Polarimetric calibration of the Sunrise UV Spectropolarimeter and Imager

F.A. Iglesias[1,2,3], A. Feller[4], A.Gandorfer[4], A. Lagg[4], T.L. Riethmüller[4], S.K. Solanki[4], Y. Katsukawa[5], M. Kubo[5], G. Zucarelli[2], M. Sanchez[2] & the Sunrise team

[1] *Consejo Nacional de Investigaciones Científicas y Técnicas, Argentina*
[2] *Grupo de Estudios en Heliofísica de Mendoza, Facultad de Ingeniería, UM, Argentina*
[3] *Facultad Regional Mendoza, UTN, Argentina*
[4] *MPI für Sonnensystemforschung, Alemania*
[5] *National Astronomical Observatory of Japan, National Institutes of Natural Sciences, Japón*

Contact / franciscoaiglesias@gmail.com

Resumen / Sunrise es un observatorio óptico montado en un globo estratosférico, dedicado al estudio de campos magnéticos en la atmósfera solar con muy alta resolución. El tercer vuelo de Sunrise incluye al *Sunrise UV Spectropolarimeter and Imager* (SUSI), que opera en el rango espectral de 313-439 nm, y cubre miles de líneas espectrales que no son accesibles desde tierra. SUSI no incluye una unidad de calibración polarimétrica a bordo. En este trabajo, reportamos acerca del estado de desarrollo de SUSI y los resultados preliminares de su calibración.

Abstract / Sunrise is an optical observatory mounted in a stratospheric balloon, developed to study magnetic fields in the solar atmosphere with very high resolution. In its third flight, Sunrise carry the Sunrise UV Spectropolarimeter and Imager (SUSI), that operates in the 313-430 nm range, covering thousands of spectral lines not accessible from the ground and thus largely unexplored. SUSI does not include a polarimetric calibration unit on board. We report about the development status of SUSI and the preliminary results of its calibration.

Keywords / Sun: magnetic fields — instrumentation: polarimeters — instrumentation: high angular resolution

1. The Sunrise mission

Sunrise is a balloon-borne, stratospheric ($\approx$ 37 km) solar observatory fed by a 1m Gregory-type reflector telescope, developed by a consortium led by The Max Planck Institute for Solar System research (MPS). The combination of large aperture, unique observing conditions above 99 % of the Earth's atmosphere and state-of-the-art instrumentation, have been essential for the great success of the first two flights in 2009 (Barthol et al., 2011; Solanki et al., 2010) and 2013 (Solanki et al., 2017), as reported in more than 100 refereed publications. The third science flight of Sunrise, planned for June 2022, includes a new gondola and completely renewed science payload. Three imaging vector magnetometers will cover the spectral range from the IR to the UV. These are SCIP (765-855 nm), TuMAg (517-525 nm) and SUSI (309-417 nm), and will allow studying small-scale, magnetohydrodynamic solar phenomena at different heights in the atmosphere simultaneously, from the low photosphere to the high chromosphere.

2. The UV spectropolarimeter SUSI

The polarimetrically unexplored UV region aimed by SUSI (Feller et al., 2020) is particularly relevant for Sunrise III main science goals. The spectral lines present in this range can be used to probe weak magnetic fields at different heights of the chromosphere, using both the Zeeman and Hanle effects. Moreover, the high density of spectral lines can be exploited to increase S/N ratio via many-line inversions (Riethmüller & Solanki, 2019). SUSI is a slit spectrograph based on a diffraction grating that includes a dual-beam, narrow-band channel for polarimetry and a slit-jaw channel with phase diversity for wide-band, context imaging. The main SUSI observing parameters are listed in Table 1. Extra details, including the instrument optical layout can be consulted in Solanki et al. (2017). Reliability is an important aspect of a stratospheric balloon mission. Thus, SUSI design was based on proven instrumental concepts, leaving innovative aspects for post-facto data processing such as the implementation of novel spectra image restoration (van Noort, 2017) and many-line inversions.

3. Polarimetric calibration of SUSI

An accurate calibration of the SUSI polarimetric response is of paramount importance to reach the desired magnetic sensitivity. Since there is no polarization state generator (PSG) onboard, SUSI polarimetric calibration must be done on the ground before flight, see Fig. 1. To assist in the development of the calibration reduction routines before SUSI integration, and to assess their accuracy in getting the instrument response under different instrumental artifacts, we developed a numeric polarimetric model of SUSI (SUSIM). SUSIM

Table 1: Main specifications of the SUSI spectropolarimeter.The specifications for Full-Stokes and Spectroscopic modes are the same unless other value is specified.

Property	Full-Stokes Mode — Spectroscopic Mode
Stokes parameters	I,Q,U,V — I
Field of View (slit ; max. scanning)	60 arcsec ; 70 arcsec
Spatial sampling ; Slit width	0.032 arcsec pixel^{-1} ; 0.060 arcsec
Prefilter ranges (RA1 ; RA2 ; RA3)[1]	309 - 338 nm ; 346 - 370 nm ; 385 - 417 nm
Spectral range on cameras[2] ; Spectral sampling[2]	19.0 - 31.5 Å ; 9.67 - 15.99 mÅ pixel^{-1}
Camera framerate	46.9 fps
Max. cadence[3]	256 ms — 21.3 ms
Slit scanning speed	0.01 - 1.46 arcsec s^{-1}
Expected sensitivity per pixel, after 1s integration[2,4]	0.7 - 1.9 % — 0.3 - 0.9 %

[1]For transmission larger than 0.5×peak transm. [2]Depends on wavelength
[3]One modulation cycle requires 12 frames. [4]Average for Q, U, V at continuum and solar disc center.

can reproduce field-dependent properties of the SUSI response due to many effects, including variable electro-optical properties of the polarization modulator, mirrors, diffraction grating, imaging sensors, etc. The calibration process involves generating 40 partially-known polarization states with the PSG. The measured intensities are used to fit, per pixel, the 4x12 modulation matrix that models the polarimetric response of SUSI, the normalized input intensity during the calibration process, and two parameters (retardance and position angle error) of a required PSG model. The fit merit function is the root-mean-squared difference between the PSG output and measured Stokes parameters, see Fig. 2. The PSG can be placed at different locations in the beam path to derive and verify the polarimetric response of different subsystems. We calibrated a) SUSI standalone, b) SUSI plus the Image Stabilization and Light Distribution unit (ISLiD), located at the second focal point (see Fig. 1), and c) the full optical path, by placing the PSG at the first focal point. We denote these as Standalone, F2 and F1 calibrations, respectively. The complete instrument response is obtained from the F1 calibration plus a model-based correction for the main mirror polarimetric effects. However, F2 calibrations plus instrument models are used for some wavelengths were no suitable artificial light source was available.

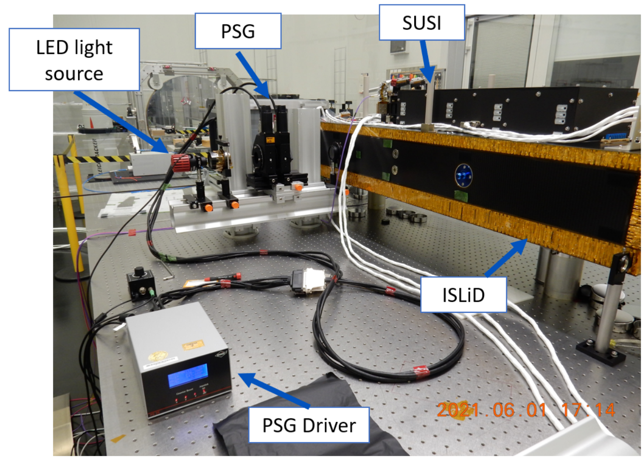

Figure 1: SUSI during a polarimetric calibration at MPS facilities.

4. Preliminary Results

- SUSI standalone modulation matrix presents vertical and oblique optical interference fringes, the former most likely produced by the slit plate. Since the intrinsic variation of the matrix elements across the sensor is smoother than the fringes, we plan to Fourier filter the latter.
- The spectral average of the F2 modulation matrix is shown in Fig. 4. By comparing standalone and F2 matrices, it is evident that ISLiD introduces $V \Longleftrightarrow U$ crosstalk that is strongly wavelength dependent due to the dispersion of the ellipsometric parameters of the dichroic beam splitter used at ISLiD exit port. Thus, we are required to calibrate each of the science target spectral regions.
- The measured polarimetric efficiencies are the expected ones for US560 camera which is in the refracted beam of the beam splitter cube used as analyzer, see Fig. 3. However, the efficiencies are lower for the US550 camera in the reflected beam of the cube, deriving in slightly higher noise in the images.
- The accuracy reached in standalone and F2 calibrations satisfies the requirements. However, the F1 calibrations performed so far are not as accurate, presenting undesired spatial fluctuations. This is may be due to strong fluctuations of the input calibration intensities that are not be properly fit. We are currently working in this issue.

References

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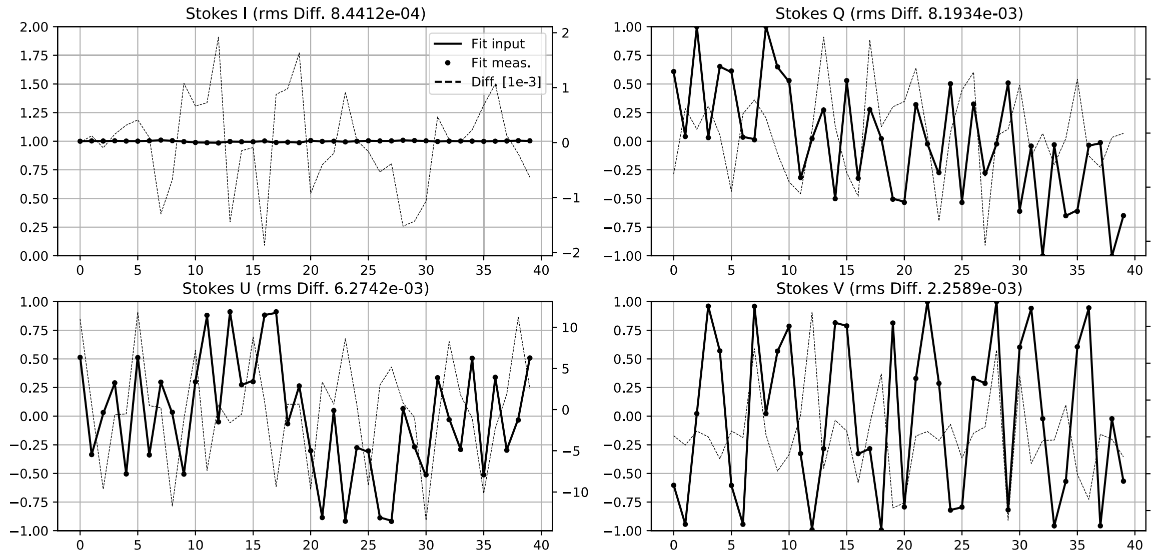

Figure 2: Stokes errors for the 40 inputs of a standalone calibration at 327.8 nm. We show the PSG output (*continuous line*), measured Stokes parameters (*dots*), and their difference (*dotted line*, ref. to the right scale in 10^{-3}).

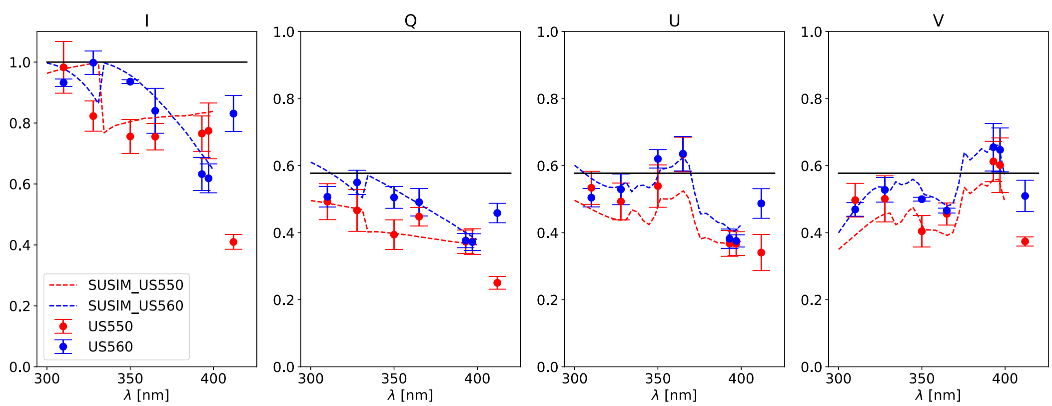

Figure 3: Measured (*dots*), modelled (*dashed lines*) and ideally balanced (*black lines*) polarimetric efficiencies at F2 vs. wavelength for each camera, see the legend. From left to right we show I, Q, U, and V efficiencies.

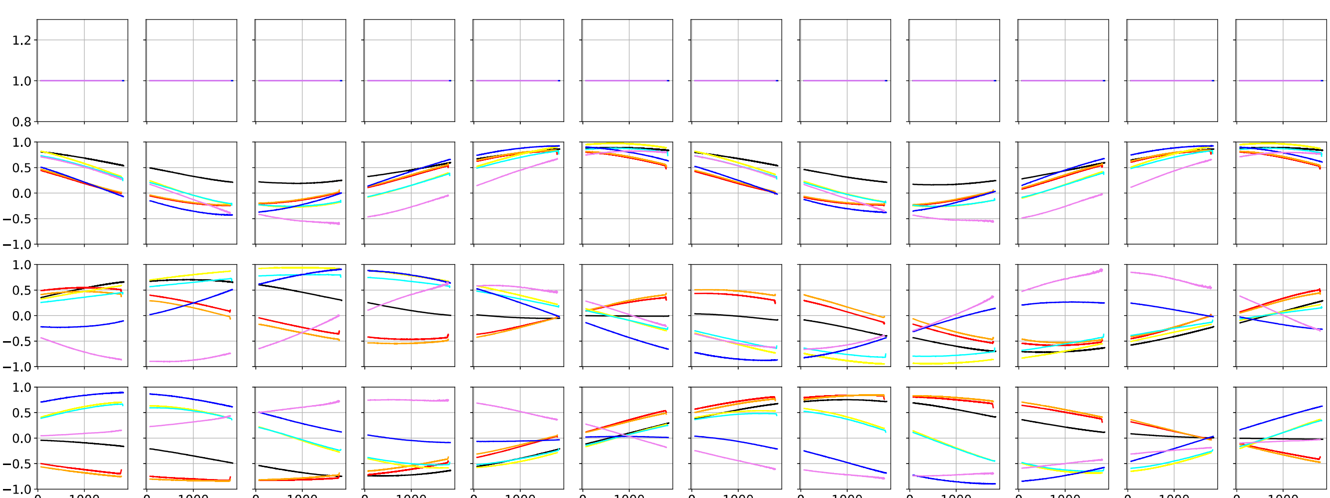

Figure 4: Spectral average of the normalized F2 modulation matrix at the following central wavelengths, all expressed in nm: 412 (*black*), 397 (*red*), 393 (*orange*), 365 (*yellow*), 350 (*cyan*), 327.8 (*blue*), 310 (*violet*). We show the transposed matrix with each row normalized to its first element, not presented here because they are all unity.