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Sunrise Chromospheric Infrared SpectroPolarimeter (SCIP) for SUNRISE III: System Design and Capability

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ABSTRACT

The SUNRISE balloon-borne solar observatory carries a 1 m aperture optical telescope and provides us a unique platform to conduct continuous seeing-free observations at UV-visible-IR wavelengths from an altitude of higher than 35 km. For the next flight planned for 2022, the post-focus instrumentation is upgraded with new spectro-polarimeters for the near UV (SUSI) and the near-IR (SCIP), whereas the imaging spectro-polarimeter Tunable Magnetograph (TuMag) is capable of observing multiple spectral lines within the visible wavelength. A new spectro-polarimeter called the Sunrise Chromospheric Infrared spectroPolarimeter (SCIP) is under development for observing near-IR wavelength ranges of around 770 nm and 850 nm. These wavelength ranges contain many spectral lines sensitive to solar magnetic fields and SCIP will be able to obtain magnetic and velocity structures in the solar atmosphere with a sufficient height resolution by combining spectro-polarimetric data of these lines. Polarimetric measurements are conducted using a rotating waveplate as a modulator and polarizing beam splitters in front of the cameras. The spatial and spectral resolutions are 0.2" and 2×10^5, respectively, and a polarimetric sensitivity of 0.03 % (1σ) is achieved within a 10 s integration time. To detect minute polarization signals with good precision, we carefully designed the opto-mechanical system, polarization optics and modulation, and onboard data processing.

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

1. INTRODUCTION

The Sun provides a unique opportunity to study how magnetic fields drive dynamic phenomena in astrophysical plasma with a detailed spatial and temporal resolution. In addition, to understand the physical mechanisms driving the dynamics, it is critically important to obtain physical quantities, such as the temperature, velocity, and

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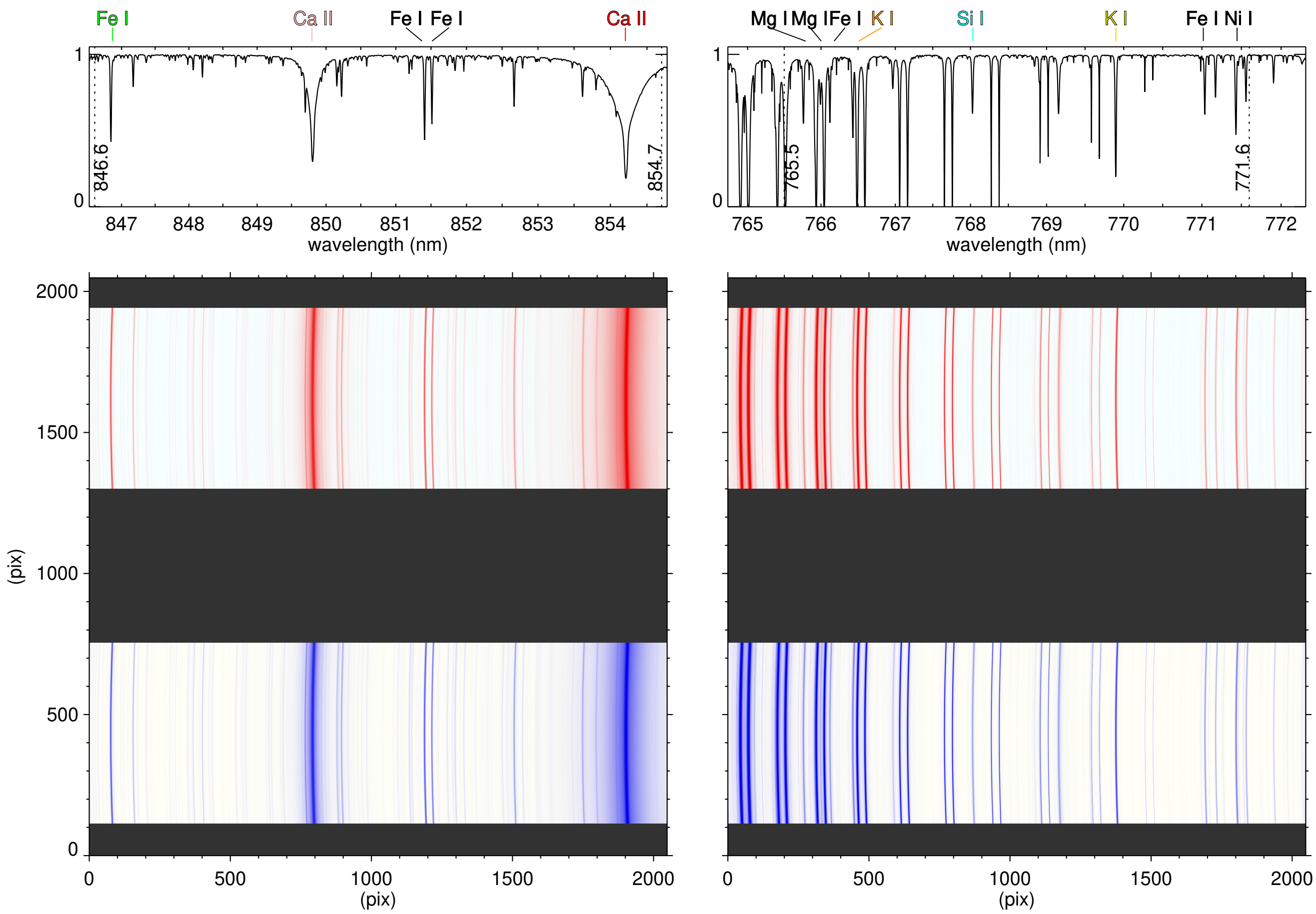

Figure 1. Simulated spectral data taken by SCIP at each channel (left, CH1 850 nm; right, CH2 770 nm). Two spectra data with the orthogonal polarization (s- and p-polarizations) states, which are illustrated by red and blue colors, are imaged onto the sensor simultaneously at each channel. The focal plane sensor has a pixel resolution of 2048×2048 with a pixel size of 11 μm. The beam separation is 13 mm when using the polarization beam splitter. Note that the saturated telluric absorptions seen in the 770 nm channel correspond to observations from ground level, which will be significantly reduced at the balloon height.

magnetic field, in a remote object using spectro-polarimetric measurements. Space-based spectro-polarimeters have been realized and provide valuable data for investigating the behavior of magnetic fields on the solar surface, i.e. the photosphere. In particular, the spectro-polarimeter[1] implemented in the *Hinode* Solar Optical Telescope[2] obtained spectro-polarimetric data of the Fe I lines at 630.15 and 630.25 nm with an echelle spectrograph and allowed us to map the magnetic fields in sunspots and quiet regions with a resolution of 0.32" owing to the diffraction-limited optical performance of a 50 cm aperture telescope and the stable observation conditions. Another mission conducting spectro-polarimetric observations was the Sunrise balloon-borne solar mission.[3–5] Sunrise carries a 1 m aperture optical telescope and allowed us to conduct seeing-free visible observations under stable conditions as well as observations within a UV range of shorter than 400 nm, which is inaccessible to a ground-based telescope. The Imaging Magnetograph eXperiment (IMaX)[6] made spectro-polarimetric observations at the Fe I 525 nm line sensitive to the solar photosphere using a narrow-band tunable filter, and provided maps of surface magnetic fields with a resolution of 0.15".

In the past two flights of Sunrise in 2009 and 2013, spectro-polarimetric observations were conducted with only IMaX in the photosphere, whereas imaging observations were used to observe the overlying lower atmosphere, i.e., the chromosphere. There is a strong demand to expand the capability of spectro-polarimetry to conduct a detailed and quantitative investigations of the chromosphere to understand the mechanisms driving the

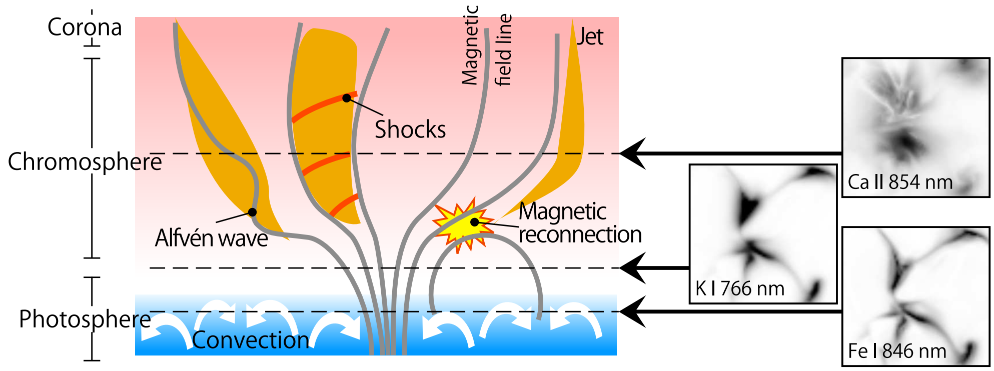

Figure 2. Science targets using SCIP. Spectro-polarimetric measurements of multiple spectrum lines from the photosphere to the chromosphere allow us to obtain three-dimensional structures of magnetic and velocity fields and reveal the nature of the jets and MHD waves responsible for heating and acceleration of the solar atmosphere.

Table 1. Key requirements of SCIP

	Science requirements	SCIP specifications
Wave. coverage	Spectral lines allowing seamless coverage of the photosphere and the chromosphere	Two wavelength bands including Ca II 850 nm and K I 770 nm lines
Spat. resolution	Enough to resolve fine scale dynamics in the chromosphere	0.21" (diffraction limit resolution at 850 nm)
Temp. resolution		Stokes IQUV: shorter than 10 s/step Stokes I only: shorter than 45 s for full FoV
Spec. resolution	Enough to get polarization signals at the chromospheric lines	$\lambda/\Delta\lambda = 2 \times 10^5$ (sampling)
Pol. accuracy		0.03% (1σ)
Field-of-view	Enough to cover a super-granular scale	58"×58"

dynamic phenomena, such as jets and MHD waves.[7] Because magnetic fields in the chromosphere are generally weak and spectrum lines emanating from the chromosphere are broad compared with photospheric lines, we need a high polarimetric sensitivity to obtain measurable polarization signals at a spectrum line sensitive to the chromosphere. The 1 m aperture Sunrise telescope is suitable for collecting the number of photons required for precision polarimetry and to resolve the fine-scale dynamics spatially and temporally. Thus we plan a third flight, i.e., Sunrise III, planned for 2022, by upgrading the focal plane instruments. IMaX is going to be replaced by the Tunable Magnetograph (TuMag) and thus will be able to switch the spectrum lines for observing a chromospheric line in addition to the photospheric Fe I 525 nm line. Observations within the UV wavelength range were conducted using the Sunrise Filter Imager (SuFI) during previous flights.[8] It is replaced with the Sunrise UV Spectropolarimeter and Imager (SUSI) in Sunrise III to make spectro-polarimetric observations within the wavelength range of 309 – 417 nm. The Correlating Wavefront Sensor (CWS), as flown in the previous flights, is an instrument for tip-tilt mirror compensation of image motions as well as for a correction of low-order aberrations using a Shack-Hartmann wavefront sensor,[9] and will be improved for better image stability.

In addition to the above three instruments, a new instrument called the Sunrise Chromospheric Infrared spectroPolarimeter (SCIP) is designed to observe near-infrared spectrum lines sensitive to solar magnetic fields in both the photosphere and the chromosphere. The SCIP instrument is developed through international collaboration among Japanese institutes including the Japan Aerospace Exploration Agency (JAXA), the Spanish Sunrise consortium led by the Instituto de Astrofísica de Andalucía (IAA-CSIC), and the German Max Planck Institute for Solar System Research (MPS) with the leadership of the National Astronomical Observatory of Japan (NAOJ).

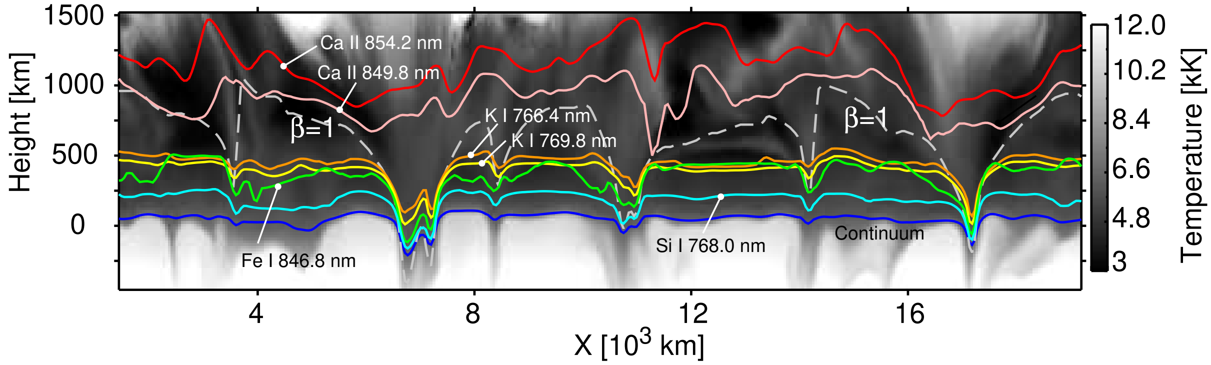

Figure 3. Formation height of key spectral lines within the observing wavelength range. By combining multiple spectral lines observed with SCIP, we can seamlessly cover the photosphere and the chromosphere. The gray scale represents temperatures within the solar atmosphere.

2. SUNRISE CHROMOSPHERIC INFRARED SPECTROPOLARIMETER (SCIP)

2.1 Science targets of SCIP

The targets of the spectro-polarimetric instrument SCIP are to (1) determine the 3D magnetic structure from the photosphere to the chromosphere, (2) trace MHD waves from the photosphere to the chromosphere, and (3) reveal the mechanism driving chromospheric jets, by measuring the height- and time-dependent velocities and magnetic fields in the solar atmosphere (Figure 2). To achieve them, SCIP is designed to observe two spectral regions centered at 850 and 770 nm in the near-infrared wavelength range (Figure 1). The two-wavelength ranges contain many spectral lines that produce measurable polarization signals owing to the existence of magnetic fields through the Zeeman effect. In particular, the Ca II lines at 849.8 and 854.2 nm are sensitive to magnetic fields in the chromosphere. The K I lines at 766.5 and 769.9 nm are sensitive to the atmosphere between the photosphere and the chromosphere. There are multiple spectrum lines, such as the Fe I 846.8 nm line, within the wavelength range sensitive to the photosphere. By combining these spectral lines, we can seamlessly cover the photosphere and the chromosphere and obtain 3D magnetic and velocity structures in the solar atmosphere,[10,11] as shown in Figure 3. It is worth noting that the 770 nm band is heavily affected by the O_2 band in the Earth's atmosphere. In particular, the K I 766.5 nm line is completely blended, and its polarimetric measurement cannot be conducted using a ground-based telescope. At the expected balloon altitude, the absorption becomes much weaker, enabling a good polarization profile of the K I 766.5 nm line for the first time.[12]

In addition to the spectral coverage, a high spatial resolution is also required to resolve the dynamic phenomena occurring in the atmosphere, where we set a goal to achieve a resolution of 0.21", which is the diffraction-limit of the 1 m aperture telescope at a wavelength of 850 nm. A polarimetric sensitivity of 0.03% (1σ) is necessary to measure weak polarization signals in the chromospheric lines, such as Ca II 854.2 nm. Owing to the 1 m aperture telescope, polarimetric sensitivity is attained through an integration for less than 10 s. This is critical for obtaining the temporal evolution of magnetic fields driving the dynamics. A spectral resolution of 2×10^5 is required to discern the polarization (Stokes) spectral profiles. The field-of-view (FOV) is limited by the upstream optics but is designed to be larger than 50"×50" by scanning perpendicular to the slit. The key requirements are summarized in Table 1. Seeing-free observations achieved using the stratospheric balloon-borne telescope allow us to map magnetic structures and their temporal evolution in the solar atmosphere with good spatial and spectral resolutions simultaneously with polarimetric sensitivity.

2.2 Design concept of the SCIP optics

Sunrise employs a 1 m aperture telescope with a Gregorian design. It feeds light into the Image Stabilization and Light Distribution (ISLiD) unit.[8] The ISLiD system is upgraded in Sunrise III to accommodate the new instrument SCIP (Figure 4) in addition to SUSI, TuMag, and CWS. The new ISLiD consists of two Offner optical systems that relay the Gregorian focus (F2) to the instruments. The first Offner system consisting of

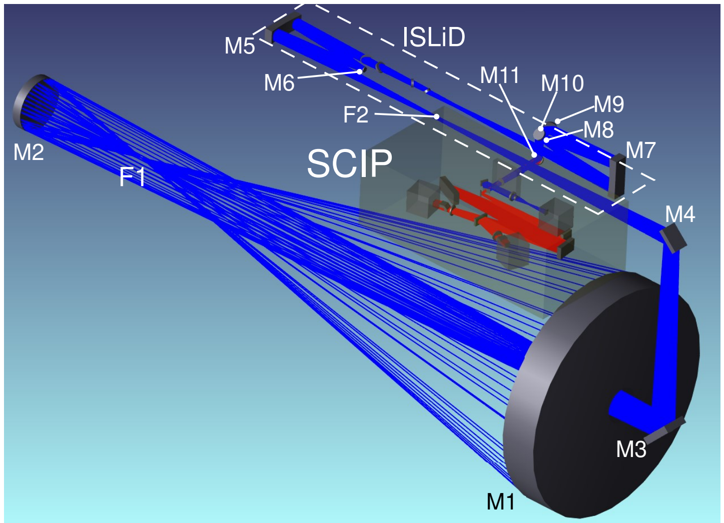

Figure 4. Layout of the SUNRISE telescope and ISLiD optics feeding light into SCIP. The Gregorian telescope creates the Gregorian focus (F2) in ISLiD. The first Offner relay system in ISLiD consists of two spherical mirrors, M5 and M6, and feeds light into SUSI, TuMag, and CWS by dichroic beam splitters. M6 is used as a tip-tilt mirror for correlation tracking driven by the CWS. The second Offner relay system consists of M7 and M8 and feeds lights into SCIP with the aid of three folding mirrors (M9, M10, and M11). M8 is mounted on a scan mirror mechanism (SMM) and used for SCIP to scan a FOV perpendicular to the slit.

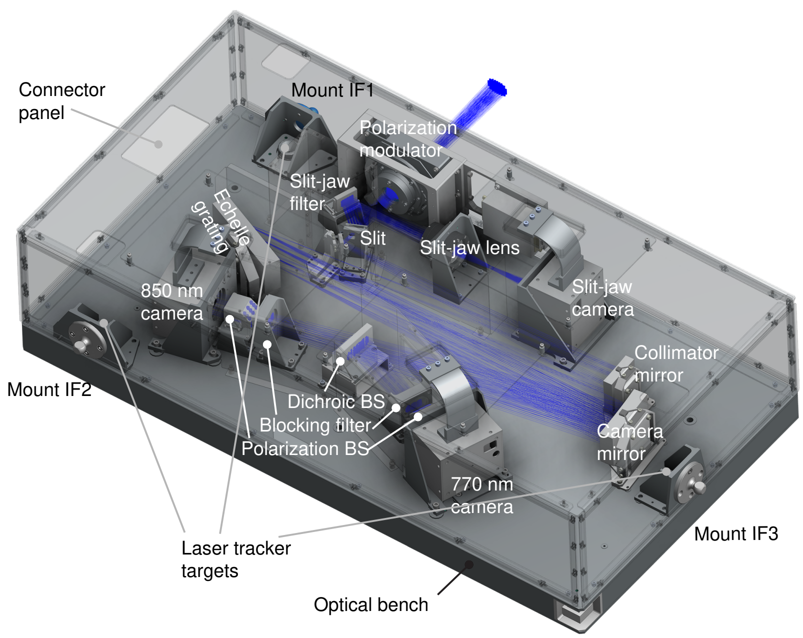

Figure 5. Opto-mechanical layout of SCIP. The blue lines show optical rays, where we use a diverging beam with F/11 in the dispersion direction by considering diffraction after the slit. The envelope size is $945 \times 500 \times 350$ mm^3.

two spherical mirrors M5 and M6 feeds light into SUSI, TuMag, and CWS by dichroic beam splitters. M6 is used as a tip-tilt mirror for correlation tracking driven by the CWS. The second Offner system consisting of two spherical mirrors M7 and M8 with three folding mirrors (M9, M10, and M11) is used to feed the F/24.2 beam into SCIP. One of the spherical mirrors, M8, is mounted on a scan mirror mechanism (SMM) and is used for SCIP to scan an FOV perpendicular to the slit.[13]

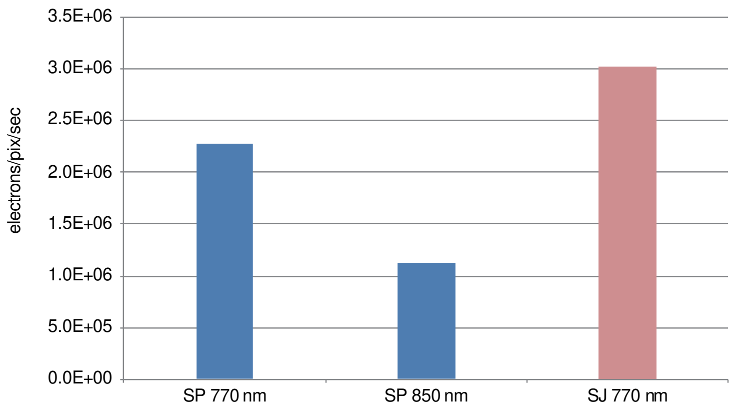

Figure 6. Number of photo-electrons per pixel and per second detected by the SP and SJ sensors based on the efficiency of the optics. The estimation was conducted for the case when the solar disk center is observed.

The spectro-polarimeter (SP) of SCIP is a long-slit spectrograph (Figure 5). At the entrance of the SCIP, a polarization modulation unit (PMU) creates a temporally modulated solar image on the slit by a rotating waveplate[14] (see Section 2.4 for details). 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 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. The dichroic beam splitter has a wedge to suppress the astigmatism aberration in the 850 nm channel. Each channel has a narrow bandpass filter with a dielectric multi-layer coating for isolating the observing wavelength range. A polarization beam splitter (PBS) is located in front of a camera to split the s- and p-polarized lights and make images of both the polarization states onto a single camera at each channel (Figure 1). A slit-jaw (SJ) optics system is used to observe a 2D image around the slit, and consists of a reflective filter and a doublet lens unit. The reflective filter transmits unnecessary passband lights to a light trap behind the filter. Details of the optical and mechanical designs are described by Tsuzuki et al.[15] and Uraguchi et al.,[16] respectively.

We use three cameras (850 nm, 770 nm, and SJ) with the same design in the SCIP. Each camera employs a back-side illuminated CMOS sensor GSENSE400BSI provided by Gpixel Inc., and its electronics are newly developed for Sunrise III. The sensor has a 2048 pixel $\times$ 2048 pixel format with an 11 μm pixel size. The quantum efficiency is as high as 60% and 40% at 770 nm and 850 nm, respectively. We can achieve a good sensitivity as well as a high-speed read-out, 48 frames per second, required for precise polarization measurements.

The polarimetric measurement is carried out by the combination of a rotating waveplate located at the optical entrance of the SCIP and the PBSs located in front of the cameras. It is important to have a good polarization modulation for both the linear and circular polarizations in the two wavelength bands of 770 nm and 850 nm. The retardation of the waveplate is designed to be $127\pm3^\circ$. We designed the SCIP waveplate consisting of quartz and sapphire birefringent plates. The design provides retardation with a small wavelength and temperature dependence.[14] Because there are multiple folding mirrors in ISLiD, we need not only an instrument-level, i.e., SCIP only, polarization calibration but also end-to-end polarization calibration combined with a telescope and ISLiD after we mount the SCIP onto the PFI structure. The polarization calibration is going to be achieved by feeding a beam of light having known polarization states. The same approach was adopted in Sunrise IMaX[6] in the previous flights.

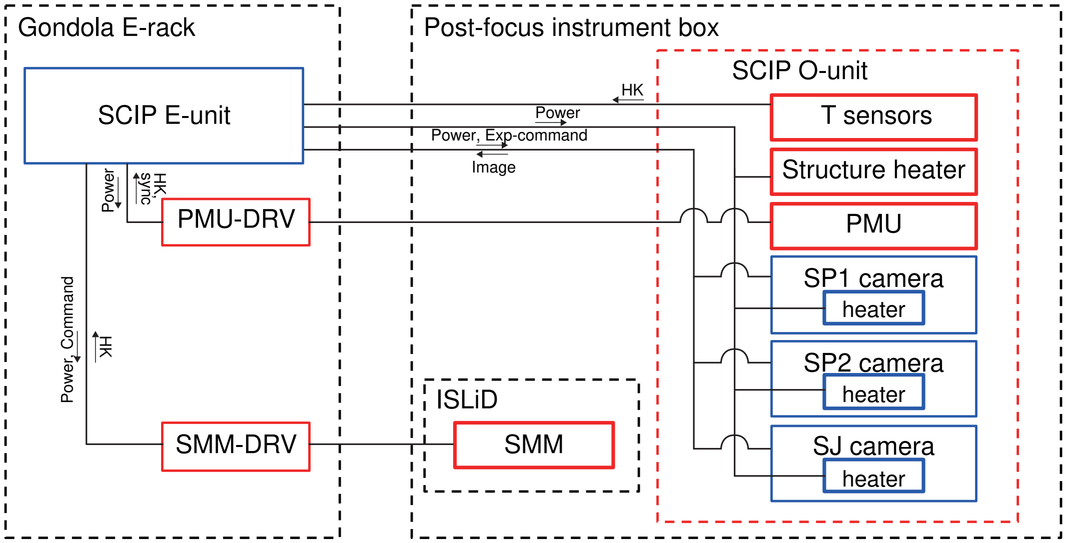

Figure 7. Block diagram of the SCIP electronics for observation control. The control electronics of the SCIP E-unit are located on the Gondola E-rack. The driver electronics boxes for PMU and SMM are also located on the E-rack and controlled by the E-unit. Exposures of the three cameras are triggered by synchronization signals generated by the PMU, and the E-unit sends an exposure command to the cameras. The E-unit receives images taken by the three cameras and applies onboard image processing. The E-unit also sends a command to the SMM to move the scan mirror. Structure and camera heaters are placed inside the O-unit for stabilizing the temperature environment of the O-unit. The red boxes indicate components developed by the Japanese team, whereas the blue boxes indicate components developed by the Spanish team.

2.3 Photon budget

To achieve a high polarization sensitivity, we have to collect sufficient photons within the interval of time that we want to resolve. When considering (1) the reflectances and transmittances of all the optical components including the telescope, ISLiD, and SCIP, and (2) the quantum efficiency of the image sensor, the total efficiency of the system is 2.4% and 4.8% at 850 and 770 nm, respectively. The worse efficiency at 850 nm is due to the mirrors in the telescope and the first half of ISLiD having an aluminum coating on the reflecting surfaces to observe the UV wavelengths. The quantum efficiencies of the image sensor also contribute to the difference. The number of detected electrons is estimated to be 1.1×10^6 e/pixel·s and 2.3×10^6 e/pixel·s at 850 and 770 nm, respectively, in a solar disk center observation based on the solar flux and the spatial and spectral samplings (Figure 6). Because the full-well capacity of the image sensor is $\sim 9 \times 10^4$ e, each exposure should be shorter than 32 ms. To achieve a polarimetric sensitivity of 0.03%, we need the accumulation of images for 10 s by considering the polarization efficiency. The SJ optics have a band-pass filter centered at 770.5 nm with an FWHM of 1 nm in front of the lens unit. A neutral density (ND) filter is also inserted in the lens unit to adjust the throughput of the SJ channel.

2.4 Observation control

For accurate polarization measurements, it is important to achieve a good synchronization between the rotating phase of the polarization modulator and exposure by the cameras. The rotating mechanism is an upgrade from that used in the Chromospheric Lyman-Alpha Spectro-Polarimeter (CLASP) sounding rocket experiment.[17] The rotation speed was 4.8 s/rot in CLASP, but it is changed to 0.512 s/rot in SCIP, which helps to reduce erroneous polarizations coming from the attitude jitter as well as the temporal evolution of the solar features. Details of the polarization modulator are described by Kubo et al.[14] The PMU sends synchronization signals 16 times in one rotation, that is, every 32 ms, to the control electronics SCIP E-unit (Figure 7). Exposures of the three cameras are triggered by the synchronization signals, and the E-unit sends an exposure command to the cameras. The E-unit receives images taken by the three cameras and applies onboard image processing, including polarization demodulation, in which accumulation and subtraction of the images are achieved depending on the rotating phase of the waveplate. The scanning function of the SMM must also be synchronized with the PMU and camera exposures to avoid image motion during exposure. In the highest cadence observation, the SCIP takes images every 64 ms with scanning. To achieve this rapid scanning observation, the SMM is designed to complete a single step within 32 ms. The E-unit sends a scan command to the SMM, whose timing is also controlled with respect to the synchronization signals from the PMU. Details of the scan mirror mechanism are described by Oba et al.[13]

Structure and camera heaters are placed inside the O-unit for stabilizing the temperature environment of the optics and the cameras during the flight. The E-unit takes care of the heater control as well as the collection of temperature information from temperature sensors distributed in the O-unit.

3. SUMMARY

The SCIP is a new instrument developed for the third flight of the SUNRISE balloon-borne solar telescope. Owing to the 1 m aperture telescope and the greatly reduced influence of atmospheric seeing at the balloon altitude, SCIP will be able to achieve a good spatial and spectral resolution of 0.2" and 2×10^5, respectively, over the broad wavelength range in the near-infrared, including many important spectral lines with a polarimetric sensitivity of 0.03 % (1σ). The SCIP instrument is now under integration at the NAOJ and is going to be sent to the MPS in early 2021 for integration into the PFI structure and, as part of the PFI, to the telescope.

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REFERENCES

[1] Lites, B. W., Akin, D. L., Card, G., Cruz, T., Duncan, D. W., Edwards, C. G., Elmore, D. F., Hoffmann, C., Katsukawa, Y., Katz, N., Kubo, M., Ichimoto, K., Shimizu, T., Shine, R. A., Streander, K. V., Suematsu, A., Tarbell, T. D., Title, A. M., and Tsuneta, S., "The Hinode Spectro-Polarimeter," *Solar Physics* **283**, 579–599 (2013).

[2] Tsuneta, S., Ichimoto, K., Katsukawa, Y., Nagata, S., Otsubo, M., Shimizu, T., Suematsu, Y., Nakagiri, M., Noguchi, M., Tarbell, T., Title, A., Shine, R., Rosenberg, W., Hoffmann, C., Jurcevich, B., Kushner, G., Levay, M., Lites, B., Elmore, D., Matsushita, T., Kawaguchi, N., Saito, H., Mikami, I., Hill, L. D., and Owens, J. K., "The Solar Optical Telescope for the Hinode Mission: An Overview," *Solar Physics* **249**, 167–196 (2008).

[3] Gandorfer, A. M., Solanki, S. K., Barthol, P., Lites, B. W., Martínez Pillet, V., Schmidt, W., Soltau, D., and Title, A. M., "SUNRISE: high resolution UV/VIS observations of the Sun from the stratosphere," *Proc. SPIE* **6267**, 62670S (2006).

[4] Solanki, S. K., Barthol, P., Danilovic, S., Feller, A., Gandorfer, A., Hirzberger, J., Riethmüller, T. L., Schüssler, M., Bonet, J. A., Martínez Pillet, V., del Toro Iniesta, J. C., Domingo, V., Palacios, J., Knölker, M., Bello González, N., Berkefeld, T., Franz, M., Schmidt, W., and Title, A. M., "SUNRISE: Instrument, Mission, Data, and First Results," *Astrophysical Journal Letters* **723**, L127–L133 (2010).

[5] Barthol, P., Gandorfer, A., Solanki, S. K., Schüssler, M., Chares, B., Curdt, W., Deutsch, W., Feller, A., Germerott, D., Grauf, B., Heerlein, K., Hirzberger, J., Kolleck, M., Meller, R., Müller, R., Riethmüller, T. L., Tomasch, G., Knölker, M., Lites, B. W., Card, G., Elmore, D., Fox, J., Lecinski, A., Nelson, P., Summers, R., Watt, A., Martínez Pillet, V., Bonet, J. A., Schmidt, W., Berkefeld, T., Title, A. M., Domingo, V., Gasent Blesa, J. L., Del Toro Iniesta, J. C., López Jiménez, A., Álvarez-Herrero, A., Sabau-Graziati, L., Widani, C., Haberler, P., Härtel, K., Kampf, D., Levin, T., Pérez Grande, I., Sanz-Andrés, A., and Schmidt, E., "The Sunrise Mission," *Solar Physics* **268**, 1–34 (2011).

[6] Martínez Pillet, V., Del Toro Iniesta, J. C., Álvarez-Herrero, A., Domingo, V., Bonet, J. A., González Fernández, L., López Jiménez, A., Pastor, C., Gasent Blesa, J. L., Mellado, P., Piqueras, J., Aparicio, B., Balaguer, M., Ballesteros, E., Belenguer, T., Bellot Rubio, L. R., Berkefeld, T., Collados, M., Deutsch, W., Feller, A., Girela, F., Grauf, B., Heredero, R. L., Herranz, M., Jerónimo, J. M., Laguna, H., Meller, R., Menéndez, M., Morales, R., Orozco Suárez, D., Ramos, G., Reina, M., Ramos, J. L., Rodríguez, P., Sánchez, A., Uribe-Patarroyo, N., Barthol, P., Gandorfer, A., Knoelker, M., Schmidt, W., Solanki, S. K., and Vargas Domínguez, S., "The Imaging Magnetograph eXperiment (IMaX) for the Sunrise Balloon-Borne Solar Observatory," *Solar Physics* **268**, 57–102 (2011).

[7] Katsukawa, Y., "Penumbral Microjets in Sunspot Chromospheres: Evidence of Magnetic Reconnection," in [*First Ten Years of Hinode Solar On-Orbit Observatory*], Shimizu, T., Imada, S., and Kubo, M., eds., *Astrophysics and Space Science Library* **449**, 201 (2018).

[8] Gandorfer, A., Grauf, B., Barthol, P., Riethmüller, T. L., Solanki, S. K., Chares, B., Deutsch, W., Ebert, S., Feller, A., Germerott, D., Heerlein, K., Heinrichs, J., Hirche, D., Hirzberger, J., Kolleck, M., Meller, R., Müller, R., Schäfer, R., Tomasch, G., Knölker, M., Martínez Pillet, V., Bonet, J. A., Schmidt, W., Berkefeld, T., Feger, B., Heidecke, F., Soltau, D., Tischenberg, A., Fischer, A., Title, A., Anwand, H., and Schmidt, E., "The Filter Imager SuFI and the Image Stabilization and Light Distribution System ISLiD of the Sunrise Balloon-Borne Observatory: Instrument Description," *Solar Physics* **268**, 35–55 (2011).

[9] Berkefeld, T., Schmidt, W., Soltau, D., Bell, A., Doerr, H. P., Feger, B., Friedlein, R., Gerber, K., Heidecke, F., Kentischer, T., v. D. Lühe, O., Sigwarth, M., Wälde, E., Barthol, P., Deutsch, W., Gandorfer, A., Germerott, D., Grauf, B., Meller, R., Álvarez-Herrero, A., Knölker, M., Martínez Pillet, V., Solanki, S. K., and Title, A. M., "The Wave-Front Correction System for the Sunrise Balloon-Borne Solar Observatory," *Solar Physics* **268**, 103–123 (2011).

[10] Quintero Noda, C., Shimizu, T., Katsukawa, Y., de la Cruz Rodríguez, J., Carlsson, M., Anan, T., Oba, T., Ichimoto, K., and Suematsu, Y., "Chromospheric polarimetry through multiline observations of the 850 nm spectral region," *Monthly Notices of the Royal Astronomical Society* **464**, 14534–4543 (2017).

[11] Quintero Noda, C., Uitenbroek, H., Katsukawa, Y., Shimizu, T., Oba, T., Carlsson, M., Orozco Suárez, D., Ruiz Cobo, B., Kubo, M., Anan, T., Ichimoto, K., and Suematsu, Y., "Solar polarimetry through the K i lines at 770 nm," *Monthly Notices of the Royal Astronomical Society* **470**, 1453–1461 (2017).

[12] Quintero Noda, C., Villanueva, G. L., Katsukawa, Y., Solanki, S. K., Orozco Suárez, D., Ruiz Cobo, B., Shimizu, T., Oba, T., Kubo, M., Anan, T., Ichimoto, K., and Suematsu, Y., "Solar polarimetry in the K I D_2 line : A novel possibility for a stratospheric balloon," *Astronomy and Astrophysics* **610**, A79 (2018).

[13] Oba, T., Shimizu, T., Katsukawa, Y., Kubo, M., Uraguchi, F., Tsuzuki, T., Tamura, T., Shinoda, K., Kodeki, K., Fukushima, K., Solanki, S. K., and del Toro Iniesta, J. C., "SUNRISE Chromospheric Infrared spectroPolarimter (SCIP) for SUNRISE-3: Scan Mirror Mechanism," in [*Ground-based and Airborne Instrumentation for Astronomy VIII*], *Proc. SPIE* (2020).

[14] Kubo, M., Shimizu, T., Katsukawa, Y., Kawabata, Y., Anan, T., Ichimoto, K., Shinoda, K., Tamura, T., Nodomi, Y., Nakayama, S., Yamada, T., Tajima, T., Nakata, S., Nakajima, Y., Okutani, K., Feller, A., and del Toro Iniesta, J. C., "SUNRISE Chromospheric Infrared spectroPolarimeter (SCIP) for Sunrise III: Polarization Modulation Unit," in [*Ground-based and Airborne Instrumentation for Astronomy VIII*], *Proc. SPIE* (2020).

[15] Tsuzuki, T., Katsukawa, Y., Uraguchi, F., Hara, H., Kubo, M., Nodomi, Y., Suematsu, Y., Kawabata, Y., Shimizu, T., Gandorfer, A., Feller, A., Grauf, B., Solanki, S. K., and del Toro Iniesta, J. C., "SUNRISE Chromospheric Infrared spectroPolarimeter (SCIP) for Sunrise III: Optical Design and Performance," in [*Ground-based and Airborne Instrumentation for Astronomy VIII*], *Proc. SPIE* (2020).

[16] Uraguchi, F., Tsuzuki, T., Katsukawa, Y., Hara, H., Iwamura, S., Kubo, M., Nodomi, Y., Suematsu, Y., Kawabata, Y., Shimizu, T., Gandorfer, A., and del Toro Iniesta, J. C., "SUNRISE Chromospheric Infrared spectroPolarimeter (SCIP) for Sunrise III: Opto-mechanical analysis and design," in [*Ground-based and Airborne Instrumentation for Astronomy VIII*], *Proc. SPIE* (2020).

[17] Ishikawa, S., Shimizu, T., Kano, R., Bando, T., Ishikawa, R., Giono, G., Tsuneta, S., Nakayama, S., and Tajima, T., "Development of a Precise Polarization Modulator for UV Spectropolarimetry," *Solar Physics* **290**, 3081–3088 (2015).