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VaST: A variability search toolkit☆

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Variability Search Toolkit (VaST) is a software package designed to find variable objects in a series of sky images. It can be run from a script or interactively using its graphical interface. VaST relies on source list matching as opposed to image subtraction. SExtractor is used to generate source lists and perform aperture or PSF-fitting photometry (with PSFEx). Variability indices that characterize scatter and smoothness of a lightcurve are computed for all objects. Candidate variables are identified as objects having high variability index values compared to other objects of similar brightness. The two distinguishing features of VaST are its ability to perform accurate aperture photometry of images obtained with non-linear detectors and handle complex image distortions. The software has been successfully applied to images obtained with telescopes ranging from 0.08 to 2.5 m in diameter equipped with a variety of detectors including CCD, CMOS, MIC and photographic plates. About 1800 variable stars have been discovered with VaST. It is used as a transient detection engine in the New Milky Way (NMW) nova patrol. The code is written in C and can be easily compiled on the majority of UNIX-like systems. VaST is free software available at http://scan.sai.msu.ru/vast/.

1. Introduction

Variable stars are important tracers of stellar evolution (e.g. Sherwood and Plaut, 1975), fundamental stellar parameters (Torres et al., 2010), 3D structure of our Galaxy (Pietrukowicz et al., 2015; Dékány et al., 2015; Gran et al., 2016) and beyond (Lah et al., 2005; Subramanian and Subramaniam, 2012; Hoffmann and Macri, 2015; Jacyszyn-Dobrzeniecka et al., 2017) as well as various astrophysical processes related to accretion (Osaki, 1996; Mukai, 2017), ejection (Russell et al., 2016) and strong magnetic fields (Cropper et al., 1989). It is believed that only a few per cent of the variable stars easily accessible to ground-based photometry are currently known (Samus and Antipin, 2015). The reason is that contemporary CCDs are very sensitive and small and hence image only a small field of view to a high limiting magnitude.

The next generation surveys Gaia (Gaia Collaboration et al., 2016; Clementini et al., 2016), VVV (Minniti et al., 2010), Pan-STARRS (Chambers et al., 2016), LSST (Ridgway et al., 2014), NGTS (Wheatley et al., 2017) and TESS (Ricker et al., 2015) employing large mosaic cameras (or multiple small cameras in case of NGTS and TESS) are expected to greatly increase the number of known variable stars. Still, these surveys have their limitations in terms of observing cadence, sky coverage, accessible magnitude range and survey lifetime. All this leaves room for variability searches with other instruments and different observing strategies. Photometric measurements needed to detect stellar variability are relatively easy to perform (compared to spectroscopy and polarimetry of objects with the same brightness), so even small-aperture telescopes are useful for finding and studying variable stars.

Large time-domain surveys employ custom-built pipelines (e.g. Bertin et al., 2002; Laher et al., 2014; Kessler et al., 2015; Mauro et al., 2015) to perform photometric data reduction and variable object detection. These pipelines are fine-tuned for the particular equipment and observing strategies employed by these surveys and, while often sharing many common pieces of code, require intervention of a software engineer to adopt them to another telescope or camera. Developing a purpose-built pipeline for a small observing project is often impractical. Instead, one would like to have data reduction software applicable to a variety of telescopes and cameras.

The problem of extracting variability information from surveys, in practice, has not been completely solved. New variable stars are still being identified in the NSVS survey data (e.g. Khruslov, 2013;

☆ This code is registered at the ASCL with the code entry ascl:1704.005.

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Sergey et al., 2014) while its observations were completed in 1999–2000 (Woźniak et al., 2004). A number of recent ground-based exoplanet transit surveys, despite having sufficient photometric accuracy and sky coverage for detecting *the majority* of bright variable stars, have so far provided only limited information on individual objects (e.g. Rodriguez et al., 2013; Norton et al., 2016) or specific classes of objects (e.g. Devor et al., 2008; Norton et al., 2011; McQuillin et al., 2012; Holdsworth et al., 2014; Labadie-Bartz et al., 2016). Better variability detection algorithms, open data-sharing policies and interfaces to published time-series that allow non-trivial searches in the whole database rather than providing access to a limited number of objects at a time are needed to fully exploit the information hidden in the data. A software to perform variability search in a set of lightcurves imported from a survey archive and visualize the search results may be useful for information extraction and debugging fully-automated search procedures.

Photographic plates used to be the primary type of light detectors in astronomy in the 20th century. Direct images of the sky recorded on glass plates contain information about the positions and brightness that celestial objects had decades ago. This information may be useful on its own or as the first-epoch for comparison with modern CCD measurements. The plates are stored in archives in observatories around the world. Many observatories are digitizing their collections in an effort to preserve the information stored on the plates and make it more accessible. At the time of writing, only the DASCH[1] (Grindlay et al., 2012) and APPLAUSE[2] (Groote et al., 2014; Tuvikene et al., 2014) archives provide source catalogs and photometry derived from the plates while others[3,4] provide only images. Performing photometry on digitized photographic images is a non-trivial task (Bacher et al., 2005; Tang et al., 2013; Wertz et al., 2016) that cannot be done well with conventional photometry software developed for CCD images. The conventional software relies on the assumption that an image sensor responds linearly to the number of incoming photons. This assumption is violated for photographic emulsion as well as for some types of contemporary light detectors including microchannel plate intensified CCDs (MICs) used in space-based UV-sensitive telescopes Swift/UVOT (Poole et al., 2008; Breeveld et al., 2010, see also Brown et al., 2014), XMM/OM (Mason et al., 2001) and fast ground-based cameras (Karpov et al., 2012). There is a need for a user-level software capable of performing photometry on images obtained with non-linear detectors.

A number of software packages for detection of variable objects have been developed recently. Some of them feature a graphical user interface (GUI) and are aimed at processing small datasets, while others have command-line interfaces and are meant as a complete data processing pipeline or as building blocks for constructing one. LEMON[5] is a pipeline based on SExtractor[6] (Bertin and Arnouts, 1996) and PyRAF for automated time-series reduction and analysis (Terrón and Fernández, 2011). It takes a series of FITS images as an input and constructs lightcurves of all objects. PP[7] (Mommert, 2017) is an automated Python pipeline based on SExtractor and SCAMP (Bertin, 2006). PP produces calibrated photometry from imaging data with minimal human interaction. While originally designed for asteroid work, the code is be applicable for stellar photometry. LEMON and PP are very similar to VaST in spirit, while they differ in technical implementation and user interface. C-Munipack/Muniwin[8] offers a complete solution for reducing observations of variable stars obtained with a CCD or DSLR camera. It runs on Windows and Linux and provides an intuitive GUI. FotoDif[9] is a Windows CCD photometry package providing capabilities similar to Muniwin. Astrokit[10] (Burdanov et al., 2014, 2016) corrects for atmospheric transparency variations by selecting an optimal set of comparison stars for each object in the field. IRAF's[11] (Tody, 1986) PHOT/APPHOT task is meant to be used to generate input photometric data for Astrokit. Variable star candidates are selected in Astrokit with Robust Median Statistics (Rose and Hintz, 2007). FITSH[12] (Pál, 2012) is a collection of tasks for advanced image manipulation (including stacking) and lightcurve extraction using aperture, image subtraction, analytic profile modeling and PSF-fitting photometry. VARTOOLS[13] (Hartman and Bakos, 2016) implements in C a collection of advanced lightcurve analysis methods providing a command-line interface to them. HOTPANTS[14] (Becker, 2015) is designed to photometrically align one input image with another, after they have been astrometrically aligned with software like WCSremap[15], SWarp (Bertin et al., 2002) or Montage (Jacob et al., 2010). HOTPANTS is an implementation of the (Alard, 2000) algorithm for image subtraction. The program is intended as a part of a transient detection/photometry pipeline. ISIS[16] (Alard and Lupton, 1998) is a complete package to process CCD images using the image subtraction method. It finds variable objects in the subtracted images and builds their light curves from a series of CCD images. DIAPL[17] (Rozyczka et al., 2017) is able to identify variable stars via image subtraction, implemented in C. TraP[18] (Swinbank et al., 2015) is a Python and SQL based pipeline for detecting transient and variable sources in a stream of astronomical images. It primarily targets LOFAR radio astronomy data, but is also applicable to a range of other instruments (including optical ones).

Most of the above packages were not available at the time VaST development was started (Sokolovsky and Lebedev, 2005). Many of them cannot construct lightcurves without finding a plate solution with respect to an external star catalog. None of the above software addresses the issue of photometry with non-linear imaging detectors. VaST provides a combination of features not yet offered by other software, including the ability to process thousands of images with tens of thousands of stars and interactively display the results in a GUI.

VaST is designed as a user-friendly software implementing the full cycle of photometric reduction from calibrating images to producing lightcurves of all objects within a field of view and detecting variable ones. VaST is capable of handling images obtained with non-linear detectors such as photographic plates and MICs. The software may be applied to images obtained with telescopes of any size with minimal configuration. VaST can be used interactively to inspect a set of images of one field in a PGPLOT[19]-based GUI. As soon as optimal source extraction and lightcurve post-processing parameters have been identified in the interactive mode, VaST may proceed non-interactively and produce lightcurves for subsequent variability searches with VARTOOLS or custom-built scripts. VaST

1 http://dasch.rc.fas.harvard.edu/.
2 https://www.plate-archive.org.
3 http://dc.zah.uni-heidelberg.de/lswscans/res/positions/q/info.
4 http://plate-archive.hs.uni-hamburg.de/index.php/en/.
5 https://github.com/vterron/lemon.
6 http://www.astromatic.net/software/sextractor.
7 https://github.com/mommermi/photometrypipeline.
8 http://c-munipack.sourceforge.net/.
9 http://www.astrosurf.com/orodeno/fotodif/.
10 http://astro.ins.urfu.ru/en/node/1330.
11 http://iraf.noao.edu/.
12 https://fitsh.net/.
13 http://www.astro.princeton.edu/~jhartman/vartools.html.
14 http://www.astro.washington.edu/users/becker/v2.0/hotpants.html.
15 http://www.astro.washington.edu/users/becker/v2.0/wcsremap.html.
16 http://www2.iap.fr/users/alard/package.html.
17 http://users.camk.edu.pl/pych/DIAPL/index.html.
18 https://github.com/transientskp/tkp.
19 http://www.astro.caltech.edu/~tjp/pgplot/.