6.07.2007

Soltan Institute for Nuclear Studies in Warsaw

Proposal for FP7 project

"TelesFor"

Robotic Telescope Forest for All Sky Continuous Monitoring

1. INTRODUCTION

All sky surveys recently became a new important trend in observational astronomy. They are needed to search for rare phenomena and for phenomena with short duration time (especially shorter than 1 day). Among them are the are optical counterparts of Gamma Ray Bursts, blazar outbursts, fast variable stars, extrasolar planet transits and asteroids approaching the Earth. Although the need is commonly recognized, today there is no system covering the whole sky full time but single fish-eye cameras with limiting magnitude about 7^m. There are two major reasons for that. One is the large cost of a possible system, the second is the huge size of the data stream.

This proposal addresses both issues. It is proposed to solve the problem of data size by on-line data reduction and analysis. The problem of cost is proposed to be solved by designing a single device consisting of CCD sensor and optics in one unit rather than coupling together camera body with telescope optics. The minimum design goals for a single module are

- limiting magnitude **>16^m** in a single exposure and **>17^m** for 10 coadded images
- time resolution **< 10s**
- field of view of >π/100 steradians, i.e. **>10°×10°**
- cost **< 10 000 Euro**

They could be realized with the following system parameters:

- optics of ***f* = 100-200 mm** and ***f/d* ~1**
- CCD with **2000×2000 pixels**, **15μm ×15μm** each

The aim of this proposal is two fold:

1. Design, build and test a single camera module, which could be then copied and combined in a system covering all sky.
2. Develop a large "intelligent" measuring system consisting of 100-200 telescopes covering all sky, which operates autonomuosly, searching for interesting phenomena and acting automaticaly in response to its finding and external alerts.

2. EXISTING SOLUTIONS

Although the need for all sky monitoring system is commonly recognized, today there is no system covering the whole sky full time. There is a number of fish-eye cameras, each one covering the whole sky, however, they have limiting magnitude of 5-7^m only. Several projects have cameras covering 1/3 of steradian (roughly 33°×33°). Among them are single cameras with f=30-50mm (BOOTES[1], ASAS, *π of the Sky*) and quartets of f=110-150 mm cameras (LOTIS[2], RAPTOR[3], ROTSE I[4]). The only system so far covering ¾ of steradian with multiple cameras is the Explosive Transient Camera (ETC)[5], It consists of 16 devices. Each

[1] http://www.laeff.esa.es/BOOTES

[2] http://hubcap.clemson.edu/~ggwilli/LOTIS

[3] http://www.raptor.lanl.gov

[4] http://www.umich.edu/~rotse

[5] http://space.mit.edu/ETC

one has an f=24mm, f/1.4 lenses and 390×292 pixels CCD. The pixel size is 22μm, which corresponds to pixscale of 2.2 arcmin. The field of view of a single camera is 20.5°×15.3°. The limiting magnitude is 11^m with a 5s exposure. The ETC system was built in 1980s and since then no other attempts to cover all sky have been made.

There are two major reasons why, in spite of the commonly recognize need, there is no system covering all sky with limiting magnitude $>8^m$. One is the large cost of a possible system, the second is the huge size of the data stream. This proposal addresses both issues. It is proposed to solve the problem of data size by on-line data reduction and analysis. The problem of cost is proposed to be solved by designing a single device consisting of CCD sensor and optics in one unit rather than coupling together standard camera with commercial optics.

Installing all sky survey systems capable of reaching further than 15^m in several places over the globe could be a breakthrough in observational astronomy. Astronomers will gain access to rare, transient phenomena, which today escape anyone attention. Patchy catalogues of variable stars could be completed. It will become possible to study variable stars of different kinds in a statistical way, with large samples of each kind. History of astronomy shows that the greatest breakthroughs often came from statistical analysis of many objects. The best know examples are the H-R diagram, cepheides and the Hubble law. No one can predict what will be the next breakthrough, but for sure it will emerge from a new high statistics observations of the sky.

3. POLAND AS A LEADER IN SKY SURVEYS

There are three major reasons why this work should be initiated by Poland. The idea of importance large-scale surveys originated to large extent from professor Bogdan Paczyński[6]. As a consequence, there is already extremely valuable experience with such surveys accumulated in Poland by "*ASAS*"[7], "*π of the Sk*y"[8], and to some extent also the "*OGLE*"[9] projects. "*ASAS*" has several years of experience with running an automatic system of a few cameras at remote site, without direct human intervention. The "*π of the Sk*y" project went further towards fully robotic system by employing a suit of self-diagnostic and self-recovery procedures. Important ingredient of this project is participation of particle physics experimentalists, experienced with handling huge data streams. This resulted in developing on-line data analysis pipeline capable of handling 6000 images of 2000x2000 pixels per night and automatically recognising short optical transients. A new project, an automated spectrograph, is currently actively pursued at the Astronomical Observatory of Adam Mickiewicz University in Poznań.

The second important reason is the specific situation of particle physics and astronomy in Poland. With the funds available for science in Poland it is practically impossible neither to become a major player in large-scale particle physics experiment at a modern accelerator or to build Polish own very large telescope (d >5m), at least in next 10 years. Polish particle physicist and astronomers can only have a limited fraction of time on international facilities. It does not mean, of course, that such international projects are not important – to the contrary, there is no doubt that they are highly recommended to pursue from the scientific point of view. On the other hand, sky surveys can become "Polish speciality". There is already well establish tradition of variability study and massive searches for rare objects (microlensing, extrasolar planets etc.).

Most, if not all the technology needed for such a project is readily available in Poland and the issue is to bring various elements into a working, efficient detector. As a result, large-scale sky survey projects have potential to bring practically entirely new quality into scientific research in Poland. They can become our contribution of the world scientific heritage, will result in developing modern, knowledge-based technologies

---

[6] B.Paczynski, "The future of massive variability searches", astro-ph/9609073
B.Paczynski, "Monitoring All Sky for Variability", astro-ph/0005284
B.Paczynski, "Monitoring Variability of the Sky", astro-ph/0108112
B.Paczynski, "Massive Variability Searches: The Past, Present and Future", astro-ph/0110388
B.Paczynski, "Massive Variability Search and Monitoring by OGLE and ASAS", astro-ph/ 0212144

[7] http://www.astrouw.edu.pl/~gp/asas/

[8] http://grb.fuw.edu.pl

[9] http://www.astrouw.edu.pl/~ogle/

with a high potential of commercial applications and, last but not least, have a huge impact on education and development of human resources in institutions involved in the project. Experience with "*π of the Sky*" shows a big difference between student's role in a large, international collaboration and a project which has been originated in and is lead locally, in Poland. Hence, large-scale automatic sky surveys can really become Polish scientific specialty with all its scientific, educational and prestige consequences.

The third advantage of developing inexpensive cameras of scientific quality with wide field optics is that they could be used by small observatories with low budget and by universities for educational purposes. It is extremely important to train students with real observations using modern equipment, so after finishing their studies they are ready to take part in larger projects.

3. TECHNICAL DESIGN

The main goal of this proposal is to design a module consisting of a CCD camera with wide field optics, optimised for all sky surveys. A full system should consist of about hundred of such modules to cover the full sky. Because of the large number of modules, one has to minimize the cost of a single unit. We assume here a target cost of the order of 10 000 euro per module.

The second goal of the proposal is to develop a data acquisition and analysis system capable of handling the large stream of data. Study of rapid phenomena, like Gamma Ray Bursts, require high time resolution. We assume 10s as a target value. This implies ~3000 frames per night per module and the data volume of 25 GB/night for 4 Mpixel CCD. This is already challenging and it still has to be multiplied by ~100 for the full sky coverage. Therefore, the system must be fully scalable. The data have to be processed on-line, as one cannot store such amount of data for a long time. Only final results of the analysis plus carefully selected frames containing interesting phenomena can be stored .

Maintenance and handling of such a large system is a non-trivial task. It has to operate in a fully automatic way. It has to have build in self-diagnostic and self-recovery procedures. It should also be immune to single failures. Hang-up of an operating system on one of the computers or even a hardware failure of one PC should not disturb the operation of the system as a whole. The system should be able to sustain a network failure lasting several hours. It should be also able to recover smoothly after a power failure at the site.

3.1. Design goals

SKY COVERAGE

From a given site, the instrumentation should cover the entire visible sky, until a zenith distance where the 5-sigma limiting magnitude has decreased by 0.5 magnitudes, relative to zenith. This corresponds to a zenith distance of 70°, assuming the instrumentation is not seeing limited. The total solid angle to be covered is thus $\Omega = 2\pi\,(1\text{-}\cos 70°) = 1.32\,\pi = 4.13$ steradians. Assuming that the number of cameras to cover such field should not be larger than 100, we conclude, that a single camera should have the field of view at least 11.6°×11.6° (not taking into account details of overlapping corners etc.). If we relax the requirement to the zenith distance of 60° we need to cover π steradians, which could be done by 100 cameras 10°×10° each.

PHOTOMETRIC ACCURACY

It would be very difficult to achieve photometric precision which is needed to search for extrasolar planet. Typical Jupiter-like planet has a diameter 10 times smaller than the star. Therefore, the transient causes about 1% decrease in the star brightness. In order to detect it one needs photometric accuracy of the order of $\sigma = 0.002$ magnitudo. One cannot guarantee a priori that such precision could be achieved with the system proposed (even for the brightest, not saturated stars). In any case, however, the best possible photometric precision is needed to study variable stars.

Fast transient detection, e.g. GRB optical counterparts, may lead to different optimisation. It does not require photon noise limited photometric accuracy, while planet search and variability study does. However, it is important to realize that for stars brighter than about 12th magnitude, depending on the effective sensitivity of the system, photometry is limited by scintillation and not photon noise. Therefore there is no conflict, if the photometry is photon noise limited at the scintillation limit. In this case we are able to optimally approach the two science cases with the same equipment, given that this requirement is fulfilled.

TEMPORAL RESOLUTION

Transient detection will benefit from the highest possible temporal resolution, as long as two requirements are fulfilled:

a) Each exposure is sky noise limited.
b) The dead time due to readout is insignificant.

While there for planet search or standard variability study there is no direct benefit from a high temporal resolution, the ability to acquire many photometric measurements with errors that are statistically independent is a way to reconcile the quite different requirements for the two science cases. The need to acquire images at the highest possible frame rate (condition a) points towards the fastest possible camera (the lowest possible F-ratio). The need to maintain an insignificant dead time points towards fast CCD readout (> 1 MHz/pixel) and/or the use of frame transfer detectors.

SPATIAL RESOLUTION

The pixel scale, in arcsec per pixel, will be limited by the assumed limit on funding, as this gives the total number of cameras and detectors. This is therefore not, in a sense, a parameter which is free (see the “CCD choice” section below). The sampling of the Point Spread Function (PSF), which we might be given as number of pixels per Full Width at Half Maximum (FWHM) is however a free parameter.

Transient detection may benefit from having less than two pixels per FWHM, because the background noise is reduced, but it makes the detection much more sensitive to single pixel noise spikes. For a massively parallel system, this is a matter of concern. It is also highly desirable that the PSF is sufficiently well sampled that a precise position can be derived, since there is no guarantee that a short transient of hitherto unknown nature can be picked up by a larger telescope after the detection.

For planet detection or variability study, it may be desired to slightly defocus to reach a higher photometric accuracy. However, if images are acquired at a high frame rate, each individual exposure need not have a very high photometric accuracy, as long as it is photon noise limited at the scintillation limit and the photometric errors of consecutive exposures are statistically independent. Statistically independent photometric errors can be obtained by dithering. We can therefore conclude that the best sampling is around 2.5 pixels per FWHM.

3.2. Outline of an example solution

Preliminary study resulted in Schmidt camera design presented in Fig. 1. The design was made with the ZEMAX program. The system consists of a spherical mirror, single corrector plate and field flattener lenses.

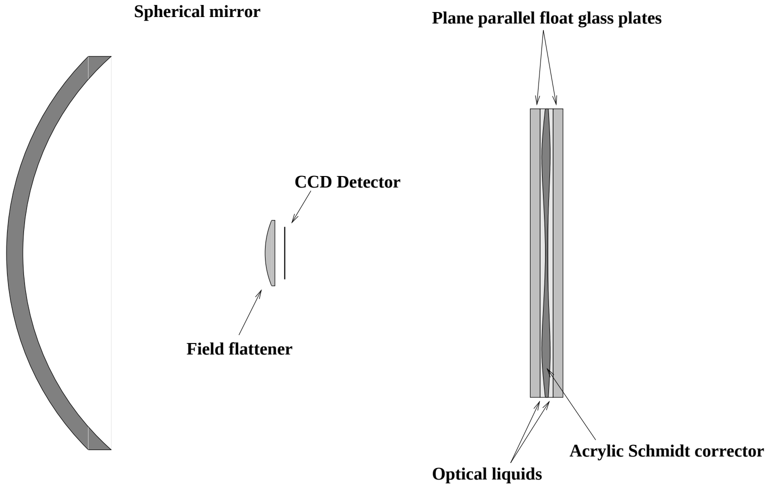

Fig. 1. Proposed camera with Schmidt optics:

- Effective aperture: 175 mm
- Focal length: 160 mm
- F-ratio: 0.9
- Field of view: 118
- Main mirror diameter: 235 mm
- PSF FWHM: 50 arcsec
- CCD array: 2032 x 2032
- Pixel size: 15μm
- Pixel scale: 19.3 arcsec

Rather simple field flattener with only two lenses should be enough. The most difficult part is the highly aspheric Schmidt corrector plate. Producing such a plate with a precision meeting the specs is a challenge. We consider a novel approach of immersing the corrector plate in between two different liquids, which are contained by two plane parallel glass plates. In such design the tolerances for the manufacture of the plate are reduced to a level where it can be cast in plastic. For the glass plates one can consider using low cost float glass, especially selected for this purpose. It seems that this is the optimum path towards inexpensive mass replication of cameras for a scaled-up project with higher sensitivity and temporal resolution.

The short focus reflector design implies, that the CCD sensor must be placed in the light beam. This has two consequences. Firstly, the Peltier module cooling the CCD cannot be air cooled in order to avoid air turbulences. Instead, we consider cooling by liquid. Secondly, the front-end electronics (preamplifier) has to stay in a shadow of the CCD. The digital electronics has to be placed separately, outside the light beam. This would imply designing the electronics especially made for this purpose.

Also the shutter cannot be placed close to the CCD. Shutter leaves placed parallel to the CCD would block a lot of light in the opened position. On the other hand there is not enough space between the CCD and the field flattener to open the leaves vertically. One possible solution is to make a large shutter outside the optics. Another possibility is to operate without a shutter at all. In such a case a frame transfer CCD could be desirable, but it has two drawbacks. One is the large area of the memorising part of the CCD, extending into the light beam. The second one is much higher price of frame transfer devices. We consider to try using a standard frame transfer CCD without a shutter. Assuming 2 MHz/pixel readout of a 2000x2000 array the charge remains on one pixel for about 1ms. This is 10^{-4} fraction of a 10s exposure, i.e. somewhat above the dynamic range of the device. This could be improved by increasing the readout speed or by using a CCD with multiple outputs. In any case, the effect should be visible only in the case of saturated stars and one should be able to reduce it to some extent by software.

The design presented above is by no means final. It should be considered as a prove of feasibility of the project. Technical solutions may change in the optimisation process, providing that the requirements listed above are fulfilled.

4. PARTICIPANTS

Soltan Institute for Nuclear Study has enough experience in EU projects to become the coordinator. Among possible Polish participants are institutes currently involved in "*π of the Sky*" experiment:

- Center for Theoretical Physics - Polish Academy of Sciences, Warsaw
- Institute of Experimental Physics - Warsaw University
- Institute of Electronics Systems – Warsaw University of Technology
- Space Study Center - Polish Academy of Sciences, Warsaw

Preliminary interests in the project has been also expressed by

- Astrophysikalisches Institut Potsdam, Potsdam
- Niels Bohr Institutet, Copenhagen