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VII Workshop on Robotic Autonomous Observatories (October 16-20, 2023)
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TOWARDS A FULLY ROBOTIC SOLAR OBSERVATORY AT THE UNIVERSITY OF GÖTTINGEN

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RESUMEN

El Instituto de Astrofísica y Geofísica de Gotinga opera un observatorio solar que permite observaciones del Sol integradas y espacialmente resueltas con una resolución espectral muy alta. La instalación consta de un siderostato de 50 cm en el techo del edificio de la Facultad que alimenta un telescopio vertical de vacío y también un espectrógrafo de transformada de Fourier (ETF) con un poder de resolución > 700.000 a 600 nm. Al implementar y ampliar el sistema de control del telescopio (pyobs), podemos controlar de forma remota el siderostato y el ETF para adquirir y guiar con precisión cualquier objetivo en el disco solar mientras realizamos observaciones espectrales. Actualmente, estamos poniendo en marcha un modo de observación totalmente robótico que nos permitirá explotar aún más las capacidades de este observatorio. En particular, el modo robótico nos permitirá realizar observaciones de alta resolución de fenómenos variables en el tiempo, como manchas solares y fáculas solares.

ABSTRACT

The Institute for Astrophysics and Geophysics in Göttingen operates a solar observatory that allows for integrated and spatially resolved observations of the Sun with very high spectral resolution. The setup consists of a 50 cm siderostat on the roof of the faculty building that feeds a vacuum vertical telescope and, finally, a Fourier Transform Spectrograph (FTS) with a resolving power of $> 700,000$ at 600 nm. By implementing and extending the telescope control system `pyobs` we are able to remotely control the siderostat and FTS to accurately acquire and guide on any target on the solar disk while performing spectral observations. Currently, we are commissioning a fully robotic observation mode that will allow us to exploit the capabilities of this observatory even further. In particular, the robotic mode will enable us to make high-resolution observations of time-dependent phenomena such as sunspots and solar faculae.

Key Words: Sun — Spectroscopy — Telescopes

1. INSTRUMENTAL SETUP

The solar telescope at the Institute for Astrophysics and Geophysics in Göttingen consists of two components: a siderostat and a vertical vacuum telescope (VTT). The siderostat is installed on top of the 5th floor of the physics building and is shown in Fig. 1. It consists of two rotating and tilting mirrors that feed light to the VTT below. The vacuum tube of the VTT is built directly into the building, so that its primary mirror is located below the 3rd floor. This telescope has been in operation since September 2008 (Schäfer et al. 2020).

From the VTT, the light enters our optical setup, which is located on the fourth floor of the building and shown in Fig. 2. The light exits the VTT through a collimator onto a parabolic mirror, which reflects the light onto our fiber pickup. The fiber pickup is a circular steel disc with a 2.5 mm hole in the center. Behind the hole is an FC/PC fiber connector such that the fiber head is parallel to the image plane. The fiber finally leads to a Fourier Transform Spectrograph, which was described by Schäfer et al. (2020) to take spectra with a resolution of $R > 7 \cdot 10^5$ at 600 nm. The light that is reflected by the steel disk is again focused by another parabolic mirror and a collimator. The light is then filtered using a neutral-density filter with an optical density of 5. Using a focus lens followed by a flat mirror, the light hits the CMOS detector of our camera. The light collected by this camera is used for acquisition and guiding.

2. SCIENCE CASES

The two science cases that are presented here both consider the Sun as a star. This means that we do not try to learn specifics about the Sun itself, but use the Sun as a very convenient test case and relate our findings to other stars. In particular,

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Fig. 1. Siderostat on top of the roof of the physics building in Göttingen. M1 on the right is tracking the target and M2 on the left is feeding the light into the vertical vacuum telescope.

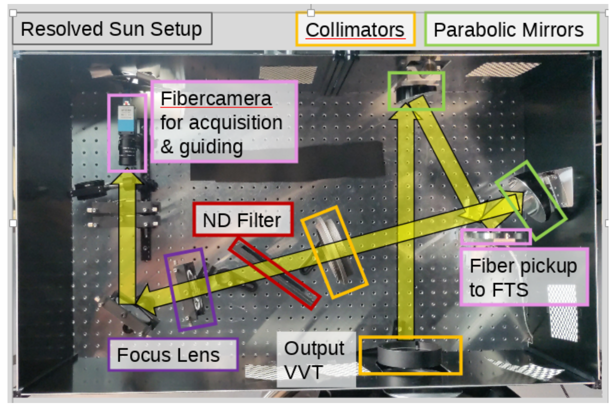

Fig. 2. Resolved sun setup. The path of the light exiting the vertical vacuum telescope to the fiber pickup and finally the fibercamera is shown.

the structure of the photosphere of a star can have a large impact on its spectrum. By observing the Sun with a high-resolution spectrograph, we are able to quantify the line-by-line effects of different features that are currently only observable for solar spectral data. This enables us to inform spectroscopic observations of other stars based on our findings.

2.1. *The Quiet Sun*

Non-active, quiet regions of the Sun still show granulation due to convection. Granulation induces changes to the observed spectral lines. This effect is relevant for stellar radial velocity measurements and exoplanet transit spectroscopy and has already been studied using the solar observatory in Göttingen by Ellwarth et al. (2023). In particular, they performed centre-to-limb observation of the sun to analyze how spectral line shapes and positions change due to granulation as a function of position on the solar disk. We can improve on the results by Ellwarth et al. (2023) by robotizing our solar observatory to enable more efficient raster observations of the solar disk.

2.2. *The Active Sun*

Observing the sun reveals many active regions such as sunspots and solar faculae. In particular, sunspots affect the wavelength and shape of spectral lines and can add such variation as to obscure exoplanets altogether. Regarding solar faculae there is currently little to no time resolved data to study any potential effect on stellar spectra. Sets of data on both these types of features from such a high resolution spectrograph would be a large step in addressing the current international effort to separate stellar activity from exoplant signals. To observe these features, we employ robotics to allow for efficient and importantly time-dependent observations.

3. OBSERVATION CONTROL SYSTEM

The observation control system (OCS) we use is the Python-based and open source `pyobs`[2] by Husser et al. (2022). Out of the box, it supports many popular cameras and includes common functionality like focusing, sky-flatfielding, acquisition and guiding and pipeline calibration. `pyobs` enables remote and fully autonomous control and is fully configurable and extendable. It follows the principle of one process per block of functionality, where these blocks are called modules. It was designed for night-time observations and is run on three night-time telescopes currently. To extend `pyobs` to solar observations, we simply implemented new modules that give us the functionality we need. In the following, we will describe the modules we added and how they work.

3.1. *Sun Camera*

As described in Sec. 1 and shown in Fig. 2, we use a camera for acquisition and guiding. This camera is implemented in `pyobs` as a simple camera module called fibercamera. The sun camera is implemented as a virtual camera that forwards all calls to the fibercamera, but it adds a world coordinate system (WCS) to each image. To do so, the sun camera needs the solar position and radius on the image. To find these parameters, we employ a solar disk detection.

[2] `https://www.pyobs.org/`

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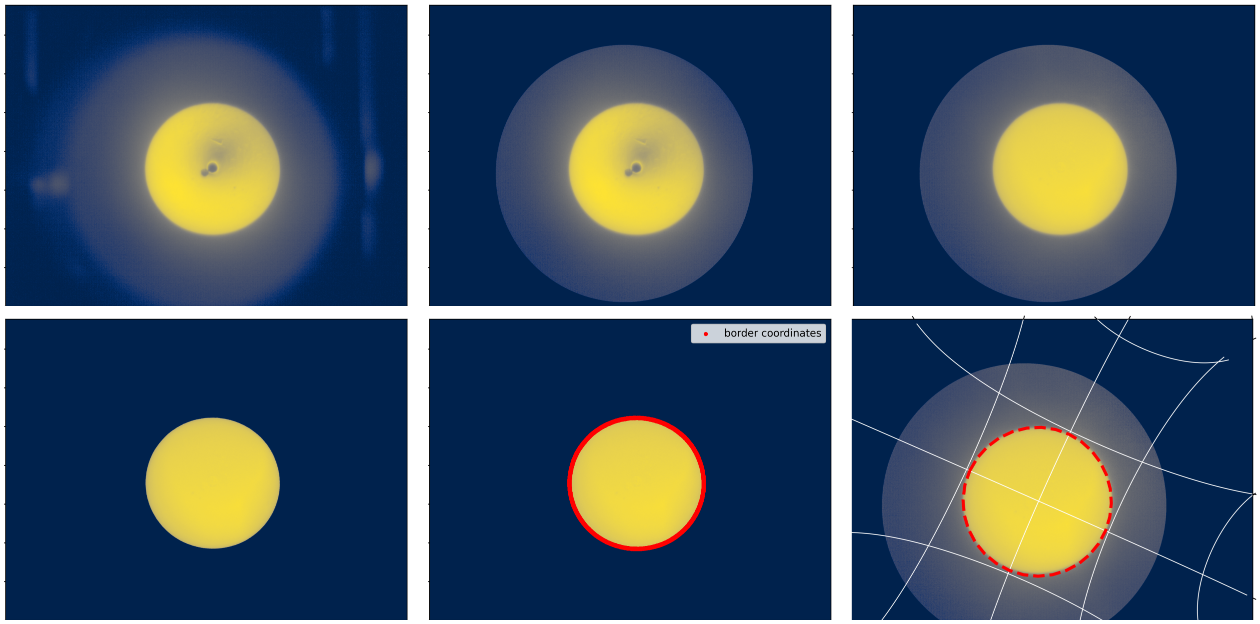

Fig. 3. Illustration of the different analysis steps for the solar disk detection, starting with the raw image from the fibercamera in the upper left panel, to the detected solar disk shown in the bottom right panel.

3.2. *Solar Disk Detection*

The aim of the solar disk detection is to derive the center and radius of the solar disk on an image taken by the fibercamera. Figure 3 illustrates the different steps of this analysis. First, we filter the background of the image that contains reflection from parts of our optical setup using a predefined mask. Then we apply a flatfield correction, which most notably causes the holes of the fiber pickup to seemingly disappear in the image.

Next, we derive a sun mask by creating a histogram of the current image, which can be seen in Fig. 4. This histogram always shows two peaks: One peak around zero that is caused by pixel that do not belong to the solar disk, and one peak offset from zero that contains the solar disk pixels. To separate these distributions, we find the minimum between them and use it as a cutoff value. Pixels with values below the cutoff value are defined to not belong to the solar disk and are filtered from the image. After that, we find the border coordinates of the solar disk pixels, which describe the outline of the sun in our image.

Due to our optical setup described in Sec. 1, the image recorded by the fibercamera contains large distortions, especially towards the edges of the image. To correct for this distortion, we use an image of a regular point grid, which is shown in Fig. 5. We detect the dots in this image using a cutoff and derive the simple imaging polynomial (SIP). By applying the SIP, we can finally fit a circle to the distortion corrected border coordinates of the solar disk pixels to derive the solar position and radius in the image.

3.3. *Solar Acquisition and Guiding*

We use a helioprojective radial coordinate frame to define the position of each point on the solar disk. This coordinate frame is defined by a radial coordinate ranging from 1 to 0 from the center of the solar disk to its limb and a counter-clockwise angular coordinate that is 0 at solar north (Thompson 2006). To acquire and guide on any target on the solar disk given this coordinate frame, we simply derive offsets between the current positions of the telescope and the target coordinates.

3.4. *Fourier Transform Spectrograph*

The Fourier Transform Spectrograph is conventionally controlled via LabVIEW using a computer that is located in the laboratory. To allow for remote control of the FTS, we added a webserver that allows us to communicate with it via `pyobs` through LabVIEW. To start and observation via `pyobs`, a setup file is needed that contains all relevant settings. The result of an observation is a FITS file that contains the spectrum, the interferogram and the field of view image from the sun camera.

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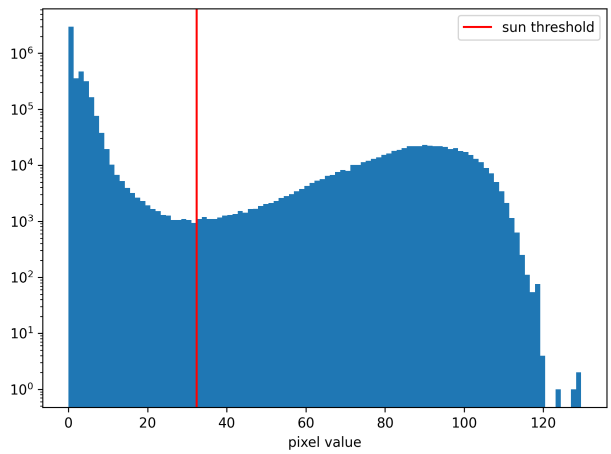

Fig. 4. Histogram of pixel values for the background filtered and flatfield corrected fibercamera image. The peak on the left corresponds to pixels that are not part of the solar disk, whereas pixels on the right belong to the solar disk. The sun threshold in red is derived as the minimum between these peaks. Pixels above the threshold are considered to be part of the solar disk.

3.5. *Robotic Solar Observatory*

We use the observation portal from Las Cumbres Observatory (LCO)[3] to manage observation requests. We modified it to allow for day-time observations and added a command-line interface to add requests and see the status of submitted requests. The robotic control of the solar observatory is implemented via the *Mastermind* module from `pyobs`. This module runs tasks that an additional scheduler module provides it with. In our case, the scheduler checks the observation portal for new requests and creates tasks based on these requests. If there is currently no active request, the scheduler will create a default task to minimize downtime. Currently, the default task is to observe the center of the Sun. Finally, the task runner executes the tasks provided by the scheduler. It has full control over the telescope, including acquisition and guiding, the cameras and the FTS.

Other remote and robotic solar observatories exist, such as the Swedish Solar Telescope (Scharmer et al. 1985), the Global Oscillation Network Group (Kennedy & GONG Team 1994) and the Laser-based Absolute Reference Spectrograph at the Vacuum Tower Telescope at the Observatorio del Teide on Tenerife (Löhner-Böttcher et al. 2017) to name just a few. However, to our knowledge, the setup presented here is one of the first ground-based robotic observatories that is capable of taking high-resolution spectra of the Sun over a large spectral range.

[3] `https://github.com/observatorycontrolsystem/observation-portal`

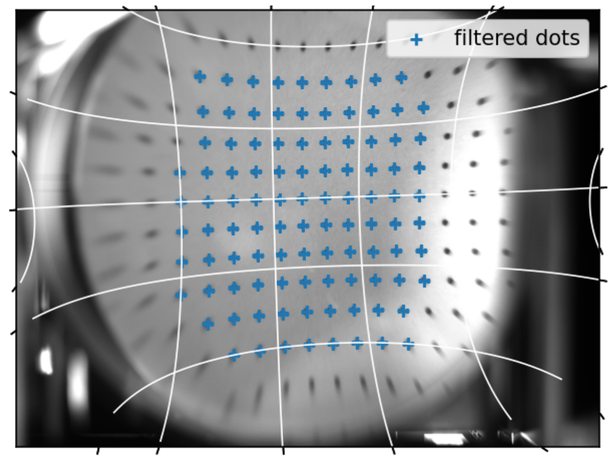

Fig. 5. Image of a regular point grid taken with the fibercamera. The distortion in the image is accounted for as shown by the white lines based on the analysis of the filtered dots.

4. SUMMARY & OUTLOOK

We presented the solar observatory at the University of Göttingen, which consists of a 50 cm siderostat, vertical vacuum telescope and a high-resolution Fourier Transform spectrograph. We demonstrated that there are multiple science cases that benefit from robotic observations with our observatory. Furthermore, we described our implementation of `pyobs` as an OCS, by extending it to support solar observations. `pyobs` allows us to remote control the observatory, and we are currently commissioning the robotic mode.

As described in Sec. 3.5, currently the default task that the scheduler creates is to observe the center of the Sun. We are working on having different observing modes for observations of the faculae, sunspots or the quiet Sun. Each mode would define and create a corresponding task. For example, in the sunspot observation mode we work out which sunspots are currently observable on the solar disk based on publicly available space weather data. The scheduler will then create default tasks to observe these sunspots. This approach still allows for the observation of specific objects by users, but minimizes downtime when there are no user defined requests.

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