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PI OF THE SKY FULL SYSTEM AND THE NEW TELESCOPE

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RESUMEN

El Pi of the Sky es un sistema de telescopios de campo amplio, que buscan fenómenos astrofísicos de escala temporal corta, en especial la emisión óptica temprana de GRBs. El sistema fue diseñado para una operación autónoma, monitoreando una gran porción del cielo hasta una profundidad de $12^m - 13^m$ y con una resolución temporal del orden de $1 - 10$ segundos. El diseño del sistema y la estrategia de observación fueron probados exitosamente con un detector prototipo operativo en el Observatorio de Las Campanas, en Chile, desde 2004 al 2009 y trasladado al observatorio de San Pedro de Atacama en marzo de 2011. En octubre de 2010 la primera unidad del sistema de Pi of the Sky, con 4 cámaras CCD, fue instalado exitosamente en el Centro de Pruebas El Arenosillo del INTA en España. En julio de 2013, tres unidades adicionales (12 cámaras CCD) fueron instaladas, conjunto a la primera, en una nueva plataforma en el INTA, extendiendo la cobertura del cielo a unos 6000 grados cuadrados.

ABSTRACT

The Pi of the Sky is a system of wide field of view robotic telescopes, which search for short timescale astrophysical phenomena, especially for prompt optical GRB emission. The system was designed for autonomous operation, monitoring a large fraction of the sky to a depth of $12^m - 13^m$ and with time resolution of the order of $1 - 10$ seconds. The system design and observation strategy were successfully tested with a prototype detector operational at Las Campanas Observatory, Chile from 2004-2009 and moved to San Pedro de Atacama Observatory in March 2011. In October 2010 the first unit of the final Pi of the Sky detector system, with 4 CCD cameras, was successfully installed at the INTA El Arenosillo Test Centre in Spain. In July 2013 three more units (12 CCD cameras) were commissioned and installed, together with the first one, on a new platform in INTA, extending sky coverage to about 6000 square degrees.

Key Words: gamma-rays: general — parallaxes — techniques: photometric — telescopes

1. INTRODUCTION

The "Pi of the Sky" (Burd A. et al. 2005) is a system of wide field of view robotic telescopes designed for efficient search for astrophysical phenomena varying on scales from seconds to months. The design of the apparatus allows the monitoring of a large fraction of the sky to a depth of $12^m - 13^m$ and with time resolution of the order of $1 - 10$ seconds.

The main goal of the "Pi of the Sky" project is to search for and observe prompt optical counterparts of Gamma Ray Bursts (GRBs) during or even before gamma-ray emission. To achieve this purpose "Pi of the Sky" selected an approach which assumes continuous observation of a large part of the sky to increase the possibility of catching a GRB. Therefore, it was necessary to develop advanced and fully automatic hardware and software for wide-field monitoring, real-time data analysis and identification of flashes.

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The full “Pi of the Sky” system is capable of continuous observation of almost 2 steradians, which roughly corresponds to the field of view of the BAT instrument on board the Swift satellite (Gehrels N. et al. 2004). The first unit of the system, equipped with 4 CCD cameras, was installed in the INTA El Arenosillo Test Centre near Huelva, Spain, in October 2010. In July 2013 the system was extended with three more units (12 CCD cameras) and is now fully operational with a total sky coverage of about 6000 square degrees. In this contribution we present the system design, review most important results obtained with the prototype detector in Chile and with the first unit of the final system in Spain, and present our plans for the future development of the project.

2. OBSERVATIONAL STRATEGY

Observations of optical counterparts of GRBs during or even before the gamma-ray emission are crucial for understanding the nature of GRBs. The standard approach, which relies on alerts distributed by the GCN (The Gamma-ray Coordinates Network) (Barthelmy S. D. et al. 1997) and assumes pointing the telescopes to the target as fast as possible, does not allow the detection of an optical outburst at the moment of or before the GRB explosion. Instead, the “Pi of the Sky” strategy is based on the continuous observation of a large fraction of the sky, which increases the chances that a GRB will occur in the observed area.

In order to ensure that all project requirements are met we decided to maintain full control over the detector design and construction. Custom designed CCD cameras were build for the “Pi of the Sky” detectors by the project members. Each camera is equipped with Canon lenses f = 85 mm, f/d = 1.2 and covers 20°x20° of the sky. The full system consists of 16 cameras placed on four specially designed equatorial mounts (4 cameras per mount). Following the field of view of the Swift satellite with the full “Pi of the Sky” system eliminates delay due to telescope re-pointing to the coordinates from GCN. Dead time, which arises from the decision process and signal propagation from the satellite to the GCN and from the GCN to the ground instruments is eliminated as well.

“Pi of the Sky” is capable of independent search for optical flashes in the sky, which requires very fast data processing and identification of events with dedicated algorithms in real-time. On the other hand, the search for transients and the analysis of variable stars are based on precise photometry, which requires detailed image analysis. To fulfill both requirements we developed two different sets of algorithms: for on-line and off-line data processing. The on-line algorithm searches for flashes in real-time by comparing a new image with the stack of recently taken frames. Any observed difference is considered as possible candidate event. All events are processed through a multilevel triggering system similar to those known from high-energy physics experiments. Off-line algorithms are used to identify all objects in an image, and to add their measurements to the database for future analysis.

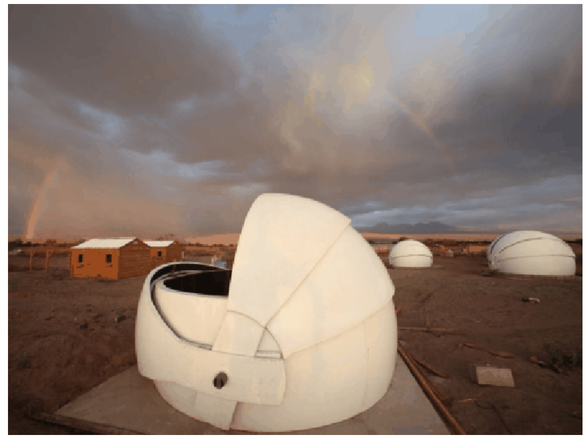

Fig. 1. Dome at San Pedro de Atacama, Chile, to which the prototype unit was moved from Las Campanas Observatory in March 2011.

3. “PI OF THE SKY” TELESCOPES

Before constructing the final version, tests of hardware and software were performed with a prototype consisting of 2 custom-designed cameras placed on an equatorial mount. The detector is fully autonomous and operates without any human supervision, although remote control via Internet is possible as well. The cameras can work in coincidence and observe the same field of view with a time resolution of 10 s. The limiting magnitude for a single frame is 12^m and rises to 13.5^m for a frame stacked from 20 exposures. Prior to 2009 all observations were made in white light and no filter was used, except for an IR-cut filter in order to minimize the sky background. Since May 2009 a Bessel-Johnson R-band filter is installed on one of the cameras in order to facilitate absolute calibration of the measurements. The prototype operated at Las Campanas Observatory in Chile from June 2004 until the end of 2009. In March 2011 the detector was moved to a new site in San Pedro de Atacama, approximately 750 km north from LCO (still in Chile) and about 2400 meters above sea level (similar to LCO, see figure 1).

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Fig. 2. Four detector units installed in July 2013 at the INTA El Arenosillo test centre in Mazagón near Huelva, Spain.

The final detector consists of 4 custom-designed mounts and 16 custom-designed CCD cameras (4 cameras per mount), which are improved versions of the cameras developed for the prototype. The cameras can operate in two modes thanks to a specially designed equatorial mount. The mechanism for deflecting cameras enable us to point all cameras at the same object (common–target mode, DEEP, common field of view 20°x20°) or deflect them by 13° along the diagonal of the CCD chip, thus covering adjacent fields (side–by–side, WIDE, total coverage 38°x38° with one mount). Due to numerous improvements, the new design of the telescope mount provides much better pointing accuracy and a shorter reaction time than the prototype. The new detector units have successfully operated at the INTA El Arenosillo test centre in Mazagón near Huelva, Spain, on the coast of the Atlantic Ocean since October 2010, and the system was completed in July 2013 (see figure 2).

4. SELECTED RESULTS

4.1. *GRB 080319B*

On March 19th 2008, at 6:12:49 UT the automatic algorithms of the "Pi of the Sky" prototype system detected a new object in the sky. A few seconds later an alert from GCN arrived – the Swift satellite detected an extremely luminous GRB, which will be referred to as GRB080319B. In the optical band its brightness was greater than all previously observed bursts. At the maximum it was as bright as 5.3^m. The optical light curve reconstructed from "Pi of the Sky" data is shown in figure 3. The most important observation was that the luminosity measured by "Pi of the Sky" was over 10,000 times

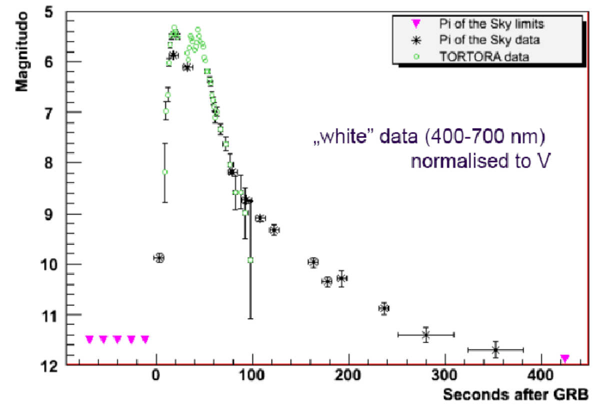

Fig. 3. The optical light curve of the "naked-eye" GRB080319B reconstructed from "Pi of the Sky" and TORTORA data (Racusin J. L. et al. 2008).

higher than expected by extrapolation from gamma to optical band. This shows that optical emission is caused by a different mechanism than emission in gamma rays (Racusin J. L. et al. 2008). The observations of this "naked-eye" GRB080319B have confirmed the usefulness of the "Pi of the Sky" observation strategy. Wide-field telescopes performing continuous observations of large part of the sky are capable of detecting GRBs at the moment or even before the explosion. GRB080319B was recognized by the "Pi of the Sky" self-triggering system independently from the alert received from the GCN.

4.2. *Search for the GRB080319B optical precursor*

To meet the requirement of monitoring a large fraction of the sky, the "Pi of the Sky" apparatus makes use of cameras with a wide field of view. For stars far from the optical axis, this causes significant image deformations, which are much larger than in other astronomical experiments. This was also the case for GRB080319B, for which the position of the burst was in the corner of the frame up to $t_0 + 36$ s. The possible precursor would therefore also be deformed and thus large uncertainties would be introduced into standard photometric and signal-searching algorithms. To improve measurements and signal seeking capabilities a model of the Point Spread Function (PSF), based on modified Zernike polynomials, was created for the "Pi of the Sky" detector (Piotrowski L. W. et al. 2013). Simulated PSFs obtained from the model are very close to real images even for the most deformed stars, as can be seen in figure 4. The precursor search was performed by fitting the PSF model at GRB coordinates to all frames covering 19 minutes prior to the explosion, on two cameras of the Pi of the Sky pro-

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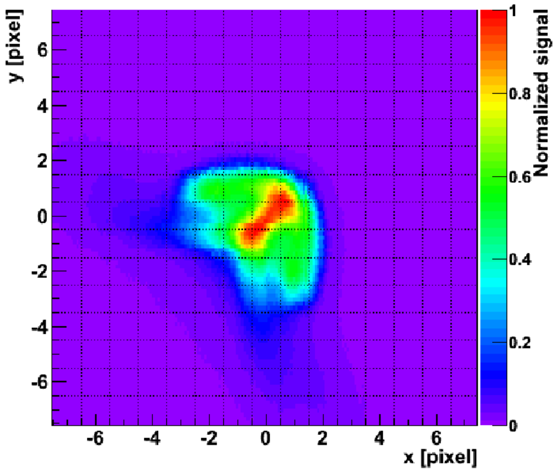

Fig. 4. An example of a highly deformed PSF in the corner of the "Pi of the Sky" frame (Piotrowski L. W. et al. 2013).

totype. No signal exceeding 3σ level has been found. The limit calculated on single frames fluctuated in most cases between 11.5^m and 12.25^m (Piotrowski L. W. 2012).

4.3. *Photometric corrections*

We have developed a series of quality filter cuts to remove measurements (or whole frames) affected by detector imperfections or observing conditions. Measurements that are placed near the border of the frame, or that are affected by hot pixels, bright background caused by open shutter or the Moon halo, or by planet or planetoid passage, can be easily recognised and removed by dedicated algorithms. By selecting only high quality measurements, an average photometry uncertainty of about $0.018 - 0.024^m$ has been achieved for stars of $7 - 10^m$.

We managed to improve photometry accuracy further by developing a dedicated color correction algorithm. When performing observations without any filter (which is the case for most of our data), we normalize our measurements to reference stars measured in V filter. Due to the wide spectral acceptance of the CCD, detector response is correlated with the stellar spectral type. The average magnitude measured by "Pi of the Sky" is shifted with respect to the catalog magnitude in V band by an offset depending on the spectral type given by B–V or J–K. The approximation of this dependence with a linear function enables the measurement of each star to be corrected, so that measured magnitude is equal to catalog V magnitude independently of the spectral type. Additional improvement of the measurement precision is also achieved when the photometric correction is not calculated as a simple average over all selected reference stars, but when a quadratic dependence of the correction on the reference star position in the sky is fitted for each frame. The distribution of χ^2 can be used to select the measurements with the most precise photometry. When applying the new algorithm to the light curve of BG Ind (Rozyczka M. et al. 2011), a brightness uncertainty of 0.013^m was achieved (see figure 5).

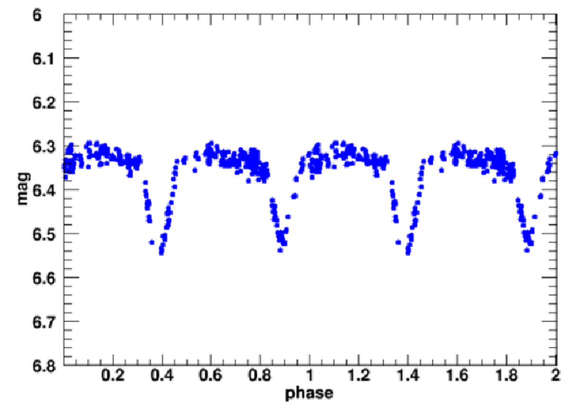

Fig. 5. Light curve for BG Ind variable obtained with dedicated spectral corrections (Rozyczka M. et al. 2011).

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4.4. *Measurements of a parallax*

Every night, when both "Pi of the Sky" sites observe, automatic algorithms search for new objects in the sky, especially GRBs, in the optical band. Unfortunately, most flashes are due to satellites or planes, and there are a number of cases which are difficult or impossible of unique identification. The best method to recognize astrophysical sources is to measure the distance to them, and the direct method to do it is to measure the parallax.

The distance between observatories in Chile and Spain is almost 8 500 km (along the Earth's chord) and, assuming that both telescopes are pointing in the same direction, we are able to measure parallax angles between 25" (a half of a diagonal of a pixel) and 14° (a half of a diagonal of a frame). This results in an observable parallax angle for objects, which are in a distance between about 20 000 km and 38.2 million km from the centre of the Earth. In this range one can measure geostationary and GPS satellites, space debris (Sokolowski M. et al. 2011), possibly also comets and planetoids. For the satellites, we are able to measure their altitude with 50 km accuracy from single observation (see figure 6) (Majcher A. et al. 2013).

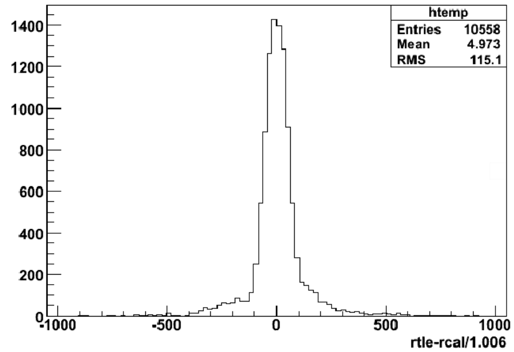

Fig. 6. Distribution of the difference between the satellite altitude calculated from parallax measurement and received from TLE databases (TLE 2013).

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5. CONCLUSIONS

The "Pi of the Sky" instruments operate in a fully autonomous mode, practically without any human supervision, and search for short-timescales astrophysical phenomena, especially for prompt optical counterparts of GRBs. The ultimate system will be able to perform continuous observations of the field of view of Swift satellite, which will allow to detect GRBs at the moment or even before the explosion. The observations of the famous "naked-eye" GRB080319B with the prototype located in Las Campanas Observatory in Chile, have confirmed the suitability of the observing strategy of "Pi of the Sky" .

During the period 2006-2009 the prototype has gathered over 2 billion measurements for almost 17 million objects. All measurements acquired by "Pi of the Sky" are publicly accessible through a user-friendly web interface on the "Pi of the Sky" home page. Effort on improving data quality is still ongoing.

The ultimate "Pi of the Sky" system with four units and 16 CCD cameras is fully operational in the INTA El Arenosillo Test Centre in Spain since July 2013. The prototype, after moving from Las Campanas Observatory to San Pedro de Atacama Observatory in March 2011, is effectively collecting new data as well.

To extend our observation capabilities we are currently working on the design of the new "PI of the Sky Plus" telescope. Fast parallactic mount, with maximum speed of up to 30° per second, absolute pointing precision of about 20", and load of up to 100 kg will allow us to use 4 lenses with $f = 296$ mm and 180 mm aperture (see figure 7).

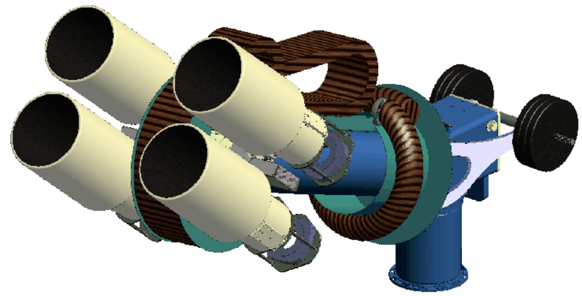

Fig. 7. Design of the new "PI of the Sky Plus" telescope.

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