

Photometric pipeline for robotic telescopes

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Abstract. PYRT is a software package to automatically process and calibrate photometric images obtained by robotic telescopes. The response model to be fitted is described with terms provided from the command line or a configuration file. It also has a limited capability to improve the astrometric solution of wide-field images.

The pipeline was used to process several million images obtained by the D50 telescope at Ondřejov. At present, it is in the process of being implemented for the wide-field Small Binocular Telescope, also at Ondřejov. It has also been tested to successfully solve a wide range of images from other telescopes ranging from large-aperture professional instruments to wide-field systems and all-sky cameras.

Key words: image processing – photometry – automation

1. Introduction

Ground-based robotic telescopes are an important tool of modern astronomy. Photometric imaging is just one example of the wide range of tasks these devices can perform in all fields of observational astronomy.

Everyone who has ever processed a photometric image has faced the problem of estimating the zeropoint, which may change not just between frames, but also across the field of view of a single frame. The principal tool of the PYRT package `dophot` is a tool to do just that, in a manner that is consistent and reliable when dealing with large quantities of frames. The package provides further tools to prepare and visualize the data in order to fit a wide range of input images.

In practice, a photometric solution of an image is closely bound to a correct mapping of its image plane coordinates to the world coordinate system (WCS, as described by [Calabretta & Greisen 2000](#)). For images with a narrow field of view, `astrometry.net` ([Lang et al., 2012](#)) provides a practically perfect solution. However, for wider-field images the projection introduces distortion which its Simple Image Polynomial (SIP) corrections have difficulty handling well. In support of wide-field imaging, `dophot` provides an optional WCS refit capability using a photometrically selected set of objects.

2. Methods

The input of the photometric calibration process is an image or set of images with a WCS header which does not have to be absolutely precise. We use `sExtractor` (Bertin & Arnouts, 1996) or `IRAF/daophot` (Stetson et al., 1990) to detect and extract raw fluxes and positions from the bitmap and using this information, we perform photometric calibration with standard stars within the field of view. The secondary standards are taken from the Atlas (Tonry et al., 2018) catalogue, which uses PanSTARRS (Kaiser et al., 2010) photometry for faint stars complemented with measurements from other sources for stars brighter than mag. 9. Under ideal conditions, we search for the zeropoint Z that minimizes δM_n for n stars

$$\delta M_n = Z - 2.5 \log_{10} I_n - m_n,$$

Which leads to an (error-weighted) arithmetic average. However, the reality is almost never this simple.

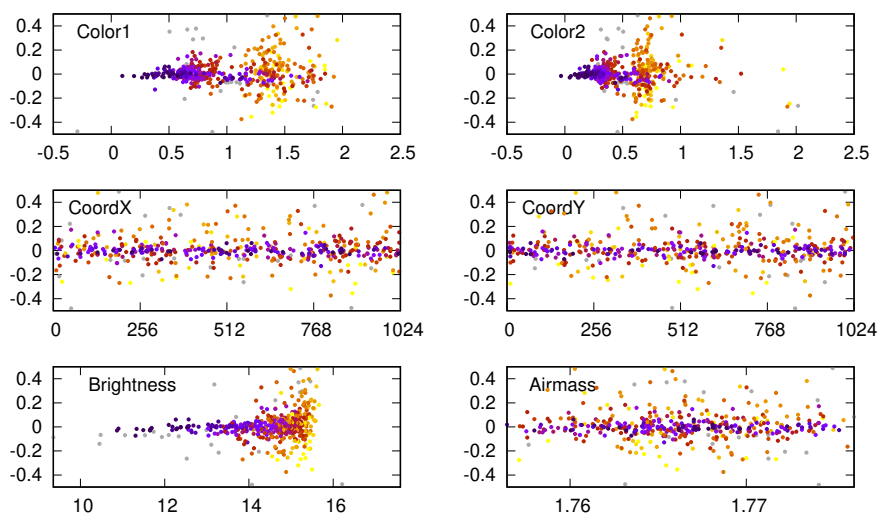


Figure 1. An example of residual plot of a photometric fit. Top two are scatter plots of color indexes ($g-r$) and ($r-i$), the second row are X/Y coordinates and the bottom row are scatter plots along detected brightness and airmass.

2.1. Terms

Variation of the photometric response may be fitted along eight main variables: four color indexes, both positional axes of the image, brightness of the object

and airmass. The fitted model parameters, known as *terms* in `dophot`, follow a simple alphanumeric syntax, for easy reference.

Most of the fitting is realised by polynomial terms, which start with "P" followed by the numeric order and the letter referring to the fitted axis. For example P3X refers to a third degree polynomial along X-axis, i.e. a $P3Xx^3$ would be summed to every reference star brightness. More than one axis may be referred to in one term, so that P2X2Y would stand for $P2X2Yx^2y^2$ and so on. Color axes are coded as C,D,E and F. At present with the Atlas catalogue, they stand for $(g' - r')$, $(r' - i')$, $(i' - z')$ and $(z' - J)$ color indices respectively, so that PC is a color term $PC(g' - r')$. A means airmass, R stands for radius from the center in this context.

Dophot is meant to be usable in routine automated operation, as a tool to study the optimal parameter configuration as well as to calibrate random contributed images. To automate, the routine would work with a single image, the typical parameter values would be imported from a configuration file and be refitted only to find small adjustments. Some of the parameters may be also loaded and kept fixed.

Some values are difficult to obtain and make sense only while fitting simultaneously many images. An excellent example of this can be the linear atmospheric reddening (PXC), a term that depends both on an object color index and airmass. Unless there is a good sampling of airmass range, the value of atmospheric reddening cannot be reliably estimated. To obtain this kind of parameters, the fitting can be run with a larger set of images being fitted simultaneously, with most parameters being common among the entire data set and the zeropoints and optionally an X/Y tilt of the response be specific for each frame. Once measured, the example value of PXC would stay fixed when calibrating images one by one.

In theory, all images from a single instrument run could be fitted simultaneously with all the effects included in the model. This approach is, however, not practical for memory and speed limitations. Also, for real-time processing, single-image fitting is desirable.

2.2. Object identification

Object positions in the image are not precise, rather they are noisy 2D positions and an identification with a naive approach is rather slow. Misidentifications can introduce undesired bias to the result, and need to be dealt with if we do not require a perfect WCS solution.

PYRT uses a KDTree algorithm in order to speed up the identifications. All nearby objects are treated equally at first, but during the fit the sigma clipping would mask any conflicting pairs. To minimize the effect of outliers to the initial solution, the initial set of zeropoints is estimated with the median and we use Cauchy's delinearization of residuals during the fine fit.

2.3. Astrometry

Images from the Small Binocular Telescope (SBT, Štrobl et al. 2019) have 4096 x 4096 pixels, FWHM 1.5 and typically around 100.000 objects. Such frames put packages such as `astrometry.net` (Lang et al., 2012) and `SCAMP` (Bertin, 2006) to serious test. While both are able to provide a correct astrometric solution based on polynomial distortion mapping, there are glitches caused by misidentification of an object and in practice neither package is sufficiently reliable.

PYRT now has an experimental feature that allows fitting a few uncommon WCS projection types in order to accommodate large-format and wide field images. Namely, we use the photometrically-selected dataset to fit zenithal polynomial projection (ZPN), zenithal equal area (ZEA) and zenithal perspective (AZP). For the SBT images we achieve very good results with ZPN projection.

PROJ	=	ZPN	fixed	
PV2-1	=	1.000000	fixed	
CD1-1	=	-0.000872551581	± 0.000000000104	(-3.141")
CD1-2	=	0.000010042013	± 0.000000000087	(0.036")
CD2-1	=	0.000010320805	± 0.000000000089	(0.037")
CD2-2	=	0.000872719794	± 0.000000000102	(3.142")
CRVAL1	=	350.2110758	± 0.0000052	
CRVAL2	=	77.5829211	± 0.0000027	
PV2-3	=	8.27432	± 0.00032	
PV2-5	=	377.34	± 0.23	
CRPIX1	=	2118.9358	± 0.0013	
CRPIX2	=	2072.5532	± 0.0032	
SIGMA	=	0.112		

Table 1. An example WCS/ZPN astrometric solution of an image taken by camera C1 of the Small Binocular Telescope. The ZPN polynomial terms are the PV2-n values. See Calabretta & Greisen (2000) for the keyword meaning and further details.

2.4. Requirements

The entire package is implemented in `python3` and uses `numpy`, `scipy`, `sklearn` and `astropy` packages, and to function properly, the Atlas catalogue needs to be available locally and `sExtractor` should be installed to provide object detection.

3. Solving common problems

3.1. Flat field correction

Flatfields do often not correct properly. The typical twilight-sky flatfield is, in fact, a combination of transmitted and scattered light. Most telescopes have at least a natural form of response drop towards the image edges, caused by the cosine projection of the pupil to the sky, and some level of vignetting may also play a role. Sky-based (and also homogeneously illuminated plane) flat-field correction often simply adds the scattered light, causing overcorrection in the image edges. Also, a gradient illumination may introduce a tilt in response along the image plane. With image-plane response fitting, these problems are easy to fix.

3.2. Clouds

Varying thickness of haze and cirrus seriously affects photometry, not just by reducing sensitivity in the field and introducing parasite light, clouds introduce patterns of varying response. For narrow-field imaging, atmospheric conditions may be corrected for by simply introducing a low-order polynomial in image coordinates. For SBT's $3.5^\circ \times 3.5^\circ$ frames, this approach has limited use and a mesh of sample values is expected to solve the issue in future versions of the package. At present, SBT frames where a simple polynomial response model does not fit well, i.e. the variance of residuals is larger than a fixed value, are understood as being tainted by weather and are not used.

If more complex polynomials need to be used to deal with problematic response (typically clouds), the Runge phenomenon (i.e. oscillation at the edges) may step in and distort corners, edges or sparsely populated areas. To deal with such situations, we are considering implementing an interpolated mesh grid approach in some future version.

3.3. Color response

Transmission bandpasses differ between instruments. One of `dophot`'s essential features is providing color term fitting on the complete sample of objects. With standard filters, the necessary correction may be as simple as a small linear term to correct for a small shift in response, but for frames taken without filter or a non-standard filter, it is necessary to use more colors and even a second degree polynomial term in order to obtain a satisfactory fit.

By its nature, `dophot` produces magnitudes in an instrumental system. If the obtained values need to be directly compared with standard measurements, further steps need to be taken to transform the dataset to a standard photometric system (harmonisation). For this reason, it is a good practice not to let the color response vary for every image in the set. The principal aim of the fitting is to create a lightcurve — a single filter time series of the object brightness.

Subtle changes in a freely-fitted color term make our life harder. They would cause every point of the lightcurve to be in a slightly different filter, which introduces noise in the lightcurves of measured objects. The color-related noise would cancel out after harmonisation, but this step is often omitted for the sake of simplicity. We therefore measure the color response in a larger sample of objects from different fields and varying airmasses, store the results in a model file and use them as fixed parameters during routine operation.

3.4. Weighted image coadding

The in-process knowledge of the response function and background noise allows for construction of an artificial flat field and weight frame. These frames can be used to weight-combine many frames with varying image quality to obtain an optimal coadd for the best photometric sensitivity. In the High Energy Astrophysics (HEA) group, this is often used when searching for faint GRB optical afterglows.

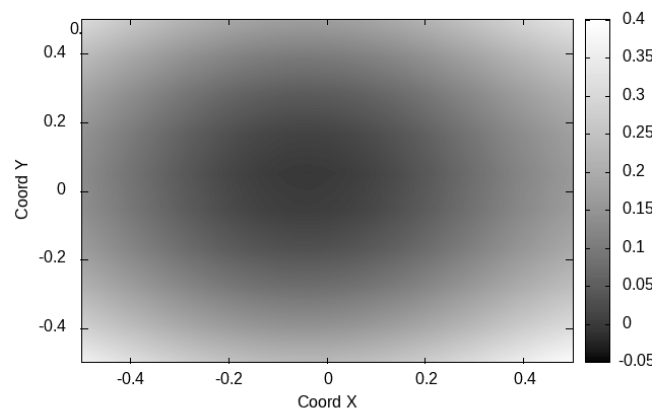


Figure 2. An example of flat-field correction computed by PYRT for a frame from the D50 telescope. Note the edges overcorrected by ~ 0.3 mag

3.5. Non-linearity

Response nonlinearity is best treated directly during image processing. Sometimes, the image was not treated or there is a residual nonlinearity in the data, which may affect all objects, just the brightest ones or even the faint end of the dataset. A linear or polynomial term may be introduced, but a great care should be taken, as this destabilizes the minimizing process and can lead to an

incorrect output. In any case, images can be treated, but need to be treated one by one, ideally reviewing the results. If saturation is a problem, `dophot` allows for an easier and safer way of omitting the brightest objects from the fit.

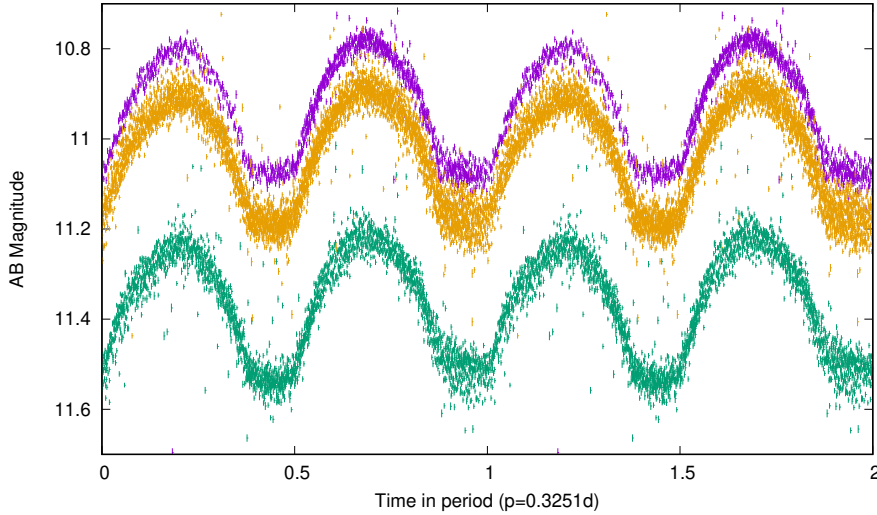


Figure 3. A lightcurve of a W UMa star NSVS 9023048 from images taken by SBT. NSVS was not a target of the frames, it was searched for only when the complete set of output was available and received no special treatment. The period and coordinates were taken from AAVSO’s VSX webpage (Watson, 2012; Gettel et al., 2006). Filters from bottom to top are SDSS g' , r' and i'

4. Results

Images taken by the D50 (Nekola et al., 2010) telescope are processed automatically and the resulting photometry of every detected object is stored in a Q3C-based (Koposov & Bartunov, 2006) photometric database. This way, a lightcurve of any object seen by the telescope can be searched in seconds.

Frames taken by the SBT are planned to be treated in the same way. For now, an important issue with the frames having incorrect astrometric solution has been solved by implementing a built-in astrometric fit. Once the code to do this is mature enough, SBT will also contribute to the photometric database.

PYRT was used also to prepare the frames for image subtraction with *hot pants* (Becker, 2015). In particular, image subtraction of SBT frames was impossible without their precise WCS mapping. The images may also be corrected

for response and some awkward-looking outputs of the image subtraction were resolved this way.

The output of PYRT at the D50 telescope is being imported to a Q3C-based database, to allow for quick cone searches of objects. This way, lightcurves for any stationary object observed with D50 can be produced in a matter of seconds.

5. Conclusions

I present a Python photometric package centered around automated and semi-automated processing of astronomical photometric images. The package's input are raw fluxes, x/y positions and a WCS mapping of the frame. The model is described by alphanumerically designated easy to remember terms. The output is a listing of AB magnitudes of each object detected in the frame. An experimental feature performs also a precise astrometric solution with the photometrically-selected set of objects. The package is in active use at D50 and SBT telescopes in Ondřejov and is available on request from the author in hope that it would be useful to others.

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