Development of Nayoro Optical Camera and Spectrograph for 1.6-m Pirka telescope of Hokkaido University

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ABSTRACT

We have developed a visible imager and spectrograph, Nayoro Optical Camera and Spectrograph (NaCS), installed at the f/12 Nasmyth focus of the 1.6-m Pirka telescope of the Hokkaido University in Hokkaido, Japan. The optical and mechanical design is similar to that of WFGS2 of the University of Hawaii 2.2-m telescope (UH88), however the camera is newly designed. The spectral coverage is 380–970 nm, and the field of view is 8.4 $\times$ 4.5 arcmin with a pixel scale of 0.247 arcsec pixel^{-1}. The SDSS (g', r', i', z') filters, Johnson (B, V) filters and a replica grism (R ∼300 at 650 nm) are equipped. The slit width can be selected from 2, 3, and 4 arcsec. We selected a 2k$\times$1k fully-depleted back-illuminated Hamamatsu CCD as a detector, because it has a high quantum efficiency ($\geq$ 80 %) over optical wavelength. The Kiso Array Controller (KAC) is used as a CCD controller. The first light observation was done on November 2011. NaCS is used mainly for long-term spectroscopic monitor of active galactic nuclei. It is also used for several astronomical observations such as light-curve measurements of asteroids and search of pre-main-sequence stars and brown dwarfs by slit-less spectroscopy as a major facility instrument of the Pirka telescope. We present the design, construction, integration, and performance of this instrument.

Keywords: optical, imager, spectrograph

1. INTRODUCTION

Long-term monitoring of active galactic nuclei (AGNs) is a way to investigate the spatially unresolved structure of AGNs. The reverberation mapping[1] can measure the distance between the central black hole of AGN and the broad line region (BLR) by observation of time lags between variabilities in the continuum radiation from inner accretion disk and the emission lines from the BLR. For these observations we built a visible imager and spectrograph for the 1.6-m Pirka telescope of the Hokkaido University at Nayoro in Hokkaido, because we can obtain many telescope times for monitoring. The slit spectroscopy mode is equipped in order to acquire the spectrum of AGN and the imaging mode is also equipped in order to do photometry of AGN. Our main targets are nearby AGNs with brighter than $r' = 15$ mag. S/N (signal-to-noise ratio) = 100 is required in order to observe a variability of 10 % of the AGN luminosity with an accuracy of 1 %. To resolve the broad line profiles (∼1500 km/s), a low spectral resolution (R ∼200 @ 650 nm) is enough, therefore, we set the spectral resolution of the instrument at R ∼300 (at 650 nm) to achieve S/N = 100 for an AGN with $r' = 15$ mag with a exposure time of about an half hour. In order to observe the Hα, Hβ emission lines and the continuum around these lines simultaneously, the spectral coverage of 450 to 730 nm is required.

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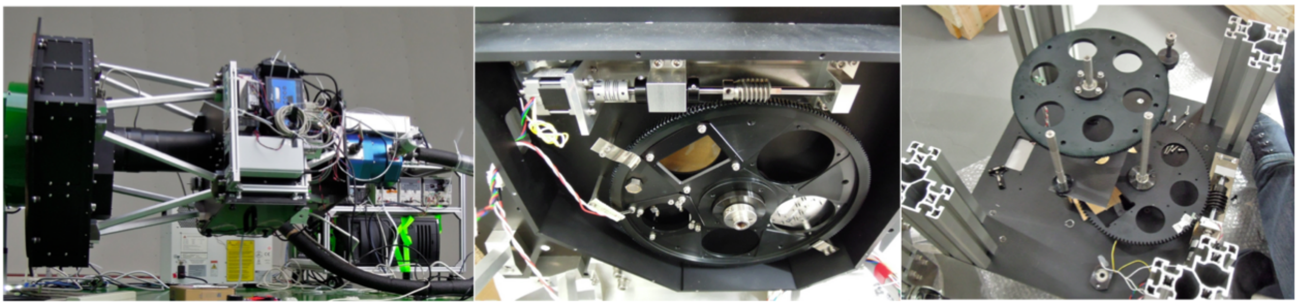

Figure 1. (left) NaCS mounted at the Nasmyth focus of the telescope. (center) Slit wheel. (right) Filter and grism wheels.

The first light observation was done on November 2011. We started the spectroscopic monitor of AGNs from November, 2012. The instrument have been also used for several astronomical observations such as light-curve measurements of asteroids and search of pre-main-sequence stars and brown dwarfs by slit-less spectroscopy as a major facility instrument of the Pirka telescope. In this paper, we present the design, construction, integration, and performance of this instrument.

2. DESIGN OVERVIEW

Figure 1 shows the pictures of NaCS, and Table 1 summarizes the major specifications of the NaCS.

Table 1. Major specifications of NaCS.

Spectral coverage	380–970 nm (Imaging), 435–820 nm (Spectroscopy)
Field of view	8.4 $\times$ 4.5 arcmin
Pixel scale	0.247 arcsec pixel^{-1}
CCD	Hamamatsu 2k$\times$1k
Array format	2048 $\times$ 1104 pixel (pixel size = 15 $\times$ 15 μm)
	+ 2048 $\times$ 48 pixel (pixel size < 15 $\times$ 15 μm)
Broad-band filters	SDSS g', r', i', z', Johnson B, V
Order-sort filter	GG435
Replica grism	
Groove spacing	300 gr mm^{-1}
Prism angle	22.25°
Prism material	BK7
Blaze angle	17.5°
Blaze wavelength	520 nm
Undeviated wavelength	650 nm
Spectral Resolution	R $\sim$300 @ 656 nm (slit width = 2 arcsec)
Size	560 mm $\times$ 560 mm $\times$ 1130 mm (without the interface box)
	720 mm $\times$ 720 mm $\times$ 1200 mm (with the interface box)
Weight	75 kg (without the interface box)
	100 kg (with the interface box)

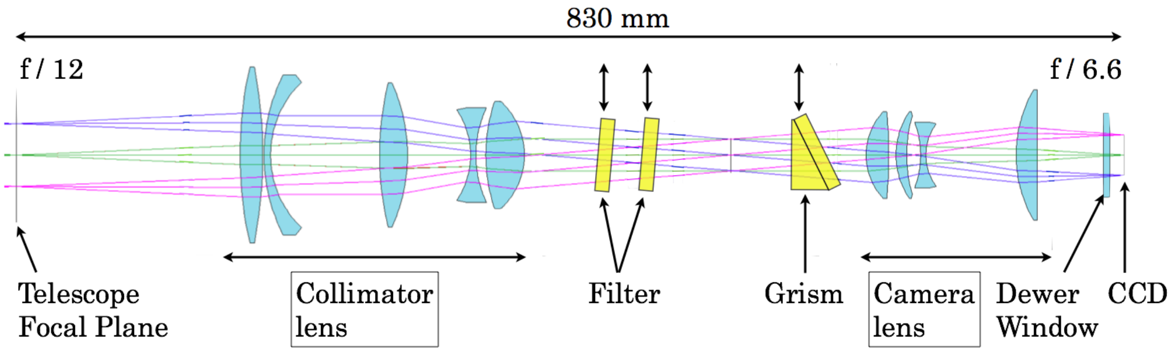

Figure 2. Optical layout of NaCS.

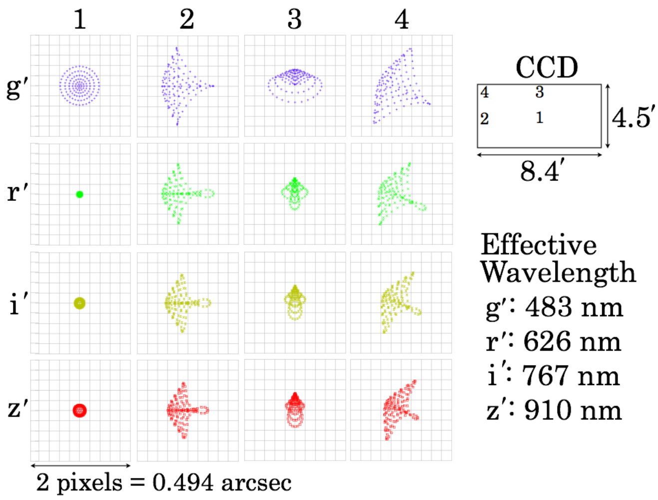

Figure 3. Spot diagram at the imaging mode. There are thefour positions (1: center, 2: left, 3: top center, 4: upper left). A square shown on each spot diagram is 2 × 2 pixel (30 × 30 μm).

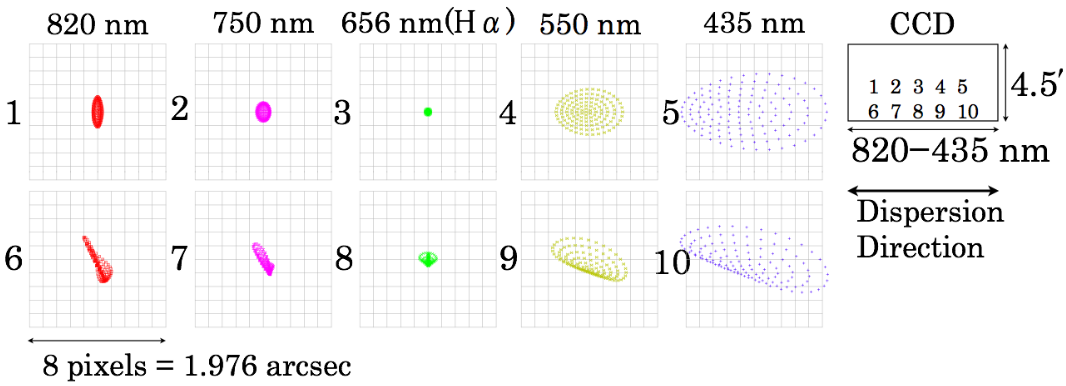

Figure 4. Spot diagram at the spectroscopic mode for objects at the center (1–5) and bottom center positions (6–10) of the CCD. A square shown on each spot diagram is 8 × 8 pixel (120 × 120 μm).

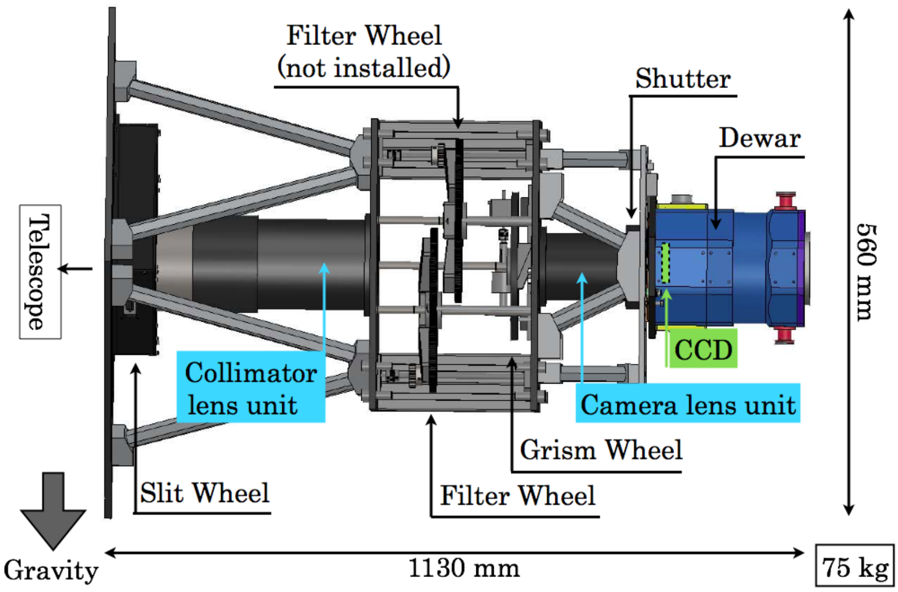

Figure 5. Mechanical layout of NaCS.

We selected a similar optical design to WFGS2[2] of the University of Hawaii 2.2-m telescope (UH88), because this optics has a wide field of view (~11.5 arcmin), and a wide spectral coverage (380–970 nm), and the imaging mode and spectroscopy mode can be switched quickly. Figure 2 shows the optical layout of NaCS. This optics consists of nine lenses and all of the lenses are treated with anti-reflection coating. The light from the Pirka telescope (f/12) is collimated by the collimator lenses and focused onto the CCD by the camera lenses after passing through a filter and/or a grism. The focal length of collimator is 285 mm and the focal length of camera is 185 mm, thus the f-number of NaCS is 6.6. The field of view of NaCS is 8.4 $\times$ 4.5 arcmin and the pixel scale is 0.247 arcsec pixel^{-1}. The spare lenses, filters and grism of WFGS2 are used.

However, we changed the distance between the collimator lens and the camera lens from 187.8 mm of the original design to 257.8 mm in order to put a baffle at the pupil in the instrument and to improve the accessibility of the grism wheel. The Prika telescope is also designed as an infrared telescope and the secondary mirror of the telescope works as the optical stop at the infrared observing mode. Therefore, there are no baffle around the secondary mirror when the telescope is set for the infrared observation and it is necessary to put a baffle at the pupil inside the instrument to avoid the stray lights from behind the secondary mirror. However, in the original design, the pupil was located inside the grism, therefore, we needed to expand that distance. As the result of this expansion, the rms radius of spot diagram got worse slightly (for example, from 0.04 to 0.10 arcsec at g'-band at the center of CCD), however, there are no influence to the imaging because it is still smaller than the typical seeing size (~1.8 arcsec FWHM) at the Nayoro Observatory. Also, although the original specification of the parfocal band is 380–770 nm, we optimized the telescope focus individually per band to obtain a better imaging performance. Figure 3 shows the spot diagrams of imaging mode. The spots are within 1/3 of the typical seeing size. Figure 4 shows the spot diagrams of spectroscopic mode. At the longer wavelength ($>$ 656.3 nm), these spots are within 1/3 of the typical seeing size. However, at the 435 nm, the spot size along the dispersion direction is comparable to the typical slit width of 2 arcsec, and then the spectral resolution got worse from 20 A to 28 A at this wavelength.

Figure 5 shows the mechanical layout of NaCS. NaCS is mounted on the Nasmyth instrument rotator. To reduce the weight, we selected a truss structure with a wheel box as similar to WFGS2. The whole size is 560 $\times$ 560 $\times$ 1130 mm and the weight is about 75 kg. There are two filter wheels and one grism wheel, but one filter wheel is not installed yet. The filter wheel can be equipped with six filters and the grism wheel can be equipped with three grisms. These wheels are driven by stepper motors. The SDSS (g', r', i', z') filters and Johnson (B, V)

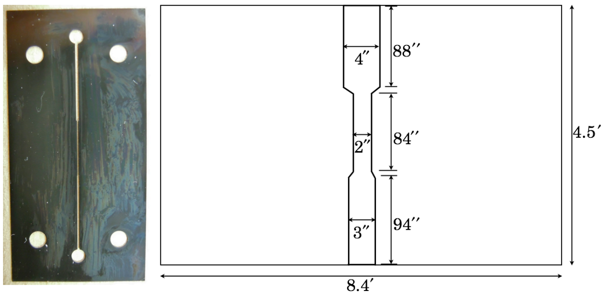

Figure 6. (left) A picture of slit. The slit is made on a stainless-steel plate with a thickness of 0.05 mm. (right) The layout of the slit.

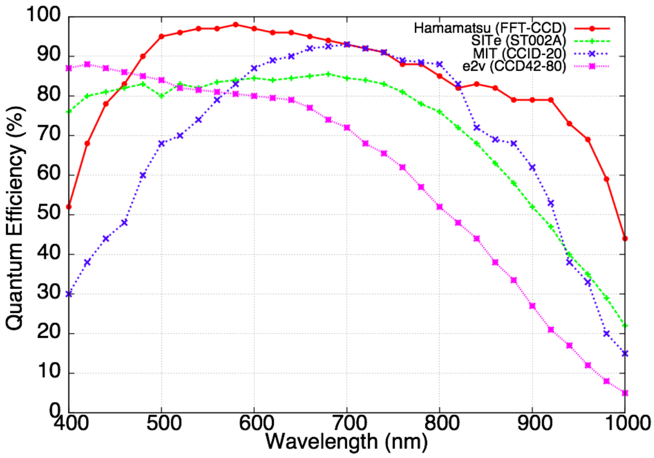

Figure 7. The quantum efficiencies of Hamamatsu , SITe, MIT, and e2v CCD. Hamamatsu CCD has high quantum efficiency (≥∼ 80%) over optical wavelength (440–920 nm).

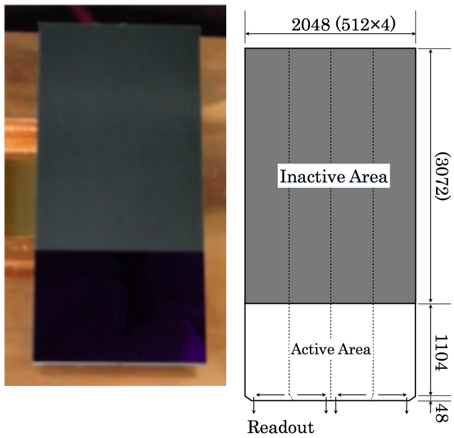

Figure 8. (left) A picture of Hamamatsu 2k×1k CCD. (right) The array format of Hamamatsu 2k×1k CCD. The first 48 × 2048 active pixels are smaller than 15 μm-square pixels, so we don't use there pixels for observation.

filters can be used as the broad-band filters. Five of them and a order-sort filter can be installed simultaneously. To avoid ghost images produced by reflections on the CCD surface, the filter is tilted by five degrees.

A slit wheel is located at the focal plane of the Pirka telescope. NaCS has a slit with three slit widths of 2, 3, and 4 arcsec (0.19, 0.28, and 0.38 mm) with a length of 84, 94, and 88 arcsec. We can select one of them depending on the seeing conditions. Figure 6 shows a picture and the layout of this slit.

We used a low-dispersion replica grism with 300 gr mm^{-1} (prism angle = 22.25° , prism material = BK7, blaze angle = 17.5° , blaze wavelength = 520 nm, undeviated wavelength = 650 nm) and an order-sort filter (GG435) that cuts the wavelength less than 410 nm to prevent the contamination of the second-order light. The spectral coverage is 435–820 nm.

The CCD is installed in the dewar and it is cooled to −100 ℃ by the CryoTiger refrigerator with PT-13 gas (Brooks Automation) and the temperature is regulated at −100 ℃ with an error of 0.5 ℃ PV by the temperature controller E5GN-R101T-FLK (Omron). A shutter, CS65 (Vincent Associates) is located in the front of the dewar. The amount of time that the shutter is open is 29 ms.

There are an interface box between NaCS and the Nasmyth rotator flange. It will have a wavelength calibration unit and an auto-guider unit.

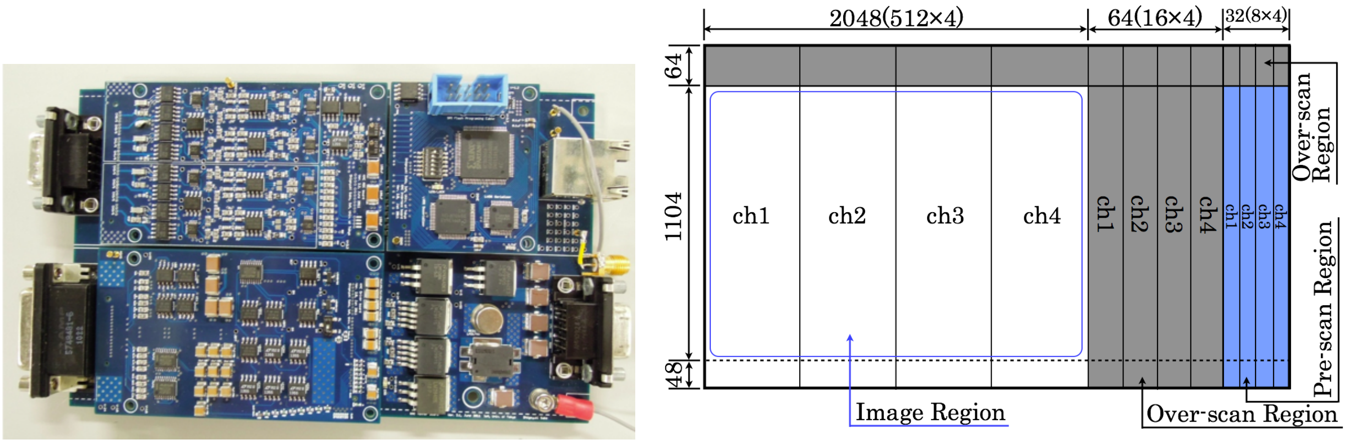

Figure 9. (left) Photograph of the KAC main-boad. The outer dimensions of the main-boad is 160 × 100 mm. (right) The layout of a raw data image of NaCS. the bottom 48 lines are not used, because the pixel size is smaller than 15 μm.

3. DETECTOR AND READOUT SYSTEM

3.1 CCD

Figure 7 shows the quantum efficiencies of Hamamatsu (2k×1k CCD), SITe (ST002A), MIT (CCID-20), and e2v (CCD42-80) CCDs.[3] We selected a fully-depleted back-illuminated Hamamatsu 2k×1k CCD as a detector, because it has the highest quantum efficiency ($\geq$ 80%) over optical wavelength (440–920 nm) than any other CCDs here. Figure 8 shows a picture and the array format of the Hamamatsu 2k×1k CCD. This CCD is the same type as the 2k×4k CCD of Hyper Suprime-Cam.[4] The active area of the 2k×1k CCD is a quarter of the 2k×4k CCD, although the chip size is same. Because the Hamamatsu CCD has four readout channels, it can be readout faster than a CCD with a single readout channel. Each channel of the 2k×1k CCD has 1104 × 512 active pixels with 15 μm-square pixel and 48 × 512 active pixels with smaller size. These smaller pixels are not used. We usually use the 2 × 2 pixel binning readout with an effective pixel scale of 0.494 arcsec pixel^{-1}, because a stellar image is over-sampled under the typical seeing condition ($\sim$1.8 arcsec) at the Nayoro Observatory.

Table 2. Measured readout noise and readout time.

Number of sampling	Readout noise (e^{-1})	Readout time (s)		
		1 × 1 binning	2 × 2 binning	4 × 4 binning
1	5.2	5.3	3.7	2.9
2	4.0	8.7	5.4	3.8
4	3.8	12	7.1	4.7

Table 3. Measured gain and bias level of each channel of detector.

	Channel 1	Channel 2	Channel 3	Channel 4	Average
Gain (ADU e^{-1})	1.88	1.83	1.85	1.86	1.86
Bias level (ADU)	5717.8	5788.8	5699.7	5842.6	5762.2

Table 4. Limiting magnitude (S/N = 10) for broad-band imaging.

	B	V	g'	r'	i'	z'
Effective wavelength[a](nm)	438	545	483	626	767	910
Effective bandwidth[b](nm)	94	87	138	138	154	137
Sky blightness (mag arcsec^{-2})	21.3	20.5	21.4	21.1	19.9	19.1
Transmittance of atmosphere	0.697	0.754	0.715	0.815	0.862	0.881
Expected overall efficiency	0.190	0.316	0.335	0.397	0.284	0.252
Measured overall efficiency	0.124	0.277	0.260	0.373	0.250	0.195
Limiting magnitude[c]						
$t = 5$ s	18.1	18.2	18.8	18.9	18.0	17.5
$t = 60$ s	20.0	19.9	20.5	20.5	19.6	19.0
$t = 300$ s	20.9	20.7	21.4	21.4	20.5	19.9

[a] From Ref. 6 (B, V) and Ref. 7 (g', r', i', z').
[b] From Ref. 8 (B, V) and Ref. 7 (g', r', i', z').
[c] 4 arcsec diameter aperture and 2 arcsec seeing are assumed. Magnitudes are presented in the Vega system for B and V bands and the AB system for g', r', i' and z' bands.

3.2 Kiso Array Controller

The Kiso Array Controller[5] (KAC) is the readout system developed in the Kiso observatory, the University of Tokyo for KWFC.[5] This system was originally designed for the MIT CCD and SITe CCD, and has 16 readout channels. We adapted KAC to the Hamamatsu CCD for NaCS. The main modification is the analog circuitry because the polarity of the Hamamatsu CCD is opposite to those of the original system in order to transmit not an electric charge but a hole. A picture of main board is shown in Figure 9(left). We reduced the readout channels from 16 to 4 for NaCS and then the size of the main board for NaCS is reduced to a quarter of that for KWFC. The readout modes for 2 × 2 and 4 × 4 pixel binning are available. The multi-sampling readout reduces the readout noise from 5.2 e^- to 3.8 e^- by sampling each pixel multiply. As the result, the limiting magnitude becomes deeper by about 0.14 mag at Hβ in the spectroscopic observation (300 s exposure with a 3 arcsec width slit) of a point-like source under the dark night condition. The readout noise and readout time with several readout setting is shown in Table 2. As shown in Table 3, the gain and bias level are slightly different between the channels, because there are a slight difference of resistance of analog circuitry between the channels. The average of gains and bias levels over the four channels is 1.86 e^- ADU^{-1} and 5762.2 ADU. The bias level varies by 8 ADU PV, depending on the CCD and ambient temperatures, the exposure time, and the signal level of image area. Figure 9(right) shows the layout of a raw data image of NaCS. The pre- and over-scan regions are gathered together into one side of the image by readout software so that it becomes easy for us to do the quick look and data reduction easy.

4. PERFORMANCES AND EXAMPLES OF OBSERVATIONS

4.1 Broad-band Imaging

Table 4 summarizes the expected and measured overall efficiencies (including the transmittance of atmosphere at airmass = 1) and estimates of limiting magnitude at S/N = 10 with various exposure times t. The measured overall efficiency was lower than the expected one. It might be due to dirt of mirrors at this observation and the further investigation is needed.

The flatness of sky background after flat fielding is +1.6/-0.7, +0.6/-0.5, +2.3/-2.6, +1.5/-0.8, and +0.9/-0.5 % at the B, V, g', r', and i'-band respectively, although the flatness of about ±1 % or less is generally expected.

By limiting the field into 4 × 4 arcmin at the center of CCD, a better flatness of within ±1 % is achieved at the V, r', and i'-bands, although the flatness is still +1.4/-0.6 % and ±1.6 % at the B and g'-bands. Moreover,

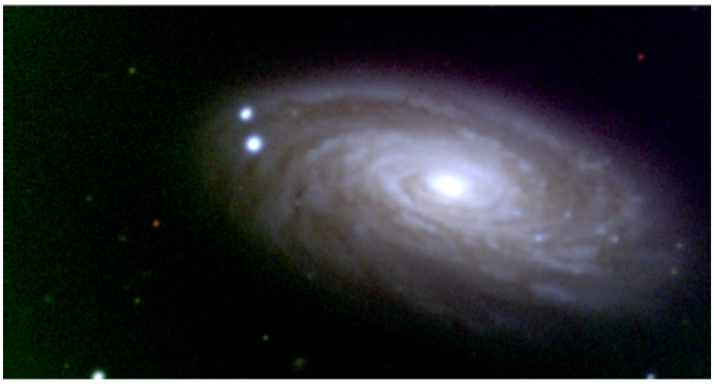

Figure 10. The pseudo-color image of three color of M88 (g': blue, r': green, i': red). The angular size of M88 is 7 × 4 arcsec.

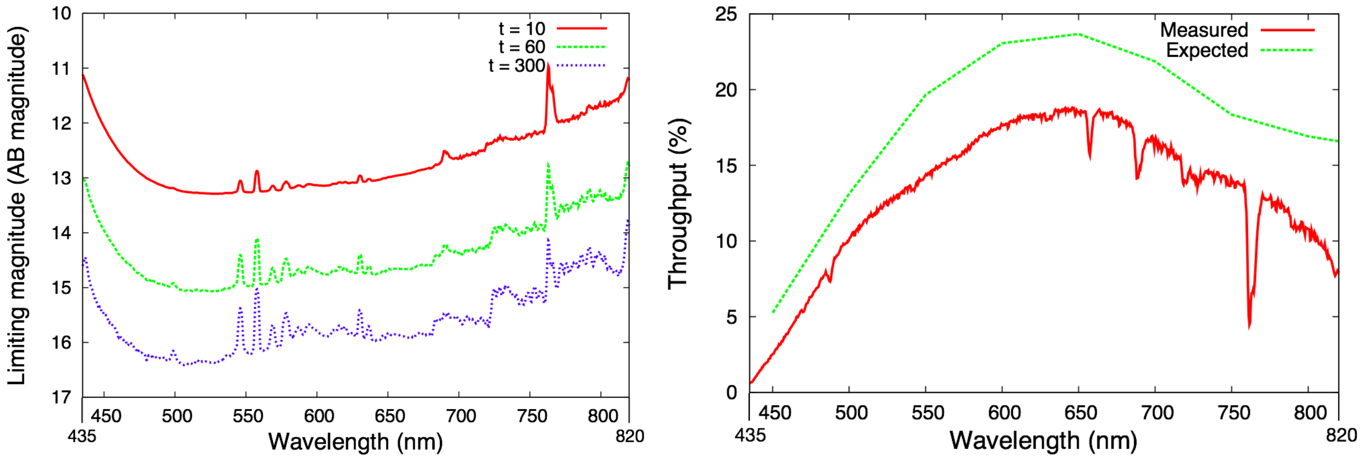

Figure 11. (left) Limiting magnitude (S/N = 10) for slit spectroscopy (slit width = 3 arcsec). (right) The observed throughput of slit spectroscopy.

the flat-field depends the rotator angle. For example, it changes by +6.6/-6.1 % at the corner of field of view at the r'-band. These reasons are under investigation.

Figure 10 shows an example of broad-band imaging of M88. M88 is a nearby spiral galaxy with an angular size of about 7 × 4 arcmin. The total exposure time is 300 s × 3 at each band. This figure demonstrates that NaCS has an enough large field of view for the relative photometry of galaxy with comparison stars around a galaxy.

4.2 Spectroscopy

4.2.1 Slit Spectroscopy

The estimates of limiting magnitude at S/N = 10 with a 3 arcsec width slit is shown Figure 11(left). The measured throughput for the slit spectroscopy with a 3 arcsec width slit is shown Figure 11(right). The loss of 25 % in throughput by the slit is not included. Transmittance of atmosphere at airmass = 1 is included. The measured throughput was lower than the expected one. It is probably due to the poor photometric condition because the transmittance of atmosphere at this observation was about 80 % of the typical value at the B and V-bands (58.1 % and 62.8 % respectively). Figure 12 shows the observed sky emission at the Nayoro Observatory at the dark night. This sky emission was used for the estimate of the limiting magnitude.

We have carried out the monitoring observation of AGN, Arp 102B. Arp 102B is a subluminous, radio-loud LINER at $z = 0.024$ that has double-peaked Balmer emission lines[9] and is $r' = 15.0$ mag. The observed spectrum

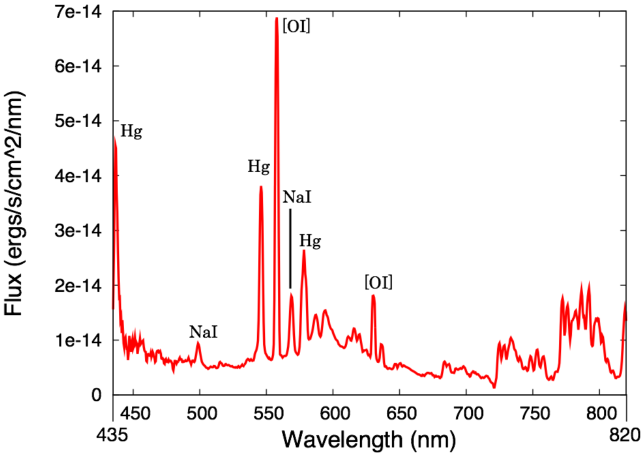

Figure 12. The observed spectrum of sky emission with 3 arcsec slit width.

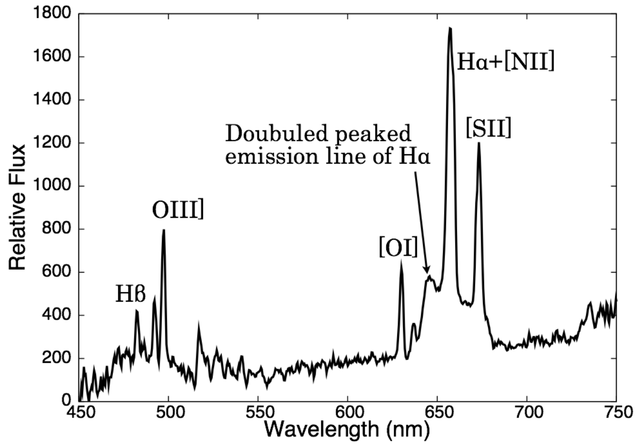

Figure 13. The observed spectrum of Arp 102B with 3 arcsec slit width. The flux of [OI] emission line was normalized to 1000.

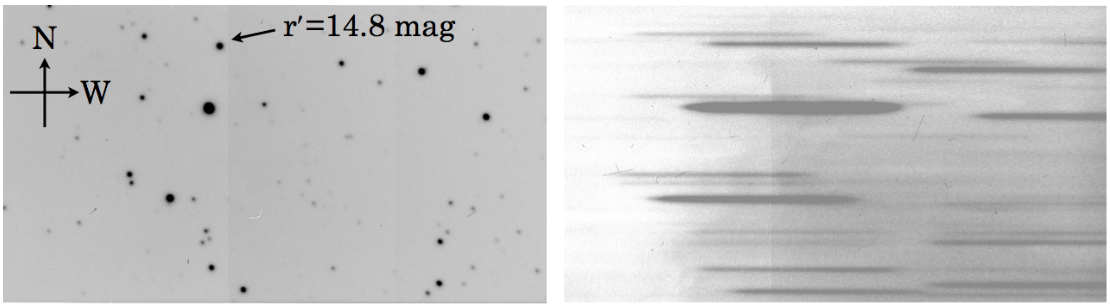

Figure 14. The r'-band image and slit-less spectroscopic image of the bright-rimmed cloud (BRC 9).

of Arp 102B with a 3 arcsec width slit in August 19, 2013 is shown in the Figure 13. The total exposure time is 300 s $\times$ 15. The spectral resolution is about R ~200Å at Hα. The S/N ratio of continuum at 656 nm achieved is 160, although this is lower than the calculated one (S/N = 260) because of the moon influence.

4.2.2 Slit-less Spectroscopy

We also carried out search of pre-main-sequence stars. The pre-main-sequence stars have a strong Hα lines in there spectrum. Figure 14 is r'-band image and slit-less spectroscopic image of the bright-rimmed cloud (BRC 9[10]) around IRAS 02326+6110 in the IC1805 region. The total exposure time is 900 s $\times$ 2. For a star with $r' =$ 14.8, S/N ratio = 20 at 650 nm was achieved. This is lower than calculated one (S/N = 80) because of the poor photometric condition. Unfortunately, no emission line stars were found in this field.

5. CONCLUSIONS

We have developed a visible imager and spectrograph, NaCS, installed at the f/12 Nasmyth focus of the 1.6-m Pirka telescope of the Hokkaido University in Hokkaido, Japan. We modified the KAC for the Hamamatsu CCD of NaCS. We confirmed that the total observation time per one AGN (r' = 15 mag, S/N = 100) is about 20 min for photometry and about 90 min for spectroscopy and NaCS is capable of observing several AGNs in a night.

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