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Accurate Photometry with Digitized Photographic Plates of the Moscow Collection

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Abstract. Photographic plate archives contain a wealth of information about the positions and brightness of celestial objects decades ago. Plate digitization is necessary to make this information accessible, but extracting it is a technical challenge. We have developed algorithms to extract photometry with an accuracy of better than $\sim$0.1 mag. in the range $13 < B < 17$ mag from photographic images obtained in 1948–1996 with the 40-cm Sternberg Institute astrograph (30×30 cm plate size, 10×10 deg field of view) and digitized using a flatbed scanner. The extracted photographic light-curves are used to identify thousands of new high-amplitude variable stars (> 0.2 mag). The algorithms are implemented in the free software `VaST` available at http://scan.sai.msu.ru/vast/

Keywords. Techniques: photometric, stars: variables: other

1. Introduction

Photography was historically the first method to record brightness of astronomical objects objectively (Krisciunas 2001). However, extracting brightness information from photographic images was never easy. Sophisticated glass-plate measuring machines, including microdensitometers (Stobie 1984) and iris diaphragm photometers (Turner & Welch 1989) were developed, but were generally slow and inefficient. Often the most practical way to extract brightness of a given object from a set of plates was by visual inspection of the plates with a magnifying glass. An astronomer would estimate the brightness of the object by comparing it visually to nearby stars of known brightness (Yendell 1905). An experienced observer can obtain magnitude measurements with an accuracy better than $\sim$0.1 mag, which is comparable to that of a measuring machine (Davis *et al.*, 2004).

It is now possible to digitise a full photographic plate in a matter of (tens of) minutes in order to make its information content accessible. Digitisation will serve the additional purpose of preserving the information if the original glass plate is lost. Some observatories around the world have made efforts to digitise their plate collections. The DASCH project at Harvard (Grindlay *et al.*, 2009, 2012), in Shanghai (Tang *et al.* 2013; Yu *et al.* 2017), Belgium (Robert *et al.* 2011; De Cuyper *et al.* 2012) and Tautenburg (Henze, Meusinger & Pietsch 2008) use a design of purpose-built measuring machine which effectively takes a digital photograph of a plate using a telecentric lens that delivers high image quality and digitisation speed. Other observatories, including the

APPLAUSE collaboration – Bamberg, Hamburg, Potsdam, and Tartu (Wertz *et al.* 2017), Sonneberg (Kroll 2009; Hippke *et al.* 2017), Rozhen (Markov *et al.* 2012), Asiago (Barbieri *et al.* 2004) and many others employ commercial flatbed scanners despite their known drawbacks of scattering light and introducing the characteristic hacksaw-like pattern of systematic errors in astrometry (Simcoe 2009).

In this work we focus on processing a specific series of plates from the Moscow collection (the 'A' series) from which we expect the most scientific return after digitisation. This series includes 22300 blue-sensitive 30×30-cm plates ($10^\circ \times 10^\circ$ field of view) taken in 1948–1996 with the 40-cm astrograph (Samus *et al.* 2010). The plates are being digitised with an Epson Expression 11000XL scanner at 2400 dpi resolution ($1''.37$/pix, 16 bit greyscale). These digitised plates are used for variable-star research (Kolesnikova *et al.* 2008, 2010; Sokolovsky *et al.* 2014a,b, 2016).

2. Data Processing Algorithm

Conventional software used for CCD photometry is often not applicable to digitised photographic plates as it relies on the assumptions that the image detector responds linearly to the number of incoming photons and that the astrometric solution for the image may be represented well if distortions are corrected with a polynomial. The `VaST` software (Sokolovsky & Lebedev 2018) that we developed relies on the well-known software `SExtractor` (Bertin & Arnouts 1996), `Astrometry.net` (Lang *et al.* 2010; Hogg *et al.* 2008) and `WCSTools`, and combines them with the original code we developed to circumvent carefully the above limitations. Here we summarise the key design points.

Astrometry. Flatbed scanners introduce systematic errors in source positions. After computing an approximate plate solution with `Astrometry.net` for each detected source, we use positions of nearby stars from UCAC4 (Zacharias *et al.* 2013) to compute the *local correction* to the source position. The resulting accuracy of $< 1''$ is sufficient to match the source images to USNO-B1.0 (Monet *et al.* 2003) (the 'A' series plates go deeper than UCAC4).

Filtering. The brightness of blended images cannot be measured accurately by aperture photometry. We do not employ image subtraction or PSF-fitting because of the non-linear response of the photographic detector to the number of incoming photons (but see Spasovic *et al.* 2016), so we need a way of discarding unreliable measurements. Two types of plots are used to identify blended sources as they appear as outliers in plots of magnitude *vs.* source size and magnitude vs. magnitude difference between two concentric apertures (Fig. 1).

Photometry. `SExtractor`, operating in CCD mode, performs source detection and photometry using a fixed circular aperture. Because of the non-linear response of the photographic density, we use the function suggested by Bacher, Kimeswenger & Teutsch (2005) to approximate the relationship between the instrumental photographic magnitude and the APASS B magnitude. The plate images are split into overlapping $16^\circ.2 \times 1^\circ.2$ subfields that are calibrated independently of each other. For the 'A' series of plates, relative photometry of the highest accuracy ($\sigma \approx 0.08$ mag.) is attained for sources in the magnitude range $14 < B < 15$. Photometric accuracy for the brighter stars is impaired as the images exceed the size of the fixed-radius aperture.

Sample results. Fig. 2 presents the magnitude–σ plot for a typical subfield that is about half-way between the plate centre and the border. This subfield includes the Mira-type variable TT Cas that has a variability amplitude covering the full accessible magnitude range (Fig. 3).

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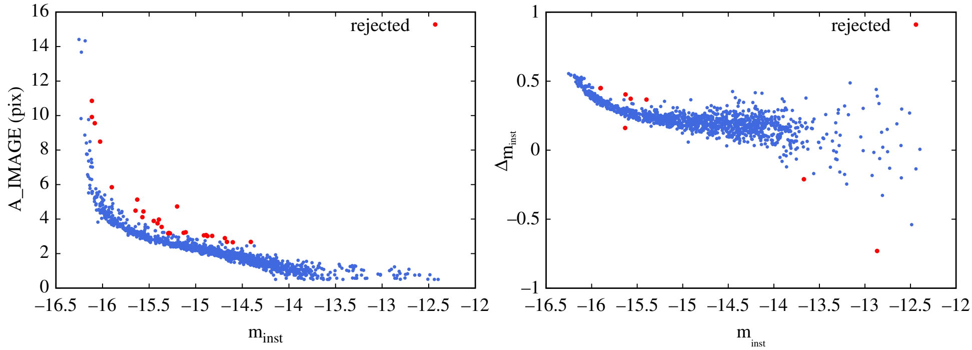

Figure 1. *Left:* Magnitude vs. source size along its major axis. *Right:* magnitude vs. difference between the magnitudes measured in two concentric circular apertures. One aperture is 30 % larger than the other. The blended images thus identified are highlighted. This blend rejection procedure is applied automatically to each image.

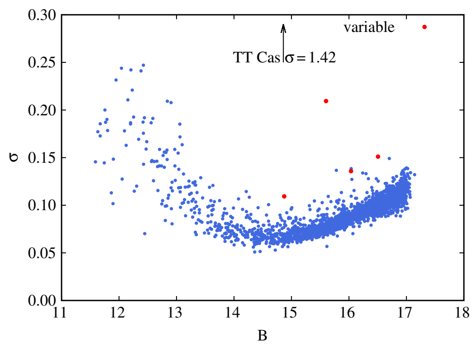

Figure 2. The magnitude vs. standard deviation (σ) plot highlights variable objects as those which exhibit a scatter that is larger than most stars of similar brightness in this field.

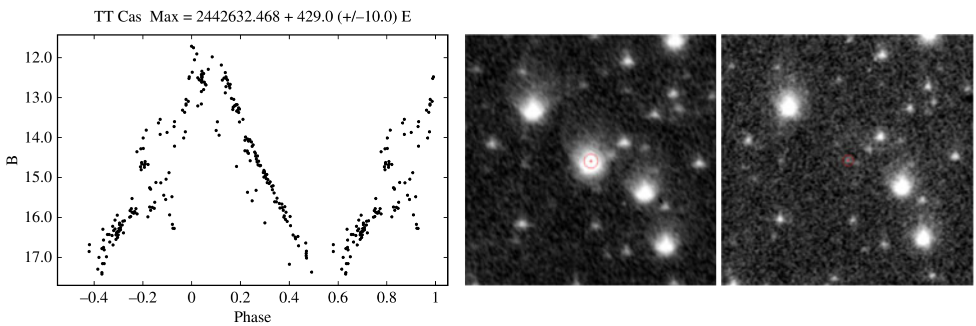

Figure 3. *Left:* Phased photographic light-curve of the Mira-type variable TT Cas. The light-curve includes 238 measurements obtained over 25 years. The derived period of 429 ± 10 d is not consistent with the previously published period of 396 d. *Right:* TT Cas imaged with the 40-cm astrograph at maximum on 1975 Aug. 7 ($B = 11.7$) and minimum on 1971 Aug. 24 ($B = 17.4$).

3. Summary

The poster described the data-processing steps, using the`VaST` code, that were followed in order to extract light-curves from a series of digitised photographic images. Implementing the steps relies heavily on `SExtractor` and `Astrometry.net` for source

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detection and astrometry. VaST takes into account the non-linear response of the photographic emulsion and can tolerate the hacksaw-like systematic errors in source positions introduced by the scanner. While our tests were confined to the plates of one specific series of the Moscow collection, the proposed processing strategy is applicable to any series of digitised photographic images of the sky.

References

Bacher, A., Kimeswenger, S., & Teutsch, P. 2005, *MNRAS*, 362, 542

Barbieri, C., *et al.* 2004, *Baltic Astron.*, 13, 665

Bertin, E., & Arnouts, S. 1996, *A&AS*, 117, 393

Davis, A., Barkume, K., Springob, C., Tam, F., & Strelnitski, V. 2004, *JAAVSO*, 32, 117

De Cuyper, J., de Decker, G., Laux, U., Winter, L., & Zacharias, N. 2012, in P. Ballester, D. Egret & N. P. F. Lorente (eds.), *ADASS XXI, ASPCS*, 461, 315

Grindlay J., Tang S., Los E., & Servillat, M. 2012, in: R. E. Griffin, R. J. Hanisch & R. L. Seaman, (eds.), *New Horizons in Time-Domain Astronomy, Proc. IAU S285*, (CUP: Cambridge, UK), p. 29

Grindlay J., *et al.* 2009, in: W. Osborn & L. Robbins (eds.), *Preserving Astronomy's Photographic Legacy: Current State and the Future of North American Astronomical Plates, ASPCS*, 410, 101

Henze M., Meusinger H., & Pietsch W. 2008, *A&A*, 477, 67

Hippke, M., *et al.* 2017, *ApJ*, 837, 85

Hogg, D. W., Blanton, M., Lang, D., Mierle, K., & Roweis, S. 2008, in: R.W. Argyle, P.S. Bunclark & J. R. Lewis (eds.), *ADASS XVII, ASPCS*, 394, 27

Kolesnikova, D. M., *et al.* 2010, *Astron. Reports*, 54, 1000

Kolesnikova, D. M., *et al.* 2008, *AcA.*, 58, 279

Krisciunas K., 2001, *astro-ph:*6313

Kroll P. 2009, in: G. Wolfschmidt (ed.), *Cultural Heritage of Astronomical Observatories: From Classical Astronomy to Modern Astrophysics*, *Proc. ICOMOS Symp.*, (ICOMOS, Paris), p. 311

Lang, D., Hogg, D. W., Mierle, K., Blanton, M., & Roweis, S. 2010, *AJ*, 139, 1782

Markov, H., Tsvetkov, M., Borisova, A., & Petrov, N. 2012, *PAS 'Rudjer Boskovic'*, 11, 201

Mink, J. 2014, in: N. Manset & P. Forshay (eds)., *ADASS XXIII, ASPCS*, 485, 231

Monet, D. G. *et al.* 2003, *AJ*, 125, 984

Robert, V. *et al.*, 2011 *MNRAS*, 415, 701

Samus, N., Antipin, S., Kolesnikova, D., Sat L., & Sokolovsky, K. 2010, in: A. Prša, M. Zejda, eds., *Binaries – Key to Comprehension of the Universe*, *ASPCS*, 435, 135

Simcoe, R. J. 2009, in: W. Osborn & L. Robbins (eds.), *Preserving Astronomy's Photographic Legacy: Current State and the Future of North American Astronomical Plates, ASPCS*, 410, 111

Sokolovsky, K. V., *et al.* 2014, *Astron. Reports*, 58, 319

Sokolovsky K., *et al.* 2014, in: L. Mišková, S. Vítek (eds.), *Astroplate 2014*, (Inst. Chem. Tech., Prague), p. 79

Sokolovsky, K. V., Kolesnikova, D.M., Zubareva, A. M., Samus, N. N., & Antipin, S.V. 2016, *Proc. Astroplate II 2016* (Prague), arXiv:1605.03571

Sokolovsky, K. V., & Lebedev, A. A. 2018, Astron. & Comput., 22, 28

Spasovic M., Dersch C., Lange C., Jovanovic D., Schrimpf A., 2016, arXiv:1610.00265

Stobie, R. S. 1984, *NASA Conf. Publ.*, 2317, 209

Tang, S., Grindlay, J., Los, E., & Servillat, M. 2013, *PASP*, 125, 857

Turner D. G., & Welch G. A. 1989, *PASP*, 101, 1038

Wertz, M., *et al.* 2017, *AN*, 338, 103

Yendell, P. S. 1905, *Pop. Astron.*, 13, 453

Yu, Y., Zhao, J.-H., Tang, Z.-H., & Shang Z.-J. 2017, *Research Astron. Astrophys.*, 17, 28

Zacharias, N., *et al.* 2013, *AJ*, 145, 44

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