Design Concepts for a Mid-Infrared Instrument for the Thirty-Meter Telescope

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ABSTRACT

A mid-infrared imager and spectrometer is under consideration for construction in the first decade of the Thirty-Meter Telescope (TMT) operation (see the companion paper by Okamoto). MIRES, a mid-infrared high-spectral resolution optimized instrument, was previously proposed to provide these capabilities to the TMT community. We have revised the design in order to provide an improved optical design for the high-spectral resolution mode with R=120,000, improved imaging with sky chopping, low-spectral resolution mode with an integral field spectrograph, and polarimetry. In this paper we describe the optical design concepts currently under consideration.

Keywords: Thirty-Meter Telescope (TMT), Infrared, Camera, Spectrograph, Image Slicer, Polarimetry, MIRES, IFU

1. INTRODUCTION

The concept of a mid-infrared echelle spectrograph (MIRES) was developed in response to an announcement of opportunity issued by the TMT project in 2005. Several papers were published to show the scientific case, feasibility, and technical drivers.[1–3] The MIRES science focused on high-resolution spectroscopy as an unmatched capability in sensitivity and spectral-resolution for future mid-IR astronomy. In addition, a design study of a mid-IR adaptive optics (MIRAO) system was undertaken and published[4] since diffraction-limited spatial resolution is essential for MIRES. The MIRAO system would be much simpler than adaptive optics systems at wavelengths less than 2.5 μm.

In 2008 discussions proceeded between members of the MIRES team and corresponding interested scientists in Japan in regard to development of a proposal for a mid-infrared instrument to be submitted to the Japan TMT office. The MIRES concept was modified to include additional capability in high angular resolution imaging and integral field spectroscopy. It was also decided that an all-reflective design would be desirable to improve throughput and avoid using difficult to obtain lens material for 8-25 μm. This paper describes the state of design studies to accommodate these additional capabilities. A significant addition is the integral field unit (IFU). The combined instrument is named "Mid-Infrared Camera, High-disperser, and Integral field unit," or MICHI. The science case for this instrument concept was presented at this meeting.[5]

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Table 1. Specifications of MICHI.

Wavelength Range	
Wavelength Range	N (7.3-13.8μm) and Q (16-25μm) bands
Imager	
Field of View	$27.5'' \times 27.5''$
Pixel Scale	$0.028''$/pix ($\sim\lambda$/2D)
Spectral Resolution	R$\sim$10-100
Detector	Raytheon Aquarius 1024$\times$1024 Si:As array
Low-dispersion Spectrometer in Imager	
Pixel Scale	$0.028''$/pix
Slit	$27.5''$ in length, $0.10''$ to $0.3''$ in width. Reflective.
Disperser	Grisms.
Spectral Resolution	R$\sim$810 at N-band, R$\sim$1,100 at Q-band
	Each band covered in a single exposure.
High-dispersion Spectrometer	
Pixel Scale	$0.027''$/pix
Slit	$2.0''$ in length, $0.10''$ to $0.3''$ in width. Transmissive.
Disperser	Echelle and cross-disperser.
Spectral Resolution	R$\sim 1.2 \times 10^5$ at N-band.
Detector	Raytheon Aquarius 2048$\times$2048 Si:As array
Low-dispersion Spectrometer with IFU	
Pixel Scale	$0.035''$/pix
Slicing Mirror Unit	Composed of 22 reflective slits.
Wavelength	N-band; Q-band is optional.
Field of View	$\sim5''$ (in length) $\times$ $2''$ (in slices of $\sim$22)
Disperser	Reflective gratings.
Spectral Resolution	R$\sim$300
Detector	Two Raytheon Aquarius 1024$\times$1024 Si:As arrays
Cold sky chopping mirror	
Chopper mirror	At the second pupil image in the MIRES fore-optics.
Throw	Up to $27.5''$ for the MIRES. Up to $55''$ for the IFU.
Chop frequency	Assuming up to a few Hz.
Polarimetric capabilities	
Method	Dual-beam polarimeter (half wave retarder and Wollaston prism based system)
Mode	Imaging- and spectro-polarimetry
Wavelength	Optimized at the N-band. Available to material transmission cutoff ($\sim$23μm)
Others	No effect to other observing modes when out of polarimetry mode.

2. MID-IR ECHELLE SPECTROGRAPH (MIRES) CONCEPTUAL DESIGN OVERVIEW

The MIRAO system is optically a 1:1 relay. Since this system was described elsewhere[4] and we assume the same performance specifications, the MIRAO system is not discussed here.

The major design drivers are:

1. All reflective design.
2. Wavelength coverage of 7.3–13.8 μm (N-band) and 16–25 μm (Q-band).
3. Internal chopper to accommodate a $27.5'' \times 27.5''$ imaging field-of-view (FOV).
4. Diffracton-limited imager (and slit viewer) for the high-resolution spectrograph using a 1K×1K array.
5. Grism mode in the imager to provide low-resolution spectroscopy.
6. High-spectral resolution spectrograph with R=120,000 using a 2K×2K array.
7. Relay optics to feed an integral field unit.
8. Fit within current TMT project instrument envelope for MIRES (cylinder of diameter 1.5 m and 3.8 m length).

Optical Research Associates (Pasedena, CA) developed a conceptual design based on these major drivers. Figure 1 shows the block diagram of the fore-optics and the MIRES sections. Our design is based on the currently available Aquarius 1K×1K Si:As arrays produced by Raytheon. 2K×2K Aquarius arrays can be scaled up from 1K×1K devices, and are being considered for production by Raytheon so it is reasonable to assume we can obtain such arrays in the near future.

2.1 Fore-optics

The fore-optics accomplishes the following: (1) Creates a first high quality image of the pupil, where there is a cold stop (crucial for an optimal MIR instrument) and a filter wheel. (2) Creates a second image of the pupil on a chopping mirror to accomplish sky chopping. (3) Relays the MIRAO focal image onto the slit. (4) Allows for the relay of the optics to the IFU by means of a mirror inserted after the chopping mirror.

Figure 2 shows the layout of the fore-optics. A two-mirror collimator forms a pupil image with a diameter of 36.6 mm. A cold stop and filter wheel is located here to suppress background emission. In addition, a Wollaston prism and half-wave plate are located here for the polarimetric modes.

The pupil image at the sky chopping mirror is 31.1 mm. The sky chopping mirror is a flat that oscillates between two positions. A proven design for a cold chopper unit (for a space based application) exists[6] and we assume a similar mechanism for our feasibility study. Sky chopping of up to $55''$ and rotation of the chop angle by $\pm 180^\circ$ is required.

Although the overall design at first appears complicated, it should be noted that each three-mirror anastigmat (TMA) would be built and aligned separately as a complete optical subsystem before being integrated into the system. This will simplify the alignment procedure tremendously and hence reduce risks and costs. There are 5 such optical subsystems in the MIRES section of MICHI. The TMAs are required for the fore-optics due to the relatively large field angles that have to be accommodated and the diffraction-limit requirement.

2.2 Relay optics to the IFU

The IFU is envisioned as a separate instrument located behind the MIRES optics. A telecentric afocal relay is provided by inserting a flat mirror into the light path right after the sky chopping mirror. It accepts the collimated beam from the sky chopping mirror and produces a collimated beam with an accessible pupil farther down the z-axis of the instrument envelope. It consists of two back-to-back Cassegrain telescopes (4 mirrors) as shown in Fig. 3.

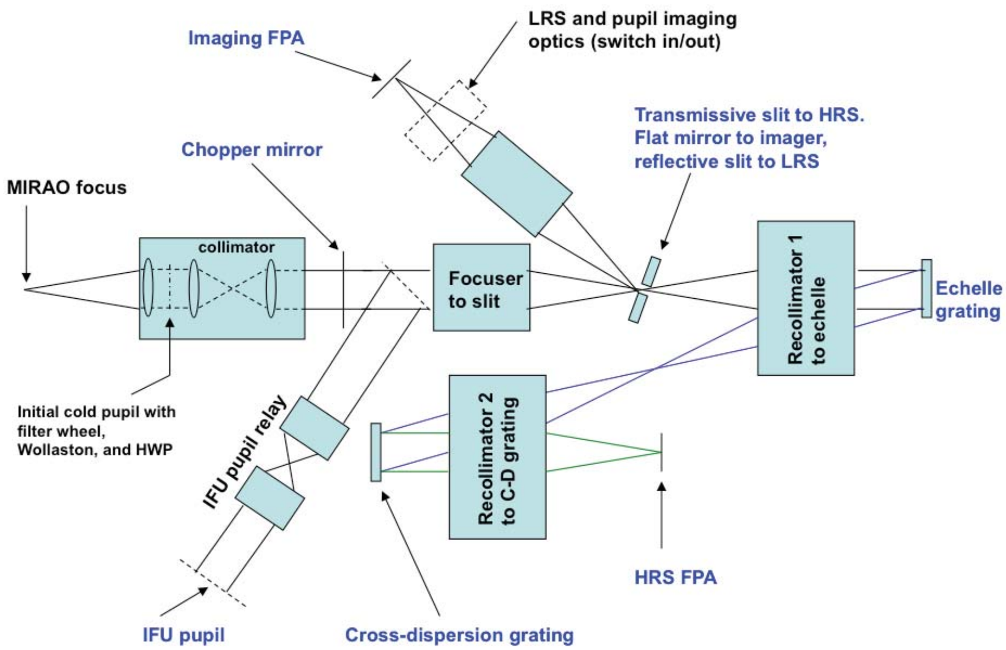

Figure 1. Schematic layout of the high-resolution spectrograph optics and slit-viewing camera (imager). Light from the mid-IR adaptive optics system enters from the left. A pupil image is formed by a two-mirror collimator and this is where a cold stop, filter wheel, half-wave plate, and Wollaston prism is located. A three-mirror anastigmat (TMA) then relays this pupil image to the sky chopping mirror. An insertable pick-off mirror sends the light to the relay optics for the integral field unit (IFU). After the sky chopping mirror, the light is sent to a second TMA which forms an image of the focal plane on the slit. The light reflected from the slit goes to the slit viewing camera, which has provision for a low-resolution spectrograph (LRS) and pupil-viewing optics. The light transmitted by the slit goes to the high-resolution spectrograph (HRS). Two focal plane arrays (FPA) are needed: a 1K×1K Si:As array for the slit-viewing camera and a 2K×2K Si:As array for the HRS.

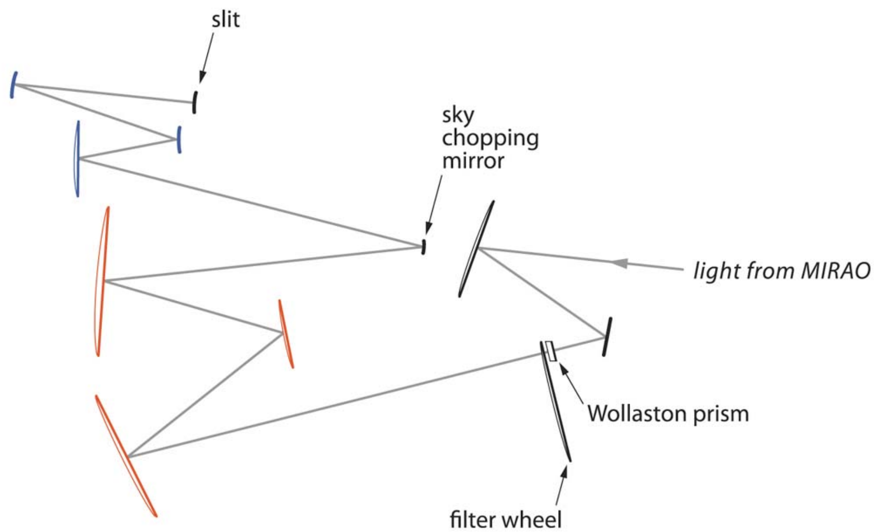

Figure 2. Optical layout of the fore-optics. A first image of the pupil is formed by a two-mirror collimator. A cold stop and filter wheel is located here. This is followed by a TMA (red) that collimates the light and forms a second image of the pupil on the chopping secondary mirror. A second TMA (blue) forms an image of the focal plane on the slit.

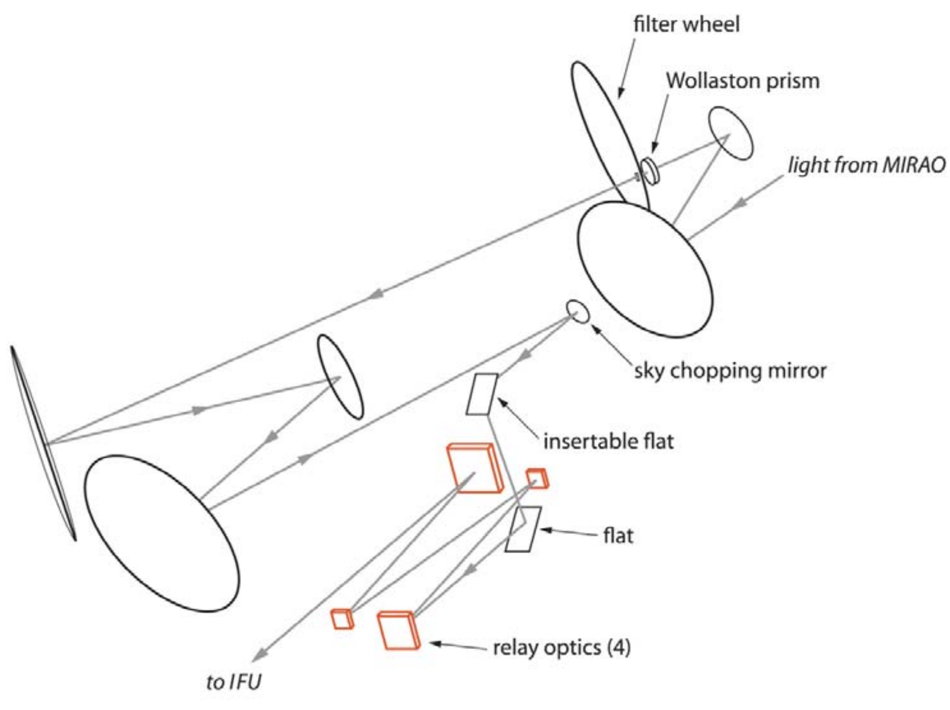

Figure 3. Optical path of the afocal relay to the IFU. To send the light to the IFU, a flat mirror is inserted into the light path right after the sky chopping mirror. From there it goes to another flat mirror before reaching the 4-mirror relay optics (red). The relay optics consists of two back-to-back cassegrain telescopes.

2.3 Slit-viewing Camera (Imager)

The FOV of the imager is 27.5″. This was determined by the need to have adequate diffraction-limited pixel sampling of the 7.3-13.8 μm range while at the same time accommodating sky chopping. MIRAO provides a 60″ diameter FOV, and therefore 27.5″×27.5″ sky regions can be accommodated for sky chopping as shown in Fig. 4a.

Light reflected by the slit is sent to the camera optics. A TMA was originally tried for the camera optics, but the distortion was found to be unacceptably high. A four-mirror anastigmat was found to be necessary to bring the distortion to a level of less than 3 pixels (center to corner). This is shown in Fig. 4b. The Strehl ratio of the image is >0.93 at N-band and ≥0.99 at Q-band.

2.3.1 Low-resolution spectrograph (LRS)

Low-resolution spectroscopy is provided through inserting one of two grisms, optimized for the N and Q bands respectively. As the grisms are in non-collimated beams, the image quality in spectroscopic mode is inferior, especially at shorter wavelengths. However, by placing a collimating singlet before the grism and a second singlet to refocus the beam after of the grism, this degradation of image quality can be eliminated. As noted, the image quality degradation is wavelength dependant, which when combined with the greater difficulty in obtaining optimal materials in the Q band, leads us to use this technique in the N band only.

The delivered Strehl ratios in the N-band is diffraction-limited. In the Q band, the Strehl ratio varies with wavelength and is about 0.26 at 16 μm, 0.86 at 20.5 μm, and 0.66 at 25 μm. We note that the key science drivers require optimal image quality in imaging and spectroscopic modes, and so we will consider methods of improving the Q band performance in a future design stage. The spectral resolution varies with the wavelength, but at central wavelengths 10.5 μm and 20.5 μm the spectral resolution is 812 and 1,139 respectively.

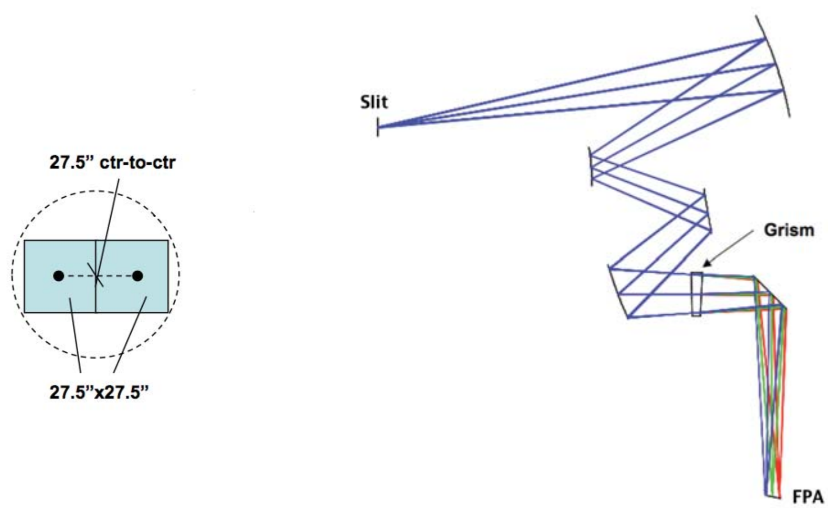

Figure 4. (a) Left. The dashed line shows a 61.5″ diameter FOV circumscribing all orientations of the 27.5″ object and sky beams of the imager. (b) Right. Light path of the imager showing location of the grism.

2.3.2 Pupil viewer

It is desirable to have a pupil viewer for checking the alignment to the telescope and for diagnosing problems. To achieve this a set of lenses was designed to be inserted into the light path right before the focal plane array (FPA) and to form an image of the primary mirror. A computation of the modulation transfer function shows that the pupil viewer will have a spatial resolution of 70 mm on the primary mirror.

2.4 High-resolution Spectrograph (HRS)

The main requirement is a maximum resolving power 120,000 with a slit width that is nearly diffraction-limited at 10.5 μm. The cross-disperser requirement is to avoid overlap of the orders at the short wavelength. A $2''$ long slit is taken as a compromise between having a sufficiently long slit while having as large of a spectral coverage as possible per exposure. The overall optical path of the HRS is shown in Fig. 5.

Recollimator 1 takes the F/7.5 beam emerging from the $2''$ slit and collimates it to an external pupil where the echelle grating is placed. Trading off performance, packaging, and the need for a R = 120,000 echelle, ORA developed a design with 125 mm pupil diameter and a recollimator focal length of 962 mm. The echelle disperses the slit across the 61.4 mm extent of the FPA. 61.4 mm represents $3.66°$ ($\pm 1.83°$) total field angle emerging from the echelle. The recollimator must form a high-quality image of this field of view in the second pass. For this field of view, a TMA will achieve high performance while a single paraboloid would give poor Strehl ratio (as low as $\sim$0.4 at the ends of the slit). Full echelle orders are matched to the detector width at 13.7 μm.

Recollimator 2 takes the dispersed F/7.5 beam emerging from double pass through Recollimator 1, and collimates it to an external pupil where the cross-dispersion grating is placed. Trading off performance and packaging, ORA developed a design with 70 mm pupil diameter and a recollimator focal length of 540 mm. The cross-disperser disperses the slits across the 61.4×61.4 mm extent of the FPA. For this focal length, 61.4 mm represents $6.5° \times 6.5°$ total field angle emerging from the echelle. A TMA is required to form a high-quality image of this field of view in the second pass.

The grating parameters are shown in Table 2. Although the echelle is large, it is smaller in size than that fabricated for the MIR spectrograph TEXES[7] and is smaller than the largest existing gratings with similar blaze angle and groove spacing.[8] The cross-disperser gratings are relatively large but within the range of commercially available gratings.

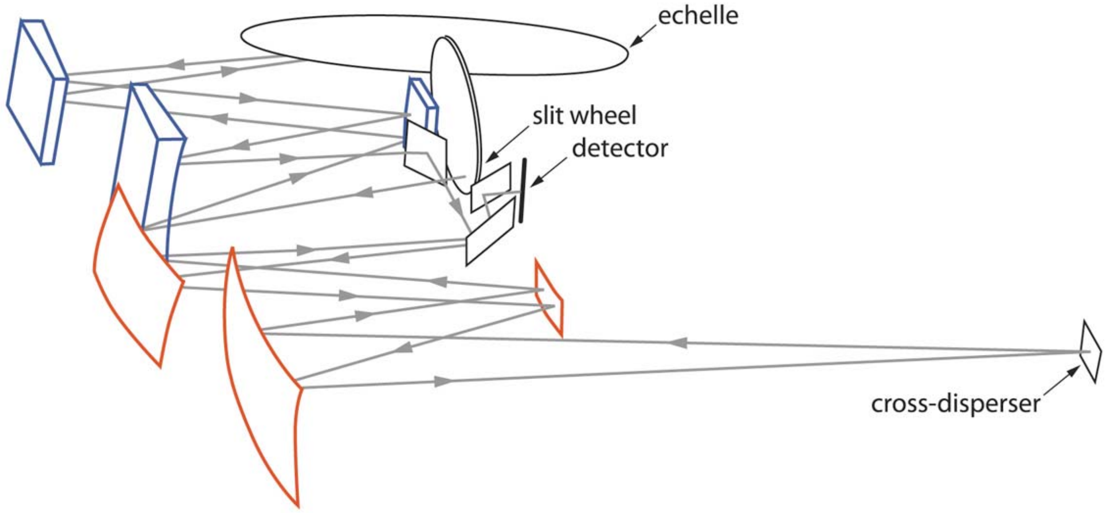

Figure 5. Light path of the spectrograph section. The transmissive slit is located at the focus of the fore-optics. There is a slit wheel to accommodate different slit widths and to change to a flat for imaging and reflective slits for the grism spectroscopy. From the slit the light goes to a TMA (Recollimator 1; blue) which collimates the light to the echelle. The TMA also refocusses the dispersed light which is sent to a second TMA (Recollimator 2; red) which collimates the light to the cross-disperser. Recollimator 2 also focusses the cross-dispersed spectrum onto the 2K×2K FPA.

2.5 Complete Optics Package

Figures 6a and 6b show the side and end views of the fore-optics and MIRES sections. The current instrument envelope for the mid-IR instrument is a cylinder with diameter 1.5m and length 3.8m. As can be seen, the

Table 2. Grating parameters for the echelle and the 2 cross-dispersers. The N-long and Q cross-dispersers use the same cross-dispersing grating but in 3rd order and 2nd order respectively.

	grooves/mm	incident angle	size
echelle	0.609	79.1°	150mm×674mm
N-short	60.9	38–54°	70mm×130mm
N-long	39.3	29–50°	70mm×130mm
Q	39.3	35–53°	70mm×130mm

current optical design would fit within this envelope.

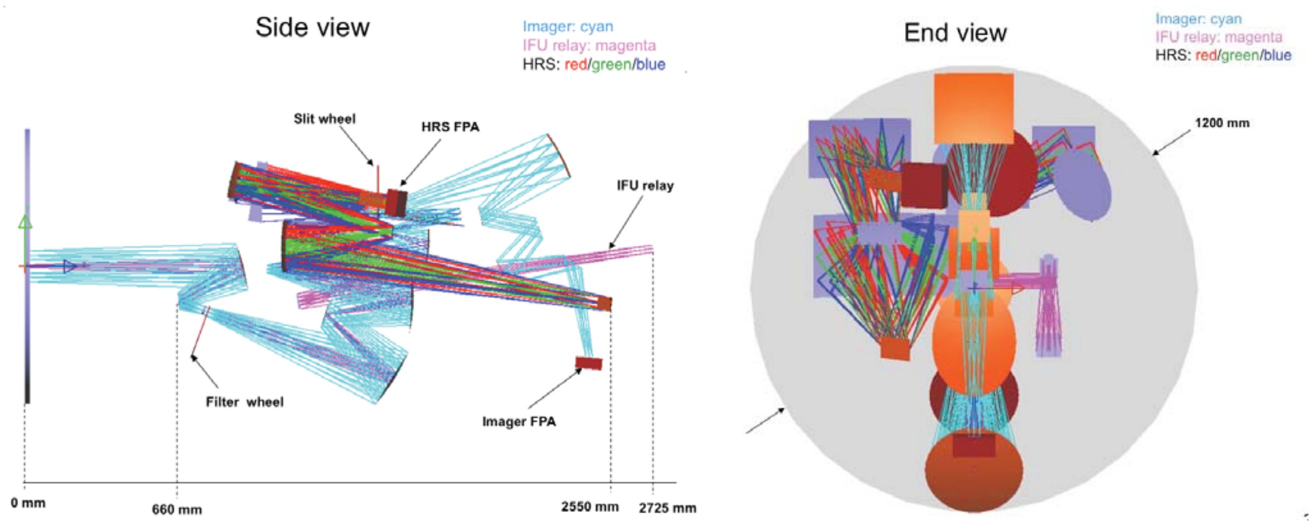

Figure 6. (a) Left. Side view of the fore-optics and MIRES sections. The overall length of the optics is 2.55 m. (b) Right. End view of the fore-optics and MIRES sections, showing that the optics will fit within a circular cross-section of about 1.2 m.

3. INTEGRAL FIELD UNIT (IFU)

Based on the science drivers, low-dispersion (R∼250–500) spectroscopy of dust and emission lines with 2-dimensional (2D) spatial information at high angular resolution is one of the most important capabilities of MICHI. We therefore conducted a preliminary feasibility study of including an integral field spectroscopic capability into MICHI.

Most of the objects discussed in the science case studies to be observed with the IFU typically has a size of 1–5″. For such compact objects, the image slicer approach is the most suitable. It achieves 2D spectroscopy by maintaining diffraction-limited spatial resolution along the slice direction. We have carried out an optical design study and provisionally set the field of view of IFU at 5″ (in slice length direction) by 2″ (in slice width direction).

Figure 7 shows the overall optical design approach for the IFU spectrometer for the N-band. It is composed of the fore-optics, image slicer optics, and spectroscopic optics. In our feasibility study, the fore-optics for the IFU was initially studied separately from MIRES. However, we have decided to replace the fore-optics with that from MIRES by using an optical relay from MIRES. It enables the cold chopper in MIRES foreoptics to be used for the IFU. Only a small modification of IFU optics will be required to accomplish this.

The image slicer optics (Fig. 8) is composed of 22 slicing mirrors, 22 pupil mirrors and 22 pseudo slit mirrors. There is a pick-off mirror to fold light from the fore-optics just before the slicing mirrors. For the slicing mirrors,

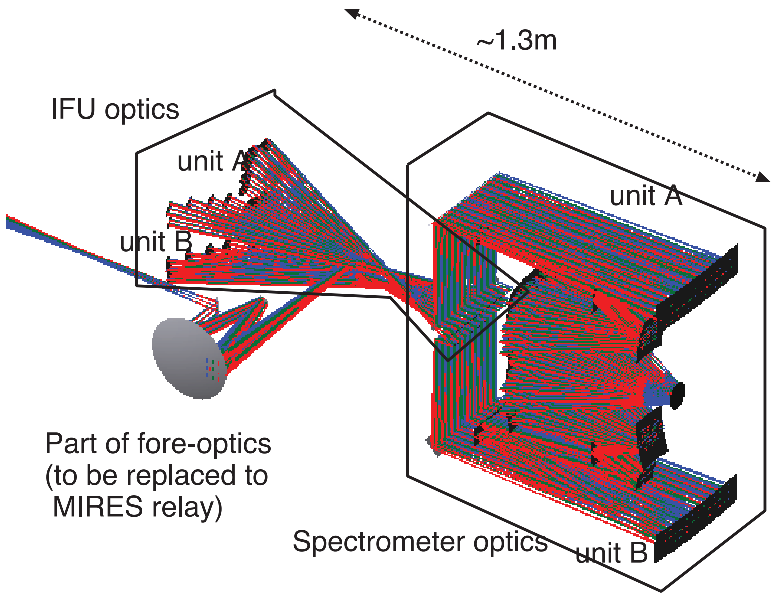

Figure 7. Overall optical-layout of the low-dispersion spectrometer with IFU, including both units A and B (see text). Each unit contains 11 slitlets having a width on the sky of 0.088″ and length of 5.0″.

we plan to adopt the fabrication method developed for a MIR image slicer prototype, Mid-InfraRed Spectrometer with an Image Slicer (MIRSIS).[9–11] Each slicing mirror is a cross-cut surface area of a separate thin aluminum plate formed by ultra-precision cutting. In our design, each mirror has width of 185μm, which corresponds to 0.088" on the sky. 11 mirrors are bundled into a slicing unit and for the full system there are two sets, unit A and B. Within each unit, there are 11 pupil mirrors, 11 pseudo slit mirrors, and individual spectroscopic optics.

In each spectroscopic optics unit (Fig. 9), light from the pseudo-slit mirrors are reflected by two flat mirrors and are collimated by an off-axis parabola. The reflective grating is located at the pupil image produced by the off-axis parabola. The diffracted light from the grating is focused onto two FPAs by the camera optics which consists of a TMA. On the FPA, the pixel scale is 0.035″/pixel and spectral resolution is R=265 at 10μm. The configuration of the spectral images on the array are shown in Fig. 10.

The overall size for the IFU optics is approximately 1m diameter by 1.3m in length. The optical design shown here is only for the N-band, but a similar system for an IFU spectrograph in the Q-band is feasible. However further discussions are needed regarding the scientific case and feasibility of including a Q-band IFU in MICHI.

4. POLARIMETRIC CAPABILITY

An optimized polarimeter eliminates the effects of variable sky transmission/emission on the measured polarization, as well as eliminating polarization from the instrument itself. Our design concept follows the commonly applied technique of using a fixed Wollaston prism to analyze the science beam. A Wollaston prism produces two orthogonally polarized beams with an angular divergence, which are imaged to the array ready for comparison. We will use a half wave retarder (or half wave plate, HWP) to modulate the input signal to the Wollaston, so that the polarimeter can completely describe the polarization signal. This technique can also provide self calibration, greatly reducing effects of instrumental polarization downstream of the HWPs, and are hence located as far upstream in the science beam as possible (see Section 2.1). The HWPs are situated in the dewar to keep them cold in order reduce thermal emission, as in several MIR polarimeters[12] and the CanariCam N band polarimeter.[13] An excellent material for use at MIR wavelengths is CdSe, and the vendor who produced the polarimetry optics for CanariCam in 2003 confirms that their capabilities remain to produce a similar or better set of optics for MICHI. The size restriction of the Wollaston was incorporated into the design phase for MICHI.

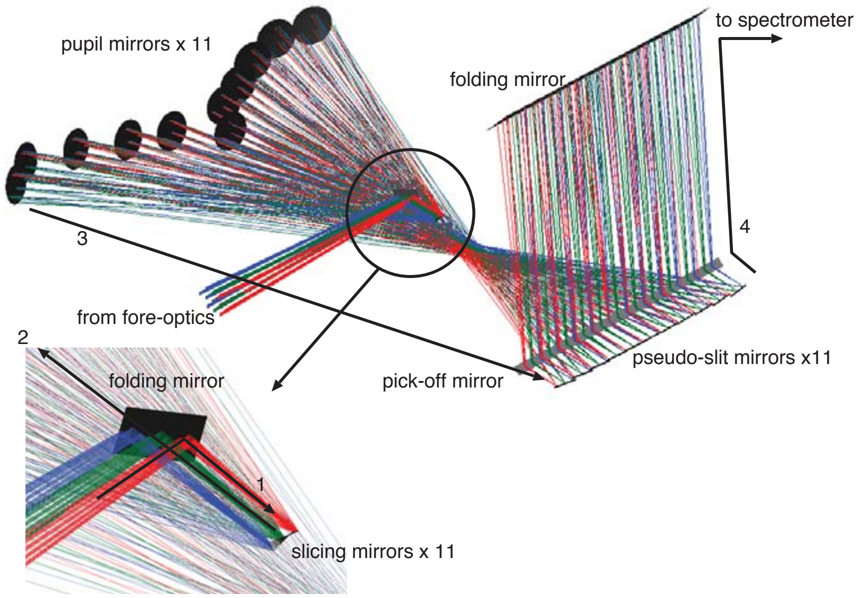

Figure 8. Optical layout of the image slicer unit A. Each image slicer unit has 11 slicing mirrors [1]. Because a slicing mirror is tilted from the neighboring one by 2.4°, the light from each mirror is reflected to the different direction [2]. The reflected light goes to a pupil mirror located near the exit pupil of the fore-optics, which then re-images the focal plane image on the pseudo-slit mirrors [3]. Each pupil mirror is individually tilted in order to line up the slit images from the different slicing mirrors onto the pseudo-slit mirror. The light from the pseudo-slit mirrors are reflected off two folding flats to send it to the spectrograph optics [4].

5. STATUS AND FUTURE PLANS

At the time of the writing of this article, we are preparing a report to be submitted to the Japan TMT office for consideration. In the coming months we will be refining the cost and schedule for MICHI.

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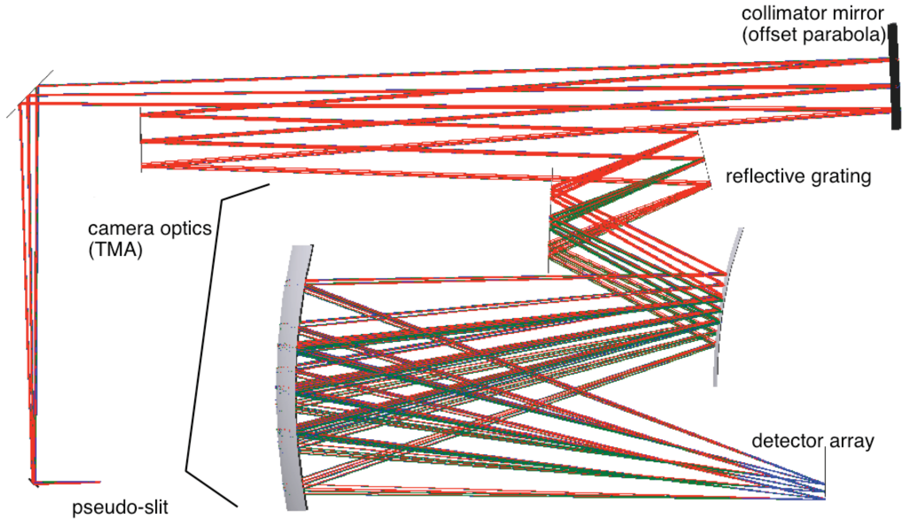

Figure 9. Optical layout of the spectrometer unit A which is located after the pseudo slit mirrors of unit A. Light from the pseudo-slit mirrors is collimated by an off-axis parabola and sent to the diffraction grating. The camera optics is a TMA which forms an array of spectra on detector.

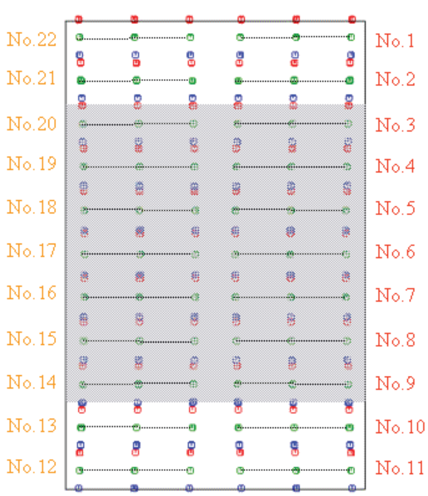

Figure 10. Spectral format on the focal plane arrays. Numerical characters beside the box represent slicer number. No.1–11 and No. 12–22 are from unit A and B, respectively. The red, green, and blue spots are focal points from the upper edge, the center, and the lower edge of each slice mirror, respectively. The black line box and the gray box corresponds to the dimension of a 1K×1.5K array and a 1K×1K array, respectively, with the pixel size of 30μm. The zeroth order light from both spectrometer units comes onto the central vertical axis of the array. Wavelength axes of the spectra of No.1–11 and No.12–22 are rightward and leftward, respectively. With this symmetric design, it is possible to arrange the A and B unit slicing optics and spectroscopic optics in a symmetrical fashion within the cryostat and to share a single FPA.

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