

SkyEye

User's manual

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who have contributed to this work.*

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1 Introduction

Variable stars are those that change their brightness in a perceptible way. Practically every star shows small fluctuations of brightness, but in most cases, they are non-measurable. Variable stars fall into main groups: pulsating stars, eruptive variables and eclipsing binaries.

Observations of variable stars are very interesting and provide a lot of valuable information about their physical features, structure and evolution. Every fan of astronomy can make them at no great costs, and obtain scientifically valuable results. The project **SkyEye** aims to facilitate these observations.

It has been launched as an educational part of the project **Pi of the sky** [14], whose goal is to create and implement successfully a system for gamma-ray bursts detection in the visible part of their spectrum. Wide-field sky surveys are conducted in the Polish observatory in Las Campanas in Chile.

The objective of **SkyEye** is to create educational software for measuring brightness of variable stars. Automation of many processes, user-friendly interface and the use of cheap webcams will enable students and amateur astronomers to make their own measurements and data analysis.

The task has been achieved on the basis of the French project **AudeLa** as additional libraries in **C/C++** and a set of useful scripts in **TCL**.

This document includes basic knowledge about astronomical observations with the use of a webcam, shows how to install and compile the program **AudeLa** and **SkyEye**. Further, it describes how **SkyEye** works and how to use it. Finally, the algorithms used in the project are described.

The program is still being developed, its latest versions and documentation can be found on the Internet, at [13].

2 Observation set

The simplest and cheapest set for astronomical observations can be built with the use of:

- webcam with CCD sensor, e.g. Vesta PCVC 750K, made by **Philips**,
- photographic lens, e.g. 58 mm f/2,0 for **Zenith** camera, 50 mm f/1,8 for **Praktica**,
- lens – camera adapter,
- mount,
- computer with a USB port and appropriate software – in this case **AudeLa** and **SkyEye**.

An example set is shown in figure 1.



Figure 1: Example set for astronomical observations.

This set has the field of view of about $4^\circ \times 3^\circ$. In **Philips** webcams **CCD Sony ICX098AK** sensor have been used, which have the diagonal of 1/4 inch, and the size of **640 x 480** pixels, pixel size **5,6 x 5,6 μm** .

Webcams' most serious limitation is their short time of exposure - the maximum time that can be obtained without modifying the electronic system is 0,2 s. However, such short time of exposure has one advantage - the proposed set does not require a driver mechanism. The maximum shift of a star's image, caused by Earth's revolution, with the time of exposure of 0,2 s, is not greater than the size of a pixel.

It is also possible to modify the electronic system of a camera in a way that will enable having long time exposures. Details can be found at [10], [11].

3 Installation, compilation

AudeLa package (basic for the **SkyEye** project) is available at [12] (source, installation version for Windows), **libskyeye** library and the necessary scripts are available at [13]. **Tycho-2** star catalogue is available at the official page [9] or at [13]. It should be copied to any folder on the disk and the path to it should be set in the configuration panel of **AudeLa** – menu **Setup/Aud’ACE/Folders...**, field **Catalogue Folder**.

3.1 Linux

AudeLa (version 1.2.3), apart from basic packages (gcc, autoconf, make) requires prior installation of:

- tcl version ≥ 8.4 ,
- tk version ≥ 8.4 ,
- gsl,
- BLT2.4z,
- pwc (Philips webcam driver) version ≥ 8.8 , (available in Linux kernel $\geq 2.4.21$).

After downloading the source, unzip it in its home directory, then go to `~/audela-x.x/dev` folder (`x.x` stands for the number of current version), create and run the configuration script, then begin compilation with the make program:

```
> cd ~/audela-x.x/dev
> autoconf configure.in > configure
> chmod +x configure
> ./configure
> make
```

Before the package is run, the path to `~/audela-x.x/binlinux` should be added to the environment variable **LD_LIBRARY_PATH**:

```
> export LD_LIBRARY_PATH=$LD_LIBRARY_PATH:$HOME/audela-x.x/binlinux
```

AudeLa should be run from `~/audela-x.x/binlinux` directory.

```
> cd ~/audela-x.x/binlinux
> ./audela
```

A detailed description of installation for a particular version of the package is included in the file `~/audela-x.x/dev/readme.txt`

3.2 Windows

The easiest way of installing the package **AudeLa** is to download and run the installation version, `audela-x.x.exe` file. To make changes in the software you have to download its source code. You will need **Visual Studio C++** version ≥ 6.0 to compile it.

After downloading the source code, unzip it in the main directory on disk **C:**, next, go to `C:\audela-x.x\dev\libaudela\vc60` and click `libaudela.mdp`, select the method of compilation: **Release**. This operation should be repeated for each library (folder) in `C:\audela-x.x\dev`.

A detailed description of installation of a particular version of the package can be found in the file `C:\audela-x.x\dev\readme.txt`. To install **SkyEye** you have to copy the `libskyeye.dll` library you downloaded from [13] to the folder `C:\audela-x.x\binwin` and the script `skyeye_interface.tcl` to the folder `C:\audela-x.x\scripts`.

4 How to use SkyEye

4.1 General scheme of functioning

A general scheme of the functioning of the algorithm for measuring the brightness of variable stars that has been included in the **SkyEye** project, is shown in figure 2.

SkyEye is a complete system that gathers and analyzes measurements. You can run the program in a step-by-step mode in order to visualize the algorithm. The first stage is to acquire photographs of the sky, either directly from a webcam, or from FITS files.

Preprocessing constitutes the next stage. The dark frame, previously prepared, is subtracted from the images. On user's request, a few subsequent images will be appropriately shifted and added up (this operation enlarges the range of observation for short times of exposure).

The next stage includes recognizing stars, eliminating the non-stars and aperture photometry. The instrumental lists of stars created in this way, can be either saved to text files, or stored in operational memory for further use.

The subsequent step is astrometric calibration. Each image (**buf** object) should have the coordinates of centre of the field and the size of a pixel. If these variables are missing from the heading of the FITS file containing the image, the user must define them manually. If the approximate area of the sky that is visible in the picture is known, a list of corresponding stars can be loaded from the **TYCHO-2** catalogue. Then, both lists are adjusted and the coordinates from the instrumental list are converted to the equatorial coordinates.

Photometric calibration is the next step - instrumental magnitudes are converted to observed magnitudes. Lists of stars thus created are then supplemented with the time and date of exposure and saved in the database of measurements.

When observations are finished, the user can pick a particular star from the database and draw its light curve or draw a variability plot for the observed region, which will enable them to pick out variable stars.

4.2 Starting AudeLa

4.2.1 Linux

Go to `~/audela.x.x/binlinux` folder and run the command `./audela`.

4.2.2 Windows

Go to `C:\audela-x.x\binwin` folder and double-click `audela.exe` or the **AudeLa** icon on the desktop.

4.3 Graphic User Interface of AudeLa

AudeLa graphic interface includes (figure 3):

- main window
- console

The following menu is available in the main window:

- **File**: loading, saving image, creating, editing and running scripts, quitting the program.

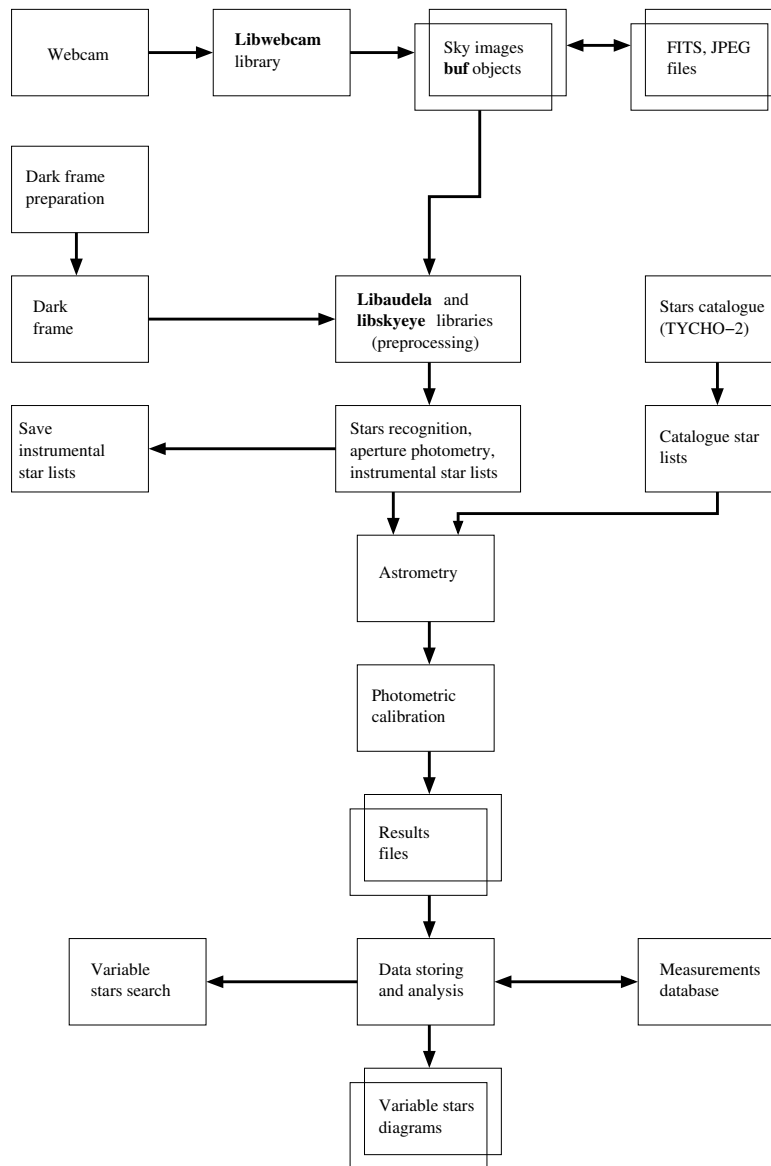


Figure 2: Flowchart of measurements of stellar variability.

- **View:** visualization method, zoom, visualization of FITS header.
- **Preprocessing:** preprocessing current image, various filters.
- **Analysis:** image analysis, e.g. histogram, statistics, Gaussian function adjustment.
- **Panel:** selecting panel e.g. acquisition of images or animation of a series of images.
- **Setup:** program settings, e.g. webcam, telescope, location of observation,
- **Help:** information about the authors, list of functions, link to project's official homepage.

The console has two fields: the upper field is used to display messages; in the lower field the user can enter commands (in **TCL** [15]).

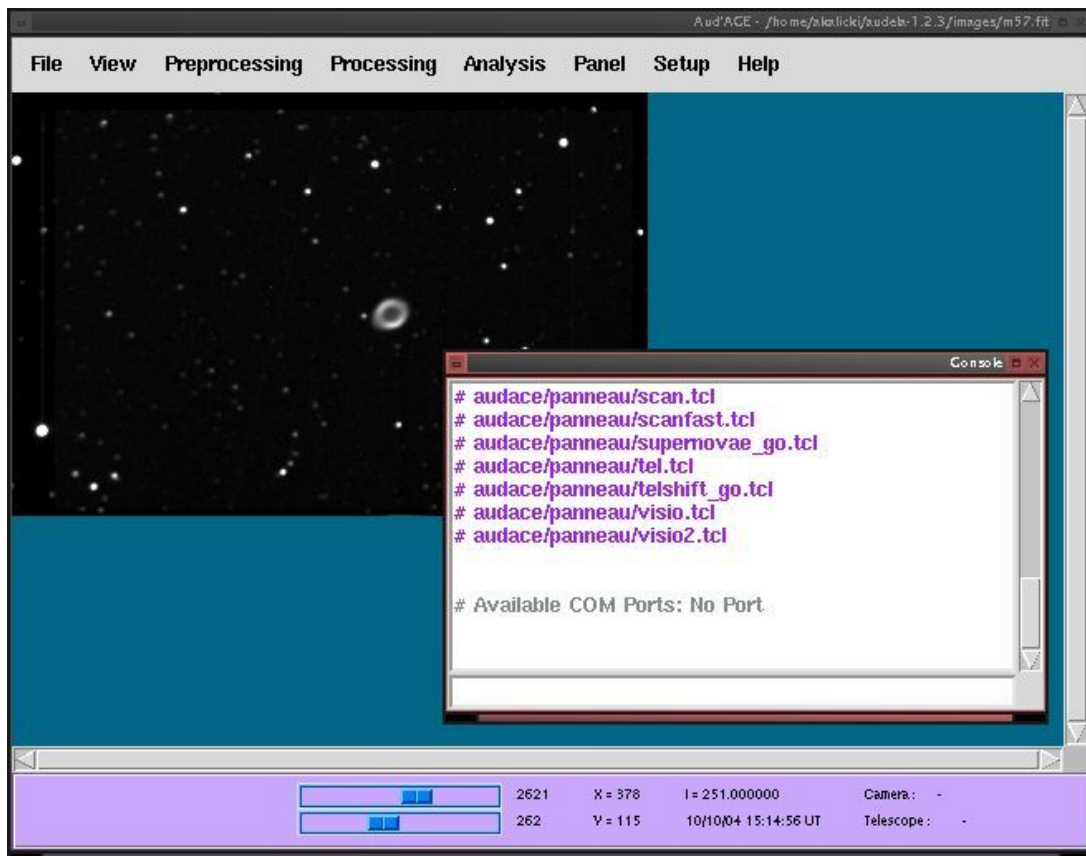


Figure 3: AudeLa – graphic interface.

4.4 Starting SkyEye

In the **File** menu click **Run a script** and select the `skyeeye_interface.tcl` file. A **SkyEye** dialog box will show up where you can choose **Preprocessing** – panel **Variable stars** or **Data analysis**. Both panels are described below.

To make the operating of **SkyEye** easier to understand, while describing program's parameters we will present settings for an example observation of **RZ Cassiopeiae (RZCas)**, performed during main eclipse at night 12.02.2003 / 13.02.2003. The observations were made as a series of a few dozen of 2.5-second exposures with the use of a Philips webcam PCVC750K, adjusted for long exposures.

The necessary data can be downloaded from the page [13]. Images in FITS format from one series from the observation and a complete database of measurements from the whole observation are available there.

RZ Cassiopeiae is an eclipsing variable. Its variability plots (main eclipse) are presented in figures 18 and 19. The latter plot was created by grouping subsequent points in threes and then interpolating between them. Variability period 1.195247d, position (2000) 02h48m56s +69°37'58", variability range 6.16 to 7.90.

4.5 Variable stars panel

The panel consists of the following tabs:

- **Source:** selecting the source of images,

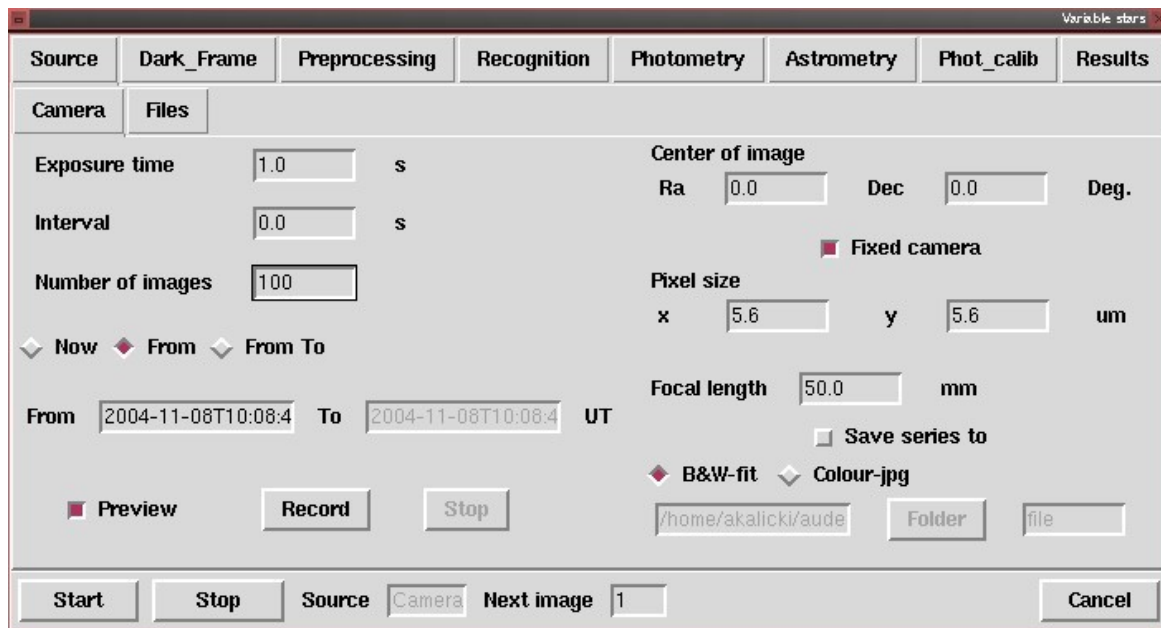


Figure 4: Panel **Variable stars**, selecting the source of images: camera.

- **Camera**: camera is the source of images, it should be configured beforehand, menu Setup/Camera, (figure 4),
- **Files**: a series of files is the source of images, (figure 5),
- **Dark Frame**: selecting from the file or preparing the dark frame,
- **Preprocessing**: preprocessing the image,
- **Recognition**: picking out stars and eliminating non-stars,
- **Photometry**: aperture photometry,
- **Astrometry**: astrometric calibration,
- **Photometry calibration**: photometric calibration,
- **Results**: measurements results database.

In the lower part of the panel, there is a command and application status bar. The measurement process is initiated with the **Start** button when all the parameters have been set (in subsequent tabs). It can be stopped at any moment with the **Stop** button. Step-by-step mode is also available for running the algorithm. Observation of subsequent stages – on tabs by pressing **View image** or **View list**.

If an error or another problem occurs (e.g. it is impossible to adjust lists) while the program is running, an appropriate message will be displayed. Depending on user's decision, the process will be either continued or aborted.

4.5.1 Source, Camera

Selecting the source of images: camera (figure 4), the following parameters should be set:

- the time of exposure (**Exposure time**),

- interval between subsequent exposures (**Interval**),
- number of frames (**Number of images**)
- planning observation:
 - **Now** initiates the acquisition of images at the moment of starting the measurement process,
 - **From** delays the acquisition of images until the given time (format RRRR-MM-DDTgg:mm:ss, universal time: UT),
 - **From To** sets the period of time when the observation will be performed,
- visualization of subsequent images from the camera, selection **Preview**,
- the centre of the photographed part of the sky **Centre of image** (in equatorial coordinates) – it should be defined with precision to ensure proper functioning of the application (e.g. give the coordinates of the observed star),
- is the camera fixed, if it is fixed, select the option **Fixed camera**. The centre of image given before is considered to be the centre of the first image; centres of subsequent images are calculated from the time and location of observation. The location of observation should be properly given in the **Setup/Aud'ACE/Observer Location** menu, time of observation is acquired from the system clock – useful information for setting these parameters can be found at [21] and [22],
- pixel size of the CCD sensor used **Pixel size** (for webcams **Philips** it is 5,6 x 5,6 μm),
- focal length of the lens (telescope) used **Focal length**, e.g. for the lens from **Praktica** it is 50 mm, and from **Zenit** 58 mm,
- **Save series to** – selecting this option will result in saving a series of images to a given folder to files with a given core of the name (e.g. name1.fit) in black and whit FITS files **B&W-fit** or colour jpeg **Colour-jpg**,

The very process of image acquisition can be started by pressing the **Record** button, and stopped with the **Stop** button.

4.5.2 Source, Files

Selecting source of images: a series of FITS files (figure 5) with a given core of the name **File** (e.g. name1.fit), that are in a given folder **Folder**.

If the headers of the files do not contain the appropriate information, you should deselect the **From image** option and give the centre of the field of observation (as for a camera), whether the camera was fixed, pixel size and focal length of the lens.

The application requires for the headers of FITS files to contain information about the location of observation (if it is missing, it is loaded from **AudeLa** settings) .

Time of observation for subsequent frames can be set in **Observation date**, one of the following tabs should be selected:

- **Manual** allows the user to set manually the time when the observation will begin **Observation started**, time of exposure **Exposure time** (only for information, it is not considered while counting the interval) and the interval between subsequent frames **Interval**,

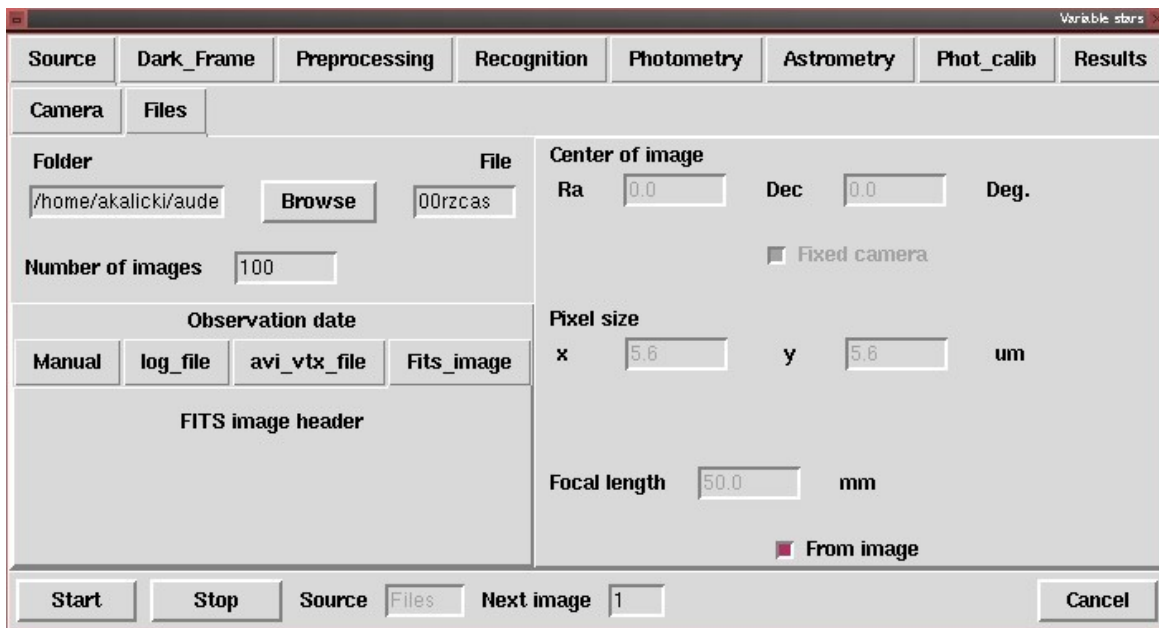


Figure 5: Panel **Variable stars**, selecting source of images: files.

- **log_file** reads from `.log` file the data generated while acquiring images by **K3CCD Tools** [19],
- **avi_xvt_file** from `.avi.xvt` file,
- **Fits_image** directly from the header of the FITS file that is being loaded.

Example:

For **RZCas** observation data, select the source of images: series of FITS files, location of the folder containing images, file name `00rzcas`, select **From image** and choose **Fits_image** tab.

4.5.3 Dark Frame

Selection or preparation of dark frame (figure 6).

If the option of subtracting dark frame was selected in the preprocessing stage, the path to the file containing it should be given here.

In this tab you can also prepare and save a dark frame. To do this, click the **Make** button – the dark frame will be created as a mean of images defined by **Source**, the **Save as** button allows to save it to a file, **View image** shows the selected frame.

Example:

For **RZCas** observation data select the `dark.fit` file containing the dark frame. You can display it by clicking **View image**.

4.5.4 Preprocessing

Preprocessing (figure 7); the following parameters should be set here:

- optional subtraction of dark frame from each image **Subtract dark frame**,



Figure 6: Panel **Variable stars**, selection and preparation of dark frame.

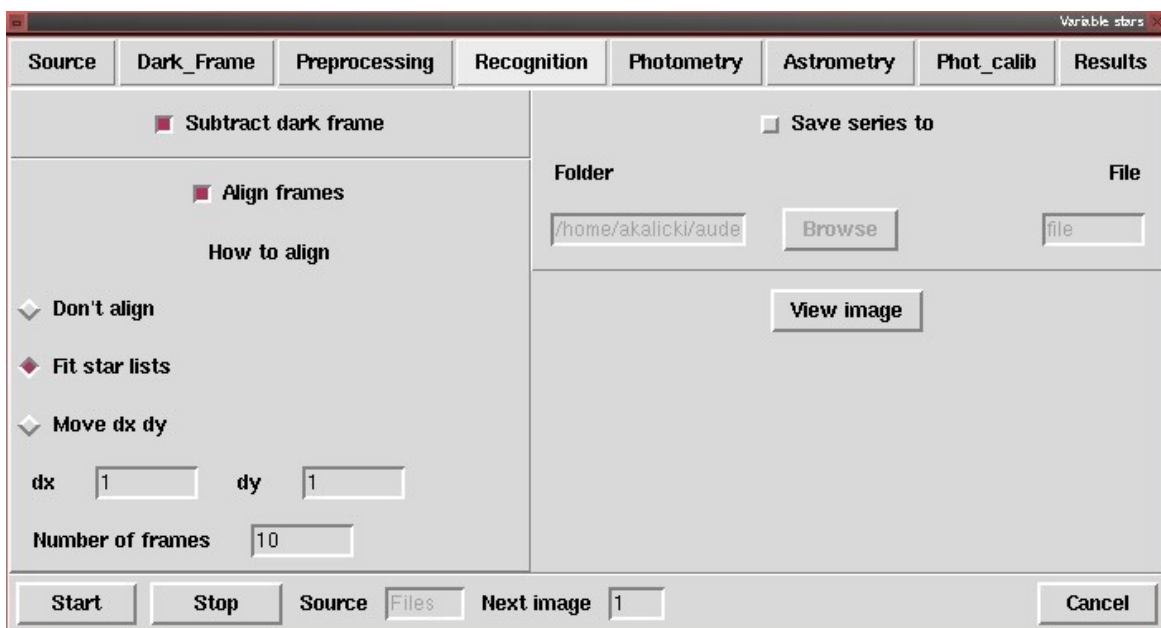


Figure 7: Panel **Variable stars**, preprocessing.

- shifting and adding frames **Align frames** – this option is useful when observations are made with a webcam that supports only short exposure times; if it is selected, the **Number of frames** should also be given, as well as the method of adding frames:
 - **Don't align** – subsequent images are added without shifting.
 - **Fit star lists** – the shift is defined by fitting the lists of stars from subsequent images (default parameters of stars recognition), the method takes into account the shift, as well as rotation; may be inefficient if few stars are recognised in the image.

- **Move dx dy** – subsequent images are shifted by dx and dy, without rotating.
- selecting **Save series to** will allow you to save images thus created in a file.

The **View image** button allows to visualize the subsequent image.

Example:

For **RZCas** observation data, select here **Subtract dark frame**, **Align frames** with the option **Fit star lists** and the number of frames to be added **Number of frames** equal to 10. Clicking **View image** will initiate the procedure and display the resulting image.

During analysis of data from other observations, you may come across frames with a small number of visible stars. In this case, shifting and adding frames using the **Fit star lists** method may be impossible. The only way left then is adding with the **Move dx dy** method. It is relatively easy to calculate the **dx**, **dy** parameters, e.g. by adding 30 frames without shifting, measure the horizontal and vertical shift of a given star (length of its trace). Apply the values divided by the number of frames (30) to **dx** and **dy**. This method will work if the photos were taken at fixed time intervals.

4.5.5 Recognition

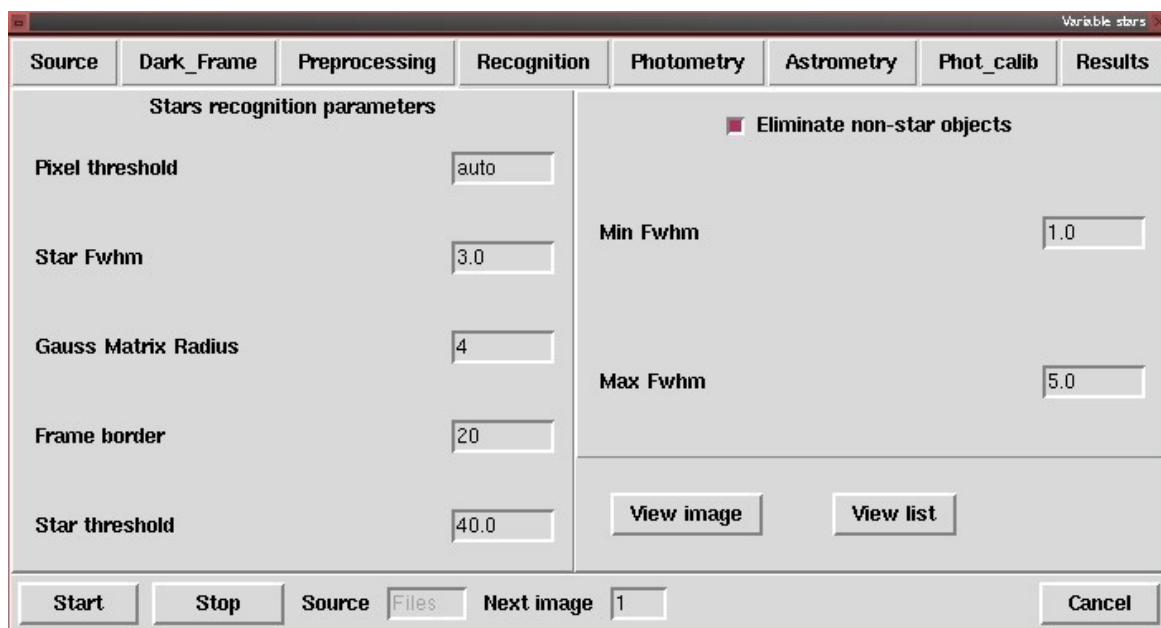


Figure 8: Panel **Variable stars**, recognition of stars.

Recognition of stars (figure 8), parameters of the **Stars recognition parameters** method (see the description of parameters in chapter 5.3.1).

The process of non-star objects elimination on the basis of their shapes can be turned off by deselecting **Eliminate non-star objects**. The **View image** button visualizes the image and marks the recognised stars, **View list** displays a list of recognised stars.

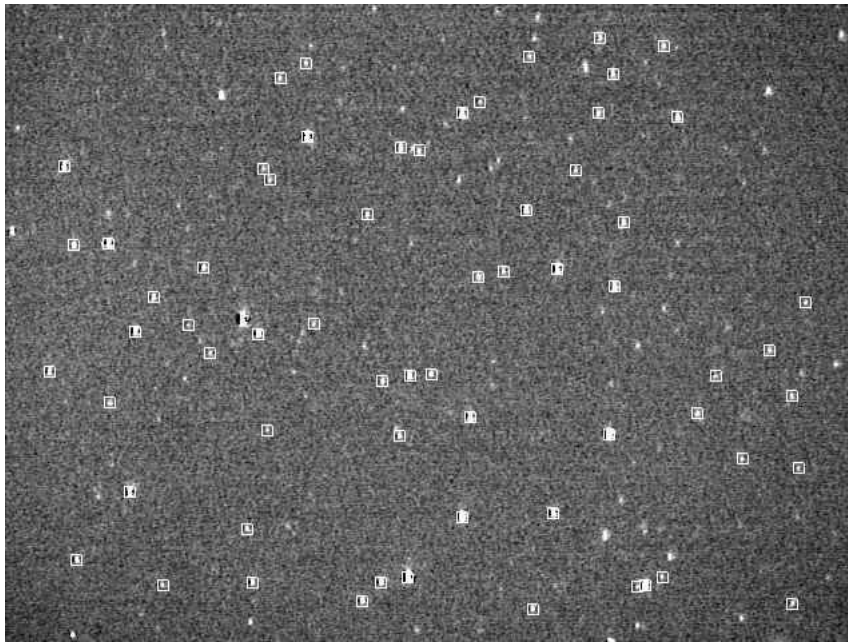


Figure 9: Marked recognised stars from **RZCas** observation.

Example:

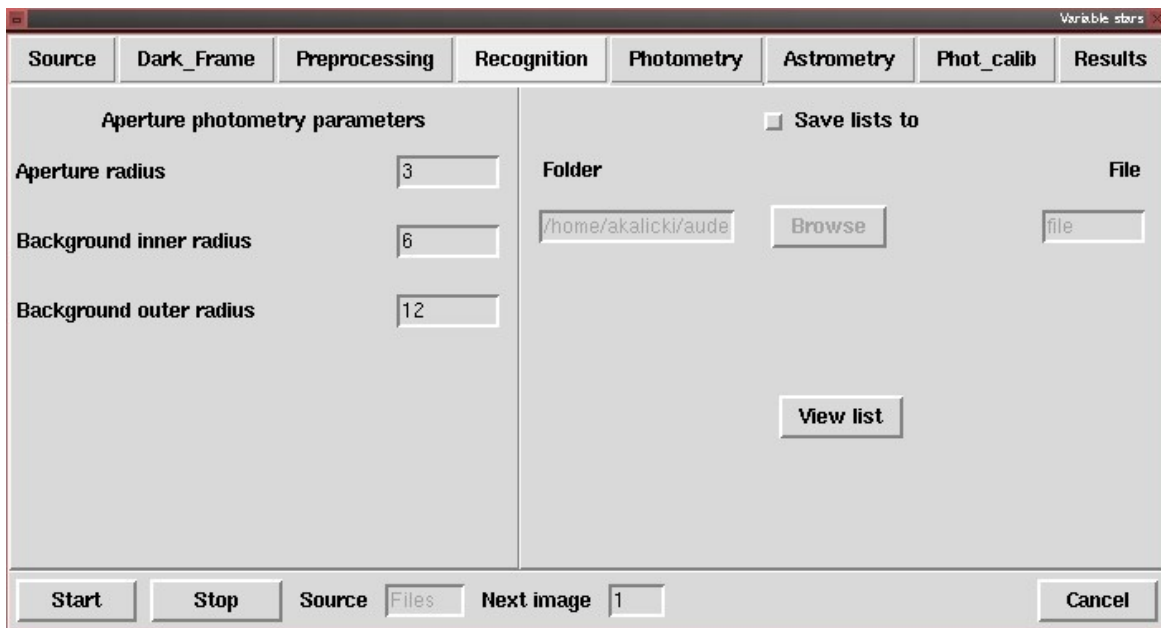
For **RZCas** observation data leave the default values of **Stars recognition parameters** and select **Eliminate no stars**. Next, click **View image** – an image will be displayed, where the recognised stars will be marked (figure 9). Click **View list** to view the list of recognised stars, e.g.:

```
DATA: NO_PHOTOMETRY
Lp.  X Y magInstr
1 396 27 159.565
2 591 31 105.115
3 269 33 188.094
4 119 45 115.021
5 481 45 603.234
6 187 47 192.202
7 283 47 339.196
8 303 51 2301.95
9 493 51 79.191
...
```

The fields of the list are: the star's ordinal number, position of the star in X and Y coordinates of the image, brightness of the pixel marked as its centre.

4.5.6 Photometry

Aperture photometry (figure 10), parameters of the method – **Aperture photometry parameters** (see the description of algorithm and parameters in chapter 5.4). The output of the method is a list containing instrumental magnitudes of stars. Clicking the **View list** will display the list, selecting **Save lists to** enables saving subsequent lists to files.

Figure 10: Panel **Variable stars**, aperture photometry.**Example:**

For **RZCas** observation data leave the default values of **Aperture photometry parameters** and click **View list**. A list of stars will be displayed, e.g.

```

DATE-OBS: 2003-02-12T22:17:00
OBS-LOC: "GPS 21.376722 E 52.659778 142"
DEC: 68.9
RA: 42.75
FOCLEN: 0.058
EXPOSURE: 2.36
PIXSIZE1: 5.6
PIXSIZE2: 5.6
NAXIS1: 640
NAXIS2: 480
DATA: APERTURE_PHOTOMETRY_DONE
Lp. X Y magInstr
1 396 27 -8.77836
2 269 32 -8.8643
3 475 44 -7.66793
4 481 44 -10.4337
5 186 47 -9.04572
6 283 47 -9.20074
7 303 50 -12.0003
8 55 63 -9.04685
...

```

The fields of the list are:

- date of observation **DATE-OBS**,
- location of observation **OBS-LOC**,
- coordinates of centre of the observation **DEC** and **RA**,
- focal length **FOCLEN**,
- exposure time **EXPOSURE**,
- pixel size **PIXSIZE1** and **PIXSIZE2**,
- size of the original image **NAXIS1** i **NAXIS2**,
- type of list **DATA**
- ordinal number of the star, the location of the star in X and Y coordinates of the image and its instrumental magnitude.

4.5.7 Astrometry

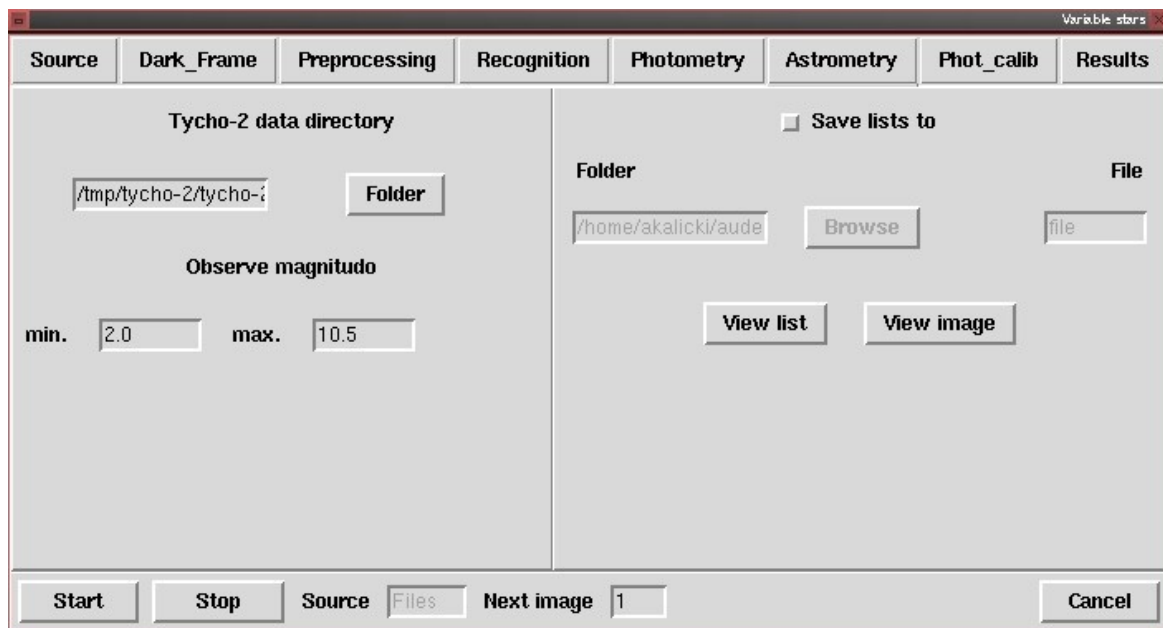


Figure 11: Panel **Variable stars**, astrometric calibration.

Astrometric calibration (figure 11). The path to the Tycho-2 catalogue, Tycho-2/data **Tycho-2 data directory** should be set here. The location of the region searched for in the catalogue is calculated on the basis of parameters given before: exposure, pixel size, focal length and image size. To limit the number of catalogue stars for the algorithm of fitting catalogue lists, set the range of the observed stars' magnitude **Observe magnitudo**: min. and max. magnitude.

Selecting the **Save lists to** option allows the user to save instrumental lists thus created to files. The **View list** button visualizes the subsequent list. The **View image** button visualizes how stars are aligned in the original image – catalogue stars are marked with squares. If the alignment is unsuccessful, the squares do not overlap with the stars in the picture.

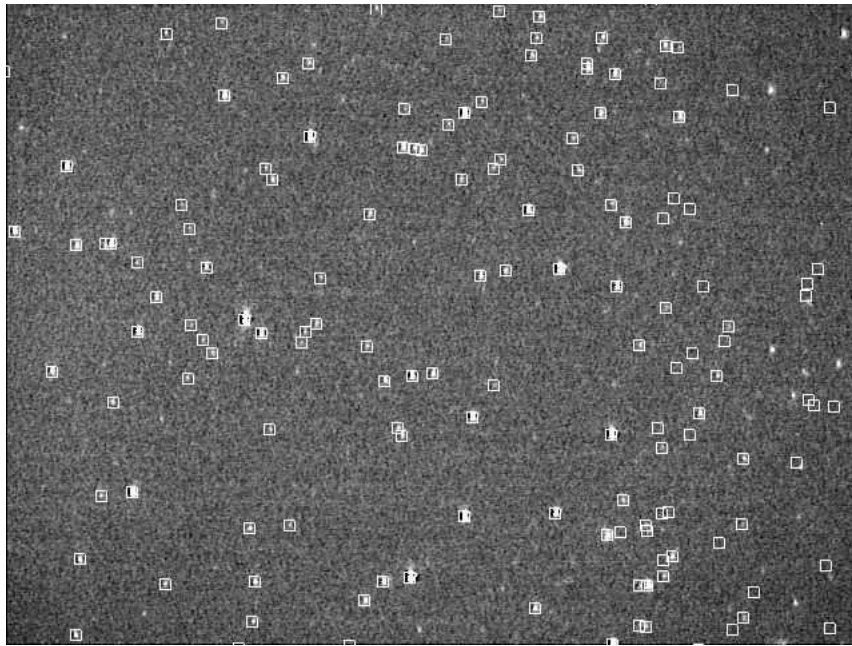
Example:

Figure 12: Successful alignment with the catalogue, marked with squares are catalogue stars, **RZCas** observation

For **RZCas** observation data, choose location for the **Tycho-2 data directory** and the range of observed stars **Observe magnitudo**: min. 2.0 and max. 10.5 magnitudo. After clicking **View list** and successful alignment, a list of stars will be displayed; click **View image** to display image with aligned stars figure 12. The list will look as in the example below:

```

DATE-OBS: 2003-02-12T22:16:26
OBS-LOC: "GPS 21.376722 E 52.659778 142"
DEC: 68.9
RA: 42.75
FOCLEN: 0.058
EXPOSURE: 2.51
PIXSIZE1: 5.6
PIXSIZE2: 5.6
NAXIS1: 640
NAXIS2: 480
DATA: ASTROMETRY_CALIBRATION_DONE
Lp. RA DEC magInstr
1 39.8785 67.6745 -8.783
2 37.0873 67.6179 -8.26625
3 41.6997 67.7326 -9.02683
4 43.8614 67.8016 -8.37317
5 38.6432 67.7441 -10.4194
6 42.8795 67.8144 -8.97252
7 41.4931 67.8071 -9.44448
8 41.2027 67.8259 -11.9571

```

...

Fields of the list are:

- date of observation **DATE-OBS**,
- location of observation **OBS-LOC**,
- coordinates of centre of the field of observation **DEC** and **RA**,
- focal length **FOCLEN**,
- exposure time **EXPOSURE**,
- pixel size **PIXSIZE1** and **PIXSIZE2**,
- size of the original image **NAXIS1** and **NAXIS2**,
- type of list **DATA**
- ordinal number of the star, position of the star in calculated equatorial coordinates RA and DEC, and instrumental magnitude of the star.

4.5.8 Photometry calibration

Photometric calibration. This tab is reserved for the future. In the present implementation the settings of the algorithm of calibration are defined automatically.

4.5.9 Results

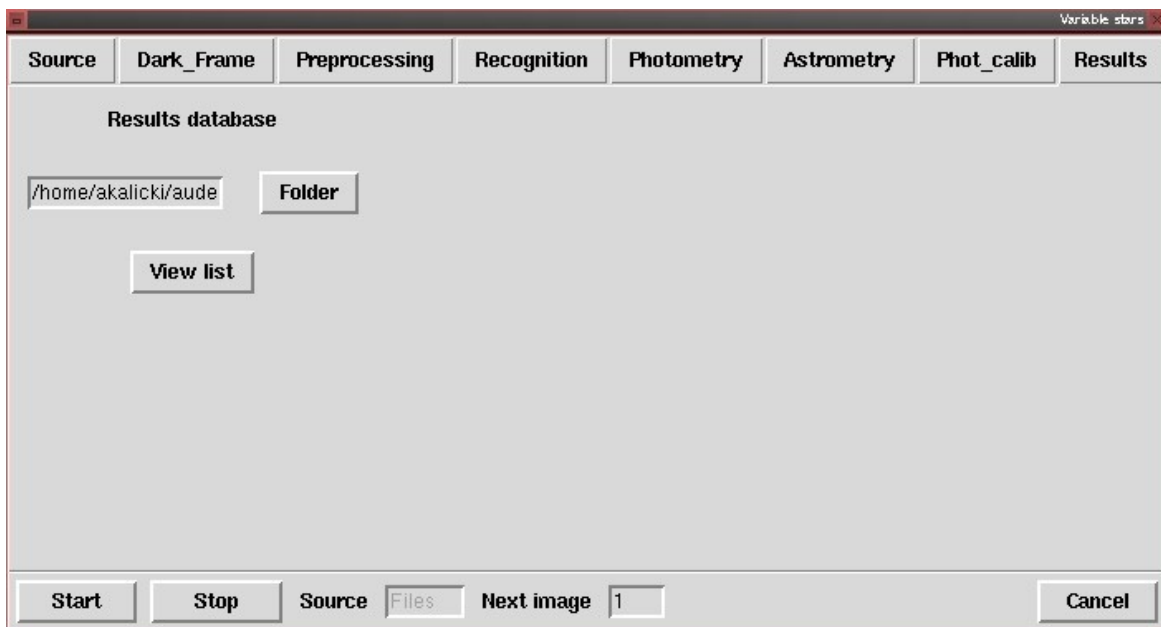


Figure 13: **Variable stars** panel , measurements results, measurements database location.

Measurements results (figure 13), measurements database location – the path to the folder with the lists of observed stars should be set. **View list** button displays the subsequent list of stars.

Example:

For **RZCas** observation data select the folder where the measurements database will be stored. Clicking **View list** will display a list of stars with their observed magnitude, which will look as follows:

```

DATE-OBS: 2003-02-12T22:16:26
OBS-LOC: "GPS 21.376722 E 52.659778 142"
DEC: 68.9
RA: 42.75
FOCLEN: 0.058
EXPOSURE: 2.51
PIXSIZE1: 5.6
PIXSIZE2: 5.6
NAXIS1: 640
NAXIS2: 480
DATA: ASTROMETRY_AND_PHOTOMETRY_CALIBRATION_DONE
Lp. RA catRA DEC catDEC ObservMagn CatalogMagn Name
1 42.9924 42.9948 68.8891 68.8885 5.98056 6.037 "4313 01573 1"
2 41.2027 41.207 67.8259 67.8247 6.14315 5.961 "4312 01404 1"
3 38.9216 38.9324 68.369 68.3678 6.61055 6.679 "4312 01101 1"
4 42.2379 42.2313 69.6346 69.6342 6.65452 6.283 "4317 01793 1"
5 40.5846 40.5946 68.0633 68.0644 7.05035 7.197 "4312 00322 1"
6 39.3881 39.3926 69.0574 69.0569 7.34639 7.446 "4312 00587 1"
7 44.2268 44.2325 68.1758 68.1779 7.59554 7.553 "4313 00433 1"
8 39.591 39.597 68.0619 68.0613 7.64469 7.711 "4312 00510 1"
...

```

Fields of the list are:

- observation date **DATE-OBS**,
- observation location **OBS-LOC**,
- coordinates of the centre of the observation **DEC** i **RA**,
- focal length **FOCLEN**,
- exposure time **EXPOSURE**,
- pixel size **PIXSIZE1** and **PIXSIZE2**,
- size of the original image **NAXIS1** and **NAXIS2**,
- type of list **DATA**,
- star ordinal number **Lp.**, star position in measured equatorial coordinates **RA** and **DEC** and in catalogue coordinates system **catRA** and **catDEC**. Next, observed magnitude **ObservMagn** and catalogue magnitude **CatalogMagn** of the star and its GSC catalogue name **Name**. If a star is not recognised, negative values -1000 are given instead of its catalogue parameters (catRA, catDEC, CatalogMagn), and the text **imageStar** is given instead of its catalogue name. The equivalents of the GSC names of stars can be found with the help of a sky chart *Cartes du Ciel*, available at [23].

To start processing click **Start** button at the bottom of the **Variable stars** panel. All the image files will be analyzed and the results will be saved in the database folder.

Next step - measurements analysis - has been presented below.

4.6 Data analysis panel

The panel consists of tabs (figure 14):

- **Database**: – measurements database folder location,
- **Region** – selection of the region and date of observation,
- **Diagram** – displays variability plot of the observed region or a selected star.

4.6.1 Database

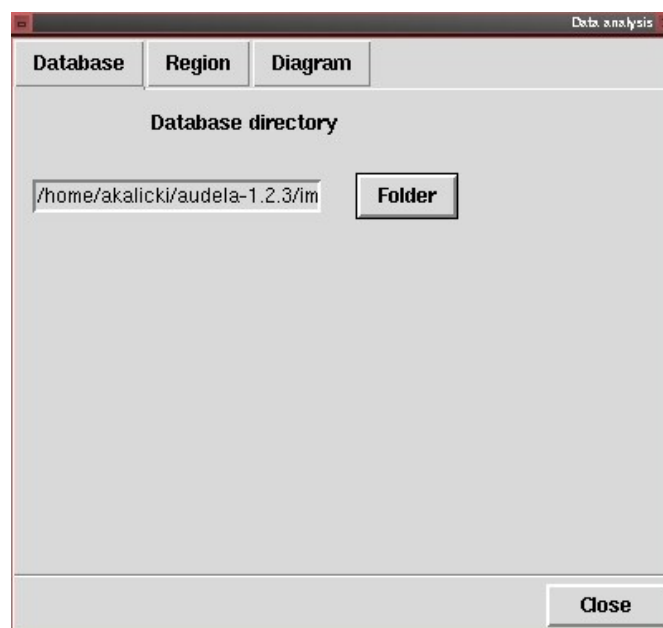


Figure 14: Panel **Data analysis**, the location of the measurements database.

The location of the measurements database folder (figure 14).

Example:

For **RZCas** observation data, select the folder with the measurements database for the star.

4.6.2 Region

Selection of the region and date of observation (figure 15). Button **Show region** displays the chart of the region (the observed stars in the region). The current implementation of this functionality does not reflect correctly the real distribution of stars. Selecting a star and left-clicking it will display its variability plot.

Right-click the plot to zoom in, hold "Ctrl" and right-click to zoom out, hold "Ctrl" and left-click to save the plot to a **PostScript** (* .ps file).

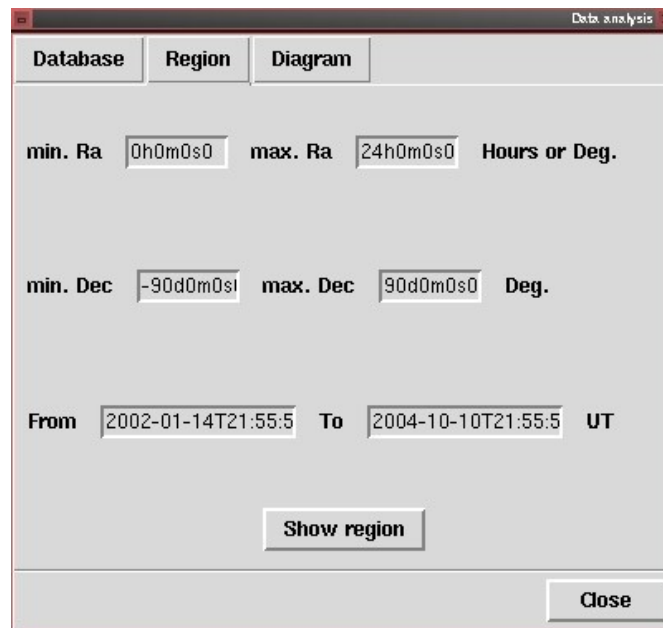


Figure 15: Panel **Data analysis**, selection of the region and date of observation.

Example:

For **RZCas** observation data, click **Show region**. A map of the region will be displayed. Right-click to zoom in.

4.6.3 Diagram

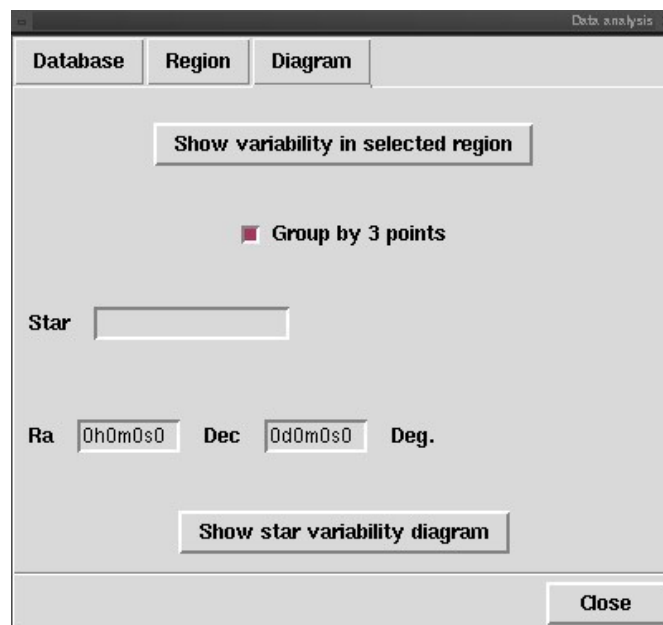


Figure 16: **Data analysis** panel, displaying the variability plot of the observed region or of a selected star.

Displaying the variability plot of the observed region **Show variability in selected region** or of a selected star **Show star variability diagram** (figure 16). Selecting the **Group by 3 points** option group three subsequent measurements in the star's variability plot and return their mean, which reduces statistic errors and minimizes the dispersion of points.

Selecting a star and left-clicking in the variability plot of the observed region will display the variability plot of the star. The following parameters are given additionally: the name of the star from the **Tycho2** catalogue, catalogue position of the star, the number of measurement points, average brightness and time of observation.

Right-click to zoom the plot in, hold "Ctrl" and right-click to zoom out, hold "Ctrl" and left-click to save the plot to a **PostScript** file (*.ps).

Example:

For **RZCas** observation data click **Show variability in selected region**. A variability plot of the region will be displayed. Next, left-click the **RZCas** star, located: about 7 magnitudo and about 0.5 std (figure 17). Its variability plot will be displayed (figure 18). Selecting the **Group by 3 points** option will group measurement points by three (their mean will be calculated), figure 19.

Save the plot to a **PostScript** file (*.ps) by holding "Ctrl" and left-clicking it.

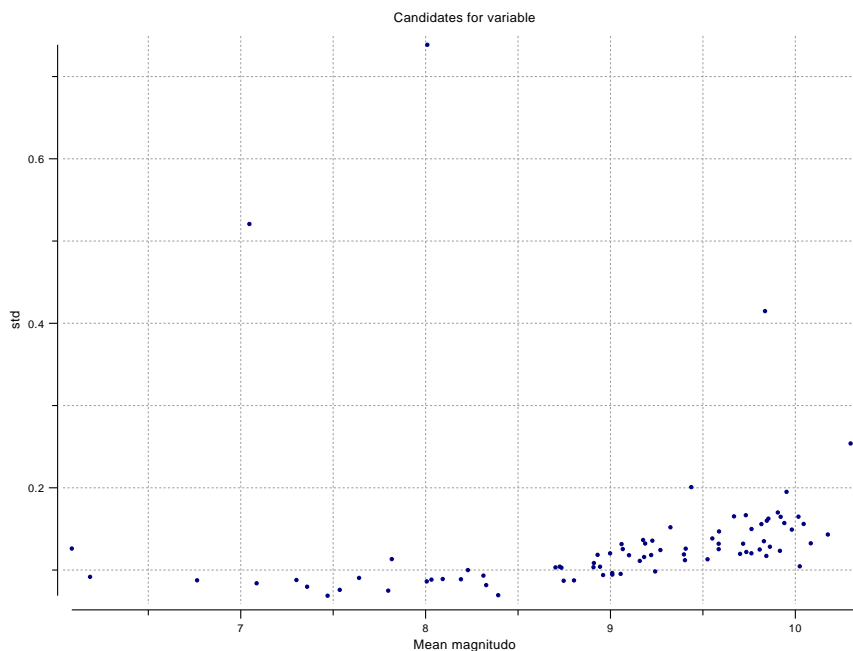


Figure 17: **RZCas**, variability plot of the observed region.

4.7 Additional commands

This chapter contains the description of authorial commands (functions) available directly from the console and possible to use in scripts.

4.7.1 Additional commands of "libwebcam" library for Linux

- `::cam::create webcam usb ?options?`

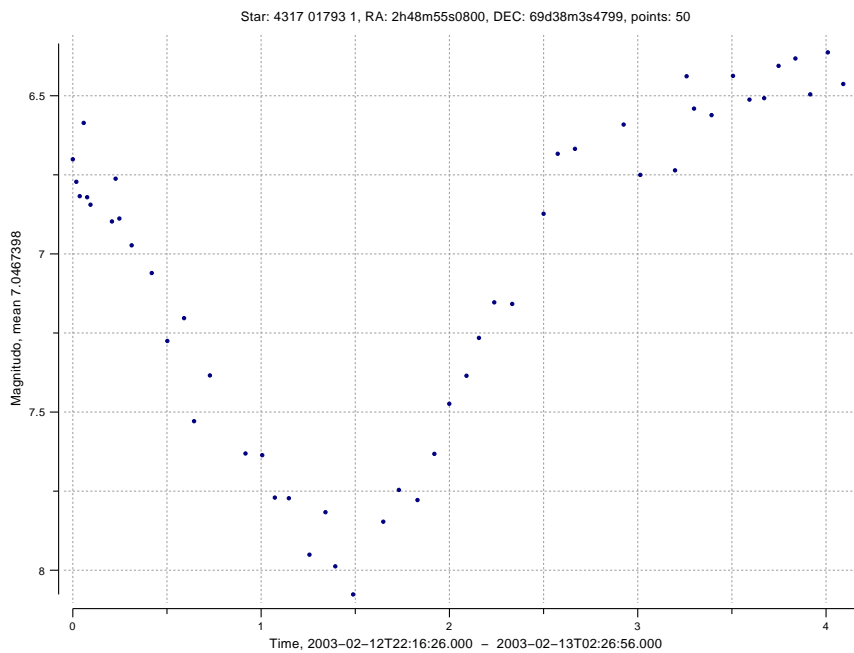


Figure 18: RZ Cassiopeiae variability plot.

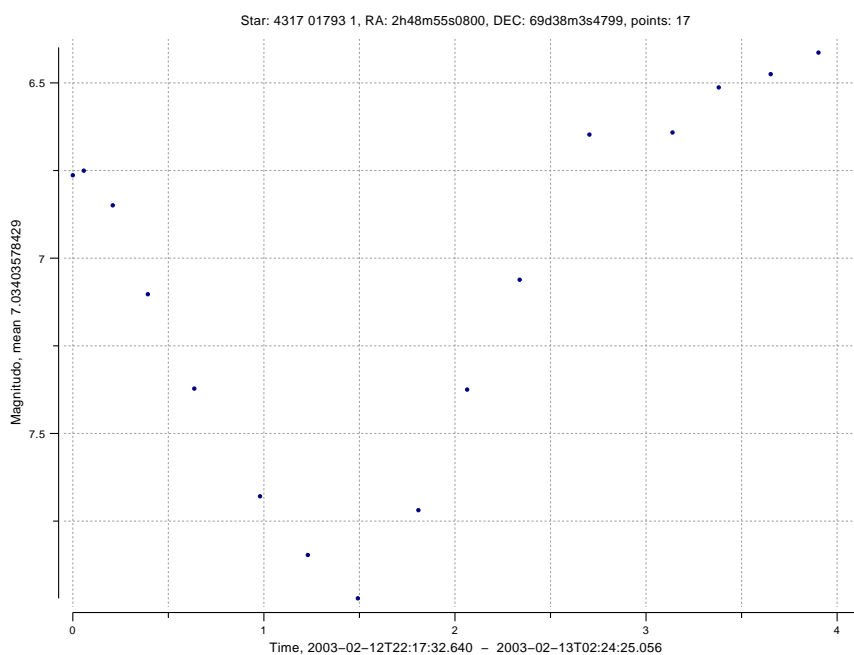


Figure 19: RZ Cassiopeiae variability plot, measurement points grouped by three.

New options:

- **-lpport port_name** – port_name name of parport device, by default /dev/parport0. Used for steering exposure time through a parallel port – only for modified cameras. May not work with some ECS main boards (e.g. K7S5A, K7S5AL).
- **-webcamdevice device_name** – device_name name of v4l device, by default /dev/video0.

- **-validframe number** – used with long exposures, defines which of the frames read from **v4l** device (**pwc** driver) contains the image of the sky (previous ones are black). Giving the number parameter equal to 0 will automatically detect the frame which contains the image of the sky, by default 3.

- **cam1 videosource**

Displays a window with camera settings (figure 20), e.g. shutter speed, brightness, reading and writing customized settings.

- **cam1 videoformat**

Selecting image size (figure 21).

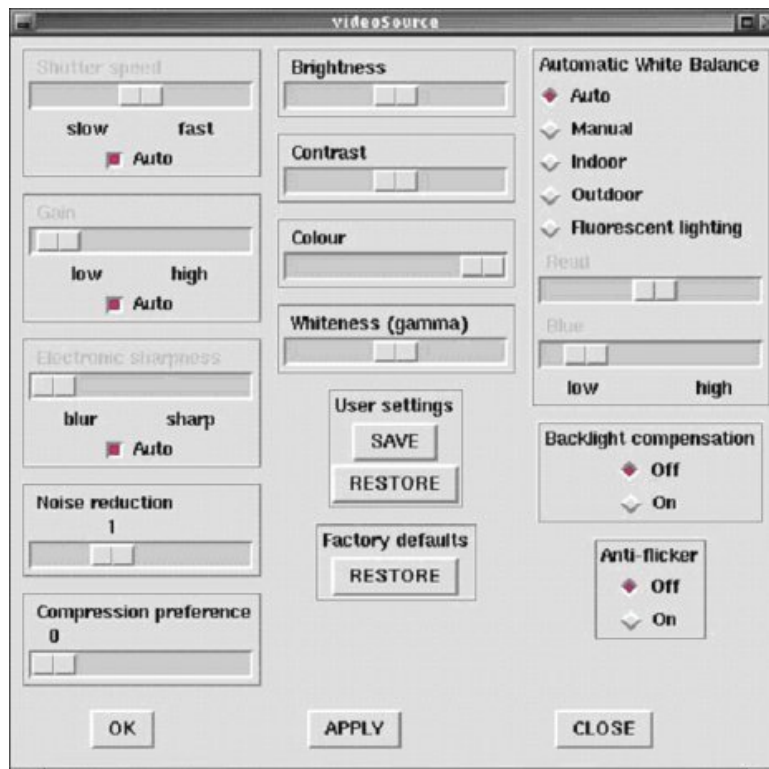


Figure 20: Camera settings.

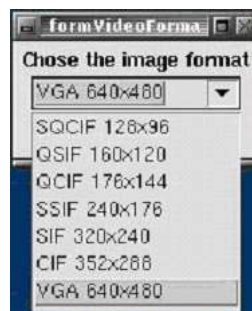


Figure 21: Selecting frame size.

4.7.2 "libskyeye" library – objects and commands

- **skyeye_buf addnb buf_num_1 ... buf_num_n**

Adding many buffers (frames) to buf_num_1.

- **skyeye_buf divc bufNum constans**

Dividing the bufNum buffer by a constant.

- **skyeye_buf subnb buf_num_1 ... buf_num_n**

Subtracting many buffers (frames) from buf_num_1.

- **skyeye_buf move bufNum {moveX moveY ?acos bsin?}**

Shifting and rotating the image in the **bufNum** buffer. If only **moveX** and **moveY** are given, the image is shifted to the left by **moveX** and downwards by **moveY**, if **moveX**, **moveY**, **acos** and **bsin** are given, the image is rotated according to this formula:

$$x' = A \cdot x - B \cdot y - moveX$$

$$y' = A \cdot y + B \cdot x - moveY$$

where:

x' and y' – coordinates of a point in the shifted image,

x i y – coordinates of the point in the shifting image,

A i B – cosinus and sinus of the rotation angle (acos i bsin).

- **::list::create ?num?**

Creates list object, instrumental list, optional num parameter is the number of the list, if no value is given, the number is set automatically.

- **::list::list**

Displays the numbers of existing lists.

- **::list::delete num**

Deletes the list with a given num.

- **::list::params {options}**

Sets parameters of the method of stars detection and aperture photometry. Available options: **-fwhm value**, **-radius value**, **-border value**, **-threshold value**, **-minFwhm value**, **-maxFwhm value**, **-r1 value**, **-r2 value**, **-r3 value**.

- **list1 getstars bufferNo threshin {options}**

Recognises stars visible in the picture from the buffer with the **bufferNo** number, and **threshin** threshold. Available options:

- **-nophotometry**, does not perform photometry. This option is useful when the user wants to detect only stars, e.g. to fit lists of stars from two shifted images and then to shift them appropriately,

- **-noeliminatenostars**, does not eliminate non-stars,
- **-markstars**, marks recognised stars in the picture with a square,
- **-dontreadkwd**, does not read from the FITS header keywords required for astrometric calibration: **DATE-OBS, DEC, FOCLEN, NAXIS1, NAXIS2, OBS-LOC, PIXSIZE1, PIXSIZE2, RA.**

- **list1 save filename**

Saves the instrumental list to a file.

- **list1 fitcat catNum ?options?**

Fits the instrumental list to a catalogue list of stars (astrometric calibration), additionally performs photometric calibration. Options:

- **catNum**, catalogue number,
- **-save filename**, saves the list of observed stars to a file,
- **-nophotcal**, does not perform photometric calibration,
- **-magnitudo minMag maxMag**, defines brightness range of observed stars (taken from the catalogue),
- **-markcatalogstars bufNum**, marks on image in bufNum fitted or not fitted catalogue stars.

- **list1 fitlist listNum**

Fits instrumental lists, **listNum** – the number of the second instrumental list. If the fitting is successful, the shifting and rotation of the second list (**listNum**) in relation to the first is returned, format: **moveX moveY A B.**

- **::cat::create type ?options?**

Creates a cat object, interface for a given stars catalogue.

Options:

- **type** – catalogue type, available: tycho2 – Tycho-2 catalogue.

- **::cat::create tycho2 tycho2DataDirectory ?options?**

Options:

- **tycho2DataDirectory**, path to the Tycho-2/data directory,
- **-num catNum**, the number of the created cat object.

- **::cat::list**

Displays numbers of the existing catalogues.

- **::cat::delete num**

Deletes catalogue with a **num** number.

- **cat1 getstars minRa maxRa minDe maxDe ?options?**

Reads a list of stars from a catalogue, from a field limited by: **minRa maxRa minDe maxDe**.

Available options:

- **-save filename**, saves the list to a file,
- **-magnitudo minMag maxMag**, defines the brightness range of the stars loaded from the catalogue.

5 Algorithms

This chapter contains a description of algorithms used in the method of measuring the brightness of variable stars (see chapter 4.1). Algorithms of stars recognition, photometry and astrometry are either taken from [6] and [7], or are their modified versions. Modifications and algorithms taken from [6] are described in detail. Algorithms from [7] are described in general to explain the significance of parameters used in **SkyEye**. Readers who wish to know the details are referred to the source text.

5.1 Loading images

In the **AudeLa** program, the library responsible for reading images from a webcam is the **libwebcam** library, images are copied to **buf** objects. The library has been enriched by the author with **Linux** support, and the version for **Windows** has been given a few useful options.

The loaded images may be colour images (RGB) or black and white, the longest exposure for unmodified webcams is 0,2 s. A way of modifying webcams so that they support longer exposures is described at [10] and [11], and consists in blocking the automatic shutter control and changing it for control via a parallel port.

Due to the facility of adding an extra lens to the telescope for astronomical purposes, the most suitable cameras are **Philips**, from the **Vesta** (PCVC) series or **ToUCam**, but only those with CCD sensors, the following types have been tried: 675K, 680K, 690K, 740K, 750K, 840K.

5.1.1 Implementation of a webcam in Linux

Authorial implementation uses **pwc** and **pwcx** modules, their description is available at [16]. They support various webcams [16]:

- Philips WebCams : PCA 645VC, PCA 646VC, PCVC 675K, PCVC 680K, PCVC 690K, PCVC 720K/40, PCVC 730K, PCVC 740K, PCVC 750K, PCVC 840K,
- Askey VC010
- Creative Labs Webcam 5, Pro Ex
- Logitech QuickCam 3000 Pro, 4000 Pro, Notebook Pro, Zoom,
- Samsung MPC-C10, MPC-C30
- Sotec Afina Eye
- Visionite VCS UM100, VCS UC300

Pwc and **pwcx** drivers meet the **V4L** (Video For Linux, version 1) standard, in this way the camera is visible from the level of the **Linux** user as a `/dev/video0` device. Loading the image boils down to a few subsequent actions:

- Opening the device
- Loading a structure that describes the device properties
- Checking if the loaded device is compatible with Philips webcams

- Setting the desired window size

Available sizes (formats):

- **SQCIF** – 128x96
- **QSIF** – 160x120
- **QCIF** – 176x144
- **SSIF** – 240x176
- **SIF** – 320x240
- **CIF** – 352x288
- **VGA** – 640x480

- Reading the image (in YUV format)
- Conversion from YUV to RGB (or to a black-and-white picture), next, copying the image to an output **buf** object.

Setting and loading webcam parameters is performed with `ioctl()` function calls with appropriate parameters. **Pwc** and **pwcx** modules give the possibility of mapping a device for a specific area of operational memory (using the `mmap()` function).

Unfortunately, for various reasons, these modules are no longer being developed. The latest versions are available at [16].

5.1.2 Controlling exposure time

Computer's parallel port is responsible for controlling the exposure time for modified webcams. Changing the state on a specific pin allows to block or release the shutter.

- In **Linux** **ppdev**, **parport**, **parport_pc** (`/dev/parport0` device) modules are used for controlling the parallel port.
 - Opening and initializing the device
 - Setting the output pins of the port
- In **Windows** systems the parallel port may be controlled in various ways, by a direct call to the port (Windows 95/98), using an built-in **PortTalk** program (Windows 95/98/NT/2000/XP, turning on and turning off in the **Setup/AudeLa/Porttalk Interface** menu) or implemented by the author using the parallel port as a printer port (Windows 95/98/NT/2000/XP). In this case it is necessary to modify the socket according to the description at [17].

5.2 Adding frames

It is typical for webcams to produce a lot of noise, even after subtracting a dark frame from an individual image only stars up to 6m – 7m can be recognised. The signal-to-noise ratio can be improved by adding several frames. Adding 20 frames extends the range to 8m, 60 to 9m, 120 to 10m. Collecting 120 frames with exposure of 0,2 s takes about a minute, in this time stars move by several pixels. Adding images (after a shift that compensates for the Earth's rotation) will result in additional averaging of noise, which substantially improves the image quality. It is possible because after the shift

the brightness values of physically different pixels are added, this procedure is especially effective in eliminating hot pixels, which - due to large differences in brightness - remain in the picture even after subtracting the dark frame. Unfortunately, because the sensitivity of CCD sensors is limited, this method will not allow to obtain images of dark objects like galaxies, the only solution is modifying the webcam and using a driving mechanism [1], [2].

Shifting images that compensates for the Earth's rotation can be achieved in two ways:

- Calculating the shift of subsequent frames, when the position of the centre of exposure is known, along with the image size
- Calculating the shift on the basis of recognizing stars and fitting lists of stars (these methods will be described later on).

An example of adding frames is presented in figures 22 and 23, the former is a single frame with exposure time of 0.2 s, the latter is a sum of 200 subsequent frames with exposures of 0.2 s.

Other good examples are shown in figures 24 and 25, the former is a single frame with exposure of 2.5 s, the latter is a sum of 30 subsequent frames with exposures of 2.5 s. In an individual picture the algorithm recognises 28 stars, after adding several frames it recognises over 200 stars. The images come from observations conducted at night on 4.09.2004 / 5.09.2004.



Figure 22: Castor, exposure time 0.2 s.

5.3 Automatic recognition of stars

The image, after subtracting the dark frame (optional), is stored in a **buf** object in the form of a table called **basic table**. Recognition of stars consists of [7]:

- finding a local luminosity maximum which is interpreted as the centre of the star,
- eliminating recognised non-stars (objects with narrow profiles – cosmic radiation, wide objects – galaxies, nebulas, the moon, meteors).



Figure 23: Castor, adding 200 frames with exposures of 0.2 s.

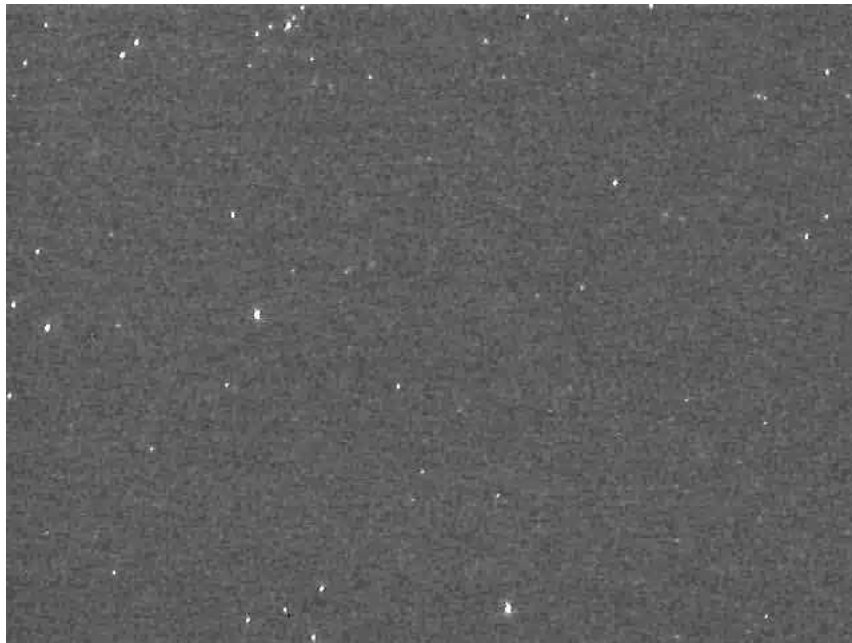


Figure 24: Single frame, exposure of 2.5 s.

5.3.1 Finding the local luminosity maxim

Finding the local luminosity maxim is performed in a working table, which is created by multiplying the basic table by square matrix, performing the role of a filter sharpening the image [6], [7]. Its elements are created according to this formula [6]:

$$C_{kl} = \frac{e^{-\frac{(k-r)^2 + (l-r)^2}{2(0,4246 \cdot fwhm)^2}}}{2\pi(0,4246 \cdot fwhm)^2}$$

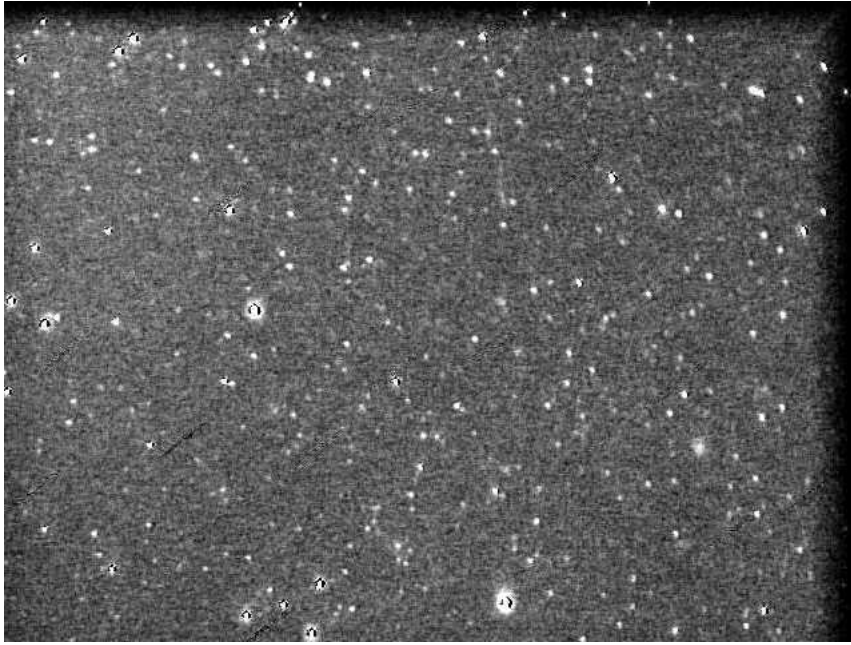


Figure 25: Adding 30 frames with exposures of 2.5 s.

where:

C_{kl} – an element of the matrix with k, l coordinates

r – matrix radius (**Gauss matrix radius**), by default 4

$fwhm$ – half-width of the profile (**Star fwhm**), by default 3.0

Next, the matrix is additionally normalised and brought to a form where the sum of the elements (volume) equals zero [6]:

$$C'_{kl} = \frac{C_{kl}}{s} - \frac{1}{d^2}$$

$$s = \sum_{k=0}^d \sum_{l=0}^d C_{kl}$$

$$d = 2r + 1$$

where:

C'_{kl} – new element of the matrix with k, l coordinates

C_{kl} – old element of the matrix with k, l coordinates

r – matrix radius (**Gauss matrix radius**), by default 4

Elements of the working table are calculated according to the following formula [6]:

if $F_{ij} \leq threshin$ then:

$$W_{ij} = 0$$

in other case:

$$W_{ij} = \sum_{k=0}^d \sum_{l=0}^d F_{i-r+k, j-r+l} C_{kl}$$

$$d = 2r + 1$$

where:

W_{ij} – element of the working table

F_{ij} – element of the basic table

C_{kl} – element of the filtering matrix

r – filtering matrix radius (**Gauss matrix radius**)

$threshin$ – background threshold (**Pixel threshold**), should be equal to: *arithmetic mean of pixel luminosity + 3 * standard deviation*

Next, for each element of the working table (with the exception of pixels from the frame border, defined by **Frame border** parameter, by default 20) W_{ij} the condition if $W_{ij} > threshold$ (**Star threshold** is checked, by default 40) and whether W_{ij} is a local maximum. Objects thus found are candidates for stars.

5.3.2 Elimination of non-stars

Two Gaussian functions are fitted to the profiles of the detected objects in the basic table, (about x and y axes and passing through the central pixel). A mean is calculated from the resultant half-widths of the profiles, if the mean is from the acceptable range of $\langle \text{minFwhm}, \text{maxFwhm} \rangle$ (default values 1 and 5) the object is considered to be a star [7].

In figure 26 a photograph is shown with objects recognised as stars marked with a square. It can be noticed that objects with wide profiles have been rejected (in this case over-exposed stars) as well as one-pixel objects with narrow profiles.

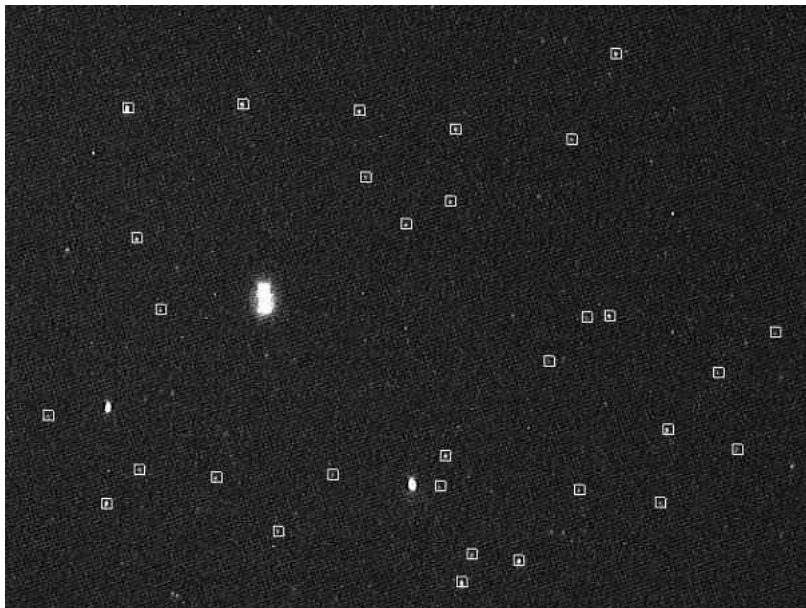


Figure 26: Castor, 2s, recognised stars.

5.4 Aperture photometry

Instrumental magnitude of a star is calculated with the following formula [7]:

$$m_i = -2,5 \log N_{app}$$

where:

m_i – instrumental magnitude,

N_{app} – signal coming from the star, reduced by the background threshold.

The signal from a star is calculated by adding luminosity of pixels within a **r1** circle (aperture, the radius is defined by the **Aperture radius** parameter, by default 3 pixels) reduced by background threshold. Background threshold is calculated as the median of luminosity of pixels outside the aperture, between **r2** (**Background inner radius**) and **r3** (**Background outer radius**) circles [7]. It is shown in figure 27, default radius values are 6 and 12 pixels.

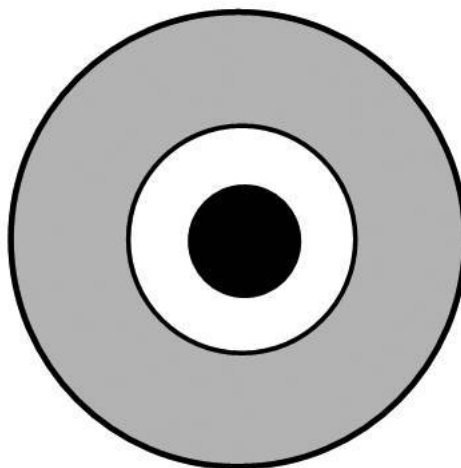


Figure 27: Calculating background threshold, background area is marked in grey, aperture in black.

5.5 Astrometry

Defining the area of the sky that is reflected in the image is calculated from the knowledge of the position of the centre of the image and its scale. The information should be included in the header of **FITS** files (buf object variables) or given by the user. Next, a list of stars corresponding to this area is loaded from the **Tycho-2** catalogue. Both lists (instrumental and catalogue) are fitted. Finally, instrumental coordinates of the recognised stars are converted to the equatorial coordinates.

5.5.1 Tycho-2 stars catalogue

The **Tycho-2** catalogue contains the positions of 2.5 million stars, proper motions values, **BT** and **VT** magnitudes. It was created on the basis of around 300 million observations conducted in the years 1989 – 1993 by the **ESA Hipparcos** satellite. It also contains stars from the **Astrographic Catalogue** and 143 other catalogues based on observations from the surface of the Earth. Detailed information about the catalogue, and the catalogue itself, can be found at [9].

The catalogue consists of four ASCII files, each of them divided with $\backslashr\backslashn$ (CR, LF) markers into records of constant length:

- `catalog.dat` – the main file in the catalogue, containing 2 539 913 records (stars) 206 bytes of length (the file is about 503 MB big),

- `suppl_1.dat` – supplement 1, 17 588 records 122 bytes long,
- `suppl_2.dat` – supplement 2, 1146 records 122 bytes long,
- `index.dat` – index file for `catalog.dat` and `suppl_1.dat`, 9538 records 42 bytes long.

The individual fields in the records are separated with a vertical bar, |. Stars in the main file in the catalogue are sorted into 9537 regions, according to **GSC** numbers. Each region covers a field of $3,75^\circ \times 3,75^\circ$. Each record of the index file contains the number of the record (in the main file in the catalogue) of the first star in the given region and the position and size of the region, given in equatorial coordinates. Thanks to this, searching as big a file as `catalog.dat` is made a lot easier.

Finding stars in a given region boils down to searching the index file in order to select **GSC** regions common with the searched region; next, searching the main file in the catalogue in order to select stars common for the chosen **GSC** regions and the searched region. Because of the catalogue's enormous scope, only stars from a range of magnitudes defined by the user (**Observe magnitudo** <**min.**, **max.**>) are selected.

5.5.2 Astrometric calibration

On the basis of such information as the position of the centre of the observation field, pixel size, focal length of the lens used for observation and frame size, the limits of the observed field are calculated. A list of corresponding stars is loaded from the catalogue, next, equatorial coordinates are converted to instrumental coordinates in order to switch from spherical geometry to flat geometry. To a catalogue list thus prepared, an instrumental list is fitted with stars recognised in the image (rotation and shift considered).

Fitting lists means finding the values of A , B , C and D parameters of equations [6]:

$$x' = A \cdot x - B \cdot y - C$$

$$y' = A \cdot y + Bx - D$$

where:

- x' i y' – coordinates of the point in the catalogue list,
- x i y – coordinates of the point in the instrumental list,
- A i B – cosine and sinus of the rotation angle,
- C i D – shift in x and y .

They describe the method of converting the coordinates of one list to the coordinates of the other list. In order to calculate these parameters, the stars from both lists are sorted according to their magnitude. Next, pairs of stars with the greatest magnitudes are selected and parameters of fitting are defined according to the following equations [6]:

$$A = \frac{y'_2 - y' - \frac{(x'_2 - x')(x_2 - x)}{y - y_2}}{y_2 - y - \frac{(x_2 - x)^2}{y - y_2}}$$

$$B = \frac{x'_2 - x - A(x_2 - x)}{y - y_2}$$

$$C = x' - Ax + By$$

$$D = y' - Ay - Bx$$

where:

x, y – coordinates of the first selected point from the list of recognised stars,

x_2, y_2 – coordinates of the second selected point from the list of recognised stars,

x', y' – coordinates of the first selected point from the catalogue list,

x'_2, y'_2 – coordinates of the second selected point from the catalogue list.

Algorithm ends its performance when such a match is found that the difference in the distance of the same stars in both lists is smaller than 2 pixels. If it is impossible to fit the lists, an error message is displayed. Instrumental coordinates from an instrumental list thus fitted are converted to the observed equatorial coordinates.

It is important that the catalogue list contains as few stars from outside the range of observed magnitudes as possible; it is also important to define precisely the centre of the field of observation. If the above conditions are not met, the fitting of the lists may be unsuccessful or the time of algorithm's performance may be very long.

5.6 Photometric calibration

The magnitude measured with aperture photometry is an instrumental value, it can change for a specific non-variable star from one exposure to the next. The difference in magnitude between two constant stars is constant, allowing for the measurement error. Differential photometry consists of calculating the difference between the magnitudes of these stars, assuming that one of them plays the role of a reference star – a standard [7].

The algorithm taken from [7] has been largely simplified in **SkyEye**. A few standards are selected from the catalogue list – stars with magnitudes from half the range of observed magnitudes. The mean value of their magnitudes becomes the magnitude of the reference star. The same reference stars are located in the instrumental list and their mean instrumental magnitude is calculated. Subsequently, the magnitude of each star is calibrated by subtracting from it the mean instrumental magnitude of a reference star and adding the magnitude of a reference star calculated before [7].

5.7 Gathering data, creating variability plots and picking variable stars

Lists of stars thus prepared, with information about time and location of the observation added, are saved as text files to the measurements database (directory with observation results).

When the observation is over, the user may select a star of interest from the measurements database and create its variability plot.

It is also possible to draw a diagram of variability for the field of observation, which is a diagram of relation between *standard deviation of the mean magnitude* and *the mean magnitude* of individual stars. The stars in its lower part can be classified as non-variables, figure 17. The stars above a certain threshold can be classified as variable stars [7].

6 Appendices

6.1 Eclipsing binaries

Eclipsing binaries are very close binary systems, whose orbit is oriented in such a way that one star eclipses the other, and vice versa, at regular intervals. Hence, two eclipses can be distinguished in one revolution. If the revolving stars differ in structure or magnitude, then one eclipse is deeper (main eclipse) and the other is shallower (secondary eclipse).

On the basis of the time difference between the observed minima we can calculate the time of one revolution, and the depth and structure of eclipses gives us information about the angle of the orbit and the shape of its constituents. The time period of eclipses compared to the time interval between them allows to calculate the diameters of stars in relation to the distance between them.

RZ Cassiopeiae is an example of such a star, its variability plot is shown in figures 18 and 19.

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