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SPARC4 - Simultaneous Polarimeter And Rapid Camera in 4 bands: first light, comissioning, and preliminary results ⋆

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Abstract. SPARC4 (Simultaneous Polarimeter And Rapid Camera in 4 bands) is a new instrument for the 1.6 m telescope of the Observatório do Pico dos Dias (OPD). It is the result of a joint effort of the Instituto Nacional de Pesquisas Espaciais (INPE) and the Laboratório Nacional de Astrofísica (LNA). In 2022 November, the instrument had its first light. The science verification and commissioning runs took place throughout 2023. The collected data show that the optical quality of the images is very good. The photometric and polarimetric modes work properly and deliver data with a signal-to-noise ratio mainly limited by photon and detector noises. A first version of a dedicated Python-based data reduction pipeline is already operational. Although the instrument works as expected, minor improvements are possible. SPARC4 is available as an OPD facility starting from 2024A.

Resumo. SPARC4 (*Simultaneous Polarimeter And Rapid Camera in 4 bands*) é um novo instrumento para o telescópio de 1,6 m do Observatório do Pico dos Dias (OPD). Ele é o resultado de uma colaboração entre o Instituto Nacional de Pesquisas Espaciais (INPE) e o Laboratório Nacional de Astrofísica (LNA). Em novembro de 2022, o instrumento teve sua primeira luz e ao longo de 2023 várias missões de comissionamento e verificação de ciência ocorreram. Os dados obtidos mostram imagens de muito boa qualidade. Os modos fotométrico e polarimétrico do instrumento estão completamente operacionais e a redução de dados mostra que os resultados são limitados pelos ruídos de fóton e intrínsecos ao detetor. Foi desenvolvida uma suíte de ferramentas de redução de dados em Python, cuja primeira versão já está operacional. De modo geral, o instrumento funciona como o esperado, mas é passível de algumas melhorias. A partir de 2024A, o instrumento está sendo oferecido como uma facilidade do OPD.

Keywords. Instrumentation: photometers – Instrumentation: polarimeters

1. Introduction

Observatório do Pico dos Dias (OPD) is the main optical astronomy facility in Brazilian territory and was responsible by a large fraction of Brazilian publications in optical observational astronomy some decades ago. Presently, OPD is undergoing a modernization in terms of instruments, telescopes, and operations (Martioli et al. 2024). Due to atmospheric site conditions, the best use of the observatory is based on differential techniques. Consistent with that, the observatory has a tradition on polarimetric techniques, which have an important contribution to OPD publications thanks to the IAGPOL polarimeter (Magalhães et al. 1996). In this context, the instrument SPARC4 (Simultaneous Polarimeter And Rapid Camera in 4 bands) was conceived to modernize the instrumental capability of OPD and to respond to the interest of the observatory users. The instrument is a simultaneous four-band imager that can be used as a standard imager or a polarimeter. The SPARC4 concept is presented in Rodrigues et al. (2012). Its development is a joint effort of the Instituto Nacional de Pesquisas Espaciais (INPE) and the Laboratório Nacional de Astrofísica (LNA).

There are similar instruments around the world. Limiting ourselves to multiband polarimeters, we can cite MOPTOP (Jermak et al. 2016), DIPOL-2 (Piirola et al. 2014), and DiPol-UF (Piirola et al. 2020). However, SPARC4 is unique because it combines dual-beam polarimetry, a relatively large field of view (5.8×5.8 arcmin^2), electron-multiplying CCDs, and simultaneous acquisition in four broad bands.

In this contribution, we describe the status of the SPARC4 development. An overview of the instrument can be found in Sect. 2. Sect. 3 presents an abridged report of the SPARC4 commissioning runs, and a brief characterization of the data quality is shown in Sect. 4. Our conclusions are presented in the last section.

2. SPARC4 description

The mechanical structure of SPARC4 is shown in Fig. 1. The upper portion of the instrument is an optomechanical subsystem that allows the user to choose a sky area of 3.4×3.4 arcmin^2 within an annular sky region around the main scientific field of view (FoV) to perform the autoguiding of the telescope. The polarimetric module of SPARC4 is in the middle portion of the instrument, before the collimator. SPARC4 can operate in two main modes, photometry and polarimetry, which can be chosen by the user using the SPARC4 Graphical Unit Interface (S4GUI), so no manual intervention is necessary. In the photometric mode, all polarimetric optics is out of the beam. The SPARC4 polarimetry is based on the dual-beam technique in which a Savart prism creates two images, ordinary and extraordinary, of all sources in the image. There are two retarder options, a half-wave plate and a quarter-wave plate, which can be used to measure only linear polarization or linear and circular polarization, respectively. After the analyzer, the white beam passes through a collimator and then is divided into bands very similar to the griz

⋆ Based on observations made at the Observatório do Pico dos Dias/LNA (Brazil).

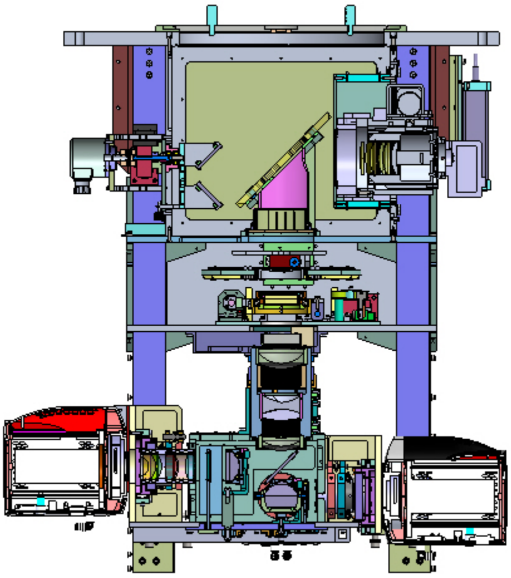

Figure 1. An illustration of the SPARC4 mechanical structure. From top to bottom, we can see the following three parts: the autoguider; the polarimetric module; and the optical box in which the white beam is spread in four colors and acquired.

bands of the Sloan Digital Sky Survey (Gunn et al. 1998) using three dichroic filters. Each beam reaches an electron-multiplying detector. The characterization and commissioning of these detectors are presented in Bernardes et al. (2018) and Schlindwein et al. (2023), respectively. The main properties of SPARC4 are shown in Tab. 1.

SPARC4 is controlled by a set of softwares. The main ones are: the SPARC4 Graphical User Interface (S4GUI); the SPARC4 instrument control system (S4ICS); and the SPARC4 acquisition control system (S4ACS, Bernardes et al. 2023). S4GUI is used to select the instrumental configuration and acquire data. A snapshot of its screen is shown in Fig. 2. S4GUI communicates with S4ICS, responsible for the control of all moving parts of the instrument, and S4ACS, a software that manages the scientific detectors. In particular, S4ACS can be used with other imagers of the observatory. S4GUI also communicates with the telescope control system (TCSPD). An example of an improvement generated by SPARC4 is the change in the communication protocol between some observatory subsystems from serial to TCP-IP. In addition, SPARC4 can be accessed and controlled remotely. S4ICS and S4ACS can be operated in a simulated mode, which is very appropriate for testing the operation of the instrument. In fact, the SPARC4 team created a TCSPD simulator, so we can simulate normal operations even when the instrument is not coupled to the telescope.

SPARC4 project also includes the development of dedicated reduction tools and a pipeline based on the Python package Astropop (Neves Campagnolo 2019). A validation of the aperture photometric routines using these tools is presented in Figueiredo et al. (2023). Campagnolo et al. (2024) describe the current status of the SPARC4 reduction software.

3. First light, comissioning, and science verification

The first light of the instrument occurred on November 04, 2022 (Fig. 3). In this run, the optics was complete, the control of the moving parts was automatized, but some observing sequences were not implemented. So we acquired most data on the photometric mode: only one polarimetric measurement was made in which we chose each waveplate position manually using the control software.

During 2023, there were several commissioning runs during which some problems were identified and corrected. For example, the use of a pulse generator to start simultaneously the acquisition in the four channels introduced an additional exposure time relative to the requested one in the first image of a sequence. So we decided to remove the pulse generator from the acquisition control loop.

In 2023, there was also a call for science verification[1]. Ten projects were submitted. The scientific cases were very diverse and were related to Solar System, interstellar medium, stellar and Galactic astronomy and extragalactic sources. Nine projects were approved, and all of them were executed during two runs in 2023 June and July. The data were delivered to the proposal PIs, and the reduction is being performed. An example of images of a rich field is presented in Fig. 4.

Currently, the instrument is fully operational and all modes work properly. As a consequence, SPARC4 is offered as an OPD facility from the call 2024A. In this call, the instrument was highly requested: 67% of the 1.6-m telescope proposals and 55% of the requested nights were for SPARC4 (private communication from the OPD Time Allocation Committee). If this demand continues in the future, it will result in a decrease in the number of instrument changes, which can positively impact the observatory operations. This is in line with the planned OPD upgrade to occur in the next few years (Martioli et al. 2024).

4. Data characterization

The optical quality is very good, consistent with the optical design. As an example, we present the point spread function of a point source in an i-band image obtained in a science verification run (Fig. 5). The image has a Full Width at Half Maximum (FWHM) of 0.62 arcsec. We have not identified any aberrations in the outer portion of the FoV. The field distortion displaces the center of the object in the border of the image by less than 5 arcsec relative to a plane projection (Schlindwein et al. 2024).

In the optimal optical setup, SPARC4 should have all four channels in par focus and par center. We could say that SPARC4 is very good, but not optimal. The image centers of the channels have a relative displacement less than 10 arcsec. Fig. 6 shows the variation of FWHM (in pixels) in the FoV for the four images acquired simultaneously. The FWHMs of the sources are in the range 0.55–1.2 arcsec, which is a very good result. However, there is a variation between the average values in the channels and a systematic variation in each image. The mechanical structure allows these adjustments, but access is very difficult and the range is limited. Moreover, we evaluate that some parts should be more tightly fixed. Therefore, we are planning an upgrade of the mechanical supports of some optical pieces.

Schlindwein et al. (2024) present the preliminary results of the photometric characterization of SPARC4, which are summarized here. The natural magnitude system of SPARC4 is very similar to the SDSS system, and the color corrections are negligible. It is possible to calibrate the magnitude level with a precision of around 0.03 mag or less, depending on the number of GAIA DR3 sources in the FoV. Some curves of the photometric error as a function of the magnitude are also shown by

[1] https://www.gov.br/lna/pt-br/composicao-1/coast/obs/opd/informacoes/2023A-chamadaSPARC4

Table 1. Main characteristics of SPARC4 and telescope.

Telescope f#	f/10
Telescope aperture	1.6 m
Final f#	f/5
Main detectors	Andor Ixon(EM)-888
Pixels	1024 × 1024
Pixel size	13 μm × 13 μm
Field of view	5.8 arcmin × 5.8 arcmin
Final platescale	0.34 arcsec/pixel
Bands	griz SDSS
Weight	≈300 kg
Modes of operation	photometry polarimetry
Time resolution	< 1 s (photometric mode - entire detector - fast readout)

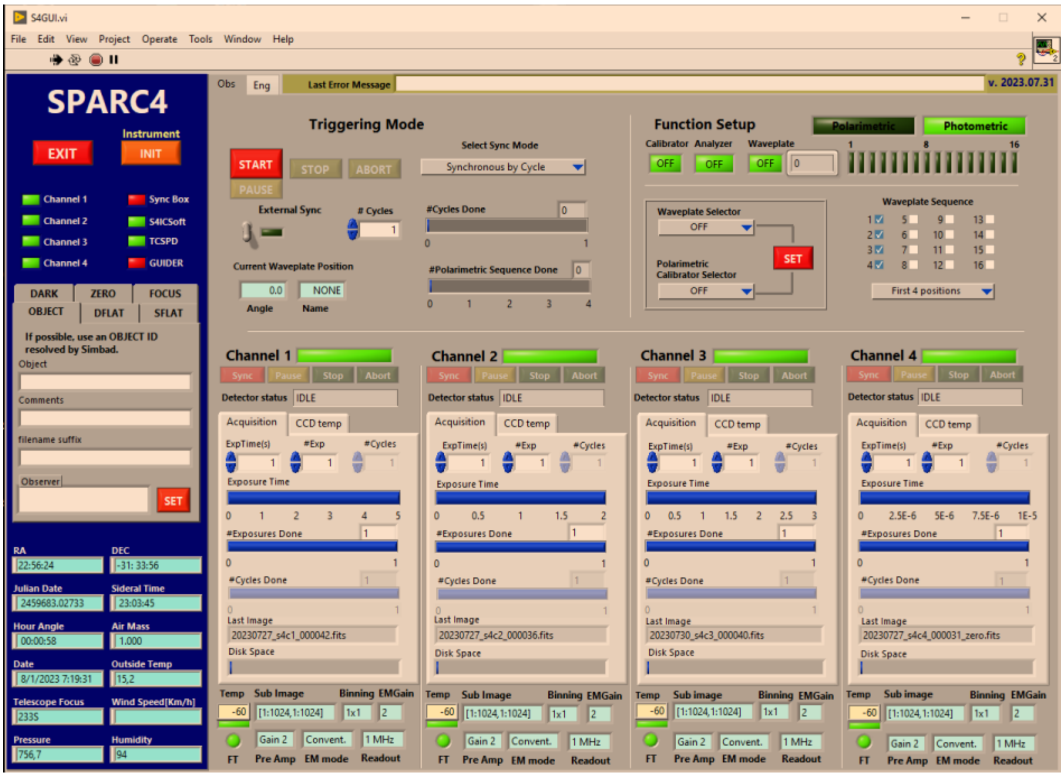

Figure 2. One of the tabs of S4GUI software. On the left on the blue background, we can see: the communication status between the instrument subsystems and between the instrument and other systems of the observatory; an area to input information to the header image; and some information from the telescope. On the gray background, we can see the portion related to the instrument configuration as the choice of the observing mode (photometric or polarimetric) and the area in which the user fills in the acquisition parameters in each channel.

Schlindwein et al. (2023). Based on these curves, an Exposure Time Calculator (ETC) was developed and is available on the OPD homepage[2].

On 15 Nov 2022, we performed the measurement of the polarimetric standard star NGC 2024 1 (?) using 16 waveplate positions separated by 22.5 deg. In each position of the waveplate, the total exposure time was 180 s. Tab. 2 shows the measured polarization, P, the observational errors, σ_P^{data}, and the errors estimated by the CCD equation, σ_P^{est}, considering the photon noise, the read-out noise, and the CCD gain. The results are presented for the standard star and for fainter field objects. Bright objects have observational errors larger than that estimated by the CCD equation probably because some error sources, such as scintillation, were not included. For faint objects, the observational errors are in excellent agreement with the CCD equation. In z band, the magnitude calibration was done using only one object, so we could estimate an error.

A more extensive characterization of SPARC4 polarimetry is presented in Mattiuci et al. (2024).

[2] `https://docs.google.com/spreadsheets/d/1RuZ94x6VTrChOgz1d7TGancq8qECzbx-pAAwqvTmRSw/edit#gid=0`

Figure 3. SPARC4 mounted in the 1.6-m telescope of OPD just before the first light on Nov 4, 2022.

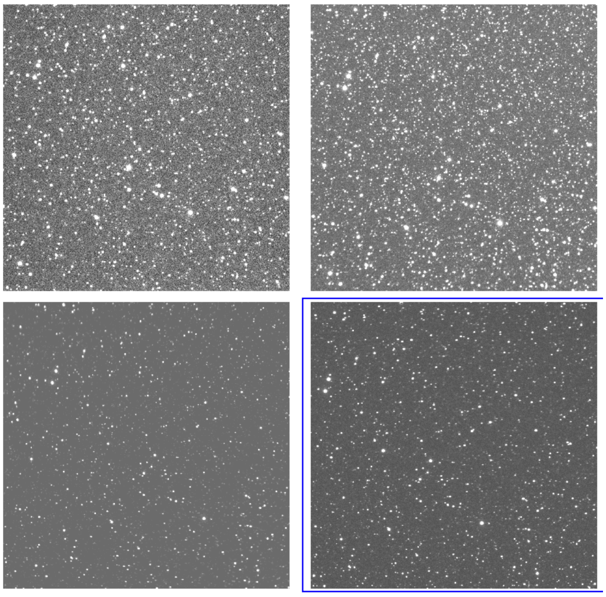

Figure 4. Images in g, r, i and z bands (from left to right, and top to bottom) of a rich field obtained during the science verification runs in 2023 June and July.

5. Conclusions

SPARC4 is a new facility instrument of OPD. It is unique because it combines dual-beam polarimetry, a relatively large field of view (5.8 × 5.8 arcmin^2), electron-multiplying frame-transfer CCDs, and simultaneous acquisition in four broad bands. SPARC4 is a versatile instrument that provides good quality images and can be used to obtain time-series of photometry or polarimetry. Therefore, it can be employed to deliver data to many scientific cases, responding to the demand of a large fraction of the OPD users. The commissioning demonstrates that it works as planned, but yet some improvement is planned for 2024A. In the present condition, SPARC4 provides high-quality data, which can increase the production of OPD science.

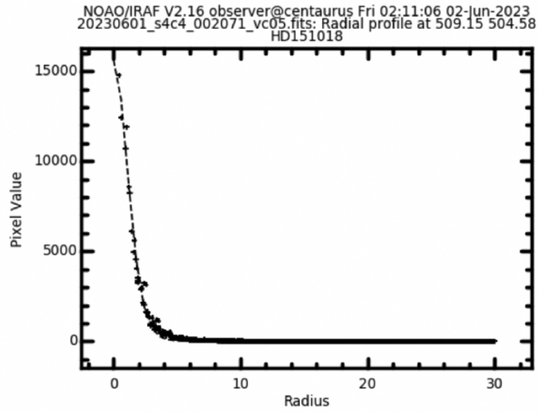

Figure 5. Point spread function (PSF) of a point source in an image in *i* band obtained in a night of science verification. The x axis is in pixels. The FWHM of the PSF is 1.82 pixels corresponding to 0.62 arcsec.

Table 2. Some polarimetric results obtained in the first comissioning run of SPARC4 occurred in 2022 Nov.

Object	Band	Mag (mag)	σ_{mag} (mag)	P (%)	σ_P^{data} (%)	σ_P^{est} (%)
NGC 2024 1	g	13.51	0.14	9.066	0.028	0.025
	r	11.62	0.11	9.861	0.017	0.0078
	i	10.320	0.054	9.526	0.011	0.0065
	z	10.1	-	8.4761	0.0097	0.0056
Field star	g	18.670	0.137	0.16	0.18	0.19
	r	16.657	0.110	0.24	0.21	0.23
	i	15.536	0.055	0.49	0.15	0.15
	z	15.7	-	0.40	0.17	0.17

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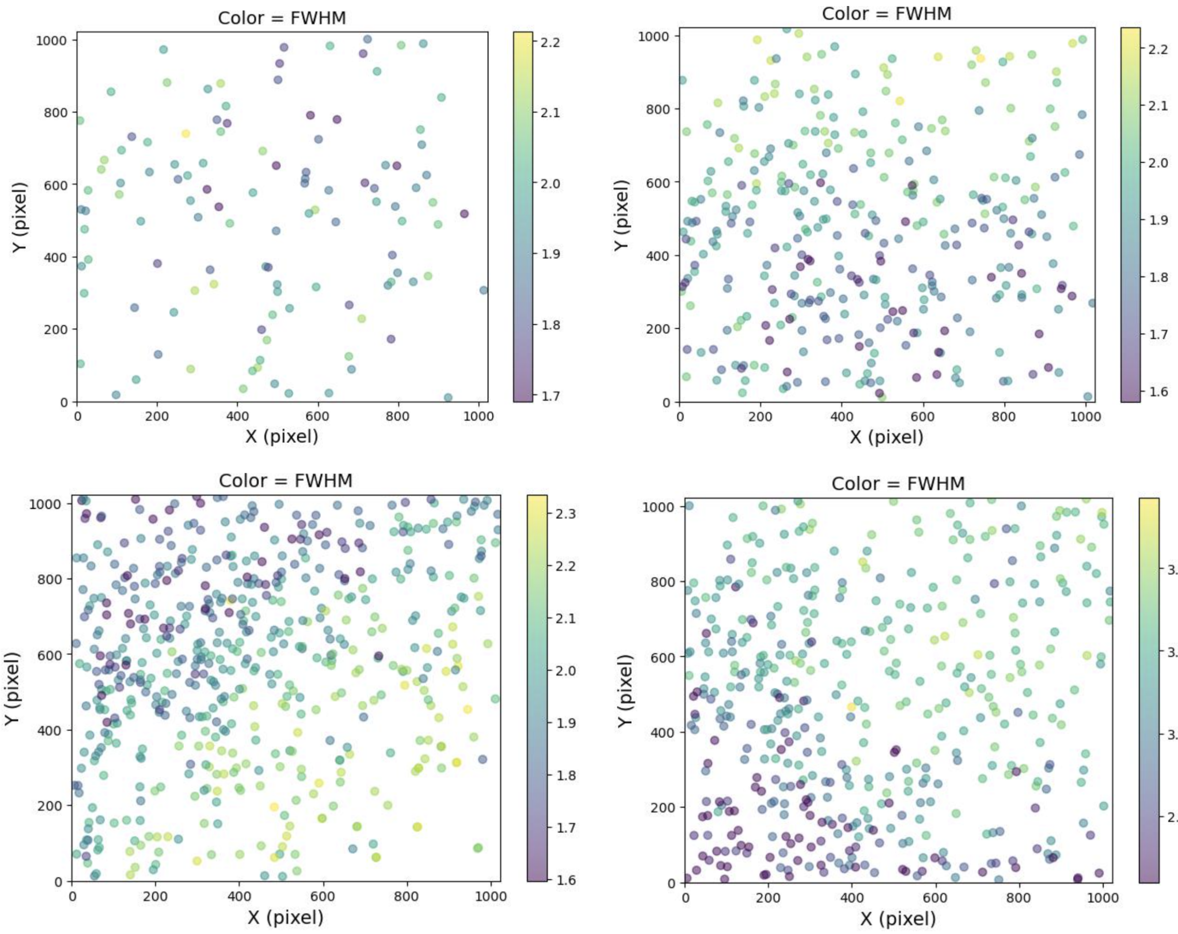

Figure 6. Dependence of the FWHM (in pixels) along the FoV. The channels g, r, i, and z are depicted in the writing direction. The images were obtained simultaneously in the commissioning run of 2023 May.

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