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Report

A new all-sky optics for aurora and airglow imaging

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Abstract: This report reviews the initial performance of a new all-sky imager (ASI-2) that utilizes commercial lenses and a high-sensitivity cooled CCD camera. The use of a commercial fish-eye lens as an optical front end and a standard camera lens as a final imaging lens makes the ASI-2 optics smaller, lighter and less expensive than the original ASI optics, with minimal degradation of optical performance. Despite the lower production cost, the speed of the ASI-2 lens system is not markedly slower than the ASI optics, with speed slightly faster than half the speed of ASI. Although the motors driving bandpass filter switching and focusing have been removed to reduce weight, the narrow bandpass filter can be exchanged manually to select specific emission lines, and focusing can be performed manually using a micrometer. The optical performance of the ASI-2 optics is measured and shown to be sufficient for auroral and airglow imaging. The ASI-2 optics is currently installed at Syowa Station, Antarctica, and is involved in observations during the 2004 polar night season.

key words: all-sky imager, aurora, airglow, optical imaging

1. Introduction

All-sky optical imaging is one of the main techniques employed in auroral and airglow studies. The features to be considered with regard to the performance of optical imaging instruments include the field-of-view, sensitivity, field flatness, spatial resolution, distortion, image acquisition rate, and monochromatism. Ease of handling, reliability, and cost performance are also important points. However, the most important aspects are the all-sky field-of-view, high sensitivity and monochromatism, and special optics are usually required to achieve sufficient performance levels. For the purposes of auroral and airglow studies, an all-sky imager (ASI) was developed by the National Institute of Polar Research (NIPR) in 1997. The ASI has excellent optical performance, balancing the characteristics above through the development of a custom lens system (Ejiri *et al.*, 1997; Okada *et al.*, 1997). The all-sky optics used in the ASI is as fast as F0.9 in total and has well-corrected aberration over its entire field-of-view. The ray paths have a parallel part with small incident angle even for the ray path from horizon so that a narrow bandpass interference filter can be inserted there.

The ASIs of the NIPR have been put into operation at the South Pole and Syowa Stations in Antarctica, and one of the two at Syowa Station has been modified to act as an imaging spectrograph, later to be installed at Longyearbyen (Taguchi *et al*., 2002). Another ASI jointly developed by the NIPR and Kyoto University has been operating in Japan and Indonesia for airglow imaging. ASIs optically identical to the NIPR ASIs have been developed by the Communications Research Laboratory (CRL), and the optical performance of those ASIs has been evaluated by Yamamoto *et al*. (2002). CRL ASIs have been operated in campaigns in Japan and Alaska (Kubota *et al*., 2000).

The state-of-the-art optical performance of ASIs has been achieved as a result of special optics design, but at very high production cost. Therefore, there is a demand for all-sky monochromatic optics with performance comparable to that of ASIs but at much lower production cost. Adapting commercial lenses for all-sky monochromatic optics is a reasonable solution for reducing production cost, although the flexibility in optical design is restricted. Our group has adapted two camera lenses, a fish-eye lens and a standard 35 mm camera lens, to form parts of the new all-sky optics (ASI-2) currently under development.

This paper describes the design and performance of ASI-2, compares the performance of the new optics with the original ASI, and presents an auroral image acquired by ASI-2.

2. New all-sky imager

The ASI-2 optics and CCD camera are shown in Fig. 1, and the main specifications are listed in Table 1. A specially manufactured 6 mm fish-eye lens of F1.4 was incorporated in the original ASI. This lens has state-of-the-art performance in terms of image reduction, resolution and speed, but has considerable size and weight. In contrast, the 16 mm F2.8

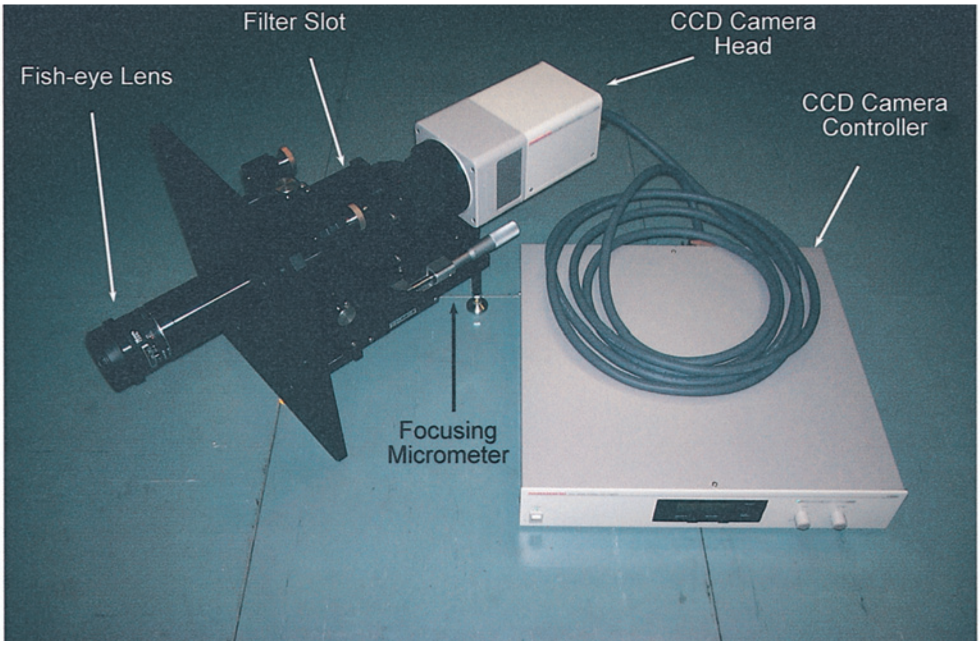

Fig. 1. ASI-2 optics with CCD camera.

Table 1. Specifications of ASI and ASI-2 optics.

	ASI	ASI-2
Optical front-end	Fish-eye lens 6 mm F1.4	Fish-eye lens 16 mm F2.8
Imaging lens	Special lens	50 mm F1.2
F number of total optics	0.98	1.2
Focal length of total optics	4.322	4.364
Field-of-view	180°	180°
Diameter of image circle	12.1 mm	11.8 mm
Length of optics	593 mm	457 mm
Total length including camera	840 mm	670 mm
Weight	20 kg	13 kg
Camera mount	C-mount	C-mount
Filter change	Motor-driven	Manual
Clear aperture of filter	66 mm	50 mm
Maximum incident angle at filter	6.66°	6.75°
Focusing	Motor-driven	Manual

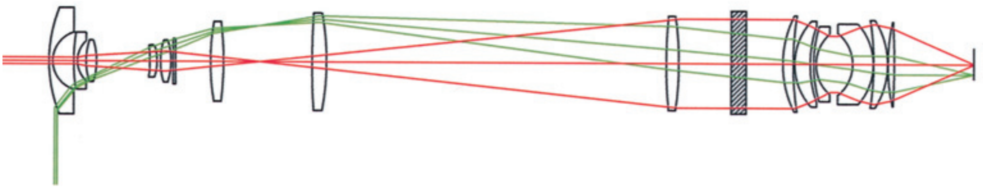

Fig. 2. Schematic of lenses and ray-paths of the ASI-2 optics. Doublet lenses are drawn as singlet lenses. The bandpass filter is indicated by a hatched rectangle.

fish-eye camera lens employed in ASI-2 has reduced size and weight. Figure 2 shows a schematic of the lenses and ray-paths from zenith and horizon. Note that the fish-eye lens used for ASI-2 projects an all-sky with equal-area projection in which the solid angles of any part in the field-of-view are proportional. This differs from the equidistant projection employed in ASI, and is reflected in the flatness of sensitivity as discussed in the next section.

The all-sky image projected by the fish-eye lens is relayed by a special collimating field lens. After passing through a narrow bandpass filter, the beams are focused on a CCD imaging device by a 50 mm F1.2 camera lens. The total length of the optics is 457 mm, and weighs a total of 13 kg including the aluminum plate fixture for installation. The original ASI optics were 593 mm in length and weighed 20 kg. Whereas filter selection and focusing were fully motor-driven in the original ASI, ASI-2 employs a filter slot in which a bandpass filter can be manually inserted, and focusing is also performed manually. These simplifications also contribute to reduction of weight and cost of ASI-2.

The light beam at the bandpass filter is 50 mm in diameter for ASI-2, compared to 66 mm for the original ASI, while the maximum angle of incidence of the beam at the filter is approximately 7° for both optics. As the overall speed of the optics is proportional to the area of the filters, the ASI optics will be 1.7 times faster than the ASI-2 optics. However, the larger number of lenses involved in the ASI optics results in more loss of light. Therefore, it is expected that the effective power of light collected by the two optics will be similar to those estimated from the étendue or throughput.

All-sky images of 512×512 pixels with a pixel size of 24 μm are acquired by the digital CCD camera, which is cooled to −60°C by a three-stage Peltier cooler. Reading the image takes up to 2 s at a data depth of 16 bits. Thus, if the exposure time is set at 2 s, an image can be taken every 5 s at the fastest rate. Read-out noise is typically 8 e^- r.m.s.

3. Calibration

3.1. Sensitivity

Sensitivity was calibrated against a National Institute of Standards and Technology (NIST) traceable 2 m integrating sphere at NIPR (Okano *et al.*, 1998). Figure 3 shows a sample image of the integrating sphere taken using a 557.7 nm bandpass filter, and Fig. 4 shows the vertical and horizontal profiles passing through the image center averaged over 50 pixel intervals. These calibration data serve as correction factors for sensitivity field flatness. The optics of the ASI-2 exhibit moderate vignetting, with sensitivity at the horizon of about half the peak sensitivity at the zenith. Comparing the sensitivity flatness of ASI and ASI-2, the horizon-to-zenith ratios of sensitivity are almost same, but ASI-2 is flatter at small zenith angles and steeper at large zenith angles (see Fig. 2 of Yamamoto *et al.*, 2002). No pixel defects were found.

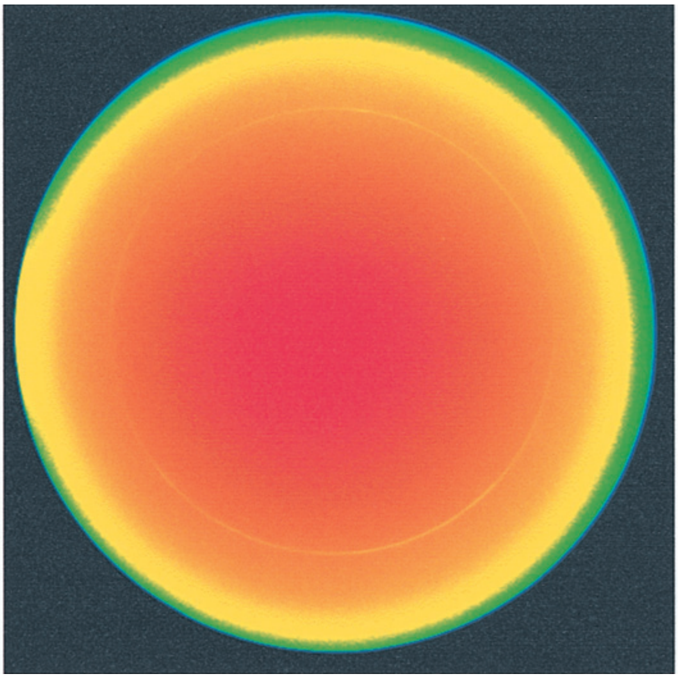

Fig. 3. Example of sensitivity maps created from images of an integrating sphere using a 557.7 nm bandpass filter after subtraction of dark counts (exposure time: 1 s).

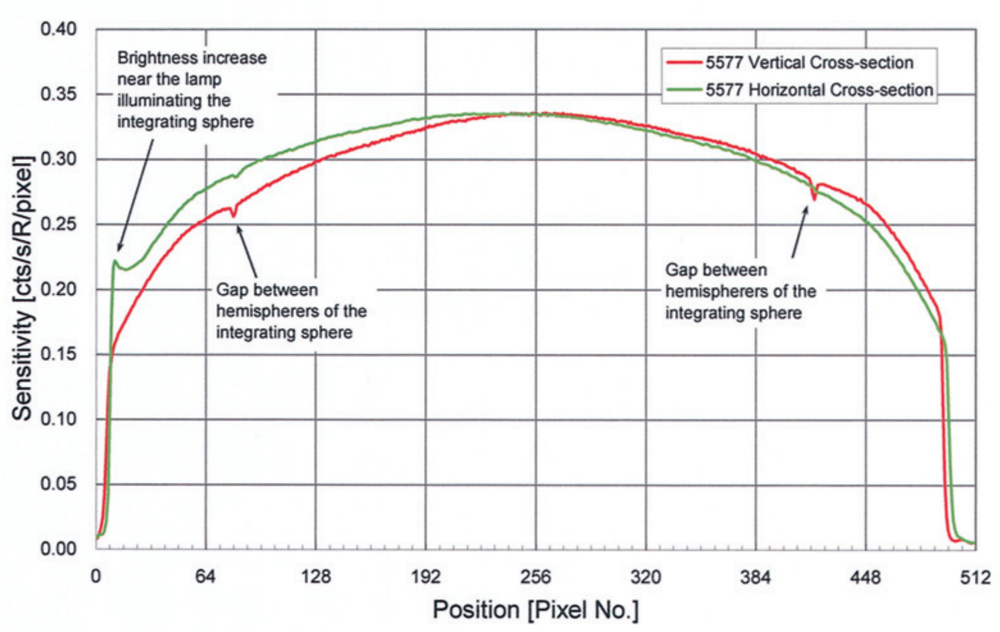

Fig. 4. Vertical (red) and horizontal (green) profiles of the sensitivity map in Fig. 3.

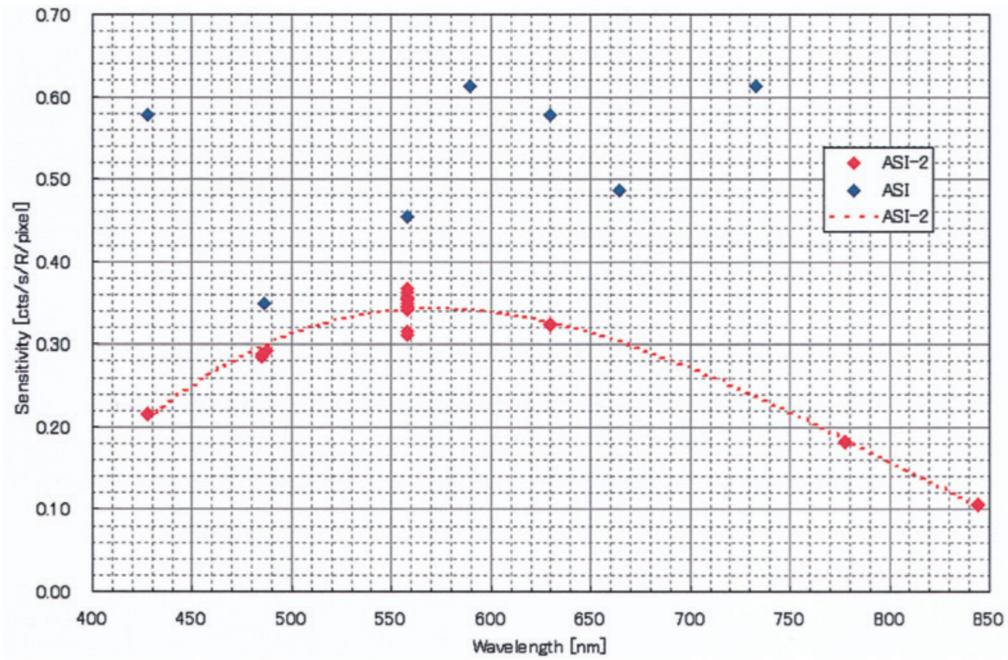

Fig. 5. Comparison of sensitivities of ASI and ASI-2.

Spectral response was obtained by sequentially inserting bandpass filters with 2–3 nm bandwidth and central wavelengths of 427.8, 486.1, 557.7, 630.0, 777.4 and 844.6 nm. The results are shown in Fig. 5 along with the sensitivities of ASI for comparison. Note that the ASI and ASI-2 have conversion factors for the amplifier of the CCD camera (one count per electron), and the ASI sensitivity data shown in Fig. 5 has been corrected accordingly for direct comparison. Scattering of the ASI sensitivity data is due to differences in filter transmission, which have not been corrected. The sensitivity of ASI-2 is 50–75% of that of ASI, consistent with the value estimated based on the optical speeds.

The linearity of response was also checked by changing the intensity of the integrating sphere through six levels from 3.0×10^{-5} to 1.0×10^{-7} W/m^2/sr/nm at 630 nm. The sensitivities calculated at these six difference inputs vary by only 1.6%.

3.2. Dark count

Dark counts due to thermally excited electrons were measured at CCD temperatures of −50 and −60°C. The results for −60°C are shown in Table 2. Dark counts increased with pre-amplifier gain. However, for exposure times shorter than several seconds, which will be sufficient for auroral observations, dark counts can be neglected even if a super-high gain is selected. The dark count at −50°C was five times that at −60°C.

3.3. Focal position

Focal plane shift was measured for different colors of incident light as shown in Table 3. Although the ASI-2 optics includes some axial chromatic aberration, the focal position of the ASI-2 optics does not shift as rapidly with color as the ASI optics. Defocusing can be manually adjusted using a micrometer attached to the translation stage securing the CCD camera.

Table 2. Dark count rate at −60°C.

Gain	Count rate (counts/s)
Super high	0.38
High	0.11
Low	0.027

Table 3. Defocusing for different colors.

Wavelength (nm)	Defocusing (mm)	
	ASI	ASI-2
391.4	−0.39	-
427.8	0.06	−0.10
484.8	-	0.00
557.7	0.21	0.05
589.3	0.24	-
630.0	0.00	0.00
730.0	−0.60	-
777.4	-	−0.15
844.6	−1.14	−0.30

3.4. Spatial resolution

Spatial resolution was tested using the setup shown in Fig. 6. An artificial star as a diffuse light source observed through 1 mm pinhole was set at a horizontal distance of 2.4 m from the fish-eye lens of the ASI-2 optics. Defocusing of an object at 2.4 m from the fish-eye lens to infinity is only 8 μm, which is so small that the artificial star image taken using the ASI-2 optics can be regarded as a point spread function (PSF) for an object at infinity. The artificial star images were taken at various zenith angles, and the full-width at half-maximum (FWHMs) of the star image in the sagittal and meridional directions or elevation

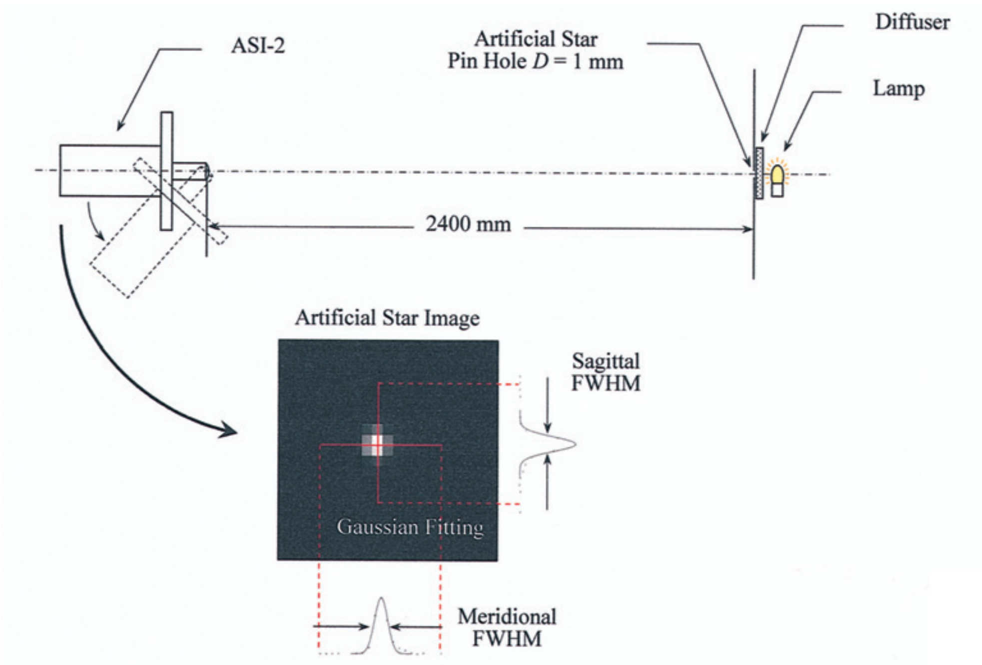

Fig. 6. Configuration employed for spatial resolution testing.

Table 4. FWHM of point spread functions.

Zenith angle (deg)	FWHM (pixels)			
	ASI		ASI-2	
	Meridional	Sagittal	Meridional	Sagittal
0	-	-	2.07	1.58
10	1.76	2.05	2.02	1.65
20	-	-	2.14	1.55
30	1.38	1.83	2.30	1.74
40	1.47	1.57	2.29	1.70
50	1.56	1.83	2.27	1.90
60	1.27	1.55	2.41	2.31
70	1.54	1.98	2.52	2.72
80	1.78	1.82	2.66	3.35
90	-	-	2.70	4.08

and azimuthal directions were measured.

The PSF of point images of four bright stars in a 557.7 nm all-sky image taken at Syowa Station was used, although these functions did not cover the entire range of zenith angle. The results are shown in Table 4. The FWHM of the PSF in the meridional direction varies moderately from 2.07 pixels at zenith to 2.70 pixels at the horizon. In the sagittal direction, the FWHM is 1.58 at zenith, better than that in meridional direction, but degrades to 4.08 pixels at the horizon. The FWHMs of the PSF for the original ASI optics remain almost constant with zenith angle, and are better than those for ASI-2. Thus, clear images are expected at zenith angles of less than 70° using the ASI-2 optics, but care should be taken when examining data at greater zenith angles.

4. Sample image

The ASI-2 optics were installed in a dark room of the Information Processing Building at Syowa Station, Antarctica. Observations using the new optics began in February 2004. A sample auroral image taken with a bandpass filter of 630 nm is shown in Fig. 7. The exposure time was set to 30 s, the same as that of a Fabry-Perot imager (FPI), to allow the image to be used as a reference image for FPI data. As such, the lowest sensitivity of the CCD camera was selected to avoid total count saturation. As inferred from the calibration results,

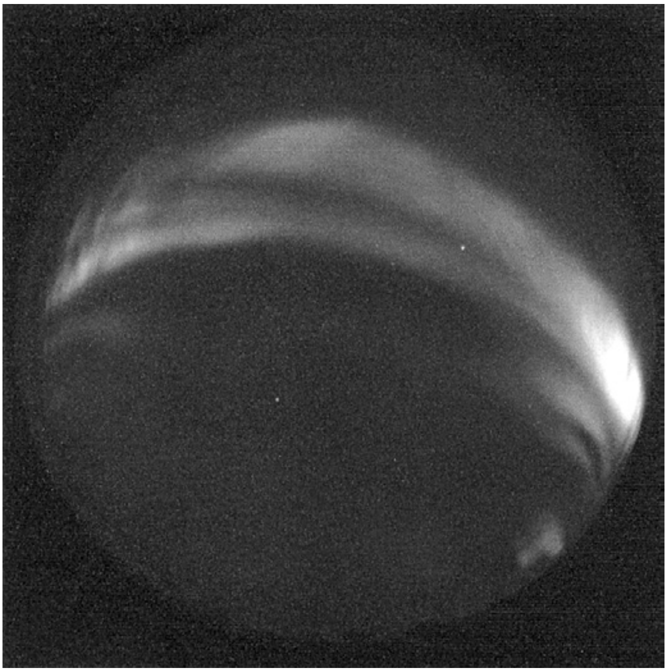

Fig. 7. All-sky image taken using the ASI-2 optics at 20h19m40s UT on March 26, 2004 at Syowa Station, Antarctica, using a 630.0 nm bandpass filter. Magnetic north and west are to the top and right of the image, respectively. Dark counts have been subtracted. Exposure time was 30 s.

the image is of good quality, although it is slightly blurred at large zenith angles. Thus, this imager is expected to be useful for absolute intensity measurements of large-scale aurora and airglow distributions. It should be noted, however, that the spatial resolution of the ASI-2 optics is currently not sufficient to resolve fine structures, particular for events far from the observatory.

5. Summary

We have developed a new compact all-sky imager for auroral and airglow studies. The new optics utilizes commercial camera lenses, a bandpass filter and a cooled digital CCD camera to reduce cost. The sensitivity of the new optics is 50–75% that of the original ASI optics, and provides an all-sky field-of-view with moderate spatial resolution. Elimination of the automatic focusing mechanism reduces the weight and production cost of the optics. One ASI-2 imager has been installed at the Syowa Station and is acquiring reference auroral images for the FPI. Prior to installation of the Syowa ASI-2 optics, three identical imagers have been in operation at the observatory and the new Chinese Arctic station at Ny-Ålesund, Svalbard since December 2003, and simultaneous image data for auroral emission wavelengths of N_2^+ 427.8 nm, OI 557.7 nm and OI 630.0 nm have successfully collected (Yang, private communication). The results of these observations will be presented in the next issue of this publication series.

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