The Optical Design of the Wide Integral Field Infrared Spectrograph

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ABSTRACT

We present the optical design of the Wide Integral Field Infrared Spectrograph (WIFIS) which provides an unprecedented combination of the integral field size and the spectral resolving power in the near-infrared wavebands. The integral field size and spectral resolving power of WIFIS are $\sim 5'' \times 12''$on a 10-m telescope (or equivalently $13'' \times 30''$on a 4-m telescope) and $\sim$ 5300, respectively. Therefore, the affordable etendue of WIFIS is larger than any other near-infrared integral field spectrographs while its spectral resolving power is comparable to the highest value provided by other spectrographs. WIFIS optical system comprises an Offner relay-based pre-slit unit, an image slicer for integral-field unit, a collimator, diffraction gratings, and a spectrograph camera. For the integral field unit, WIFIS uses the Florida Image Slicer for Infrared Cosmological and Astrophysics which is a set of 3 monolithic mirror arrays housing 22 image slicers. The collimator system consists of one off-axis parabola and two lenses, while WIFIS relies on 3 different gratings to cover the entire JHK bands. The spectrograph camera uses 6 lenses of CaF2 and SFTM16, delivering the f/3 final beam onto a Hawaii II RG 2K × 2K detector array. WIFIS will be an ideal instrument to study the dynamics and chemistry of extended objects.

Keywords: Infrared, Integral field spectroscopy, Spectrograph, Integral field unit

1. INTRODUCTION

The integral field spectroscopy has become more and more popular and important in modern astronomy for its intrinsic ability to measure three dimensional spectra simultaneously. For the detailed studies of extended sources, the integral field spectroscopy can potentially provide more or less complete data sets to understand their dynamics and chemistry. Most of the current integral field spectrographs (IFSs), especially in the near infrared (NIR) wavebands, of large telescopes have been developed to be optimized with the adaptive optics systems. Therefore, their field of views are usually narrow, which makes them somewhat inefficient for observations of certain objects where larger integral fields are preferred. This includes star forming regions and supernova remnants in the Galaxy, the centers of local galaxies, and merging galaxies at high redshifts, (e.g. Moon et al. 2009,[1] Chou et al. 2010 submitted)

In this paper, we present the final optical design of WIFIS which utilizes most of the 4 million detector pixels of a Hawaii II RG 2K × 2K detector array to achieve the best combination of the integral field size, spectral resolving power, and spectral coverage obtainable within a single exposure. With a 2K array and the Nyquist sampling per resolution element, the maximum spectral resolving power within a single passband can be estimated by calculating the spectral coverage of each resolution element $\delta\lambda$. The spectral coverage in H-band is $\sim 0.3\ \mu$m and thus the spectral coverage per resolution element $\delta\lambda$ is 0.3/1024. This leads to a spectral resolving power $R = \lambda/\delta\lambda = 5600$ in H-band. Based on the same calculation, the maximum spectral resolving power in J- and K-band is more or less the same as in H-band. On the other hand, the largest slit length (or integral field) can be achieved with a 2K ×2K detector array for the case of the Nyquist sampling (assuming no grating projection effect). Given a typical slit width of $\sim 0.3''$, a 2K × 2K detector array can provide a slit length of $\sim 300''$.

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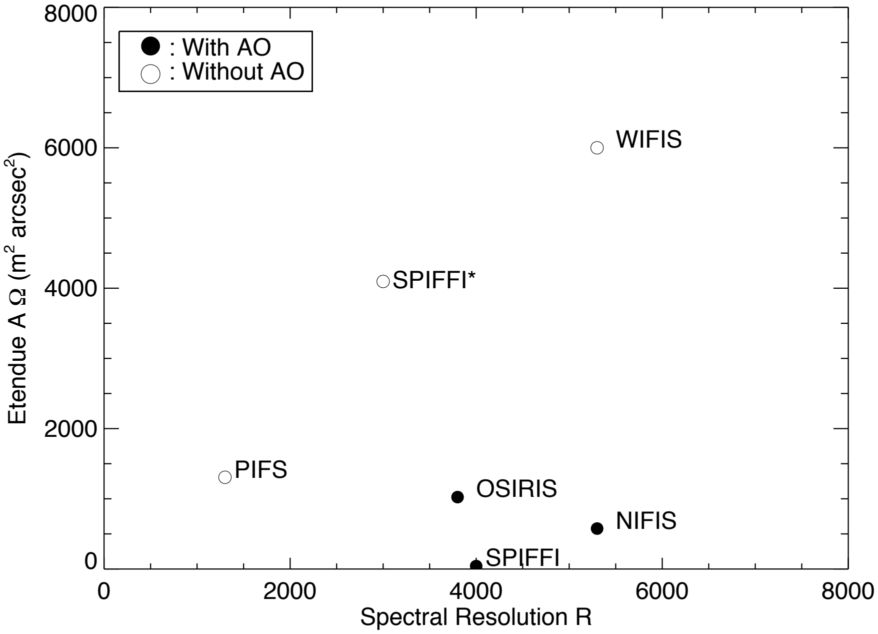

Figure 1. Etendue versus spectral resolution diagram for instrument listed in Table 1. Solid circles represent IFSs working with an adaptive optics (AO) system, and open circles represent IFSs operating under the natural seeing condition. WIFIS is designed to operate under the natural seeing condition and can provide incomparable etendue as well as high spectral resolving power.

In practice, WIFIS provides a spectral resolving power R ∼ 5300 and a 5″x 12″ integral field of view on a 10-m telescope (or equivalently 13″× 30″on a 4-m telescope) with a single exposure of each J, H, and K NIR wavebands. Table 1 lists the basic parameters of NIR IFSs on large telescopes (including the WIFIS) and Figure 1 compares their etendue and spectral resolving power, showing that the WIFIS has the best combination compared to other IFSs.

Instrument	Telescope	Spectral Resolution	FOV	Spectral Coverage (μm)	Adaptive Optics
NIFS	Gemini 8-m	5300	3″× 3″	0.94 –2.50	Altair
OSIRIS	Keck 10-m	3900	1″.6 × 6″.4	1.0 – 2.4	KECK AO
SPIFFI*	VLT 8-m	3000	8″× 8″	1.0 – 2.45	None
SPIFFI	VLT 8-m	4000	0″.8 × 0″.8	1.0 – 2.45	SINFONI
PIFS	Palomar 5-m	1300	5″.5 × 9″.5	1.0 – 2.5	None
WIFIS	10-m class	5300	5″× 12″	1.14 – 2.35	None

Table 1. Summary of important specifications of integral field spectrograph that operate in near infrared regime on large telescopes.

2. OPTICAL DESIGN

The WIFIS optical system is composed of three major parts: an Offner relay, an integral field unit called Florida Image Slicer for Infrared Cosmological and Astrophysics (FISICA) and a spectrograph. Figure 2 shows the ray-tracing optical layout of the WIFIS optical design. The size of the whole WIFIS design is 1.4 meters in length and 0.8 meters in height.

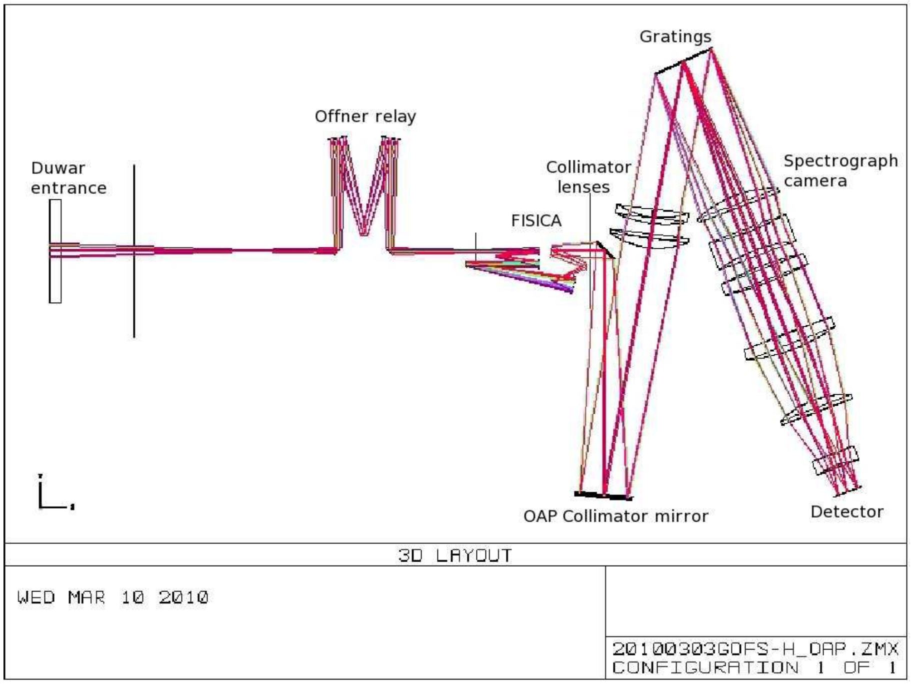

Figure 2. Optical layout of the WIFIS design. Light from the dewar entrance proceeds to the Offner relay. The integral field unit FISICA changes the input focal ratio to a half and arranges the sliced images into a pseudo long-slit. The output long-slit will be collimated, dispersed and focus by the spectrograph part of WIFIS.

2.1 Offner Relay and Integral Field Unit

In order to create a pupil location and to relay the telescope focal plane inside a dewar to reduce the thermal background, we use an Offner relay system (Murphy et al. 1995[2]) as the re-imaging optics in WIFIS. The Offner relay is composed of two concave and one convex spherical mirrors, with a pupil location at the second convex mirror.

The integral field unit of WIFIS is called FISICA, which is basically a 22-element image slicer. FISICA has been built, tested and worked with the Florida Multi-object Imaging Near-IR Grism Observational Spectrometer (FLAMINGOS) on Kitt Peak 4-m telescope (Eikenberry et al. (2004)[3]). The basic principle behind FISICA is to divide the input 2-D field from the telescope focal plane into 22 "slices" and to reform these slices in series to create a pseudo long-slit. The origin of the virtual slit image locates at the telescope focal plane such that the spectrograph will see a long-slit image coming from the telescope.

FISICA is composed of a three-mirror re-imageing system, an image slicer mirror, a pupil mirror array and a field mirror array. The optical layout of the FISICA system is shown in Figure 3. In Figure 3, light from the telescope focal plane enters a three-mirror re-imaging relay that magnifies input beam by a factor of two, and then focuses at the 22-element slicer mirror array. The slicer mirror array has 22 powered and tilted slices that reformat sliced images to 2 × 11 pupil mirror array. The geometry of 2 × 11 pupil mirror array was chosen to minimize the field angles of the integral field unit, which reduces aberrations. The pupil mirror array creates another relayed image of the telescope focal plane along the linear array of 22 field mirrors. This image is demagnified by a factor of four from the slicer mirror, or two times faster than the input beam. Two fold mirrors then relay the output "sliced" image to the spectrograph. In Figure 3, the actual final rays proceed out of the figure to the right from the last mirror, while the figure shows the "reverse-traced" rays to show the output rays do indeed originate from the telescope focal plane. The output focal ratio of FISICA is f/8 if the input beam from the telescope is f/16. FISICA can provide an integral field of $\sim 6'' \times 12''$on a 10-m telescope and the output slit dimension is 0.098 mm × 100 mm or $0''.27 \times 264''$.

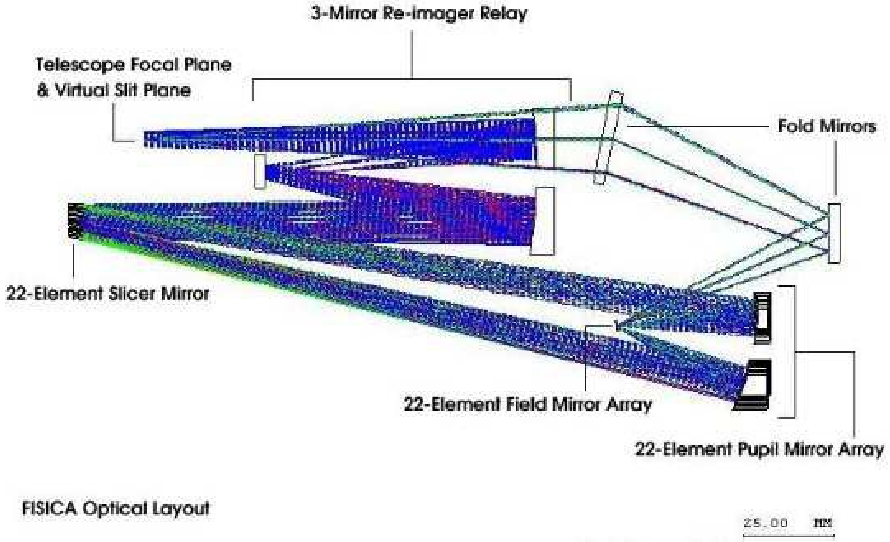

Figure 3. Optical concept layout for FISICA, the figure is taken from Eikenberry et al. (2004)[3] . See text for design concept illustration.

2.2 Spectrograph: Collimator, Grating, and Camera systems

The spectrograph is composed of a collimator system, three reflecting gratings for different passbands and a six-lens spectrograph camera. A flat fold mirror is used between the FISICA assembly and the collimator system to avoid the vignetting caused by FISICA. The size of the fold mirror is 45 mm × 110 mm and it is located at 35 mm away from the FISICA assembly.

The collimator system is composed of an off-axis parabola (OAP) mirror and two achromatic correction lenses. To maximize the spectral resolution while minimizing the anamorphic magnication effect (small anamorphic magnication means large projection effect on the grating), a collimated beam of $\sim$ 100 mm in diameter is used and the distance between the collimator mirror and the FISICA assembly is 460 mm. The off-axis angle is seven degrees, which avoids the vignetting problem while minimizing the spherical aberrations. Two correction lenses were added in the collimator system to further reduce aberrations introduced by the OAP mirror. For the material of these two correction lenses, we use CaF2 and SFTM-16 (Brown et al. 2004[4]) because they have similar change in index of reflection, and therefore were chosen as the lens material because of the achromatic property. Overall, the collimator system slightly reduces the focal ratio of the FISICA output beam from f/8 to f/7.

The distance between the grating and the collimator is 742 mm and the physical size of each grating is 100 mm × 120 mm to accommodate the $\sim$100 mm collimated beam. The anamorphic magnification is set to be $\sim$0.8 for three passbands. The gratings for WIFIS are selected from the grating catalog of the Richardson Grating Inc., and Table 2. presents important parameters. We choose the fused silica as the grating substrate and the gold coating for the grooves to increase the reflectivity.

Although it is possible to achieve the same spectral resolving power with a smaller collimated beam and higher groove density gratings, the anamorphic magnification will decrease in such a case. Lower anamorphic magnification produces uneven magnification in both spectral and spatial directions such that the size of integral field is reduced. On the other hand, it is very difficult to obtain an unity anamorphic magnification because the angle between the collimated and diffracted beams will be unacceptably small. Thus, we set the anamorphic magnification to be 0.8 to maximize the size of integral field also to minimize the grating projection effect. As a result, the projected slit length on the detector is 80 % of the pseudo long-slit length originally provided by FISICA. This means the field size of the WIFIS optical system will be $5'' \times 12''$ (not $6'' \times 12''$) on a 10-m telescope.

	J	H	K
Groove Density (lines/mm)	500	400	300
Incident Angle (degrees)	34.7	35.5	35.5
Blaze Angle (degrees)	20.00	18.67	17.46
Blaze Wavelength (μm)	1.37	1.63	2.04

Table 2. Summary of important specifications of three diffraction gratings used in WIFIS.

The spectrograph camera is composed of five spherical lenses and one aspherical lens. The surface of aspherical lens is described by a fourth order odd-polynomial (first surface of lens 3). All camera lenses are made by CaF2 and S-FTM16 achromatic pair to minimize the chromatic aberrations. The largest lens (lens 4) has a diameter $\sim$ 160 mm and the lens 2 has the largest thickness of 31 mm. Table 3 shows the summary of material and size information of all lenses used in WIFIS. The effective focal length of the spectrograph camera is 321.66 mm.

	Material	Diameter (cm)
Correction lens 1*	CaF2	13.5
Correction lens 2	SFTM-16	12.3
Camera lens 1	CaF2	15.0
Camera lens 2	SFTM-16	14.2
Camera lens 3*	CaF2	15.1
Camera lens 4	SFTM-16	16.2
Camera lens 5	CaF2	12.9
Camera lens 6	SFTM-16	7.1

Table 3. Summary of lens material and diameters in WIFIS design. Star sign denotes the lens with an aspherical surface.

Generally the spectrograph camera focal ratio is given as:

$$f_2 = \frac{w' f_1}{rw} \tag{1}$$

where w', w, r, f_1 and f_2 represents the projected slit width, the slit width, the anamorphic magnification, the focal ratio of the collimator and the focal ratio of the camera, respectively. The projected slit width is 36 μm (two-pixel sampling), the slit width is 0.098 mm as provided by FISICA, the anamorphic magnification is set to be 0.8 and the focal ratio of the collimator is 7. As a result, the camera focal ratio is 3.2 and this is consistent with the 100 mm grating pupil beam and an effective focal length of $\sim$ 320 mm.

The spectral resolving power can be derived with the spectrograph parameters:

$$R = \frac{\lambda \rho m F_{\text{cam}}}{w' cos(\beta)} \tag{2}$$

where ρ, m, F_{cam}, w' and β represents the grating groove density (lines/mm), the grating diffraction order, the focal length of the spectrograph camera, the projected slit width and the grating diffraction angle, respectively. With the two-pixel sampling and the grating parameters, the theoretically expected spectral resolving power of WIFIS is 5500 in J-band and 5800 in both H- and K-bands. The spatial resolution is $6/22 = 0''.27$ on a 10-m telescope. Using the same equation in determining the camera focal ratio, the total integral field size is given as:

$$w' = rw(\frac{f_2}{f_1}) \tag{3}$$

where r is 1 because there is no anamorphic magnification in the spatial direction, w equals 100 mm represents the slit length given by FISICA. As a result, the projected slit length w' is 45.7 mm which is greater than the detector size $\sim$37 mm. That is, only $\sim$80% of the pseudo long-slit is covered by the detector.

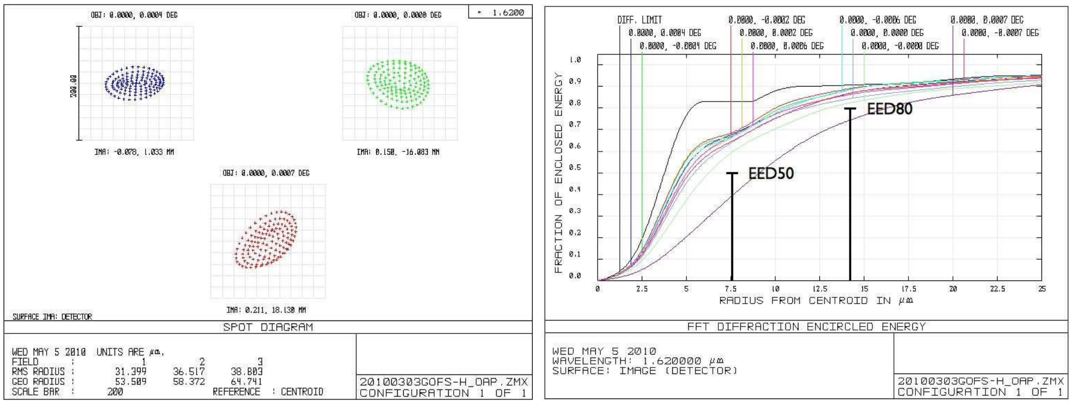

Figure 4. Left panel shows a typical spot diagram at $\lambda = 1.62\mu$m. Right panel shows a typical encircle energy diagram at the same wavelength. Different colors indicate light from different fields.

3. SYSTEM PERFORMANCE

3.1 Spectral Resolving Power

The theoretically expected spectral resolving power of WIFIS is ∼5500 in the NIR regime. In practice, however, the system performance needs to take the spot size (i.e. spot diagram, see Figure 4 left panel for an example) and the seeing effect into consideration. To estimate the system practical performance, we made an assumption that both spot and seeing point spread functions (PSFs) follow the Gaussian distribution. The FWHM of the corresponding PSFs is the 50% encircled energy diameter (EED50, see Figure 4 right panel for an example) and the ideal slit width (36 μm). The final slit width is the convolution of both the spot and the seeing PSFs. Table 4 shows the expected and practical spectral resolving power averaged in each J-, H- and K-band. On average WIFIS has a resolving power R ∼ 5300 in the NIR regime.

	Spectral Resolution (Expected)	Spectral Resolution (Practical)
J	5500	5400
H	5800	5400
Ks	5800	5100

Table 4. Expected and practical spectral resolutions in J-, H- and K-band.

3.2 Integral Field of View

Due to the non-unity anamorphic magnification, the 2K × 2K detector array can only accept ∼ 80% of pseudo long-slit provided by FISICA. In practice, it is also important to know which part of the integral field can not be covered by the detector array. FISICA orients sliced images from the center of the integral field to one end of the pseudo long-slit, and the sliced images from both edges of the integral field are oriented to the other end of the pseudo long-slit. Therefore, the most reasonable configuration is to maintain the center of the integral field. As a result, we use 18 out of 22 slices provided by FISICA to achieve an integral field of view of $5'' \times 12''$.

3.3 Tolerance Analysis

We conducted the tolerance analysis of the WIFIS optical design mainly by monitoring the wave front error (WFE) variation on the detector plan. Under the condition of WFE $\ll 1$, the variation of the encircled energy diameter is proportional to the WFE change. We found that in terms of element surface curvature, the correction lenses in the collimator system, spectrograph camera lens 1, 4, 5 and 6 require higher surface manufacture accuracy of 0.01%; the spectrograph camera lens 2 requires 0.05% accuracy. Rest of the surfaces can accept 0.1% tolerance. The dominant WFE sources orginate from the element tilt and the air space between the lenses.

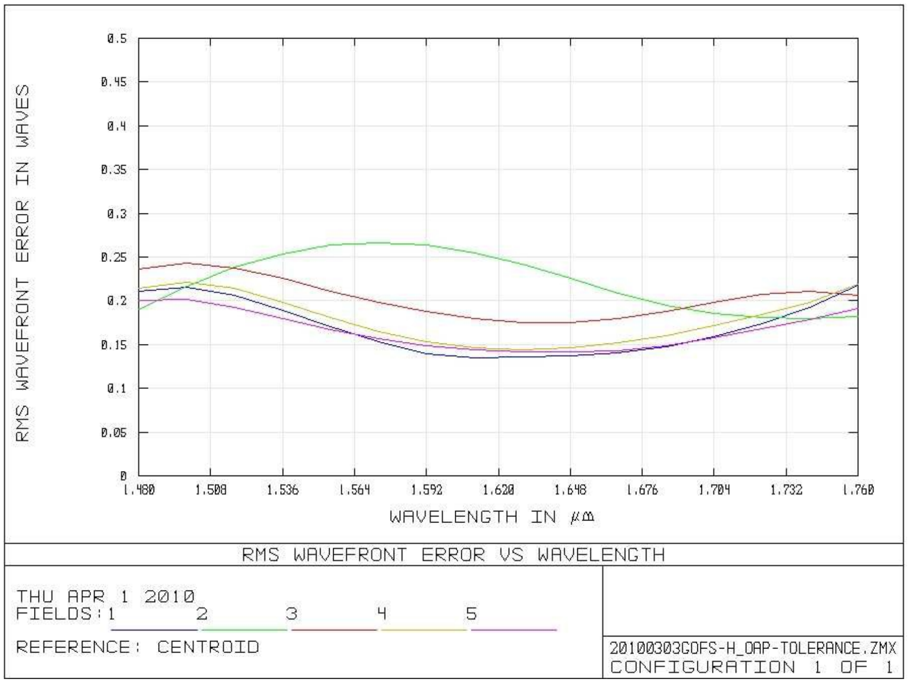

Figure 5. A typical WFE distribution along the wavelength coverage in H-band

The tilt of the collimator mirror and the distance between the two correction lenses are very sensitive to small manufacture errors. The distances between the spectrograph camera lens 2 and 3, and the lens 5 and 6 also require higher alignment accuracy (±0.05 mm). For the element tilt, all elements can accept ±0.4 mrad tolerance in the spatial direction. In the spectral direction, each component in the collimator system (including the fold flat mirror), the spectrograph camera lens 3 and 4 require ±0.2 mrad accuracy, the rest elements can accept ±0.4 mrad tilt tolerance.

We expect the system performance degradation due to the manufacture or alignment error is less than 5% under the tolerance accuracy mentioned above. The perfomance degradation may reach $\sim$8% at the longer wavelength side in each passband (for example, $\lambda > 1.74$ in H-band or $\lambda > 2.34$ in K-band). In general the WFE variation along the wavelength is smooth and stable, which means the spectral resolution variation within a single band is also smooth and stable. Figure 5 shows a typical WFE variation along the wavelength in H-band. The similar variation trend also shows in J- and K-band.

4. SUMMARY

WIFIS is an image slicer-based IFS which can deliver an average spectral resolving power R$\sim$5300 in each J-, H- and K-band within a single exposure. The integral field of view provided by WIFIS is $5'' \times 12''$on a 10-m class telescope under the natural seeing condition. This unrivaled combination of the spectral resolving power, spectral coverage and the integral field of view can greatly help us in studying extended astronomical objects. The application of WIFIS can improve our understanding to supernova remnants, star forming regions, outflow jets, and galactic central disks in the nearby universe; At higher redshifts, WIFIS can also broaden our knowledge towards the galaxy and galaxy mergers.

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