. Zemax Optic Studio 15

Zemax Optic Studio models optical systems via ray tracing. Point sources of light can be added to the field of view and their rays traced to the final image plane. The DiM is added to an already-established Zemax model of GeMS with a three by three array of 1 micron wavelength emitting stars in the eighty by eighty arcsecond field of view. However, due to the limitations of Zemax, the DiM cannot be modeled with the hexagonal spot pattern. A diffractive grating rotated in increments of forty-five degrees is used (see figure 3) to produce first order diffraction spots in the same place on the image plane as the eight outer stars. The equation for the separation between lines, equation 3, can be derived using the Fraunhofer diffraction equation, equation 1, assuming that sin(θ) = θ at small angles, and multiplying the angular separation by the pupil magnification, equation 2.

$$d sin\theta = n\lambda \quad (1)$$

$$M = \frac{D}{s} \quad (2)$$

$$dM sin\theta = n\lambda \rightarrow \frac{dD\theta}{s} = n\lambda \rightarrow d = \frac{\lambda sn}{\theta D} \quad (3)$$

Where d is the separation between lines in microns, θ is the angular separation between the central star and the diffracted spot in radians, n is the diffraction order number, λ is the wavelength in microns, M is the pupil magnification, D is the diameter of the primary mirror in meters, and s is the diameter of the laser guide star image on the pupil in meters. θ needs to be multiplied by the square root of 2 for a diffraction spot in the corner of the three by three field. The inverse of d is the lines per micron used for the diffraction grating. For a diffraction spot on axis, the DiM diffraction grating is 0.033937 lines/micron and for a diffraction spot forty-five degrees from an axis, the diffraction grating is 0.047994 lines/micron.

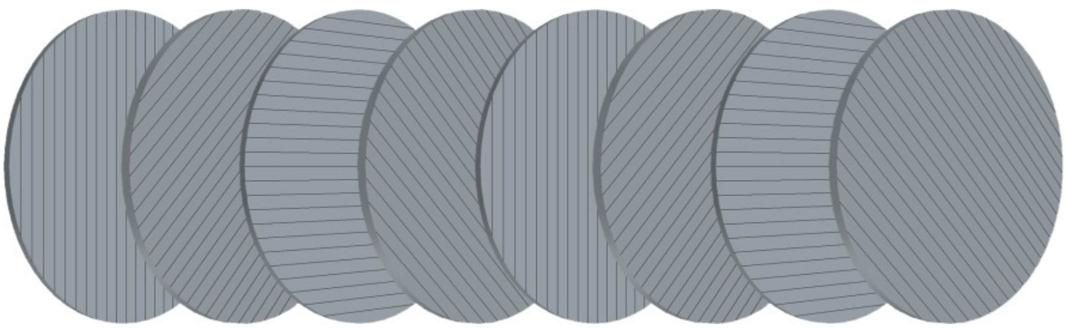

Figure 3: A 3D model of the diffractive grating and simulation process used in Zemax.

The DiM is inserted into three different locations: after the first fold, after the 80 mm pupil, and as a filter in the science camera filter wheel. Our ideal location is after the first fold and thus is the most thoroughly modeled version. A Zernike representing an astigmatism is added to one of the deformable mirrors (DM9) to test the effects of aberrations on the system. Spot diagrams, visual representations of the resulting star images on the image plane, are produced for the test cases with and without the mask, with diffraction and without diffraction, and with and without the astigmatism (see Figures 5a and 5b).

2.3. IDL and Proper

IDL is a programming language used for data analysis and visualization. The Proper Propagation Library is a collection of IDL functions used to model optical systems. Using the Proper functions, GeMS is modeled in IDL, initially as a perfect system. In this instance, only one wavelength is modeled at a time. A matrix of opaque circles following the hexagon pattern shown in Figure 1b makes up the DiM. The Zernike Proper function adds astigmatism to DM9, the same way astigmatism is modeled in Zemax. In order to create the star field, the central star that Proper propagates is offset and then tilted multiple times (Figure 4c). The final image data from all the stars is averaged together to create one image with the entire star field. Positions for the stars are chosen based on the locations of the diffracted spots, which form a hexagon pattern in the final image and thus, the star field is not a square array like in the Zemax model, as seen in Figure 4c.

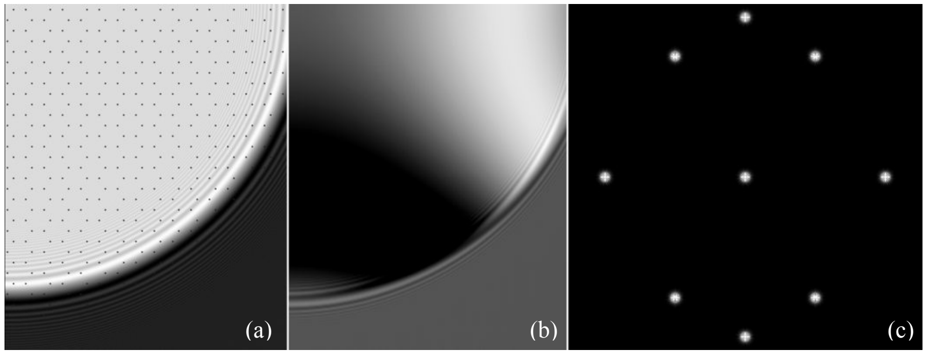

Figure 4: (a) A portion of the wavefront just after it propagates through the DiM. (b) A portion of the wavefront just after it propagates through DM9 with the astigmatism and no DiM. (c) The star field.

The model is propagated using four different combinations of conditions: (1) central star only, DiM in place, no astigmatism; (2) central star only, DiM in place, astigmatism on DM9; (3) entire star field, no DiM, no astigmatism; (4) entire star field, no DiM, astigmatism on DM9. All four resulting images can be compared to see how the diffraction from the central star is related to the surrounding stars in the star field when astigmatism is added.

3. RESULTS

Based on the Zemax and IDL models of the DiM, the diffracted spots are able to encode aberrations on the instruments in GeMS. The Zemax spot diagrams of the diffracted spots are shown in Figure 5 with and without astigmatism added. Simulated images from IDL and Proper are shown below the spot diagrams in Figure 5. Both models are run with a wavelength of one micron. With the only change to the system between the first column and the second column in Figure 5 being the added astigmatism, we know that the astigmatism is influencing the diffraction spots.

Further modifications to the models must be made to test the relationship between the diffraction spots and the reference stars. This would include incorporating the entire spectrum of wavelengths and comparing the diffraction spots to the reference stars with and without aberrations. Different dimensions for the spot pattern and DiM can also be tested to ensure that the entire field of view is evenly distributed with diffraction spots.

4. SUMMARY

While adaptive optics correct for distortions from the atmosphere, they cause their own systematic distortions to the data. Adding a DiM to the optics system of the telescope just before the adaptive optics system produces diffraction spots that encode the systematic errors and enable the correction of those errors. The DiM was computationally tested for the Gemini South Telescope and its adaptive optics bench, GeMS. First, it was designed in AutoCAD to test for fit within the bench. This also provided a visual model of the DiM. Unfortunately, the AutoCAD model of the DiM could not be tested within the GeMS bench because the bench models were not available for this test yet.

Next, the DiM was modeled in Zemax Optic Studio 15. This tested how the light rays would propagate through the entire telescope system with the DiM added. The DiM was shown to add minimal distortion and the diffraction spots did adopt an aberration added to one of the mirrors. However, Zemax was not able to model the hexagonal dot pattern and a simple grating was used instead, making the results less accurate to the proposed design.

Finally, the telescope system was modeled in IDL to simulate the final on-sky results. The pattern on the mask was able to be properly modeled in IDL and the diffraction spots in the final images correspond with the theoretical outcome. When an astigmatism was modeled on one of the mirrors, a change in the diffraction spots can be seen. One drawback of this simulation is that all wavelengths were not modeled. In order to better test the effectiveness of the diffraction spots, a spectrum of wavelengths should be tested.

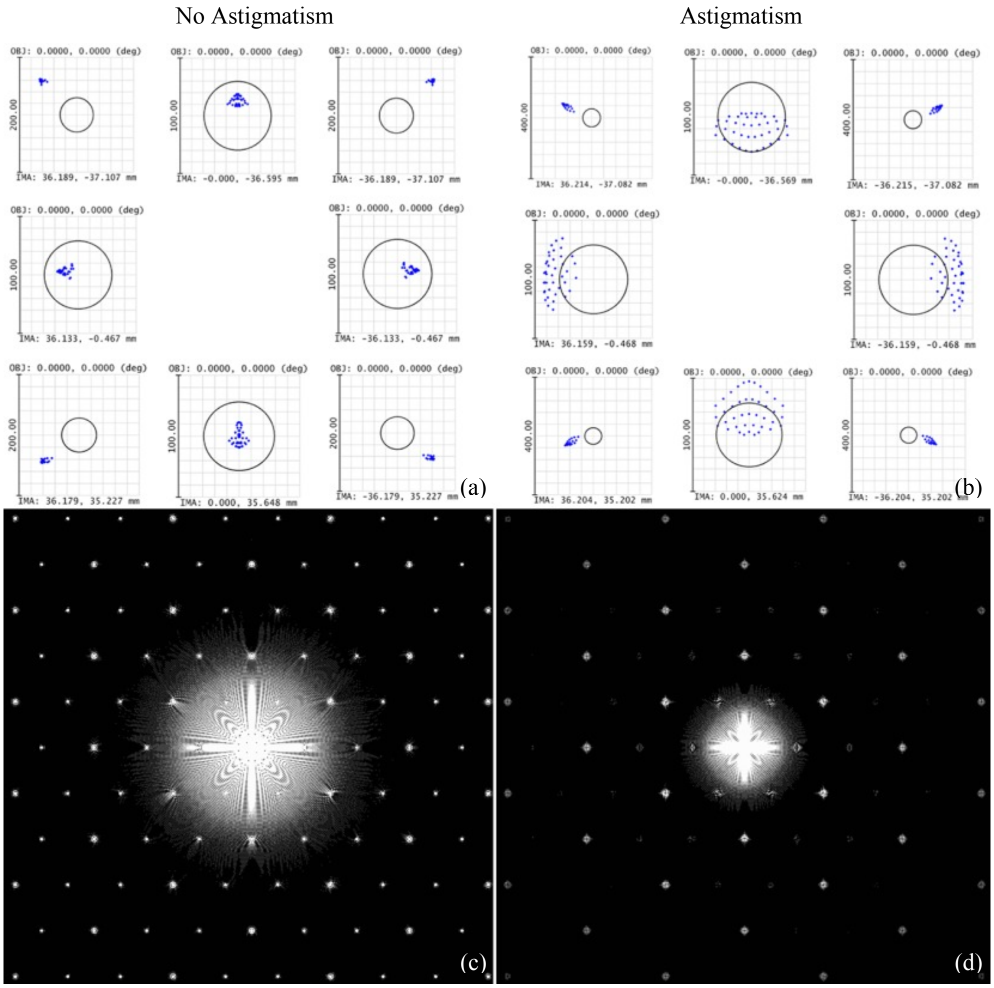

Figure 5: Resulting diffraction spots with and without astigmatism added to DM9. Figures a and b are Zemax diagrams. Figures c and d are simulated on-sky images from IDL.

5. ACKNOWLEDGEMENTS

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