Optical Design for an Infrared Multi-Object Spectrometer (IRMOS)

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ABSTRACT

The optical design for an Infrared Multiple Object Spectrometer (IRMOS) intended for Astronomical research is presented. To accomplish spectroscopy of multiple objects simultaneous, IRMOS utilizes a Micro-Mirror array (MMA) as an electronically controlled slit device. This approach makes object selection simple and offers great versatility for performing spectral analysis on many objects within a field location. Furthermore, it allows a field location to be imaged without spectra prior to object selection. The optical design of IRMOS has two distinct stages. The first stage reduces an f/15 incoming beam to f/4.6, with a tilted focal plane located at the MMA (the MMA removes some of the tilt of the focal plane, since the micro-mirrors tilt individually). The second stage consists of the spectrometer, capable of resolutions of 300, 1000, and 3000 in the astronomical J, H and K bands. This stage transforms the tilted focal plane into a collimated pupil on a grating, and then re-images onto a HAWAII detector. When used with the Kitt Peak National Observatory 4 meter telescope, a plate scale of ~0.2 arcseconds per pixel is realized at both the MMA and the detector. A total of 6 mirrors are used, two flat fold mirrors, two off-axis concave aspheres, one off-axis convex asphere, and one off-axis concave biconic mirror. The selection of a biconic surface in this design helped reduce the overall size of the instrument by reducing the size and number of necessary mirrors, simplifying alignment.

Keywords: IRMOS, biconic, optimization, merit function, diamond turning, diamond machining, gratings, Digital Micro-mirror Device, Micro-Mirror Array, resolution, spectrometer, multi-object, infrared

1. INTRODUCTION

Spectrometers enable key astronomical measurements, such as velocities of galactic components, composition of stars, nebula chemical makeup, and age. They operate by allowing a very tiny portion of the sky, typically the size of roughly an arc second in diameter, to pass into a set of optics that distribute the spectrum of the light onto a detector so that measurements of intensity versus wavelength can be made. Since the field of view of a spectral source is typically so small, it is desirable to be able to acquire spectra on many objects during a single observation. These types of spectrometers are known as Multi-Object Spectrometers. They allow for more efficient use of valuable telescope time by permitting spectral observations on many objects simultaneously.

Historically, multi-object spectrometers have fallen into one of two categories. Some spectrometers offer large fields of view with a significant amount of flexibility for object selection. These typically use either custom-made masking plates or robotically positioned optical fibers. The masking plate spectrometers are very labor intensive (although cost effective when comparing with single-source observations), and require a well-known object field prior to fabrication of the plates. The typical procedure involves a survey of field locations by an imaging device. The images are analyzed to determine object locations, and then a plate of sheet metal is custom drilled, providing a slit mask. For infrared applications this may also require insertion of the mask into a cryogenic Dewar. Spectrometers that use robotically positioned optical fibers tend to be very complex in design, and very expensive to build, implement, and maintain. For these spectrometers, each individual optical fiber is positioned by a servo mechanism. These types of spectrometers are also very challenging for infrared applications, since the mechanisms and fibers would all need to operated at very cold (less than 150K) temperatures in an evacuated dewar. Integral field spectrometer, while simpler in design, offer only limited fields of view, and are not well suited for survey type applications. These spectrometers might use something like an optical fiber bundle that maps to a vertical arrangement of fibers to be imaged by the spectrometer.

With space born telescopes such as NGST, wide field survey capability is desirable, but not attainable with previous wide-field multi-object spectrometers. Mask plates are not an option, since there is no access to the instrument for changing the plates. A system that automatically fabricates and installs mask plates could be conceived, but the complexities of such a system are cost prohibitive, and prone to failure. Robotic systems that position optical fibers have service problems that

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make them undesirable for spaceflight. The concept of using a micro-mirror array for the mask of a spectrometer alleviates many problems for a multi-object spectrometer, whether or not the spectrometer needs to be mounted to a space based telescope.

Texas Instruments has developed Micro-Mirror Arrays (MMAs), typically used for digital light projection systems, called a Digital Micro-mirror Device, or DMD. These MMAs have micro-mirror spacing of 17 microns, with each mirror being 16 microns square. The micro-mirrors are individually addressable in one of two tilt configurations. By using this device as the mask of a spectrometer (operating in reflection), the micro-mirrors can be addressed to send light into the spectrometer, or to a light dump. Furthermore, the actual geometry of each "slit" that is created by the MMA can be adjusted. For example, a slit could consist of a 2x2, 1x3, or 2x4 set of mirrors, or any other combination of mirrors, tailored to the object being observed.

Since this concept has advantages for an NGST instrument, we have undertaken to construct such an instrument for a ground-based observatory, and test this approach. Building such an instrument not only allows for testing of the technology, but also provides a highly useful, facility-class instrument for Kitt Peak.

2. METHODS

2.1 The Telescopes

IRMOS is designed for operation at the 4m and 2.1m telescopes of the Kitt Peak National Observatory. The 2.1m telescope provides a wider field of view while the 4m telescope offers for greater sensitivity. Each of these telescopes has an IR optimized secondary mirror, operating at f/15 (4m) and f/14.7 (2.1m). Such focal ratios are not well suited for IRMOS, since the plate scales at the telescope focal plane are just too small: a typical star would overfill many pixels, and require a large number of micromirrors for a slit. It is desirable to have plate scales of roughly 0.2 arcsec/pixel (on the 4m telescope), so an f/4.6 beam incident on the MMA will be required (the telescope is actually 3.8m diameter). Good seeing conditions at Kitt Peak can deliver 0.6" resolution, and a point object would therefore cover a three mirror diameter area at the MMA.

Since the most important science would be conducted on the 4m telescope, the design of this instrument was optimized for this telescope. The 4m telescope is sufficiently large to accommodate a very large and heavy instrument, and does not present much of a design challenge as far as instrument size is concerned. The 2.1m telescope, however, does have some size and weight limits that had to be addressed. One of the more important considerations while designing this instrument was to make it small enough (and therefore hopefully light enough) such that it could be used on the 2.1m telescope. Image quality still had to be very good on the 2.1m telescope, since most of the engineering during commissioning of this instrument would occur on this telescope. Furthermore, there are opportunities for science to be conducted with this instrument on the 2.1m telescope when it is not being used on the 4m.

2.2 Micro-Mirror Array

The use of an MMA in a spectrometer presents some design challenges. There are two configurations for each micro-mirror, "on" or "off". These two configurations are tilted +/- 10 degrees with respect to the backplane of the array. The micro-mirrors do not tilt along the local x or y axis. Rather, they tilt along a diagonal. This creates a titled, distorted focal plane that enters the spectrometer. There are essentially three beams to manipulate in the design of this instrument, the incident beam, and the two reflected (on and off) beams. Since each beam will have a focal ratio of 4.6, managing the spatial complexities of these beams can also present problems.

A Texas Instruments Digital Micromirror Device with 848 x 600 pixels was chosen for this instrument. Resulting in a field of view of ~170 x 120 arcseconds on the 4m telescope and ~300 x 210 arcseconds on the 2.1m telescope.

2.3 Detector

A Rockwell Science Center HAWAII-I detector (HgCdTe) was chosen as the imaging device for this instrument. This detector has 1024 x 1024 pixels, 18.5 microns each. It is desirable to maintain essentially the same plate scale in the spectrometer as in the front end for the purposes of mapping the MMA onto the detector (simplifying slit configurations). To achieve this, an adjustment of focal ratio from f/4.6 to f/5.0 is necessary in the spectrometer. This arrangement uses approximately 600 pixels on the detector vertically, and the spectra are spread vertically, to maximize the amount of spectra that can be imaged onto the detector.

2.4 Aluminum Mirrors

All powered optics in this design were initially chosen to be mirrors, since this eliminates the need for correction of chromatic aberrations, and simplifies the thermal problems associated with cooling different glasses with different coefficients of thermal expansion. By choosing mirror surfaces, and keeping the sizes of the mirrors under a certain value, diamond turning an aluminum substrate is an available method of fabricating the optics. Since aluminum is a common material, and a good choice for the optical bench, making aluminum mirrors allows the design to expand and contract thermally with minimal variation in optical performance.

Since IRMOS is an infrared instrument, it is housed within a cryogenic dewar, and maintained at ~80K. Because of the extreme temperature difference from fabrication temperature and operation temperature, it is desirable to choose a material that has a very well known coefficient of thermal expansion. This allows a warm prescription to be generated such that after the warm optics are cooled to operating temperature they will match the design prescription. Aluminum makes a good choice for a substrate material because it's properties are very well known in the region of interest.

2.5 Gratings and Resolution

IRMOS was designed to operate in the astronomical J (1.1 μm), H (1.6 μm) and K (2.2 μm) bands, with spectral resolutions ($\lambda/\delta\lambda$) of 300, 1000, and 3000 in each band. Knowing the size limitations of the overall instrument (to be capable of being installed on the 2.1m), the grating configurations for this instrument were presumed to require groove densities ranging from 33 to 600 lines per millimeter. One grating position has a mirror, for the purposes of imaging the MMA onto the detector. This allows the field to be imaged (since the MMA has an image of the field location at it's surface) for the purposes of object selection and slit configuration.

Like the mirrors, the Gratings are made of aluminum. They are replica gratings, and will have a gold surface for high reflectivity. An initial review of gratings offered by some manufacturers showed that a 50mm diameter effective area on the gratings would be a good design consideration. Therefore, the design of the optics proceeded with a limitation of a 50mm diameter illumination footprint on the gratings.

2.6 Software & Design

For the design and optimization software, Zemax was chosen. To begin, a user-defined surface had to be written to simulate the surface of the MMA (this user-defined surface was developed by E. Mentzell). This surface was approximated by a series of tilted flat squares, each 17 microns wide. Although this does not simulate light that is lost between the mirrors, it was an approximation that was acceptable for design purposes.

The first stage of the design of this instrument began with the "front end" optics, or the focal reducer. The goal was to convert the f/15 beam of the telescope to f/4.6. This set of optics was also chosen to be downstream of the telescope's focal plane, with the assumption that this instrument could be installed downstream of focus more easily than upstream. In addition, a tilted focal plane at the MMA was desired for the purposes of managing the off beam. A 10 degree angle of incidence was chosen such that most of the "off" beam would be reflected back in the direction from which it came. This stage was designed by developing a Zemax merit function that optimized RMS spot radius, a working focal ratio of 4.6, and a 10 degree angle of incidence on the MMA surface (the last surface). To prevent the optical path from folding onto itself, minimum angles of incidence were implemented in the merit function. During the design process of this stage, the MMA was actually not used, because user defined surfaces result in slower optimization runs. Upon completion of this stage, however, the surface model of the MMA was installed.

The second stage of optics is the spectrometer. This stage utilizes the "on" beam by collimating it onto a diffraction grating, essentially at a pupil. The light reflecting off of the grating is then re-imaged onto a detector. Although quite simple in concept, this stage of the instrument was very complicated to design. It is in this stage of the instrument that the effects of the MMA, such as image tilt and distortion, become noticeable. Furthermore, the gratings add considerable astigmatism to the optical path. A slight change in focal ratio was necessary, because the detector has pixels measuring 18.5 microns, and maintaining a 1:1 re-image of the MMA on the detector was desired.

Writing a merit function to satisfy all of these requirements was somewhat complex. A multiple configuration design was employed due to the different gratings. The design of this instrument was performed under sequential ray tracing routines, and since each different grating required a different tilt, all of the downstream optics had to be adjusted as well (the downstream optics can't move for different configurations). The merit function started with the basic optimization for RMS spot radius. Added to this were operands to control the positions of the optics for each grating configuration, to make sure they do not move for the different configurations. These operands extracted the global coordinates of the vertex of each mirror, and compared them with the values for a single configuration (for example, a five configuration file would compare the global coordinates of the first configuration with the coordinates of all the subsequent configurations).

Since the gratings needed to be 50mm in diameter or less (illuminated area), two operands were added to control the footprint at that surface. One of these operands limited the diameter of the illumination footprint to within 50mm. The other operand assured the light bundle hitting the surface was well centered with the vertex. This latter operand was required to prevent the beam from moving off-axis, which can distort the diameter of the required illumination footprint because the radius is measured from the vertex of the surface to the intersection of the outermost ray.

Since the optics are all diamond turned aluminum, there is a limit to the size of a parent surface (the term parent surface will be used to describe the axially symmetric surface from which the off-axis component is obtained). Even though the illuminated size of the mirror might be small, since we are using these mirrors off-axis, the size of the parent surface needs to be controlled so that these mirrors can be fabricated using a well-known process. Therefore, operands were added to control the size of each parent surface.

The overall size of this instrument had to be controlled. To do this, limits to path length were implemented. The angle of incidence at each surface had to be controlled, to prevent the optical path from folding onto itself. Typically, minimum angles of incidence were implemented, as opposed to setting a preferred angle of incidence. This method assists the optimization routines in finding a solution more quickly. Since spectra needed to be aligned vertically onto the detector, several operands were used to modify the orientation of the detector for optimal spectral orientation. The x-coordinates at the detector of several different wavelengths were compared, and their difference was minimized. The angle of incidence on the detector was allowed to be a variable during optimization. This allows the focal plane to be tilted, and quickens optimization. No parameters were used to encourage a collimated pupil at the grating. Since several different grating configurations existed, optimization occurred over these different configurations, and it was presumed that such parameters would not be necessary.

3. RESULTS

3.1 The Front-End Optics

This merit function was quite simple, and design of this stage of optics took very little time. The result was a set of two off-axis aspheres, the first being convex, and the second being concave. A fold mirror was added to reduce the overall length of this stage of the instrument, and is downstream of the second mirror. Although neither of these two off-axis aspheres is easy to test, they are relatively easy to fabricate. Image quality on the MMA resulted in RMS spot radii of approximately 10 to 15 microns over most of the field of view, and degrades to 25 microns at the corners. This is better than the requirement of 25 microns over most of the field of view (and up to 34microns at the corners) for this stage of the optics, and allows some margin for fabrication and alignment tolerances. For reference, an airy radius for a diffraction limited system would be 7 microns.

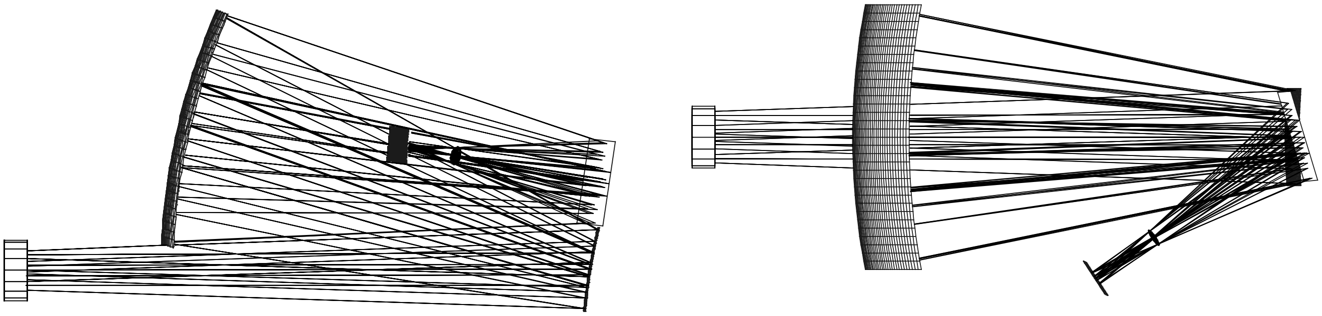

Figure 3.1. Layout of the front-end optics, showing a side view (left) and a top view (right). At the far left in each picture is the dewar window. The focal plane of the telescope is approximately 5” in front of this window.

A pupil plane is developed in front of the DMD, creating a good location for a cold stop to block radiation emanating from the region surrounding the primary mirror of the telescope. Due to oversizing of this cold stop to help alignment tolerances, total light loss at this surface is roughly 15%.

3.2 Spectrometer

The merit function for this stage of the instrument took considerable trial and error to develop. Using a design involving 5 grating configurations, and a user-defined surface slows optimization routines considerably. During the design of this stage, the merit function had to be modified frequently (refer to sect. 4.1) to accomplish the desired results.

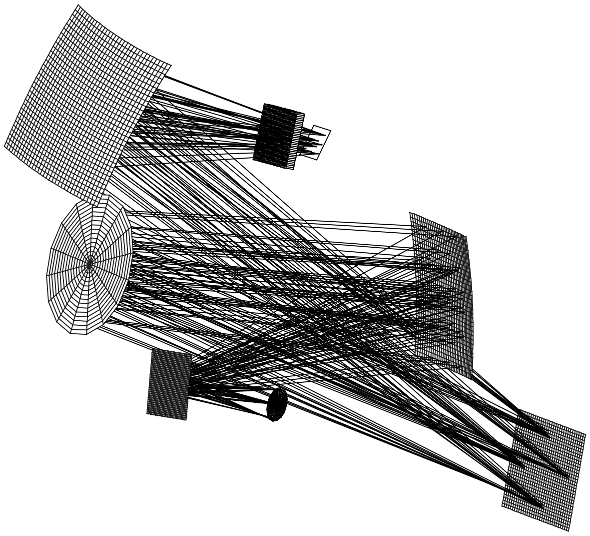

Figure 3.2. The layout of the spectrometer. Included in this view is the pupil from the front-end optics, and the DMD can be seen as the square shape in the lower-left side of the picture.

The resulting optical design for the spectrometer is compact, but required the use of a special surface for the imaging mirror. It was presumed that a mirror that could correct for considerable astigmatism would be required, and a toroidal shape was attempted, but image quality never quite reached the level that was required. By using a biconic surface, however, acceptable image quality was attained. A biconic surface is very similar to a toroidal surface. It has different radii in the x and y directions. However, unlike a toroid, it has different conic values in the x and y directions. A biconic with one conic value set to zero was also attempted (a cross between a toroid and biconic), but did not meet the image quality requirements.

The resulting design involves 2 powered mirrors, a grating, and a fold mirror. Image quality met requirements with a small amount of margin for fabrication tolerances. Spot sizes were less than 3 pixels in diameter across nearly the entire field of view in most grating configurations. Using the highest resolution grating resulted in the worst spot sizes, getting up to 4 pixels in diameter at the corners.

The resolution modes required for this instrument include 300, 1000, and 3000 in the J, H, and K bands. To achieve this, gratings with groove densities between 60 and 600 were required. Mirror sizes for this stage of the instrument are modest, with sizes of roughly 3” x 4” for each mirror except the fold mirror, which was smaller. Although no operands were written to encourage either a pupil or a collimated beam at the grating, these features did develop in the final design.

4. DISCUSSION

4.1 Merit Functions and Optimization routines

The merit function is basically a tool that the optimization process uses to judge whether improvements have been made. Zemax has two optimization routines that use the merit function, the “local” and “global” optimizers. The local optimizer is considerably faster than the global optimizer. However, the global optimizer is more thorough, and is therefore often capable of determining a much better design than the local optimizer. The optimizers can be thought of as a ball rolling down a hill, with the shape of the hill being defined by the merit function, and the direction of the ball movement being a variable. The goal is to get the ball to roll to the lowest point on the surface. Using the local optimizer, the ball will roll until it finds a local minimum. This minimum is not necessarily the lowest minimum, but it is found relatively quickly. The global optimizer will give the ball a shove out of it's local minimum, to see if it can roll to a lower minimum elsewhere. It will forever continue to increase the strength of that shove until it finds a new minimum (in which case it will start over again), or until the routine is halted. The merit function can be thought of as an attempt by the user to increase the size of some of the bumps on that hill, or increase the depths of some of the local and global minima. This can help prevent the ball from rolling into places it should not go (for example, non-physical solutions). However, there are instances for which this can greatly hinder the ability to find the best solutions. It is not uncommon that the best solution for a design might involve working through territory that is not physical. In addition, the local optimizer can typically find some high performance solutions that are non-physical in a relatively short period of time. While this may seem pointless, it is often the case that a slight decrease in performance may mean the different between a physical and non-physical solution, and a good solution can be found quickly by allowing some undesirable intermediate configurations. A good place to start with a merit function is to make it very general, and allow some non-physical solutions. Start with the very basic functions that need to be attained, and optimize for them. Then, the merit function can be altered to work toward a more realistic solution. This can give indications of trouble areas in the layout, and allow a designer to understand why a solution is difficult to find.

The spectrometer stage of this instrument was designed in this manner. The basic functions as described in section 2.6 were written into the merit function. Initially, the optics were allowed to fold on top of each other, as no constraints on angle of incidence or locations of components were implemented. As expected, the initial optimization returned a solution that was non-physical. However, the merit function was then modified with the more stringent real-world requirements. By noticing the path that the design took to get to a real solution, some trouble areas became apparent, and modifications to the layout were made to accommodate the problems.

4.2 Biconic Surfaces

Biconic surfaces are different from the types of optical sufaces that are commonly fabricated. Typically, a surface must have an axis of revolution to be easily fabricated. This is especially true for traditional diamond turning techniques used for making aluminum mirrors. However, machines have been built to allow the fabrication of these free-form types of surfaces, with some limitations. The technique is diamond machining, and typically involves machines with at least 4 degrees of freedom (three translational and one rotational), such as the Nanotech 500FG, a machine produced by Moore's Nanotechnology division.

The limitations associated with making these types of surfaces are related to the degree of complexity of the surface and the amount of time and money that is available to fabricate the component. These machines typically can not handle fast changes in curvature without requiring large fabrication times. For the biconic in this instrument, the radii of curvature are sufficiently similar, differing by approximately 10%, and the conic values are both similar. After contacting a couple of vendors that have a machine capable of making this mirror, it was determined that the cost would be acceptable. However, the fabrication tolerance requirements for this mirror might be difficult to achieve with such a process, and as of the writing of this paper, the mirror has not been produced. Verbal interaction with some companies that have this machine suggests that similar mirrors have been made with results that would be acceptable for this instrument, but the margin between fabrication tolerances that are attainable and the fabrication tolerances that are acceptable is very narrow.

4.3 Testing

Testing the optics in this instrument is not a trivial process. The first mirror in the spectrometer is a prolate ellipsoid, and is not so difficult, but the other mirrors are a concern. Two of the mirrors are oblate ellipsoids, and one of them is convex. These are difficult surfaces to test. The biconic mirror will also be difficult to test.

There are two methods that are being investigated to test these mirrors. One method is the use of computer generated holograms to interferometrically test the figures. This method is the most thorough method, but is quite expensive. The setup is time consuming, and the components are exspensive. However, this gives a detailed view of the surface.

Another option available is the use of Profilometry. Machines have recently been built that allow a surface to be measured one point at a time. By mapping out several hundred points, a profile of the surface can be generated. This process is much less expensive than the use of computer generated holograms, but does not offer the detail of an interferometric map. Profilometry is not as accurate, although precision is quite high (details as small as a few tens of nanometers can be detected). Accuracy degrades over long distances (in excess of a couple inches), under which effects such as machine table sag can become apparent.

For this instrument, the use of profilometry will be used in combination with CGH testing, for a thorough understanding of any surface errors, and as a backup means of verifying one setup as compared with the other.

5. CONCLUSIONS

The use of an MMA in a spectrometer is a novel means of dealing with an old problem: it allows multi-object capability combined with a relatively wide field of view and immediate acquisition of spectra after imaging a field location. The optics required to build such an instrument, although challenging, are not unrealistic, overly bulky, or too expensive, making such an instrument an attainable endeavor.

Given the complexities that an MMA introduces into a spectrometer design, considerable time should be spent developing an optimization plan. Acceptable trade-offs in the layout of the optics should be known before limiting the optimization routines to parameters that are overly strict.

6. ACKNOWLEDGEMENTS

We would like to thank Moore's Nanotechnology division for their assistance in helping us find a manufacturer capable of making the Biconic Mirror.

We would like to thank Werner Preuβ and the Institute for MicroMachining (Labor Fur Mikrozerspanung) at the University of Bremen in Bremen, Germany for their assistance with fabrication issues for the Biconic Mirror. LFM has a Nanotech 500FG machine capable of making this mirror, and they have provided us with invaluable information regarding their expertise with this machine, and the processes of diamond machining, diamond turning, and profilometry.

The optics for this instrument was designed entirely with the use of Zemax-EE.

We are grateful to Texas Instruments for providing us with detailed information regarding the DMD.

IRMOS is being built by a collaboration between the Space Telescope Science Institute, NASA's Goddard Space Flight Center, and the National Optical Astronomy Observatories.