A Warm Near-Infrared High-Resolution Spectrograph with Very High Throughput (WINERED)

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\textbf{ABSTRACT}

WINERED is a newly built high-efficiency (throughput \(> 25 - 30\%\)) and high-resolution spectrograph customized for short NIR bands at 0.9-1.35 \(\mu\)m. WINERED is equipped with ambient temperature optics and a cryogenic camera using a 1.7 \(\mu\)m cut-off HgCdTe HAWAII-2RG array detector. WINERED has two grating modes: one with a conventional reflective echelle grating (\(R \sim 28,300\)), which covers 0.9-1.35 \(\mu\)m simultaneously, the other with ZnSe or ZnS immersion grating (\(R \sim 100,000\)). We have completed the development of WINERED except for the immersion grating, and started engineering and science observations at the Nasmyth platform of the 1.3 m Araki Telescope at Koyama Astronomical Observatory of Kyoto-Sangyo University in Japan. We confirmed that the spectral resolution (\(R \sim 28,300\)) and the throughput (\(> 40\% \text{ w/o telescope/atmosphere/array QE}\)) meet our specifications. We measured ambient thermal backgrounds (e.g., 0.06 [e\(^{-}\)/sec/pixel] at 287 K), which are roughly consistent with that we expected. WINERED is a portable instrument that can be installed at any telescope with Nasmyth focus as a PI-type instrument. If WINERED is installed on a 10 meter telescope, the limiting magnitude is expected to be J=18-19, which can provide high-resolution spectra with high quality even for faint distant objects.

\textbf{Keywords:} infrared, spectrograph, spectrometer, high dispersion, high resolution, immersion grating, atomic spectroscopy, molecular spectroscopy, kinematics, abundance, gamma-ray burst, exoplanet

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1. INTRODUCTION

High resolution spectrograph in near-infrared (NIR) wavelength range is a powerful tool to explore a variety of astronomical objects from planets to cosmological objects by measuring chemical abundance and gas dynamics with atomic and/or molecular lines. We are developing a NIR high-resolution spectrograph WINERED (Warm Near infrared Echelle spectrograph to Realize Extreme Dispersion; Ikeda et al. 2006, Yasui et al. 2006, 2008). The primary objective of WINERED is to realize "NIR high-resolution spectrograph with high sensitivity" by achieving high throughput (>25 –30%), which is about twice as high as those of conventional high resolution spectrographs. WINERED has a wide wavelength coverage mode, "Wide-Mode" with a normal reflective echelle grating, which can simultaneously cover a wide wavelength range (0.9-1.35µm) with a resolving power that is comparable to those of many IR high resolution spectrographs (R∼29,000; Yasui et al. 2006). WINERED also aims for the highest spectral resolution (R∼100,000) by developing ZnSe or ZnS immersion grating (“High-Resolution-Mode”) while this immersion grating is now under development.

Because the wavelength range of WINERED is limited to 0.9-1.35 µm, where the ambient thermal background is very small, a warm optical system with no cold stop can be realized. Because of the compact design (the size is 1.8m × 1.0m × 0.5m and the total weight is ~250 kg), WINERED, which is now located at the Nasmyth platform of 1.3 m Araki Telescope at Koyama Astronomical Observatory of Kyoto-Sangyo University, can be moved to any larger telescopes as a PI-type instrument.

This paper is structured as follows: §2 shows the optical performance of WINERED from the engineering observations. §3 briefly presents our science grade array and its cassette. §4 shows the results of the ambient background measurement. §5 presents the detection limits of WINERED. In §6, we comment on our future plan.

2. OPTICAL PERFORMANCES

2.1 Overview

WINERED has two observational modes, one is wide wavelength coverage mode (“Wide-Mode”) covering 0.90-1.35 µm in one exposure with R=28,300 using a reflective echelle grating. The other is high-resolution mode ("High-Resolution-Mode"), which has two setting, Y and J that cover 0.96-1.13 µm and 1.12-1.35 µm, respectively, with R=103,000 using ZnSe or ZnS immersion grating. The optical configuration of WINERED is shown in Figure 2 of Yasui et al. (2008). Overall specifications and optical parameters are summarized in Tables 1 and 2 respectively. At present, WINERED has been completed except for the immersion grating. We mount WINERED on the Nasmyth focus of the 1.3 m Araki Telescope of Koyama Astronomical Observatory (KAO) at Kyoto-Sangyo University in Kyoto Japan and has started engineering and science observations with Wide-Mode (Figure 1). Almost all optical components are in the ambient environment with room temperature except for the camera lenses and the infrared array, which are operated with ~90 K and 70 K in a cryostat, respectively.

|                        | High-Resolution-Mode | Wide-Mode |
|------------------------|----------------------|-----------|
| Maximum spectral resolution | 103,000 (2-pix sampling) | 28,300 (2-pix sampling) |
| Wavelength coverage    | Y: 0.96-1.13 µm      | 0.90-1.35 µm |
|                        | J: 1.12-1.35 µm      |            |
| Volume                 | 1800 mm(L) × 1000 mm(W) × 500 mm(H) |

Table 1. WINERED basic specifications.

2.2 Coverage

Figure 2 shows the echellograms of α Boo (Arcturus) and a flat-lamp obtained with Wide-Mode. We confirmed that the entire wavelength range, 0.90-1.35 µm (m=41-61), is covered in a single exposure by investigating the echellogram of Th-Ar comparison lamp. Figure 3 shows the Wide-Mode spectra of a A0V star (HIP 58001) and P Cyg, which show broad hydrogen absorption lines and strong emission lines, respectively. This wide wavelength range of about 4,500 ˚A can be covered in one exposure, which should enables extensive classifications of a variety of astronomical objects.
Figure 1. The 1.3 m Araki Telescope at KAO (left), and WINERED installed on the Nasmyth platform of the telescope (right). The cover of WINERED is removed for viewing purpose. The slit, the collimator, the echelle grating, and the cross-disperser (VPH) are in the ambient environment with room temperature. The figure in left top corner of this panel shows covered WINERED.

|                            | High-Resolution-Mode | Wide-Mode |
|-----------------------------|----------------------|-----------|
| Slit                        | Width                | 100, 200, 400 µm |          |
|                             | Length               | 3.12 mm   |          |
| Collimator                  | Focal length         | 770 mm    |          |
|                             | Clear aperture       | 84 mm     |          |
| Echelle                     | Type                 | ZnSe or (ZnS) immersion grating | classical echelle grating |
|                             | Blaze angle          | 70 deg. | 63.9 deg. |
|                             | Groove density       | 31.80 gr/mm | 31.60 gr/mm |
| Cross-disperser             | Frequency            | 710 lines/mm (Y) | 280 lines/mm |
|                             |                      | 510 lines/mm (J) |          |
|                             | Bragg angle          | 20.8 deg. (Y) | 9.3 deg. |
|                             |                      | 17.9 deg. (J) |          |
| Camera                      | Focal length         | 266.80 mm |          |
|                             | Clear aperture       | 128.25 mm |          |
| Detector                    | Array format         | 2k×2k (Teledyne, HAWAII-2RG) |          |
|                             | Pixel size           | 18 µm × 18 µm |          |
|                             | Cut-off wavelength   | 1.76 µm |          |
| Slit viewer                 | FOV                  | 4.8′ × 3.5′ (w/ the 1.3 m Araki Telescope) |          |
| Wavelength region           |                      | 0.6 – 0.9 µm |          |
| Artificial light source     |                      | Th-Ar (for wavelength calibration) |          |
|                             |                      | Halogen lamp |          |

Table 2. Optical parameters of WINERED.
Figure 2. Echellogram of $\alpha$ Boo (left) and a flat-lamp (right). The faint spectra seen between low orders are the ghosts from the 2nd-order lines of the VPH cross-disperser (HAWAII-2RG has the sensitivity for the optical wavelength). However, because the ghosts are enough separated from the object spectrum, they do not produce any critical problem.

Figure 3. Top panel: the spectrum of a star HIP 58001 (A0V). Broad Pa$\beta, \gamma, \delta$ absorption lines are clearly seen. The strong telluric absorption features due to water vapor are seen between $z, Y$, and $J$-bands. Bottom panel: the spectrum of P Cyg. Pa$\beta, \gamma, \delta$, emission lines as well as very strong Hel emission have clear P Cygni profiles.
2.3 Spectral Resolution

We measured the spectral resolution of Wide-Mode using the Th-Ar lamp. The measured spectral resolutions are defined as the FWHM of single Th-Ar emission lines. Figure 4 shows the obtained spectral resolution as a function of wavelength. We confirmed that the designed spectral resolving power ($R = 28,300$) is achieved through the entire wavelength range.

![Figure 4. Measured spectral resolution for N-mode. The black points show the measured values. The solid line shows the target spectral resolution, which is defined by 2-pixel sampling.](image)

2.4 Throughput

In order to estimate the throughput of WINERED, we observed a photometric standard star (HD87822), which is listed in the IRTF Spectral Library, with the 400 $\mu$m ($=6''$) wide slit to avoid the flux loss at the slit during engineering observation using our engineering array. We assumed that the efficiency of the telescope, determined by reflectance of mirrors and vignetting by the baffle for the secondary mirror and the pupil aperture (This is because WINERED is designed for f/11 telescopes though f-number of Araki telescope is 10), is about 0.5 from the past measurements of the telescope. The atmospheric absorption at the KAO site is calculated with LBLRTM code (Clough et al. 2005) accessing the HITRAN database (Figure 5: bottom panel). The obtained throughput of the optics as a function of wavelength is shown in Figure 5. While the black curve in the figure is in the case without the EG array, the red curve is in the case with the SG array assumed. The throughput included an array QE in $J$-band is found to be over 40% as designed. However, the throughput at shorter wavelengths is unexpectedly degraded (down to 20% at $z$-band). We consider that the aerosol scattering is more efficient in the actual city environment than we expected in our calculation, but more investigation is necessary.

3. INFRARED ARRAY

We use a 1.7 $\mu$m cut-off 2k×2k HAWAII-2RG array to suppress ambient thermal backgrounds at longer wavelengths beyond H-band, and SIDECAR ASIC and JADE for readout electronics. A science grade (SG) array has been installed.

3.1 Array Cassette

Figure 6 shows the new design of our array cassette. We designed this cassette for safe assembly, releasing thermal stress, and easily cooling to the purpose temperature.
Figure 5. Estimated throughput of WINERED for Wide-Mode using EG array. The top panel shows the throughput (Black: WINERED optics only, Red: WINERED optics times QE of the SG array, Dark gray: as observed with the EG array, whose QE is 30-60% from Teledyne Inc.. The bottom panel shows the assumed telluric absorption spectrum for estimating the throughput.

Figure 6. Array cassette.

3.2 Performance of the SG array
The performances of the SG array are summarized in Table 3. The quantum efficiency (QE) was measured by Teledyne Inc.. Readout noise was measured from the variance of dark frames with short integration time (15
sec) for which Poisson noise from the dark electrons is negligible. With the Fowler-sampling, the readout noise decreases from $19.2 \pm 2.9 \, [e^{-}]$ (NDR=1) to $5.3 \pm 1.0 \, [e^{-}]$ (NDR=32). The dark current was estimated from the ramp sampling over 1,500 sec and is found to be $7.6 \pm 0.2 \times 10^{-3} \, [e^{-}/s]$. Conclusively, we can say that this SG array meets our specifications.

The conversion gain is set to be $2.27 \, e^{-}/ADU$ for the detector bias of 0.25 v. Readout time is about 1.45 sec per frame for 32-ch output operation mode with 100 kHz pixel rate. The detector is reset 4 times before readout, so it takes at least 10 sec to obtain one frame even for the minimum integration time. The counts of the output frame are corrected with those of the reference pixels. To reduce readout noise, we use Fowler-sampling of 2, 4, 8, 16 non-destructive reads depending on the integration time during actual observations.

| QE [%] | Readout noise (NDR=1) [e^{-}] | Readout noise (NDR=32) [e^{-}] | Dark [e^{-}/s] | Full well [e^{-}] |
|-------|-------------------------------|-------------------------------|---------------|------------------|
| 63-114 | $19.2 \pm 2.9$                | $5.3 \pm 1.0$                | $7.6 \pm 0.2 \times 10^{-3}$ | $1.4 \times 10^5$ |

Table 3. Science grade array performance. QE is provided by Teledyne Inc.. The uncertainty of QE is probably over 10% (from Teledyne Inc.).

4. AMBIENT THERMAL BACKGROUND

All optical components except for the camera lens and the infrared array are placed under the ambient temperature. To block the ambient thermal background over 1.35 $\mu$m as much as possible, a thermal cut filter is coated on the cold camera lens in front of the array (Yasui et al. 2008), and additional thermal blockers (PK50 and a custom thermal cut filter) are installed. When the ambient temperature is sufficiently low, the noise from the ambient thermal background is expected to be less than the readout noise ($\sim 5 \, e^{-}$) by combination of the thermal cut filter, the thermal blockers and a 1.7 $\mu$m cut-off array.

We measured the ambient thermal background by putting a black cover on the window of the cryostat so that the detector looks at a black body with the room temperature. We confirmed that leak of light is negligible for this measurement. A cold mask with two holes at the center/edge was installed at the 4 mm distance from the array. The hole size is 3.2 mm which is determined as no vignetting for the full FOV of the camera lens. We measured the ambient thermal background in the bright region and estimated the dark current and detector bias in the shadow region caused by the mask simultaneously, which were found to be negligible.

![Figure 7. Measured ambient thermal backgrounds. The black points are the measured values. The black line is the expected ambient thermal background in the optimum case. The red lines show an equivalent readout noise for 1800 sec and the dark current. Hatched region shows the nominal operating temperature of WINERED.](image)

We measured the ambient thermal background only at the lab temperatures (287–299 K), which is higher than the typical operation temperatures we expect on the telescopes. The relation between the ambient temperature...
and photon counts is shown in Figure 7. This figure shows that the measured ambient background counts are well correlated with ambient temperatures (∼0.06 e−/sec/pix at 287 K and ∼0.14 e−/sec/pix at 299 K) and are roughly consistent with those we expected for the temperatures. There are some differences of counts between the holes, but the ratios are almost constant for all the temperatures. The noise from the ambient thermal background is expected to be less than readout noise under ∼280 K if the ambient thermal background decreases with decreasing ambient temperature like optimal case. To further verify this expectation, we will measure ambient thermal backgrounds at low temperatures (<280 K) in the telescope dome during the cold winter months.

5. DETECTION LIMIT

Table 4 summarizes the estimated limiting magnitudes of WINERED for various telescopes. The ambient background count highly depends on the environment. For Araki Telescope, we adopt the ambient thermal background at around 290 K, which is about an average ambient temperature throughout the year. For the other telescopes, we adopt the ambient thermal background at 273 K. The value is extrapolated from our measured thermal background at 287–299 K, assuming that the logarithm of the ambient thermal background decreases linearly with decreasing temperature. Table 4 shows that goal magnitudes are achieved if ambient backgrounds decrease as we expect. If WINERED is installed on a 10 meter telescope, the limiting magnitude is expected to be mJ=18-19, which can provide high-resolution spectra with high quality even for faint objects.

| Location        | Araki 1.3m | WHT 4.2m | Magellan 6.5m | Keck 10m |
|-----------------|-----------|----------|---------------|----------|
| Seeing          | 3′.0      | 0′.8     | 0′.6          | 0′.4 (0′.2) |
| Pixel scale (/pix) | 0′.82      | 0′.23    | 0′.15         | 0′.098   |
| Slit width for R_max | 1′.65      | 0′.47    | 0′.30         | 0′.20    |
| Ambient Temperature (K) | 290        | 273      | 273           | 273      |
| Thermal Background (e−/s/pixel) | 0.08        | 0.01     | 0.01          | 0.01     |
| Goal m_J        | 12.8      | 15.9     | 16.5          | 17.6 (18.4) |
| m_J             | 13.1      | 16.6     | 17.4          | 18.3 (19.1) |

Table 4. Estimated detection-limit of WINERED of Wide-Mode in J-band for the total integration time of 8 hrs (1800 sec×16) and S/N=30. Goal m_J, and m_J are the magnitudes when the parameters (e.g., throughput, QE of a detector, and the ambient background) of Ikeda et al. (2006) and of this paper are assumed, respectively. For the case with the Keck telescope, the use of a focal reducer from f/15 to f/11 is assumed. In the line of Keck, the values in parentheses are shown using AO.

6. CURRENT STATUS AND FUTURE PLAN

Since the first light on May 23 2012, we have conducted engineering and science observation four times to obtain ∼200 spectra of a variety of astronomical objects. The ZnSe or ZnS immersion grating is being developed and the detail will be reported elsewhere. We plan to fabricate the final large immersion grating (probably with ZnSe) and to install it to complete High-Resolution-Mode of WINERED.

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