Optical Design of an Infrared Multi-Object Spectrometer Utilizing a Free-Form Optical Surface

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ABSTRACT

The optical design for an InfraRed Multi-Object Spectrometer (IRMOS) is presented along with fabrication and metrology results. IRMOS presents a challenging set of design problems through the use of a micro-mirror array (a Texas Instruments DMD) and a multi-stage optical layout. This instrument is unique in that it is one of the first principal investigator-class astronomical instruments that make use of a free-form optical surface as one of the key components of the design (i.e., the camera mirror). This surface type is biconic, and allowed for a substantial reduction in the overall size and weight of the instrument, yet allowed all of the system requirements to be met. The design has been fabricated and the designed performance shows a strong correlation with the as-built instrument. The biconic mirror was fabricated using a Precitech Freeform precision diamond machining center, with results meeting the manufacturing tolerances allocated. This challenging instrument has shown that free-form optical surfaces can be applied to research-grade instrumentation, and allows for greater flexibility in the design.

INTRODUCTION

Research-grade instrumentation in optical astronomy has long been based on optical designs that use surfaces that are rotationally symmetric. Most refractive designs use lenses with simple spherical radii of curvature for each side, and the lenses are commonly used on-axis (the chief ray of the optical design goes through the center of curvature of the lenses). In the Infrared, however, some instruments are finding advantages by using mirrors rather than lenses, for a variety of reasons. Reflective designs for such instruments often use off-axis surfaces, but the parent surface is still rotationally symmetric. As the functionality of these instruments increases, so does the complexity of the optical requirements. Using the historical methods of optical design, it is becoming increasingly more complex to accommodate the requirements of some instrumentation without involving a large number of optical surfaces and therefore large and heavy instrumentation enclosures. For instrumentation that is operating in the infrared, the entire optical assembly needs to be cooled to cryogenic temperatures (typically 80K or below) to reduce or eliminate noise due to thermal emission of the instrument. This adds mechanical constrains to an instrument, on top of the already difficult optical constraints.

One instrument that is a research-grade, facility class instrument is called IRMOS (Inra-Red Multi-Object Spectrometer). Historically, spectrometers have had a slit separating two stages of an optical layout. The first stage of the layout is typically a focal reducer, focal expander or re-imager, depending on the requirements. The purpose is to image a source onto a slit. This slit allows light from within a very narrow field width to enter the spectrometer, acting as a field stop. The spectrometer then breaks up this light into its spectra and images the spectra onto a detector. Some spectrometers have multi-object capability, which have multiple slit locations at the input of the spectrometer. These types of spectrometers are usually complex to use or have limited functionality due to the need to install a slit with precisely defined opening locations. Commonly, one needs to install a slit-plate prior to observing spectra. The slit plate has to be precisely manufactured to match the plate scale of the front-end optics of the instrument. One plate is good for observing only under the conditions for which it was designed (i.e. one small part of the sky only), so this is not an efficient method of getting spectra from a variety of sources over the course of an evening's observations. Some spectrometers that have been designed to alleviate this problem have had very complex arrangements, such as robotic positioning devices to place fiber-optics at various field locations, or integral field devices that take a small area and spread the spectra from that entire area into a 2-dimensional array of spectra. These solutions all have their limits. IRMOS is a spectrometer designed to alleviate some of these issues.

The general concept behind IRMOS is to have a programmable slit for the spectrometer. This allows both multi-object capability and user selectable source locations on-the-fly. There is no need to wait for a mask to be manufactured and installed. There are no moving parts (per se) associated with selecting various objects within a field of view for observation. The field of view is also substantially wider than a comparable integral-field device, and virtually eliminates all issues related to using fiber optics in a research grade instrument (such as spectral attenuation that needs to be calibrated). To accomplish this, a Texas Instruments Digital Micromirror Device (DMD®) is implemented as the field programmable slit. The DMD is an 848x600 "pixel" device, with each micro-mirror measuring 16 microns square, and spaced 17 microns between mirrors (center-to-center).

The TI DMD imposes some interesting complexities to the optical design. Most notable is that the reflectance from the "surface" is not like that from a normal surface. The individual mirrors tilt about their own 45º axis, so from the viewpoint of the spectrometer, this is a tilted object plane. Furthermore, the tilting has an azimuthal orientation of 45º so the object plane also appears skewed. The amount of tilt at each micro-mirror is 10º. These are affects that need to be addressed in the optical design. Normally, such a tilted object plane introduces a significant amount of astigmatism to an optical design, and for this spectrometer poses the most significant design issue.

METHODS

All of the optics within IRMOS are reflective, with the exception of filters and a dewar window. An all-reflective design eliminates chromatic aberrations and reduces the number of optical surfaces where spurious reflections can occur (small reflections occur at all dielectric boundaries). This helps control stray light and improves contrast. Initially, it was thought that all of the optics could be manufactured using diamond-turned aluminum.

The first stage of the optics is a focal reducer. The instrument is designed to be mounted to one of several large telescopes (>2m) with a focal ratio of ~F/15. This focal ratio imaged directly onto the DMD would offer a prohibitively narrow field of view given observing conditions that typically do not produce spot sizes much better than 1 arcsecond. To provide a larger field of view and a plate scale that better matches observing conditions, a focal reducer was designed to convert the F/15 beam to F/4.6. This will provide spot sizes on the DMD that are about 2-3 mirrors in diameter. To address some of the tilt problems that the DMD would impose, this first stage of optics was designed with an incident angle on the DMD of 10º. This stage also provides a very useful re-image of the pupil just in front of the DMD. The pupil needs to be re-imaged so that thermal emission from the edge of the primary and secondary mirrors can be masked. A cold stop is placed at this location and is sized to cut off the undesirable thermal emission. The use of a cold stop is a common necessity for research-grade astronomical instruments that observe in the infrared.

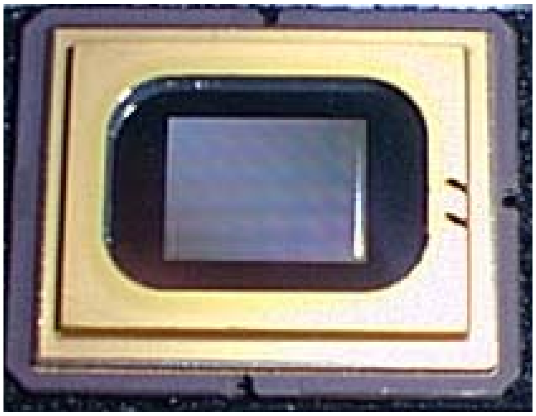

Figure 1. A Texas Instruments Digital Micro-mirror Device (DMD). This device has 848x600 pixels.

The spectrometer stage of this instrument must address another optical design issue in addition to the issues created by the use of a DMD. The diffraction grating that is used to disperse the light into spectra creates additional astigmatism. This can complicate the instrument design substantially, as the axes of astigmatism that are generated by the spectrometer and the DMD need to be aligned. If they are not aligned, DMD astigmatism that is corrected will not correct the spectrometer astigmatism, and vice versa.

Creating an optical design for the spectrometer that addressed all of the issues was not a simple task. The software used to design the instrument was Zemax-EE, which allows a user to assign a set of parameters for optimization. The optimization routine can then search for the best design by using a hill-descending algorithm. This set of parameters is called a merit function, and provides metrics for the system including things like image quality, focal ratio, the size of the optics and their spacing. A complex merit function had to be generated that would allow the optimizer to converge to a solution that could be fabricated.

Numerous attempts to get this model to converge simply resulted in designs that were too big and bulky or involved too many optical surfaces. The size of the instrument would be too large to meet the requirements of the telescopes onto which the instrument needs to be installed. To get the design to converge, a free-form shape was included in the model: a biconic. A biconic mirror is defined by the following equation indicating sagital depth:

$$z = \frac{\dfrac{x^2}{R_x} + \dfrac{y^2}{R_y}}{1 + \sqrt{1 - \dfrac{(1+k_x)x^2}{R_x^2} - \dfrac{(1+k_y)y^2}{R_y^2}}} \quad (1)$$

with R_x and R_y as the radii of curvature in the respective directions, and k_x and k_y the respective conic values. This is considered a "free-form" shape due to the lack of rotational symmetry. This is a surface that can not be manufactured using a conventional diamond-turning technique.

Using a biconic surface allows the optical design to correct for all of the astigmatism introduced in the various stages of the instrument. The result is an instrument that is much smaller than it would otherwise be, small enough to be installed on even the smaller 2m class telescopes (useful for wide field work and testing).

To manufacture this mirror, a relatively new technology can be used similar to diamond turning but having additional degrees of freedom. The process is diamond machining. One can think of diamond turning as a highly precise metal turning lathe, with precision of typically 5nm, rather than the common 10 microns of a conventional precision metal turning lathe. Diamond machining is similar to conventional machining, but with a similar three orders of magnitude improvement in precision.

At the time that IRMOS was designed, diamond machining was a new and emerging technology. Moore's Nanotechnology division was the only company providing machines that could reputedly manufacture the surface on an aluminum blank. By the time the mirror was fabricated, however, Precitech was releasing its Freeform Precision Diamond machining center, and eventually became the machine that was able to produce the mirror within the tolerance specifications of the project.

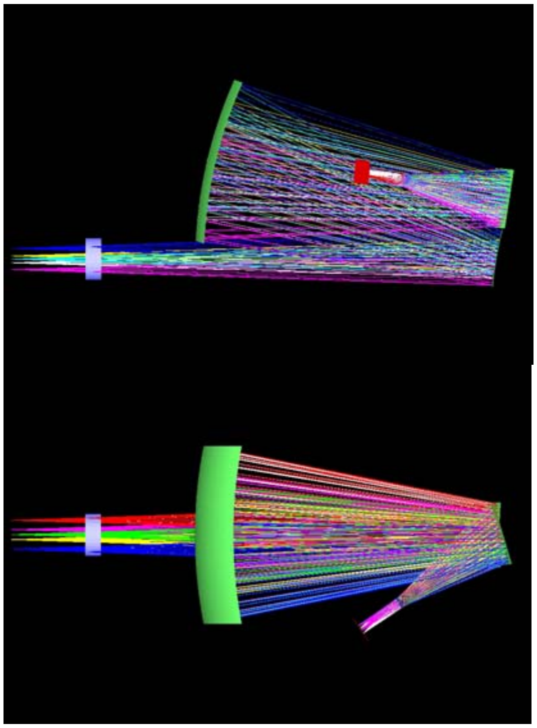

Figure 2. IRMOS First-Stage optics. The Telescope focal plane is shown at the far-left in these pictures. The DMD can be seen at the other end of the optical path, near the middle of these pictures.

RESULTS

The first-stage optical design of IRMOS produced spot sizes on the DMD that are about 20 to 30 microns (RMS diameter). This corresponds to sub-arcsecond imaging on a 4-meter telescope, assuming perfect seeing conditions. Convolving the spot sizes with actual seeing conditions will provide considerably larger spots, but this stage should allow most of the energy of a spot to fit within a diameter of 3 mirrors, and still have room for manufacturing tolerances. Figure 2 shows the optical layout for this stage of the instrument.

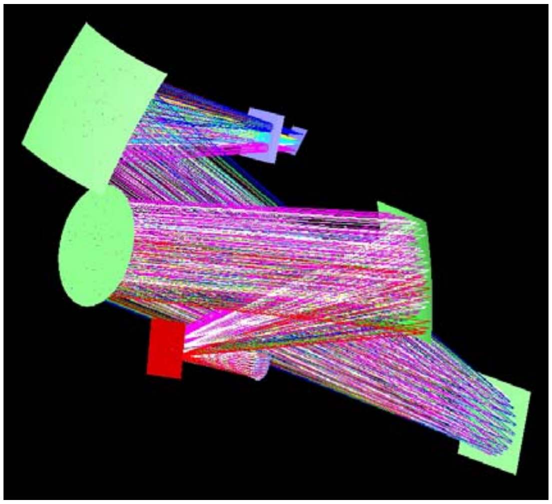

Figure 3. Optical Layout of the IRMOS Spectrometer. The biconic mirror is the upper right surface. The DMD is seen at the lower left of this picture.

The second stage of the optics has slightly larger spot sizes, but still in the neighborhood of 20-30 microns depending on field location. This stage is not as susceptible to degradation due to seeing conditions, as its performance is dominated by the size of the slit. The detector is a HAWAII HgCdTe, 1024 x 1024 pixel array with 18 micron pixels. Figure 3 shows the layout of the spectrometer stage of optics, and Figure 4 shows the optical layout of the complete instrument.

The fabrication of the diamond-turned optics was relatively straightforward. One of the mirrors contained the vertex, which presents a small issue for fabrication. It is difficult to machine near the vertex due to the need to have the tool precisely on-center to avoid a bump. However, this mirror is the largest of all the mirrors, so the vertex problem does not pose a significant problem.

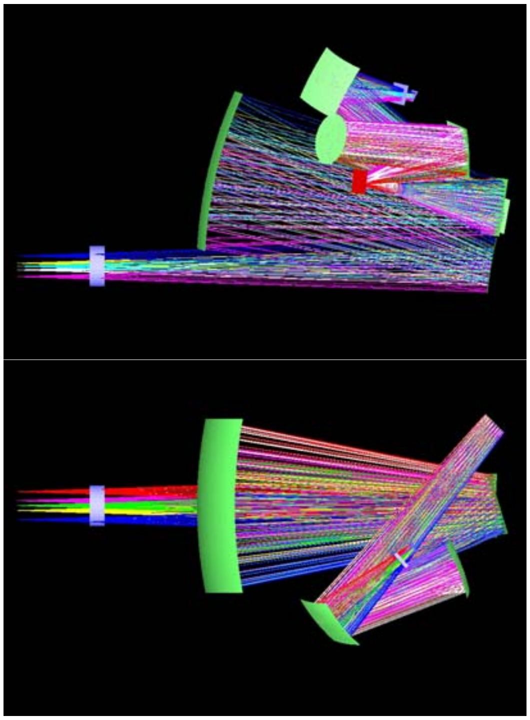

Figure 4. Complete layout views of IRMOS, showing both stages of the optical design.

Metrology

After the mirrors are fabricated, they need to be tested to determine compliance with allocated tolerances. One of the surfaces is convex and a prolate ellipsoid. Two of the mirrors are oblate ellipsoids, and one is biconic. Due to the complexity of the surfaces for this instrument, computer generated holograms (CGH) were chosen for testing. Using a CGH for testing allows considerable flexibility in testing due to the ability to accommodate a very complex surface shape. Without a CGH, a complex optical setup is needed to be able to measure the surface error. Such setups can require a considerable amount of time to design. A test setup involving a CGH is not trivial, but it is much more simple than testing involving null lenses or other test surfaces.

The tolerance on the wavefront quality of the mirrors was derived based on the requirements of the instrument, but were specified in a manner to help facilitate their fabrication. It was known that the wavefront quality requirements for these mirrors would probably be greater than possible with diamond turning given conventional methods of specifications for the entire surface. Commonly a surface error is specified as the departure of the entire surface from the prescribed value. However, since none of the mirrors are near a pupil, this would be unnecessarily difficult. The footprint of each field location on these mirrors only illuminates a portion of the mirror, so the tolerance was specified with some flexibility. The tolerance was needed to be less than ~λ/10 RMS over any given field illuminated footprint. Relaxing the tolerance to this value made fabrication of the mirrors considerably easier, eliminating the need for secondary polishing processes after diamond turning/machining.

The results of the fabrication of the mirrors demonstrated the ability to consistently generate surface roughness on the order of 10 nm or less. The overall wavefront error for each surface was less than ~1/10 λ RMS at 630 nm for any given region of the surface that a field location would illuminate. This demonstrated a successful approach to specifying the tolerances for these mirrors, and yielded mirrors that have satisfactory performance and are economically viable to produce.

Integration and Testing

All of the mirrors for this instrument have been fabricated and are currently being integrated into the cryostat. A complete test of the entire system has not yet been completed, but some initial testing looks promising. Figure 5 shows a sample spectrum from the full system, using an F/15 white-light beam into the center field position of the first-stage optics. A 3x3 set of micro-mirrors was turned "on" and the spectra was obtained. The image was taken using a mux from a HAWAII detector, so the image had to be generated in the Z band (~800nm to 1000nm). The sensitivity of the mux is much greater closer to 800nm due to the sensitivity of silicon, but this is a good demonstration of the capability of the system to date. The width of this spectral line is roughly 7 pixels, and a reduction in this width is anticipated after the full system metrology is complete and every mirror has been verified as being located in the correct location. The width of this spectrum is very uniform, indicating that the astigmatism inherent in the various stages has been corrected by using the biconic surface.

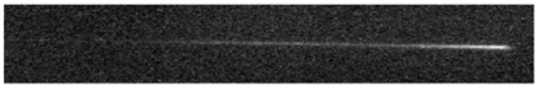

Figure 5. Sample spectra from IRMOS, imaged onto the mux for the HAWAII detector.

The integration and testing of this instrument is anticipated to be complete within several weeks of the date of this conference.

CONCLUSION

The benefit of adding a free-form shape to an optical design is clearly presented in the case of IRMOS. An instrument that would have otherwise been prohibitively large (and possibly not even small enough to allow it to be built) has been made into a manageable size through the use of a biconic surface. The technology of fabricating these free-form surfaces has matured to a point that their implementation into more systems is a worthwhile consideration.

ACKNOWLEDGEMENTS

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