Pi of the Sky telescopes in Spain and Chile. Photometric analysis of the Pi of the Sky data

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**Scientific motivations**

**General goal:**

Study objects varying on scales from seconds to months

- Search for prompt optical counterparts of Gamma Ray Bursts (optical observation before and during GRB)
- Search for other flash like phenomena (supernovae, novae, flare stars explosions)
- Continuous monitoring of interesting objects (blasars, AGNs, variable stars)
Pi of the Sky collaboration http://grb.fuw.edu.pl/pi

Leading Polish academic and research institutions:

- Center for Theoretical Physics, Polish Academy of Science
- National Center for Nuclear Research
- University of Warsaw:
  - Faculty of Physics
  - Faculty of Mathematics, Informatics and Mechanics
- Warsaw University of Technology
  - Faculty of Physics
  - Institute of Electronic Systems
- Space Research Center
- Nicolaus Copernicus Astronomical Center
  - Inspired by prof. B. Paczyński
  - Cooperation with Creotech Ltd. (CCD cameras)
Custom designed cameras

- 2048 x 2048 pixels each
- Canon lenses, f=85 mm, f/d=1.2
- FoV of one camera 20° x 20°
- Fast, programmable electronics (FPGA, μP, RAM)
- Ethernet and USB2.0 interface
- Readout noise \(\approx 15 - 20e^-\)
- 2 stage Peltier cooling of CCD
- Shutter designed for \(10^7\) cycles
- Humidity and temperature measurement inside and outside chamber
Custom designed mounts

Prototype in Chile:
- ASAS mount, design by Pojmański

Final system in Spain:
- New design with 4 cameras by J. Grygorczuk (CBK)
- Classical equatorial system
- Additional mechanism for deflecting cameras
- Controlled by ethernet via Controller Area Network (industrial standard)
- Build at Space Research Center and University of Warsaw, Faculty of Physics
Observation mode

Two observation modes:

- **Side by side (WIDE)**
  - Cameras deflected by $15^0$
  - ➞ cover adjacent fields

- **Common-target (DEEP)**
  - Cameras axis parallel
  - ➞ all camera observe the same field

- Reaches any point in the sky in less than 40 seconds
Status of Pi of the Sky telescopes

Pi of the Sky detector in Chile, 2004 - 2009

- ASAS dome, Las Campanas Observatory - Carnegie Institution of Washington
- 2 cameras (coincidence)
- Time resolutions: 10 s, 2 s readout time
- Range: 11.5 - 12.5 mag
- IR-cut + R Johnson-Bessel filter (since May 2009)
The naked-eye burst - GRB080319B

- Automatically identified by on-line flash recognition algorithm
- Optical observation during gamma emission with 10s time resolution
- The brightest optical counterpart of GRB, peak brightness 5.3 mag
- Published in Nature 11 Sept 2008, Vol. 455 No. 7210
Status of Pi of the Sky telescopes

Moving prototype to San Pedro de Atacama Observatory, Chile, March, 2011

The SPdA panorama

The open dome and cameras at sunrise
San Pedro de Atacama Observatory, Chile

- Institute of Astrophysics of Andalusia (40 cm telescope)
- MicroFun project (40 cm telescope)
- 2 x 200 mm lenses by Alain Maury
- A variety of „tourist” telescopes

309 observing nights in 2010

Meteo info in realtime from Alain's weather station
New site in Spain

INTA El Arenosillo, Huelva, October 2010
The Ultimate System

- Two sets of 12 CCD cameras
- Satellite and other near-Earth objects rejection by parallax
- FoV 1.5 sr ($\approx$SWIFT)
GLORIA – GLObal Robotic-telescopes Intelligent Array

Main goals:
- Open-access network of robotic telescopes for citizen science
- Web 2.0 environment for easy access to telescopes and data
- Free software for telescope control and data analysis
- Opened for interested participants

http://robtel.eu
Observation strategy

**standard approach:**

- wait for GRB alert listening to GCN

**new approach:**

- look everywhere, all the time with self-triggering - **Pi of the Sky**

- Following center of field of SWIFT
- Reacts to alerts from GCN
- Evening and morning all sky scan
- On-line flash recognition algorithm looks for flashes
- System observes pre-defined overlapping $20^\circ \times 20^\circ$ fields
On-line analysis
Flash recognition in real time analysis frame by frame:
- Dark frame subtraction
- Fast photometry including numerical filter
- Comparison with reference image (series of previous images)
- Multilevel selection system to reject backgrounds (fluctuations, hot pixels, cosmic ray hits, satellites)
- Multilevel trigger concept - ideas from particle physics
Standard reduction

Off-line analysis

Algorithms optimized for data reduction:

- Adding 20 subsequent frames
- Dark frame subtraction, flat correction
- Multiple aperture photometry (ASAS)
- Astrometry, reference star selection
- Normalization to V magnitudes from TYCHO catalog
- Cataloging of raw data to the database
Pi of the Sky database

Open access to all raw data:
http://grb.fuw.edu.pl/pi/databases

Data period May 2006 - April 2009
16.7 million of objects,
2.16 billion measurements

Data period May 2006 - Nov 2007
10.8 mln of objects,
1002 mln measurements

Data period July 2004 - June 2005
4.5 mln of objects,
790 mln measurements
System of dedicated filters to remove bad measurements or frames:

- Hot pixels
- Measurements near CCD edge
- Planet or planetoid passage
- Columns around bright stars (reading the chip with the shutter opened)
- Frames with strong and varying sky background
- Frames with large astrometric error
Photometry accuracy significantly improves after removing bad quality data
For stars $7^m - 10^m$  
$\langle \sigma_m \rangle \approx 0.015$ achieved

Histogram of sigma magnitude for stars with magnitude $<12.5$
Approximate color calibration algorithm

The spectral sensitivity of Pi of the Sky detector

Only UV-IR filter, CCD sensitivity relatively wide

Average $\lambda \approx 585$ nm - closest to V filter
The spectral sensitivity of Pi of the Sky detector

- Detector response is correlated with the star spectral type (B-V or J-K)
- Reference stars measurements are corrected for spectral type:
  \[ M_{\text{corr}} = M - 0.2725 + 0.5258 \times (J-K) \]
- Can be used to improve photometry accuracy
Reference star selection

- Reference stars $6^m - 10^m$ with angular distance smaller than 5 degrees
- Accepting reference stars with $M_{\text{coor}} - V < 0.2$
- Accepting reference stars with $RMS_{M_{\text{coor}}} < 0.07$
- Accepting reference stars with number of measurements $> 100$
Photometry correction and quality

Correction calculation
- Quadratic dependence fitted to selected reference stars
- Weights depending on star distance and brightness

Correction fit quality estimate
Average square distance of the reference stars from the fitted correction surface
- Average shift of about 0.05-0.06
- For about 20% of frames calculated average shift is greater than 0.058
- This information can be used to select measurements with most precise photometry
BG Ind light curve

Uncorrected light curve for BG Ind variable

Corrected light curve for BG Ind variable
BG Ind light curve

**Uncorrected light curve for BG Ind variable**

**Corrected light curve with correction quality cut (1 sigma)**
BG Ind light curve

Fit residua vs phase for BG Ind variable before photometry correction

Fit residua vs phase for BG Ind variable after photometry correction

Histogram of residua fit for BG Ind variable before photometry correction

Histogram of residua fit for BG Ind variable after photometry correction
BG Ind light curve

Uncorrected light curve for BG Ind variable

- Quality improves significantly
- Uncertainty of the order of $0.013^m$ can be obtained


Absolute properties of BG Ind - a bright F3 system just leaving the Main Sequence
M. Rozyczka, J. Kaluzny, W. Pych, M. Konacki, K. Malek, L. Mankiewicz, M. Sokolowski, A.F. Zarnecki
GH Car light curve

Uncorrected light curve for GH Car variable

Corrected light curve with correction quality cut

Histogram of residua fit for GH Car variable before photometry correction

Histogram of residua fit for GH Car variable after photometry correction
Comparision between prototype and final detector

Uncertainty of magnitudo measurement

LCO

INTA

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Spectral corrections for new detector at INTA

Before correction

After correction
Reference stars magnitude shift

Detector in LCO

New unit in Spain

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Pi of the Sky telescopes & photometry data analysis
Summary - Pi of the Sky status:

- New detector unit in Spain
  - Successful 12 months of operation, detector working as expected
- Prototype in Chile:
  - Taking data again after moving from LCO to San Pedro de Atacama Observatory in March 2011
A system of dedicated filters to remove bad measurements or frames, like reading the chip with open shutter, passing planet or planetoids, strong and varying sky background, hot pixels

Approximate color calibration algorithm based on the spectral type of reference stars

For new data system of dedicated filters is applied with cataloging procedure

Quality filters available in interface

Correction of photometry available on request
Summary - Pi of the Sky database:

- Public databases:
  - [http://grb.fuw.edu.pl/pi/databases](http://grb.fuw.edu.pl/pi/databases)
  - Access to billions measurements through user-friendly web interface
  - Downloading large packets of light curves of multiple stars
  - Quality filters allow excluding poor quality data
THE END