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Improving precision of Pi of the Sky photometric measurements

M. Siudek^{1*}, K. Małek¹, L. Mankiewicz¹, R. Opiela¹, M. Sokołowski²,
A. F. Żarnecki³

¹*Centre for Theoretical Physics of the Polish Academy of Sciences, Al. Lotnikow 32/46,
02-668 Warsaw, Poland*

²*National Centre for Nuclear Research, Hoza 69, 00-681 Warsaw, Poland*

³*Faculty of Physics, University of Warsaw, Hoza 69, 00-681 Warsaw, Poland*

Abstract. Pi of the Sky is a system of robotic telescopes designed for observations of short timescale astrophysical phenomena, like prompt optical GRB emission. The apparatus is designed to monitor a large fraction of the sky with $12^m - 13^m$ range and time resolution of the order of 1 – 10 seconds. All measurements taken by the Pi of the Sky detector located in Las Campanas Observatory (LCO) in Chile are available on the Pi of the Sky website through a dedicated interface which also allows to download the selected data. Pi of the Sky database from period 2006 - 2009 contains more than 2 billions measurements of almost 17 millions of objects. In order to facilitate analysis of variable stars we have developed a system of dedicated filters to remove bad measurements or frames. They are needed to remove measurements affected by detector imperfections (hot pixels, measurement close to CCD edge, background due to opened shutter) or observation conditions (planet or planetoid passage, moon halo). With approximate color calibration algorithm taking into account appropriate corrections based on the spectral type of reference stars the photometry algorithm can be improved further. This process is illustrated by the analysis of the BG Ind system where we have been able to reduce the total systematic uncertainty to about 0.05 magnitudes.

Keywords : Gamma Ray Burst (GRB) – prompt optical emissions – optical flashes – variable stars – robotic telescopes – photometry

*email: gsiudek@cft.edu.pl

1. Introduction

“Pi of the Sky” (Burd et al. 2005; Malek et al. 2010) is a robotic telescope designed for continuous observations of astrophysical phenomena varying on scales from seconds to months, especially for prompt optical counterparts of Gamma Ray Bursts (GRBs). Other scientific goals include searching for novae and supernovae stars and monitoring of interesting objects such as blazars, AGNs or variable stars. The design of the apparatus allows to monitor a large fraction of the sky with a range of $12^m - 13^m$ and time resolution of the order of 1 – 10 seconds.

For efficient search for prompt optical counterparts of GRBs we have designed a system consisting of 2 sites separated by a distance of about 100 km allowing to reject flashes from satellite and other near-Earth object by parallax. Each site will consist of 12 custom-designed CCD cameras placed on specially designed equatorial mounts (4 cameras per mount). The full Pi of the Sky system will be capable of continuous observation of about 1.5 steradians in order to increase a chance of occurring a GRB in the observed area. The whole system is under construction now. In October 2010 the first unit of the new Pi of the Sky detector system was successfully installed in the INTA El Arenosillo Test Centre in Spain.

Necessary tests before constructing the final version were performed with a prototype consisting of 2 custom-designed cameras placed on an equatorial mount. The prototype had been working in Las Campanas Observatory (LCO) in Chile since June 2004 till the end of 2009. In March 2011 detector was moved to a new site San Pedro de Atacama, approximately 750 km north in Chile. As it was in the LCO this site is equipped with two cameras working in coincidence and observing $20^\circ \times 20^\circ$ field of view with a time resolution of 10 seconds. Each camera is equipped with Canon lenses $f = 85\text{mm}$, $d = f/1.2$, which allows observation of objects to about 12^m (about 13.5^m for 20 co-added frames). Detector is fully autonomous and operate without any human supervision, although remote control via Internet is possible as well.

2. Data processing

“Pi of the Sky” detector has been designed mainly to search and observe prompt optical counterparts of GRBs during or even before gamma emission. To manage this goal it has been necessary to develop an advanced and fully automatic software for real-time data analysis and identification of flashes (Burd et al. 2005). On the other hand analysis of variable stars or searching for nova stars demands precise and time consuming image analysis and data reduction. Thus the Pi of the Sky data analysis consists of on-line and off-line parts. In the normal observing mode images are analyzed on-line in order to find optical flashes. Moreover in order to search for transients with longer timescales a series of scans at the beginning and at the end of the night systematic all-sky scans are performed. During one scan the detector takes three 10s images for each of the ~ 30 pre-defined fields, which are observed each time. An

off-line analysis operates on the scan observations in order to search for novae, supernovae and other optical transients not associated with GRBs.

The on-line analysis enables to find transients in single-image timescales, and allows to distribute alerts to the community for follow-up observations. Off-line data analysis is performed with data based on 200 second exposures obtained by co-adding 20 images and it acts on reduced data cataloged in the database. The aim of the reduction procedure is to reduce the raw data stored as images into essential data describing stars coordinates and brightness. In order to achieve this goal, the following main steps are performed: photometry, astrometry and cataloging to the database.

Reduction pipelines are different for reducing single image and scan images, but almost all of the steps are the same. After dark image subtraction (in order to subtract signal offset and effects of hot pixels) and division by a flat image (allowing to correct non-uniformity of the optics and differences between pixels amplifications) aperture photometry adopted from ASAS experiment (Pojmanski 1997) is used. The procedure finds stars on the frame and determines their coordinates on the CCD chip and brightness. Resulting lists are an input for astrometry, which ensures transformation of chip coordinates into celestial coordinates. The astrometry procedure is an iteration procedure where stars from lists are matched against catalog stars in a given position in the sky. Currently the identification is based on stars from the TYCHO catalog. The identification procedure assumes that identification is positive if an investigated star is closer than 2 arcmin to a star in the TYCHO catalog. After astrometry, star magnitudes are normalized according to V filter magnitudes in the catalog of reference stars. Reduced data are next loaded to the publicly accessible databases, which provide easy data access for broad spectrum of data analysis. Off-line analysis is performed on cataloged data and consists of several different algorithms developed for different purposes, such as looking for nova stars or analysis of variable stars.

3. Pi of the Sky data

Each camera collects about 2 000 – 3 000 frames by night with time resolution of 10 seconds and 2 seconds of readout time. During six years of observations the prototype located in Chile has gathered a large amount of data valuable for astronomical research, e.g allowing identification and cataloging of many different types of variable stars (Majczyna et al. 2008). All data gathered by the prototype are stored in publicly accessible databases and are available on the Pi of the Sky web page: <http://grb.fuw.edu.pl/pi>. Currently three databases are available with star measurements from period:

1. May 2006 – April 2009 containing over 2 billions of measurements for almost 17 millions of objects
2. July 2004 – June 2005 containing almost 800 millions of measurements for about 4.5 millions of objects

3. May 2006 – November 2007 (subset of the first database) containing over 1 000 millions of measurements for almost 11 millions of objects

Both first and third databases contain star measurements collected with Canon EF 85mm, $f/d = 1.2$, data from the second database were gathered with Carl Zeiss Planar T* photo lenses 50mm, $f/d = 1.4$. The third database is the biggest one and includes about 2.16 billion measurements for about 16.7 millions objects. We are open to share our data and to ensure easy public access so a dedicated interface has been developed (Biskup et al. 2008). In order to facilitate a large-scale searches of our databases please send an e-mail to the author.

Interface allows selecting stars according to their type, magnitude, coordinates etc, displaying their light curves and other properties. It is now also possible to download large packets of light curves of multiple stars.

3.1 Selection of data with high-precision measurements

The web interface not only displays star light curves and their properties but also allows to remove low quality data. Many aspects of the analysis, e. g. including search for and identification of variable stars, require to select only data with high measurement precision. Low quality of data makes period determination and classification quite challenging. In order to facilitate large-scale searches demanding high-quality light curves, we developed a system of dedicated filters. This system of data-quality cuts is available on the Pi of the Sky web interface and allows to reject measurements affected by detector imperfections (hot pixels, measurements close to CCD edge, background due to opened shutter) or observations conditions (planet or planetoid passage, a strong Moon background).

The system of filters can significantly improve photometry accuracy (see Fig. 1). For stars with range $7^m - 10^m$ average photometry uncertainty $\sigma \approx 0.018 - 0.024^m$ has been achieved. Application of data-quality cuts can improve the identification and period determination of variable stars (see Fig. 2).

4. Photometry correction with approximate color calibration algorithm

It turns out that after application of the dedicated filters described above the quality of the data can still be improved. The prototype located in LCO was equipped only with IR-UV-cut filter¹, which resulted with relatively wide spectral sensitivity (see Fig. 3). As a result the detector response is correlated with the star spectral type. The

¹From May 2009 we have a standard R filter installed on one of the cameras

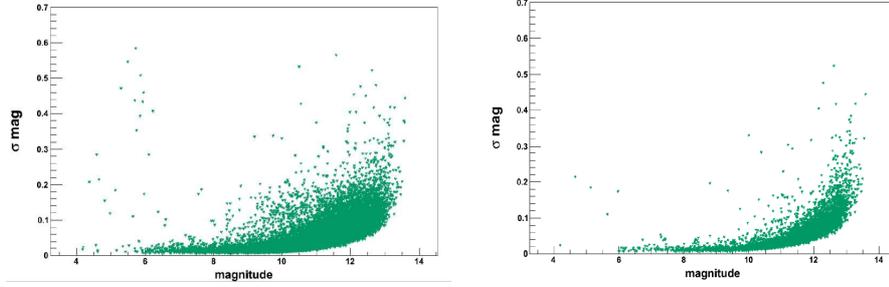


Figure 1. Precision dispersion of star brightness measurements from standard photometry for 200s exposures (20 co-added frames) from Pi of the Sky prototype in Las Campanas Observatory in Chile. Large dispersion (left) is mainly caused by false measurements. After applying quality cuts (right) photometry accuracy improves significantly.

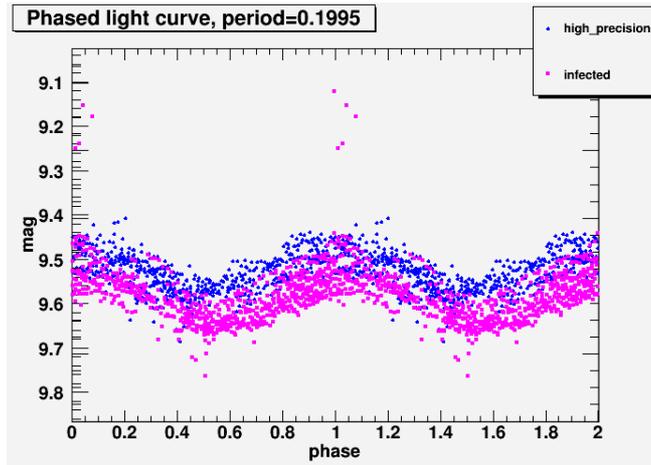


Figure 2. Light curve of the WY Hor variable star. With blue dots measurements with high precision are selected. Measurements marked with pink squares could be affected by detector imperfections or weather conditions and can be eliminated from further analysis.

average magnitude measured by “Pi of the Sky” (M_{PI}) is shifted with respect to the difference of cataloged magnitude given by B–V or J–K (see Fig. 4). Approximation of this dependence with a linear function

$$M_{cor} = M_{PI} - 0.2725 + 0.5258 * (J - K) \quad (1)$$

allows to correct the measurement of each star, so that measured magnitude (M_{cor}) is equal to the catalog V magnitude independently of the spectral type. Systematic error of the fitted linear function is negligible (under 1%), uncertainty of coefficients is mainly caused by the selection criteria and the range of fit, and is of the order of 3%. After applying the correction, distribution of the average magnitude shift for

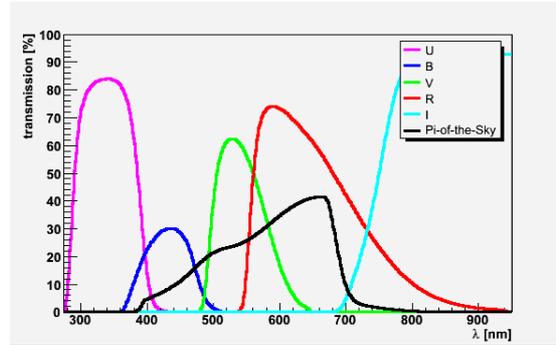


Figure 3. Transmission curves of standard photometric filters. The average wavelength of Pi of the Sky detector corresponds to the V filter .

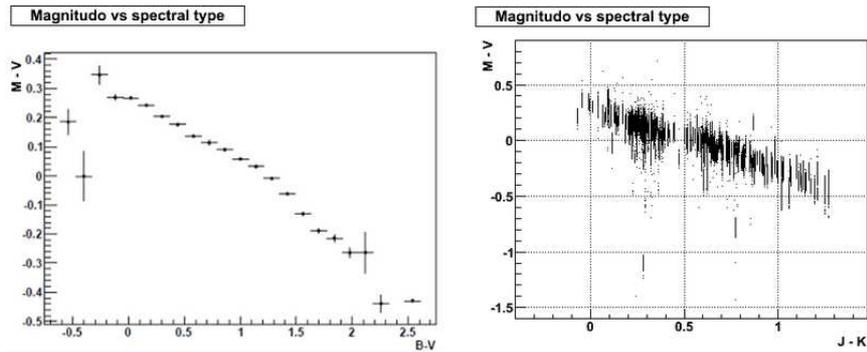


Figure 4. Average difference between the “Pi of the Sky” magnitude and catalog V magnitude for reference stars, as a function of the spectral type given by B–V (left) and J–K (right).

reference stars becomes significantly narrower (example of reference stars for BG Ind variable Rozyczka et al. (2011) are shown in Fig. 5).

Magnitude corrections are calculated by considering differences between measured and expected magnitudes ($M_{corr}-V$) for the selected reference stars. For good results it is enough to consider stars from the field of 5 degrees, that gives us mainly about 1 500 reference stars. Best results are obtained when a quadratic dependence of the correction on the reference star position (Ra,Dec) is fitted for each frame. After the correction surface is fitted, the quality of the fit can be estimated by calculating the average square distance of the reference stars from the surface (see Fig. 6):

$$s^2 = \langle (M_{corr} - V - dM(Ra, Dec))^2 \rangle \quad (2)$$

where $dM(Ra,Dec)$ is the fitted magnitude correction function and “ $\langle \rangle$ ” denotes the weighted average. For about 20% of the frames the calculated s^2 is greater than 0.058, after removing these measurements the star light curve can be improved. Applying

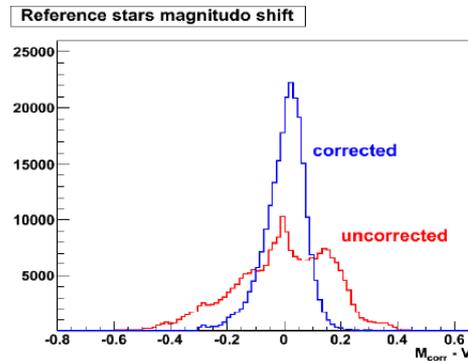


Figure 5. Distribution of the average magnitude shift for reference stars after standard photometry (red) and after spectral correction (blue).

a new algorithm for the BG Ind system the photometry quality was improved and a total systematic uncertainty of the order of 0.05^m has been obtained (Rozyczka et al. (2011)).

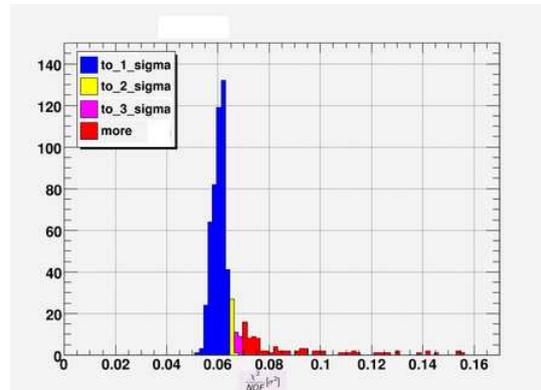


Figure 6. Distribution of s^2 . This information can be used to select the measurements with the most precise photometry

The effect of the photometry correction with a distribution of s^2 on the reconstructed BG Ind light curve are shown in Fig. 7.

5. Conclusions

The Pi of the Sky prototype located in LCO has gathered a large amount of data during the period of 2006 – 2009. All measurements are publicly accessible through a user-friendly web interface on Pi of the Sky Home Page. Effort on improving data quality

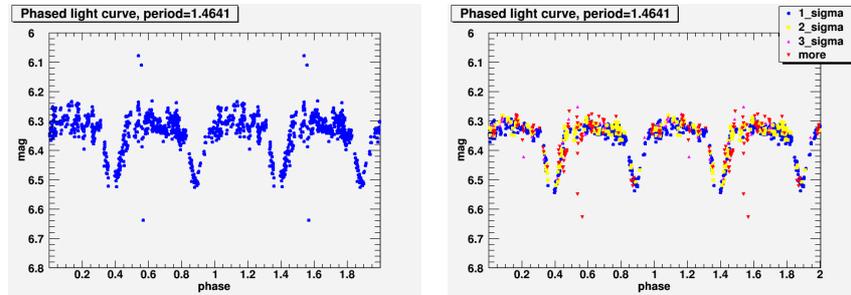


Figure 7. Uncorrected light curve of the BG Ind variable (left) and after spectral corrections with quality cuts (right)

is still ongoing. A system based on data-quality cuts allows to remove measurements from star light curve measurements, which could be affected by different factors due to detector imperfections or weather conditions. Measurements quality can be improved by an approximate color calibration algorithm and a total photometry uncertainty of the order of $4\sigma \approx 0.05^m$ can be obtained (Różycka et al. 2011).

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