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Development of an imaging hyperspectral camera using the ultraviolet and visible wavelength AOTF

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ABSTRACT

A spectroscopic camera has been developed which has spectral resolution of less than 1.5nm in the ultraviolet (UV) and visible wavelength bands (320-580 nm). Its main components are a specially coated UV objective lens, a UV Acousto-Optic Tunable Filter (AOTF) with a thermo-electric cooling system, and a imaging system based on a high-gain avalanche rushing amorphous photoconductor (HARP) developed by NHK Science and Technical Research Laboratories. Research is currently under way to develop the hyperspectral camera into a sensor package for airborne and ultimately space-based remote sensing applications.

This paper presents the basic principle and configuration of the hyperspectral camera, and gives details of tests to measure its performance. The results of spectral resolution tests analyzing very close two spectra from a helium-discharge lamp demonstrate the camera's high spectral resolution performance. Full color and spectral images obtained by a spectrometry experiment are also presented to demonstrate the camera's hyperspectral capabilities.

Keywords: hyperspectrum, spectral image, AOTF, HARP, UV, remote sensing

1. INTRODUCTION

Unlike creatures such as the honeybee and butterflies, human vision does not extend to the ultraviolet. However, we can view the ultraviolet using special camera which is sensitive to the appropriate wavelengths. Hitherto, remote sensing in ultraviolet range is not so popular, but it is very useful. We have therefore developed a hyperspectral camera with a spectroscopic capability that makes it possible to acquire images at arbitrary selected wavelengths from the ultraviolet to visible range.

The National Aerospace Laboratory (NAL) has been conducting research since 1994 on an AOTF-based imaging spectro-polarimeter which is able to measure the polarimetric properties of arbitrary specific wavelengths of solar rays reflected from land and sea surfaces[1-3]. Development of a hyperspectral camera which can acquire images in the wavelength range of 320-580 nm was successfully completed in 1999. This camera has allowed the capture of images at arbitrary selectable wavelengths from the ultraviolet to visible range, which was previously impossible[4-6].

2. SPECTROSCOPIC SYSTEM

The key component of a hyperspectral camera is a band-pass filter that transmits light of an arbitrary selected wavelength. Traditional spectral image capture uses a selection of fixed-wavelength band-pass filters. The limitations of this are obvious: only discrete wavelengths may be selected, the number of wavelengths is limited by the number of

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filters that can be installed, and the filters must be physically interchanged, which increases mechanical complexity and reduces reliability. However, use of an electronically tunable filter affords much greater flexibility: its transmission wavelength can be selected continuously over a range, allowing it to replace many fixed-wavelength filters, and yielding a mechanically simpler and more reliable instrument.

We have previous experience in the use of AOTF as the band-pass filter in visible and near infrared spectro-polarimeters. Based on this experience, an AOTF was chosen as the band-pass filter for the development of a UV and visible hyperspectral camera.

2.1 Principle of a UV AOTF

An AOTF is a spectroscopic device that uses acoustic distortion generated by an applied ultrasonic wave inside a birefringence crystal to change the plane of polarization of the wavelength of light passing through the crystal that corresponding to that of the ultrasonic wave. By varying the frequency of the ultrasonic wave, the wavelength of light affected can be arbitrarily selected. Use of a polarizer and an analyzer before and after the AOTF ensure that only a specific wavelength is transmitted. An AOTF has no moving parts, it allows arbitrary wavelengths to be extracted, and the wavelength can be changed rapidly[7].

There are two types of an AOTF: a collinear type made from SiO_2 (quartz) and a non-collinear type made from TeO_2 (tellurium dioxide). The wavelength range of the non-collinear type is 350-4500 nm, and this does not cover the ultraviolet range. Therefore, the collinear type was used to cover the ultraviolet spectrum. Figure 1 shows the principle of the collinear AOTF. Unpolarized white light from the left side of the figure first passes through a linear polarizer so that only the horizontally polarized component enters the quartz crystal of the AOTF. Spectral decomposition then occurs in the crystal between an applied ultrasonic wave and a corresponding wavelength of incident light such that the plane of polarization of this wavelength is rotated to perpendicular to the plane of polarization of the incident light. The light emerging from the crystal then passes through another linear polarizer. As a result, only the selected wavelength is transmitted on to a detector.

2.2 Cooling the UV AOTF

A maximum electrical power of 15 Watts is used to drive a small quartz crystal of a UV AOTF of 5 mm square aperture, and cooling is therefore necessary to prevent temperature rise of the crystal. Regular manufactured AOTFs are water-cooled and require a coolant flow rate of 1.5 liters per minute. However, portability is an issue in outdoor experiments, and so thermo-electric cooling using a Peltier element was adopted. Specifications of the UV AOTF used this instrument are shown in Table 1.

3.IMAGING SYSTEM

An AOTF is a spectroscopic device with high spectral resolution (*i.e.* a narrow pass band). The imaging detector of the hyperspectral camera must have therefore high sensitivity over the desired wavelength range, in this case from ultraviolet to visible range. A New Super-HARP pickup tube, developed by NHK Science and Technical Research Laboratories, was selected as the imaging device. A HARP utilizes avalanche multiplication effect of the amorphous selen (a-Se) photoconduction target which impressed a high electric field. This imaging device gives extremely high sensitivity, high image quality, and low lag. Moreover, its spectral sensitivity is flat at ultraviolet wavelengths 200-400nm. The new Super-HARP gains sensibility of 600 times of a conventional SATICON pickup tube by using a target voltage of approx. 2500 V [8,9]. The specification of the imaging system with HARP is shown in Table 2.

4.DEVELOPMENT OF THE HYPERSPECTRAL CAMERA

The imaging device with HARP is sensitive to light from the ultraviolet to visible spectrum, but it has no spectroscopic function; that is, it cannot by itself capture images of light at specific wavelengths. To develop an instrument for spectroscopic imaging at arbitrary wavelengths from the ultraviolet to visible ranges, we combined a UV AOTF, the new Super-HARP, and an optical system designed for the ultraviolet range.

The specifications of the resulting hyperspectral camera are shown in Table 3, and a schematic diagram is shown in Figure 2. The objective lens is based on a UV Nikkor manufactured by Nikon, treated with a special lens coating to match it to the wavelength range of the imaging device. Light passing through the objective lens is collimated by a collimator lens, then passes through a polarizer so that only the horizontally polarized component of incident light is transmitted to the UV AOTF. An analyzer at the output of the UV AOTF separates light of the selected wavelength, and this is relayed by an imaging lens to the imaging device. Figure 3 shows a photograph of the inside of the spectroscopic module of the instrument. In the center is the thermo-electrically cooled UV AOTF, which has two linear polarizers on its right and left. The white box of the right side is the new Super-HARP imaging system. Figure 4 shows a appearance photograph of the UV and visible hyperspectral camera. The short black cylinder on the front side is a viewfinder. A finder mirror may be inserted or removed from the instrument's optical path by rotating a knob on the top front face, allowing through the lens viewfinding similar to a single lens reflex camera. Ventilation ports for cooling are opened in the central top face and sides. The spectroscopic module of the instrument has dimensions of 140mm width, 145mm height, and 282mm length, excluding projections such as the objective lens, viewfinder, and feet. The imaging system module is 90mm wide, 100mm high, and 210mm length. The total weight of the instrument including the objective lens is 8.44 kg. The system can accept interchangeable objective lenses using the Nikon F mount system. Normally, a 105mm UV Nikkor lens with a special coating is used.

5.PERFORMANCE OF THE HYPERSPECTRAL CAMERA

5.1 Tuning characteristics

The wavelength selected by the AOTF can be altered by changing the frequency of the applied ultrasonic wave. This can be controlled by a computer. The tuning characteristics of filtered light wavelength versus AOTF acoustic input frequency, which extends to RF, is shown in Figure 5.

5.2 Spectral characteristics

The instrument measured the spectrum of light from a helium-discharge lamp. The experimental result of wavelengths of spectral lines of a helium-discharge lamp compared against scientific tables are shown in Figure 6. The instrument demonstrated a high spectral resolution performance in discriminating two very close spectra. However, intensity of the spectrum is not calibrated in the experiment.

5.3 Spatial resolution

The spatial resolution of the instrument was examined by imaging a USAF 1951 chart. The spatial resolution of the instrument is higher at wavelengths around 470nm, where the instrument has good sensitivity. The spatial resolution was determined to be 36 lines per millimeter (LPM); however, since this measurement was derived from an image file captured by a personal computer, it is believed that this is the theoretical spatial resolution of the image acquisition system. The spatial resolution ability of an AOTF element alone has been measured in excess of 100 LPM in a previous experiment.

5.4 Observation plane of polarization

This instrument has a linear polarizer before the AOTF, so only the horizontally polarized component of incident light is imaged. It is therefore necessary to take into account polarization of objects under observation.

5.5 Spectral range

When transmittance of component parts, the spectral characteristics of the filter, and the amount of stray lights are taken into account, the spectroscopic range of this instrument is 580-320nm. At other wavelengths, there is insufficient sensitivity of the camera and abnormalities in the filter light. Figure 7 shows spectral range of instrument.

6.SPECTRUM EXPERIMENT

Sample spectral images of cabbage butterflies are shown in Figure 8. The male and female cannot easily be distinguished when viewed under visible light; however, when the ultraviolet lights are viewed, the male appears dark as it absorbs ultraviolet light, whereas the female reflects ultraviolet light and so appears bright. The changes in the image observed while the wavelength is continuously varied are very interesting.

A full color and spectral images of the yellow flower Gazania longiscapa are shown in Figure 9. The middle of the petals absorb ultraviolet light at 370 nm, but this wavelength is reflected from the periphery. The purpose of this coloration is thought to be to attract honey bees. Because it is a yellow flower, the flower petals completely absorb light at 450 nm, and are highly reflective at 570 nm.

7. CONCLUSION

A hyperspectral camera that can select wavelengths arbitrary from ultraviolet to the visible spectrum was developed. Until the development of this instrument, cameras with sensitivity to ultraviolet light had been developed, but there was no camera with a spectroscopic capability to give images at arbitrary wavelengths with high wavelength resolution in the ultraviolet range. Development of this instrument was enabled by latest technologies such as an ultraviolet tunable filter, an imaging device with ultraviolet sensitivity, and optical system to transmit in ultraviolet range. There still exist several improving points, *e.g.* reducing stray lights.

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REFERENCES

1. Takao Suzuki, Hirohisa Kurosaki, Shigeharu Enkyo, and Hajime Koshiishi, “Development of an imaging spectro-polarimeter”, *Proc. of SPIE*, Vol. 2873-12, pp50-53, 1996.
2. Takao SUZUKI, Hirohisa KUROSAKI, Shigeharu ENKYO, and Hajime KOSHIISHI, “Application of an AOTF imaging spectro- polarimeter”, *Proc. of SPIE*, Vol.3121-47, pp351-360, 1997.
3. Takao SUZUKI, Hirohisa KUROSAKI, Shigeharu ENKYO, and Hajime KOSHIISHI, “Development of an AOTF (Acousto-Optic Tunable Filter) spectro-polarimeter”, *Journal of The Remote Sensing Society of Japan*, Vol.21, No.5, pp.458-464, 2001.
4. Hirohisa KUROSAKI, Takao SUZUKI, Yoshiyasu TAKEFUJI, Kenkichi TANIOKA, Souichi OKA, Hiroshi TAGASHIRA and Hirokimi SHINGU, “Development of an imaging UV and visible radiometer using AOTF”, *Proc. of 26th remote sensing symposium*, pp33-34, SICE, 2000.
5. Hirohisa KUROSAKI, Takao SUZUKI, Yoshiyasu TAKEFUJI, Kenkichi TANIOKA, Souichi OKA, Hiroshi TAGASHIRA, Hirokimi SHINGU, Hirokazu ICHIKAWA and Atsushi ITOH, “Development of a UV and visible hyperspectral camera”, *ITE Technical Report*, Vol.25, No.19, pp.49-54, 2001.
6. Hirohisa Kurosaki, Takao Suzuki, Yoshiyasu Takefuji, Kenkichi Tanioka, Souichi Oka, Hiroshi Tagashira, Hirokimi Shingu, Hirokazu Ichikawa and Atsushi Itoh, “Development of a UV and visible hyperspectral camera using AOTF”, *Proc. of the 30th conference of the remote sensing society of Japan*, pp.155-156, 2001.
7. Norman J. Berg, John M. Pellegrino, “Acousto-Optic signal processing”, Marcel Dekker, 1995.
8. M. Kubota, T. Kato, S. Suzuki, H. Maruyama, K. Tanioka, K. Sameshima, T. Makishima, K. Tsujii, T. Hirai and T. Yoshida, “Ultrahigh-sensitivity New Super-HARP camera”, *IEEE Transactions on Broadcasting*, Vol.42, No.3, pp.251-258, 1996.
9. Misao Kubota, Tsutomu Kato, Shiro Suzuki, Hirotaka Maruyama, Keiichi Shidara, Kenkichi Tanioka, “ULTRAHIGH-SENSITIVITY CAMERA WITH NEW SUPER-HARP TUBE”, *NHK Laboratories Note*, No.449, 1997.

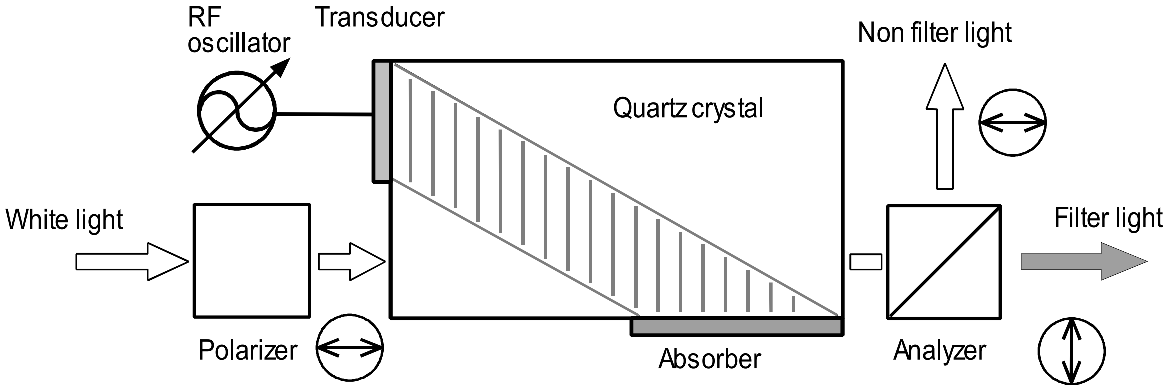

Figure 1: Principle of collinear AOTF

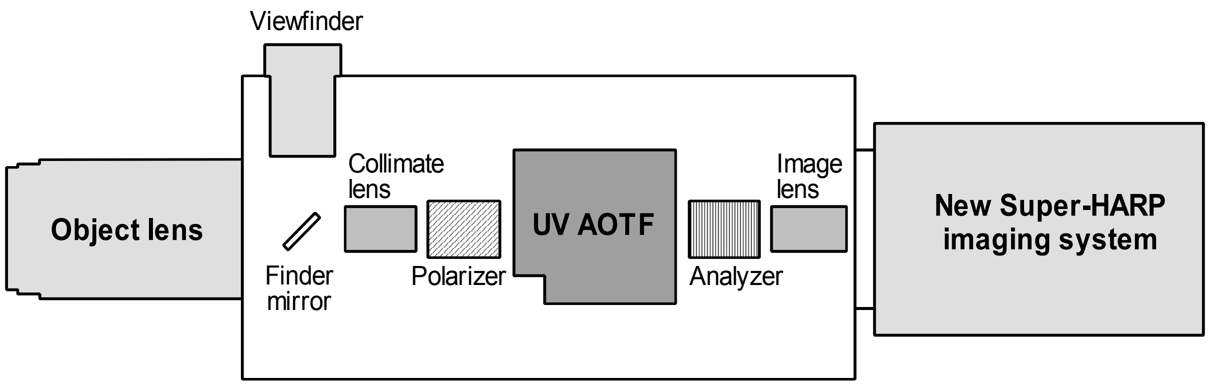

Figure 2: Conception diagram of UV and visible hyperspectral camera

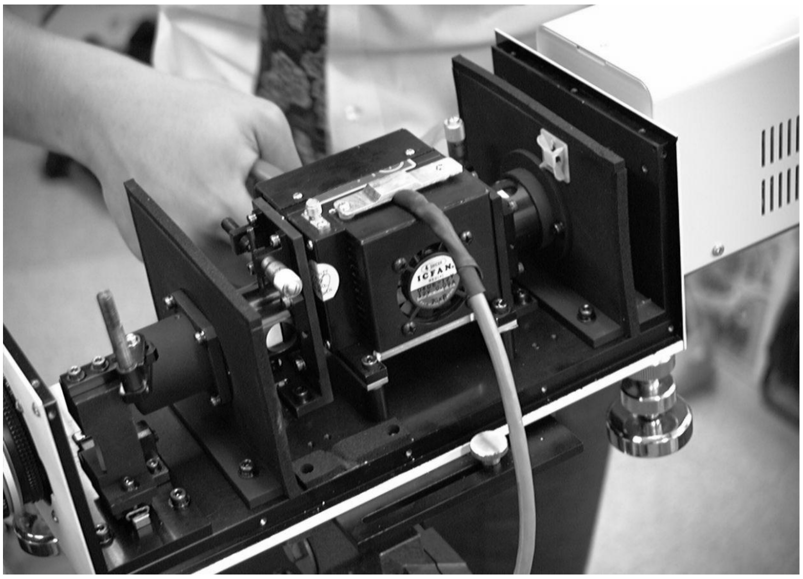

Figure 3: Interior photograph of the camera's spectroscopic section

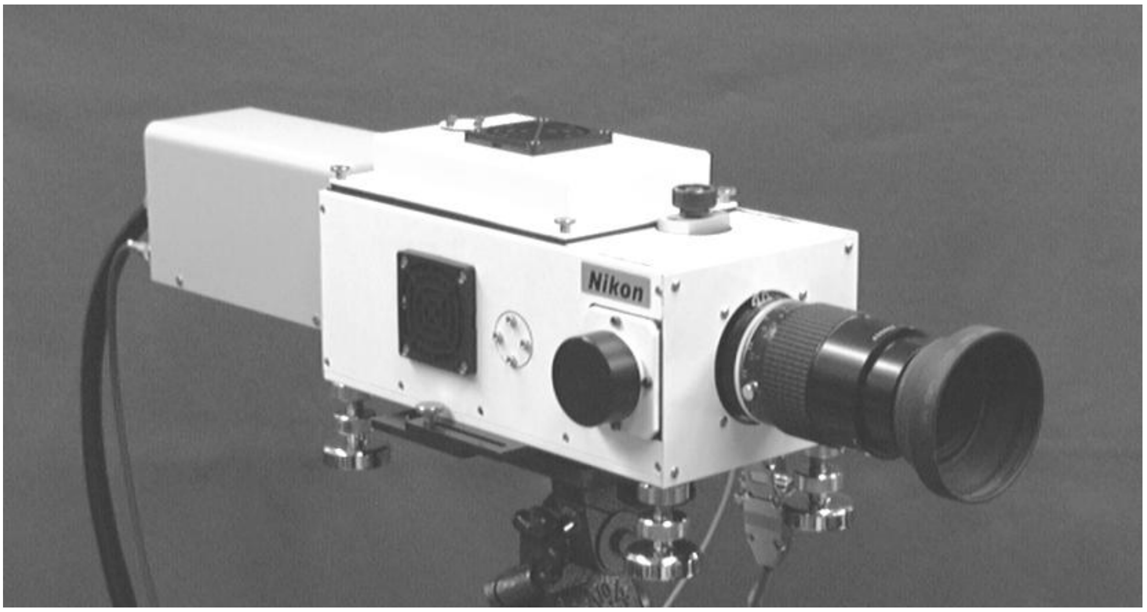

Figure 4: Appearance photograph of the UV and visible hyperspectral camera

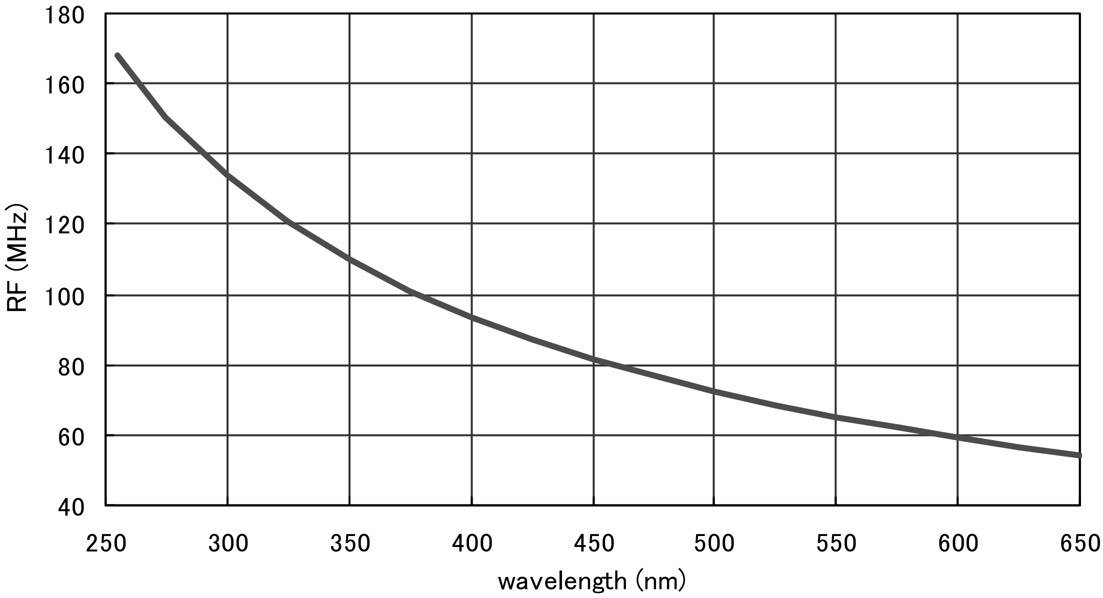

Figure 5: Tuning characteristic of filter light wavelength versus applied acoustic RF signal

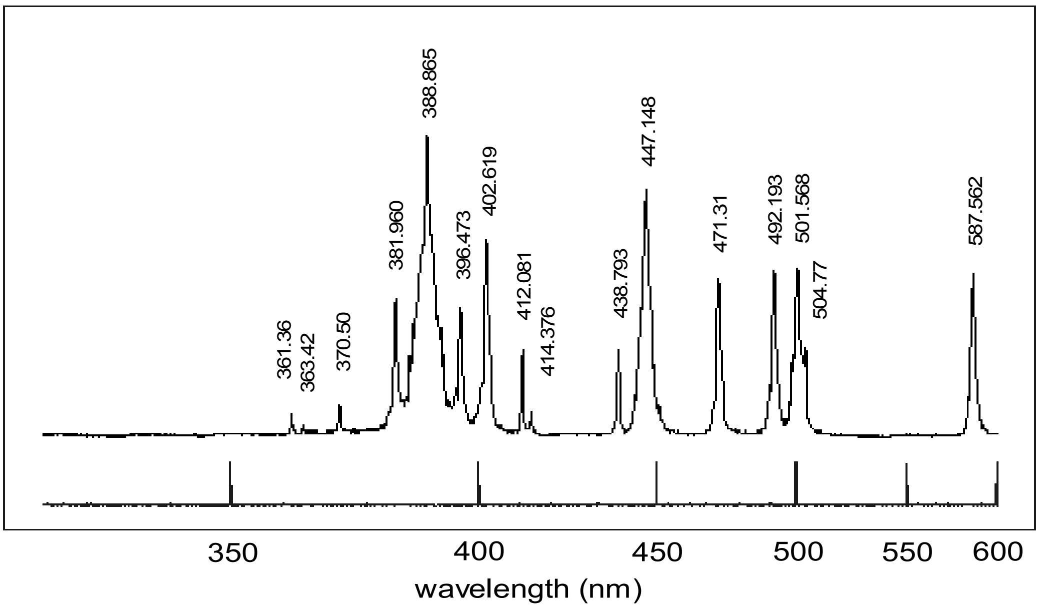

Figure 6: Spectral analysis for helium-discharge lamp light

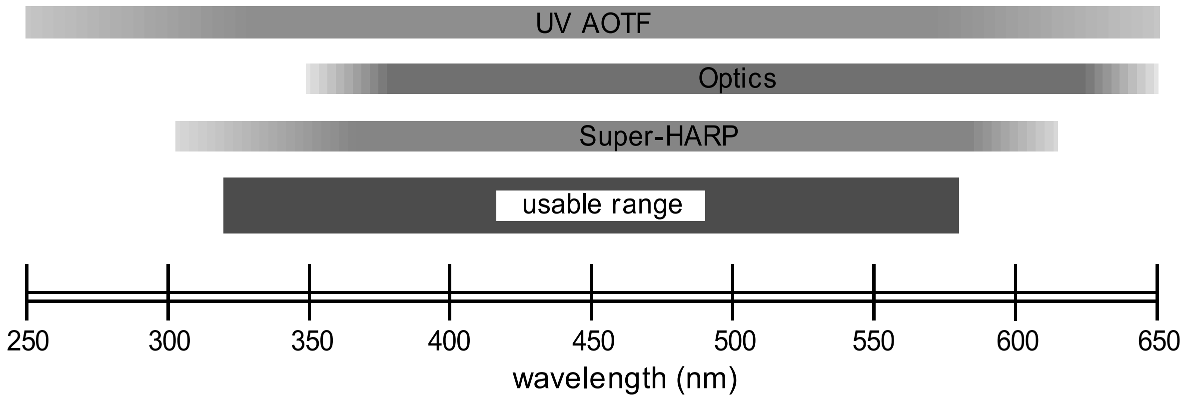

Figure 7: Spectral range of UV and visible hyperspectral camera

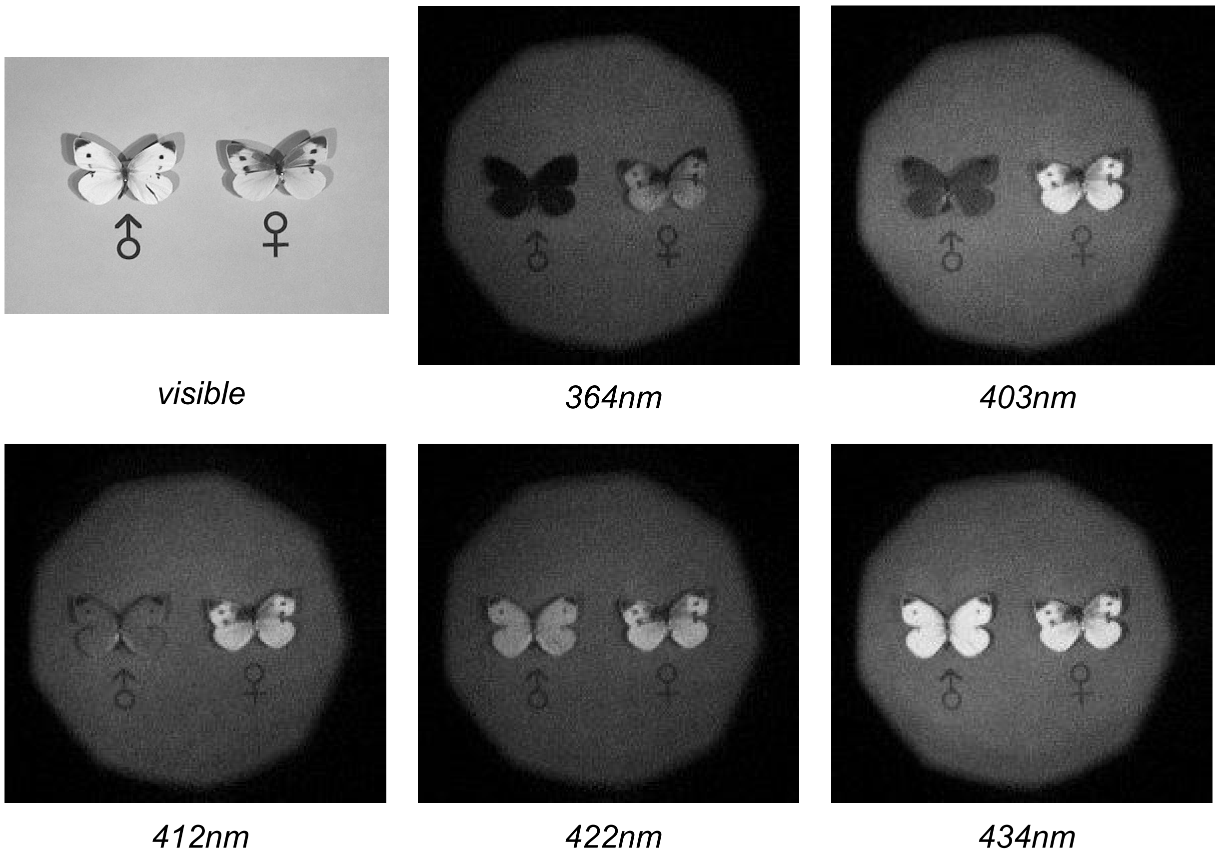

Figure 8: Spectrum images of sample of cabbage butterflies

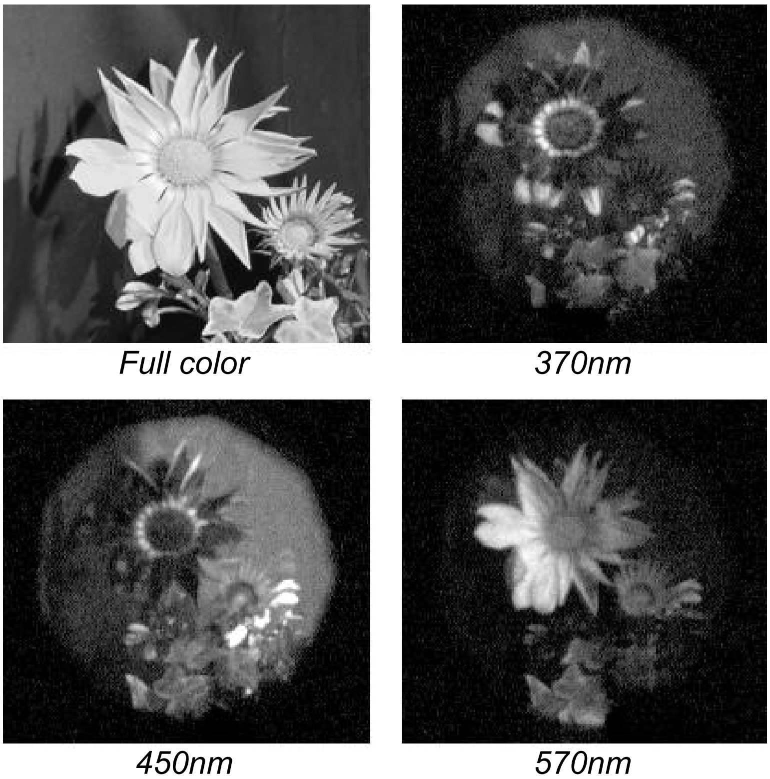

Figure 9: Full color and spectral images of a Gazania longiscapa

Table 1: Specifications of the UV AOTF used this instrument

	Units	Specifications	Test data
Substrate	-----	Quartz	Quartz
Spectral range	nm	250 - 650	250 - 650
Corresponding drive frequency	MHz	50 - 175	53 - 168
Optical aperture	mm	5.0 square	5.0 square
Acceptance angle	deg	5 - 9	5 - 9
Separation angle	deg	0	0
Spectral resolution	-----	0.23nm @ 250nm	0.65nm @ 488nm
	-----	2.0nm @ 650nm	
Diffraction efficiency at the peak	%	10 - 15	8% @ 633nm @ 10W 15% @ 543nm @ 12W 20% @ 488nm @ 12W
Polarization	-----	Linear	Crossed

Table 2: Specification of new Super-HARP system

Imaging tube		2 / 3 inch of new Super-HARP imaging tube
Synchronous		internal
Scanning frequency	Horizontal	15.734kHz
	Vertical	60.0Hz
Scanning line		525 line
Interlaced ratio		2 : 1
Aspect ratio		3 : 4
Signal output		1.0Vp-p
Resolution	Horizontal	500TV line over
	Vertical	400 TV line over
S/N ratio		52 dB @ 435nm
Lens mount		C mount
Operating temperature range		10 - 30ºC
Power		DC12V
Electrical requirements		40W
Dimension Weight	Camera head	W90mm H104mm L240mm 1.9kg
	CCU	W260mm H80mm L346mm 3.6kg

Table 3: Specifications of UV and visible hyperspectral camera

F number		8.0	design
Image size		3.5mm	design
Wavelength	Instrument	350 - 650nm	design
	AOTF	250 - 650nm	catalog
	Prism	220 - 2800nm	catalog
	HARP	350 - 600nm	reference
Object lens		105mm	design
Collimate lens		40mm	design
Imaging lens		40mm	design
Spatial resolution		30 line pair / mm	