

Near-Infrared and Mid-Infrared Spectroscopy with the Infrared Camera (IRC) for AKARI

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Abstract

The Infrared Camera (IRC) is one of the two instruments on board the AKARI satellite. In addition to deep imaging from 1.8 to 26.5 μm for the pointed observation mode of the AKARI, it has a spectroscopic capability in its spectral range. By replacing the imaging filters by transmission-type dispersers on the filter wheels, it provides low-resolution ($\lambda/\delta\lambda \sim 20\text{--}120$) spectroscopy with slits, or in a wide imaging field-of-view (approximately $10' \times 10'$). The IRC spectroscopic mode is unique for space infrared missions in that it has the capability to perform sensitive wide-field spectroscopic surveys in the near- and mid-infrared wavelength ranges. This paper describes the specifications of the IRC spectrograph and its in-orbit performance.

Key words: infrared: general — instrumentation: spectrographs — space vehicles: instruments — techniques: spectroscopic

1. Introduction

The Infrared Camera (IRC: Onaka et al. 2007) is one of the two instruments on board the AKARI satellite (Murakami et al. 2007), and is mainly designed for deep imaging over 1.8–26.5 μm for AKARI's pointed observation mode. In order to obtain rich multi-color information of astronomical objects at near- and mid-infrared (hereafter, NIR and MIR) wavelengths, the IRC is composed of three channels (NIR, MIR-S, and MIR-L), each equipped with a selectable filter wheel to cover a wide wavelength range. In addition to the multi-color photometry capability, a spectroscopic mode was also introduced in its spectral range to enhance the IRC's capability of analyzing the spectral energy distribution of brighter sources.

By replacing the imaging filters by transmission-type dispersers on the filter wheels, it provides low-resolution ($\lambda/\delta\lambda \sim 20\text{--}120$) slit-less spectroscopy in its imaging field-of-view (FOV) (approximately $10' \times 10'$) for the first time in space infrared observations. The IRAS LRS also provided slit-less spectroscopy (Neugebauer et al. 1984), but it made observations of anything that was located in the wide entrance apertures of the separate blue and red spectrometers, whether a single object, or multiple objects, or even bright diffuse emission. Deconvolving these entangled spectra was often problematic. IRC slit-less spectroscopy, on the other hand, enables multi-object spectroscopy, providing the advantage of efficient observations of multi-objects in a region, although it suffers from high background, particularly in the MIR where the zodiacal emission is dominant. While a slit spectrograph, such as the Infrared Spectrograph (IRS) on Spitzer (Houck et al. 2004), provides better sensitivity in high background regions, the IRC slit-less spectroscopy allows a serendipitous survey of interesting objects with blank field observations. Note that the IRC also has small slit areas for all three channels to allow the spectroscopy of diffuse sources. Compared to

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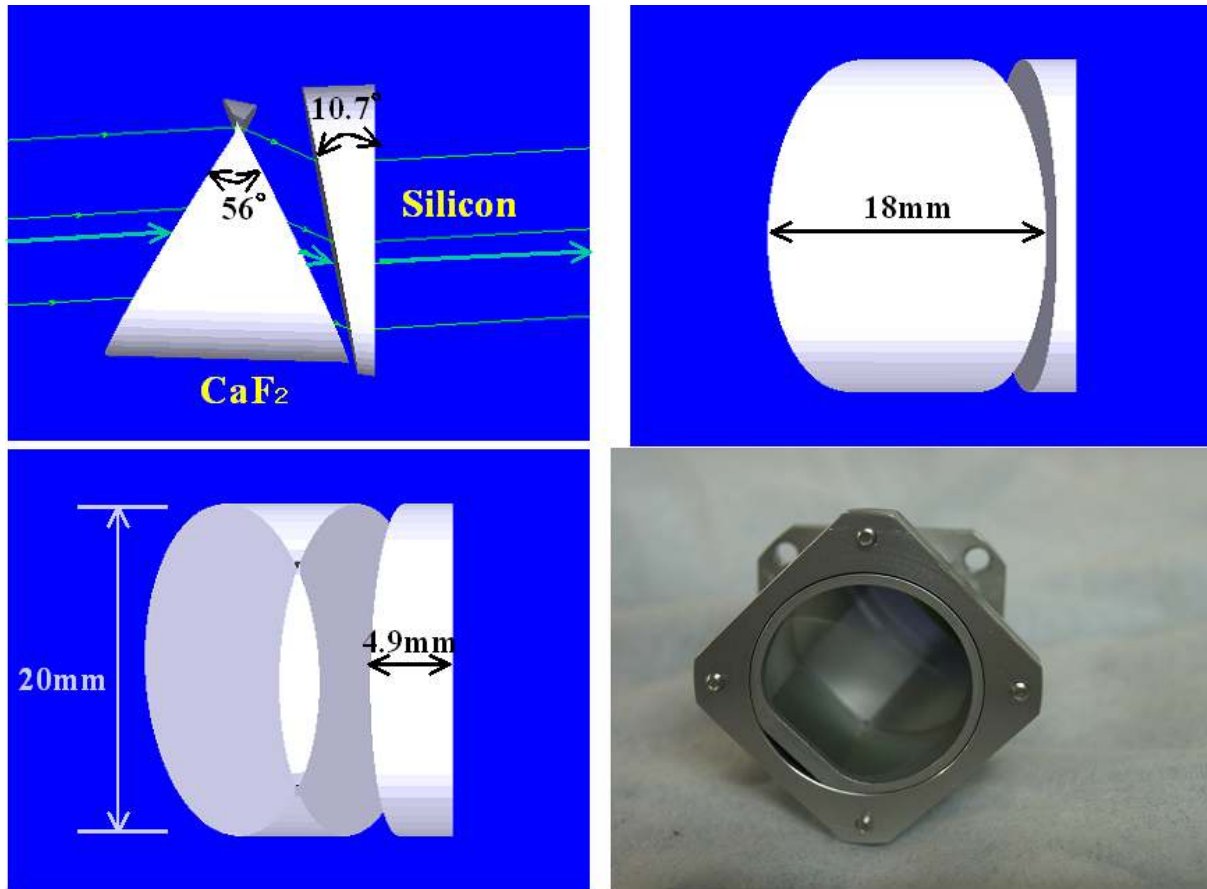


Fig. 1. Drawings and a picture of NIR prism (NP). (upper left, upper right, and lower left) Schematic drawings of the prisms comprising the NP. (lower right) A picture of the assembled NP in its holder, seen from the ray incident side.

the ISOCAM CVF mode on the ISO satellite (Cesarsky et al. 1996), which also provided multi-object spectroscopic capability, the IRC achieves higher sensitivity in a short exposure, thanks to the large format arrays with low read noise.

Another advantage of IRC spectroscopy, by comparison with the IRS in particular, is that the IRC can perform NIR spectroscopy ($2\text{--}5\ \mu\text{m}$), where there are interesting lines, such as $\text{H}_2\ v1\text{--}0$ rotational lines and hydrogen recombination lines, and dust bands, such as $3.1\ \mu\text{m}$ water ice, and the 3.3 and $3.4\ \mu\text{m}$ unidentified infrared bands.

This paper describes the specifications of the IRC spectrograph and its in-orbit performance. See Onaka et al. (2007) for details of the general IRC design and its imaging performance.

2. Design and Characteristics of the IRC Spectroscopic Mode

The IRC spectroscopic mode shares most of the basic hardware and software designed for its imaging mode (e.g., camera optics, electronics for controlling the cameras, software for controlling/reading out detector arrays, communication with the satellite attitude control system). Under these hardware/software constraints, we decided to focus mainly on slit-less spectroscopy in its imaging FOV to make the

spectroscopic mode more attractive and powerful in terms of science, be simple and reliable in terms of instrument development and operation, and not compromise any capabilities and/or performance of the IRC imaging mode. In order to fully utilize its capability for spectroscopic surveys by minimizing loss of spectral information due to source overlap or contamination, the size of the spectral images along the dispersion direction is restricted to be about one fifth of the FOV. Therefore, only low spectral resolution is available for slit-less spectroscopy.

One must also acknowledge some weaknesses of slit-less spectroscopy. One is the higher background in spectroscopic images. Although the MIR background from space is faint enough to make slit-less spectroscopy viable, the spectral images suffer higher background noise, because emission from compact sources is dispersed relative to broad band imaging, while that of the background changes very little with respect to broad band imaging. Another limitation is poorer uniformity of calibration. The positional dependence of the spectral calibration should be taken into account to obtain uniformly calibrated spectra observed with slit-less spectroscopy, and this requires much more detailed calibration information than for slit spectroscopy. However, since the IRC does not have any good built-in calibration lamps, we must observe celestial objects as our calibrators to construct the calibration

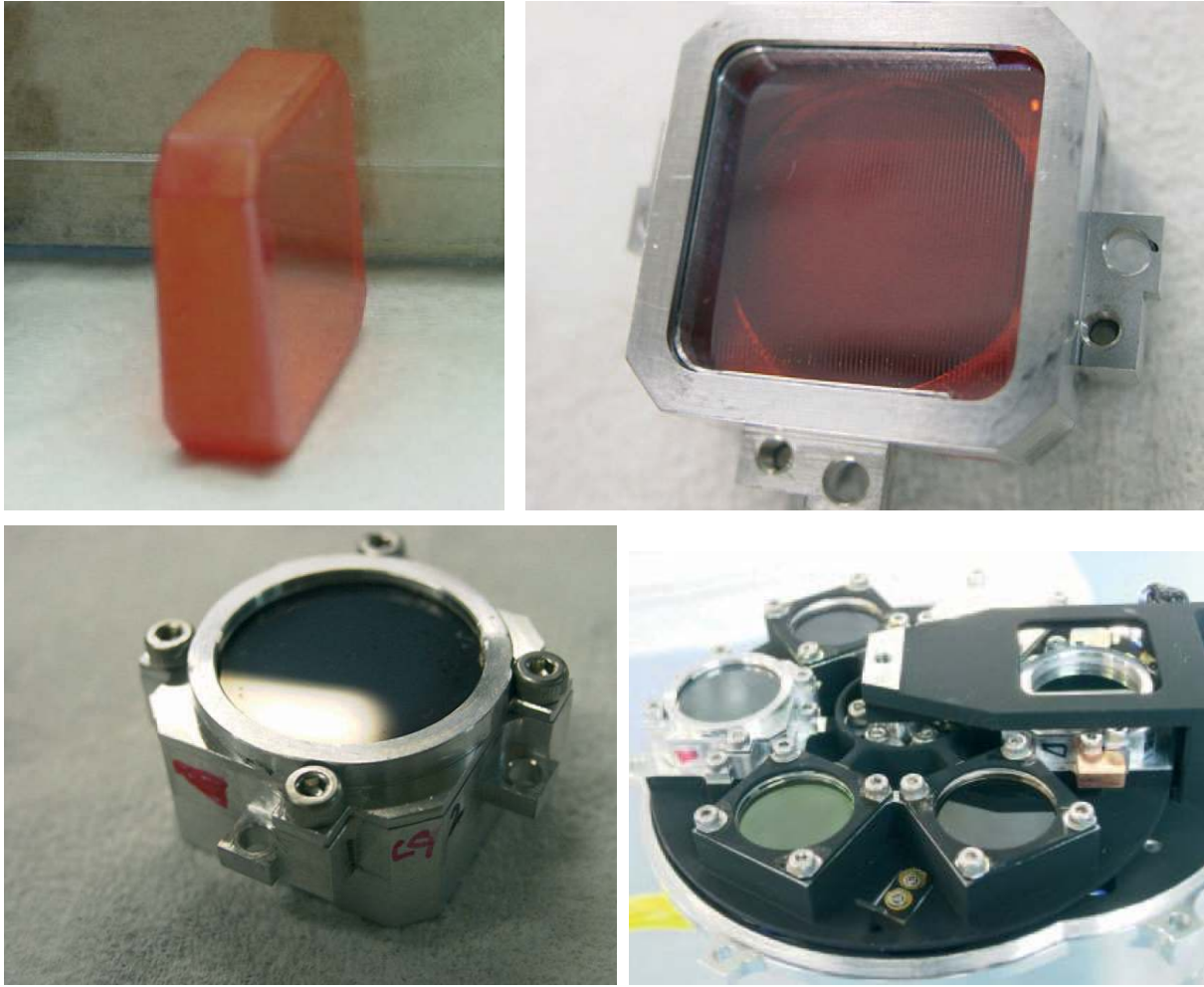


Fig. 2. Pictures of the MIR-L grisms. (upper left) The *LG2* grism. The dimensions of the *LG2* grism are 20.0 mm, 20.0 mm, and 6.0 mm in height, width, and thickness, respectively. (upper right) The *LG2* grism stored in its holder. (lower left) The same holder as shown in upper right, but is seen upside-down, showing the order-sorting filter. Dimensions of the order-sorting filter are 19.9 mm and 2.0 mm in diameter and thickness, respectively. (lower right) The MIR-L filter wheel mounting the *LG1* and *LG2* as well as three imaging filters (*L15*, *L18W*, and *L24*). The filter wheel has a diameter of 90.0 mm. Note that the picture shows the filter wheel set up for laboratory tests. MIR-S grisms (*SG1* and *SG2*) were assembled and installed onto their corresponding filter wheels in a very similar way, and *NG* was also mounted in a comparable fashion but its order-sorting filter is directly coated on its surface.

database. In reality, because of the limited cryogenic lifetime of AKARI and very tight target visibility constraints posed by the nature of its orbit (solar-synchronous near-earth polar-orbit for the All-Sky Survey; Murakami et al. 2007), the available calibrators are rather limited. In spite of these difficulties, however, we have so far achieved good calibration performance, as detailed in the following sections, so that we can indeed conduct deep blank-field spectroscopic surveys across the entire IRC wavelength range (T. Wada et al. 2007, in preparation).

3. Instrumentation Specific to the IRC Spectroscopy Mode

To add spectroscopic functionality to the IRC, we developed and installed dispersers and focal-plane aperture masks with slit areas. Here we describe them in more detail. Also see

Onaka et al. (2007) for more information on the IRC in general.

3.1. Dispersers

We developed transmissive dispersers of direct-vision type, and mounted them on filter wheels. Basic specifications of the dispersers were determined by requiring that the dispersed image length be as small as one fifth of the total array size (except for a higher dispersion grism in the NIR channel), while still covering the entire wavelength range of the channels. The dispersion (wavelength increment per pixel) is simply determined by the required wavelength coverage and the spectral image length, and the spectral resolving power is determined by the point spread function (PSF) size in the imaging mode, which is set either by the wavefront error (at $\lesssim 7.3 \mu\text{m}$) or the diffraction limit (at $\gtrsim 7.3 \mu\text{m}$) of the telescope optics (Kaneda et al. 2007). The thus-designed dispersers provide a rather low resolving power ($R = \lambda / \delta\lambda$)

Table 1. Specifications of dispersers.*

Channel	Name	Effective coverage μm	Dispersion $\mu\text{m}/\text{pixel}$	R^\dagger	L^\ddagger pixel
NIR	<i>NP</i>	1.8–5.5	0.06 §	19 at 3.5 μm	54
	<i>NG</i>	2.5–5.0	0.0097	120 at 3.6 μm	258
MIR-S	<i>SG1</i>	4.6–9.2	0.057	53 at 6.6 μm	62
	<i>SG2</i>	7.2–13.4	0.097	50 at 10.6 μm	60
MIR-L	<i>LG1</i> *	(11–19)	(0.173)	(34 at 14.4 μm)	(46)
	<i>LG2</i>	17.5–26.5	0.17	48 at 20.2 μm	53

* All of the values were measured in-orbit. However, *LG1* is not available in orbit, and numbers shown in parentheses are based on its design.

† Spectral resolving power (R) in the slit-less spectroscopy mode, that is defined by $\lambda / \delta\lambda$, where $\delta\lambda$ is the smallest resolving element size corresponding to the FWHM of the point spread function in *N3*, *S9W*, and *L18W* for NIR, MIR-S, and MIR-L channels, respectively.

‡ Size of dispersed spectroscopy images within ranges where spectral response curves are larger than 5% (for *NP* and *NG*) or 20% (for *SG1*, *SG2*, and *LG2*) of their peaks.

§ Dispersion of *NP* is not linear, and the quoted value is a representative one measured at 3.5 μm .

Table 2. Design of dispersers.

Name	Disperser		Order-sorting filter				
	Type	Material	Grooves mm^{-1}	Prism/blaze angle $^\circ$	Material	Type †	Spectral coverage μm
<i>NP</i>	prism	CaF ₂ /Si	NA	56/10.7	NA	NA	NA
<i>NG</i>	grism	Ge	47.6	2.86	Ge	SC	> 2.5
<i>SG1</i>	grism	KRS-5	10.02	2.6	ZnS	BP	5.0–8.3
<i>SG2</i>	grism	KRS-5	5.71	2.2	ZnS	SC	> 7.0
<i>LG1</i> *	grism	KRS-5	3.83	2.3	CdTe	BP	11.0–19.0
<i>LG2</i>	grism	KRS-5	3.70	3.4	CdTe	SC	> 17.7

* Not available in orbit.

† SC = short-end cut, BP = band-pass cut.

of ~ 20 –50. In addition, a higher-power disperser for the NIR channel was introduced. Utilizing the full dimension of the NIR detector array, its resolving power was set to be as large as possible, $R \simeq 120$, determined mostly by the array size and the PSF size.

For low-dispersion spectroscopy, we chose a prism for the NIR channel and gratings for the MIR-S and MIR-L channels. The NIR prism (*NP*) simultaneously covers the entire wavelength coverage of the channel (1.8–5.5 μm). The *NP* is comprised of two individual prisms to form a single low-dispersion direct-vision prism (figure 1). For the MIR-S channel, since the channel covers a wide spectral range of more than an octave (5–13 μm), two gratings (*SG1* and *SG2*) handle the short and long halves of the wavelength coverage, respectively, in the first-order. Similarly, for the MIR-L channel, two gratings (*LG1* and *LG2*) cover the wavelength range of the channel. Order-sorting filters were also developed to limit the grating dispersers to their desired wavelength ranges by rejecting higher-order shorter-wavelength light. For *SG1* and *LG1* that cover short half of the MIR-S and MIR-L wavelength ranges, respectively, the filters block longer-wavelength light, whereas filters for *SG2* and *LG2* covering the longer half block shorter-wavelength light.

In addition, since the MIR-L and MIR-S channels are also sensitive to the MIR-S and NIR wavelength ranges, respectively, the *SG1* and *LG1* filters should also block shorter-wavelength light. Therefore, band-pass filters were adopted for filters of both *SG1* and *LG1*. Note that the longer wavelength light for the *SG2* is blocked by the transmission of the ZnS filter. For the *LG2* filter, the longer wavelength light is beyond the long wavelength cutoff of the Si : As detector array and the CdTe filter.

For higher-dispersion spectroscopy in the NIR channel, we developed a grating (*NG*) to cover 2.5–5.0 μm . In order to avoid order wrapping of the spectral images, the shortest wavelength range (1.8–2.5 μm) of the NIR channel is blocked by the order-sorting filter, which is coated on the surface of *NG*. The gratings and their corresponding order-sorting filters were mounted together in grating holders for *SG1*, *SG2*, *LG1*, and *LG2* (figure 2), while a grating coated by its order-sorting filter was mounted in its holder for *NG*. After assembling optical elements in their holders to form individual dispersing elements, they were mounted on their corresponding filter wheels. Since these dispersers are heavier than other imaging filters, two dispersers were located at opposite sides of the wheel for better balance of their weight. Tables 1 and 2

summarize the specifications and design of the dispersers.

As for the *LG1*, although it worked well in the IRC's single-component tests in the laboratory, it became opaque¹ during AKARI's system-integration tests after assembling the entire observing system (including the telescope and two science instruments) within the cryostat, and has not been available since then.

3.2. Aperture Masks

In addition to slit-less spectroscopy, slit spectroscopy, and higher-dispersion spectroscopy in a small aperture are also available for diffuse and point-like targets, respectively. The focal-plane aperture masks of the IRC have unique shapes with various types of substructure at the sides of the main FOV for imaging (see Onaka et al. 2007 for the illustration). Here, we describe the design and purposes of the aperture masks in more detail.

There are three narrow slits for the spectroscopy of diffuse sources. The first one, the Ns slit, is a narrow slit for the NIR and MIR-S channels, while the Ls slit is another narrow slit for the MIR-L channel. The Ns slit is shared by both the NIR and MIR-S channels by means of a beam splitter. The widths of these slits are chosen to match typical imaging PSF sizes for the channel (5'' width for the Ns slit and 7'' for the Ls slit, corresponding to the PSFs of the *S9W* and *L18W* filters, respectively) to maximize the resolving power of the dispersers. Another slit for higher dispersion spectroscopy, the Nh slit, is created at the outer part of the Ns slit, which is not covered by the MIR-S channel. Its width is narrower than that of the Ns slit to match the imaging PSF size of the N3 filter (3''), giving the highest spectral resolution with the *NG*. Note that the absolute pointing accuracy of the telescope is only as good as $\sim 3''$ (Onaka et al. 2007), which is not accurate enough to locate a compact source at these narrow slits and, hence, these slits are useful only for observing diffuse sources extended well over $\sim 3''$. Since we take a direct image of the targeted area as well as spectroscopy images, without changing the telescope pointing attitude (see section 4 below), the observer can obtain slit position information from the image with an accuracy of $\lesssim 3''$.

In addition to narrow slits, another small aperture, the Np aperture, is created for the spectroscopy of single targeted sources with the *NG*. The smaller aperture ensures that contamination of the spectra by source overlap is minimal, even for higher-dispersion spectroscopy with the *NG* whose spectral image length is as large as the full array size. We do not have a 'peak-up' capability to locate an object on the slit, and we totally rely on the satellite pointing accuracy. Therefore, the size of the aperture is set as 1' by 1' according to the absolute pointing accuracy expected prior to launch, taking account of a possible thermal deformation of the satellite/telescope structures.²

¹ The *LG1* became opaque as a result of micro-cracks propagating in the substrate most likely due to an unexpected abrupt change in the temperature of the cryostat during the ground test operation.

² After tuning the satellite attitude control system in orbit and the ground supporting software for observation planning, the current absolute pointing accuracy of the telescope is 3'' or better (Onaka et al. 2007).

4. The Astronomical Observing Template (AOT) for Spectroscopy

An astronomical observing template (AOT) for the spectroscopic mode (AOT04) is designed to cover the entire spectral range of the channel within a single pointing opportunity. To cover the entire spectral coverage of the IRC, however, one needs to make at least two pointings for a target; one for the NIR and MIR-S channels, and a second for the MIR-L channel. In the first half of the pointing period, spectroscopic exposures with the first disperser (*NP* or *NG* for the NIR channel, *SG1* for the MIR-S channel, and *LG2* for the MIR-L channel) will be made, and more exposures with another disperser (*NP* or *NG* for the NIR channel, *SG2* for the MIR-S channel, and *LG2* for the MIR-L channel) will follow in the last half, after taking a single imaging exposure for a source position reference (the "reference image"). The sequence is schematically illustrated in Onaka et al. (2007). For slit-less spectroscopy, the reference images provide wavelength reference positions in the spectral images. The reference images are taken with wider-band filters (*S9W* for the MIR-S channel and *L18W* for the MIR-L channel), or near the center of the wavelength coverage of the channel (*N3* for the NIR channel). The telescope pointing will not be dithered because the reference image should be taken at exactly the same position where spectroscopy is done.

The AOT accepts two types of options. Since two NIR dispersers (*NP* and *NG*) are complementary to each other, i.e., both cover a similar wavelength range with different dispersions, observers need to choose one of the two according to their scientific goals. Also, observers must specify the pointing offset preset of the telescope boresight according to their desired observing mode. For slit-less spectroscopy, one selects the offset for either the center of the NIR/MIR-S imaging FOV or the center of the MIR-L imaging FOV. For slit spectroscopy of diffuse sources, one selects the offset for either the Ns, Nh, or Ls slit. For point-source spectroscopy with the *NG*, one selects the Np aperture.

5. Performance and Calibration of the IRC Spectroscopy Mode

5.1. Repeatability of Disperser Insertion Position

Repeatability of the filter-wheel positions when inserting the dispersers is very important to ensure good wavelength calibration. Each wheel is connected directly to a stepping motor with 24 latching positions. Any error in filter wheel rotation relative to its nominal insertion position would result in a tilt of the spectrum, leading to an erroneous wavelength calibration. During one year of operation of the filter wheel rotation, with over ~ 500 pointing opportunities for spectroscopy, the errors of the disperser insertion angles (or the differences in orientation of a dispersed spectroscopy image from its nominal orientation) have never exceeded an angle $\lesssim 1^\circ$, or $\lesssim 1$ pixel shift along the spatial direction over the dispersed spectroscopy image length of 50–60 pixels (see table 1). This assures sufficient accuracy for wavelength calibration.

5.2. Sky Brightness and Noise Conditions in Spectroscopy Images

The slit-less spectroscopic images of the background (sky) emission (mostly zodiacal emission) are found to be as bright as that in the direct images, and are within the range of our pre-launch expectation. With the high background in the MIR, we can achieve background-photon-noise-limited conditions in the long exposure frames of ~ 16 seconds (see Onaka et al. 2007 for short- and long-exposure frames). However, the zodiacal light is much fainter in the NIR channel, so that exposures need to be longer than 44 seconds to be background limited. The exposure time of individual sub-frames in the spectroscopic mode is rather short: the same as that for imaging observations. But, compared with conventional slit spectroscopic observations, several sub-frame images can be stacked with less degradation of the performance by array-readout noise.

For slit spectroscopy with *NP*, *NG*, *SG1*, *SG2*, and *NG* spectroscopy in a small aperture (*Np*), array-readout noise usually dominates the background noise, due to the faintness of the sky per pixel. The noise in the spectrum is dominated by background-photon noise at longer wavelengths (*LG2*).

5.3. Wavelength Calibration and Its Accuracy

The wavelength calibration curves (wavelength as a function of pixel) were basically measured by observing bright emission-line objects. The results of a computer ray-tracing simulation of the NIR optics were also taken into account for *NP*. Most of the calibration observations were made during the initial performance verification (PV) phase, and additional observations were made during the calibration time. One should measure calibration curves at various positions across the imaging FOV and slit areas to define the positional dependence of the calibration curves. However, such a detailed calibration program was not possible because of the limited visibility of the calibration objects and the small number of pointing opportunities available for calibration during both the PV phase and the calibration time. Therefore, we measured the wavelength calibration curves either in the slits or near the imaging FOV center, and the results were checked by another measurement made at another location. An extended planetary nebula (PN) was selected for wavelength calibration in the slits, and compact sources, such as Wolf-Rayet (WR) stars, compact star-forming regions, and an AGN, were selected for observation near the imaging FOV center. Due to the low spectral resolution (except for *NG*), one can detect only bright emission-lines with large equivalent widths, even for bright objects, and the number of detectable emission lines is relatively small (2–4) (see section 7 and figure 7 for the slit spectrum of the PN). Therefore, we adopted simple linear wavelength calibration curves for all of the grisms. The wavelength calibration curve for *NP* is not linear, and low-resolution spectroscopy would not provide an adequate shape for the function at shorter wavelengths, where the resolution is even smaller, so we defined the shape of the calibration curve by computer ray-tracing simulations of the NIR camera optics and the *NP* prism.

For *NG*, *SG1*, and *SG2*, a bright planetary nebula located

within AKARI's constant viewing zone (CVZ), NGC 6543, was observed through slits, and the wavelength calibration curves measured there were checked by slit-less spectroscopy of the bright WR stars, WR 128 and WR 133 (van der Hucht 2001). For *LG2*, a compact and bright AGN (Mrk 3: e.g., Weedman 2005) was observed in the slit-less spectroscopy mode, and the measured calibration curve was checked both by additional slit-less spectroscopy of bright knots (presumably compact star-forming regions) along the spiral arms of a nearby galaxy, M 81, and by slit spectra of the PN, although the latter shows only a single emission line within the range of *LG2*. For *NP*, slit spectra of the PN were taken to check the simulated wavelength calibration curve, and a small pixel offset between the simulated function and the observation was determined by using a few emission lines at longer wavelengths where the calibration curve is closer to linear and the spectral resolution is larger. The measured wavelength calibration curve was checked by slit-less spectra of the WR stars. In all cases, the fitting error (residual) of the wavelength calibration curves is typically 0.5 pixel for all dispersers.

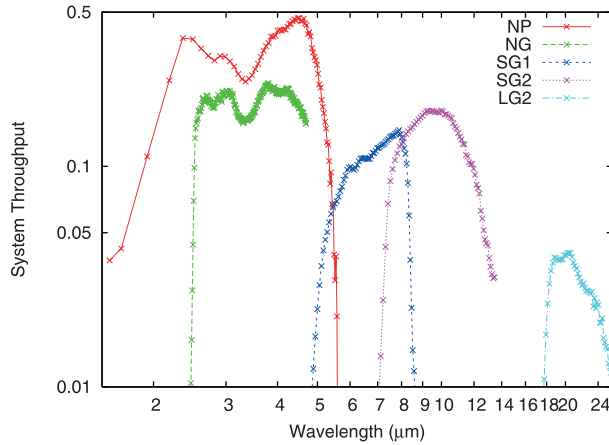
Some wavelength calibration errors are unique to our slit-less spectroscopy. One type of error arises from uncertainties in the wavelength reference positions, since there are no such well-defined references in IRC slit-less spectroscopy, like the slits for conventional slit spectroscopy. Although we take reference images to define wavelength reference positions of the detected sources by measuring their locations on the images, their positions would be shifted if the telescope pointing attitude were to drift in the wavelength direction during the pointing period.³ As described below, the drift (or shift of image positions) could be measured by using *NP* or *NG* spectra and comparing their locations on the reference image. The typical accuracy of shift measurements is 0.5 pixel or less for *NP* and about 0.5 pixel for *NG* (see subsection 6.1 for more details).⁴ Another type of error occurs when comparing wavelength calibrations of objects observed at different positions across the imaging FOV and slit areas. Since it is difficult to measure the detailed positional dependence of the calibration in orbit, we rely on pre-launch laboratory testing with a special pin-hole mask installed instead of the aperture mask in flight. We took a pair of imaging and spectroscopic images of a continuum source through the grid, exactly as for the spectroscopy AOT operation in orbit, and measured the positions of the holes in the imaging and spectroscopy modes. For the grisms, we measured the positions of zeroth-order light images as positional references on the spectroscopic images. By comparing their positions, we found that the pixel shift from the ideal uniform wavelength calibration is typically 0.5 pixel for all grisms. For the prism (*NP*), we found that the pixel offset changes significantly over the entire array, although we could not quantitatively characterize the shift because no good positional indicator (like zeroth-order images of grism spectral images) is available in the prism spectra. Fortunately, in orbit, we found that

³ Typical drift rate is 2'' per minute or less.

⁴ Because wavelength calibration accuracy is determined by the accuracy of correcting the drift of the telescope attitude, or the objects' movement on detector arrays, here we present the wavelength error in units of pixel. See table 1 to find errors in μm .

Table 3. Standard stars for flux calibration.

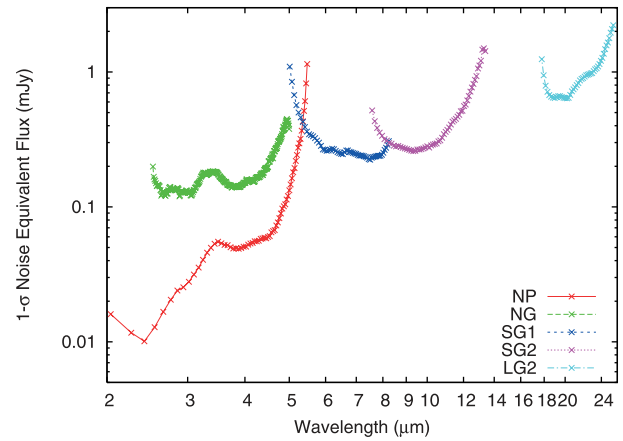
Star	2MASS J	Type	A_V (mag)	Target dispersers
2MASS J17564393+6920089		A4 V	0.508	<i>NP</i>
KF06T2	17583798+6646522	K1.5 III	0.189	<i>NP</i>
KF09T1	17592304+6602561	K0 III	0.000	<i>NG/NP</i>
Bp +66 1073	18030959+6628119	K1 III	0.000	<i>NG/SG1/SG2</i>
NPM 1+67.0536	17585466+6747368	K2 III	0.161	<i>NG/SG1/SG2</i>
HD 42525	06060937-6602227	A0 V	0.000	<i>NG/SG1/SG2/LG2</i>
HD 42701	06065055-6716599	K3 III	0.604	<i>LG2</i>

**Fig. 3.** System throughput of the IRC spectroscopy mode.

many blue field stars show prominent pseudo-spectral features around $2.4 \mu\text{m}$ (see subsection 6.1 below for more details), and we could measure the pixel shift over the entire FOV, as we did for the gratings on the grid images at the laboratory. We successfully fitted the pixel offset by using a higher-order function of the pixel locations, with an accuracy of $\lesssim 0.5$ pixel over the entire FOV. We confirmed that the measured function reproduces the laboratory images, though less precisely. The thus-measured pixel offset function was taken into account to represent the wavelength calibration curves and to calibrate the observed spectra of *NP*. We suspect that any mis-alignment between the two prisms comprising the *NP* causes the positional dependence of the wavelength calibration. Combining all of these sources of error in fitting and creating the calibration curves, the overall accuracy of the wavelength calibration is typically about 1 pixel for all dispersers.

5.4. Flux Calibration and Its Accuracy

A flux calibration was made based on slit-less spectroscopic observations of flux standard stars, and spectral response curves were calculated based on their spectral templates in flux density (mJy) units. A list of standard stars was taken from the infrared standard star networks (Cohen et al. 1999, 2003; Cohen 2007), and we selected our targets from the list by considering the visibility and brightness of the stars (table 3). Several stars are common to the IRAC flux calibration program onboard Spitzer (Reach et al. 2005). In order to check the validity of the spectral templates, we observed at least two stars

**Fig. 4.** Sensitivity as a function of wavelength. The plot shows the one-sigma noise-equivalent flux (in mJy) at the ecliptic poles as a function of wavelength. Because of smaller dispersion at shorter wavelength in *NP*, the *NP* has higher sensitivity at shorter wavelength.

per disperser; one an A type dwarf showing only Hydrogen absorption lines, and the other a K type giant showing several broad absorption features from $2\text{--}10 \mu\text{m}$, to validate the calibration for each disperser, except for the *LG2* where only one K type star is available. Since we found no significant systematic differences in the spectral response curves among the observations (above the 10% level), the spectral response curves that were measured with brighter stars (K type stars for *NP* and *LG2*, and A type stars for other gratings) were adopted.

The spectral response curves were then used to derive the end-to-end system throughput of the AKARI/IRC in orbit, including the telescope optics, camera optics of the IRC with disperser inserted, and quantum efficiency of the detectors (figure 3). The system throughput is well within the range of pre-launch expectation, based on throughput measurements of all the individual optical components as well as the quantum efficiency of the detectors. A dip in the throughput at around $3.4 \mu\text{m}$, found in both *NP* and *NG*, originates from the beam splitter. The sensitivity is calculated based on the system throughput and the observed noise levels in orbit. Here, the noise is a typical fluctuation of the sky counts on the stacked and fully-calibrated images, after masking out all of the source spectra; the measurement was done after smoothing over 2×2 pixels for all dispersers to roughly match their spectral and spatial

resolutions. The one-sigma noise-equivalent flux spectrum for slit-less spectroscopy at the ecliptic poles, where the background zodiacal light is faintest, is shown in figure 4. The sensitivity agrees well with the range of the pre-launch expectation based on the expected system throughput as well as readout- and sky-photon noises for all grisms, except for *NP*. For *NP* we found that the sensitivity is worse than expected by a factor of 2 or more, although the system throughput at the spectral range is as good as expected. This is because the spectra of many faint field stars can be detected with *NP*, especially at around $2.4 \mu\text{m}$, where the sensitivity per pixel is largest, amplifying the sky fluctuations around any target spectrum.

Monitoring of the sensitivity stability in both the imaging and spectroscopic modes has been on-going since the initial PV phase. Because the IRC spectroscopic mode shares most of the optical components of its imaging mode (except for imaging filters and dispersers), and operation of the detector arrays is exactly the same for both modes, results of the sensitivity monitoring in the imaging mode should provide us with a good measure of the sensitivity stability in the spectroscopic mode. Results of the imaging sensitivity monitor are briefly described in Onaka et al. (2007). It is stable at a level of 5% over almost one year in all filters. The results of more detailed studies will be presented elsewhere (T. Tanabé et al. 2007, in preparation). Sensitivity monitoring of the spectroscopic mode has been conducted less frequently. Although it is difficult to perform accurate sensitivity monitoring in the slit-less spectral mode, no systematic trend in sensitivity has been found at the 20% level in all of the dispersers. In summary, so far there are no indications of temporal variations of the sensitivity in either the imaging or spectroscopic modes.

There is a noteworthy influence of a wavelength calibration error on the flux calibration for slit-less spectroscopy. Because of the very low dispersion and wide spectral coverage with single dispersers, the spectral response per pixel changes greatly near the ends of their spectral coverage. In addition, due to the slit-less nature of this IRC spectroscopic mode, the wavelength calibration accuracy is not as good (~ 1 pixel; see subsection 5.3). As a result, flux calibration errors that arise from the wavelength mismatch between the observed spectra and the spectral response curve could be much larger near the band ends than around the band center. The data reduction tool kit (see below) incorporates this kind of error when plotting spectra with error bars.

After considering all sources of errors, as mentioned above, the overall flux calibration accuracy is estimated to be 10% for all dispersers around their central wavelengths, and it gets worse (20%) around longest and shortest wavelengths of the spectral coverage of each disperser.

6. Data Reduction

The IRC team has been developing a software suite (the so-called toolkit) for reducing the IRC spectroscopic images. The software is written in IDL, and utilizes the IDL Astronomy User's Library at Goddard Space Flight Center,

NASA.⁵ With the software, one first performs a series of basic data reductions of the array images (dark subtraction, linearity correction, correction of various kinds of image anomaly, etc.) to derive basic-calibrated images, and then applies spectroscopy-specific calibration on the basic-calibrated images to derive spectroscopic products. Since the array operation and data acquisition sequence (or the AOT operation) in the spectroscopic mode follow exactly the same pattern as that for the imaging mode, the same techniques can be used for the basic reduction of the array images in the spectral images. Note, however, that we are still investigating the causes of, and correction methods for, anomalies, and currently the anomaly correcting routines are not fully implemented. See Onaka et al. (2007) for more details on the basic data reduction. Here, we describe only the spectroscopy-specific calibrations. First, we describe data-reduction techniques that are unique to slit-less spectroscopy, and then comment on calibration techniques common to conventional slit spectroscopy.

6.1. Extracting the Spectral Images for Each Source

Finding accurate wavelength reference positions is the key to deriving well-calibrated spectra from slit-less spectroscopy, because any drift in telescope pointing would cause errors in wavelength calibration and, hence, flux calibration that requires the wavelength-dependent spectral response function. Since source positions that are measured on the reference image provide the wavelength reference positions on the spectral images, the reference and spectral images should be taken at exactly the same telescope pointing. In reality, however, because pointing drift is often observed within a single pointing period, the amount of drift should be measured by using the IRC data, themselves, and be corrected accordingly. First, we apply a cross-correlation technique to find the pixel shift between spectral sub-frame images, and the shift is corrected before stacking them. Next, we need to align the stacked spectral image to the reference image to find accurate wavelength reference positions as well as the locations of extraction boxes for each source. For this purpose, we detect field stars and compare their positions in reference and spectral images, since field stars can be observed at any sky orientation in the NIR channel, although they are much fainter in the MIR-S and MIR-L channels. Along the spatial direction, it is simple to measure shifts, because the spectra of continuum point sources show a rather sharp ridge structure that can be traced in the spatial direction. Along the wavelength direction, shifts can be measured by using the characteristics of spectral response curves that create pseudo-spectral features in data number, before flux calibration. For *NP*, the spectra of most field stars show prominent peaks around $2.4 \mu\text{m}$, where the throughput plot shows a local peak (figure 3), because the *NP* has a lower dispersion at shorter wavelengths, and typical field stars have blue colors in the wavelength range. For *NG*, since the response curve shows a rather sharp cut-off to its shortest wavelength range (around $2.5 \mu\text{m}$: figure 3) due to an order-sorting filter, an abrupt drop in data number spectra can be seen at that wavelength for most field stars.

⁵ (<http://idlastro.gsfc.nasa.gov/>).

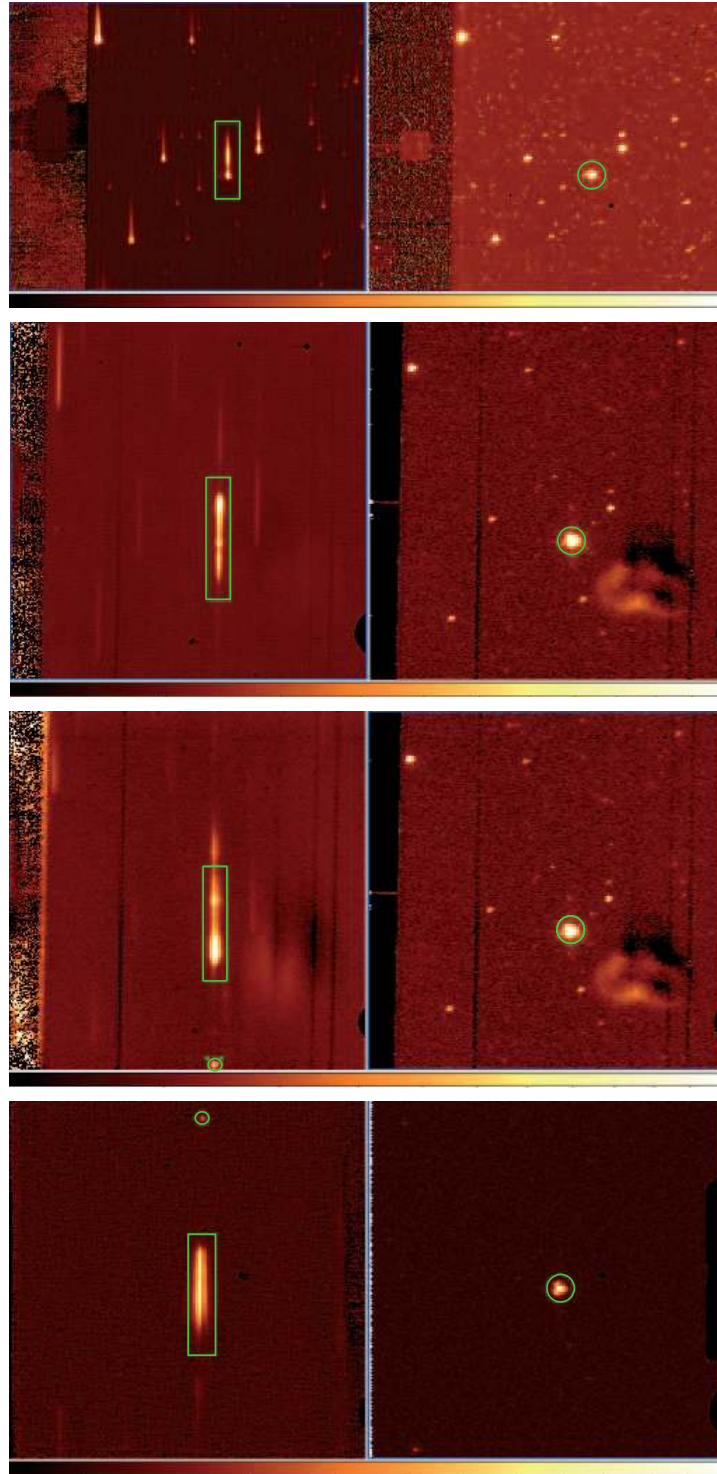


Fig. 5. Images for the slit-less spectroscopy observations of UGC 5101. Images shown are basic-processed data (after dark subtraction, linearity correction, flat fielding, and stacked among frames, etc.) of spectroscopy (left) and reference (right) images. Spectral images of *NP* (top), *SG1*, *SG2*, and *LG2* (bottom) are shown on the left side, and reference images of *N3* (top), *S9W*, *S9W*, and *L18W* (bottom) are shown on the right side. The slit areas are located on the left side of the NIR and MIR-S images, and on the right side of the MIR-L image. The spectra and reference images of UGC 5101 (a bright object located near the center of each image) are marked in green on all of the images. The wavelength increases upward in *NP*, *SG1*, and *SG2*, and downward in *LG2*. The zeroth-order light images are seen below the object in *SG2*, and above the object in *LG2*, and they are indicated by green circles. The zeroth-order light image is located outside the FOV in *SG1*. The second-order light images, which are not marked, can also be seen at just above the object in *SG1* and *SG2*, and at just below the object in *LG2*. Some kinds of anomaly (dark vertical stripes and an incorrectly flattened area at lower right) are also seen, especially in the *S9W*, *SG1*, and *SG2* images. Note that sizes of the NIR images (*NP* and *N3*) are reduced to be half of the MIR-S and MIR-L images for clarity of the figures.

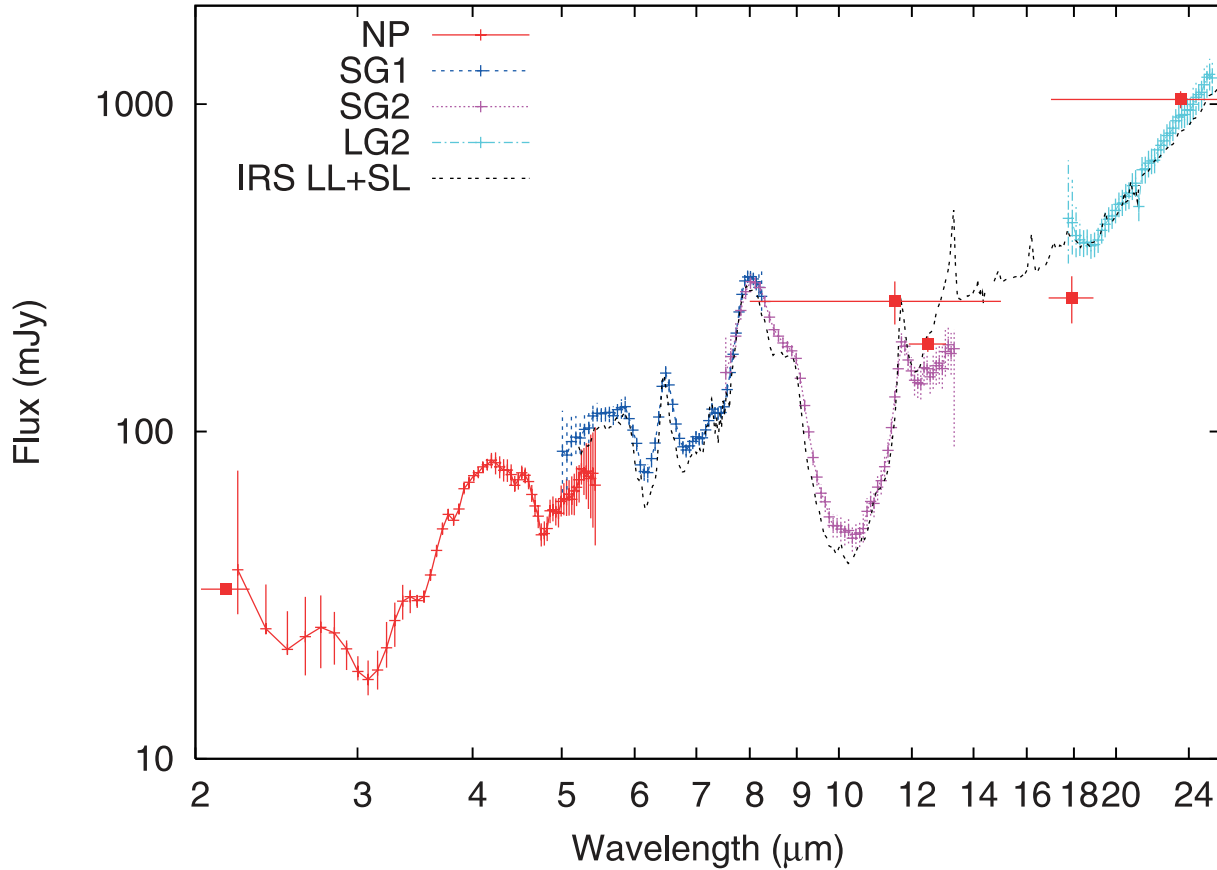


Fig. 6. Extracted one-dimensional spectrum of UGC 5101. The four spectra of *NP*, *SG1*, *SG2*, and *LG2* are shown in red, blue, magenta, and cyan, respectively. The one-sigma error bars are also shown. Some photometry data taken from literature are overlaid in red, that are 2MASS (K_s), ground-based 12.5 μm and 17.8 μm , and IRAS 12 and 25 μm data. The IRS spectrum, taken with low-resolution short- and long-wavelength modules, is also overlaid in black broken lines on the plot.

These features change little in shape for most stars, regardless of their spectral types, because the Rayleigh–Jeans part of the spectrum is observed across the wavelength range. For the MIR-S and MIR-L channels, the pixel shift measured at the NIR channel is adopted, after considering the pixel scale differences. In addition to these spectral features, one can also detect point-like images of zeroth-order light for brighter point sources, even in spectral images with the gratings, providing another method to find and correct the pointing attitude drift in the wavelength direction.

6.2. Flat-Fielding

There are some difficulties in flat-fielding of the slit-less spectroscopic images. First, we should apply a kind of aperture correction for spectral images of the background light that is not required for spectra of compact sources. Note that the slit-less spectroscopic image of even the spatially-flat background is not flat at all due to overlapping of the zeroth- and higher-order light images with the first-order light image (for grism spectroscopy images), as well as dispersed ‘edge’ images of the imaging aperture (for all dispersers). Here, ‘aperture correction’ implies flattening the background sky image before removing the background contribution underlying the object spectra. In addition to the aperture correction, we should treat the color-dependence of the flat response, since

IRC spectroscopy covers a wide spectral range simultaneously, and the color-dependence of the flat response cannot be neglected. Therefore, in order to take all of these flat characteristics into account, we apply a flat-field correction twice; first for aperture correction and pixel-to-pixel flat correction of the background, and then for wavelength-dependent flat-field correction (or color correction) for individual compact objects. For the aperture correction and flat-field correction of the background, the sky-flat images were created by stacking large numbers of observed spectral images with a three-sigma clipping rejection algorithm so as to remove any overlying compact sources as well as cosmic-ray hits. The flattened background is then subtracted from the observed slit-less spectroscopic images. After extracting spectral images for each source and calibrating their wavelengths, a color correction can be applied throughout each extracted source spectrum. Here, the amount of the color correction for a given pixel is estimated by using sky-flats for two different imaging filters ($N3$ and $N4$ sky-flats for color-correcting *NP* and *NG*; $S7$ and $S15$ sky-flats for color-correcting *SG1* and *SG2*; and $L15$ and $L24$ sky-flats for color-correcting *LG2*), and interpolating two sky-flat images along the wavelength direction for the pixel.

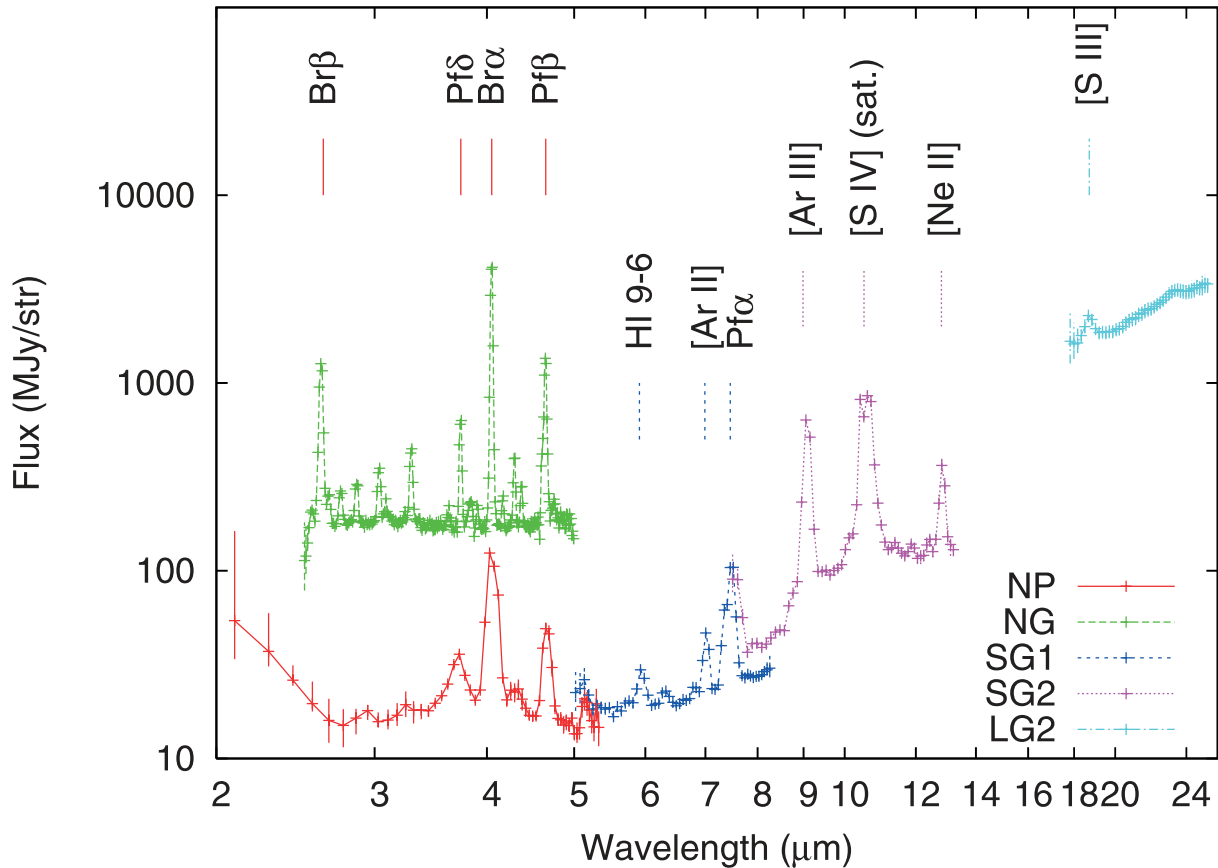


Fig. 7. Slit spectrum of NGC 6543. The spectra of NP, NG, SG1, and SG2 were taken at the Ns slit, while that of LG2 was taken at the Ls slit. The NG spectrum is multiplied by 10 for clarity of the plot. At the NIR channel, since the spectra were taken at a wider Ns slit, the emission lines are as wide as ~ 4 pixels, being wider than the spectra at the narrower Nn slit, whose width is ~ 2 pixels. The [S IV] emission line is saturated.

6.3. Spectroscopy Calibrations Common to Conventional Slit Spectroscopy

After extracting spectral images of each object, the two axes of the extracted images correspond to the spatial and wavelength directions. Therefore, the following calibration can be made in a similar way to that for conventional slit spectroscopy. The wavelength calibration can be achieved simply by applying the wavelength calibration curve to each extracted spectrum in the same way as for slit spectroscopy. After a color correction, the spectral sensitivity is only a function of wavelength, and a flux calibration can also be made in the same way as for slit spectroscopy.

Finally, we remark on data reduction for IRC slit spectroscopy. Reducing slit spectroscopy images can be done more simply than for the case of slit-less spectroscopy, since we do not have to take care of extraction, wavelength calibration, and color-correction of individual source spectra according to the locations of the sources. On the other hand, one must take much more care in subtracting the contribution of scattered light within a camera body and/or within an array substrate, especially for MIR-S and MIR-L channels, in analyzing slit spectral data. One obvious reason is that the background level is much lower in the slit areas. Another reason that is unique to the IRC is that a larger number of sky photons directly illuminate the detector arrays, even in

slit spectroscopy, through the imaging FOV adjacent to the slit areas. Note that the scattered light is not spatially uniform due to aperture substructures and edges around the detector arrays, making an estimation of the scattered-light contribution difficult. See Sakon et al. (2007) for more discussion and techniques for removing the scattered-light contribution in analyzing images in slit spectroscopy.

7. Examples of the IRC Spectra

To demonstrate the IRC's spectroscopy capability, we present spectra of a compact source, UGC 5101, observed with the slit-less spectroscopic mode, and of an extended source, NGC 6543 (PN), observed in slits.

UGC 5101 is a heavily obscured ultra-luminous infrared galaxy (e.g., Genzel 1998) at a redshift of $z = 0.0394$. A recent MIR spectroscopic study of the galaxy, made with the IRS onboard Spitzer (Houck et al. 2004), revealed that it shows rich absorption features as well as PAH emission bands (Armus 2004), both of which create a series of broad bumps across the NIR and MIR spectral ranges. Because of these prominent spectroscopic characteristics, we chose this object to check the wavelength and flux calibrations of the IRC spectroscopic mode that were measured separately, as described in the previous sections. The observation was

made on 2006 April 22, during the PV phase. Two pointed observations were performed, once with a target at FOV center of NIR and MIR-S and another at that of MIR-L, to cover the entire spectral range of the IRC. We chose AOT04 operation with the *NP* in the NIR channel for both of these observations. Figure 5 shows the entire spectral and reference images, before extracting the target's spectrum, to illustrate the basic ideas on the appearance of the images in slit-less spectroscopy. Since the object is very bright in the MIR, zeroth- and second-order light images can be also seen (except for the *SGI* image where the zeroth-order light is located outside the FOV). Figure 6 shows the extracted spectrum. The spectrum was compared with previous photometric results available in the literature [2MASS (Skrutskie et al. 2006) data in the NIR, IRAS (Beichman et al. 1988), and ground-based 12.5 μm and 17.8 μm MIR data (Soifer et al. 2000)], and we found that the IRC spectrum is basically consistent with this photometry. The IRS spectrum (Houck et al. 2004), the “post-BCD” spectra (program id: 105; AOR KEY: 4973056) obtained from the Spitzer science archive,⁶ is overlaid for a comparison. We found that the two spectra agree very well, indicating that both the wavelength and the flux of the IRC spectra are well calibrated when compared with the precursor. A detailed discussion of the detected spectral features will be made elsewhere (T. Nakagawa et al. 2007, in preparation).

NGC 6543 is a bright PN located near the north ecliptic pole. Because of its brightness and convenient location for observing with space telescopes in near-earth polar-orbit, this object was used for calibrating both the flux and the wavelength of the mid-infrared instruments on IRAS (e.g., Neugebauer et al. 1984), ISO (Valentijn et al. 1996), and Spitzer (Houck et al. 2004), as well as to study its physical conditions (e.g., Bernard-Salas et al. 2003). As expected, the observed spectrum (figure 7) reveals rich emission lines, including Hydrogen recombination lines and fine-structure

lines of various excitation levels. We have successfully identified all of the bright emission lines reported in Bernard-Salas et al. (2003). We found that the emission-line widths are very close to the slit widths measured in the reference images, indicating that all of the dispersers work well in orbit, delivering their expected resolving powers.

8. Summary

The Infrared Camera (IRC) on board the AKARI satellite has the capability of spectroscopy as well as multi-color photometry. In this paper, its spectroscopic mode is described in detail in terms of dispersers and aperture masks with slit areas, in-orbit calibration, operation, data reduction, and overall performance with examples of spectra. In particular, we have described the characteristics of its unique slit-less spectroscopy observation mode, which was made available for the first time from space in MIR. We found that the overall in-orbit performance of the IRC spectral mode is well within the expectation from pre-launch experiments, and it satisfies the original design goal, except for the loss of one disperser, the *LGI*. So far, about 500 pointed observations were made with IRC spectroscopy within one year of AKARI's science operation without any serious problems, and one may expect scientific results from the spectroscopic data very soon.

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⁶ The NASA/IPAC Infrared Science Archive is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.