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Flexible Variable Star Extractor — new software for variable stars detection using CCD photometry

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We developed a computer program for variable stars detection using CCD photometry. It works with "varfind data" that could be exported after processing CCD frames using `C-Munipack`. The program chooses the comparison stars automatically, processes all time series using multiple comparison stars to get final light curves. We developed few filters and criteria that allow reducing the impact of outlying points, imaging artefacts and low quality CCD frames without careful manual time series reduction. We implemented the calculation of various variable detection indices. The pipeline has a possibility of plotting a two-channel diagram of selected pair of indices or mean brightness of the star for manual check if any outlying point is a variable candidate. The program is available at `http://uavso.org.ua/varsearch/`

Key words: stars: variables: general, methods: data analysis, methods: statistical

INTRODUCTION

A distinct advantage of the CCD photometry is a capability of measuring brightness of hundreds of stars in the same field of view simultaneously. We know from the experience, that within 10-20 arc. minutes of any primary object of investigation there is at least one more known variable star and sometimes we may discover an unknown one. Over the years of using CCD photometry different techniques for variable stars detection were developed. In the recent years due to intensified interest in discovery of extrasolar planets using transit photometry some of these techniques were improved.

One of the simplest algorithms is based on the noise level dependency to the mean brightness of the star. The fainter an objects is, the smaller is the signal-to-noise ratio and the noisier is the measurement of the object. According to the statistics, if all stars were constant, the dependence of standard deviation of brightness vs. mean brightness of an object would have a parabola-like shape. A variable star should have larger standard error comparing to a constant object of the same mean brightness. Particularly, this algorithm is implemented in the `C-Munipack` software package[1], one of the most popular complete solutions for photometric CCD images reduction. It requires manual viewing of every suspected variable stars' light curve to approve or reject the candidate.

However, for noisy data this solution does not work well for various reasons. In this case in such diagram many variable stars could appear in a heap of points, and many constant stars with lack of data or outlying points will be located above the curve like they are variables. Particularly, the necessity of this work arise from the fact that we found no solution capable to analyse few experimental series of CCD images obtained in 2015 using guider telescope for the purpose of searching unknown short period variables (field of view about 1 degree, more then 10000 detected stars). The development of the improved algorithm started in the beginning of 2016.

THE METHOD OF CALCULATIONS

Usually, the standard deviation of brightness vs. mean brightness dependence is used for detection of variability. In `C-Munipack` the differential magnitudes are calculated as

$$\mathrm{m}_{i,j} = \mathrm{mag}_{i,j} - \mathrm{mag}_{C,j},$$

where mag is an array of instrumental magnitudes, i is an index of object, C is an index of an automatically or manually chosen comparison star and j is a number of frame. The mean magnitude of each star $\bar{\mathrm{m}}_i$ is computed using robust mean algorithm and the

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[1] Motl D., `http://c-munipack.sourceforge.net/`

standard variance using trivial formula

$$s_i^2 = \frac{1}{N_i - 1} \sum_{j=1}^{N_i} (\mathrm{m}_{i,j} - \bar{\mathrm{m}}_i)^2. \quad (1)$$

These values are plotted in the graph and user can make the decision whether a star is variable or not.

As was mentioned in [3], using of the artificial comparison star instead of the control star made possible to increase accuracy estimates by a factor of 1.3-2.1 times for clear and cloudy nights, respectively. This algorithm implemented in `MCV` [2] was applied to observations of different variables and its effectiveness is well proven. So, we decided to use it for variable star detection. Obviously, the use of processed final magnitudes instead of raw instrumental ones to calculate the s_i^2 allows to decrease the noise and influence of the scatter of some particular comparison star to the data. The main drawback is that it is computationally more expensive so it takes relatively more time to process the same data set.

We read $\mathrm{m}_{i,j}$ and $\sigma_{i,j}$ from the data exported from `C-Munipack`. First we calculate the weighted mean magnitude for every star in the data set where weight of each observation is inversely proportional to the square of the individual observation error estimate (standard deviations):

$$\bar{\mathrm{m}}_i = \left(\sum_{j=1}^{N_i} \frac{1}{\sigma_{i,j}^2} \right)^{-1} \cdot \sum_{j=1}^{N_i} \frac{1}{\sigma_{i,j}^2} \cdot \mathrm{m}_{i,j}. \quad (2)$$

Then we calculate standard variance σ_i^2 of each star (Eq. 1) with and without Bessel's correction, where $\bar{\mathrm{m}}_i$ is determined using Eq. 2.

At the next step we choose the comparison stars according to few criteria, that could be adjusted by program settings. All of them were determined experimentally. First, star should not be close to the frame border because these data usually has lower quality (default value: 50 pixels). The comparison star should be measured at least at 70 percent of CCD frames. It should have $\sigma_i^2 \leq 1.5\bar{\sigma}^2$, i. e. less then average standard variance of the star in the data set. The total number of selected comparison stars should not exceed the limit (default: 1000). Since the stars are ordered from bright to faint, the last limit cuts the most faint objects that usually do not fit to previous criteria or obtain negligibly low weights at the next step. In some cases it is necessary to limit the number of comparison stars to traditional 10-15.

Next we determine weights of selected comparison stars using some iterations and calculate the final magnitudes of all stars using the obtained artificial comparison star and the known magnitude of selected comparison star (entered by user). Now user could view light curves of any star (see Fig. 2) and export it to the text file.

`Search Variables` menu runs the calculation of different variability detection indices used to distinguish variables from constant stars in the timescale of the time series duration. Hereafter we use mean weighted magnitude of the stars (Eq. 2) re-calculated using the final light curves. We determine standard deviation σ_i, χ^2 (Eq. 3), Median absolute deviation (Eq. 4), Robust median statistic (Eq. 5), Normalised excess variance (Eq. 6) and von Neumann ratio (Eq. 7).

$$\chi_i^2 = \sum_{j=1}^{N_i} \frac{(m_{i,j} - \bar{\mathrm{m}}_i)^2}{\sigma_{i,j}^2}, \quad (3)$$

$$\mathrm{MAD}_i = \mathrm{median}\left(|\mathrm{m}_{i,j} - \mathrm{median}(\mathrm{m}_{i,j})|\right), \quad (4)$$

$$\mathrm{RoMS}_i = (N_i - 1)^{-1} \sum_{j=1}^{N_i} \frac{|\mathrm{m}_{i,j} - \mathrm{median}(\mathrm{m}_{i,j})|}{\sigma_{i,j}}, \quad (5)$$

$$\sigma_{\mathrm{NSX},i}^2 = (N_i \cdot \bar{\mathrm{m}}_i)^{-1} \sum_{j=1}^{N_i} \left[(\mathrm{m}_{i,j} - \bar{\mathrm{m}}_i)^2 - \sigma_{i,j}^2\right], \quad (6)$$

$$\frac{1}{\eta_i} = \frac{\sum_{j=1}^{N_i} (\mathrm{m}_{i,j} - \bar{\mathrm{m}}_i)^2}{\sum_{j=1}^{N_i} (\mathrm{m}_{i,j+1} - \mathrm{m}_{i,j})^2}. \quad (7)$$

Most of the indices implemented in the form recently published in [4], except von Neumann ratio, which was calculated in inversed and simplified way. The chi-squared value is used in the form of square root.

User may plot any pair of these variability detection indices, raw σ_i and mean brightness $\bar{\mathrm{m}}_i$ of the star in the diagram. In any case, most of constant stars will form a group of points, and any outlying point may correspond to a variable star. The decision whether an object is a variable or not is left to the user who can view a light curve and periodogram of any star in one click. User can mark the viewed star as variable or false alarm, this way it does not necessary to remember all objects in large field of view. After checking all outlying points in one diagram it is possible to check another one (see Fig. 1). At any step it is possible to remove some outlying points or even whole CCD frames from the data set and re-calculate the light curves and variability indices.

RESULTS AND CONCLUSIONS

We tried to analyse few experimental series of wide-field CCD images obtained in 2015 using guider telescope for the purpose of searching unknown short

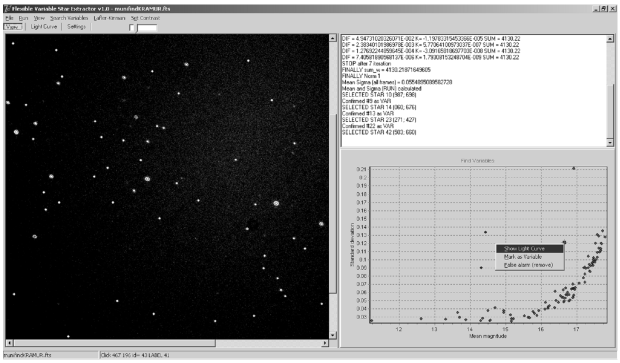

Fig. 1: Main workplace of the software. The chart on the left, log data in the right top and two-channel diagram on the left bottom.

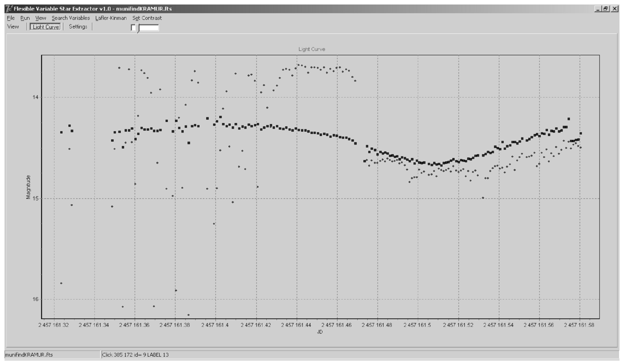

Fig. 2: The light curve of EW eclipsing system (noisy curve with circles — raw instrumental, smooth curve with rectangles — final magnitudes).

period variables. Due to relatively big scatter of the light curves we were not able to do this research using known software so we decided to improve one of the most popular algorithms to decrease the influence of noisy data and outlying points. It was done and significantly improved the speed of semi-automatic search for variable stars in generic field of view. At the same time it was not sufficient to do our primary task so we decided to implement other variability detection indices and include the possibility of viewing two-channel diagrams of any pair of parameters. Finally we left all of them except Lag-1 autocorrelation as we found it ineffective in all our data sets. We found that different indices are more or less effective for detecting different types of variable stars and, of course, it depends on the timescale of data set and the period of variable star. So, we suggest checking at least few two-channel diagrams marking possible variable stars at all of them. As the result of this work, the new software "Flexible Variable Star Extractor" was developed. It works with the data exported from `C-Munipack`, chooses the comparison stars automatically unless user does not prefer to do it manually, then processes all time series to get final light curves and at the final step calculates all available variable detection indices. The user-friendly interface allows plotting a two-channel diagram of selected pair of indices, choosing there outlying points corresponding to variable stars candidates and view light curves in one click.

Average time spent for automatic part of the process (between the data file opening and plotting the diagram) for 111 stars in 1024×1024 px `FITS` is about 5 seconds, program takes 55 MB RAM, for the CCD field of 1677×1264 px with 33200 stars it takes about 85 seconds and 913 MB RAM. The program is a freeware, current stage is beta. We are still working on some improvements in scientific and technical parts. Further information and updates available at the official website[2]. This program will be applied also to the observations obtained within the international campaign "Inter-Longitude Astronomy" [1] and "Astroinformatics" [5].

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