Improving the Photometry of the Pi of the Sky System

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Abstract

The "Pi of the Sky" robotic telescope was designed to monitor 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 the optical counterparts of Gamma Ray Bursts (GRB). The system design, the observation methodology and the algorithms that have been developed make this detector a sophisticated instrument for looking for novae and supernovae stars and for monitoring blasars and AGNs activity. The final detector will consist of two sets of 12 cameras, one camera covering a field of view of $20^\circ \times 20^\circ$. For data taken with the prototype detector at the Las Campanas Observatory, Chile, photometry uncertainty of 0.018–0.024 magnitudo for stars 7–10^m was obtained. With a new calibration algorithm taking into account the spectral type of reference stars, the 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

The "Pi of the Sky" experiment [1, 2] was designed for continuous observations of a large part of the sky, in the 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 blasars and AGNs activity. The large amount of data obtained in the project also enables 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, the Center for Theoretical Physics (Polish Academy of Science), the Institute of Experimental Physics (Faculty of Physics, University of Warsaw), the Warsaw University of Technology, the Space Research Center (Polish Academy of Sciences), the Faculty of Mathematics, Informatics and Mechanics (University of Warsaw), Cardinal Wyszynski University, the Pedagogical University of Cracow.

2 Detector

The full "Pi of the Sky" system will consist of 2 sites separated by a distance of ~ 100 km, which will allow rejection by parallax of satellites and other near-Earth object. Each site will consist of 12 highly sustainable, custom-designed CCD survey cameras. The 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 observing the same field (increasing measurement precision and/or time resolution) and "Wide", when the cameras cover adjacent fields (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 2011.

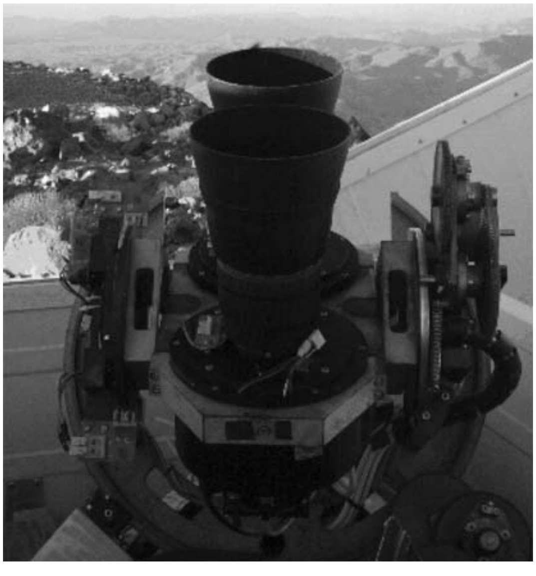

Fig. 1: The "Pi of the Sky" prototype detector located in the Las Campanas Observatory in Chile

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 Figure 1). It consists of two CCD cameras ($2\,000 \times 2\,000$ pixels, 15 $\mu m \times 15$ μm each) observing the same field of view ($20^\circ \times 20^\circ$) with a time resolution of 10 seconds. Each camera is equipped with Canon lenses $f = 85$ mm, $d = f/1.2$, which enables them to observe objects to $\sim 11^m$ ($\sim 13^m$ for 20 coadded frames). The prototype allows fully autonomous running including diagnostics and recovery from known problems. Human supervision is possible via Internet.

3 Data processing

With each camera taking about 3 000 images per night, processing the large amount of data is a non-trivial task. The search for fast optical transients (e.g. GRB flashes) requires very fast data processing and identification of events in real-time. However, nova star search and variable star analysis are based on precise photometry, which requires time-consuming detailed image analysis and data reduction. To meet both requirements, two independent analysis paths were developed: the on-line part, which takes fast data scanning in real-time, and the off-line part, which performs a detailed data analysis.

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 enable alerts to be distributed to the community for follow-up observations.

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

The resulting image, after the Laplace filter, is compared with the reference image stored in memory (based on a series of previous images). Any difference observed (above the 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, a 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 in an image, and to add their measurements to the database. The reduction pipeline consists of three main stages: photometry, astrometry and cataloging. The data stored in the catalogue is then subjected to off-line analysis, which consists of several different algorithms.

Algorithms optimized for off-line data reduction are applied to the sums of 20 subsequent frames, which is equivalent to an analysis of 200 seconds of exposure. After dark frame subtraction and flat correction, multiple aperture photometry is used, adopted from the 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 the astrometry procedure. This is an iteration procedure where stars from the list are matched against reference stars from the catalog (the TYCHO catalog is currently used). After successful reference star matching, their measurements are used to calculate the photometry corrections (the final measurement is normalized to V magnitudes from the 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 the period from July 2004 until June 2005, and contains about 790 mln measurements for about 4.5 mln objects, while the new one covers the period from May 2006 until April 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 maximum efficiency. All collected data is stored in the data base. Additional cuts have to be applied in the analysis stage to select data with high measurement precision. It is necessary to remove measurements affected by detector imperfections (hot pixels, measurement close to the CCD edge, background due to an 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).

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

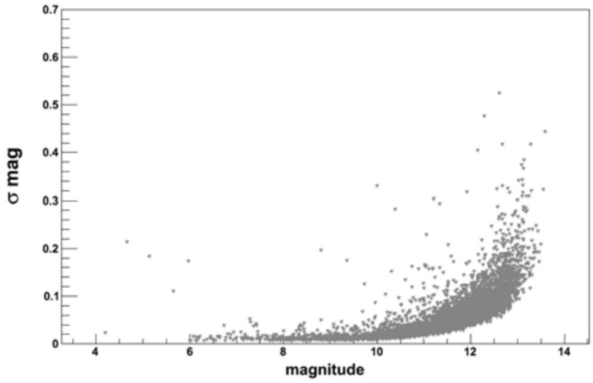

Fig. 2: Precision of star brightness measurements from standard photometry, for 200 s exposures (20 coadded frames) from the "Pi of the Sky" prototype in the Las Campanas Observatory in Chile

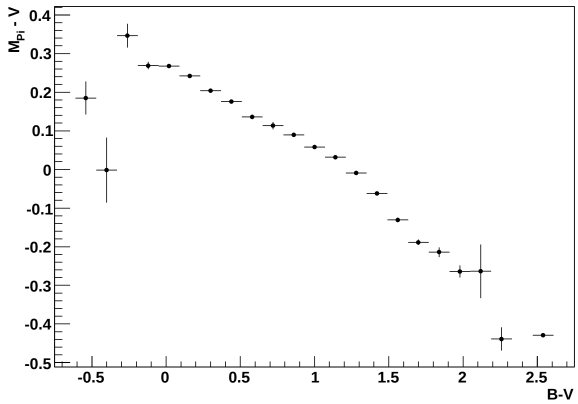

Fig. 4: Average difference between the "Pi of the Sky" magnitudo M_{Pi} and the catalogue V magnitudo for the reference stars, as a function of the spectral type given by $B - V$

4.2 Spectral corrections

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

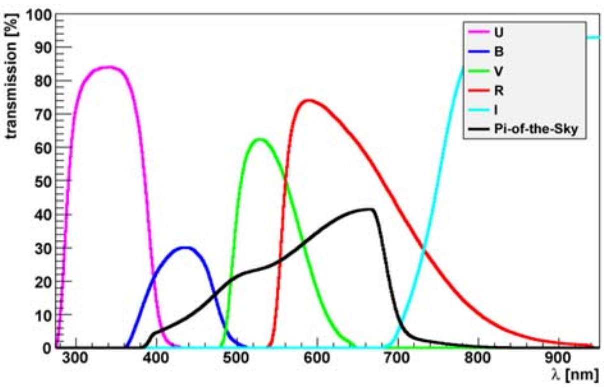

Fig. 3: Spectral sensitivity of the "Pi of the Sky" detector, as resulting from the CCD sensitivity and IR+UV filter transmission, compared to the transmission curves of standard photometric filters

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

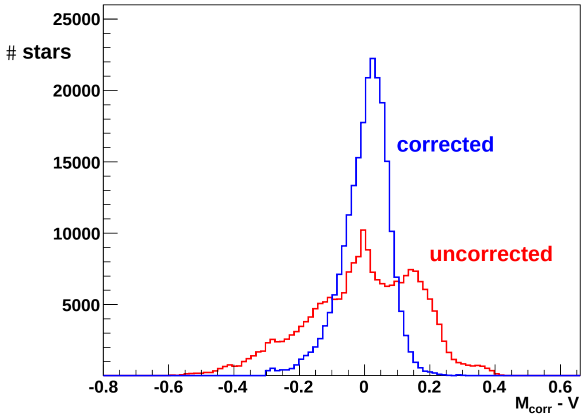

Fig. 5: Distribution of the difference between the measured reference star magnitudo and the catalogue V magnitudo before (red) and after (blue) spectral correction

Corrected reference star measurements are used to evaluate additional photometry correction for the studied object (the BGInd variable star is used as an

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

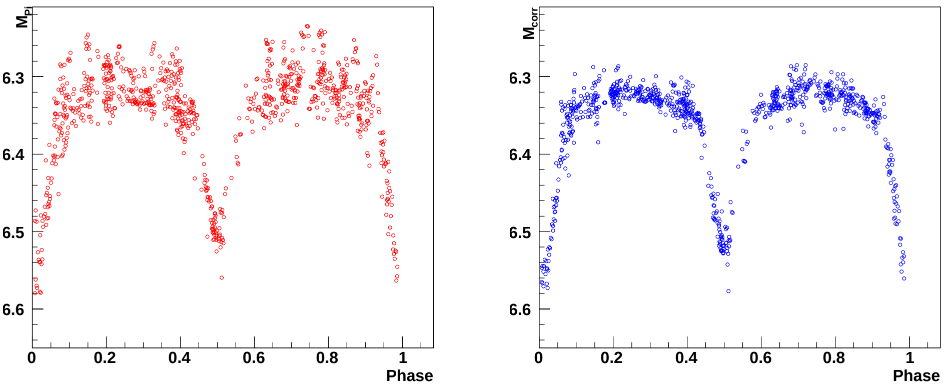

Fig. 6: Phased light-curve of the variable star BGInd before (left) and after (right) the new correction procedure described in this work

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 most stable photometry corrections, resulting in the smallest uncertainty in the final BGInd brightness determination. Significantly improved measurement precision is also obtained when the photometry correction is not calculated as a simple average over all selected reference stars, but when a quadratic dependence of the correction on the reference star position in the sky is fitted for each frame. The effect of the new photometry correction procedure on the reconstructed BGInd light curve is shown in Figure 6. After applying the new corrections, the measurement quality improves significantly. Uncertainty of the order of 0.013^m can be obtained.

5 Conclusions

The "Pi of the Sky" prototype has been working since 2004, and has delivered a large amount of photometric data, which is publicly available [4]. With improved understanding of the detector and new filtering algorithms, the data quality and the stability of the photometry algorithm can be significantly improved. 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 magnitudo error of the star 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 measurement precision of $\sim 0.01^m$ for stars up to 10^m (in optimal observation conditions). An independent study is also under way to prepare a photometry algorithm based on a detailed PSF (Point Spread Function) model.

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