Detection of short optical transients of astrophysical origin in real time

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Detection of short optical transients of astrophysical origin in real time is an important part of existing robotic telescopes. The faster a new optical transient is detected the earlier follow-up observations can be started, allowing for deeper studies of the object. The real-time pipeline designed for identification of optical flashes with the "Pi of the Sky" project will be presented in detail. Solutions from other selected experiments will also be addressed.

1 Introduction

The first robotic telescopes were supposed to work autonomously and without too much human attention. The development of these devices was mainly stimulated by difficulties with optical observations of Gamma-Ray Bursts (GRBs) ([1],[2],[3],[4],[5]). These powerful explosions occurring in a distant Universe act on very short timescales ranging from a fraction of second up to hundreds of seconds. They were discovered by VELA satellites in late 60s [1]. In the beginning only gamma and X-ray observation were possible. Optical observations were practically impossible due to difficulties in fast determination of the burst position in the sky. The first method used for this purpose was triangulation, which required detection of a burst by at least 3 satellites on the orbit. The position of the burst was determined even days after the explosion. Optical telescopes observed the area of the interest long time after the most interesting and intensive moments of these events. The idea of automatic identification of optical transients (OT) has arised from the GRB localization problems. In 1991 the BATSE detector on board the CGRO [6] satellite was launched. It was able to determine the position of a burst quickly and send an alert to the GCN network [7]. The main problem was the accuracy of order of 5^o, which in fact excluded identification and observations of optical counterparts with large telescopes. The pipeline which would automatically identify transients in optical images would allow to find optical counterparts of BATSE bursts. Since that times people were working on such kind of algorithms. A great step forward in GRB science was the launch of the Beppo-SAX satellite [8] in 1996, which was equipped with X-ray camera, allowing for fast determination of the burst position with the accuracy of < 5 arcmin. In 1997 the first optical counterpart of the gamma-ray burst was observed, which led to determination of redshift, distance and finally established cosmological distances to GRBs, excluding many theoretical models. This discovery was one of the main forces driving rapid development of robotic telescopes. Another break-through came in 1999 when ROTSE [9] robotic telescope for the first time observed optical emission from the GRB 990123 contemporary with the γ-rays. The hunting for prompt optical emission has began. Many fast and automatic robotic telescopes have been build in order to quickly react to GCN alerts [7] and observe prompt optical signal as early as possible. During last decade these devices became more and more sophisticated. They are in many cases fully automatic and autonomous, not requiring almost any human attention. Typically they wait for the GCN alert about the GRB and in such a case quickly move to the burst position, reaching it typically in less than 60 seconds. The most basic requirements for robotic telescopes are already achieved, but new challenges are coming. Now, it is not enough to react to external alerts from the satellite. Robotic telescopes are expected to perform own data analysis in real time, find interesting events and send alerts to the community so that larger telescopes can observe such objects as fast as possible. Since the very beginning robotic telescopes were producing a lot of optical data which was typically analysed off-line, nowadays experiments are supposed to go much further. As it can be clearly seen from the example of gamma-ray bursts, off-line and late identification of the phenomena is not satisfying and does not guarantee a chance of follow-up observations which could allow deeper studies of the object. Real time discovery, alert distribution and immediate reaction of large telescopes and other detectors is needed to successfully investigate short timescale astrophysical phenomena. The regime of short timescale (of order of seconds and less) is relatively unexplored area. The examples of GRBs, blazars and Active Galactic Nuclei (AGNs) show that the most violent and interesting astrophysical processes occur on very short timescales. Thus many interesting processes can be expected in this regime. Of course these can be optical transients related to GRBs, as it was already confirmed by observations of prompt optical emission from at least a few GRBs (990123 [9], 041219A [25], 080319B [24]) these processes may have even very bright optical counterparts. Especially the case of GRB080319B showed that brightness of prompt optical flash from the GRB can reach even 5^m which makes them accessible even for the "naked-eye wide field detectors". This further confirms the necessity and suitableness of building wide field systems for observations of prompt optical signal from GRBs. It also motivates for developing real-time pipelines able to self-trigger follow-up observation without GCN alert requirement. Currently we have a solid prove that such short time optical transients can even reach brightness of order of 5^m. Wide field systems of photo camera lenses and even fish-eye cameras can be very effective tools for automatic identification of such events in real time. Discovered OTs should be immediately distributed via global communication networks (like VOEventNet [22] or other), which have big chances to become very successful extensions of the famous GCN network. One of the most important and interesting processes that could be detected with such kind of analysis are untriggered GRBs or orphaned afterglows. Current GRB models predict that optical emission may be less collimated than high energy emission and thus there may be more optical flashes related to GRBs than γ-ray flashes. Observation of such kind of events would probably be one of the milestones in understanding of GRBs. Besides long GRBs there are also short GRBs (ΔT <2s). In very few cases optical counterparts have been observed, but relatively long time after the outburst. Optical observations of short GRBs in early phase would give enormous input to theoretical understanding of these processes. Except gamma-ray bursts there other processes which should be identified as fast as possible in order to allow deeper investigations. These can be supernovae explosions (SN), cataclysmic variables like novae or dwarf nova explosions, but also activity of AGNs and blazars. Another area where very similar tools are required is automatic identification of Near Earth Objects (NEOs) and Potentially Hazardous Asteroids (PHAs). One of the most important motivations for such kind of analysis is that every time technology allows to enter new regime, new type of phenomena can be discovered. It is very probable that on timescales of seconds and less there are optical processes in the Universe which were not yet classified or even observed. In order to systematically study such kind of processes effective pipelines for real time identification are required. Typically they are implemented in wide field systems, but the synergy between wide field and large telescopes will allow for good coverage of optical lightcurves. However, recently similar pipelines have been developed also for large telescopes and this direction is also very promising, giving chances for detection of fainter OTs.

Finally there are practical reasons for such kind of pipelines, astronomical experiments produce more and more data. In certain point they can reach amounts which will not be possible to store permanently. They may almost approach the amounts produced by the high energy experiments and thus it may be necessary to use similar methods for reducing the stream of data by using on-line selection triggers. Real time analysis pipelines can identify interesting event candidates in the images and store only raw data related to this events and ignore the rest of the data. It may be necessary to develop specific triggers for specific type of phenomena, exactly like in the particle physics experiments. Probably today it is not yet a very crucial problem, but it may become an issue in the near future, when experiments like LSST [10] will start to produce 30 TB of data per night.

Summarizing, the pipelines for real time identification of short optical transients are very important and promising tools for investigation of the relatively unexplored window in astrophysics. They can also become unavoidable for experiments producing huge data streams.

2 Methods of identification of optical transients in short timescales

In this section we give on overview of methods used for identification of optical flashes. We concentrate on short ($\leq$10s) optical flashes, but also methods for detection of longer timescale events will be described. Depending on the type of experiment and especially on the exposure times, different methods of flash recognition have to be implemented. Exposure time is the main limitation for the complexity of image analysis. New image has to be analysed when the next one is being collected, thus time and CPU consuming algorithms cannot be used. The situation is different in case of longer exposures where much more sophisticated algorithms can be implemented. Typically implemented methods will be described in the first subsection. In the second subsection methods used in the pipeline developed for the "Pi of the Sky" experiment will be described.

2.1 Identification of new objects in the sky

The main purpose of the algorithm looking for optical transients is to analyze new image of the sky and find new objects which were not present in the previous images nor in the star catalogs. The purpose is to find candidates for optical flashes with high efficiency, but also to effectively reduce the background so that the amount of events which require visual inspection is reasonable. The first step is to compare new image with the reference image. The type of reference image depends on the realization of the algorithm. It may be serious of previous images taken in similar conditions just a moment ago or it may be a reference image resulting from combination of best images of the same field of the sky taken before at very good observing conditions. Another way is to compare new image with the reference catalog of astrophysical objects, both solutions can be combined to obtain most satisfying result. The implementation of the method depends on the specific needs and characteristics of the experiment. Typically experiments collect subsequent images and in case they are analysed in real time, the time period for the analysis of new image is limited by the exposure time, because every new image must be analysed when the next image is being collected. In case of the short time scale ($\leq$ 10s) surveys, like for example "Pi of the Sky" (10s exposures), this may be a strong limitation, imposing requirements on the type of analysis methods that can be implemented. In case of such short timescale surveys image subtraction method is widely used. Images are taken in almost the same conditions so previous image can be subtracted from the new one, exhibiting changes in the sky. Precise and exact method of image subtraction was described in [11]. However, in many application this method can be too time consuming, thus very simple, pixel based subtraction is used. In case of sub second exposures, like in the case of TORTORA experiment ([12],[13]) it is probably the only method that can be used. There are many variations of this method, in some cases reference image or median of images from earlier observations (i.e. taken at very good observing conditions) is used for subtraction. Typically after subtraction, image exhibiting changes in the sky is obtained and the list of flash candidates can be built by selection of pixels where signal exceeds certain threshold (5σ or so). However, first problem one has to be aware of is that subtraction of images causes several types of artifacts to appear in the image. For example Point Spread Functions (PSF) of stars fluctuate and subtraction can "produce signal" at the edges of stars PSF. Suppression of this type of false alerts by rejection of alerts close to edges of stars or division by variability map is one of the first task of such an algorithm. After this step a list of flash candidates is produced and later steps have to reject background events. Typical background that has to be handled by subsequent cuts of the algorithms is mainly due to :

- sky background fluctuations
- fluctuations of faint stars
- fluctuations of PSF of bright stars
- saturated stars
- cosmic rays hitting CCD chip
- defects of the CCD matrix (hotpixels, bad columns etc)
- artifacts (strip due to permanently opened shutter)
- flashes due to artificial satellites
- flashes due to planes

In case of observations in longer timescales ($\geq$ 30 seconds) the situation is usually easier. The amount of time is large enough to implement much more sophisticated algorithms. In such a situation exact photometry can be executed, usually sextractor package is used [14] as one of the fastest photometric programs. However, in many cases other photometric packages are used. After photometric analysis a list of stars in the new image is produced and it is compared with the reference list of stars in the observed field. The reference list can be obtained from external star catalogs like USNO, GSC or SIMBAD depending on the limiting magnitude of the survey. It can also be obtained from the self produced star catalog or it can be a list of stars extracted from the reference image which was collected at very good observing conditions. After comparison of the two lists of stars a list of new objects in the sky is produced. They are candidates for optical transients and has to be verified by more sophisticated analysis. The usage of exact photometry has many advantages over the simple pixel based image comparison. First of all it produces list of stars and if the photometry deals well with edges of stars PSF and does not produce "false stars" from the PSF fluctuations the problem of star PSF fluctuations can be easily avoided. In case of longer timescale exposures most of the background types listed above are irrelevant. Typically a few ($\geq$2) images of exposure time $T \geq 30s$ are collected within an interval of a few hours or so and new objects are required to be visible on at least 2 images. Such requirement rejects all background events due to cosmic-rays hits, flashing satellites and planes. The price for this are of course short optical transients, rejected by such requirement.

2.2 Identification of short optical flashes in the "Pi of the Sky" experiment

Pi of the Sky experiment

The "Pi of the Sky" system is designed for observations of large fraction of the sky with temporal resolution of order of $\leq$10s. The system will consist of two farms of 16 cameras (Fig.1), installed in a distance of several dozens of kilometers. Each camera will cover field of view of $20°\times20°$, which will result in a total sky coverage of $\sim$2 steradians. This corresponds to field of view of Swift BAT [15] and Fermi LAT [16] detectors. Every GRB detected by the Swift satellite, in the observing range of the "Pi of the Sky" system, will already be in its field of view. The algorithms will analyze images in real time in search for short optical flashes [23]. The two sets of 16 cameras will observe the same part of the sky. The large distance between two sets is needed by the algorithms to use parallax to reject short optical flashes caused by artificial satellites and other near Earth sources. Design and development of the prototype was the first step towards the final "Pi of the Sky" system. The prototype was installed in Las Campanas Observatory (LCO) in Chile in June 2004. It consists of two custom designed, low noise cameras [17] installed on a paralactic mount. Each camera has a CCD with 2000 x 2000 pixels of $15\times15\mu m^2$. They are equipped with CANON EF f = 85 mm, f/d = 1.2 photo lenses, giving pixel scale of 36 arcsec/pixel and covering $20°\times20°$ field of view. The cameras continuously collect 10 second images of the same field in the sky with 2 second breaks for CCD readout. The values of limiting magnitude are the same as expected for the final system, which is 12^m on single 10 s exposure and reaches 14-15^m on 20 averaged images. More details about the prototype and final design of the system can be found in [18],[19] and [23].

First level trigger - identification of flashes from single camera

The aim of this type of the algorithm is to find optical flashes occurring in a single image (time scale $<$ 10 sec). The signature of such events is the following. Interesting event is an object which appears in a new image of the sky and was not present in the previous images of the same field taken a moment ago. In the "Pi of the Sky" experiment in order to find candidates for new objects in the new image a similar approach to those described in the

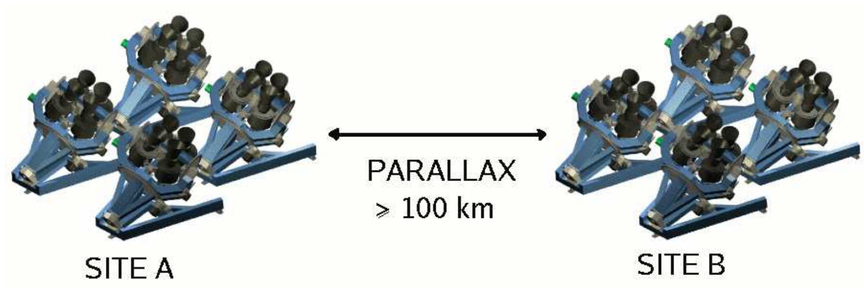

Fig. 1. Configuration of final system, able to cover whole Swift's field of view. The parallax will allow to automatically reject short optical flashes from near Earth objects in real time.

previous section was chosen. New image is compared to series (typically 7) of previous images collected just a moment before.

The first step is subtraction of dark frame. In the next step, image is transformed by special transformation called `laplace`[1]. Value of each pixel is calculated as simple function of several surrounding pixels. Values in pixels just around transformed pixel are summed and values in other pixels far from it are subtracted with proper weight. This transformation is equivalent to calculation of a simple aperture brightness for every pixel.

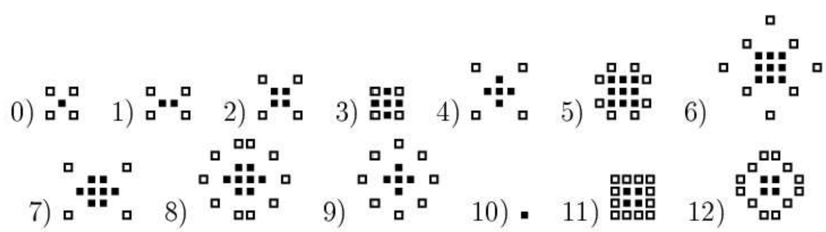

Fig. 2. Different `laplace` "apertures" tested for on-line flash recognition algorithms

Several types of filters which were tested are shown in Figure 2. Images before and after applying the `g54 laplace` filter (aperture 4 in Fig. 2) are shown in Figure 3, it can be clearly seen that stars are sharper on the filtered image. Finally, one filter was chosen. For current setup equipped with Canon f=85mm, f/1.2 photo lenses, `laplace` 12 is used. On-line algorithm is based on transformed images, distribution of pixel values after such transformation is centered around zero. For every collected image a Gaussian curve is fitted to this distribution and threshold required for signal T_n is calculated as multiplicity of dispersion value (σ_B), typically T_n = 5-6σ_B.

[1] because it resembles a discrete version of Laplace operator

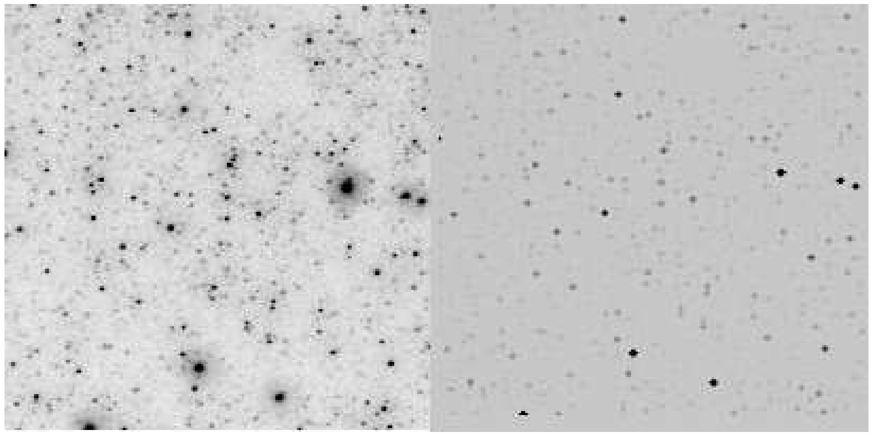

Fig. 3. Sky image before (left image) and after (right image) applying the `laplace` filter

At this stage, algorithm must handle the highest data rate, of order of number of pixels ($4 \cdot 10^6$), so it must be very fast and simple. It should preserve most of the signal and reject big fraction of non-interesting pixels. At this stage flash-like events in a single camera are identified. The following two criteria are required to select candidates for new objects in the sky :

- $\boldsymbol{T_n}$ - this cut selects stars on new image by requiring signal in the analysed pixel. The condition for signal presence is $\boldsymbol{N(x,y) > T_n}$, where N(x,y) is value of pixel (x,y) resulting from recalculation of new image with the `laplace` filter and the threshold $\boldsymbol{T_n}$ is specified by configuration parameters in multiplicities of $\boldsymbol{\sigma_B}$ value. The goal of this cut is selection of all stars in new image.
- $\boldsymbol{T_v}$ - this cut rejects objects present on previous images. It requires that there is no signal on the previous frame. "Previous frame" in this case means not just one single image, but average of several previous images. The condition imposed on value of pixel in the "previous image" is the following : $\boldsymbol{P(x,y) < T_v}$, where P(x,y) is the value in pixel (x,y) on the average of $\boldsymbol{N_{aver}}$ previous images. Pixels remaining after this cut should be new objects which appeared on new image and were not present on previous images.

After this two cuts the list of flash candidates is created, most of them are due to background which is rejected by the following criteria :

- **MinLaplace** - rejects pixels which have value on previous image lower than minimal allowed value (T_{MinLap}). This cut allows to reject edges of bright stars where values of pixels after `laplace` filter often become negative, but can also vary to values exceeding T_n.

- **IfMoreAfterTv** - rejects the whole image if number of pixels accepted after T_v cut exceeds certain limit N_{MaxTv}. This cut allows to reject images with big number of events which are usually due to system error, Moon light or clouds. The image is bad, all events are certainly rubbish so they are rejected and no further analysis of this image is performed.
- **SkipOverlaps** - checks number of accepted pixels in certain radius $R_{overlap}$ from current pixel and leaves only one event and skips the others. This cut narrows the number of pixels to be analysed which are related to the same object to a single one.
- **Shape** - object shape indicator S is calculated. It is defined as :

$$S = \frac{S_{cluster}}{S_{circle}} \tag{1}$$

  where $S_{cluster}$ is area of cluster and S_{circle} is the area of the smallest circle circumscribed on this cluster. Cluster is defined as group of pixels around current pixel with values satisfying $N(x, y) \geq T_{cluster}$. Shape is required not to be elongated by imposing : $S > T_{shape}$.
- **BlackPixels** - this cut rejects pixels which have much smaller signal than neighboring pixels causing that value after `laplace` filter is high due to underestimation of the background level.
- **HotPixels** - due to CCD chip defects some pixels can give much higher signal than normal, good pixels. Such effects should generally be subtracted by the dark image subtraction. However, sometimes it is not enough, because new hot pixels can appear temporary during a night and become quiet again later. Two ways of rejecting such events have been implemented. The first one is calculation of average value in pixel on previous images. Second anti-hotpixel cut is rejection of pixels by the list of known hot-pixels. This list is updated regularly when new defects are found.

After the above cuts list of event candidates from a single camera is created, typically it consists of not more than several dozens of events per image.

Second level trigger - transient verification

The goal of the second level trigger is to verify events from a single camera and reject remaining background, which at this stage is mostly due to cosmic-ray hits, satellites and planes.

The action at this level depends on the type of the system setup. Generally three configurations are possible :

- Two cameras on a single mount working in coincidence.
  In this configuration events found by the first camera are verified in the corresponding image from the second camera. Only events present in images from both cameras are accepted. This configuration is realized by the prototype system in LCO.

- Confirmation of event on the next images.
  It is also very effective way of rejecting flashing satellites and cosmic-ray hits. However, short optical flashes are rejected by such a requirement. Thus this is not the best way that would fulfill all the requirements for the ideal algorithm.
- Two cameras in distant locations working in coincidence.
  This will be realized in the final version of the "Pi of the Sky" system. Cameras will be paired, both cameras in the pair will observe the same field in the sky. Spatial and time coincidence of the flash in both cameras will be required.

In any case coincidence requirement is one of the most important cuts. The main goal is rejection of cosmic rays hitting the CCD chip and imitating astrophysical flashes. In many cases cosmic-ray hits have Point Spread Function (PSF) completely different than PSF of stars and they could be rejected by a shape recognition procedure. However, in some cases they are very similar to PSFs of the stars. Even if this is a very small fraction of all cosmic ray events this would cause all flashes found by the algorithm to be uncertain. A way of definite rejection of all cosmic rays events is required for credible flash recognition algorithm. Probability that different cosmic ray particles will hit two chips in the same time and in the same positions (with respect to stars) is negligible. Coincidence is also very effective way of rejecting background events due to sky background fluctuations, edges of bright stars and clouds. In the prototype version collection of images by two cameras is synchronized so the only parameter is the angular distance of events in both cameras. Currently used default value is $R_{coinc} = 150$ arcsec. It was determined from distribution of angular distances of corresponding stars in both cameras. (Fig. 4).

After coincidence requirement the remaining events are real optical transients coming from the sky. However most of them are background events, mainly due to flashing satellites. In order to reject most of such events a databases of orbital elements in Two Lines Element (TLE) format are retrieved from the Internet every evening and combined to a single larger database containing ≈ 13000 orbital elements. For every image, positions of all satellites in the database are calculated (using the predict package [20]) and every flash candidate is verified. In case it is closer than $R_{sat} = 0.5^{\circ}$ from any of the satellites it is rejected. The rejection radius was determined from distribution of angular distances from flashes to closest satellite from the database which is clearly peaked around zero (Fig. 5).
The red dots on this plot represent distribution of distances from randomly distributed flashes to the closest satellite from the catalog. A clear peak at $R_{sat} < 0.5^{\circ}$ is visible, it corresponds to real satellites.

The orbital elements databases are not complete and many satellites are not included there. In order to reject such kind of objects event candidates from many consecutive images are examined against track conditions. In case

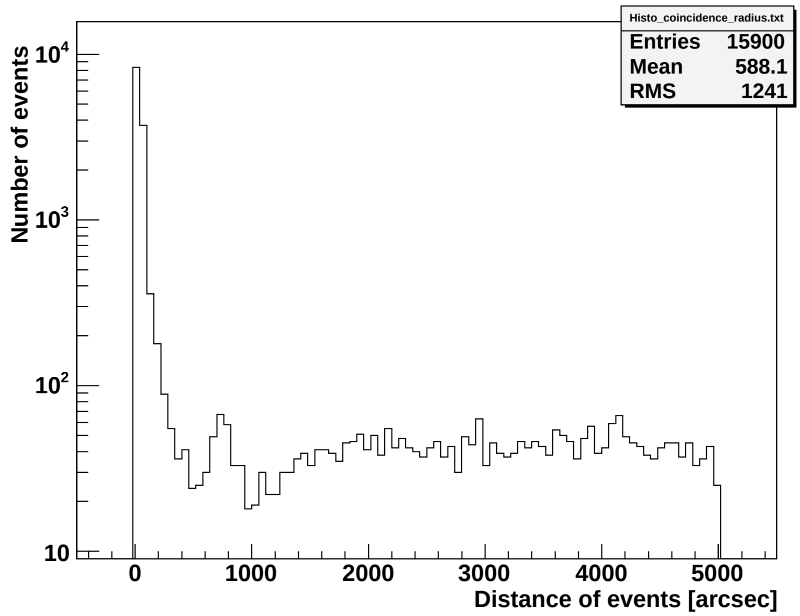

Fig. 4. Distribution of angular distances between events from corresponding images collected by cameras k2a and k2b during night 2006-05-28/29.

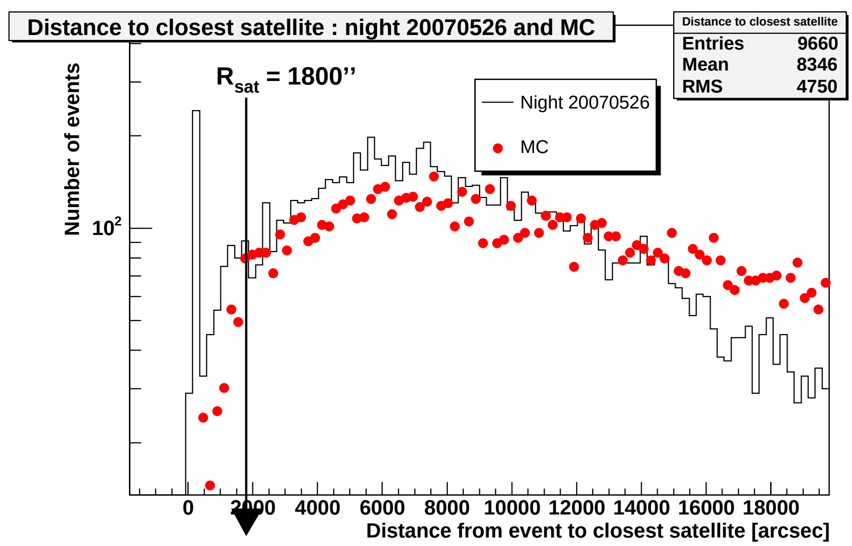

Fig. 5. Distribution of distance from flash event candidate to the closest satellite from the catalog. For events found by coincidence algorithm during night 2004.10.28/29. For comparison distances from randomly generated flashes to the nearest satellite are shown with red dots, combinatorial background is nicely reproduced

it is possible to fit track to set of events from different images and velocity of object is constant all events on the track are rejected. This rejects big fraction of flashing satellites and planes (Fig. 6), however it is possible that rarely flashing (rotating) satellites can survive this cut.

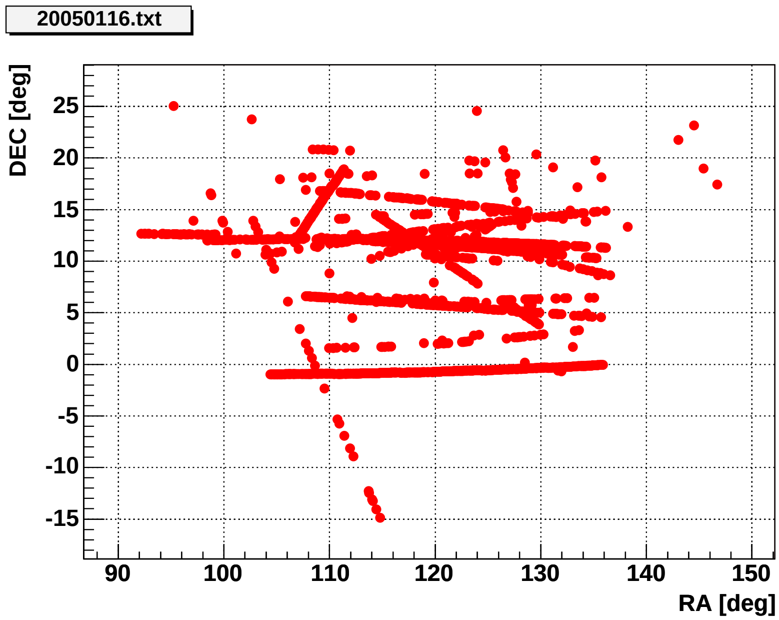

Fig. 6. Events rejected by track cut during single night 2005-01-16/17

Artificial satellites orbiting the Earth may rotate and sometimes reflex Sun light causing flash-like events. That is why a track cut cannot remove all the satellites from the sample, the most problematic are those entering the FOV of the telescope and flashing once or twice. Another problem is that verification whether an event belongs to a track requires collection of some images after the burst. In order to confirm the event the program must wait for some time and thus it is not real time transient identification any more. Better "ultimate weapon" is needed in order to definitely reject satellites in real time.

This is a coincidence between cameras installed in distant locations. In such configuration, it is possible to reject near Earth flashing objects by using a parallax (Fig. 1). In the prototype version of the experiment two cameras are installed on single mount. However, this method was tested by coincidence with the RDOT experiment [21] located at La Silla in a distance of $\approx$ 30 km. The final design of the "Pi of the Sky" experiment will consist of the sites in a distance of several dozens of kilometers (Fig. 1).

The Table 1 shows a maximal distance to which artificial satellites can be rejected assuming optics and CCD chip used for the final design of the "Pi of the Sky" experiment (pixel angular size of 36 arcsec). The distance of 100 km would be optimal and would reject all objects even further than the orbit of the Moon. Building of such a wide field systems is quite expensive project. However, the number of robotic systems looking for optical transients is rapidly growing up, thus another promising possibility may be looking for coincidences of transients with other experiments. Development and joining networks like VOEventsNet [22] will allow to correlate events from different experiments (not only optical) in almost real time.

Table 1. Maximal distance for rejection of artificial satellites with the parallax and angular size of a pixel 36 arcsec

Site distance [km]	Maximum distance [km]
18	103,000
50	286,000
100	572,000

Third level trigger - final confirmation and classification

The first two levels of trigger retain very small number of events. On average it is not more than 20 per night. It depends strongly on weather conditions and in case of cloudy night this number can reach hundreds. However, in the full system the number of events will be 16 time larger reaching 300-400 per night and this will be much more difficult to inspect. For this reason the third level of the trigger (TLT) has been implemented. It checks final events accepted by previous levels which ensures that only small number of events will be examined. Thus it is possible to implement much more sophisticated and time consuming algorithms to check every event. Current implementation of the TLT consists of several cuts. As an example, criteria developed for rejection of plane and meteor-like events will be described. Simple Hough transform [2] - uses small image part surrounding the event. It finds pixels with signal above certain level T_{hough} and creates distribution of ϕ coordinate ($\phi = atan((y - y0)/(x - y0))$). In case this distribution has significant peak this means it is probably due to straight line from a plane or a satellite (Fig. 7).

Event will be considered as straight line due to a plane if the maximum of this distribution fulfills the following condition (Fig. 7) :

[2] Hough transform is a technique of image transform from (x,y) to cylindrical (r,ϕ) coordinates in order to find particular shapes in an image

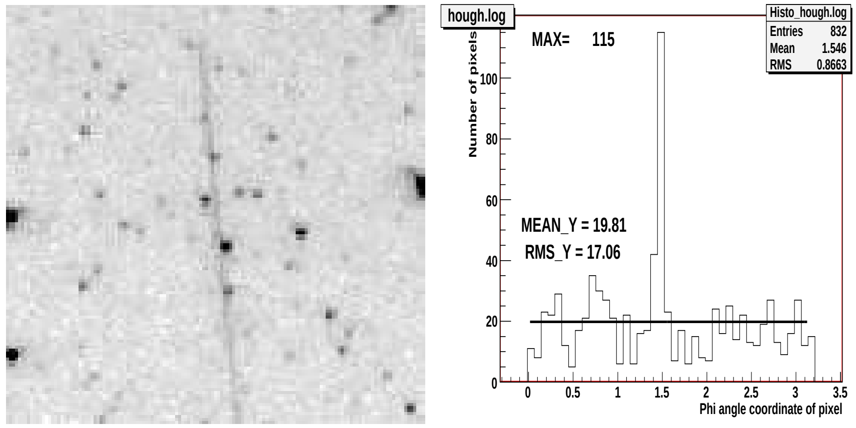

Fig. 7. Original event image (left image) and distribution of ϕ angle coordinate for background plane-like event (right image)

$$
\begin{aligned}
N_{max}(\phi) > MEAN_Y + T_{hough\_distr} * RMS_y \\
AND \\
N_{max}(\phi) > T_{hough\_height} * MEAN_Y
\end{aligned}
\tag{2}
$$

More details about implementation of the real time pipeline for detection of optical transients in the "Pi of the Sky" experiment can be found in [23].

Testing and results

The "Pi of the Sky" prototype in Las Campanas Observatory collects data since June 2004. The algorithm is tested every night. The efficiency of flash recognition was determined by simulating optical flashes and counting how many of artificial stars added to real sky images were identified and how many of them were wrongly rejected. This efficiency is typically of order of 70%-80% for cloudless nights and objects brighter than 11^m. Overall efficiency of the algorithm for stars brighter than 12^m is ≈35%. Further improvements of the algorithm are planned. The greatest success of the experiment, but also of the real-time pipeline for OTs was automatic discovery of the optical transient from GRB080319B ([24]). Another interesting event was automatic identification of outburst of flare star CN Leo (RA = $10^h56^m29^s$, Dec = $+7^o01$') on 2005.04.02 1:13:40 UT. There were a few events which were observed on 2 consecutive 10s images, but only on a single camera (second one was not working then). There were more than 200 events visible on a single 10s exposures, but on both cameras. None of them was correlated with any other astrophysical events from other experiments. Most of them are probably due to flashing satellites which were not rejected by the algorithm. However, some of them can be due to interesting astrophysical processes. In the near future

OTs discovered by the "Pi of the Sky" detector will be automatically published via the VOEventNet network. Basing on statistics of optical transients identified by the prototype in LCO preliminary upper limits on number of OTs brighter than 11^m on the whole sky was determined, these are :

- OT with T< 10s : N<300 events/4π/day
- OT with T> 10s : N<2 events/4π/day

3 Implementation of real time pipelines in other experiments

Number of telescopes and wide field systems is rapidly growing up. In many cases the main goal is strictly related to GRBs, but covers also other short time scale processes, especially optical transients. It is impossible to present all experiments which developed pipelines searching for OTs or other processes in real time. The choice of the experiments presented in this contribution had to be subjective. The idea was to present several experiments focused on different areas of astrophysical processes and present variety of application in which real-time pipelines are already very important tools. Most of the experiments presented here collect images with exposures times ≥30s, in many cases a few images of a given field are collected and later after a few hours next set of images from the same field is collected. In most cases algorithms require object to be visible on at least 2 images from a single or both sets of images. Thus several problems, typical for algorithms acting on ≤10s images are irrelevant (Sec. 2). Particularly satellites, cosmic-ray hits and planes are easily rejected by such requirements. The price for this is the time resolution and short optical transients, which are definitely lost.

Perhaps one of the most advanced systems for wide field observations is RAPTOR experiment [25]. It already consists of two sites RAPTOR-A and RAPTOR-B separated by a distance of 38 km. The single site consists of 4 wide field cameras covering FOV of 40^ox40^o and a fovea telescope which is used for follow-up observations. The parallax gives a possibility of rejecting near Earth objects. Integration time is typically 30s, the algorithm compares new images with self-produced star catalog. The catalog is typically started from the GSC star catalog and extended when new data is collected. The system is planned to be extended to large array of wide field cameras.

Another very advanced project from the opposite site of the Earth is MASTER system in Russia ([26],[27],[28]). According to author's knowledge it already consists of 6 wide field cameras, each covering FOV of 25.5^ox39.8^o. The experiment covers timescales > 0.15s, reaching 13^m on 5s exposures. Real time pipeline was implemented and is successful in searching for supernovae explosions with several events automatically discovered. The important part of the system are 40cm telescopes for follow-up observations of the detected transients.

The ROTSE system ([9],[29]) was so far probably one of the most important robotic telescopes in the history. It was the first experiment to observe optical emission contemporaneous with the γ-ray emission from GRB. It definitely confirmed that it is possible to be done which triggered rapid development of robotic telescopes and wide field systems. Since that time ROTSE changed its strategy from the wide field systems to narrow field (1.85^ox1.85^o) telescopes located in 4 sites around the world. Typical exposure times are 20 - 60s. Pipeline for automatic identification of optical transients was implemented and about 30 supernovae events per year are identified and also some optical transients of unknown origin.

Another very successful wide field system is TORTORA ([12],[13]). It was the first experiment which shown that it is possible to observe optical signal from GRB080319B with sub second time resolution ([24]). The camera covers 24^ox32^o FOV and collects 1/7 second images, which are analysed in real time in search for optical transients. In the case of TORTORA another important issue arises, the amount of data produced by such high time resolution system can be enormous, making implementation of real-time analysis inevitable.

The first Polish robotic telescope and one of the first in the world is the All Sky Automated Survey (ASAS) ([30],[31]). The system is located in Las Campanas Observatory in Chile and also in Maui at Hawaii Islands. It consists of wide field cameras covering 8^ox8^o. Typically 2-3 minute exposures are collected on each field. The system scans the entire sky every 1-2 days. New objects in the sky are identified in real-time by comparison of list of stars from new images with the own star catalogs from previous observations. The main goal of the experiment is creation of catalog of variable stars. However, pipeline designed for optical transients discovered many new cataclysmic variable stars and also several comets.

Perhaps one of the first real-time pipelines ever implemented was the one developed for the OGLE experiment [32]. It is not robotic telescope, but the pipeline for automatic discovery of optical gravitational lensing events was a very successful one and is definitely worth presenting here. Analysis of this type of phenomena requires good coverage of optical lightcurve so early detection and distribution of alert in the community was very important issue. In order to find brightening due to gravitational lensing differential photometry technique was used [11]. The cumulative reference image of the same field observed in previous seasons is subtracted from new image in order to find variations. The OGLE group also developed pipeline dedicated for optical transients which discovered many supernovae events (New Objects in OGLE Sky - NOOS system). OGLE microlensing events are already distributed over VOEventNet network in almost real-time.

Recently real-time pipelines for OTs were implemented and tested on the data from several large telescope. One of the examples can be Catalina Real-Time Transient Survey (CRTS) [33] which used images from Catalina Sky Survey (CSS) in order to find optical transients. The telescope observed 8^ox8^o FOV and collected four 30s exposures of a given field every 30 minutes. Real-time pipeline based on image subtraction technique was implemented. The transients are also verified against star catalogs USNO-B, SDSS and PQ survey. The survey detected 350 events in 6 months. They were mostly supernovae, cataclysmic variables, UV Ceti flare stars, blazars and Near Earth Objects. One of the important feature of these experiment is that events are published in real-time through the VOEventNet network and can be correlated almost in real-time with observations from other experiments.

Similar example is the Palomar Transient Factory [34] which uses 1.2m telescope in Palomar Observatory. It covers FOV ≈ 7.8 deg^2 and reaches 21^m on 30s exposures. Real-time pipeline for OTs was developed in order to search for SNs and also exotic optical transients of unknown origin.

There are currently many efforts to implement and deploy real-time pipelines on large telescopes. The main goal for this is to study the discovery potential of such devices in the short time scale region and background studies. They provide a science-driven testbed for future projects such as the Large Synoptic Survey Telescope (LSST) which is planned to start collecting data in 2014 [10]. The LSST will be 8.4m telescope, with FOV of 3.5^ox3.5^o and 3.2 gigapixel CCD mosaic. It will cover time scales $>$ 10s scanning the whole sky every 3-4 days. One of the important points of the scientific program is discovering of OTs in real-time. The experiment will produce up to 30 TB of data per night. Such amounts of data will probably have to be analysed in real-time, thus development of fast real-time pipelines is one of the most important software issues in the project. On the other side there is plenty of fish-eye cameras observing night sky all around the world. Since the famous GRB080319B it is already clear that even such kind of devices can be very successful and provide interesting scientific results. In many cases real-time pipelines were implemented and search for optical transients. For example CONCAM system [35] consists of 11 stations all around the world. They collect 180s images of the whole sky reaching limiting magnitude of 6.8^m. The pipeline analysis good quality events, compares them to reference images collected at good conditions and automatically rejects false alerts due to planets or variable stars. Recently one interesting optical transient OT060420 of unknown origin and brightness of $\approx 5.5^m$ was identified and reported in [36].

4 Conclusions

The number of experiments implementing real-time pipelines is rapidly growing up. They span from the very small fish-eye all sky cameras, through complex wide field systems to large (not only) robotic telescopes. They cover time scales from fraction of second up to hours and days. The areas of scientific interest also form a reach variety. There are many interesting and successful solutions in the field. Probably the best solution are stereo observations with the two systems in distant locations. This allows for real-time rejection of near Earth objects, especially flashing artificial satellites. The problem is that this doubles the cost of the system. The main problem with many optical transients discovered in different experiments is that they lack confirmation from other experiments. Thus attention should also be paid to joining networks (like VOEventNet). They allow distribution of alerts about optical transients and correlation with other experiments in almost real-time. In certain moment number of observatories may reach the point where correlation with other experiments will be as efficient as stereo double-systems. Probably close cooperation of many individual pipelines is one of the most important goals for the nearest future. The data streams from optical telescopes are becoming larger and larger, this will also imply requirements for fast real-time data analysis tools. Creation of good standard solutions, widely used and tested by the community would probably saved a lot of future efforts. Implementation of pipeline for identification of short optical transients in the "Pi of the Sky" data was presented. It successfully works on the data from the prototype system in LCO and is planned to be used in the final design of the system. The final system will correlate OTs from two farms of wide field cameras separated by a distance of several dozens of kilometers. It will be able to credibly identify optical transients of astrophysical origin in real-time.

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