Apparatus to Search for Optical Flashes of Extragalactic Origin

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Abstract-- **An apparatus is described to search for optical, point-like flashes in the sky at the time scale of seconds. Such flashes are expected to accompany gamma ray bursts (GRB) observed routinely by satellites and proven to be of extragalactic origin. So far only one such flash has been recorded shortly after the GRB, because standard methods of observational astronomy are not suitable for the time scale of seconds.**

In this paper, a novel approach is proposed based on experience from particle physics experiments. An apparatus is described which monitors the sky continuously. The large data stream is analysed on-line and potentially interesting events are selected by a multilevel trigger system.

In the first phase of the project the apparatus consists of two CCD cameras, especially designed for this project and a robotic mount used to scan interesting regions of the sky. In the second phase the experiment will consists of two sets of 16 cameras on fixed mounts, covering almost all visible sky.

I. Introduction

PERHAPS the most powerful cosmic processes ever observed are gamma ray bursts (GRB) [1]. They stand for one of the most difficult and most interesting puzzles of today's astrophysics. Those are 0.01-100 s short pulses emitted by extragalactic sources. Energy of typical burst is estimated to be of the order of 10^{51} erg. Intensity of the burst is often higher than the total background from all other gamma sources in the sky.

So far, phenomena responsible for GRB have not been unambiguously identified. There are hints that certain type of supernovae explosions could be the source of bursts energy. Among other hypothesis are neutron star collisions leading to black hole creation or quark star collapse. Certainly, in such kind of processes extremely high energy density states are created. Study of those processes may bring new information about fundamental interactions involved in processes responsible for bursts and give new direction to particle physics.

In order to proceed with understanding the physics of GRB one needs to observe them also in wavelengths different than gamma rays. It is natural to expect that GRB should be accompanied by bright optical flashes [2]. The outcome of optical searches has been rather limited so far. Only about 30 GRB (out of several thousand detected by satellites) were identified with optical sources. All but one were observed by large telescopes, many hours after the GRB. Only once a bright optical flash was observed, a few seconds after GRB trigger [3]. It was caught by ROTSE group equipped with a small robotic telescope. A flash was observed as bright as 8.6^m and could be seen by eye with simple binocular. This is only a single observation, but it stands as a proof that such flashes exist, hence the search is not hopeless.

Systematic search for such phenomena with typical astronomical equipment is rather difficult. Professional telescopes with long focal length are designed to observe faint objects and they have extremely narrow field of view (typically 30×30 arcsec^2). More suitable for this kind of search are small telescopes of relatively short focal lengths (135-500mm) with robotic mounts [4]. They are guided by satellite signals towards a given position in the sky. Unfortunately, also in this case the delay of the signal received from the satellite and the inertia of the device itself make the chance for the flash observation within a minute to be rather small.

II. "*Π of the Sky*" Project

In the present paper we propose an approach completely different from the classical one. Two major drawbacks of classical robotic telescopes are long trigger signal propagation time and large mechanical inertia of the device. The former one can be overcome by self-triggering and/or pipeline memory. The later one can be eliminated by a static design. The static design implies full hemisphere coverage to achieve

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high efficiency. This in turn leads to large data volumes. With required time resolution of the order of seconds the data stream is impractical to write on any mass storage. Most of the data analysis must be done in real time. Only small fraction of the data can be stored, which calls for a multi-level trigger system.

We have designed a system, which consists of two sets of CCD cameras installed on fixed mounts and working in coincidence. Each set contains 16 cameras covering almost all visible sky. A single camera is equipped with lenses of focal length *f*=50mm and aperture *d*=*f* /1.4. It covers 33° × 33° field. Exposure time of 5s should give limiting magnitude about 11^m. The camera contains a 2000 × 2000 pixels CCD with 15 µm pixels, which gives the scale of 1 arcmin / pixel.

III. PROTOTYPE APPARATUS

Fig. 1. Prototype apparatus at the test site in Brwinow near Warsaw.

A. CCD cameras

Two CCD cameras have been constructed, based on CCD442A sensor by Fairchild Imaging with 2032×2032 sensitive pixels. The sensor is cooled with a stack of Peltier modules. The electronics is designed for fast readout of 2 MHz / pixel in order to read the entire chip in 2s. Clocking and control of the camera is realised with an FPGA, which makes the system flexible. Digitisation is performed with 16-bit ADC. On board RAM makes possible to read out the previous frame while the next one is under exposure. The data are read-out through USB 2.0 interface. Special attention was given to a shutter design. Assuming 5s exposures all night for a couple of years the shutter must sustain over 10^7 cycles.

B. System installation

The two cameras are installed on a common mount in such a way that they observe the same field (Fig. 1). The mount can reach any point in the sky in less than one-minute time.

The system has been installed at the Las Campanas Observatory in Chile (Fig. 2) in June 2004. The mount with the cameras is housed by the dome of the ASAS project [5] (Fig. 3) together with other ASAS telescopes (Fig. 4). The apparatus is controlled by a PC located in the dome (Fig. 5). Another PC, located in the Control Room (Fig. 6) is used for off-line data analysis. Nearby 10” ASAS telescope (Fig. 7) could be used to follow up “π of the Sky” triggers.

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

Fig. 3. The ASAS dome, fully opened. “*π of the Sky*” cameras seen in the middle.

Fig. 4. The “π *of the Sky*” apparatus in the ASAS dome at LCO.

Fig. 5. The ASAS / “π *of the Sky*” dome, partially opened. A PC controlling the system seen through the service door.

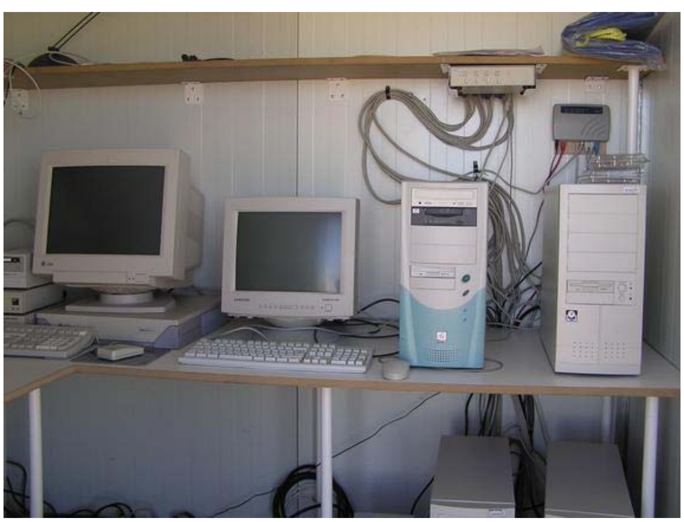

Fig. 6. The Control Room

Fig. 7. The ASAS 10” telescope, which could be used to follow up “π *of the Sky*” triggers.

C. *Operation and data flow*

The system is fully autonomous, but also fully controllable via Internet. It is designed to be immune to network failures. 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. 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 arrive, the mount automatically moves towards the target and exposures are being taken. Twice a night an all sky scanning is performed. 17 fields are visited and two images of each are taken by both cameras. A single scan last about 20 minutes.

Because the mount follows the sideral movement, one can take longer exposures than in the case of a fixed system. We have chosen 10s as a compromise between the magnitudo 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 could be reexamined in case of late arrival of an external alert. If a flash candidate was found a 100×100 pixel samples of ±7 frames are stored permanently for the record.

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 [6].

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 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.

Basic information about the system (<20kB) 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

D. Software

Both PCs 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. The communication between modules it based on CORBA. Flash recognition algorithms and fast photometry are custom developed, whereas precise photometry and astrometry is adopted from ASAS [5].

Special care has been taken to ensure seamless recovery after a system failure without human intervention at the site. The cameras have build in hardware watchdog, which automatically resets the camera and thus reestablishes connection with the PC in case of protocol failure. Both PC have “Wake on LAN” and “Boot from LAN” capabilities and can be started from the net in case of file system failure. Each computer can be remotely reset or powered down/up by the relays driven by the second one.

E. System performance

The prototype *“π of the Sky”* system operates regularly from July 2004. Till the end of September, 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 20 000 stars and the results consists of 10 billion photometric measurements.

The limiting magnitude is 10-11^{m} for single frames (Fig. 8) and 11-12^{m} for frames coadded by 20 (Fig. 9). 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.

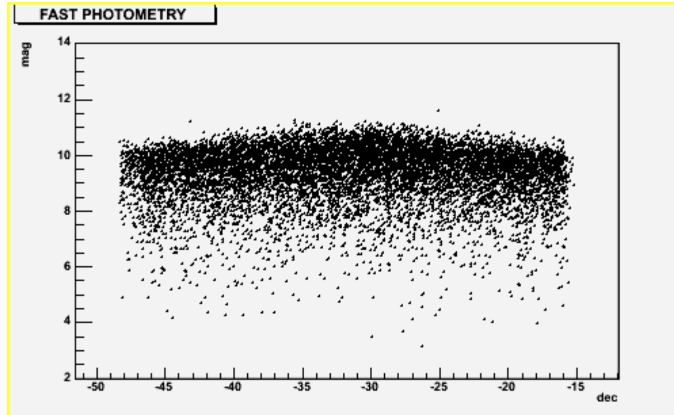

Fig. 8. Fast photometry magnitudo of stars vs position in the frame (degrees).

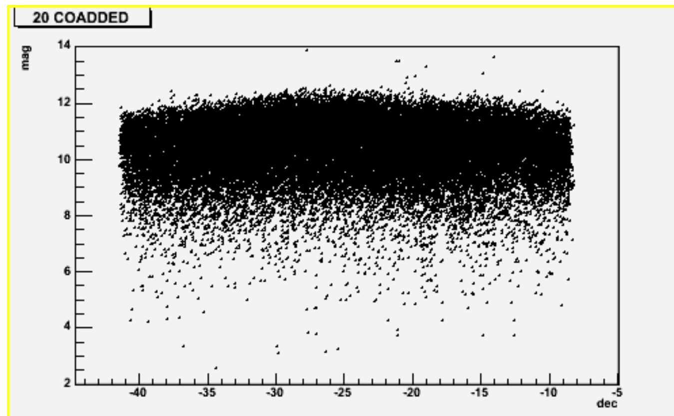

Fig. 9. Precise photometry magnitudo of stars vs position in the frame (degrees).

IV. First Results

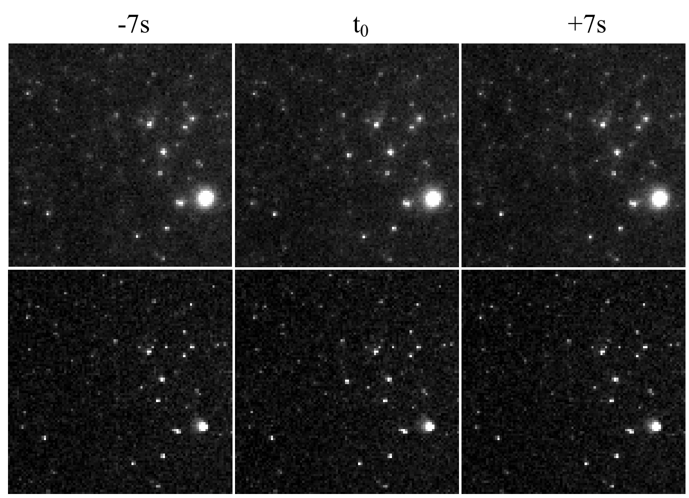

Fig. 10. Optical flash detected at 2004.07.04, 4:01:19 UT. The object is seen in the center of the middle column images. The upper row contains images taken by CCD camera without any filter. The lower one – with an IR-cut filter.

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. An example is shown in Fig. 10. It is an optical flash ~9^m detected at 2004.07.04, 4:01:19 UT. It's position is RA= 17h 40m 39s, Dec= -11° 13' (J2000) ± 1 arcmin. Origin of the flash has not been verified. The flash was inside the field of view of the HETE satellite, but no HETE alert was issued. No satellite from a database (containing 8000 satellites) could be responsible for the flash.

So far the most interesting event observed was an optical transient lasting >10s, which cannot be explained by a satellite reflex. It was observed during tests with a single camera, at 2004.02.21, 0:27 UT, RA = 11h 18m 44s, Dec = -6° 6.5' (J2000.0) ± 1 arcmin. The object brightness is 9.0^m and 9.7^m on two consecutive frames taken with fixed mount camera. The object coincides within 1 arcmin with LEDA 114805 galaxy. It was outside HETE FOV.

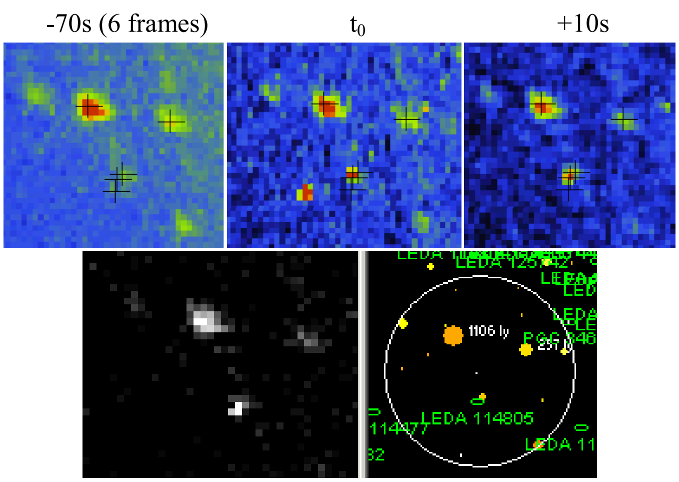

Fig. 11. Optical flash detected at 2004.02.21 0:27 UT. The upper row shows images of three epochs. The object is seen in the second and the third. The second image contains a cosmic ray in the lower-left part. The lower row gives a comparison of the image with the sky map. The flash coincides with the LEDA 114805 galaxy.

So far, no optical transient coinciding with a known GRB was found. Limits for optical counterparts have been given for a few GRB. So far only one GRB was inside the FOV during the burst. It was GRB 040825A. Derived limits are not very strong because of bad weather conditions:

- >10^m for $t < t_0$ - 11s
- >10^m for $t = t_0$
- >9.5^m for $t > t_0 + 7$s

V. Perspectives

Apart from searching for GRB optical counterparts the *"π of the Sky"* apparatus can be used to study variable stars, rotation of asteroids etc. The work is going on to increase precision of the photometry and to detect automatically all kind of variability. The range of phenomena, which could be studied, is very wide. A nice example is given in Fig. 12, which shows a meteor trace blown by the wind. 10s exposures have been taken with 4s interval.

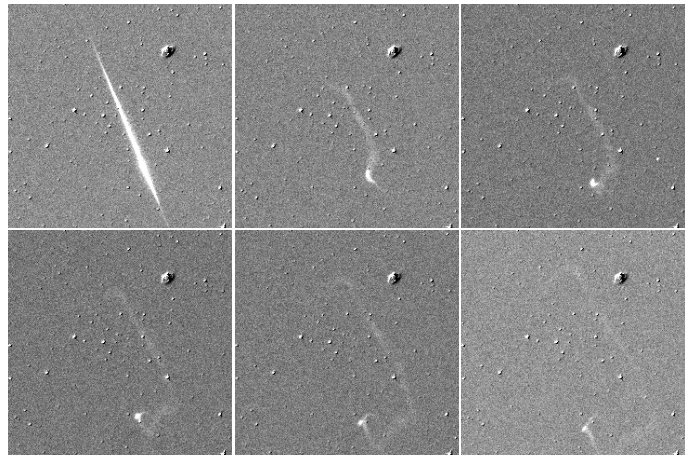
Fig. 12. A meteor trace blown by the wind (background subtracted).

At present, we continue the work towards the final system containing 2×16 cameras to cover all the sky. The project is now moving from a conceptual to a technical level. Among the problems to be solved is the maintenance of the complex system and the coherent work off all its nodes (cameras + computers). It is a pioneering work towards large farms of robotic telescopes, which is one of the most promising directions of the future astronomy.

The *"π of the Sky"* apparatus can be also considered as an Earth based prototype of a lighter, yet more powerful system, which can operate in the space [7].

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VII. References

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