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Sunrise Chromospheric Infrared spectroPolarimeter (SCIP) for SUNRISE III: Thermal-Vacuum Test of the SCIP Optical Unit

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ABSTRACT

The Sunrise Chromospheric Infrared spectroPolarimeter (SCIP) is an instrument for the third flight of the SUNRISE balloon-borne solar observatory planned for 2022. To verify the high spatial and spectral resolutions required in the balloon flight, the SCIP optical unit was subjected to a thermal-vacuum test in which the SCIP optical unit was installed in a vacuum chamber and was exposed to the thermal vacuum environment expected in the balloon flight. We verified the heater control performance and the temperature distribution in the SCIP optical unit in hot and cold conditions created by the shrouds in the vacuum chamber. We confirmed the optical performance, such as spatial and spectral resolution, and an air-to-vacuum difference of the optics by injecting the laser and white lights through a vacuum window.

Keywords: balloon, near-IR, polarization, spectrograph, sun, focal-plane instrument, thermal-vacuum test

1. INTRODUCTION

SUNRISE is a balloon-borne observatory dedicated to an observation of the Sun and carries a 1 m diameter aperture Gregorian telescope.[1,2] The balloon platform allows us to conduct seeing-free stable observations as well as UV observations from an altitude higher than 35 km. For the 3rd flight of SUNRISE in 2022, a near-IR spectro-polarimeter instrument called Sunrise Chromospheric Infrared spectroPolarimeter (SCIP) is newly developed for observations of the solar chromosphere and the photosphere with a spatial and spectral resolution of 0".2 and 2×10^5, respectively, and with 0.03% (1 σ) polarimetric sensitivity in 10 sec integrations.[3] The SCIP was designed to achieve these performances in spectral regions centered at 850 nm and 770 nm in the near-infrared wavelength range where there are many spectrum lines useful for diagnostics of the solar atmosphere. The SCIP optical unit (O-unit) is a package containing the optical system whose size is $940 \times 500 \times 350$ mm^3.

The optical system of SCIP consists of the spectrograph and the slit imager[4] as shown in Figure 1. At the entrance of the SCIP, a polarization modulation unit (PMU) creates a temporally modulated solar image on the slit by a rotating waveplate.[5] The SCIP spectrograph consists of an echelle grating and two aspheric mirrors located in a quasi-Littrow configuration. The first aspheric mirror (collimator mirror) works to feed a collimated beam onto the echelle grating, whereas the second one (camera mirror) makes spectral images onto an image plane. The shape of the aspheric surfaces is optimized to obtain good image quality along the slit and over the wavelength ranges and is represented as a non-axisymmetric high-order asphere. The beam is then

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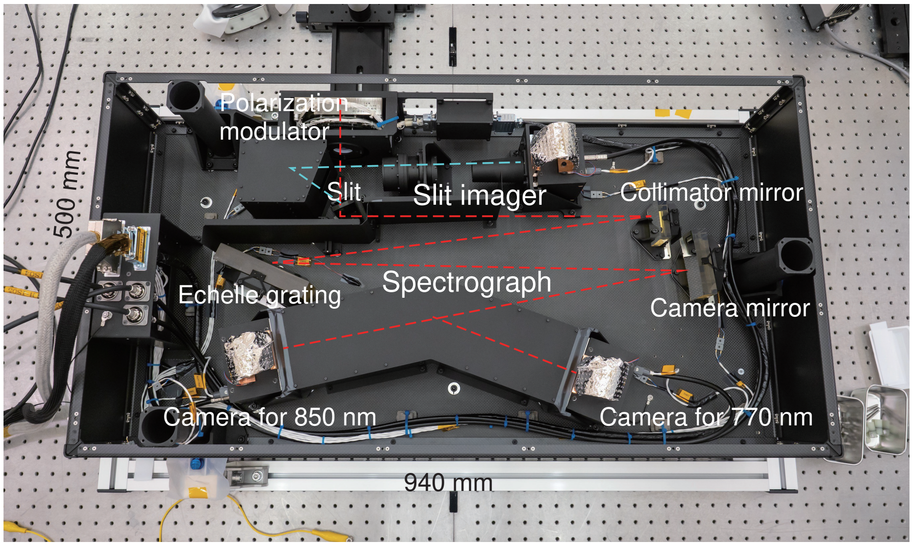


Figure 1. Inside of the SCIP O-unit. The SCIP optical system consists of the spectrograph and the slit imager whose chief rays are depicted by the red and blue dashed lines, respectively. The optical elements and the cameras are mounted on the optical bench made of the CFRP-aluminum-honeycomb sandwich panel.

divided into two wavelength channels by a dichroic beam splitter. One channel uses the 19th diffraction order to observe the 850 nm wavelength band, and the other uses the 21st order to observe the 770 nm wavelength band. Spectral images of the two wavelength bands are obtained by the two cameras simultaneously. There are polarization beam splitters in front of each camera to split the s- and p-polarized lights and make images of both the polarization states onto a single camera. A slit imager is used to observe a 2D image around the slit and consists of a band-pass filter centered at 770.5 nm and a lens system. All the optical elements and the cameras are mounted on the optical bench made of a CFRP-aluminum-honeycomb sandwich panel with lightweight and a small coefficient of thermal expansion (CTE) to keep the wavefront errors within the tolerance under temperature variation expected during the balloon flight. The reflective optical elements are critical for the wavefront error and are supported by a quasi-kinematic mount consisting of flexures. The materials of the flexure pads were selected to match the CTE of glass substrate materials.[6]

The mechanical design was analytically verified using the finite element analysis to meet the wavefront error requirement in the temperature range of 10 to 30°C, where the O-unit was supposed to be assembled at 20°C.[6] To experimentally verify the optical performance under the environment expected in the balloon flight, we conducted a thermal-vacuum (TV) test by installing the SCIP O-unit in a vacuum chamber and applying thermal cycling and a thermal balance test in which a temperature gradient was created by copper shrouds in the vacuum chamber to simulate the thermal environment expected in the flight. We here report the configuration used in the TV test and the results obtained by the test.

2. SCIP THERMAL DESIGN

In order to keep the temperatures of the SCIP O-unit within the operational temperature range of 10 to 30°C, an operational heater was installed on the back surface of the optical bench (Figure 2 [a]). We distributed six polymide thermofoil heaters (MINCO HK6913) which had a resistance of 188 Ω each. The heater dissipates the power of 24 W with a 27.6 V supply. We used a simple on/off control of the operational heater by reading a temperature sensor (AD590LF) located around the center of the back surface. Thanks to relatively thick (4 mm) CFRP skins of the sandwich panel in the optical bench contributed to making a uniform temperature distribution by the simple on/off control of the heater. The nominal temperature range was 20±1°C, but the heater set point can be changed by a command. Note that a non-operational heater was also installed onto the optical bench before the flight, but it was not there in the TV test.

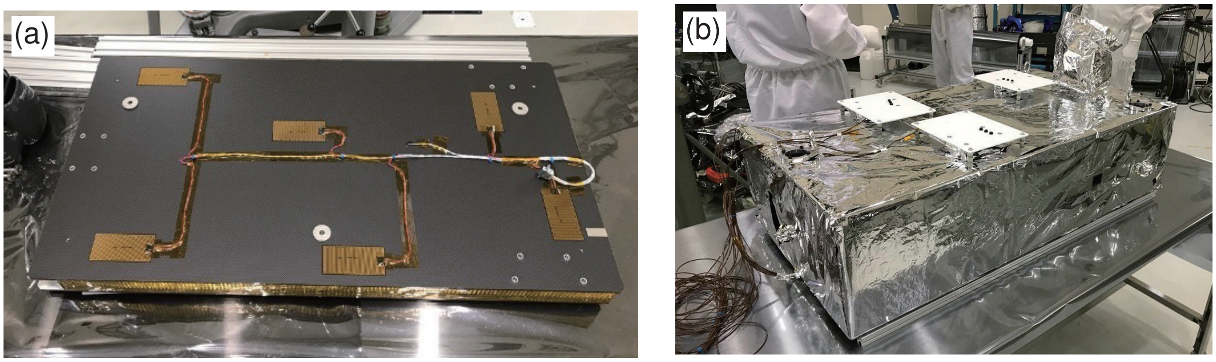


Figure 2. (a) Back surface of the optical bench. Six thermofoil heaters were distributed on the back surface for the operational heater. (b) SCIP O-unit covered by SLI. There are three radiators with white paint attached to each camera. Thermocouples were installed to monitor the temperatures of the optical bench, the upper cover of the O-unit, the radiators, and SLI during the TV test.

The three cameras using a CMOS sensor dissipate a power of 3.8 W each. To dump the power dissipation in the cameras, a radiator was connected to each camera by a copper thermal strap (TAI P5-503) with a length of about 100 mm. The radiator is coated with white paint (Aeroglaze A276) and its size was designed to keep the sensor temperature at around 20°C by radiative cooling. The cameras were equipped with a heater to maintain the constant temperature of the CMOS sensor by a PID control. Its capacity was 5.5 W in each camera. Dark currents of the CMOS sensor were small enough at a temperature lower than 30°C because of the fast read-out of the sensor (32 frames per second). The SCIP O-unit is covered with a single layer insulator (SLI) having a low emissivity ($\epsilon < 0.1$) surface for thermal insulation from the surrounding environment (Figure 2 [b]).

3. CONFIGURATIONS OF THE THERMAL VACUUM TEST

The SCIP O-unit was installed in a big vacuum chamber dedicated for thermal-vacuum tests of space-borne instruments at the Advanced Technology Center (ATC) of NAOJ (Figure 3). The vacuum chamber was used for a test of the Hinode Solar Optical Telescope.[7] The vacuum chamber was equipped with two independent copper shrouds inside to make a temperature gradient between the upper and lower sides of the chamber. The SCIP O-unit was mounted on the lower shroud with insulation by glass-epoxy spacers. The temperatures of the copper shrouds were controlled by two independent buscirculators with Galden as a heat transfer fluid. The upper shroud was set colder to mimic the flight environment to have larger radiative cooling from the top surface, especially from the camera radiators. For operating the SCIP O-unit, the SCIP electronics unit (E-unit) was developed by the Spanish consortium for powering the three cameras, PMU, and the heaters, and for controlling observations by synchronously running PMU and the cameras. Because the thermal environment expected during the flight is completely different between the O-unit and E-unit, the E-unit was located outside of the vacuum chamber in this TV test, and they were connected to each other through a vacuum feedthrough. The E-unit was tested in a separate TV test in Spain. We constructed a low-vacuum condition at around 1 torr using a dry vacuum pump with constant dry N_2 leakage. There were 10 temperature sensors (AD590LF) inside the O-unit which were read out by the E-unit. We installed additional thermocouples outside of the O-unit which were read out by a temperature logger.

The important items in the TV tests are to verify the air-to-vacuum differences of the optics. In the spectrograph, the wavelength positions of spectrum lines in an image change from air to vacuum. The spectrum positions were aligned in air considering the change to have the spectrum lines at the desired positions in vacuum. The slit imager used a lens system that had a non-negligible focus offset between air and vacuum. Thus, the focus position of the slit imager was aligned to be off-focus in air to have in-focus in vacuum. These items could be verified only in a vacuum condition. It was also important to verify the spatial and spectral resolution did not vary when the temperatures of the SCIP O-unit were maintained by the operational heater. We built an optical system to feed lights into the SCIP O-unit through a vacuum window as shown in Figure 4. We used an IR

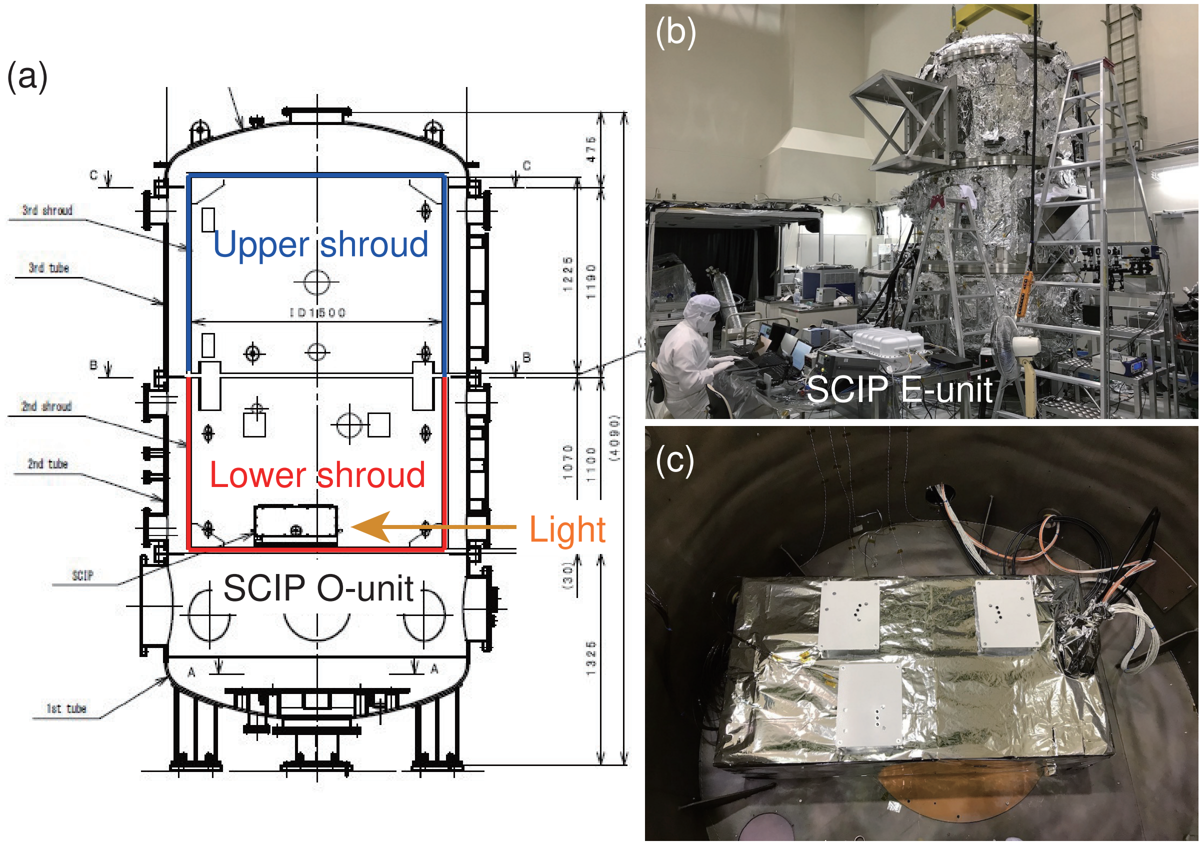


Figure 3. (a) Vacuum chamber used in the TV test. The vacuum chamber is equipped with two separate copper shrouds to make a temperature gradient between the upper and lower sides. The SCIP O-unit was set on the lower shroud with insulation by glass-epoxy spacers. For the optical test, we fed lights from a vacuum window into the O-unit. (b) Outlook of the vacuum chamber. The SCIP E-unit was located outside of the vacuum chamber, which was connected to the O-unit through a vacuum feedthrough. (c) SCIP O-unit inside the lower shroud. The three radiators were faced to the upper shroud.

Table 1. TV test modes

Mode	Upper shroud	Lower shroud	Optical bench heater	Camera heater
H1	−35°C	11°C	On at 20°C	Off
H2	−36°C	11°C	On at 20°C	On at 23°C
C1	−36°C	−1°C	On w/ duty 100%	On at 20°C
C2	−35°C	−1°C	On at 12°C	On at 15°C

lamp (NIPPON PI PIS-UHX-NIR) and tunable lasers (Sacher Lasertechnik TEC-520) for feeding white-lights and monochromatic lights.

4. RESULTS

4.1 Temperature Control

We made four different test modes in the TV test for verification of the thermal control function as shown in Table 1. In the hot modes H1 and H2, the upper and lower shrouds were set at the temperatures of −36 to -35°C and 11°C, respectively. In the cold modes C1 and C2, the upper and lower shrouds were set at the temperatures of −36 to −35°C and −1°C, respectively. The temperature profiles are summarized in Figure 5. Note that we could not keep the constant temperature in the upper shroud for a long period because the buscirculator for the upper shroud did not function normally and we had to warm up occasionally. We changed the setting of the

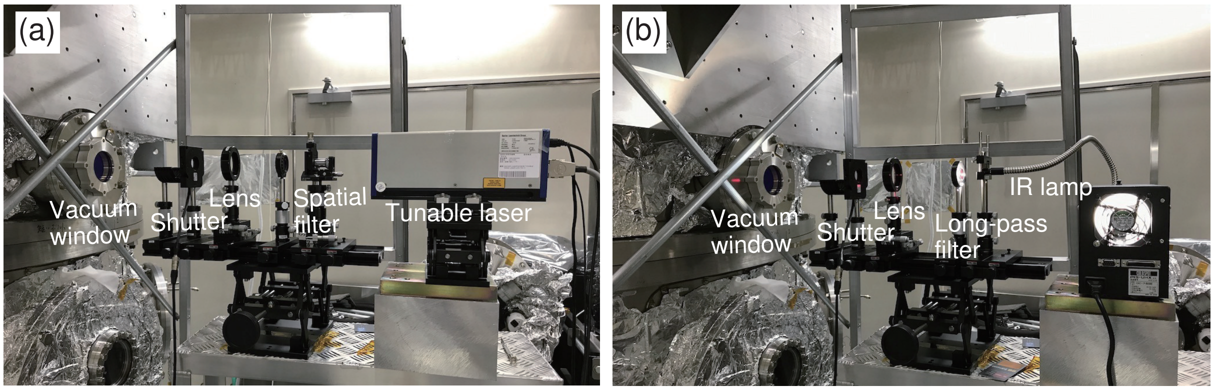


Figure 4. (a) Optics to feed monochromatic lights from the tunable lasers into the SCIP O-unit through the vacuum window. A diverging beam was created by a spatial filter, which was collimated by a lens to illuminate the full length of the slit. (b) Optics to feed white-lights from the IR lamp. To cut short-wavelength visible light, a long-pass filter was inserted in the optics.

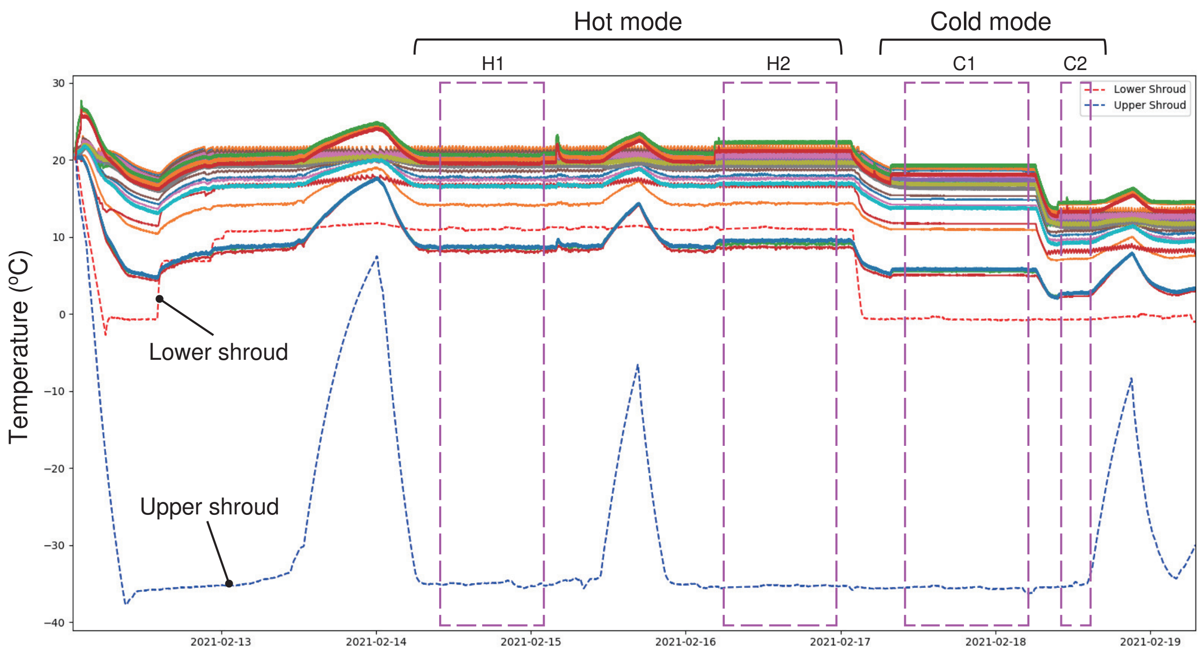


Figure 5. Temperature profiles of the shrouds and the SCIP O-unit in the TV test. The test modes are indicated by H1, H2, C1, and C2.

operational heaters of the optical bench and the cameras as shown in Table 1. We first started the test with the H1 mode in which the operational heater of the optical bench was set at 20°C while the camera heater was disabled. We confirmed the temperatures of the camera sensor were similar to the optical bench temperature. Then we enabled the camera operational heater at 20°C in the H2 mode to see the functions of the camera with the heater. In the C1 mode, we kept the 20°C setting for the operational heater of the optical bench. Because of the colder environment by the lower shroud, the heater could not keep the optical bench at 20°C but reached 17 to 18°C with a 100 % duty cycle. In the C2 mode, we changed the heater set point of the optical bench to 12°C to check the heater on/off control in the cold condition while the camera heater was changed to 15°C. Through these tests, we confirmed the function of the operational heaters for both the optical bench and the cameras. It was demonstrated that we could keep the temperatures of the O-unit higher than 10°C in the cold

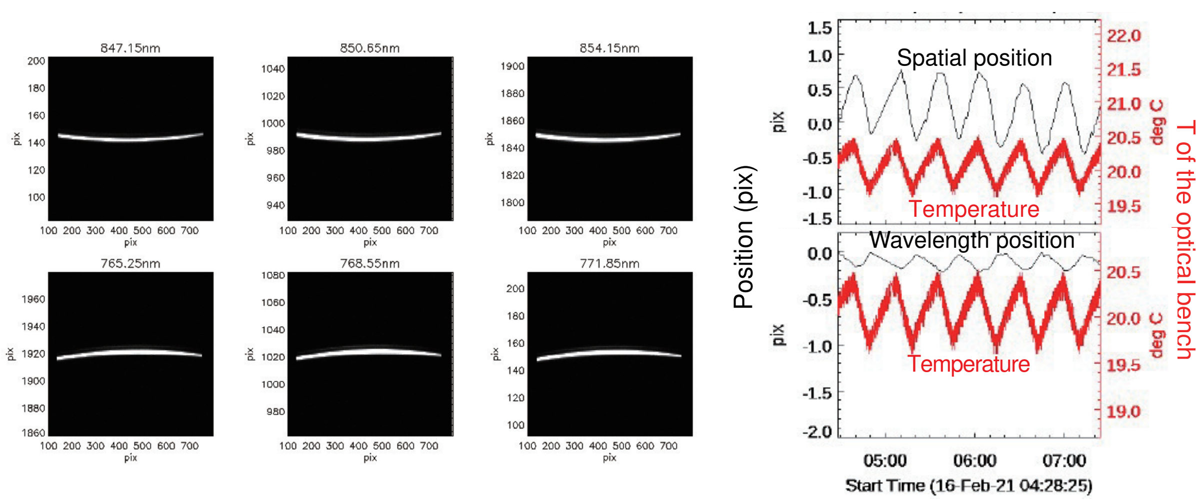


Figure 6. (left) Images of the laser lights taken with the spectrograph. The spatial and wavelength directions correspond to the horizontal and vertical directions, respectively. We derived spatial and wavelength positions from these images. (right) Stability of the spatial (top) and wavelength (bottom) positions of the laser light with temperature variations of the optical bench.

environment. Note that the thermal environment in the TV test was not exactly identical to the one expected during the flight. We need thermal model analysis to fully verify the condition during the flight.

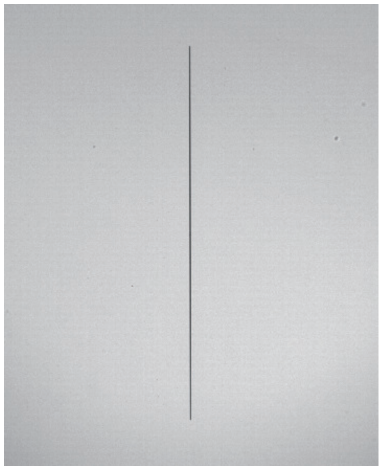
4.2 Optical Measurements

The air-to-vacuum difference of spectral positions was measured by feeding laser lights into the spectrograph as shown in the left panel of Figure 6. We changed the wavelengths of the laser lights with the tunable laser and confirmed that the offset between air and vacuum was expected for both the 850 nm and 770 nm bands. We monitored the stability of the spectral resolution as well as the spatial and wavelength positions in the H2 mode in which the temperature of the optical bench was maintained by the on/off control of the operational heater. The spatial position was determined using the edge along the spatial direction. We found the spatial position varied with an amplitude of less than 1 pixel associated with the temperature ripple of 0.8°C caused by the heater on and off while the wavelength position did not vary much. This was caused by a slant of the reflective optics in the spectrograph, i.e. the collimator and camera mirrors, and the grating, due to a bi-metalic effect in their support mechanisms.[8] The temporal variation of spatial and spectral positions of the spectrum data could be corrected by post-processing.

The air-to-vacuum focus offset in the slit imager was measured using a slit width by feeding white-light. In the alignment in air, a focus scan of the slit imager camera was done to find the optimum focus position in which the slit was the narrowest, as shown by the blue line in the right panel of Figure 7. Then the focus position of the camera was moved to the nominal position by applying the expected air-to-vacuum focus offset. The slit became broader at the nominal position, as shown by the red line in the right panel of Figure 7. We confirmed the slit width in vacuum became closer to the one measured at the optimum focus position in air, as shown by the black line in the right panel of Figure 7. Thus we verified the air-to-vacuum focus offset experimentally in the TV test. The stability of the slit width was confirmed in the H2 mode when the optical bench heater was operated with the on/off control.

5. SUMMARY

We made the TV test to verify the thermal control function and optical performance of the SCIP O-unit in the thermal vacuum environment expected in the balloon flight. The big vacuum chamber at the ATC, NAOJ



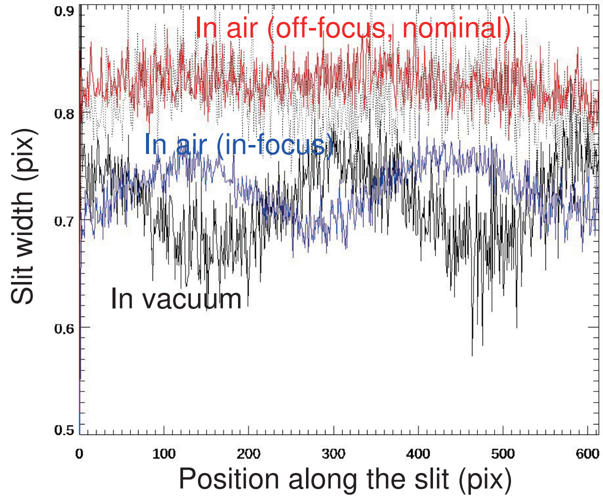


Figure 7. (left) Slit image taken by the slit imager. (right) Slit widths of the slit imager measured after the alignment in air at the optimum focus position (blue), in air at the nominal off-focus position (red), and in vacuum in the TV test (black).

was equipped with two independent shrouds inside which allowed us to apply the temperature gradient to the O-unit. We verified the function of the operational heater of the optical bench and the cameras in the hot and cold conditions. We constructed the optical system to feed white- and laser-lights through the vacuum window to measure the optical performance in the thermal vacuum condition. We verified the air-to-vacuum wavelength change of the spectrograph as well as the air-to-vacuum focus offset of the slit imager. The stability of the spectral and spatial resolutions was also confirmed when the O-unit temperature was maintained by the operational heater. The test result provided evidence to guarantee the performance of the SCIP O-unit in the balloon flight.

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