Processing service of optical frames for the formation of high-precision observations of asteroids and satellites

LEMUR IS:

One of the best software for automatic multithreaded data processing of astrometric and photometric optical observations.

Implemented as a service and independent standalone/local/built-in/corporate software.

High level of data processing automation due to the many years of formalized experience of astronomy professionals and amateurs, customers and developers.

Relieves the observer's stress by removing the operations such as manual frames comparing for objects detection, and much more.

LEMUR CAN:

Organize automatic detection of moving objects and light curves on frames from many telescopes of the observatory!

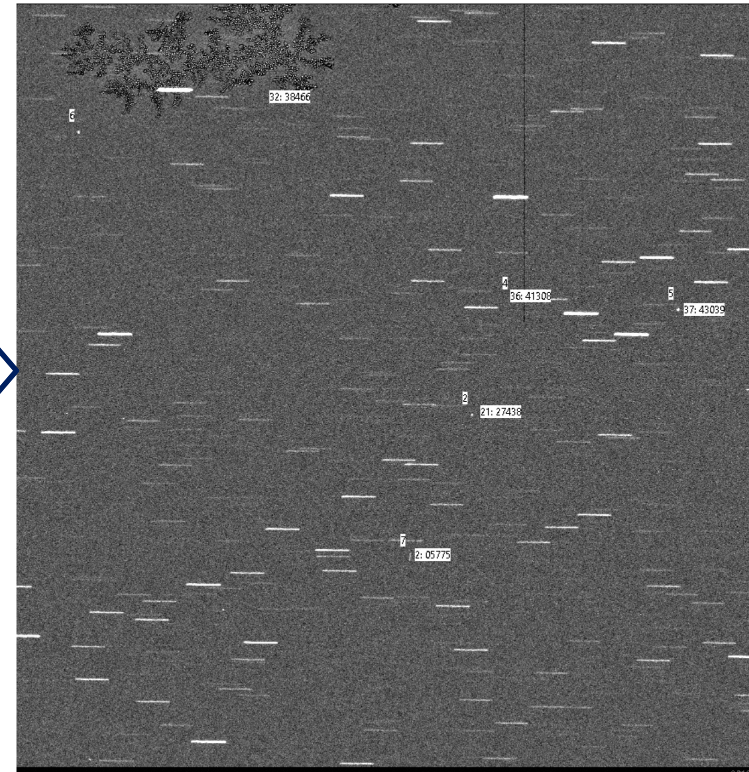
Help create a moving object detection service for processing frames of amateur astronomers!

Automate your observational astronomy tasks!

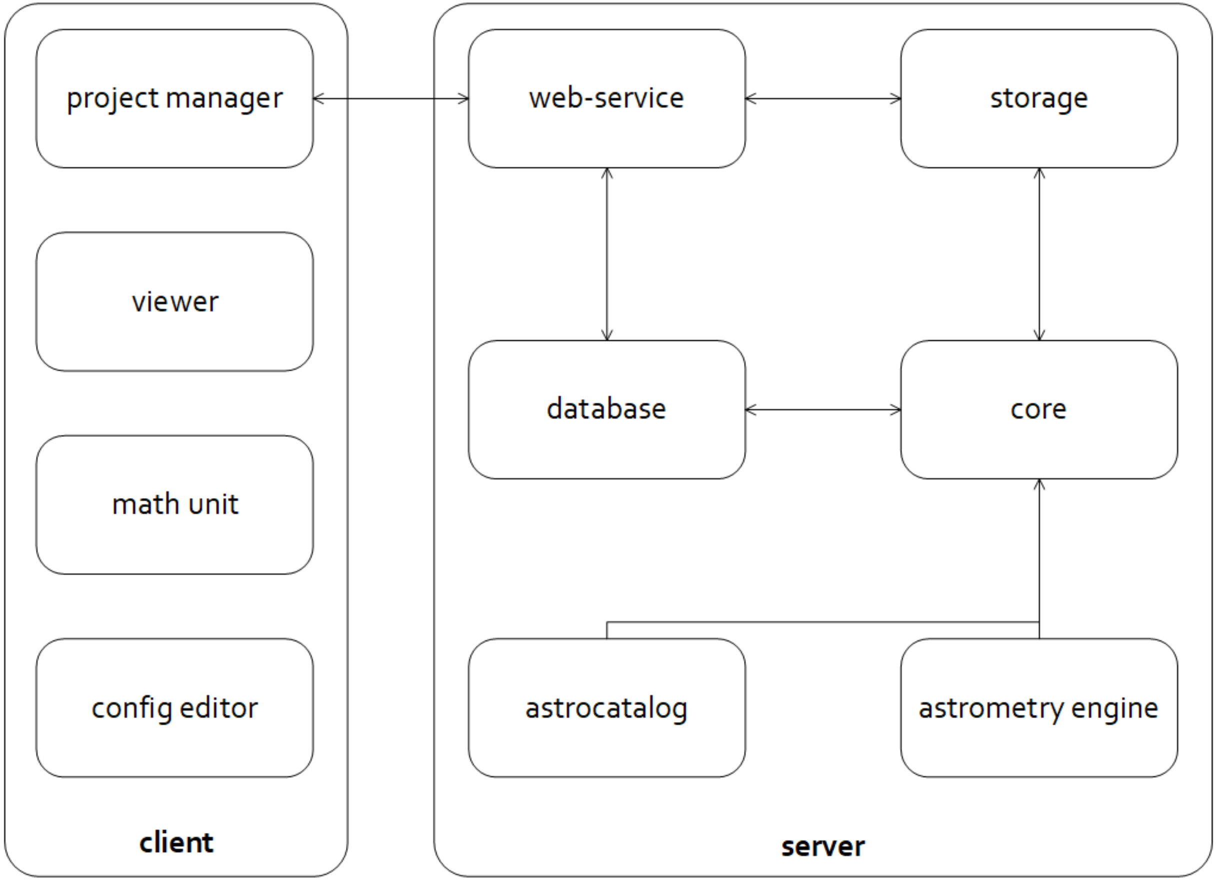
Raw frames

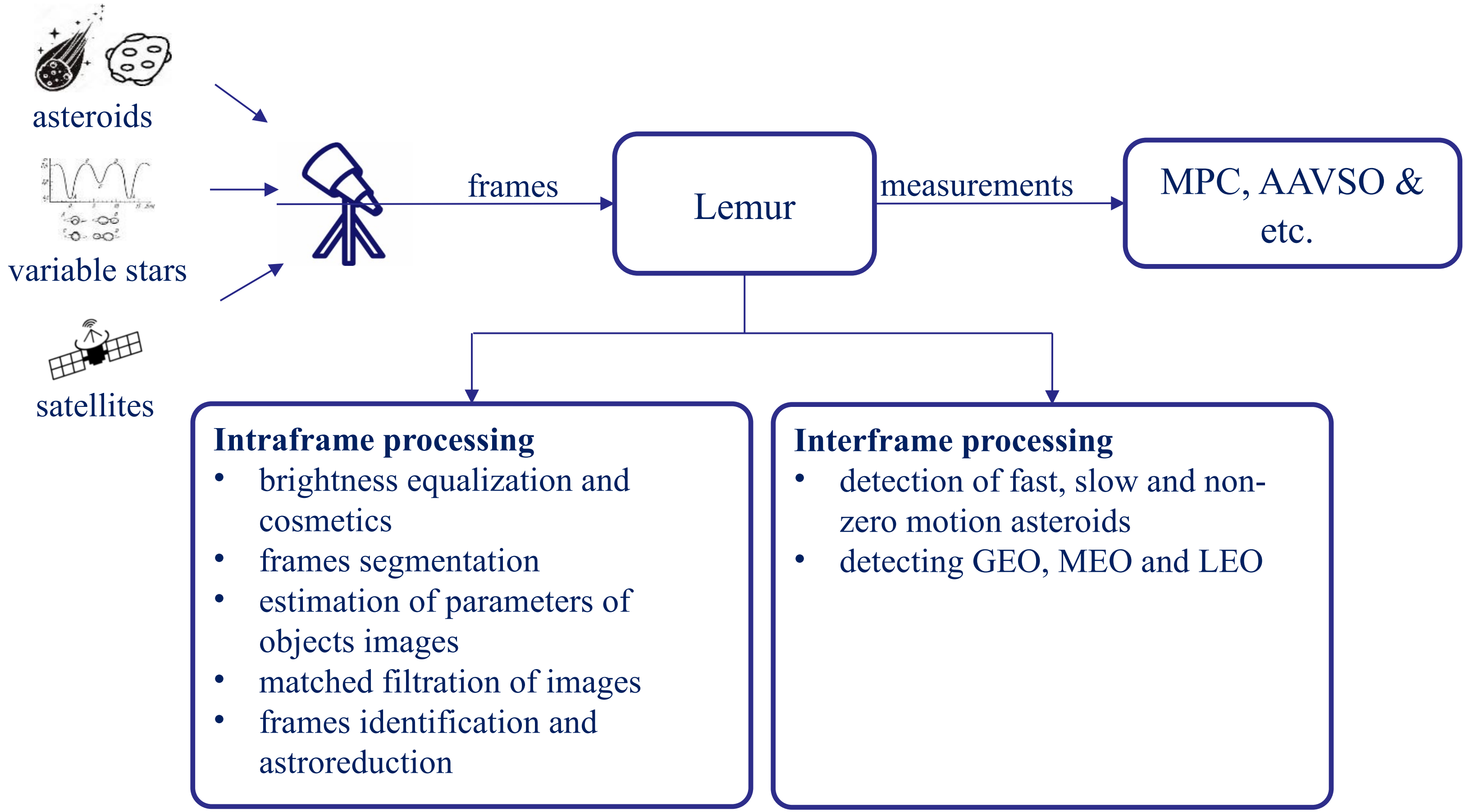
after proc.

Satellites detected

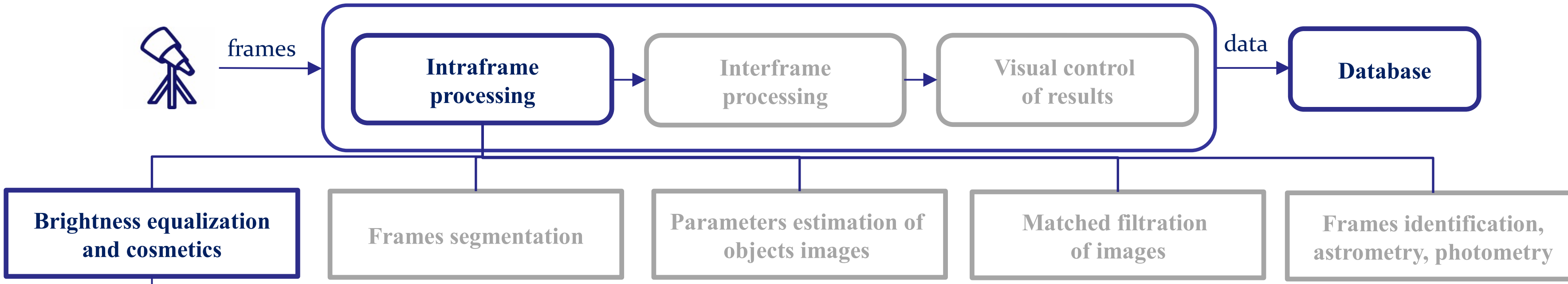


Lemur architecture



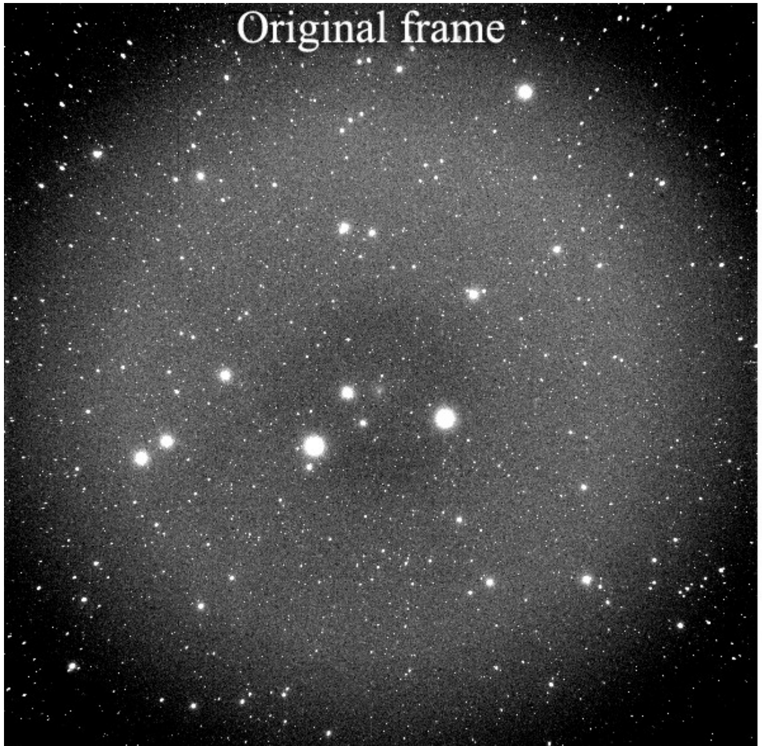


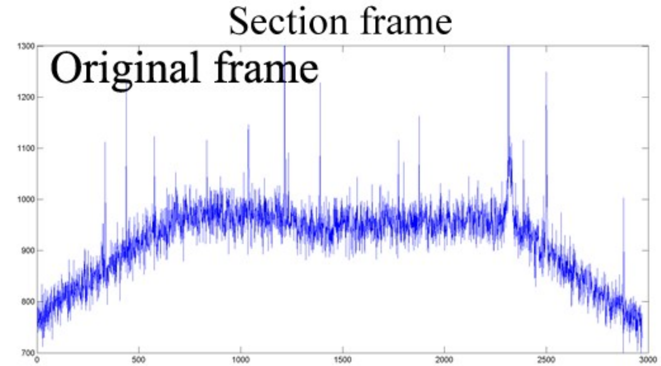
asteroids
variable stars
satellites
frames
Lemur
measurements
MPC, AAVSO & etc.
Intraframe processing
• brightness equalization and cosmetics
• frames segmentation
• estimation of parameters of objects images
• matched filtration of images
• frames identification and astroreduction
Interframe processing
• detection of fast, slow and non-zero motion asteroids
• detecting GEO, MEO and LEO

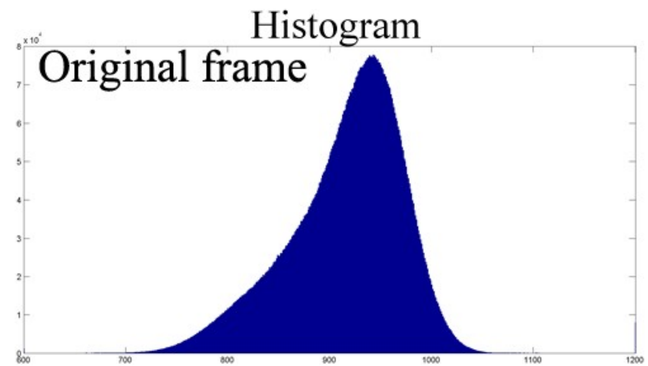


- compensates uneven sensitivity and defects of the CCD-camera;
- eliminates spurious illumination from extraneous light sources (lights, passing cars), as well as uneven illumination of the frame at “dawn” or near bright stars;
- allows to dispense with flat frames;
- the use of aligned in brightness frames significantly reduces the errors in detection and parameters estimation of objects images.

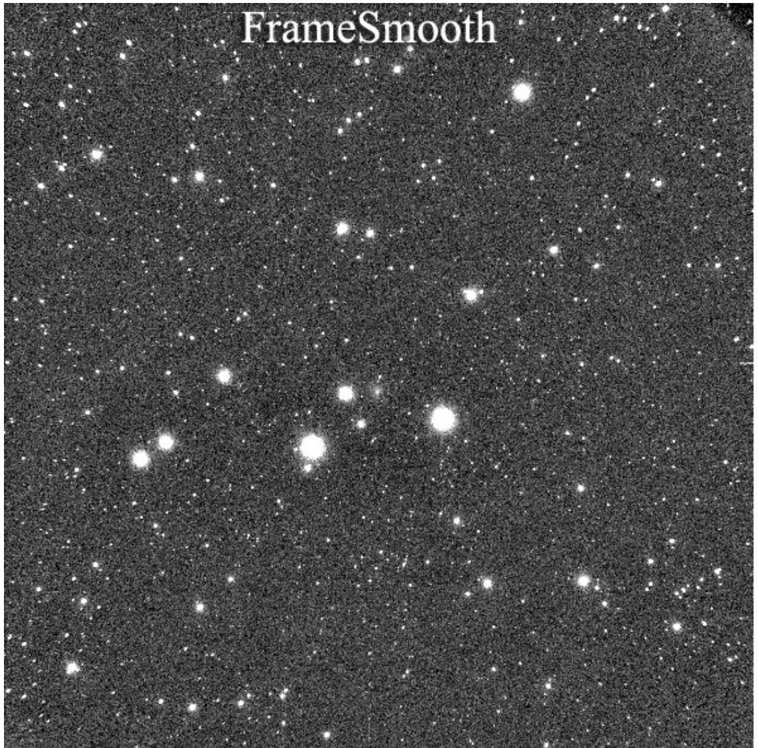
Brightness equalization of digital images



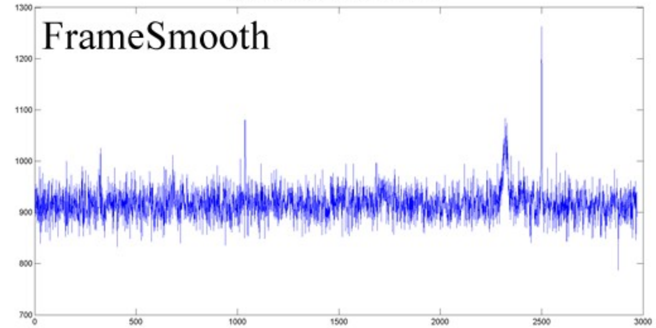




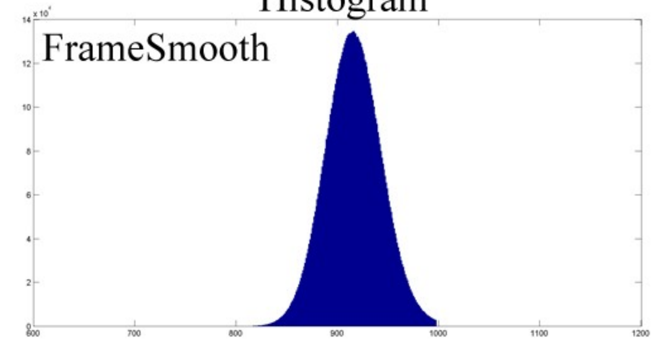
Comparison of alignment results with Lemur (FrameSmooth) and MaxImDL



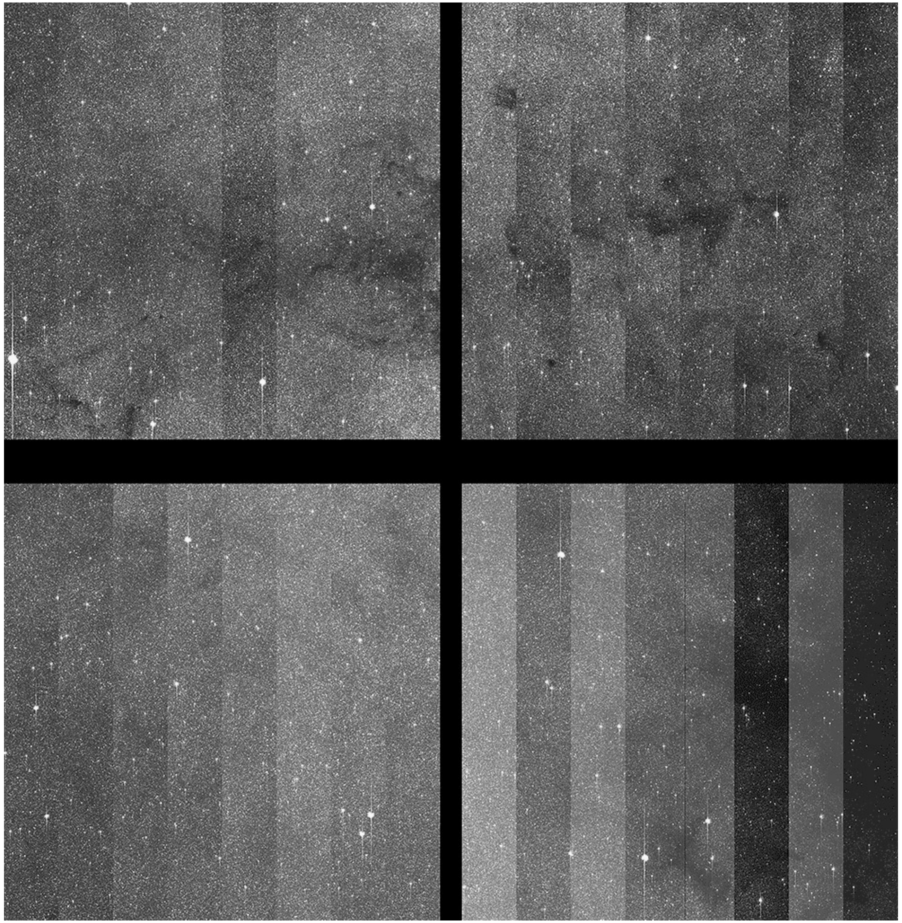
Section frame



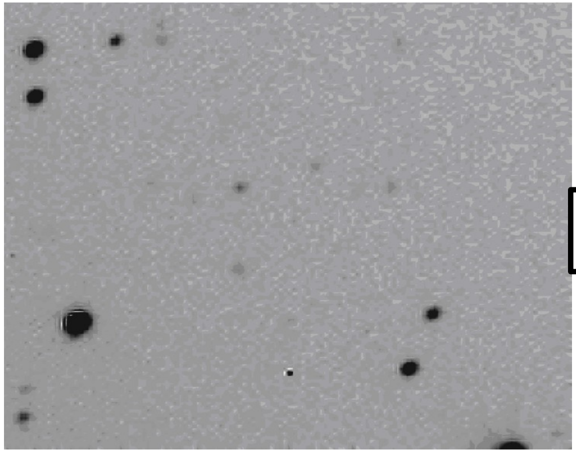
Histogram



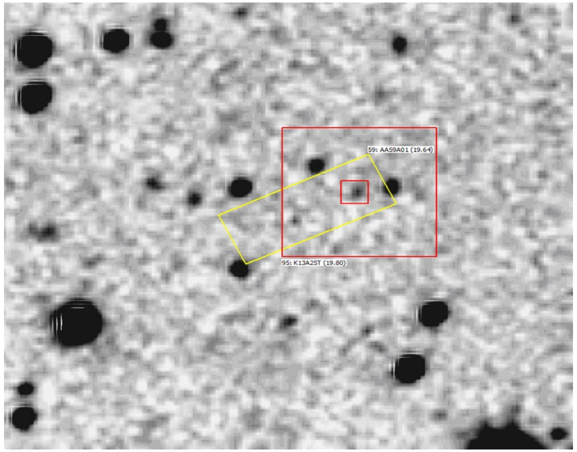
Brightness equalization of multi frames



Brightness equalization of multi frames

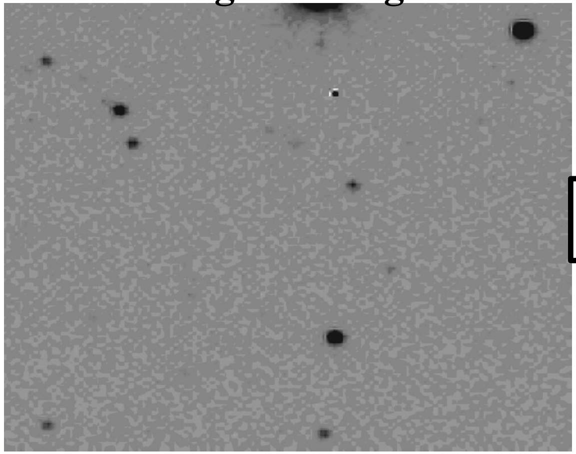


FrameSmooth

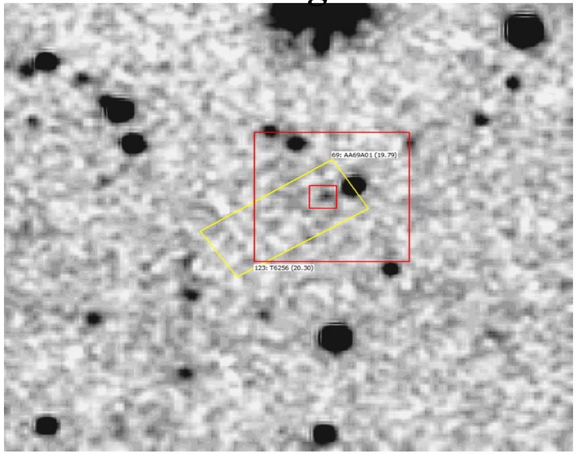


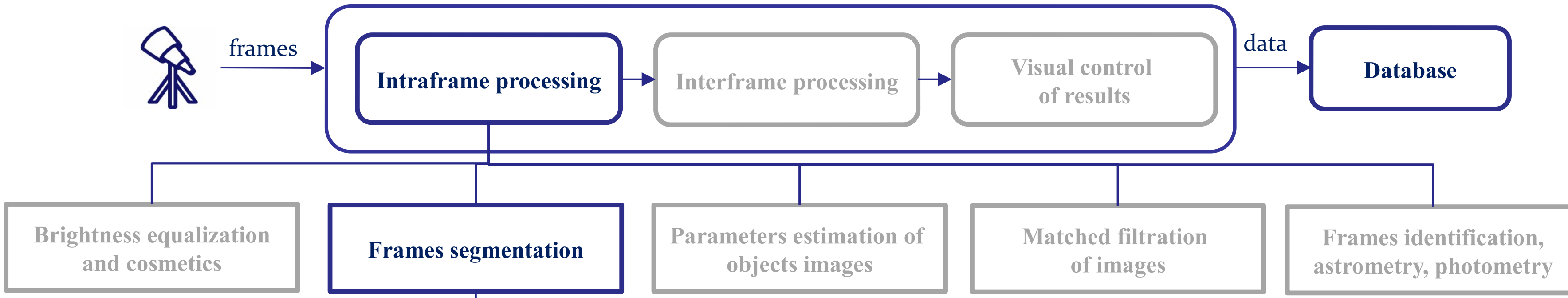
Original image

Processing result

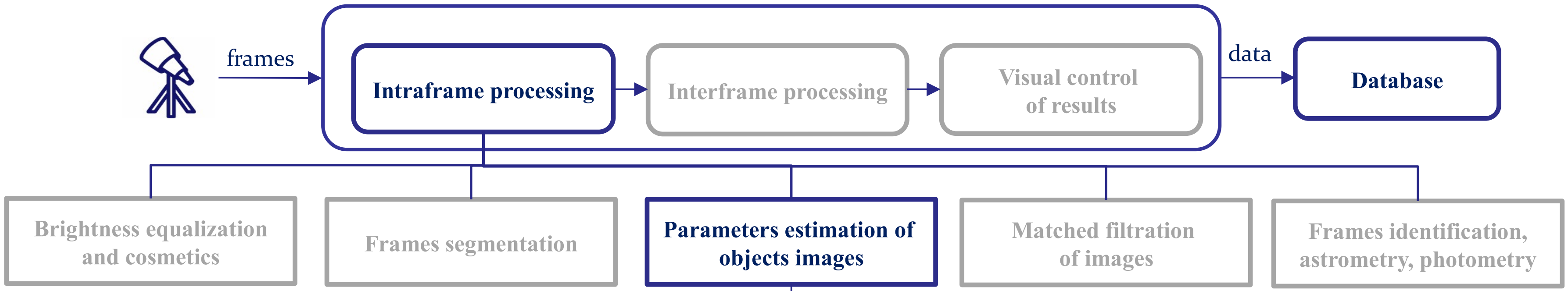


FrameSmooth





- determines the set of CCD-camera pixels which correspond to the objects images in frame;
- uses a complex of classical and original segmentation methods with their adaptive automatic selection for each frame and segment in it;
- classifies objects images into “circular/extended”, and also selects “anomalous pixels”;
- forms segments for objects with small size and for images of large stars with diffraction stretches;
- forms segments for super-extended objects.



- determines the exact rectangular coordinates of objects, instrumental brightness, signal-to-noise ratio, length and other image parameters;
- analytical parameters estimation of point and stroke images of objects before and after the matched filter;
- parameters estimation of the objects images with an analytically undefined profile before and after the matched filter;
- instrumental brightness estimation of circular and extended images, as well as images of objects with an analytically undefined profile.

Parameters estimation of object's image in CCD-frames

Computational method for determining the objects position in CCD-frames

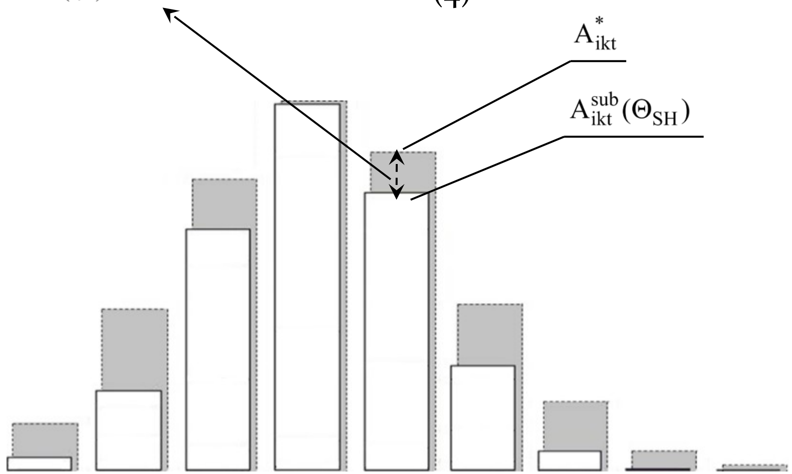
Quality criterion for determining the position of object's image:

$$F_{\Delta AG1}(\Theta_{SH}) = \sum_{i,k}^{N_{SIFP}} \underbrace{\left(A^{*}_{ikt} - A^{sub}_{ikt}(\Theta_{SH})\right)}^{2} \xrightarrow[\Theta SH]{} \min$$

Minimum sum of squares of deviations between experimental and model brightness of pixe in the intraframe processing area

$$\Delta A_{SH(i,k)} = A^{*}_{ikt} - A^{sub}_{ikt}(\Theta_{SH}) \qquad (4)$$

Deviation between experimental and model brightness of pixel



Real and model object's image

– real object's image

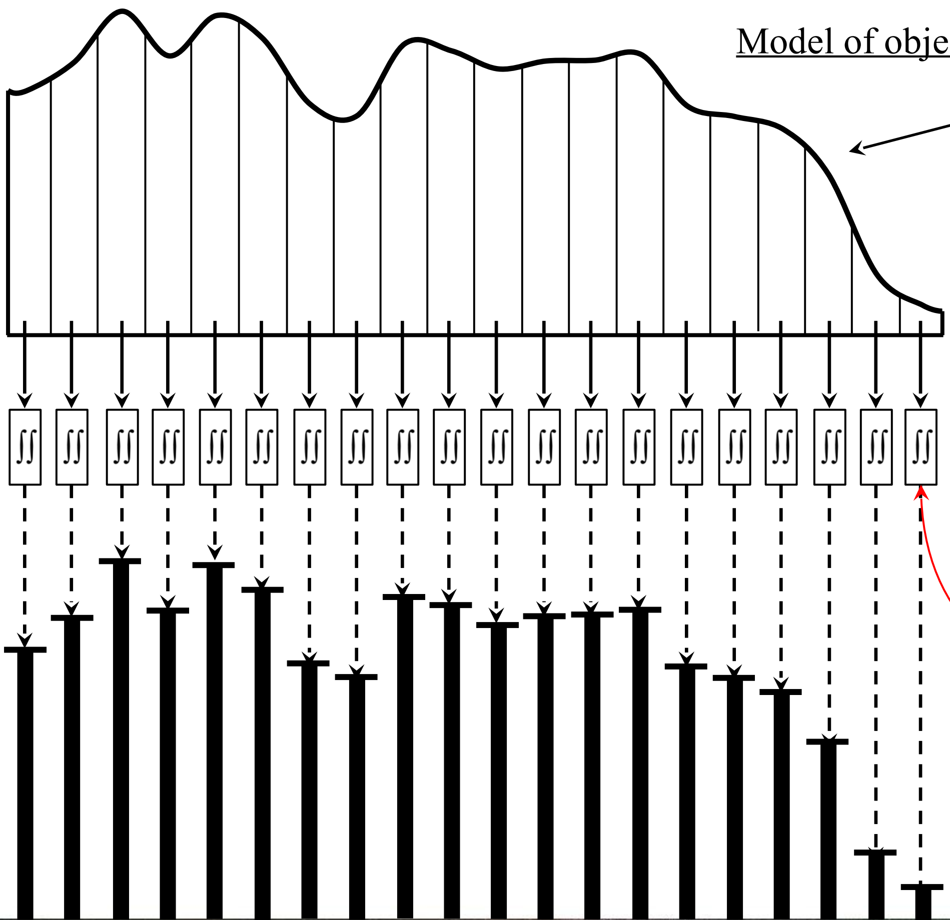
– model of object's image

$\Theta_{gen\tau}$ – vector of estimated parameters

A^{*}_{ikt} – experimental brightness of pixels

$A_{ikt}(\Theta_{gen\tau})$ – model brightness of pixels

Subpixel Gaussian model of extended images of object



Model of object's image

Subpixel model of extended image of object:

$$f_\tau^{sub}(x_{it}, y_{kt}, \Theta_\tau^{sub}) = C_{residual}^{sub} +$$

$$+ A_{subGt}\exp\left\{-\frac{1}{2\sigma_{subGt}^2}\left[(x_{it} - x_\tau(\Theta_\tau^{sub}))^2 + (y_{kt} - y_\tau(\Theta_\tau^{sub}))^2\right]\right\}$$

Model brightness of ik-th pixel in subpixel model of image:

$$A_{ikt}(\Theta_\tau^{sub}) = \boxed{\int_{x_{bi}}^{x_{ei}}\int_{y_{bk}}^{y_{ek}}\int_{\tau_t-\Delta/2}^{\tau_t+\Delta/2}} f_\tau^{sub}(x_{it}, y_{kt}, \Theta_\tau^{sub})dx_{it}dy_{kt}$$

Borders (beginning and end) of ik-th pixel in CCD-matrix by coordinates x and y:

$$x_{bi} = x_{it} - \frac{\Delta_{CCD}}{2}; \qquad y_{bk} = y_{kt} - \frac{\Delta_{CCD}}{2};$$

$$x_{ei} = x_{it} + \frac{\Delta_{CCD}}{2}; \qquad y_{ek} = y_{kt} + \frac{\Delta_{CCD}}{2}.$$

Subpixel Gaussian model of extended images of object

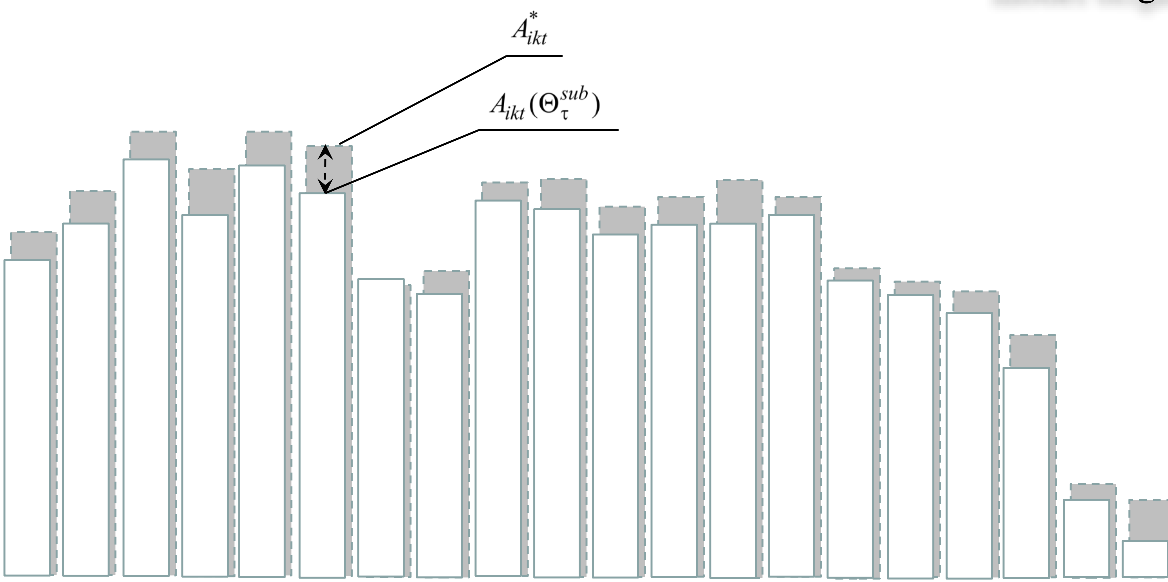
Quality criterion for determining the position of object's image:

$$F_{\Delta A\tau}(\Theta_\tau^{sub}) = \sum_{i,k}^{N_{IPS}} \underbrace{\left(A_{ik\tau}^{*} - A_{ik\tau}(\Theta_\tau^{sub})\right)}^2 \xrightarrow[\Theta_\tau^{sub}]{} \min$$

<u>Minimum sum of squares of deviations</u> between experimental and model brightness of pixel in the intraframe processing area

$$\Delta A_{SH(i,k)} = A_{ik\tau}^{*} - A_{ik\tau}(\Theta_\tau^{sub})$$

Deviation between experimental and model brightness of pixel



Real and model object's image

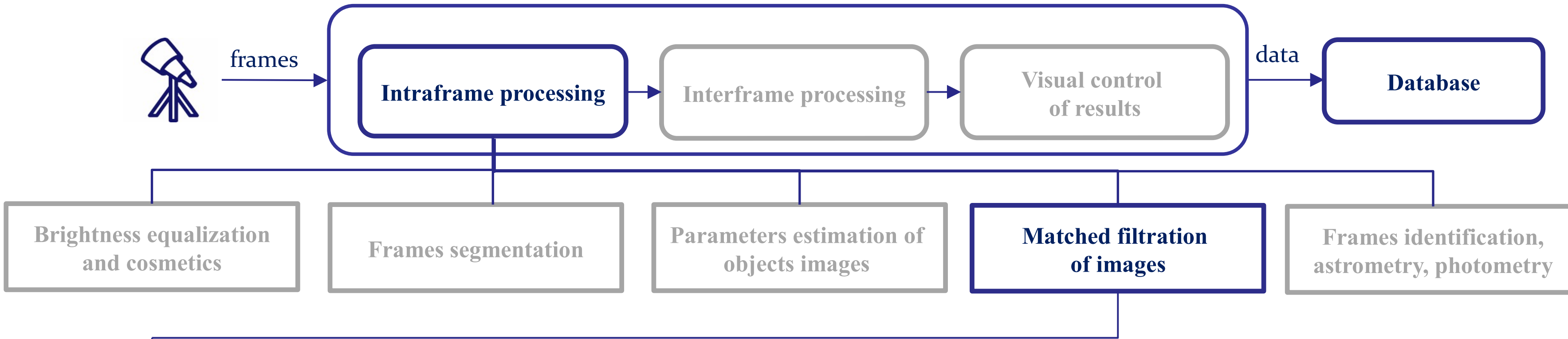
– real object's image

– model of object's image

Θ_τ^{sub} – vector of estimated parameters

$A_{ik\tau}^{*}$ – experimental brightness of pixels

$A_{ik\tau}(\Theta_\tau^{sub})$ – model brightness of pixels

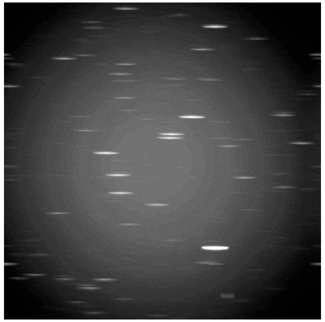


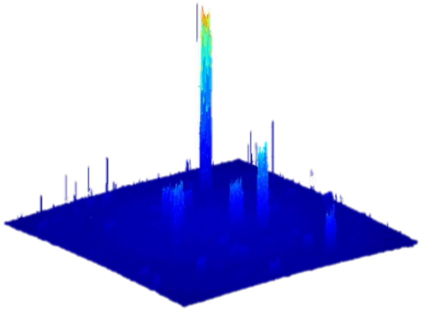
- selects images of faint stars and objects;
- reduces the number of false objects;
- matched filtration is implemented for images of objects: point (frames with diurnal rotation), stroke and with an analytically undefined profile (frames without diurnal rotation).

Matched filter for extended images of objects

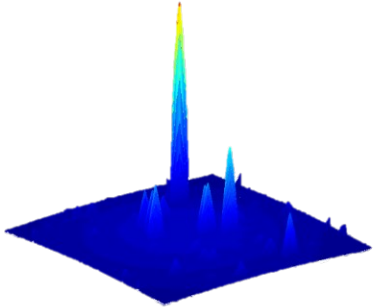
Matched filter for extended images of objects for CCD-frames taken without the diurnal tracking

Frame with extended objects





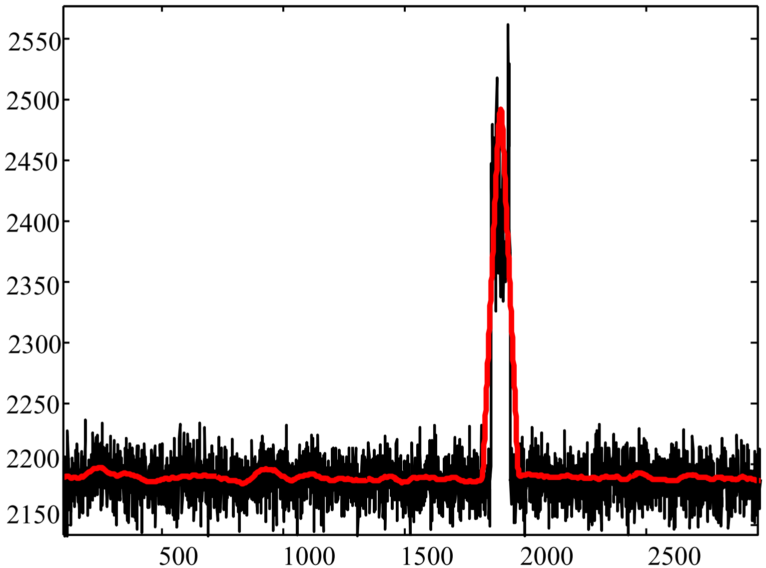
Processing result of matched filter

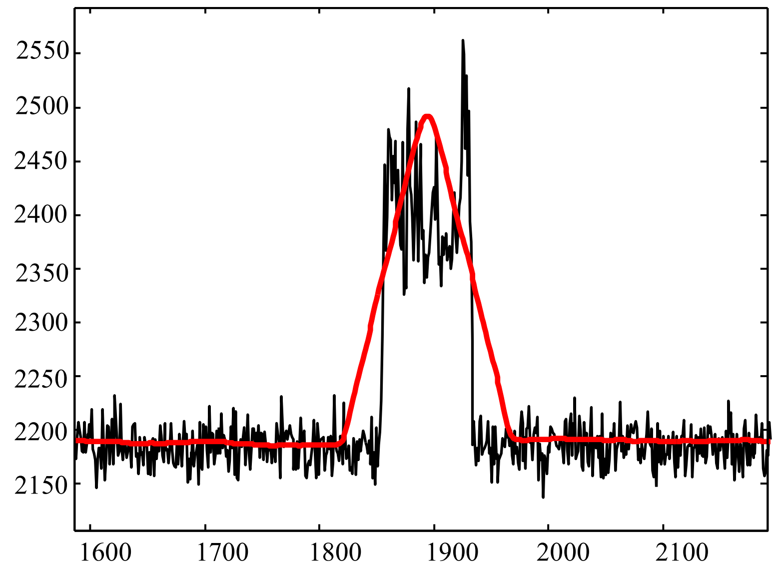


2D

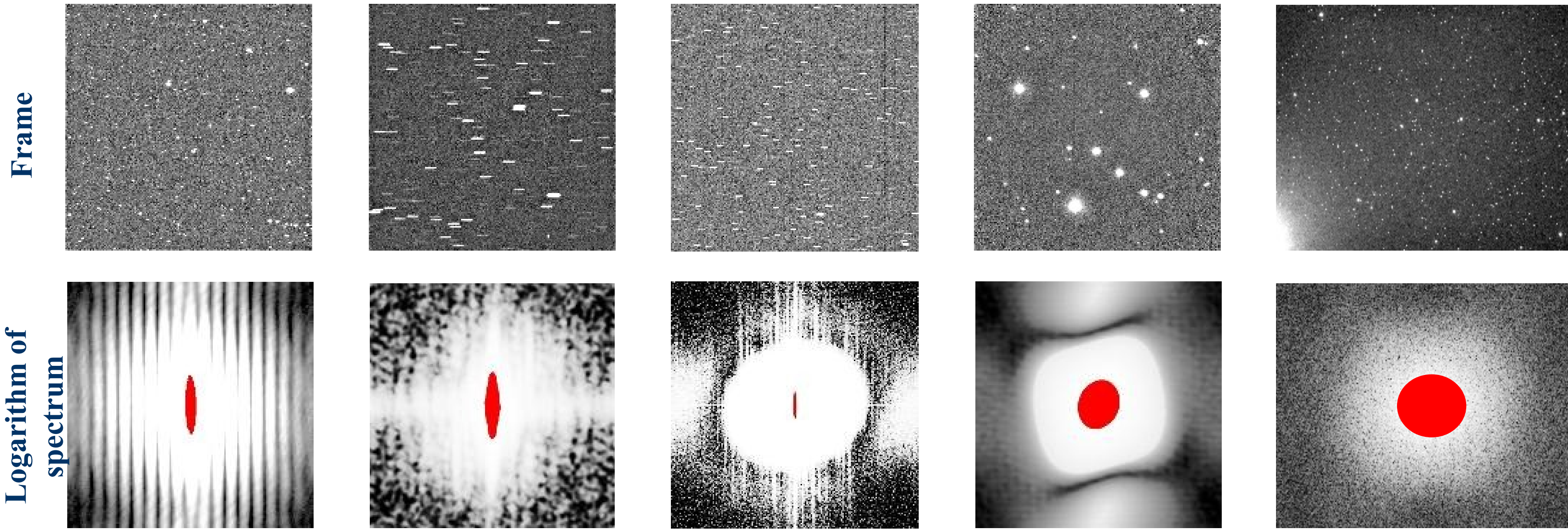
3D

Cross-section image of object before and after applying the matched filter for extended images of object





Examples of CCD-frames and their spectrums with extended images of objects



Failure in diurnal tracking

Without diurnal tracking

AES tracking

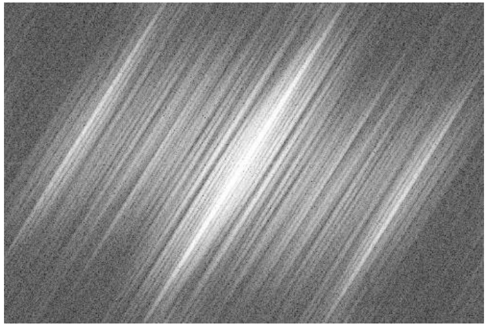
Mistake in diurnal tracking

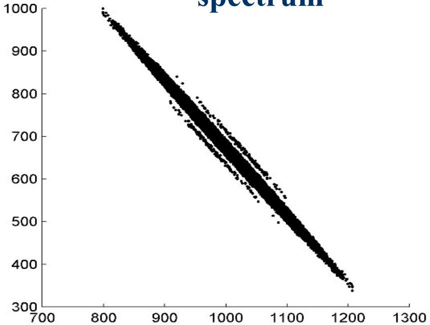
Diurnal tracking

Examples of CCD-frames and their spectrums with extended and point images of objects

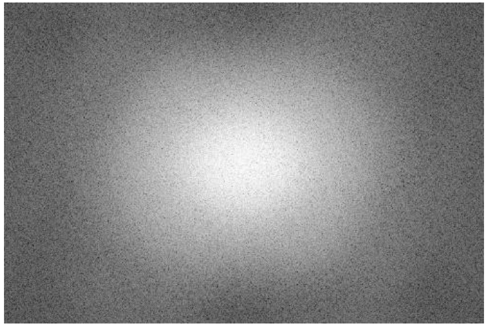
Frame | **Spectrum** | **The brightest harmonics of spectrum**

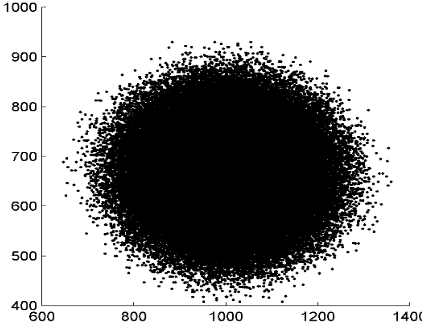
Frame with extended images of objects





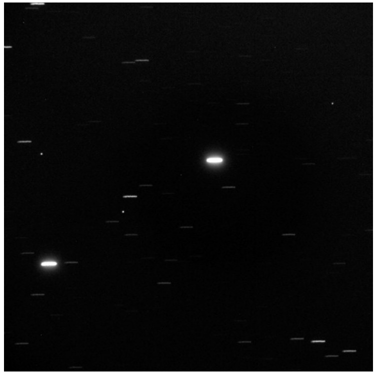
Frame with point images of objects



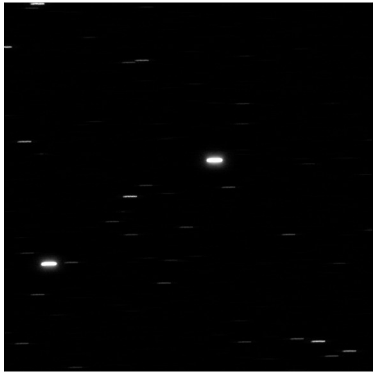


GSO frames addition with stars strokes subtraction

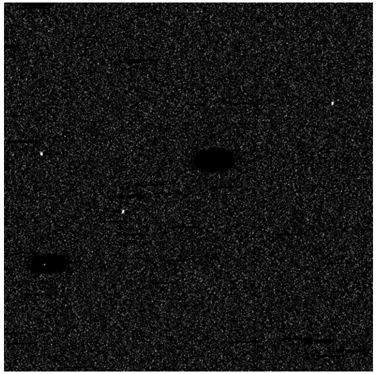
GEO 35815, 38245, 32050



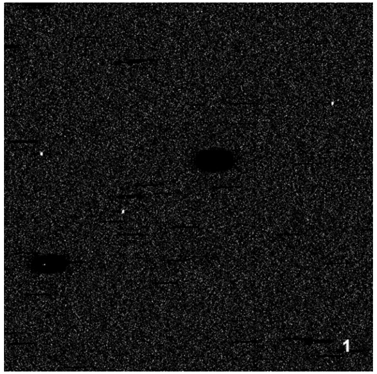
Raw frames



Frames with stars, GSO are invisible



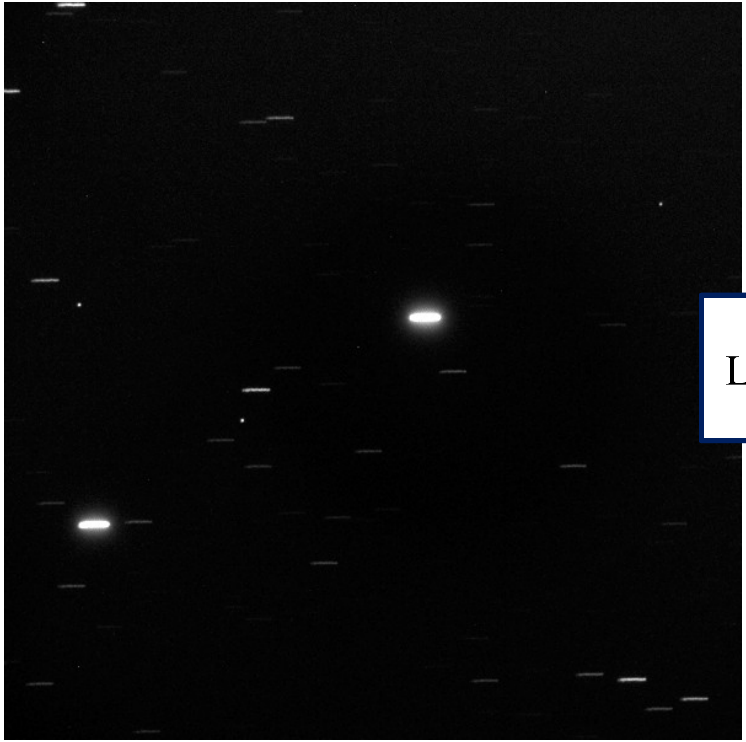
Frames with GSO without stars



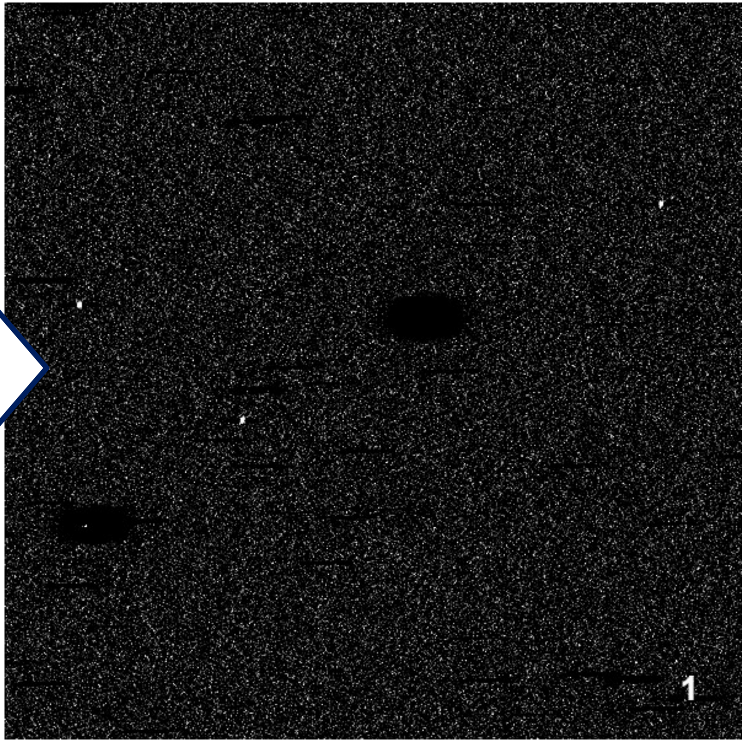
Frames addition

GSO frames addition with stars strokes subtraction

GEO 35815, 38245, 32050

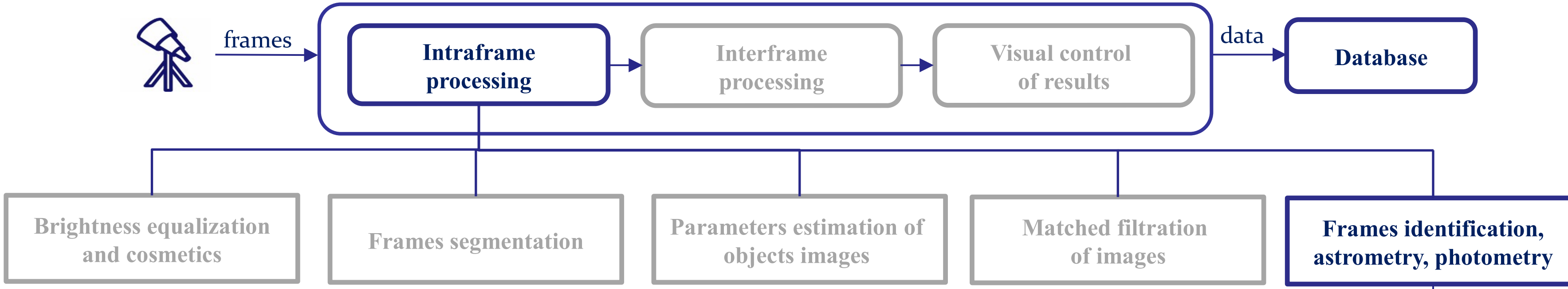


Raw frames



Frames addition

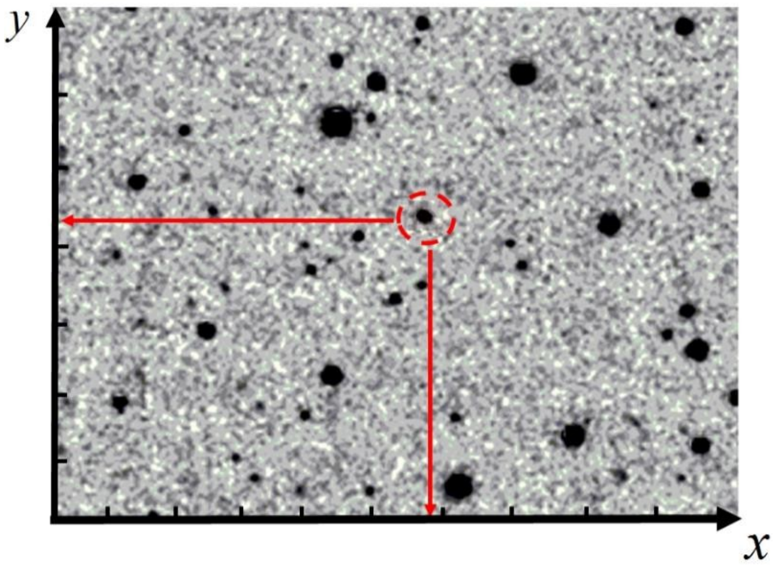
Lemur



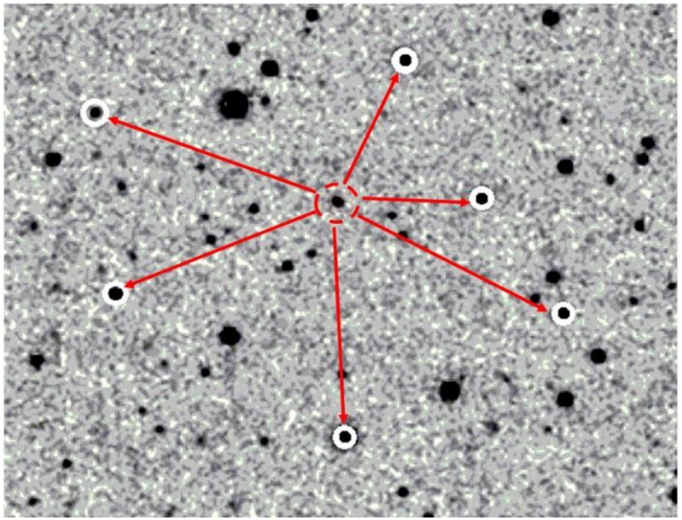
- finds the correspondence between stars images in frame and data of modern star catalogs;
- forms a catalog of objects motionless in a series of frames;
- establishes an analytical relationship between the rectangular frame coordinate system and the ICRS;
- photometry: establishes an analytical connection between instrumental brightness and brightness in the selected star catalog;
- linear, cubic and fifth degree astrometric reduction models are available;
- automatic selection of astrometric reduction model is implemented;
- robust automatic selection of reference stars is implemented.

Selection of reference stars in digital images

Determination of objects angular position in space according to data from images



a) absolute method



b) relative method

Frames identification with stellar catalogs and astrometry

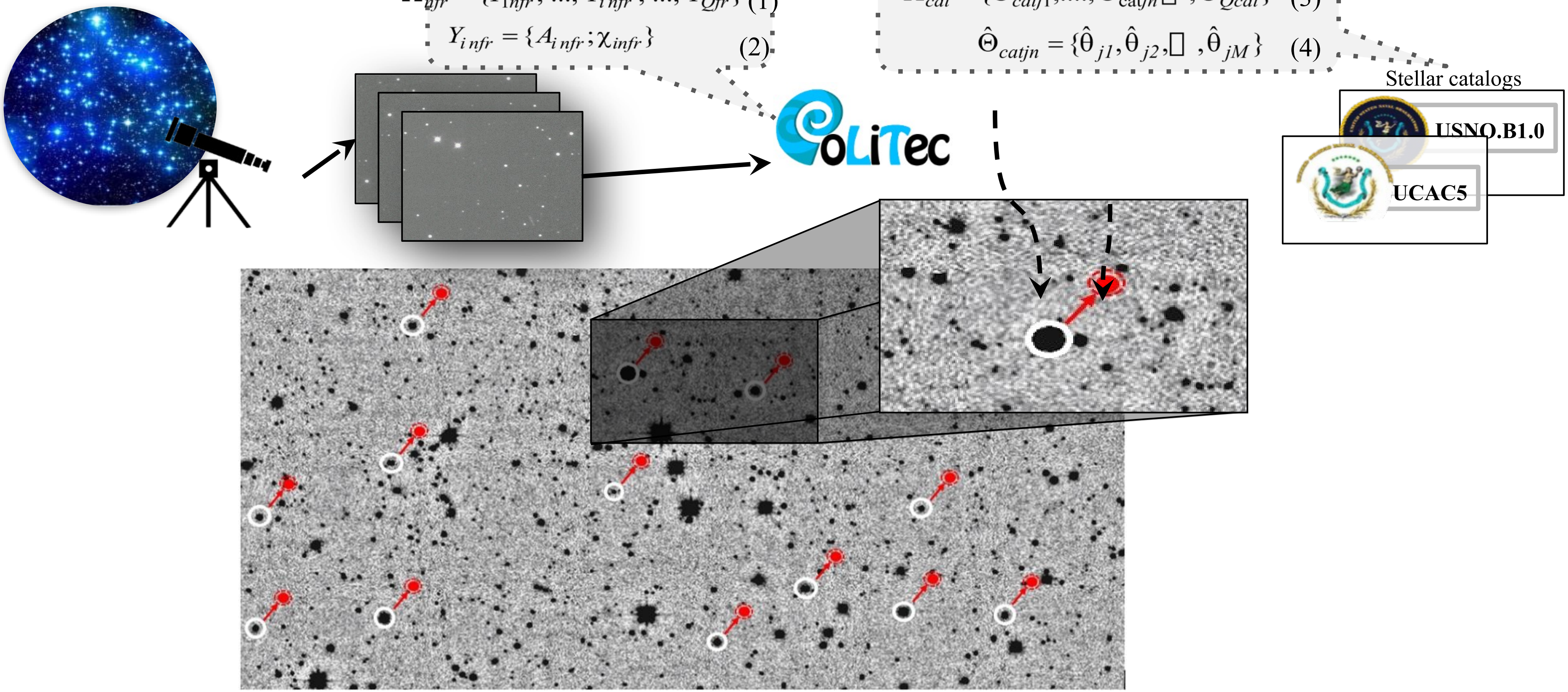
Identification of measurements in frame with measurements from stellar catalog

$$\Omega_{nfr} = \{Y_{1nfr}, \ldots, Y_{i\,nfr}, \ldots, Y_{Qfr}\} \quad (1)$$

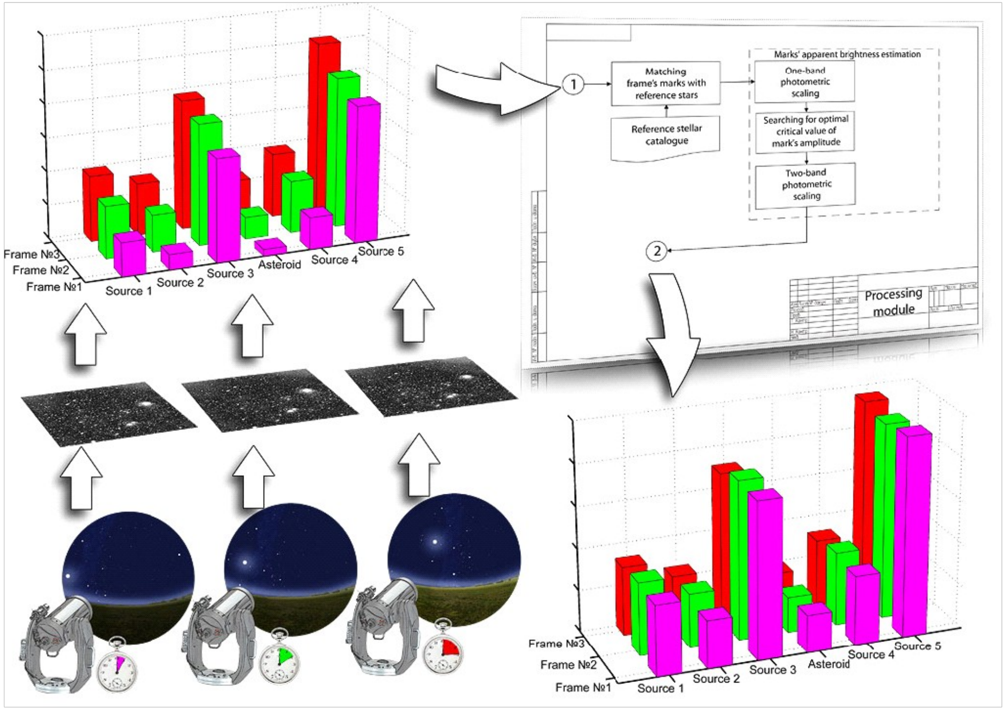
$$Y_{i\,nfr} = \{A_{i\,nfr}; \chi_{infr}\} \quad (2)$$

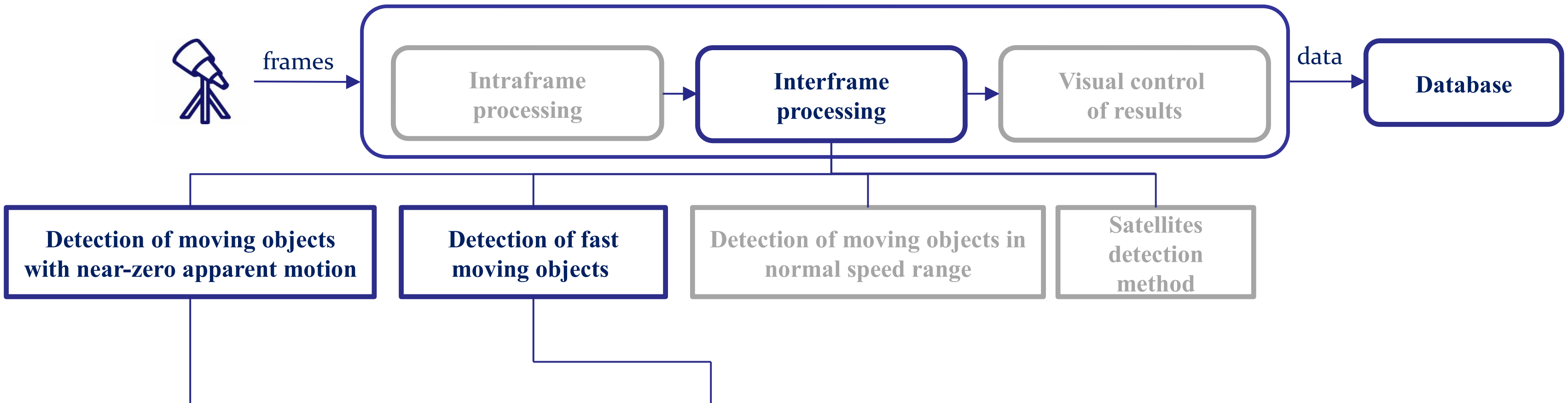
$$\Omega_{cat} = \{\hat{\Theta}_{catj1}, \ldots, \hat{\Theta}_{catjn}, \ldots, \hat{\Theta}_{Qcat}\} \quad (3)$$

$$\hat{\Theta}_{catjn} = \{\hat{\theta}_{j1}, \hat{\theta}_{j2}, \ldots, \hat{\theta}_{jM}\} \quad (4)$$



Estimation of asteroids apparent brightness by its signals amplitude



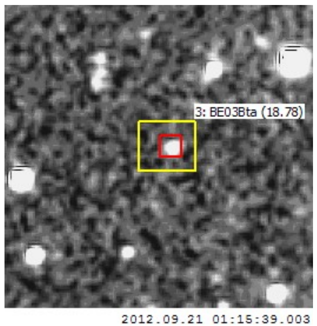


Detects objects with almost imperceptible visible movement (commensurate with errors in position estimation of objects), including objects approaching the Earth at large distances.

detects objects with images blurred by their own motion;

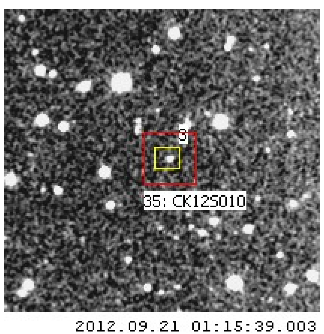
discovers NEO when they are approaching the Earth

Lemur can detect both very slow and very fast moving object



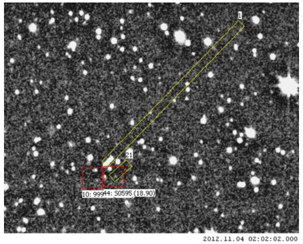
You can see the real images, where Lemur discovered famous comet ISON. On these frames comet is practically not moving between frames. The size of comet about 5 pixels, but it moved only 3 pixels from first to fourth frame.

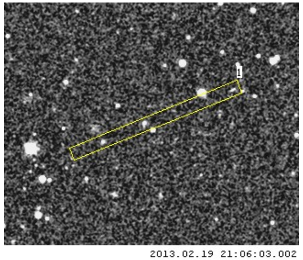
Lemur

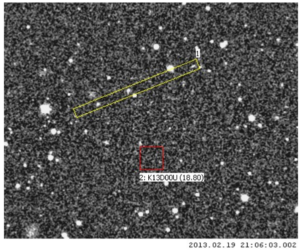


Lemur

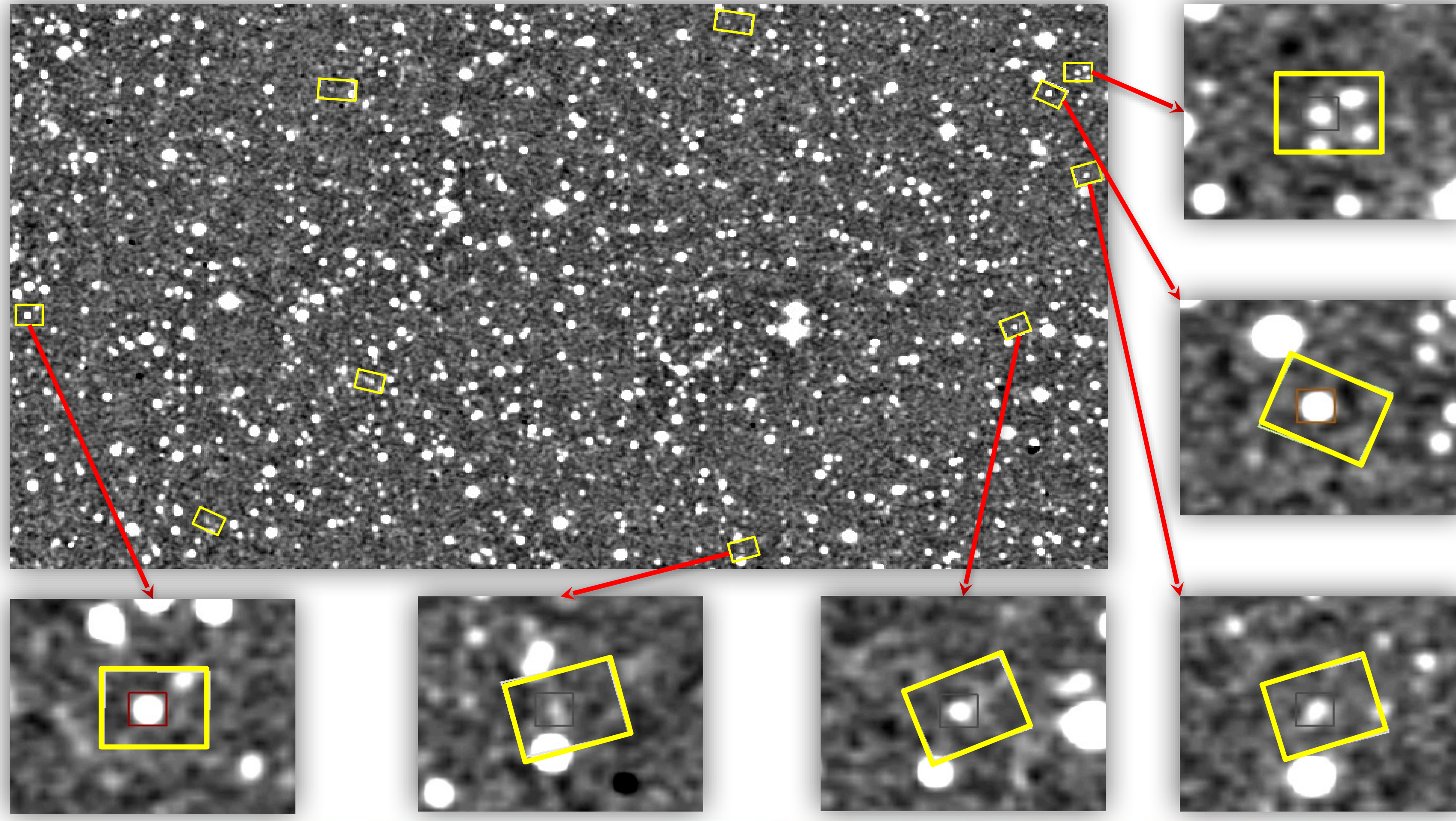
Lemur can detect faint fast moving objects (FMO) by their tracks.



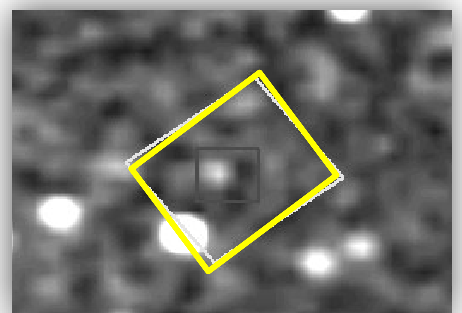




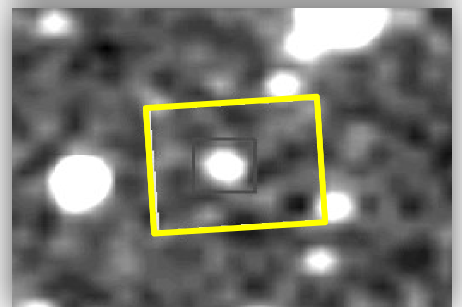
Lemur can detect both very slow and very fast moving object



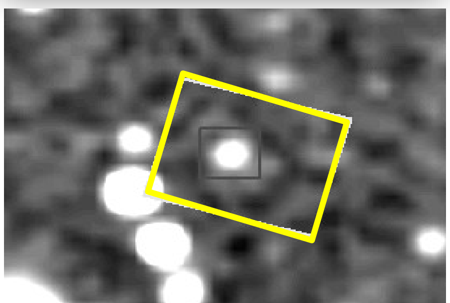
Lemur can detect both very slow and very fast moving object



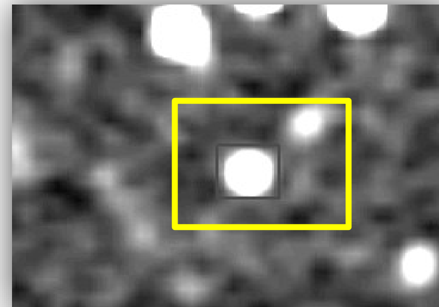
Brightness, mag	19.48
V, arcsec/min	0.282
Vra, arcsec/min	0.212
Vde, arcsec/min	0.186
V, pix/frame	0.921
Vx, pix/frame	0.705
Vy, pix/frame	0.591
S, pix/series	2.763



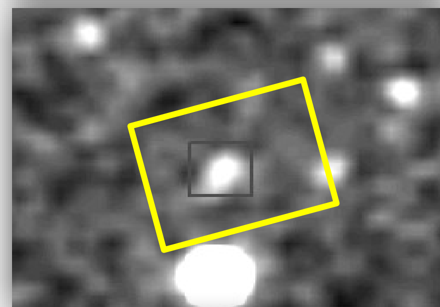
Brightness, mag	17.88
V, arcsec/min	0.360
Vra, arcsec/min	0.358
Vde, arcsec/min	0.036
V, pix/frame	1.175
Vx, pix/frame	1.171
Vy, pix/frame	0.091
S, pix/series	3.525



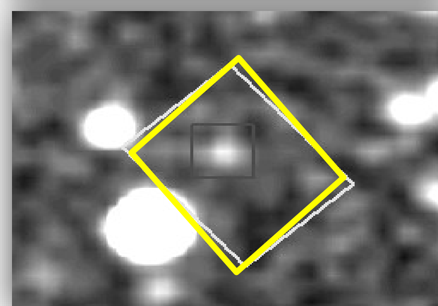
Brightness, mag	18.85
V, arcsec/min	0.400
Vra, arcsec/min	0.318
Vde, arcsec/min	0.241
V, pix/frame	1.305
Vx, pix/frame	1.056
Vy, pix/frame	0.766
S, pix/series	3.915



Brightness, mag	17.45
V, arcsec/min	0.451
Vra, arcsec/min	0.441
Vde, arcsec/min	0.094
V, pix/frame	1.467
Vx, pix/frame	1.441
Vy, pix/frame	0.274
S, pix/series	4.401



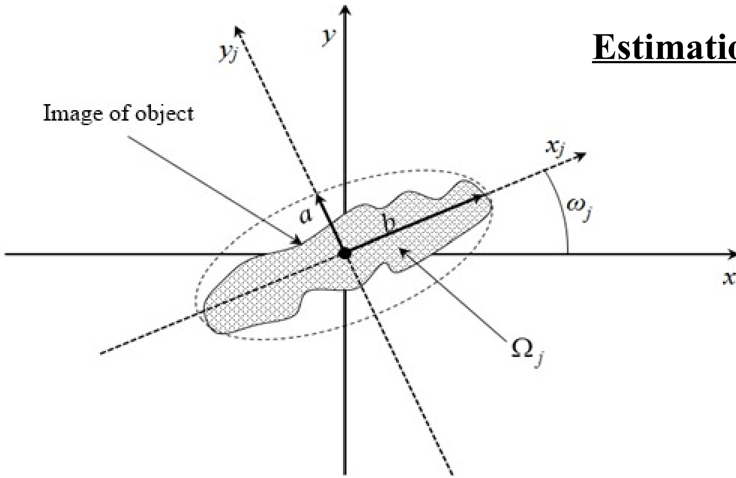
Brightness, mag	19.11
V, arcsec/min	0.515
Vra, arcsec/min	0.494
Vde, arcsec/min	0.144
V, pix/frame	1.683
Vx, pix/frame	1.626
Vy, pix/frame	0.433
S, pix/series	5.049



Brightness, mag	19.64
V, arcsec/min	0.638
Vra, arcsec/min	0.434
Vde, arcsec/min	0.468
V, pix/frame	2.084
Vx, pix/frame	1.378
Vy, pix/frame	1.564
S, pix/series	6.252

Method for detection of extended images of objects

Selective signs of extended images of objects during intraframe processing



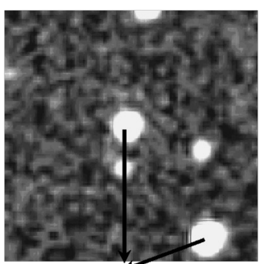
Estimation of elongation and orientation of object's image

Eccentricity estimation:

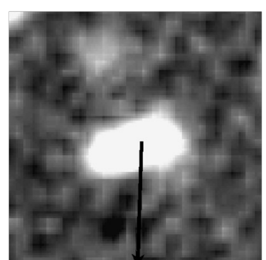
$$\varepsilon_j = \frac{m_{20} + m_{02} - \sqrt{\left(m_{20} - m_{02} + 4m_{11}^2\right)}}{m_{20} + m_{02} + \sqrt{\left(m_{20} - m_{02} + 4m_{11}^2\right)}}$$

Inclination angle of object:

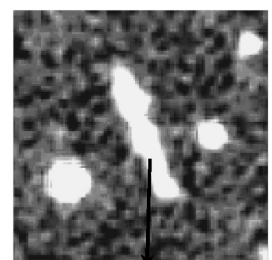
$$\omega_j = \frac{1}{2}\arctan\frac{2m_{11}}{m_{20} - m_{02}}$$



$\varepsilon = 0.0$



$\varepsilon = 0.8$

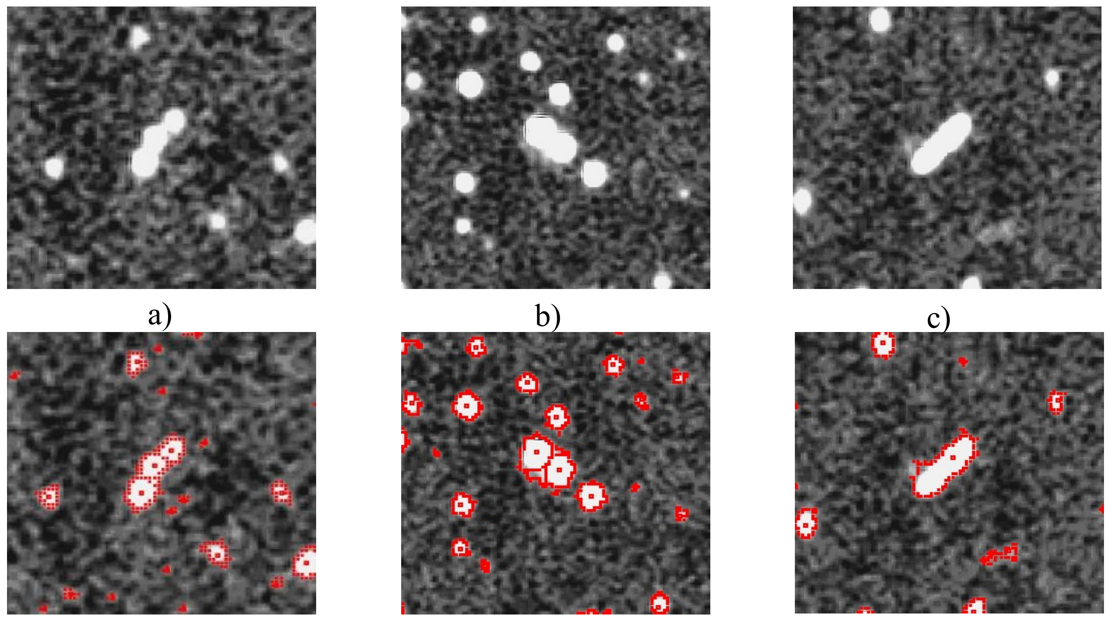


$\varepsilon = 1.0$

Examples of objects images (from point to long)

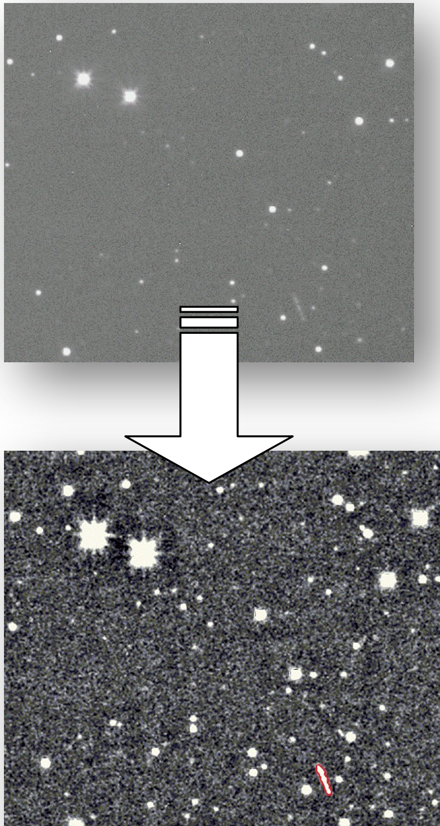
Method for detection of extended images of objects

Checking the belongings of extended images to objects from internal catalog with appropriate rejection (rejection of images of close stars)



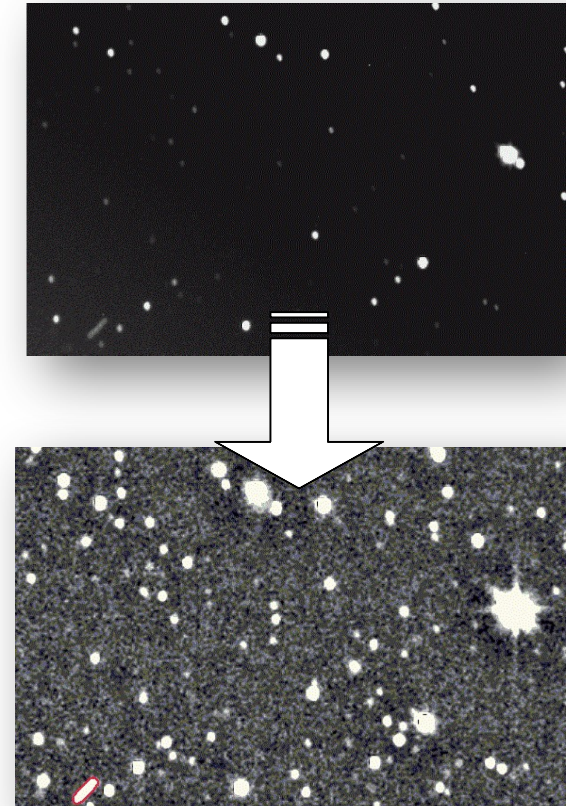
Extended images of objects

Working examples of proposed method for detection of extended images of objects



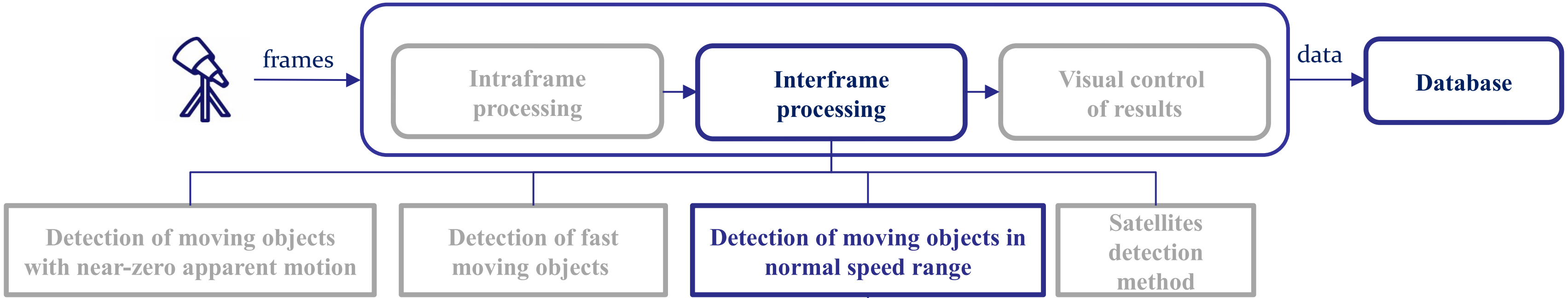
Characteristics of object 1:

frame	X_1	Y_1	ε_1	ω_1
1	2557	284	0.9	135.0
2	2637	200	0.9	130.6
3	2707	127	0.9	137.9
4	2779	53	0.9	131.7



Characteristics of object 2:

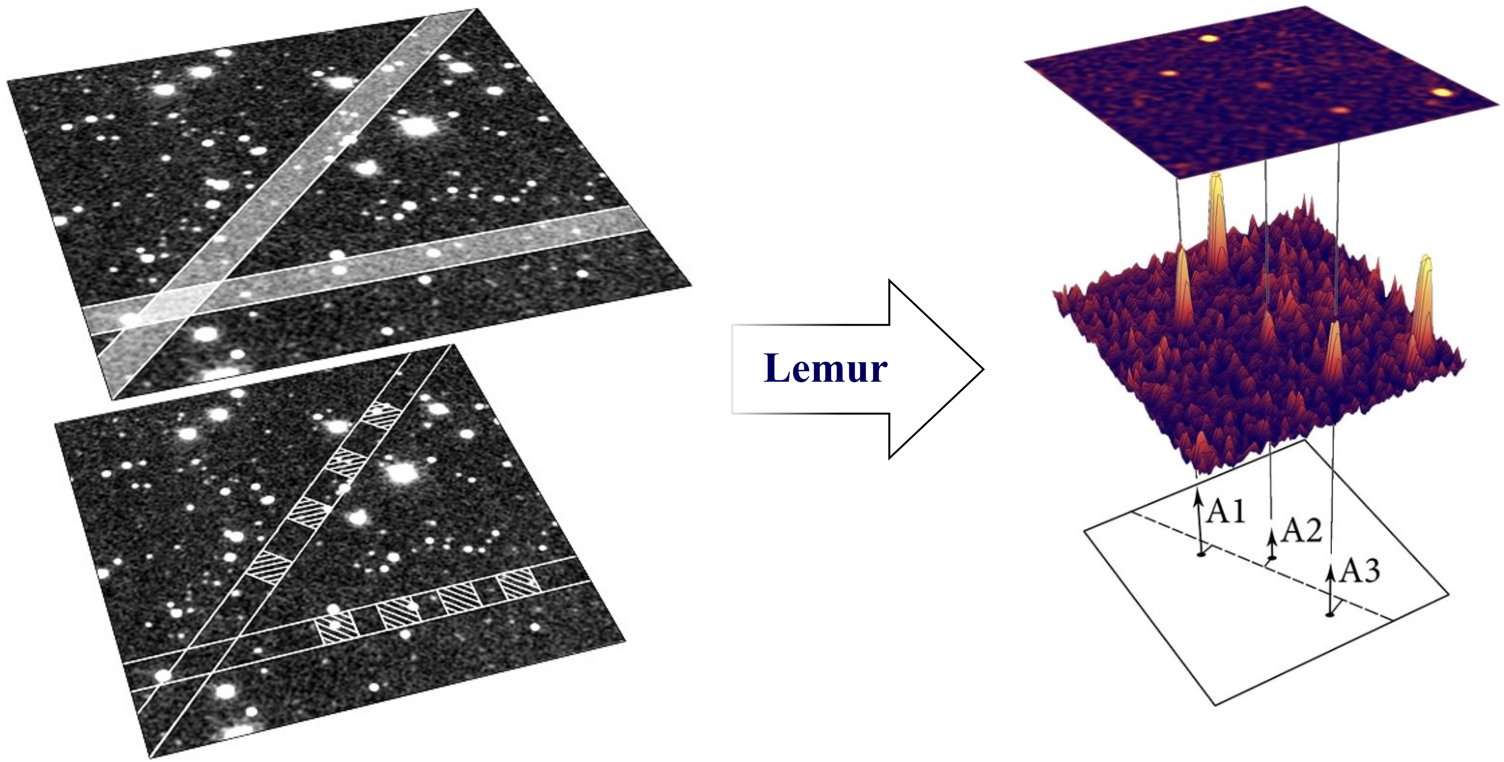
frame	X_2	Y_2	ε_2	ω_2
1	1575	1655	1.0	120.7
2	1539	1559	1.0	111.0
3	1503	1465	1.0	116.6
4	1467	1366	1.0	114.2

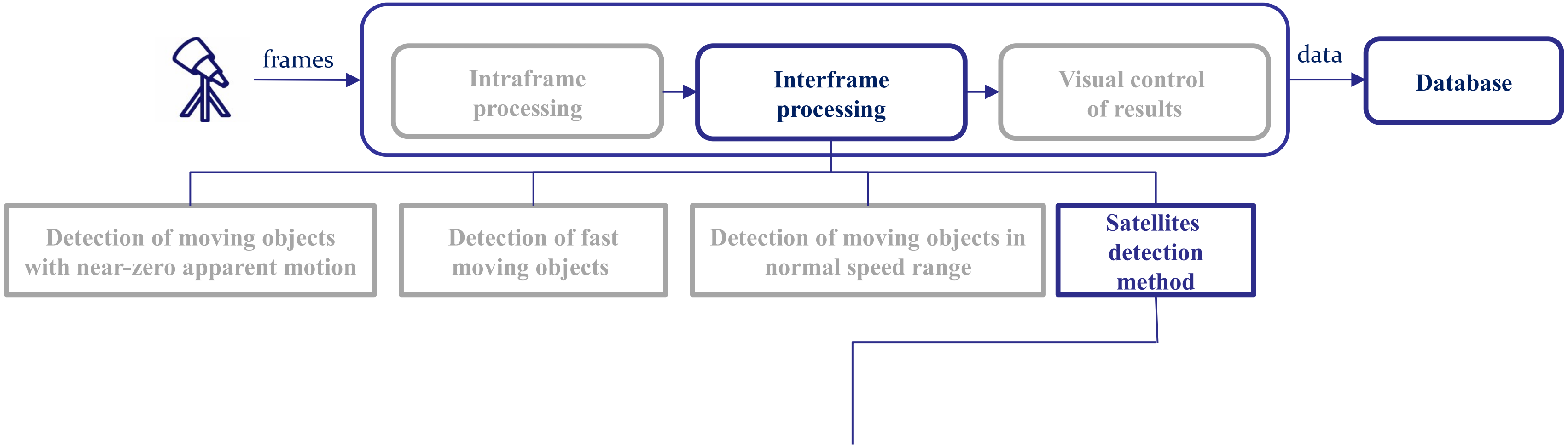


- detects and discovers comets, asteroids and satellites in automated mode;
- uses the method of light collecting, which allows energy accumulation of the objects images along trajectories with unknown parameters, which provides high quality detection in telescopes with small aperture;
- works at low thresholds and allows to see very faint and hardly observable objects, for observation of which by traditional methods it is necessary to increase the observing potential in several times;
- software has a linear complexity with the measurements number per frame, which allows working at low thresholds and detecting a motion against the background of 5000 false measurements and 20,000 stars.

Detection of slow and fast moving objects

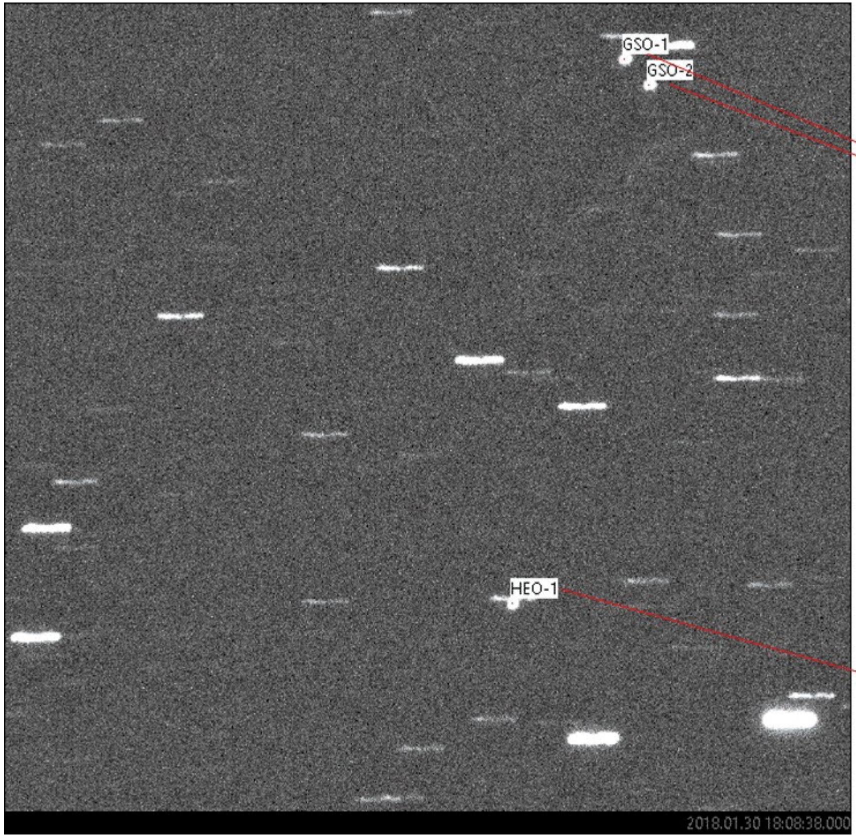
Algorithm for moving object detection

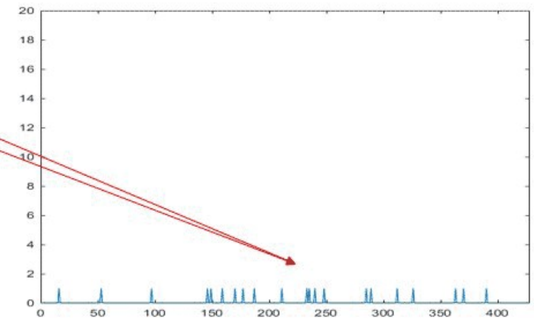


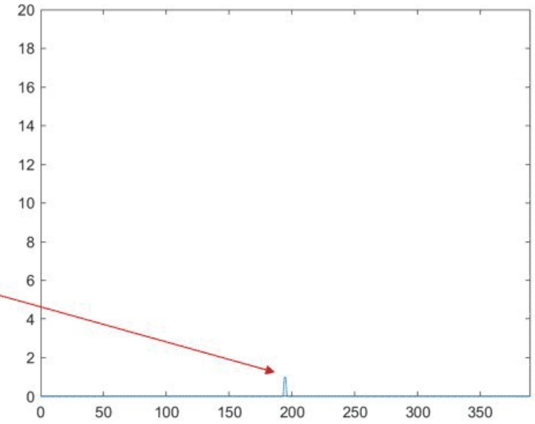


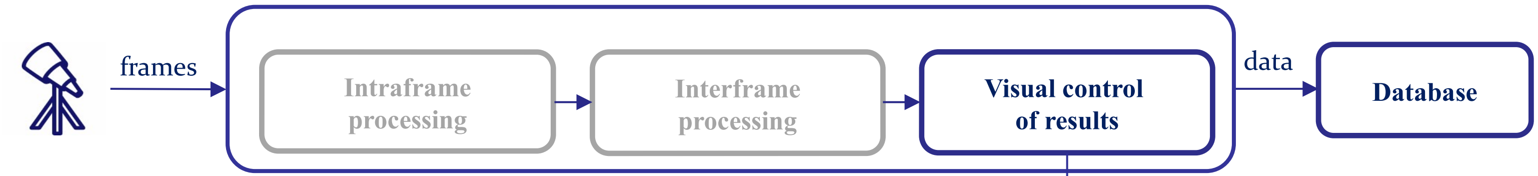
Detects satellites with geostationary orbit or high-elliptical orbit on frames with stars background like as strokes made by fixed mounting telescope. Detects satellites with low (LEO) and medium (MEO) Earth orbit.

GSO-Hough detection method



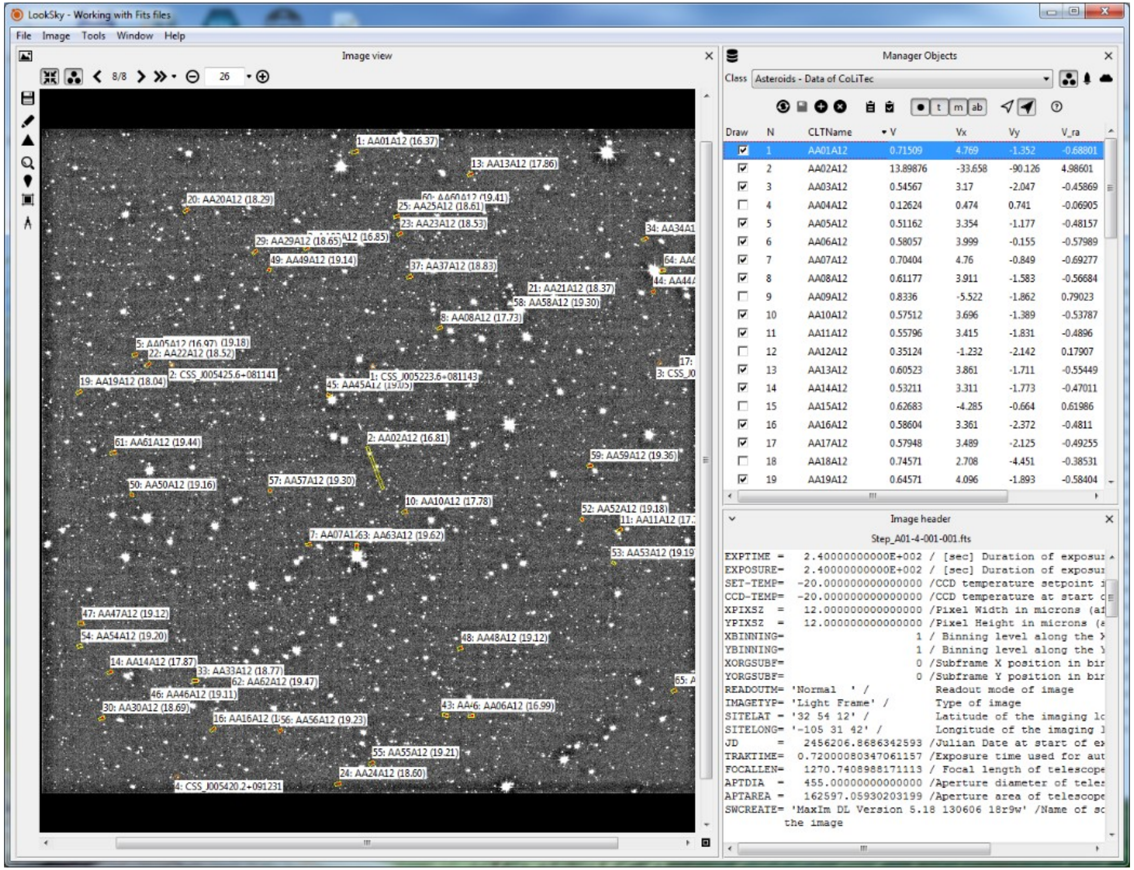


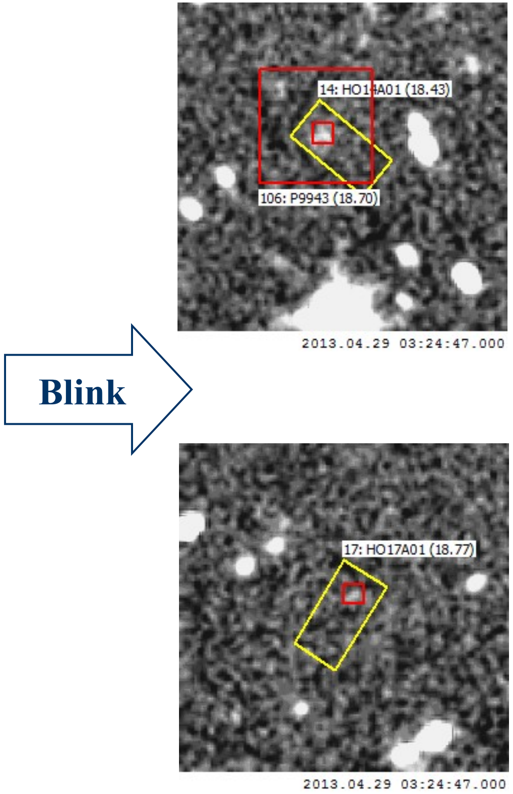




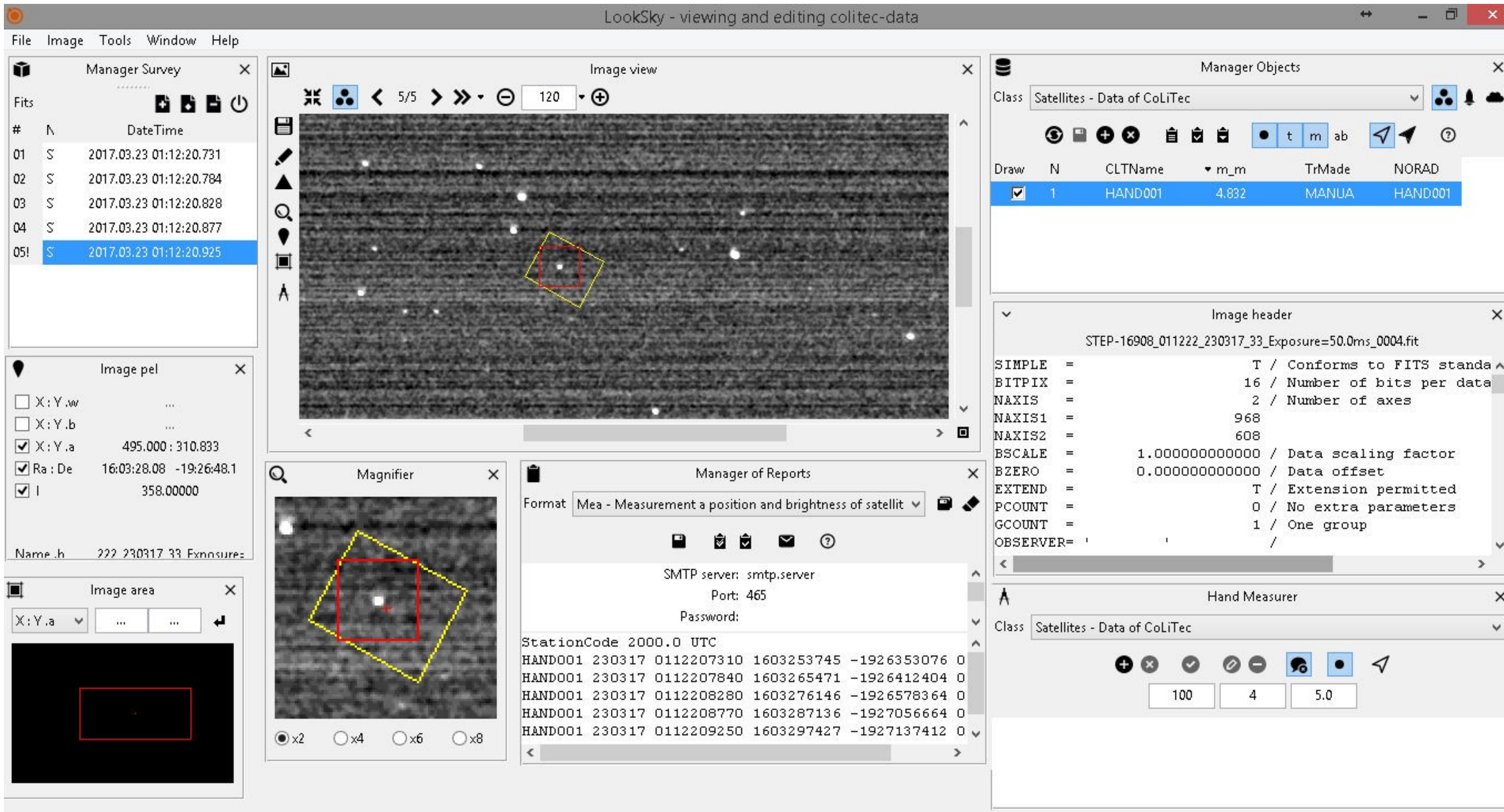
- visualization of a series of frames and detected satellites, comets, asteroids;
- automated satellite measuring in a series of frames: it suffices to mark the satellite in two frames, after which its measurements will be done automatically in the remaining frames with ability to control;
- analysis of satellite measurements in a series of frames: visualization of deviations and measurements censoring;
- reports generation with measurements of asteroids and satellites in the international formats;
- initial determination and clarification of satellite orbit elements;
- on-line loading and identification of detected asteroids and comets from MPC data allows to quickly make a decision about the possible presence of new asteroids and comets in series of frames.

LookSky –visual inspection of asteroids detected

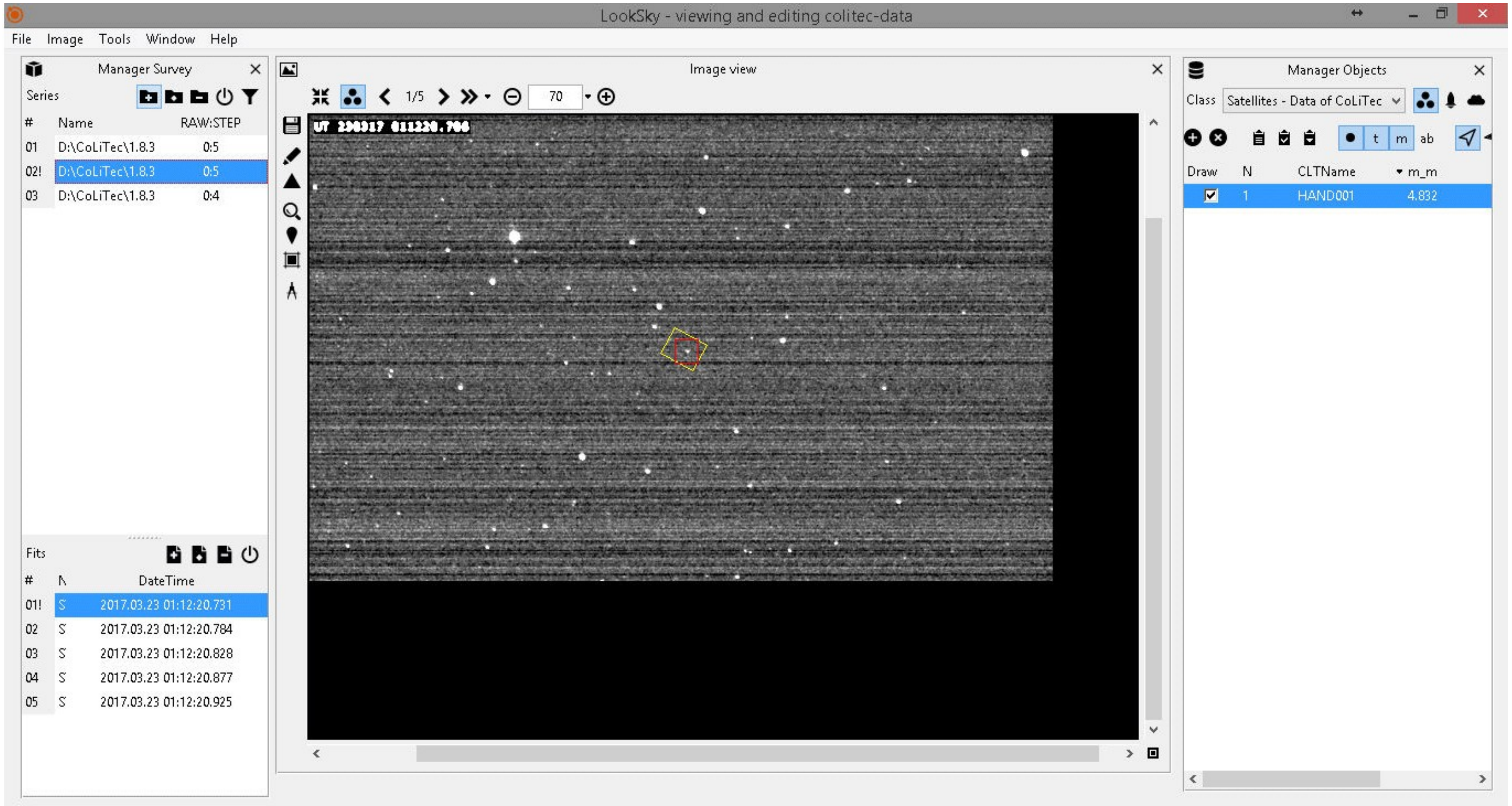




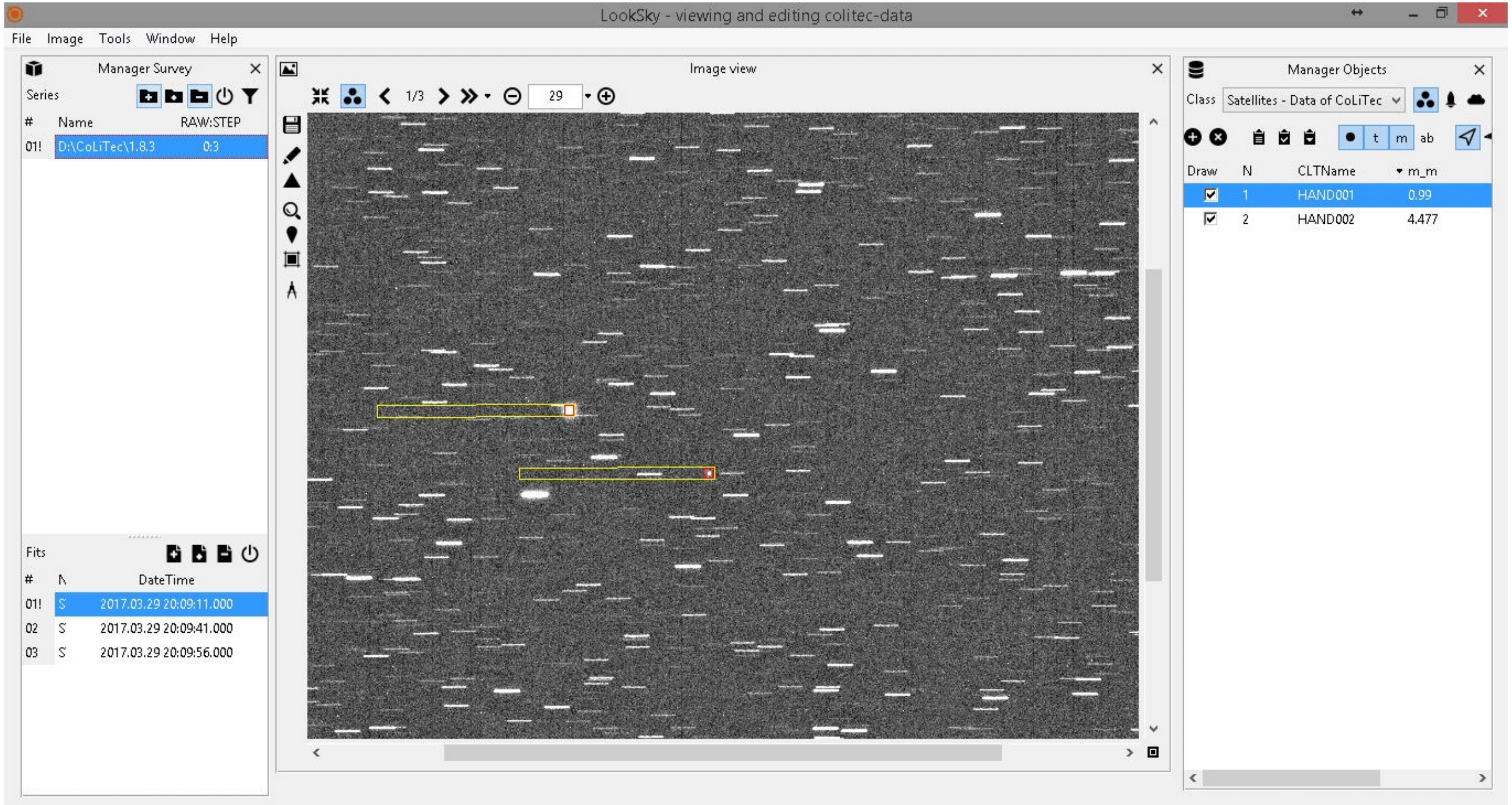
LookSky –visual inspection of satellites detected



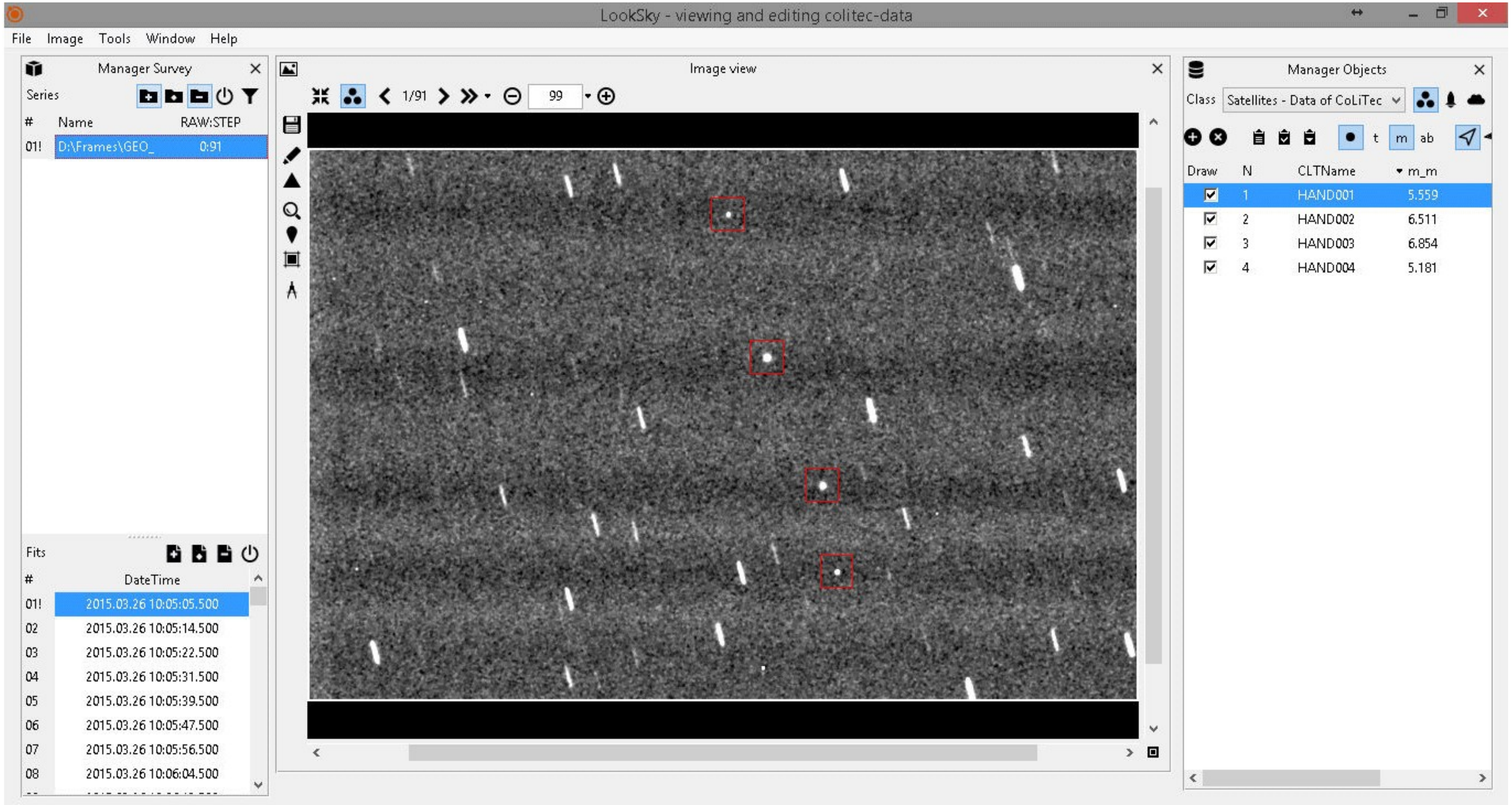
Displaying and navigation of astronomical frames with satellites



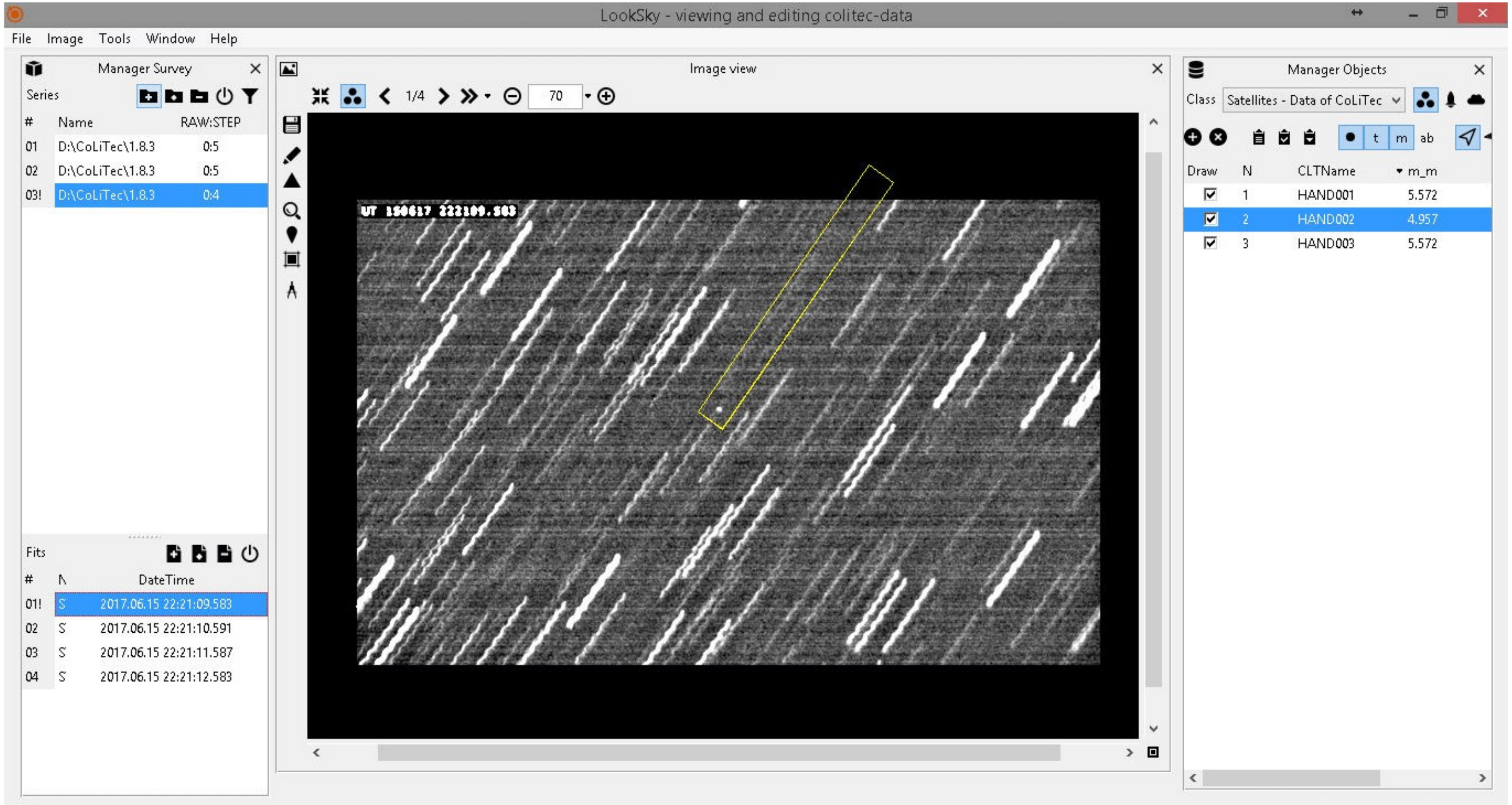
Displaying and navigation of astronomical frames with satellites



Displaying and navigation of astronomical frames with satellites



Displaying and navigation of astronomical frames with satellites



Our immediate goals:

Online and mass photometry.

Implement the TLE service - it will allow the observer to see the data from the NORAD catalog on the processed frames.

To implement the stacking of the frames in the given range of speeds in order to automatically find the super-weak objects of the solar system.

Improving segmentation, fitting, astrometry, and more...

Thank you!

We are ready for the collaboration!

Savanevych Vadym

[Scopus]

[NASA ADS]

Briukhovetskyi Olexander

[Scopus]

[NASA ADS]

Dikov Yevhen

[Scopus]

[NASA ADS]

Dmytrenko Artem

[Scopus]

[NASA ADS]

Khlamov Sergii

[Scopus]

[NASA ADS]