

Scientific Validation of SPARC4's Reduction Software

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Abstract. We present tests and new developments of the ASTROPOP astronomical reduction package for use on SPARC4 data. In all comparison tests, ASTROPOP demonstrated to have equal or better performance than common tools used by the astronomical community. The next steps will be to validate the polarimetry, the photometric calibrations using literature catalogs and the astrometric correction. With this, SPARC4, in addition to being efficient in the observation part, will have a set of equally efficient routines to deliver the reduction products to the end user.

Resumo. Nós estamos apresentando testes e novos desenvolvimentos do pacote de redução astronômica ASTROPOP para ser usado nos dados da SPARC4. Em todos os testes de comparação, o ASTROPOP demonstrou ter igual, ou melhor, desempenho do que as ferramentas comuns usadas pela comunidade astronômica. O próximo passo será validar a polarimetria, as calibrações fotométricas a partir de catálogos da literatura e a correção astrométrica. Com isso, a SPARC4, além de ser eficiente na parte de observação, terá um conjunto de rotinas igualmente eficientes para entregar os produtos de redução ao usuário final.

Keywords. Methods: observational – Instrumentation: photometers – Techniques: image processing

1. Introduction

The Simultaneous Polarimeter And Rapid Camera in 4 bands (SPARC4) is an imager, with an expected time resolution of 1s or better, capable of observing simultaneously 4 photometric bands (g, r, i, z) in both photometric and polarimetric modes with a field-of-view of 5.6×5.6 arcmin². The scientific cases of SPARC4 are: compact binaries; the modes of pulsating stars; steady and variable circumstellar envelopes, from their geometry to their composition; stellar population and star clusters; magnetic field and grains in interstellar medium; the origin of the variable emission from blazars; transient phenomena in solar system such as transits and occultations (Rodrigues et al. 2012).

This instrument will be installed on the 1.6-m Perkin-Elmer Telescope at the *Observatório do Pico dos Dias* (OPD)/LNA. Over the years, publications with data obtained by the OPD have been comparable to other telescopes that are part of LNA. SPARC4 is expected to increase the scientific production of OPD as measured by refereed articles, theses, and dissertations (Rodrigues et al. 2012).

One of the objectives of the SPARC4 project is the development of a free data reduction software that can adapt to the image processing, photometry and polarimetry requirements of the instrument, and that can also be used for the automatic production of reduction products. This software is the ASTROnomical POLarimetry and PHotometry Pipeline (ASTROPOP) (Neves Campagnolo 2019). This code is written in Python and uses the standard `ASTROPY`¹ `5 FITS Image HDU` class.

ASTROPOP can perform image preprocessing, source detection, photometric and polarimetric reduction and astrometric and photometric calibration. In this work, we compare the performance of ASTROPOP in source detection and aperture photometry relative to other common used Python packages.

2. Comparison Methods

Two important photometry packages are `SExtractor` (Bertin & Arnouts 1996) and `DAOPHOT` (Stetson 1987) originally developed for IRAF. ASTROPOP is based on their Python versions: `SEP` (Barbary 2016) and `PHOTUTILS` (Bradley et al. 2020). `SEP` consists of a C library with no dependencies outside the standard library, and a Python module that wraps the C library in a Pythonic API. `PHOTUTILS` is an affiliated package of `ASTROPY` that primarily provides tools for detecting and performing photometry of astronomical sources.

We used data from a HATS-24b planetary transit (Oliveira et al. 2019), observed using one of the SPARC4 CCD. HATS-24b orbits a G or F type star having magnitude $V = 12.830$ and effective temperature of 5800 ± 300 K.

2.1. Source Detection

`SEP` is able to detect extended and point sources, while `PHOTUTILS` only deals with point sources. `PHOTUTILS` uses the Full Width at Half Maximum (FWHM) as a main parameter for point source detection.

ASTROPOP is limited to point source reduction. It performs the source detection in three steps. First, the code uses `SEP` to make a segmentation map. Then an initial value of the FWHM of the Point Spread Function (PSF) from Moffat or Gaussian fitting is calculated. Finally, the point source detection is performed using `DAOPHOT` algorithm.

In Figure 1, we present the field of Hats-24 with the objects detected using `SEP`, `PHOTUTILS` and `ASTROPOP` separately. Most (about 98%) sources are found by the 3 methods. The brightest star of this field is a saturated source and ideally should be discarded as a source by the algorithm. As we can see in Figure 1, `SEP` detects two sources in this object, `PHOTUTILS` detects one source and `ASTROPOP` detect any source. It is because `ASTROPOP` can identify saturated objects and ignore them. Some very faint objects are not detected by the three

¹ <https://astropy.org>

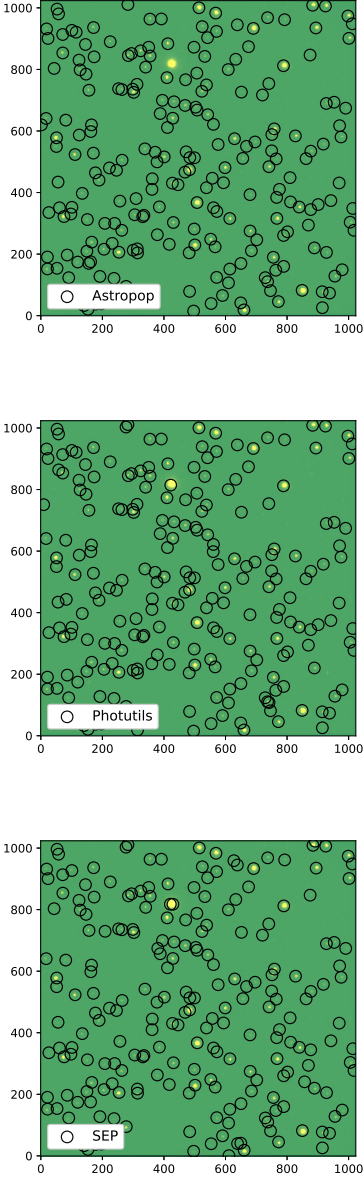


FIGURE 1. Detection with SEP, PHOTUTILS and ASTROPOP.

methods, but they are not relevant in most applications. So we consider ASTROPOP performs well in source detection.

2.2. Aperture Photometry

ASTROPOP uses SEP for the aperture photometry. However, the sky count per pixel is calculated differently from SEP. SEP subtraction is based on the average of the pixels inside the background annulus, without any cleaning or source masking. According to (Neves Campagnolo 2019), ASTROPOP masks the contribution of other sources and obtains the sky value by calculating the median of the annulus pixels by the MMM mode estimator from DAOPHOT which is equal to $3 \times \text{median} - 2 \times \text{mean}$

The aperture photometry error from SEP *FLUXERR* is:

$$\text{FLUXERR} = \sqrt{\sum_{i \in \mathcal{A}} \left(\sigma_i^2 + \frac{p_i}{g_i} \right)} \quad (1)$$

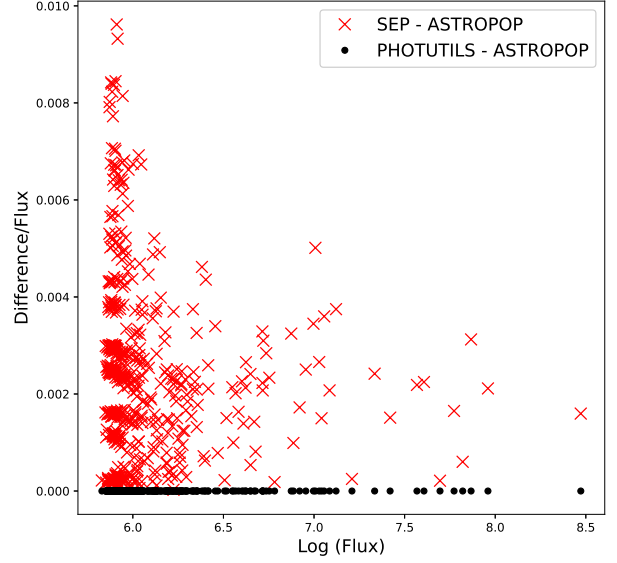


FIGURE 2. Fluxes obtained with ASTROPOP versus fractional fluxes compared with SEP and PHOTUTILS.

where \mathcal{A} is the set of pixels defining the photometric aperture, σ_i is the standard deviation of the noise (in ADU) estimated from the local background, p_i is the measurement image pixel value subtracted from the background and g_i is the effective detector gain in e^-/ADU at pixel i . In the preprocessing of the images, ASTROPOP converts the counts from ADU to e^- . Therefore we use gain equal to 1 in this step. This also means that the ASTROPOP flux and errors are in e^- .

In Figure 2, we show the difference of the fluxes versus flux obtained with ASTROPOP compared with SEP and PHOTUTILS. As we can see, in spite of the different way to subtract the local background, ASTROPOP resembles PHOTUTILS with a negligible quantify. But the differences relative to SEP are larger, but still acceptable, always smaller than 1%.

We compare the SEP estimated errors with those resulting from the CCD equation:

$$\frac{S}{N} = \frac{N_\star}{\sqrt{N_\star + n_{pix}(2N_{sky} + N_{dark} + N_{rdnoise}^2)}} \quad (2)$$

where N_\star is the total flux of the object, n_{pix} is the number of the pixels considered for the aperture photometry, N_{sky} is the number of sky photons per pixel, N_{dark} is the number of dark electrons by pixel in the considered integration time and $N_{rdnoise}$ is the rms readout noise in electrons per pixel (Howell 2000).

In Figure 3, we compare the ratio of the aperture photometry error from ASTROPOP with the CCD equation error, that is the denominator of Equation 2, versus the aperture photometry error for each comparison (Ci) and the main target (T1) (see 2.3). Figure 3 shows that the ASTROPOP error is not the same as the CCD error, but is really close. We did not expect a perfect similarity because these are real data, but this result is quite satisfying.

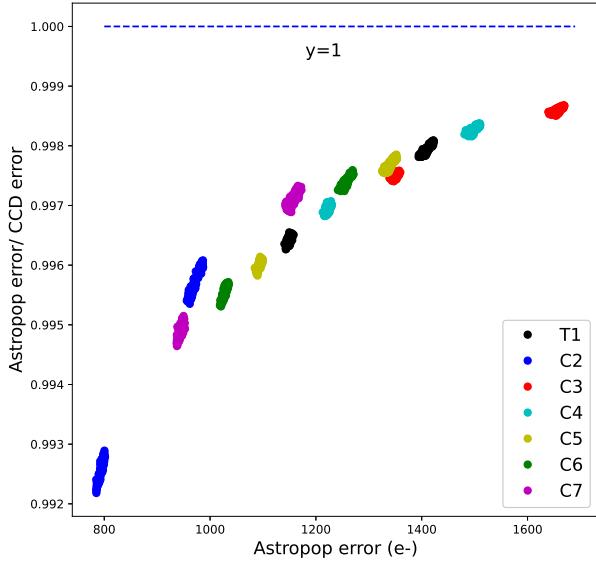


FIGURE 3. Ratio of the aperture photometry error from ASTROPOP with CCD equation error versus the aperture photometry error from ASTROPOP, the dashed blue line indicates $y=1$.

Parameter	Value	unit
T_C	2457948.709321	BJD
P	1.34849540	days
R_p/R_*	0.12801	-
a_p/R_*	4.561	-
i	85.97	degrees
e	0	-
ω	90	degrees
u_1	0.19187	-
u_2	0.36543	-

TABLE 1. Input parameters values to fit the model.

2.3. Differential Photometry

The differential photometry was compared with the published light curves of the planetary transit of Hats-24b (Oliveira et al. 2019), where we use the same comparison sources used by the authors. Figure 4 is an image of Hats-24 field of view, where T1 is denoted by a white cross and the C_i 's are circled in black.

The differential photometry is presented in Figure 5. We can see in blue the differential light curve and in red, off-transit data. In orange, we have the model calculated using the BATMAN package (Kreidberg 2015) with the parameters obtained by the authors to fit the transit, the parameters values are in table 1. Finally, the residuals, in green, represent, in a approximately, the dispersion of the data with respect to an average light curve. As we can see, the dispersion of the off-transit data is within 1% comparable to the photometric error.

2.4. Error Propagation

ASTROPOP uses the Python class 'Qfloat' which represents a quantity in terms of its unit and error:

```
1 qf = QFloat(1.0, 0.001, 'm')
2 print(qf.nominal)
```

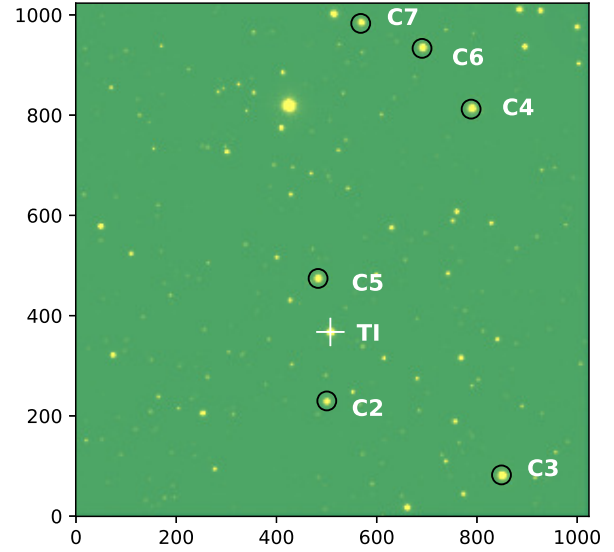


FIGURE 4. One image example of Hats-24 field of view: The main target (T1) is denoted by white cross and the comparisons stars are circled in black.

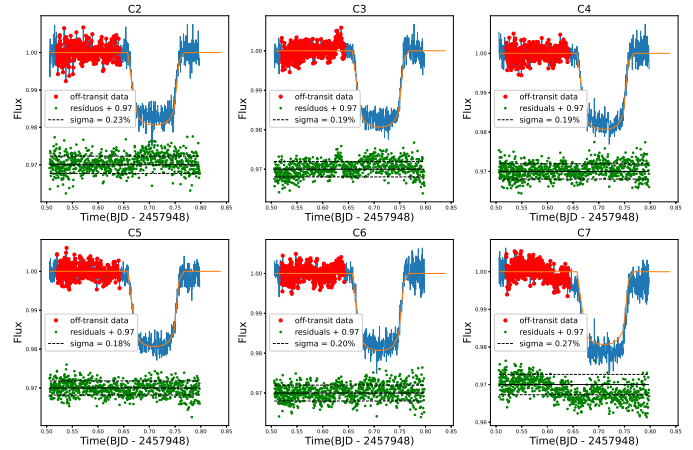


FIGURE 5. Differential photometry for HATS-24b. The differential light curve is in blue, off-transit data are in red, the model in orange and the residuals are in green.

```
1 1.0
2 print(qf.uncertainty)
3 0.001
4 print(qf.unit)
5 m
6 print(qf)
7 <QFloat 1.000+ -0.001 m>
```

When 'Qfloat' quantities are used as arguments of arithmetic operations, the errors are propagated accordingly and the necessary unit conversions are also done, as in the example below

```
1 qf1 = QFloat(60, 0.5, 'km')
2 qf2 = QFloat(7000, 700, 'm')
3 qf1 + qf2
4 <QFloat 67.0+ -0.9 km>
```

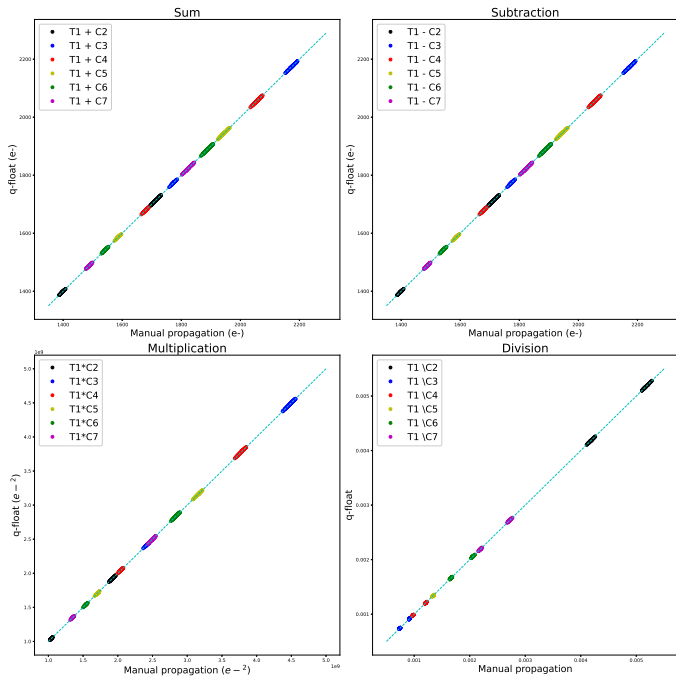


FIGURE 6. Error propagation for the four basic operations sum, subtraction, multiplication and division using T1 and the comparison objects.

```

5 | t = QFloat(2.0, 0.1, 'h')
  | qf1 / t
7 | <QFloat 30+-2 km / h>

```

In differential light curves, the error should be propagated because we divided the flux of the science object with the flux of the other comparison targets. We have verified that the 'Qfloat' error propagation gives exactly the same result of the usual error propagation given by:

$$\sigma_f = \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 \sigma_x^2 + \left(\frac{\partial f}{\partial y}\right)^2 \sigma_y^2 + \left(\frac{\partial f}{\partial z}\right)^2 \sigma_z^2 + \dots} \quad (3)$$

where σ_f is the standard deviation of the function f , σ_x is the standard deviation of the function x , and so forth.

We can see this result in Figure 6, where for a better verification of the 'Qfloat', we tested the four basic operations, sum, subtraction, multiplication and division using T1 and the comparison objects. But ASTROPOP can also take care of the error propagation in square roots and logarithmic expressions.

3. Conclusion and Perspectives

We compare ASTROPOP source detection and photometry procedures with SEP and PHOTUTILS, which are two commonly used Python tools for treating CCD photometry, very well accepted by the astronomical community.

ASTROPOP detection works the same or better than these tools and performs well aperture and differential photometry. Also, the error delivered by ASTROPOP is similar to that obtained using the CCD equation. The propagation of errors is taking into account automatically in all reduction steps by the use of 'Qfloat' variables.

The next steps for ASTROPOP development and tests are already in progress. They are related to the polarimetric reduction and the astrometric and photometric calibrations.

We are also developing Jupyter Notebooks and an automatic reduction pipeline based on ASTROPOP for SPARC4 users. We plan to make publicly available all routines for reduction of SPARC4 data soon.

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