Photometric analysis of Pi of the Sky data

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Introduction.
Reduction and analysis of collected data.
Color correction.
Statistical data quality estimate.
Examples.
Summary.
Introduction.

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)
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)*
Detector in SPDA.

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

The SPdA panorama

The open dome and cameras at sunrise
Detector in INTA.

INTA El Arenosillo, Huelva, October 2010
Detectors parameters.

- 2048 x 2048 pixels each
- Canon lenses, f=85 mm, f/d=1.2
- FoV of one camera $20^\circ \times 20^\circ$
- Fast, programmable electronics (FPGA, $\mu$P, 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
Two observation modes:

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

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

- Reaches any point in the sky in less than 40 seconds
Future plans.

- Two sets of 8 or 12 CCD cameras (≈ 240 km).
- Satellite and other Near Earth Objects rejection by paralax (870 - 6800 km from the Earth centre).
- FOV about 1.5 sr (≈ SWIFT)
- First site to be completed this year.
Future plans.

New platform should be accomplished by March 15 at latest.
Recent observations - GLORIA.

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
Recent observations - GLORIA.
Recent observations - parallax.

- Since March 2011 we are able to observe a parallax of objects close to the Earth,
- It is very important, because it allow us to reject false triggers, mostly due to artificial satellites, other kinds of rockets and space debris elements.
Recent observations - parallax.

Between 20600 km and 38.2 million km one can find:
- geostationary and GPS satellites,
- space debris,
- the Moon,
- near Earth comets, planetoids, etc.
Fig. 5. Differences between distances to satellites calculated and taken from TLE base. There is a correction to Earth's radius and 1000 km cut.
Recent observations - BW Scl.
Reduction and analysis.

* on-line reduction.
  - flash recognition in real time analysis frame by frame.
  - dark frame substraction.
  - fast photometry including numerical filter.
  - comparison with reference image (series of previous images).

* off-line reduction.
  - algorithms optimized for data reduction.
  - adding 20 subsequent frames.
  - dark frame substraction.
  - multiple aperture photometry (ASAS)
  - astrometry
  - normalization to V magnitudes from TYCHO catalog.
  - cataloging of raw data to the database.

* additional analysis.
  - multilevel selection system to reject strong backgrounds (fluctuations, hotpixels, cosmic ray hits, satellites).
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Photometry accuracy significantly improves after removing bad quality data.

For stars $7^m \text{ – } 10^m$

$\langle \sigma_m \rangle \approx 0.018 \text{ - } 0.024$ achieved.
We also introduce additional correction taking into account facts that:

* we have not any filters.
* detector response is correlated with the star spectral type (B-V or J-K).
* catalog stars measurements are corrected for spectral type:

\[ M_{\text{corr}} - M = -0.2725 + 0.5258 \times (J - K) \] (1)
Catalog stars cuts.

- 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 $> 100$
Color calibration algorithm.

Normalization method
- quadratic corrections fitted to reference stars
- weights depending on distance and brightness

Correction fit quality check
Average square distance of the reference stars from the fitted correction surface
- $\chi^2$ of about 0.05-0.06
- For about 20% of frames calculated $\chi^2$ is greater than 0.058
- This information can be used to select measurements with most precise photometry
Results.

Uncorrected light curve for BG Ind variable

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

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Różyczka, M., Kałużny, J., Pych, W., Konacki, M., Malek, K., L. Mankiewicz, M. Sokołowski, A.F. Żarnecki,

Absolute properties of BG Ind - a bright F3 system just leaving the main sequence

Statistical methods.

In this case, in order to check if the measurement is good or not we are taking into account statistical properties of the whole frame. Every frame which contain analysed star measurement is analysed in the same way:

- for each catalog star visible on given frame we calculate median (Med) based on measurements taken from the same field.
- for each catalog star visible on given frame we calculate $M_{\text{corr}} - \text{Med}$ values where $M_{\text{corr}}$ is corrected catalog star magnitude given by the (1) equation.
- $M_{\text{corr}} - \text{Med}$ histograms.
Statistical methods.

- divide all analysed frames for "good" and "bad" depending on the percentage of the catalog stars which have $M_{corr} - Med$ greater than $2\sigma$.
- $\sigma$ is taken from Gauss function fitted to $M_{corr} - Med$ histogram calculated for all catalog stars visible on given field.
we assume "good" frames have $\leq 10\%$ bad catalog stars, and "bad" frames have $> 10\%$ bad catalog stars.
Statistical methods.

* for all frames belongs to given field we can calculate their quality.
* for each frame from given field we find all stars measurements.
* calculate $<M>$ and $\sigma < M >$ for every star based on each group of frames (good/bad/all). We also taking into account the quality of the data.
Statistical methods.
Statistical methods.
Example HD 276 star.

**Light Curve 5114863**

- Time [HJD] vs Magnitude

**Histogram for 5114863**

- Constant: 237.3 ± 0.0
- Mean: 7.79 ± 0.00
- Sigma: 0.02399 ± 0.000034
Example HD 276 star.
Example HD 276 star.
Example HD 276 star.
Example HD 276 star.

**5114863 light curve**

- Magnitude vs. Time

**Light Curve 5114863**

- Magnitude vs. Time [HJD]
Example HD 276 star.
Summary

- A lot of informations about Pi of the Sky project you can find on the project webpage [http://grb.fuw.edu.pl](http://grb.fuw.edu.pl).

- We created a system of dedicated filters to mark bad measurements or frames which is applied with cataloging procedure for new data.

- To improve the quality of the data we created approximate color calibration algorithm based on the spectral type of catalog stars.

- We also developed another statistical method, taking into account all stars on the frame, allowing to reject bad quality exposures.

- After the new frame selection is applied, photometry accuracy of 0.01-0.03 can be obtained. Further improvement is possible in dedicated analysis of selected objects.

- The quality of the data is good enough to be used by another scientists in their research.