Pi of the Sky — all-sky, real-time search for fast optical transients*,**, A. Burd¹, M. Cwiok², H. Czyrkowski², R. Dabrowski², W. Dominik², M. Grajda¹, M. Husejko¹, M. Jegier¹, A. Kalicki¹, G. Kasprowicz¹, K. Kierzkowski², K. Kwiecinska³, L. Mankiewicz⁴, K. Nawrocki⁵, B. Pilecki⁶, L.W. Piotrowski², K. Pozniak¹, R. Romaniuk¹, R. Salanski¹, M. Sokolowski⁶, D. Szczygieł⁶, G. Wrochna⁶,*, and W. Zabolotny¹

¹Institute of Electronic Systems, Warsaw University of Technology, Nowowiejska 15/19, 00-665 Warsaw, Poland
²Institute of Experimental Physics, Faculty of Physics, Warsaw University, Hoża 69, 00-681 Warsaw, Poland
³Department of Mathematics and Natural Sciences, Cardinal Wyszynski University, Dewajtis 5, 01-815 Warsaw, Poland
⁴Center for Theoretical Physics, Polish Academy of Science, Al. Lotników 32/46, 00-668 Warsaw, Poland
⁵Astronomical Observatory, Warsaw University, Al. Ujazdowskie 4, 00-478 Warsaw, Poland
⁶Soltan Institute for Nuclear Studies, Hoża 69, 00-681 Warsaw, Poland

Abstract

An apparatus to search for optical flashes in the sky is described. It has been optimized for gamma ray bursts (GRB) optical counterparts. It consists of 2 × 16 cameras covering all the sky. The sky is monitored continuously and the data are analysed on-line. It has self-triggering capability and can react to external triggers with negative delay. The prototype with two cameras has been installed at Las Campanas (Chile) and is operational from July 2004. The paper presents general idea and describes the apparatus in detail. Performance of the prototype is briefly reviewed and perspectives for the future are outlined.

Key words: Gamma rays: bursts, Instrumentation: detectors, Techniques: photometric, Methods: miscellaneous

PACS: 98.70.Rz, 95.75.Rs, 95.55.Aq
1 Introduction

Gamma ray bursts (GRB) are one of the most intriguing phenomena in the Universe. Several thousands of them have been observed by gamma ray detectors carried by satellites. In order to understand their nature, observations should be carried out in all wavelengths. Optical domain is especially important, because of high spatial resolution and possibility of detailed spectral analysis. Unfortunately, only a few dozens of GRB sources have been seen in visible light. Moreover, most of them have been observed as late as hours or days after the burst as very faint afterglows. So far, only one GRB was caught by an optical device within the first minute after a GRB (Akerlof et al. 1999). The observation was made by a small robotic telescope ROTSE equipped with photo-lenses of 10 cm aperture (Akerlof et al. 2000). Typical professional telescopes have too large inertia and too small field of view to be able to react promptly to GRB alerts from satellites.

Since then, many small robotic telescopes have been build and installed around the globe in order to search for GRB optical counterparts. Representative examples are BOOTES (Ceron et al. 2003), MASTER (Lipunov 2004), RAPTOR (Vestrand et al. 2003), and ROTSE-III (Akerlof et al. 2003). Recent review was written by (Andersen & Pedersen 2004).

Typically, they have optics of rather short focal length and cover relatively large field of view (1-100°). They await for GRB alerts distributed by the GCN system (Barthelmy et al. 2000) and move to the target as soon as possible in order to take exposures. During long periods between GCN alerts these systems typically observe a chosen Field Of View (FOV) and collect data in search for transient phenomena of astrophysical interest.

Unfortunately, so far the GRB930123 recorded by ROTSE remains the only optical observation at the time comparable to the duration of the gamma burst itself. The reason is two-fold. First, decision making process and propagation of the triggering information from a satellite to the observing device takes time. Second, the inertia of the devices, although much smaller than that for large telescopes, is still responsible for a significant delay. During this time the object in question is fading rapidly and it goes beyond the limiting magnitude of the device before the first exposure begins. It is expected that alert system associated with the "Swift" satellite (Gehrels et al. 2004), scheduled for launch this year, will operate more efficiently and limit delay related to

\* http://grb.fuw.edu.pl
\**This work is supported by the Polish Committee for Scientific Research under grant 2 P03B 038 25
\* Corresponding author.

Email address: wrochna@fuw.edu.pl (G. Wrochna).
signal propagation from satellite detector to GCN. However, even the fastest systems cannot guarantee systematic observations of the critical region of the sky prior to the satellite trigger. Certainly, such observations may reveal additional phenomena associated with GRB and shed a new light on their physical nature (Paczynski 2001).

2 The idea of the real-time search with multilevel trigger system

In order to overcome the two major problems of classical robotic telescopes we propose a different approach, based on author’s experience from particle physics experiments. Trigger propagation time can be eliminated if the device has self-triggering capability. Inertia of the system does not matter if the object in question is already inside FOV before the investigated phenomenon (e.g. GRB) takes place. The apparatus described in this paper exhibits those two features.

We propose to build a system consisting of a number of CCD cameras covering as wide field of view as possible. The cameras monitor continuously the sky taking relatively short (5-10 s) exposures. The data are analyzed on-line, in search for optical transients. The idea is simple: it is enough to check for a presence of a star-like object in a given frame, which was not present in preceding frames. However, practical realization is difficult, because of large data stream involved (see an example below). It is impossible to invent a single algorithm, which is fast enough, and has high efficiency and low rate of false triggers at the same time. The problem could be solved by implementing a multi-level trigger system. The first level algorithms are very simple and have high efficiency for interesting events, but they produce a lot of background. The rate of background events at this stage can be several orders of magnitude higher than the rate of real events we are looking for. The only purpose of the first level algorithms is to reduce the data stream to be analyzed by higher levels. Thus, the second level algorithm can be somewhat more complicated and perform better background rejection. The highest levels deal only with a very low rate of suspected events and can employ sophisticated algorithms to clean up the final sample.

Selected events can be submitted to larger telescopes to follow and/or can be checked against GRB triggers from other sources, even if they come much later. The data cannot be stored for a long time, because of limited disc space, but can be temporarily kept in some buffer, to examine any late arriving external alerts.
3 "π of the Sky" apparatus design

Practical realization of the ideas outlined in the previous section may look as follows. One observing module consists of a $4 \times 4$ matrix of CCD cameras. The camera is based on CCD with $2000 \times 2000$ pixels $15 \times 15 \, \mu\text{m}^2$ each. Equipped with lenses of focal length $f = 50 \, \text{mm}$, the camera covers $33^\circ \times 33^\circ$ field of view. The module of 16 cameras covers almost all visible sky down to $20^\circ$ above the horizon. This is a solid angle above $\pi$ steradians and hence the name of the apparatus — "π of the Sky".

The most common background sources for flash recognition algorithms are cosmic rays crossing the CCD and sunlight reflexes from artificial satellites. In order to fight this background two twin modules should be installed at some distance of the order of 10 km. Cosmic rays can be eliminated by taking simple coincidence. Flashing satellites could be resolved by their parallax.

Gamma ray bursts typically have duration of 0.01-100 s. GRB930123 flash observed by ROTSE also had the decay time of the order of dozens of seconds. Therefore, the exposure time of 2-10 s seems to be optimal to search for GRB related flashes. With the focal length of $f = 50 \, \text{mm}$ and the pixel size of $15 \, \text{mm}$ one can take 5 s exposures on a static mount. This is very convenient and significantly reduces the cost. The CCD sensitive area is $30 \times 30 \, \text{mm}^2$ and can be illuminated with standard camera lenses, commercially available for a low price.

With 5 s exposures and 1 s readout time one can take 10 frames per minute, i.e. 5000-10000 frames per night. This imposes severe requirement for the mechanics of a shutter, which for a few years of operation must sustain $10^7$ opening cycles. Single frame from one camera occupies 8 MB (megabytes). The average data rate from a single camera is thus $1.3 \, \text{MB/s} = 3 \, \text{GB/h}$. Two modules, 16 cameras each, produce the data stream of 100 GB/h, i.e. 1 TB/night. This poses the limit on the temporary data storage. Most of the analysis must be done on-line, in real time. Only carefully selected data can be kept for further inspection.

Realisation of the project outlined above is foreseen in the following steps:

- **Phase-0.** Tests with one and with two cameras on a fixed mount.
- **Phase-1.** Two cameras observing the same field, installed on a robotic mount.
- **Phase-2.** Two modules, 16 cameras each, as described above.
- **Phase-3.** Four pairs of modules installed around the globe, to maximise the coverage and observing time.
4 Phase-0 tests

The phase-0 of the project has been already completed. Tests have been performed at Brwinow (52.14725° N, 20.71850° E), 30 km West of Warsaw. We have started with a modified G-16 camera (Smith 2003) equipped with a Kodak CCD KAF-0401E. It has $768 \times 512$ pixels, $9 \times 9 \mu m^2$ each. Images from about 50 nights between November 2002 and September 2003 have been recorded. In the meantime the first prototype of $2000 \times 2000$ pixel camera has been built. It was used for further tests from October 2003. The first final camera for the phase-2 has been completed in February 2004, whereas the second one in June 2004 (Fig. 1).

Almost 200 GB of data have been collected in different configurations. Those include both, fixed and robotic mounts. The data have been used thoroughly to design and tune flash recognition algorithms. Major background sources have been identified and their rates have been measured. At least one interesting fast optical transient has been observed. The results will be published elsewhere.

Fig. 1. The "π of the Sky" cameras and the mount at the test site in Poland.

Fig. 2. The Las Campanas site. Left to right: ASAS dome housing "π of the Sky" apparatus, ASAS 10" telescope dome, Control Room.

5 "π of the Sky" phase-1 system

The phase-1 system has been installed at the Las Campanas Observatory in Chile in June 2004 (Fig. 2). Regular operation started in July 2004. The system consists of two custom designed CCD cameras installed on a robotic mount (Fig. 1).

The cameras are based on CCD442A sensor by Fairchild Imaging. The CCD has $2032 \times 2032$ sensitive pixels, $15 \times 15 \mu m^2$ each. It is read out with a frequency 2 MHz/pixel, so the entire matrix is read out in 2 s. After amplification,
the signal is digitized by 16-bit ADC and stored in a memory. The camera is read out and controlled by a PC through a fast USB 2.0 interface. Data transfer takes less than one second and can be done while the next exposure is already being taken. Readout speed, amplifier gain and other parameters are programmable via USB. The sensor is cooled with a stack of two Peltier modules about 35 degrees below the ambient temperature. Special heavy-duty mechanical shutter was designed to sustain over $10^7$ opening cycles. A prototype has been tested at high frequency in a lab. The first signs of degradation have appeared after $1.2 \cdot 10^7$ cycles. Details of the camera design will be published elsewhere.

Each camera is equipped with Planar-T* photo-lenses by Carl-Zeiss of a focal length $f = 50$ mm and an aperture $d = f/1.4$. Focusing is performed by a step motor with a controller build into the camera and remotely controlled through the USB. The effective field of view is $33^\circ \times 33^\circ$. The two cameras are installed on a common mount in such a way that they observe the same field. The mount we use was originally designed for the ASAS experiment (Pojmanski 2000) and modified to suit the "π of the Sky" needs.

It is driven by step motors controlled by a PC through RS232 serial interface. The mount can reach any point in the sky in less than one-minute time. The whole setup is installed in the ASAS dome together with other ASAS telescopes.

6 Operation and data flow

The apparatus is controlled by a PC located inside the dome. Second PC, located in a nearby Control Room is used for off-line data analysis. The system is fully autonomous, but also fully controllable via Internet. During the normal operation the system runs autonomously according to the preprogrammed schedule. Dedicated script language has been developed to make the schedule programming easy and flexible.

For most of the time the cameras follow the field of view of the HETE satellite (Ricker et al. 2002). Its position is read out from the Internet in regular intervals and the mount position is automatically corrected accordingly. If the HETE FOV is not visible, another location in the sky is programmed. The system is also listening to GCN alerts received directly and through another server in Warsaw as a backup. Should an alert located outside the current FOV arrive, the mount automatically moves towards the target and exposures are being taken. Twice a night an all sky scanning is performed. 16 fields are visited and three images of each are taken by both cameras. A single scan last about 20 minutes.
Because the mount follows the sidereal movement, one can take longer exposures than in the case of a fixed system. We have chosen 10 s as a compromise between the magnitude reach and time resolution for short flashes. The images are immediately analyzed while in the computer RAM in search for flashes with a rise time of the order of seconds. Then, they are temporarily stored on a disc and can be reexamined in case of late arrival of an external alert. If a flash candidate is found the 100 $\times$ 100 pixel samples of $\pm 7$ frames are stored permanently for the record.

In the meantime, the images are copied to the second PC, which superposes the images and searches for optical transients with a rise time of minutes. During the day, two analyses are performed in parallel on the temporarily stored data. The first PC runs fast photometry on individual frames, which can be used later to study rapidly varying objects. The second PC performs precise photometry (Pojmanski 2000) on images superposed by 20. This could be used to study variable stars etc. The results are stored permanently on a disc. Out of almost 30 GB of data taken every night, about 2 GB of results is stored permanently. After 2-3 months a 200 GB removable disc with the results is replaced and taken to Warsaw for further analysis.

7 Software

Both PC are running the Linux operating system. The software is mostly custom written in C++. It consists of a number of modules taking care of different devices: the mount, the cameras, the data acquisition system, the GCN server, etc. All modules are governed by the central module "piman" scheduling the tasks and controlling the information flow. The communication between modules is based on CORBA. Image processing classes make use of "cfitsio" package (Pence 1993). Flash recognition algorithms and fast photometry are custom developed, whereas precise photometry and astrometry is adopted from ASAS (Pojmanski 2000).

Monte Carlo technique was extensively used in development of the algorithms. Optical flashes were simulated by cutting star images from real sky images and pasting them into images under study at random locations. This method was used to evaluate efficiency of flash detection algorithm. Details are described in (Piotrowski & Sokolowski 2004).

The flash recognition algorithm compares a given frame with several preceding ones. It searches for a star-like object, which is missing on preceding frames. Most of the false events are caused by cosmic rays, but those are easily eliminated by coincidence of the two cameras. The most severe background is due to the sunlight reflexes from artificial satellites. We try to eliminate those in
two ways. First, we search for aligned flashes in a single frame, or in different frames. Second, we check the time and location of the flash against a database. Every evening a fresh database is built by merging several ones available on the Internet (McCants 2004).

8 System reliability

The apparatus operates at the Las Campanas Observatory without a permanent human supervision. Therefore, the system must be very reliable. It was achieved by employing self-diagnostics and remote monitoring, as well as hardware redundancy and flexible configuration.

Special care has been taken to ensure seamless recovery after a system failure without human intervention at the site. The cameras have a hardware watchdog build in, which automatically resets the camera and thus reestablishes connection with the PC in case of protocol failure. In addition to the direct Internet connection the two PC are connected together with a Gbit Ethernet. It ensures fast data transfer between the two PC and also serves as a backup in case one of the direct connections breaks. Both PC have "Wake on LAN" and "Boot from LAN" capabilities and can be started from the net in case of a file system failure. Remote file system could be installed and used to recover the local one. Each computer can be remotely reset or powered down/up by the relays driven by the second one. This feature has proved itself to be extremely useful in case of system hang-ups.

The system is designed to be immune to network failures. It can run autonomously for many days. Each night it reads the current schedule from a script and a default script is executed if no current script is found. The system can be effectively monitored with a very small bandwidth. Direct communication with the system is provided by a console module "pshell" which can run at any place and interact with the system exchanging short COBRA packets. Basic information about the system (< 20 kB) is automatically copied every 10 min to a WWW server in Warsaw. Selected sky images are compressed to 4 kB JPEG and also copied to the Warsaw server every 20 min. Should any failure occur, the system sends an SMS with the appropriate information to a mobile phone of a person in charge.

9 System performance

The phase-1 "π of the Sky" system operates regularly from July 2004. Till the end of October, three nights were lost for the maintenance after a double
disk failure and several more due to weather conditions. About half a million
sky images have been taken, accounting for 4 terabytes of data. Each frame
contains about 20000 stars and the results consists of 10 billion photometric
measurements.

The limiting magnitude is $10 - 11^m$ for single frames and $11 - 12^m$ for frames
coadded by 20 (Fig. 3 and 4). Exact limit depends on the sky background,
which strongly varies with the Moon phase. It also depends on the position in
the frame. The corners are somewhat less illuminated than the center.

![FAST PHOTOMETRY](image1)

![PRECISE PHOTOMETRY](image2)

Fig. 3. Fast photometry magnitude of stars vs position in the frame (degrees).

Fig. 4. Precise photometry magnitude of stars vs position in the frame (degrees).

During the first three months of the regular operation, several short optical
flashes have been detected. Most probably they are caused by sun reflexes from
artificial satellites, although they do not correspond to any satellite listed
in commonly available databases. One optical transient lasting $> 10$ s was
observed during tests with a single camera, which cannot be explained by
a satellite reflex. So far, no optical transient coinciding with a known GRB
was found. Limits for optical counterparts have been given for a few GRB
(Cwiok 2004). Detailed results will be published elsewhere.

10 Perspectives

Current efforts in the project concentrate in two areas. First, the software
is still being developed to improve flash recognition algorithms and increase
precision of the photometry (Fig. 5 and 6). The work is going on to develop a
database with photometric measurements, which can be used to study variable
stars, etc. Second, the design of the phase-2 apparatus ($2 \times 16$ cameras covering
all the sky) is moving from a conceptual to a technical level. At the same time
we search for optimal locations of the phase-3 systems.

The "$\pi$ of the Sky" apparatus can be also considered as an Earth based proto-
type of a lighter, yet more powerful system, which can operate in the space
Fig. 5. Precision vs brightness for the fast photometry.

Fig. 6. Precision vs brightness for the precise photometry.

(Tsarevsky 2002). On the other hand it stands as a milestone towards future telescope "farms" monitoring all sky in search for rare and rapid phenomena. The system is already integrated with GCN (Barthelmy et al. 2000) and OTC (Kuvshinov & Lipunov 2004) networks. "π of the Sky" triggers will be soon automatically sent to the robotic telescopes of ASAS. We also consider to integrate our system with more sophisticated networks, e.g. TALON (White et al. 2004).

Technological progress in image sensors, electronics and computers will undoubtedly push observational astronomy towards huge data streams, which have to be analyzed on-line. Real time event selection mechanisms, large system issues, maintenance and operation problems are the areas that need a lot of research and development. The "π of the Sky" experiment is one of the first steps on this new land.

Acknowledgments

We are very much obliged to B. Paczynski for his support and encouragement. This project from the very beginning benefits from the experience gained with All Sky Automatic Survey (ASAS), generously shared with us by its leader, G. Pojmanski.

References

C. Akerlof et al., "Observation of contemporaneous optical radiation from a γ-ray burst", Nature 398, p. 400, 1999.
C. Akerlof et al., "Prompt Optical Observations of Gamma-Ray Bursts", ApJ 532, L25, 2000. http://www.rotse.net/

C. Akerlof et al., "The ROTSE-III Robotic Telescope System", PASP 115, 132-140, 2003. http://www.rotse.net/

M.I. Andersen and H. Pedersen, "Gamma-ray burst optical follow ups with robotic telescopes", AN 325, No. 6-8, p. 483, 2004.

S.D. Barthelmy et al., "GRB Coordinate Network (GCN): A Status Report", in R.M.Kippen et al. (Eds.), "Proceedings of the 5th Huntsville GRB Workshop", 526, 731, 2000. http://gcn.gsfc.nasa.gov/

C. Cern et.al, "The BOOTES experiment in Southern Spain as a complement to GTC for GRB research", Rev. Mex. Astro. y Astrof., Ser. Conf., vol. 16, p. 77, 2003. http://laeff.inta.es/BOOTES/

M. Cwiok et al., "GRB040825A: optical limit before GRB", GCN Circular 2677, "GRB040916 optical limits 17 min after GRB", GCN Circular 2725. http://gcn.gsfc.nasa.gov/gcn3/archive.html

N. Gehrels et al., "The Swift Gamma-Ray Burst Mission", astro-ph/0405233 2004. http://swift.gsfc.nasa.gov/

D. Kuvshinov and V. Lipunov, "The Optical Transients Center". http://otc.pereplet.ru

V.M. Lipunov, "MASTER: The Mobile Astronomical Systems of Telescope-Robots", AN 325, pp. 580-582 (2004). http://observ.pereplet.ru

M. McCants, "Satellite Tracking", http://users2.ev1.net/~mmccants/

B. Paczynski, "Optical Flashes Preceding GRBs", astro-ph/0108522 2001.

W.D. Pence, "FITSIO: a subroutine interface to FITS format files", PRE-34031, Greenbelt, MD: NASA, 7 Oct 1993. http://heasarc.gsfc.nasa.gov/docs/software/fitsio/

L.W. Piotrowski, M. Sokolowski, "Simulation of point-like optical flashes in the sky", in: R.S. Romaniuk (Ed.), "Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments II", Proc. SPIE Vol. 5484, p. 290-299, 2004.

G. Pojmanski, "The All Sky Automated Survey", Acta Astronomica 50, p. 177, 2000. http://www.astrouw.edu.pl/~gp/asas/

G. Ricker et al., "GRB 010921: Localization and Observations by the High Energy Transient Explorer Satellite", ApJ 571, L127, 2002. http://space.mit.edu/HETE/

R. Smith, "Genesis CCD", http://www.genesis16.net/

G.S. Tsarevsky, "ASTRAL: All-sky Space Telescope to Record Afterglow Location", presented at the workshop "An Australian astronomical payload for FedSat-II", Epping, Australia, October 2002. http://www.atnf.csiro.au/people/rnorris/fedsat/
W.T. Vestrand et al., "Searching for Optical Transients in Real-Time: The Raptor Experiment", in: "Gamma-ray burst and afterglow astronomy 2001 — A Workshop Celebrating the First Year of the HETE Mission", AIP Conference Proceedings, Volume 662, pp. 547-549 (2003)

W.T. Vestrand et al., "The Raptor Experiment: A System for Monitoring the Optical Sky in Real Time", in: R.I. Kibrick, "Advanced Global Communications Technologies for Astronomy II" Proceedings of the SPIE, Volume 4845, pp. 126-136 (2002); astro-ph/0209300

http://www.raptor.lanl.gov

R.R. White et al., "TALON - The Telescope Alert Operation Network System: Intelligent Linking of Distributed Autonomous Robotic Telescopes", Proc. SPIE: 5496 (2004) pp. 302-312.