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VIRTUAL OBSERVATORY AND COLITEC SOFTWARE: MODULES, FEATURES, METHODS

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ABSTRACT. In this article we described complex processing system created by the CoLiTec project. This system includes features, user-friendly tools for processing control, results reviewing, integration with online catalogs and a lot of different computational modules that are based on the developed methods. Some of them are described in the article.

The main directions of the CoLiTec software development are the Virtual Observatory, software for automated asteroids and comets detection and software for brightness equalization.

The CoLiTec software is widely used in a number of observatories in the CIS. It has been used in about 700 000 observations, during which 1560 asteroids, including 5 NEO, 21 Trojan asteroids of Jupiter, 1 Centaur and four comets were discovered.

Keywords: Techniques: image processing, photometric – Astrometry – Methods: analytical, data analysis, numerical, statistical – Minor planets, asteroids – Comets: general – Stars: variables: other

1. Introduction

International efforts for collecting of the astronomical data sources led to creation of international alliance of national observatories (IVOA). It coordinates activities of standardization description, search, access and data publishing.

Alliance includes all virtual observatory projects, each of which solves its own scientific and technological problem. The main purpose of this organization became bringing together astronomical observation results of ground and space instruments, providing astronomers with powerful and easy-to-use instruments for accessing collected data.

The IVOA main purpose is to union national observatories in the international virtual observatory; to develop sets of standards and technologies; to combine archives of ground and space instruments that will provide researches a comfortable way to access them, as well as providing astronomers with powerful mechanisms for investigation of observational data.

Currently, there are twenty national and international projects of the Virtual Observatory (VO) in the world. Each of them share experience with another projects and develop common standards for working with astronomical data. For example, US VO is focused on providing new research opportunities in astronomy to the community. As part of the community Spanish VO is focused on NEO detection. The main scientific area of Australian VO is creation of a theoretical astrophysical observatory for the galaxies simulation.

The International Virtual Observatory integrates enormous amount of data that contain various spectral ranges carrying unique information about celestial objects, which gives possibilities of their use in specific scientific applications, such as CoLiTec software (Savanevych et al., 2012).

The general tools for accessing information in IVOA are applications and services such as Astrogrid, Aladin, Topcat, SkyView. These tools allow users to work with surveys, catalogs and archives. Access to them is provided according to IVOA standards.

2. Virtual observatory

CoLiTec project develops the Virtual Observatory taking a part in the international astronomer community (Vavilova et al., 2012).

The first step was creating software for storing and publication of CCD-frames. It allows user to archive and search frames by specified parameters and may be accessed via Aladin.

The next step was creation of automatic frames loader in collaboration with Vihorlatsky observatory.

Frames uploaded through the web-interface are moderated and then processed with the On-Line Data Analysis System (OLDAS), as a part of the CoLiTec software. Processed frames are stored in the database from which they are published through SIAP protocol.

Processing sequence of Virtual Observatory server contains full stack of processing operations, that provided by the CoLiTec software (Savanevych et al., 2012).

At the first time CoLiTec project presented the national project of Ukrainian Virtual Observatory (UrkVO) as a part of the international astronomer community (Vavilova et al., 2012).

CoLiTec project created the software for storing and publication of CCD-frames that allows to archive and search frames by specified parameters (coordinates). External access to the storage is provided of its own web-interface and can be accessed through Aladin. Software was implemented with using of VO technologies, including SIAP access protocol. It allows receiving the additional frames from external resources such as the SDSS and 2MASS.

Also CoLiTec project created the universal system for storing light curves of variable stars, together with a series of frames on which they were received - Vihorlatsky Virtual Observatory (ViVO). The system has the frames lifecycle which consists of the following steps:

• Collection step, that includes taking image of the sky area and its transformation to the fit format;

• Analyzing step contains moderation and preprocessing;

• Accumulation step allows to store collected data;

• Publication step provides access to already stored data.

At data collection step astronomer with a telescope and specified software takes images of the interesting sky areas and transform it to fit format.

Then user loads raw frames to the server via the web-interface. These raw frames will be moderated before its processing. At this stage faulty and unsupported frames are rejected. OLDAS system processes frames as soon as they successfully uploaded on the server. This technique allows to greatly speed up processing and provides user immediate notification of emerging issues. Processed data will be stored in the database and publishing via SIAP protocol.

The web-interface is the primary tool for frames uploading and management. It allows user to determine frames affiliation to the series and telescopes. Also you can view and edit the already uploaded series. Frames processing management allows user to select processing type (asteroids detection, frames background alignment, publishing). You can also start and stop processing, enable or disable notifications messaging.

The frame storage consists of two parts:

1. The first part is storage of fits metadata. It is the information obtained from fit header and it also includes fit path in file system.

Currently fits metadata keeps next information from fit header, such as right ascension, declination of the image center, exposure time, telescope parameters, with which the frame was received (latude, longitude, aperture), information about observer. Storage of fits metadata is implemented using PostgreSql database.

2. The second part is storage of fits files that are stored as separate files in specified order. This avoids overhead connected with deployment and supporting of specialized storage facilities, such as file databases.

Data search inside the fit files is not expected, therefore selected storage method allows the conveniently control data placement on a different media with data compression.

Fits coverage from the storage can be represented on a celestial sphere, which is covered with a grid divided by segments. Also it contains main points of the poles, equator, current axis of rotation. Each point corresponds to one or more frames in this part of the sky.

According to IVOA recommendations for photometric data storing the software for frames storing extends with light curves and cross-references. This one allows receiving all relevant information such as required frames, light curves or photometric measurements (brightness).

ViVO provides flexibility and ability to convert values from IVOA existing formats of photometric data representing. This solution is based on the subject mediator that solves all IVOA requirements.

The subject mediator consists of the following elements: initial data format that will be converted (data from the storage); a set of conversion rules (for example, right ascension conversion from degrees to angular seconds); target formats with already specified structure, for example VSX, Vizier.

The developed system involves the ability to automatically publish loaded light curves in the catalogs of variable stars. In the absence of technical capability to send information to the directory (for example, publication to the magazine), the system will prepare the most complete data for publishing that will reduce time costs for user.

Publishing of results is performed in several formats:

• IVOA SOAP standard for photometric data;

• Vizier catalog, that provides access to data from Aladin software;

• The most widely known catalogs of variable stars such as IBVS, JAAVS, VSX.

ViVO web-interface represents light curves as a graph of brightness measurements variation. It is plotted by measurements from storage, data from different catalogs and telescopes. Detailed information about the appropriate magnitude and dimension of this frame is displayed after clicking on a point of the graph that represents the specific measurement.

3. CoLiTec software

Software for automated frames processing of asteroid surveys given as series of frames is necessary for the most effective astronomical observations.

This possibility is provided by the CoLiTec software allows not only to detect asteroids, but also to perform astrometric and photometric measurements in real time with the visual confirmation of processing results, http://www.neoastrosoft.com (Savanevych et al., 2012).

Full reliability of the detection of moving objects is retained up to the lower limit of SNR equal to 3 units in case of a minimum series consisting of four frames, with no stars covering of asteroid (Savanevych et al., 2015).

Detection of moving objects on the series of CCD-frames is performed in two stages.

Intraframe processing is designed to estimate the objects position at fixed times. Also cosmetic processing, frame alignment and brightness equalization are performed in this stage.

Interframe processing is used to detect and estimate objects trajectories. The core of CoLiTec software consists of preliminary objects detection based on accumulation of statistics that proportional to the signals energy along possible object motion paths. Such accumulation is performed by multivalued transformation of the objects coordinates that equivalent to the Hough space-time transformation (Savanevych et al., 2012) (see Figure 1).

CoLiTec software has the following features:

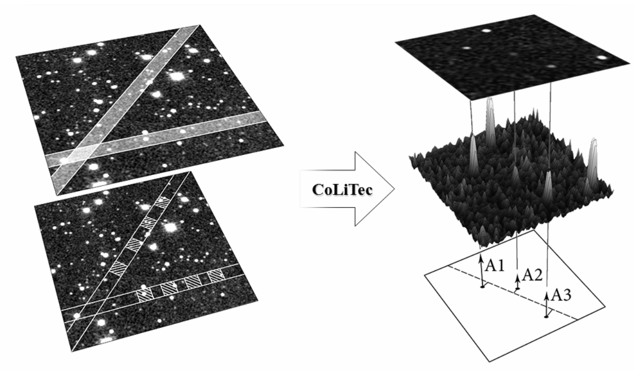

Figure 1: Algorithm for moving object detection

• Automatic detection of faint moving objects (SNR>2.5);

• Working with very wide field of view (up to 10 degrees²);

• FrameSmooth software for brightness equalization;

• Auto calibration and cosmetic correction;

• Fully automatic robust algorithm of astrometric reduction;

• Automatic rejection of the worst observations;

• Detection of very slow and very fast objects (from 0.7 to 40.0 pix./frame);

• LookSky – processing results viewer with user-friendly GUI;

• Multi-threaded support for multi-cores systems and local network;

• Processing pipeline managed by OLDAS (On-line Data Analysis System);

• CoLiTec Control Center (3C) with processing monitoring and logging.

These features allow effective using of CoLiTec software at the different observatories in the world.

The OLDAS mode is especially significant. It allows for near real-time data processing and assigns confirmation of the most interesting objects at the night of their preliminary discovery.

CoLiTec software equipped with the modern viewer of obtained results with a user-friendly GUI. LookSky runs independently of the main program and it can be used for independent review of CoLiTec processing results while the main program is processing data (see Figure 2).

Complex frame reduction was added in the last version of LookSky. This complex processing includes the following features:

• Frame processing by filter, background equalization;

• Coordinates reduction;

• Track and Stack;

• Search of objects by queries to the world Databases, such as Minor Planet Center, Variable Star Index, HyperLeda;

• Hand measuring.

A mobile version of the viewer is available. CoLiTec processing results can be monitored from anywhere in the world. It only requires any modern smartphones, a tablet or laptops running on any OS platform. After connection to our web-interface, you can perform different operations, for example, send a report to Minor Planet Center (MPC), including quick report to NEOCP.

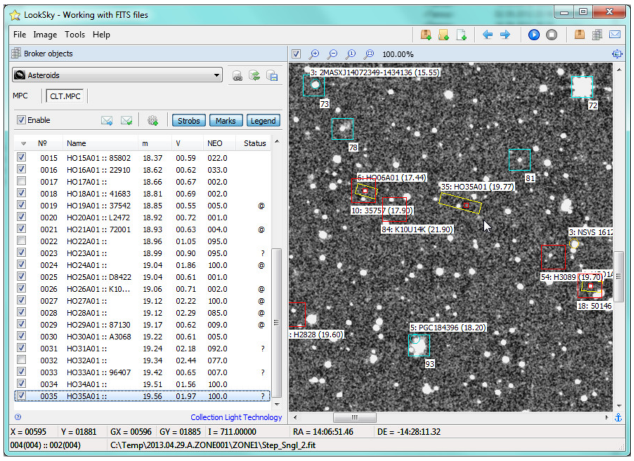

Figure 2: LookSky – processing results viewer with user-friendly GUI

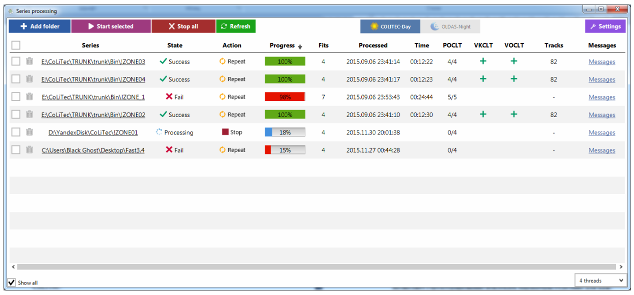

Figure 3: CoLiTec Control Center (3C) – system for managing the processing pipeline with user-friendly GUI

New principles and cross-platform technologies were applied to CoLiTec software. Some approaches for the quality control of performed process were refactored.

Java FX as cross-platform technology was used in GUI creation of basic modules. These modules are CoLiTec Control Center (see Figure 3), configuration editor ThresHolds and processing pipeline.

Some of the approaches for the quality control of performed process:

• Ordered storage of all required processing parameters allows extracting all necessary parameters for each module. Currently XML technology is used. These approaches are not only used in the configuration editor, but also at the each processing stage, as internal verification of the main processing bus.

• Multithreading, the ability to manage individual treatment processes. Tracking system of all running modules during processing was implemented. This system allows correct tracking, managing and terminating processes at any stage without data loss.

• System for deciding of the processing results allows to adapt the user settings and inform user about correct results at the each stage of processing.

Enhanced control of input and output data is held at the each stage of processing. It allows to detect damaged data from the existed one. The following sequence of the operations is performed for all modules at the each processing step.

CoLiTec software contains the system for monitoring processing messages with a detailed logging of handling process (see Figure 4). This approach is realized by change ex

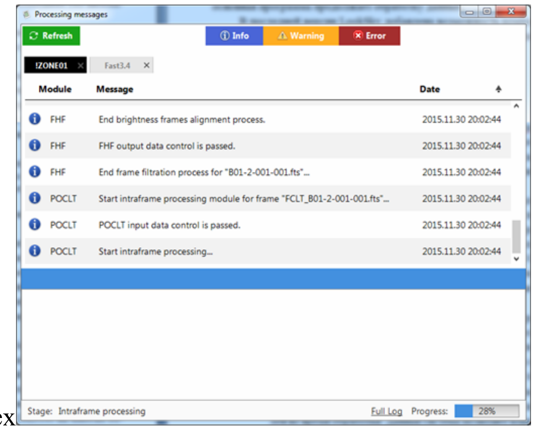

Figure 4: System for monitoring the processing messages with user-friendly GUI

data with a relational database. PostgreSQL was selected for such uses, because it may be applied on any operation systems.

CoLiTec software also includes the pipeline for digital video processing. It is presented as a flexible platform for receiving and processing video in any resolution, as well as easy integration of different modules required to improve image quality, delineation and recognition of moving objects in the video series.

CoLiTec software has abilities for detecting very slow and very fast objects. Range of visible velocities of detected asteroids is from 0.7 to 40.0 pixels per frame. For example, the fasters NEO is K12C29D asteroid (40.0 pix./frame) (see Figure 5) or the slowest object is ISON C/2012 S1 comet 0.8 pix./frame).

These possibilities are provided by the different computational methods that developed by authors and implemented in the CoLiTec software.

One of them is a new iteration method for accurate estimation of asteroid coordinates, which is based on the subpixel Gaussian model of a discrete object image (Savanevych et. al., 2015). This model of the object image takes into account a prior form of the object image and consequently it is adapted more easily to any forms of real image. The method operates by continuous parameters (asteroid coordinates) in a discrete observational space (the set of pixels potentials) of the CCD-frame.

In this model, a real coordinate distribution of photons hitting the pixels in the CCD-frame is not known and the form of this distribution is known a priori. It allows to determine associated parameters from a real digital object image. The advantages of subpixel Gaussian model become more obvious for the fainter celestial objects. This method has a high measurement accuracy along with a low calculating complexity due to a maximum likelihood procedure, which is implemented to obtain the best fit instead of a least-squares method and Levenberg-Marquardt algorithm for the minimization of the quadratic form (Savanevych et al., 2015).

The another method, which implemented in CoLiTec software, is the method for determining equatorial coordinates of celestial objects based on an assessment of their position in the digital frame (Pohorelov et al., 2016).

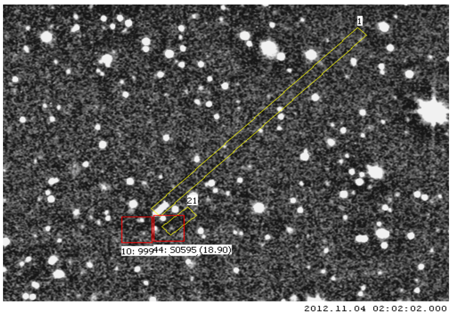

Figure 5: K12C29D asteroid – NEO (40.0 pix./frame)

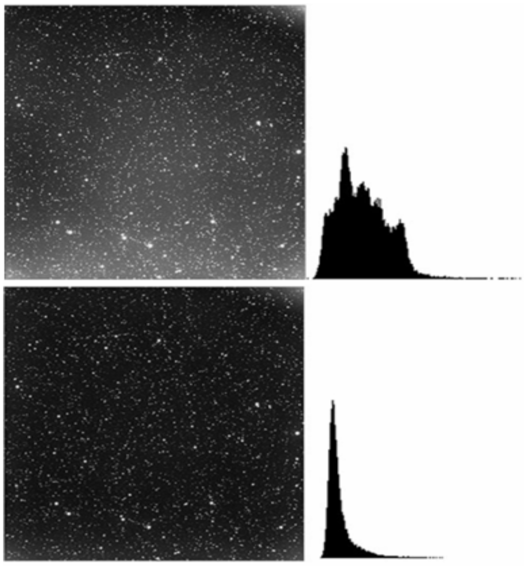

Figure 6: Frame filtration

Different reduction polynomial models (cubic and fifth-power) were implemented in this method. Also it allows to assess the significance of the reduction model coefficients and determine the influence of the polynomial model power on the accuracy of object's position assessment. The reduction models were built using the selected set of reference stars (for example, from UCAC4 catalog) (Zacharias et al., 2013). This method also takes into account the peculiarities of astronomical reduction in long-focus and short-focus optical systems.

CoLiTec software contains the module for brightness equalization of astronomical images. It based on the alignment of the interference substrate on the large CCD-frames without using of service (Master) frames (dark current frames – dark, noise reading frames – bias, «flat field» frames – flat).

Some cases when it is impossible to get Master-frames or calibration of received image don't lead to the desired result, for example, in the presence of ambient light. The images of celestial objects (stars and asteroids) in a separate frame are point, and with the atmosphere turbulence, can be presented as «blurred points», that produced slowly varying brightness changes (see Figure 6).

The method allows processing frames in the different frequency range. The stars and asteroids are formed by high-frequency spectral components of the image. However,

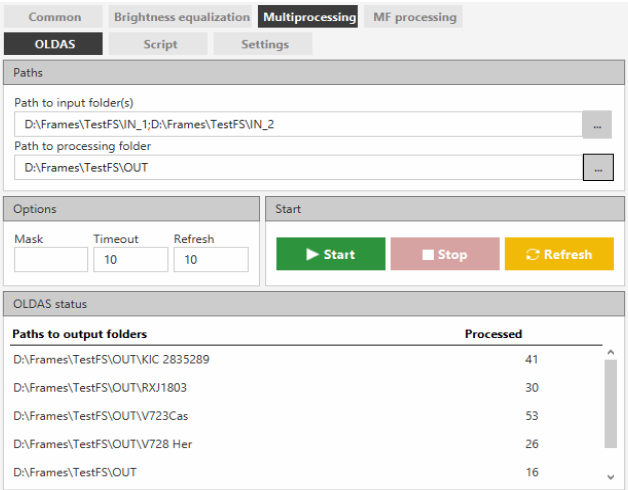

Figure 7: FrameSmooth – software for brightness equalization of astronomical frames with user-friendly GUI

the frame background is the low-frequency component. The subtraction of the low-frequency background variations allows leaving the unchanged high-frequency components of the image.

If the pulsed noise is the limited set of peak values against of zeros it is consider to use median filtering as a method for nonlinear image processing. The median filter is implemented as a local processing procedure by sliding window with specified sizes that includes an odd number of image counts. These filters increase twice signal and noise ratio (SNR) of objects images, including dim.

The range of mean values of background pixels brightness was reduced in two times by the 5% level of the maximum histogram value. This decrease is greater the larger the size of the window is being used.

These methods lead to increasing of astrometry accuracy indicators and stars photometry quality as well as the quality indicators of asteroids and comets detection.

They are implemented and successfully used as part of CoLiTec software of automated asteroids and comets discoveries on the series of CCD-frames and the FrameSmooth free software (see Figure 7).

The CoLiTec software is widely used in a number of observatories in the CIS. For the first time in the CIS, asteroids and comets were discovered in the automated mode using this software. It has been used in about 700 000 observations, during which four comets C/2011 X1 (Elenin), P/2011 NO1 (Elenin), C/2012 S1 (ISON) and P/2013 V3 (Nevski) out of seven discovered in the CIS and the Baltic States over the past 20 years were identified using CoLiTec. Thus, the comet C/2010 X1 (Elenin) was discovered on December 10, 2010, using the CoLiTec software. It was the first comet discovered by a CIS astronomer. In total, the CoLiTec software was used for discovery more than 1560 asteroids, including 5 NEO, 21 Trojan asteroids of Jupiter and 1 Centaur. Discovered asteroids include four of 16 asteroids detected during the whole history of astronomy of the Soviet Union, CIS, and Baltic states, approaching the Earth; and one of the two centaurs discovered in the CIS and Baltic states. Individual MPC electronic circulars were devoted to three asteroids (2011 HY52, 2011 QD23, 2011 RC17).

Approximately 80(86)% of positional CCD-measurements and 74(75)% of discoveries of asteroids were made using the CoLiTec software in 2012 (2011).

Considerable achievements of the CoLiTec software are associated with the detection of objects with near-zero apparent motion. For example, at the time of discovery, the image size of the comet C 2012 S1(ISON) was 5 pixels, and it shifted by 3 pixels for 4 frames (Khlamov et al., 2016). The Centaur 2013 UL10 was shifted by 10 pixels with the image size of 4-5 pixels at the time of discovery.

The CoLiTec project has been supported for several years by such organizations as ISON (Elenin et al., 2013), MAO NASU and RI NASU. In 2014, the CoLiTec software was recommended to all members of the Gaia-FUN-SSO network (https://gaiafunsso.imcce.fr) for analyzing observations as a tool for detecting faint moving objects on CCD-frames.

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