Acta Polytechnica **54**(3):225–230, 2014
doi:10.14311/AP.2014.54.0225

available online at http://ojs.cvut.cz/ojs/index.php/ap

PHOTOMETRIC ANALYSIS OF PI OF THE SKY DATA

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Abstract. Pi of the Sky is a system of two wide field of view robotic telescopes, which search for short timescale astrophysical phenomena, especially for prompt optical GRB emissions. The system was designed for autonomous operation, monitoring a large fraction of the sky with 12^{m}–13^{m} range and time resolution of the order of 1–10 seconds. Two fully automatic Pi of the Sky detectors located in Spain (INTA — INTA El Arenosillo Test Centre in Mazagón, near Huelva.) and Chile (SPDA — San Pedro de Atacama Observatory.) have been observing the sky almost every night in search of rare optical phenomena. They also collect a lot of useful observations which include e.g. many kinds of variable stars. To be able to draw proper conclusions from the data received, adequate quality of the data is very important. Pi of the Sky data is subject to systematic errors caused by various factors, such as cloud cover, seen as significant fluctuations in the number of stars observed by the detector, problems with conducting mounting, a strong background of the moon or the passing of a bright object, e.g., a planet, near the observed star. Some of these adverse effects have already been detected during the cataloging of individual measurements, but the quality of our data was still not satisfactory for us. In order to improve the quality of our data, we have developed two new procedures based on two different approaches. In this article we will report on these procedures, give some examples, and we will show how these procedures improve the quality of our data[1].

Keywords: Gamma Ray Burst (GRB), variable stars, robotic telescopes, photometry, astrometry, data quality, photometric corrections.

1. Introduction

Pi of the Sky is a system of two wide field of view robotic telescopes designed for efficient searches for astrophysical phenomena varying on scales from seconds to months. The design of the apparatus allows a large fraction of the sky to be monitored with a range of 12^{m}–13^{m} and 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. Other scientific goals include searching for nova stars and flare star explosions, and looking for new, as yet undetected variable stars. 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. It was therefore necessary to develop advanced and fully automatic hardware and software for wide-field monitoring, real-time data analysis and identification of flashes[1].

2. Methods to improve data quality

2.1. Color correction

As was mentioned above 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 an open shutter or by the Moon halo, or by planet or planetoid passage, can easily be recognized and removed by dedicated algorithms. By selecting only high quality measurements, average photometry uncertainty of about 0.018^{m}–0.024^{m} has been achieved for stars from 7^{m} to 10^{m} (see Figure 7) [1].

We were still not satisfied with the quality of our data. We have been looking for new methods, and for algorithms which can help us to improve the quality of our data. We have managed to improve the photometry accuracy further by developing a dedicated color correction algorithm. When performing

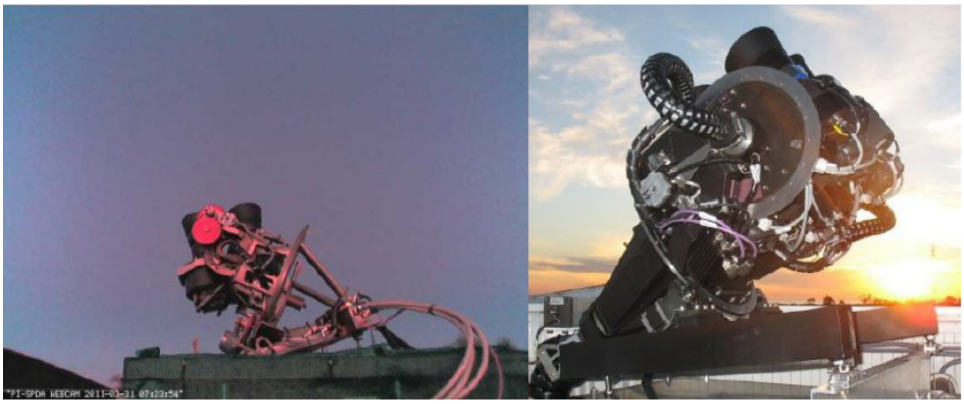

Figure 1. Two currently working Pi of the Sky detectors. The prototype detector (on the left), and the new detector (on the right).

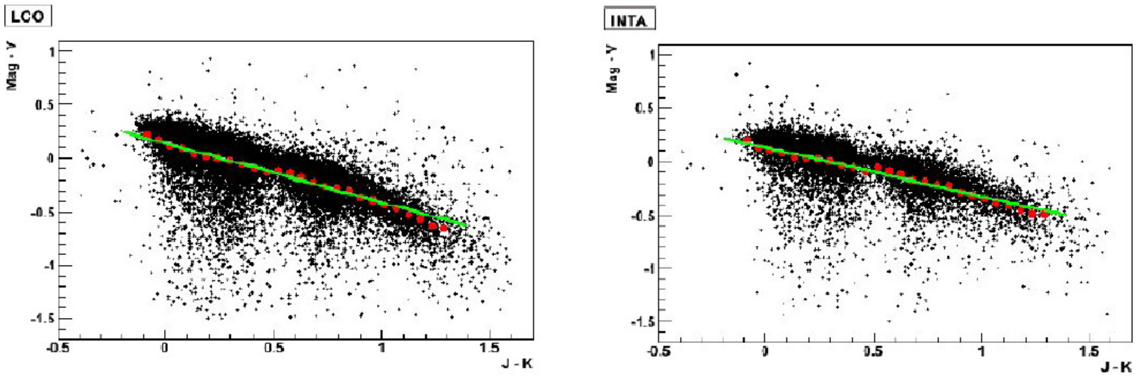

Figure 2. The detector response is correlated with the spectral type ($B - V$ or $J - K$) of catalog stars.

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, the CCD detector response is correlated with the stellar spectral type. As determined by the manufacturer, the CCD detectors used in the Pi of the Sky project have the greatest sensitivity in the near infrared, while the average wavelength is, in their case, $\langle\lambda\rangle \approx 585\,\text{nm}$, which corresponds approximately to a wavelength characteristic of the V filter. The CCD detectors sensitivity varies according to the wavelength λ, and affects the quality of the results of measurements taken in white light. Two objects with the same luminosities, from which the first one shines in near infra-red and the second e.g. in blue will have different brightnesses on our detectors. An object shining in the near infra-red will be brighter than a blue object. Since neither of the INTA cameras present in the new detector has a filter installed that can deal with this effect, we must take this effect into account when cataloging our data [1].

The average magnitude measured by Pi of the Sky is shifted with respect to the catalog magnitude in the V band by an offset depending on the spectral type given by $B-V$ or $J-K$. We have already determined that in the case of data collected by the prototype detector in Chile, the correction of the standard photometry used in the Pi of the Sky project, which is based on taking into account the dependence of the sensitivity of the CCD chip on the observed star type, may be approximated by the following formula:

$$M_{\text{corr}} = M - 0.2725 + 0.5258 * (J - K) \quad (1)$$

The J and K values correspond in this formula to the brightnesses of the object tested, in the J and K filters, respectively. M is the brightness of the analyzed object, measured by the detector and normalized to the brightness of the catalog stars in V. M_{corr} represents the corrected magnitude, which takes into account color correction. The prototype's cameras, however, have chips made by a different manufacturer (Fairchild) than cameras in Spain (STA), so the color calibration also had to be repeated for the data collected by the new detector (see Figure 2) [1, 2].

Approximating of this dependence with a linear function enables the measurement of each star to be corrected, so that the measured magnitude is equal to the catalog V magnitude, irrespective of the spectral type. Equation (1) gives us information about the corrected magnitude only for catalog stars which have J and K brightness values. If we want to calculate the photometry corrections for any stars visible in the resulting figure, we use a special procedure which requires the use of only the best catalog stars. We are interested in catalog stars in the range of magnitude from 6^{m} to 10^{m}, and we reject stars with a magnitude

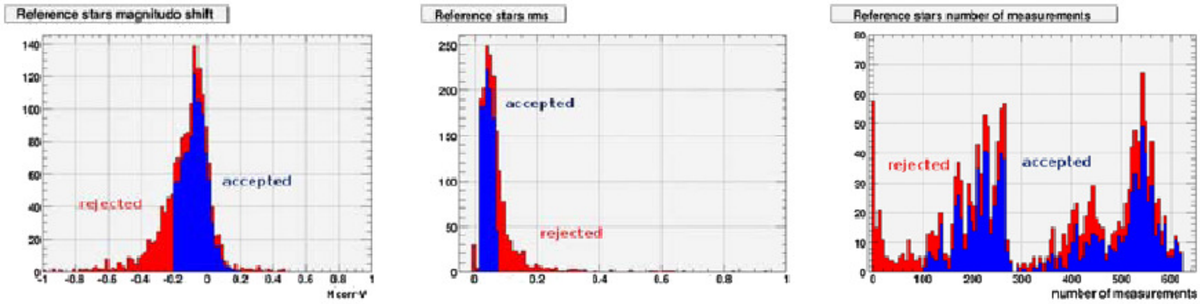

Figure 3. For calculating photometry corrections, only the best catalog stars were used (blue), after rejecting stars with a magnitude shift ($M_{\text{corr}} - M$) bigger than 0.2, RMS_{corr} bigger than 0.07 and with fewer than 100 measurements.

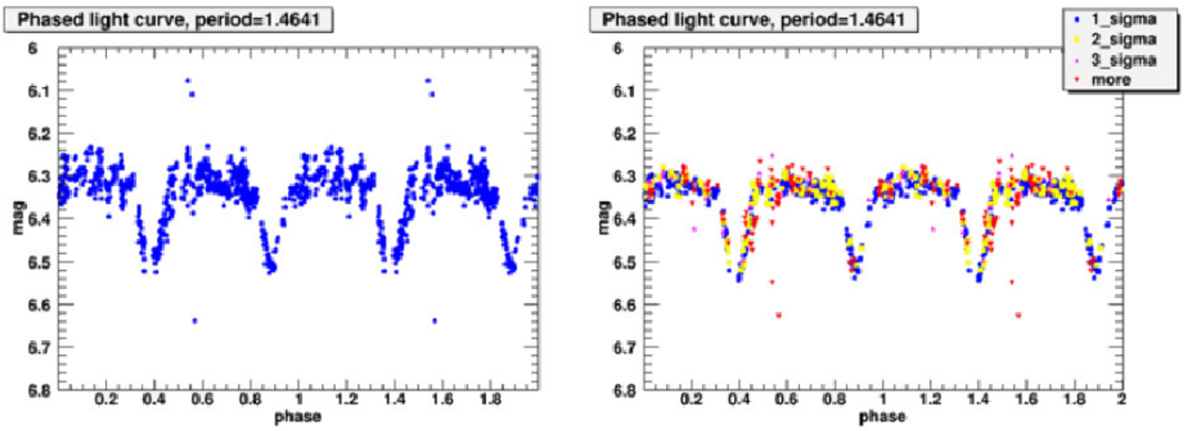

Figure 4. Uncorrected light curve for BG Ind variable (left) and after spectral corrections with correction quality cut (right).

shift ($M_{\text{corr}} - M$) bigger than 0.2. The catalog stars should also have more than 100 measurements, and we accept only catalog stars which have $RMS_{M_{\text{corr}}} < 0.07$ (see Figure 3) [1, 2].

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. In this case, for the selected catalog stars we calculate the quadratic surface correction, and we try to interpolate the value of the correction in the point where our analyzed star exists. The average square distance of the reference stars from the fitted correction surface (χ^2) gives us additional, independent information about the quality of the analyzed measurement. Spectral correction and additional χ^2 distribution allow the selection of only measurements with the highest precision [2].

The effect of photometry correction with a distribution of χ^2 on the reconstructed BG Ind light curve is shown in Figure 4. In this case, application of the new algorithm improved the photometry quality, and uncertainty sigma of the order of 0.013^{m} was obtained. We also applied photometry correction to other stars, with as good results as in the case of BG Ind variable [3].

2.2. Statistical methods

Another way, independed from the previous methods, that we also considered for improving the data quality, was a study of the statistical properties of a whole frame or even a group of frames. In this method, we calculate the quality of a single frame, and on the basis of this quality we have information about the quality of a single measurement on the analyzed frame. At the beginning of this correction procedure we calculate the median for each catalog star visible on a given frame. The median is calculated on the basis of only the best measurements (measurements which have quality = 0 and fit quality $\leq 1\sigma$) taken from the same field as in the case of the analyzed frame. Later, for each catalog star visible on the analyzed frame we calculate the $M_{\text{corr}} - Med$ value, where Med is the median calculated before and M_{corr} represents the corrected catalog star magnitude taken from the analyzed frame which takes into account the dependence observed magnitude from the brightness of the catalog star [2].

In order to determine the quality of an analyzed frame, we check how many catalog stars (which are visible on this frame) have $|M_{\text{corr}} - Med| > 2 * \sigma$. These stars will later be reffered to as "*bad*". The σ value is calculated by creating an $M_{\text{corr}} - Med$ histogram for all catalog stars visible on all frames

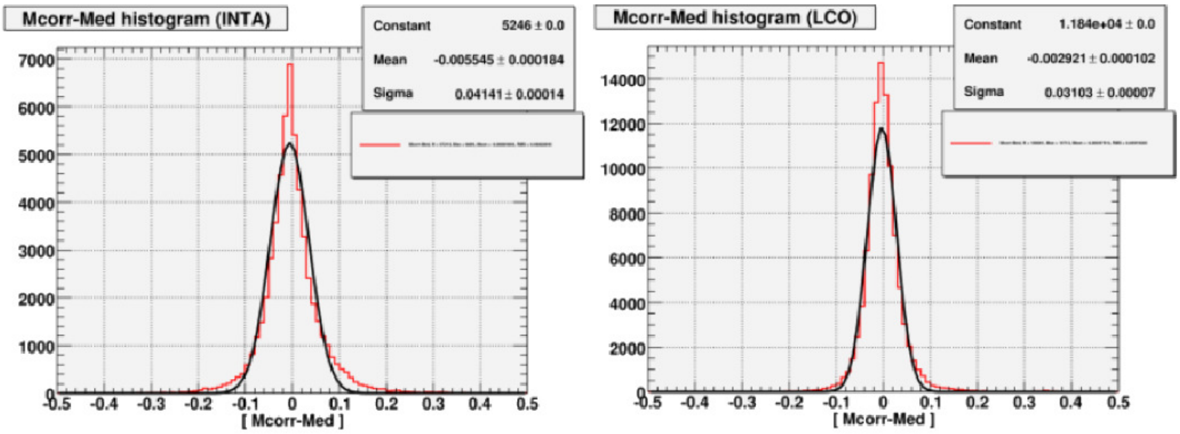

Figure 5. The Gauss function fitted to $|M_{\mathrm{corr}} - Med|$ histogram. Thanks to this fit we can obtain the value of σ, which is later used to calculate the quality of the analyzed frames.

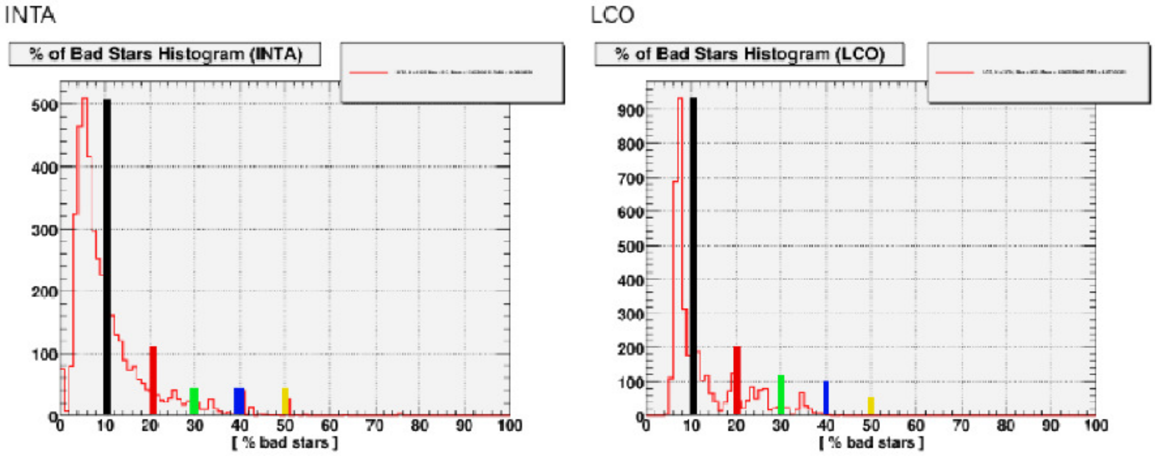

Figure 6. Histograms of the percentage of bad catalog stars in a single frame. These histograms were created for a given range of frames, and for each frame it was calculated what percentage of catalog stars from the analyzed frame have $|M_{\mathrm{corr}} - Med| > 2\sigma$. We assumed that the best frames have less than 10 % bad catalog stars and the worst frames have more than 50 % bad catalog stars.

coming from the same field as in the case of the analyzed measurement. To this histogram we can fit the Gauss function which gives us the value of σ, and this is later used to obtain the quality of the analyzed frames (see Figure 5). We assumed that the best frames have less than 10 % bad catalog stars and the worst frames have more than 50 % bad catalog stars (see Figure 6). Each frame which contains an analyzed star measurement is analyzed in the same way [2].

If we know which frames are good and which are bad, we can calculate $\langle M \rangle$ and $\sigma \langle M \rangle$ values based on each group of frames. We can calculate these values based on measurements taken only from the best frames, from the worst frames, or from all frames. We also take into account the quality of the data calculated using the previous methods. Our results are given below (see Figure 7). The photometry accuracy improves significantly when this method is used. After removing bad data, σ from 0.01^{m} to 0.03^{m} is achieved (see Figure 7) [2].

3. Comparison of methods

After calculating each correction separately, we can ask which correction is the best. We would like to find the combination of methods that gives us the best analyzed light curve quality, without removing a lot of data from this light curve. As we see in Fig. 9, in some cases after using some combination of methods the quality of the analyzed light curve improves significantly, and it is almost the same as in cases when we apply all corrections and remove more data from the analyzed light curve. It is more cost-effective is use a small number of corrections and not to remove a lot of data, so that we can have more information about the analyzed light curve (e.g. we can calculate the period more precisely). The choice of the appropriate method is unfortunately dependent

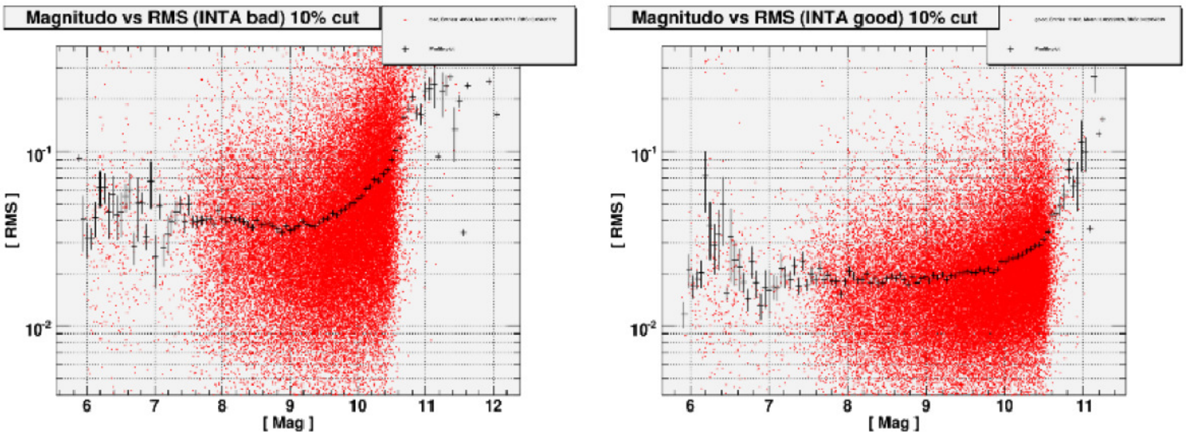

FIGURE 7. $\sigma\langle M\rangle$ vs $\langle M\rangle$ plot. On the left we can see points with positions corresponding to $\langle M\rangle$ and $\sigma\langle M\rangle$ calculated on the basis of all measurements. On the right we can see points with positions corresponding to $\langle M\rangle$ and $\sigma\langle M\rangle$ calculated on the basis of only the best measurements. As we see, after using this method the quality improves significantly and $\sigma \sim 0.03^{\mathrm{m}}$ is achieved for stars from 7^{m}–9^{m}.

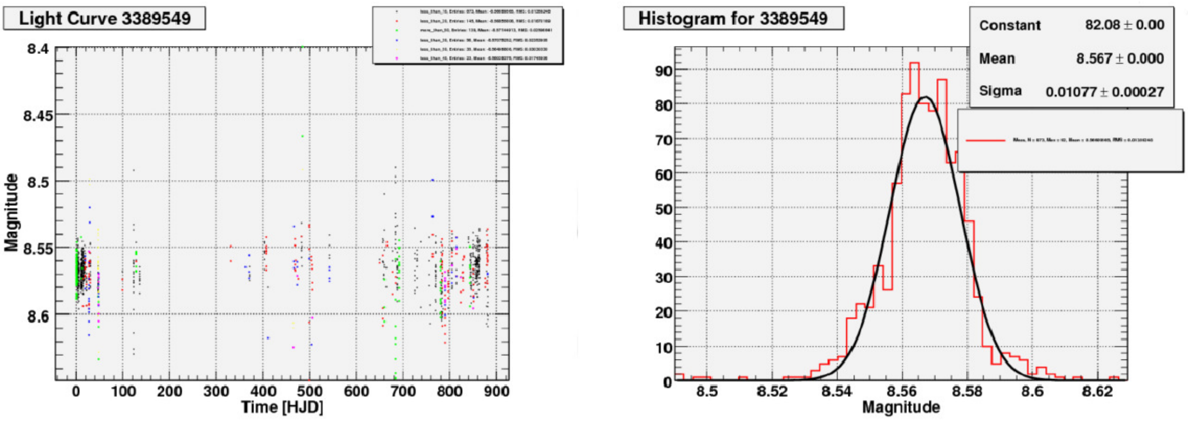

FIGURE 8. The light curve of an analyzed star after using the statistical data quality estimate method (on the left). Colors represents the quality of the analyzed measurements. A histogram of this light curve after removing all bad data (on the right). As we see, after using this method the light curve quality improves significantly and $\sigma \sim 0.01^{\mathrm{m}}$ is achieved.

on the star that is to be analyzed, and varies from star to star.

4. Conclusions

A lot of informations about the Pi of the Sky project can be found on the project web page, which is available on the `http://grb.fuw.edu.pl`. We have created a system of dedicated filters to mark bad measurements or frames. This system is applied with the cataloging procedure for new data. To improve the quality of the data, we have created an approximate color calibration algorithm based on the spectral type of catalog stars. We have also developed another statistical method which analyzes all stars on the frame, allowing bad quality exposures to be rejected. After the new frame selection is applied, photometry accuracy of 0.01^{m}–0.03^{m} can be obtained. Further improvement is possible in dedicated analysis of selected objects [3]. In the Pi of the Sky project we have developed a pipeline which allows us to analyze selected interesting objects in a fully automatic way. As a result we get a corrected light curve of the analyzed star, where each measurement has the quality calculated [1].

In the Pi of the Sky project we have developed our own pipeline which allows us to analyze selected interesting objects in a fully automatic way. As a result, we get a corrected light curve for a star, where each measurement has the quality calculated. Unfortunately, these procedures are not fast enough to be implemented in the automatic off-line reduction stage, so we have to run this only for selected objects. We are trying to improve this procedure and make it faster. However, this is a very complex problem, and we do not yet have a pipeline of this kind.

Acknowledgements

We are very grateful to G. Pojmański for providing access to the ASAS dome and for sharing his experience with us. We would like to thank the staff of the Las Campanas Observatory, the San Pedro de Atacama Observatory and the INTA El Arenosillo Test Centre in Mazagón near

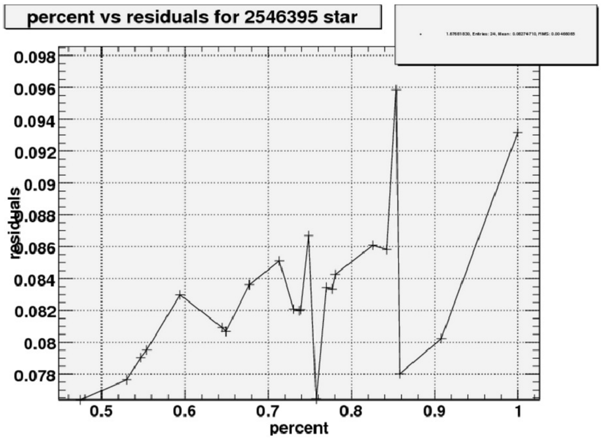

FIGURE 9. Comparison of the photometry correction methods used here. The x-axis represents the percentage of data that has not been removed from the analyzed light curve. The y-axis represents the analyzed light curve quality. As we see, in some cases after using some combination of methods the quality of the analyzed light curve improves significantly, and it is almost the same as in the case when we apply all corrections and remove more data from the analyzed light curve.

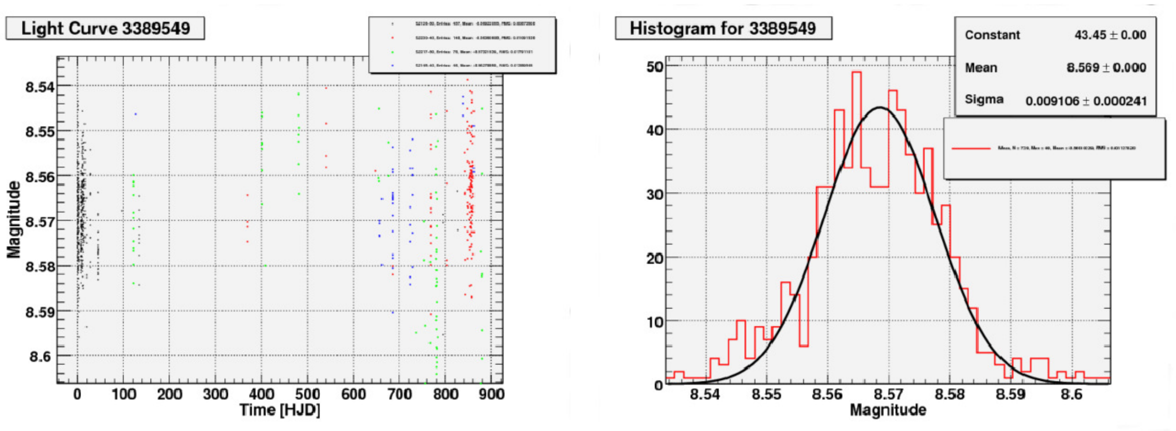

FIGURE 10. The analyzed star light curve after using all that corrections described above (on the left). Colors represents the observed fields. The light curve histogram after removing all bad data is shown on the right. As we see, after using this methods the light curve quality improves significantly and $\sigma \sim 0.009^{\mathrm{m}}$ is achieved (at the beginning, the value for σ was $\sim 0.02^{\mathrm{m}}$).

Huelva for their help during installation and maintenance of our detector.

This work was co-founded by the Polish Ministry of Science and Higher Education in 2009-2013 as a research project, and by POLISH-SWISS ASTRO PROJECT co-founding under the Swiss program of cooperation with new member states of the European Union. KM and LWP acknowledge support from JSPS Postdoctoral Fellowships for Foreign Researchers.

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