Improving photometry of the Pi of the Sky

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Abstract

The "Pi of the Sky" robotic telescope has been designed for monitoring of a significant fraction of the sky with good time resolution and range. The main goal of the "Pi of the Sky" detector is to look for short timescale optical transients arising from various astrophysical phenomena, mainly for optical counterparts of Gamma Ray Burst (GRB). System design, observations methodology as well as developed algorithms also make this detector a sophisticated instrument looking for novae and supernovae stars and monitoring of blasars and AGNs activity. Final detector will consist of two sets of 12 cameras, one camera covering field of view of $20° \times 20°$. For data taken with the prototype detector at Las Campanas Observatory, Chile, photometry uncertainty of $0.018 - 0.024$ magnitudo for stars $7 - 10^m$ was obtained. With new calibration algorithm taking into account the spectral type of reference stars stability of the photometry algorithm can be significantly improved. Preliminary results from the BGInd variable are presented showing that uncertainty of the order of 0.013 can be obtained.

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

1 Introduction

"Pi of the Sky" experiment [1, 2] has been designed for continuous observations of a large part of the sky, in search for 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 blasars and AGNs activity. A large amount of data obtained in the project also allows the identification and cataloging of many different types of variable stars. The "Pi of the Sky" project involves scientists, engineers and students from leading Polish academic and research units: The Andrzej Sołtan Institute for Nuclear Studies, Center for Theoretical Physics (Polish Academy of Science), Institute of Experimental Physics (Faculty of Physics, University of Warsaw),

Warsaw University of Technology, Space Research Center (Polish Academy of Science), Faculty of Mathematics, Informatics and Mechanics (University of Warsaw), Cardinal Wyszynski University, Pedagogical University of Cracow.

2 Detector

The full "Pi of the Sky" system will consist of 2 sites separated by a distance of $\sim$ 100km, which will allow satellite and other near-Earth object rejection by parallax. Each site will consist of 12 highly sustainable, custom-designed survey CCD cameras. Cameras will be placed on custom-designed paralactic mounts (4 cameras per mount) with high tracking precision and two observation modes: "Deep", with all cameras observed the same field (increasing measurement precision and/or time resolution) and "Wide", when cameras cover adjacent field (maximizing FoV). Pairs of cameras will work in coincidence and will observe the same field of view. The whole system will be capable of continuous observation of about 1.5 steradians of the sky, which roughly corresponds to the field of view of the Swift BAT instrument. The full system should be completed by the end of 2010.

Hardware and software solutions were tested with a prototype device installed in the Las Campanas Observatory in Chile in June 2004 and upgraded in 2006 (see fig. 1). It consists of two CCD cameras (2000×2000 pixels, $15\mu m \times 15\mu m$ each) observing the same field of view ($20° \times 20°$) with a time resolution of 10 seconds. Each camera is equipped with Canon lenses $f = 85mm$, $d = f/1.2$, which allows observation of objects to $\sim 11^m$ ($\sim 13^m$ for 20 coadded frames). Prototype allows fully autonomous running including diagnostics and recovery from known problems. Human supervision via Internet is possible.

3 Data processing

With each camera taking about 3000 images per night processing of a large amount of data is a non-trivial task. Search for fast optical transients (eg. GRB flashes) requires very fast data processing and identification of events in real-time. On the other hand, nova star search and variable star analysis are based on precise photometry, which requires detailed image analysis and data reduction which is time consuming. To match both requirements two independent analysis paths were developed: on-line part, which takes of fast data scanning in real-time off-line part which performs detailed data analysis.

Figure 1: "Pi of the Sky" prototype detector located in the Las Campanas Observatory in Chile.

3.1 On-line analysis

On-line data analysis is based on dedicated fast algorithms optimized for transient search. In the full system, real-time frame by frame analysis will allow to distribute alerts to the community for follow-up observations.

After the dark frame subtraction an image is transformed by special transformation called Laplace filter. New value for each pixel is calculated taking into account a sum of pixels around it and a sum of pixels surrounding central region. The idea of this transformation is to calculate simple aperture brightness for every pixel (fast aperture photometry algorithm).

Resulting image, after Laplace filter, is compared with the reference image stored in memory (based on series of previous images). Any difference observed (above estimated noise level) is considered as a possible "candidate event". All events are then processed through a set of selection algorithms to reject backgrounds such as background fluctuations, hot pixels, cosmic ray hits or satellites. Coincidence between cameras is crucial for CCD related background and cosmic ray recognition. To allow for efficient background rejection multilevel selection system, with pipeline data processing similar to trigger systems in particle physics experiments is used.

3.2 Off-line data reduction

The aim of the off-line data analysis is to identify all objects on an image, and add their measurements to the database. The reduction pipeline consists a three main stages: photometry, astrometry and cataloging. The data stored in the catalogue are then a subject to off-line analysis, which consists of several different algorithms.

Algorithms optimized for off-line data reduction are applied to sums of 20 subsequent frames, which is equivalent to the analysis of 200 seconds exposure. After dark frame subtraction and flat correction multiple aperture photometry is used, adopted from ASAS [3] experiment. The procedure prepares lists of stars with (x, y) coordinates on CCD and estimated magnitudes for each camera. The lists are then an input for astrometry procedure. It is an iteration procedure where stars in from the list are matched against reference stars from the catalog (TYCHO catalog is currently used). After successful reference star matching their measurements are used to calculate photometry corrections (the final measurement is normalized to V magnitudes from TYCHO catalog). Finally, all measurements are added to the PostgreSQL database.

All data taken by the "Pi of the Sky" prototype and stored in the project databases are publicly accessible. Two data sets are currently available: the first database covers period VII.2004-VI.2005 and contains about 790 mln measurements for about 4.5 mln of objects, the new one covers period V.2006-IV.2009 and includes about 2.16 billion measurements for about 16.7 mln objects. A dedicated web interface has been developed to facilitate public access [4].

4 Photometry

4.1 Data quality cuts

Off-line data reduction algorithms are designed for highest efficiency. All collected data are stored in the data base. Additional cuts have to be applied on analysis stage to select data with high measurement precision. Their 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). Dedicated filters, taking into account all known effects, have been developed to remove bad object measurements (or whole images).

Photometry accuracy obtained after applying standard set of cuts to remove bad quality data is illustrated in fig. 2. For stars from 7^m to 10^m average photometry uncertainty of about $0.018 - 0.024^m$ has been obtained.

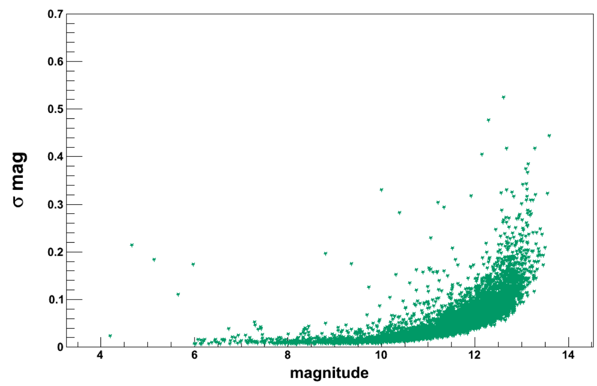

Figure 2: Precision of star brightness measurements from standard photometry, for 200s exposures (20 coadded frames) from "Pi of the Sky" prototype in the Las Campanas Observatory in Chile.

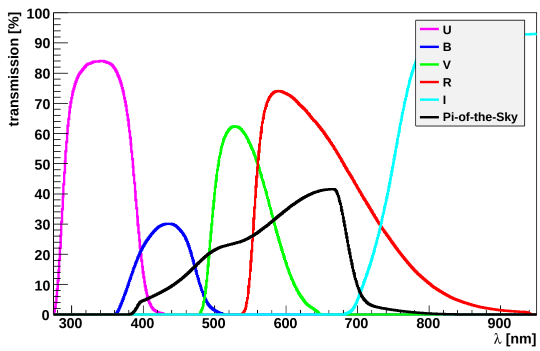

Figure 3: Spectral sensitivity of the "Pi of the Sky" detector, as resulting from the CCD sensitivity and IR+UV filter transmission, compared to transmission curves of standard photometric filters.

4.2 Spectral corrections

Until 2009 the prototype detector installed in LCO was not equipped in any filter, except for IR+UV cut filter[1]. This resulted in a relatively wide spectral sensitivity of the "Pi of the Sky" detector, as shown in fig. 3. The average $\lambda \approx 585$ nm is closest to V filter, which we use as reference in photometry corrections. When trying to improve photometry precision for BGInd variable star, we observed that average magnitudo M_{Pi} of reference stars, as measured by "Pi of the Sky" is shifted systematically with respect to catalogue magnitudo V depending on star spectral type given by the difference of catalogue magnitudo $B - V$ or $J - K$, see fig. 4.

[1]Since summer 2009 one of the cameras is equipped with a standard R filter

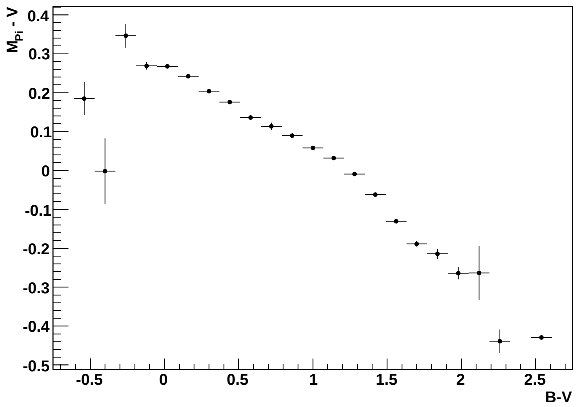

Figure 4: Average difference between the "Pi of the Sky" magnitudo M_{Pi} and catalogue V magnitudo for reference stars, as a function of the spectral type given by $B - V$.

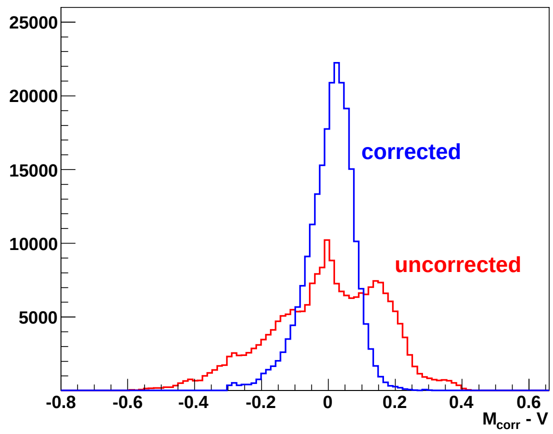

Figure 5: Distribution of the difference between the measured reference star magnitudo and the catalogue V magnitudo before (red) and after (blue) spectral correction.

The dependence of the average differences between measured and catalog magnitudo on the spectral type has been be approximated by a linear function. This allows to correct measurement of each reference star so that, on average, measured magnitudo M_{corr} is the same as catalogue V magnitudo independently of the spectral type. This so called "spectral correction" significantly reduces systematic uncertainties in reference star magnitudo measurements. Distribution of the average magnitudo shift for reference stars used in BGInd analysis, before and after spectral correction is shown in fig. 5.

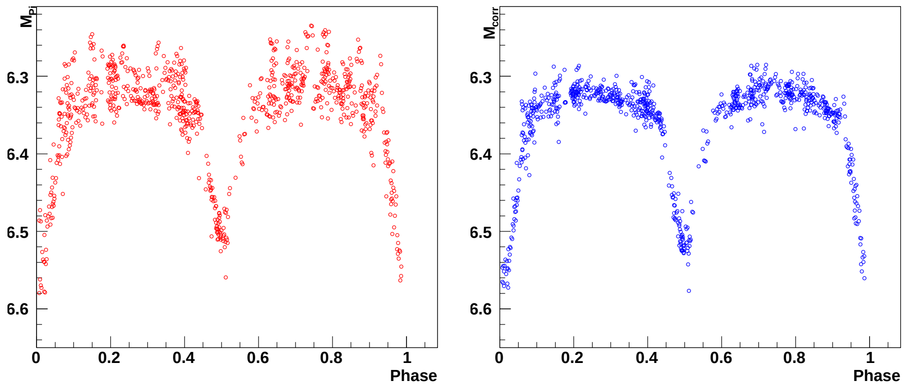

Figure 6: Phased light-curve of the variable star BGInd before (left) and after (right) new correction procedure described in this work.

Corrected reference star measurements are used to evaluate additional photometry correction for the studied object (BGInd variable star is used as an example). To calculate the correction only reference stars with catalogue magnitudo $6 < V < 10$, and with angular distance from the object smaller than 4 degrees are used. These cut values were found to result in the most precise and stable photometry corrections, resulting in the smallest uncertainty in the final BGInd brightness determination. Significant improvement of measurement precision is also obtained when the photometry correction is not calculated as a simple average over all selected reference stars, but a quadratic dependence of correction on the reference star position on the sky is fitted for each frame. The effect of the new photometry correction procedure on the reconstructed BGInd light curve is shown in fig. 6. After applying new corrections measurement quality improves significantly. Uncertainty of the order of 0.013^m can be obtained.

5 Conclusions

"Pi of the Sky" prototype working since 2004 delivered large amount of photometric data which are public available [4]. With improved understanding of the detector and new filtering algorithms data quality and stability of the photometry algorithm can be significantly improved. The work on the new photometry corrections is still ongoing and further improvements are still possible. Additional corrections can take into account the dependence of the star magnitudo error on its catalogue brightness, CCD pixel structure and pixel response non uniformity as well as information on the correction quality from the fit. We hope to be able to obtain the measurement precision of $\sim 0.01^m$ for stars up to 10^m (in optimal observation conditions).

Independent study is also under way to prepare photometry algorithm based on detailed PSF (Point Spread Function) model.

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References

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[4] "Pi of the Sky" measurement databases are available at `http://grb.fuw.edu.pl/pi/databases`