Processing pipeline for data mining of the primary orbits of the Solar System objects using the Väisälä method

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Abstract

In this paper we presented the processing pipeline for data mining of the primary orbits and discovery of the new Solar System objects using the CoLiTec software and classical Väisälä method. The 1st step of a such method is performing the sequential astronomical observations and the classical astrometric data reduction. It is implemented as a combination of the general mathematical algorithms for processing of the astronomical frames incapsulated in the CoLiTec software. It contains the inverse median filter, astronomical calibration with usage of the master-frames, detection of the astronomical objects and its trajectories in series of frames and others features. After that the especial parameters of the object's orbit (right ascension and declination) are calculated at the certain time. When we receive at least two observations of the same object under study at different moments, the classic Väisälä algorithm can be applied. For this, the primary orbit from the two nearest observations is calculated. Then the geocentric rectangular coordinates and the appropriate geocentric velocity components are computed. This give us an opportunity for determining the Keplerian elements of orbit of the investigated object at any time we are interested in. The developed algorithm is implemented as a processing pipeline that includes a combination of the CoLiTec software and created tool with encapsulation of the Väisälä method. The created processing pipeline for data mining of the primary orbits and discovery of the new Solar System objects using the CoLiTec software and classical Väisälä method is practically verified. Using it a few new asteroids are first reported and a few lost small bodies of the Solar System are found in the Kyiv comet station and the Odesa - Mayaky observatory.

Keywords

Data mining, processing pipeline, astronomical observations, CoLiTec software, Väisälä method, image processing, image calibration, astrometric reduction, object detection, positional coordinates, orbit determination, Solar System objects

1. Introduction

The asteroid-comet hazard is a big potential problem in the XXI century. It leads to the developing astronomical scientific direction like an image processing, which includes the following algorithms for astrometric reduction [1], photometric reduction [2], detection or even discovery of the Solar System objects [3], etc.

A common goal of all scientific and technological algorithms is to automate as much as available processes without any human actions. In general cases it can be done by the different astronomical scientific processing pipelines. In these pipelines the various data mining [4] and knowledge discovery in databases (KDD) [5] tasks are used for speeding up and optimizing the astronomical

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data processing.

The astronomical scientific information is collected from the different historical archives, clusters, Virtual Observatories [6], clouds, astronomical astrometric and photometric catalogues [7], different servers and other storages.

Almost all astronomical scientific observations are created by the charge-coupled device (CCD) [8] and performed during the specified observational period of the investigated small celestial objects of the Solar System (SSOs) [9] (like, comets or asteroids [10]), as well as the artificial satellites [11]. After performing the series of observations of the investigated SSOs it is required to analyze the results of observation, which can include the period and shape of rotations determining of such investigated SSOs.

That is why it is required to create a mathematical method to determine a primary orbit and discovery of the new Solar System objects using the CoLiTec software and the classical Väisälä method. Such a method gives a possibility for estimating the geocentric rectangular positional coordinates of a SSO under study with and calculating the different Keplerian elements of the SSO's orbit. At the same time this algorithm can improve the conditional expectation of the correct discovery [12] of the real SSOs.

The Väisälä algorithm is a very useful algorithm when used in the different situations [13]. Its importance becomes noticeable with the particularly short observation arcs, which are insufficient to confirm an exact orbit and predict a position of the investigated small astronomical Solar System object during the next week.

2. Related Works

Each Solar System object presented in a CCD-frame has a typical form of its image [14]. The common methods for the image processing [15] and machine vision [16] are developed for detection/recognition such images of SSOs and an estimation of their positional and motion parameters [17]. Such methods are based on the analysis of only those pixels that potentially belong to the investigated object. The disadvantages of such methods are very low accuracies when the typical form of object has a different shape [18].

The methods for pixelization and segmentation by the aperture brightness [19] will work only with a single image of each SSO. A method for the matched filtration [20] uses a model of the object's image, which is analytically determined. The disadvantages of the methods above are the big complexity and low accuracy during the processing, when an image has a several peaks of magnitude.

Methods for the Wavelet analysis [21] or even time series analysis [22] are not so effective, because we do not have a big volume of the input data to be analyzed. Also, the disadvantage of such algorithms is the corrupting of the general statistics and possibility to process only clear measurements without any deviations in the typical form of image.

3. Processing pipeline for data mining of the primary orbits of the Solar System objects

3.1. Astronomical calibration

Astronomical image calibration is a critical process in astrophotography and observational astronomy [23]. These calibration frames are used to correct different imperfections and artifacts introduced during the image acquisition process, ensuring the accuracy and quality of the final images:

- Bias Frames. Bias frames capture the electronic signal present in the camera sensor when no light is allowed to enter the telescope. They record the baseline electronic offset or zero signal level of the sensor. Bias frames help correct for the sensor's inherent electronic noise, such as readout noise and amplifier offsets;

- Dark Frames. Dark frames are images taken with the telescope or camera covered, capturing the thermal signal produced by the sensor itself. This signal is a result of heat generating random electronic noise in the detector. Dark frames help in correcting thermal noise, hot pixels, and other sensor-specific imperfections;
- Flat Frames. Flat frames are images of a uniformly illuminated surface or a blank, evenly illuminated part of the sky. They are used to correct for variations in sensitivity across the camera sensor, as well as for dust specks or imperfections in the optical system. Flat frames help to normalize the pixel-to-pixel sensitivity differences in the sensor and remove any vignetting or dust shadows.

The calibration process involves the following steps:

1. Acquisition: Bias, dark, and flat frames are captured under specific conditions matching the settings used for the actual astrophotography session. It's important to ensure that the exposure times and temperatures match those of the light frames (images of celestial objects).
2. Subtraction: The bias frame is subtracted from all the frames (light, dark, and flat) to remove the electronic offset and noise present in the images.
3. Dark Subtraction: Dark frames are subtracted from the light frames to eliminate the thermal signal caused by the camera sensor's temperature during image acquisition.
4. Flat Fielding: Flat frames are used to normalize the response of the sensor. Light frames are divided by the normalized flat frames to correct variations in pixel sensitivity and eliminate artifacts caused by dust, vignetting, or optical imperfections.
5. Post-Processing: Once the calibration process is completed, further image processing techniques, such as stacking, alignment, and color calibration, are often applied to enhance the final image quality.

Calibrating images with bias, dark, and flat frames is crucial in producing high-quality astrophotographs and ensuring accurate scientific analysis by removing unwanted noise and artifacts introduced during the imaging process.

In the developed algorithm we performed the different actions for the astronomical data calibration, like calibration dark frames subtracting, calibration bias frames subtracting and calibration flat frames fielding/dividing [24].

3.2. Orbit determination

Every astronomical observation of the investigated astronomical object provides the topocentric directions to it:

$$\begin{cases} X_i = -G_{1i} \cos\varphi_i \cos\theta_i, \\ Y_i = -G_{1i} \cos\varphi_i \sin\theta_i, \\ Z_i = -G_{2i} \sin\varphi_i, \end{cases} \tag{1}$$

where a coefficient G and a local sidereal time (θ) are calculated by the following equations:

$$\begin{aligned} G_{1i} &= \frac{a_e}{\sqrt{1-\left(2f-f^2\right)\sin^2\varphi_i}} + H_i, \\ G_{2i} &= \frac{\left(1-f\right)^2 a_e}{\sqrt{1-\left(2f-f^2\right)\sin^2\varphi_i}} + H_i, \end{aligned} \tag{2}$$

$$\theta_i = \theta_{g0} + \frac{d\theta}{dt}\left(t_i - t_0\right) + \lambda_{Ei}, \tag{3}$$

where φ_i, λ_{Ei} are the geodetic latitude and longitude of the observer;

H_i is the altitude of the observer;

Earth ellipsoid model recommended by the IERS [25];

semi-major axis (a_E) of 6378171.364331512 m;

inverse of polar flattening ($1/f$) of 297.7736994668283;

θ_{g0} is Greenwich Mean Sidereal Time (GMST).

After astrometric reduction to the Earth center, we received the right ascension (α_i) (RA) and declination (δ_i) (DE) for the current time (t_i).

This gives us a possibility to create a system of connection equations:

$$\begin{cases} \rho_i \cos\alpha_i \cos\delta_i = x_i + X_i, \\ \rho_i \sin\alpha_i \cos\delta_i = y_i + Y_i, \\ \rho_i \sin\delta_i = z_i + Z_i, \end{cases} \tag{4}$$

where X_i, Y_i, Z_i are rectangular geocentric equatorial coordinates of the Sun;

x_i, y_i, z_i are rectangular heliocentric equatorial coordinates of an investigated astronomical object.

Geocentric coordinates of the Sun can be taken from SS model. And geocentric distances (ρ_i) and heliocentric coordinates (x_i, y_i, z_i) of an investigated astronomical are unknown in system 4.

3.3. Väisälä algorithm

General representation of the Väisälä algorithm requires the 2 nearest astronomical observations of the same investigated object at times t_1 and t_2.

So, we can calculate the primary orbit from such two observations using a set of the following parameters (t_1, α_1, δ_1, t_2, α_2, δ_2).

To calculate the geocentric rectangular coordinates of an investigated object we can use the following system of equations:

$$\begin{cases} x_2 = \Delta_2 \cos\alpha_2 + X_2, \\ y_2 = \Delta_2 \sin\alpha_2 + Y_2, \\ z_2 = \Delta_2 \tan\delta_2 + Z_2, \end{cases} \tag{5}$$

where $\Delta_2 = \rho_2 \cos\delta_2$.

To calculate the geocentric velocity components of an object we can use the following system:

$$\begin{cases} \dot{x}_2 = \dfrac{\Delta_1 \cos\alpha_1 - F_1 x_2 + X_1}{G_1}, \\ \dot{y}_2 = \dfrac{\Delta_1 \sin\alpha_1 - F_1 y_2 + Y_1}{G_1}, \\ \dot{z}_2 = \dfrac{\Delta_1 \tan\delta_1 - F_1 z_2 + Z_1}{G_1}, \end{cases} \tag{6}$$

$$\Delta_1 = \frac{F_1 r_2 + X_1 x_1 + Y_1 y_1 + Z_1 z_1}{x_2 \cos\alpha_1 + y_2 \sin\alpha_1 + z_2 \tan\delta_1},$$
$$F_1 = 1 - A\tau^2, G_1 = \tau - B\tau^3, \tag{7}$$
$$A = \frac{r^3}{2}, B = \frac{A}{3},$$

where $\tau = k(t_1 - t_2)$ is a time interval between two nearest observations;

k is a gravitation constant.

The determined parameters $(x_2, y_2, z_2, \dot{x}_2, \dot{y}_2, \dot{z}_2)$ will be used for calculation the Keplerian elements of the orbit of an investigated object at a time t_2.

3.4. Processing pipeline for data mining of the primary orbits of the Solar System objects

An architecture of a processing pipeline for data mining of the primary orbits and discovery of the new Solar System objects using the CoLiTec software and classical Väisälä method is presented in Figure 1. Such method contains the next steps.

1. Perform the observations of the investigated SSOs.
2. Perform the classic data reduction process using bias, flat, and dark calibration frames.
3. Perform the astrometric reduction of the investigated SSOs by the CoLiTec software.
4. Calculation of a primary orbit of the investigated SSOs by the Väisälä algorithm.
5. Repeat the astronomical observations of the investigated SSOs to confirm a discovery of the new SSOs.

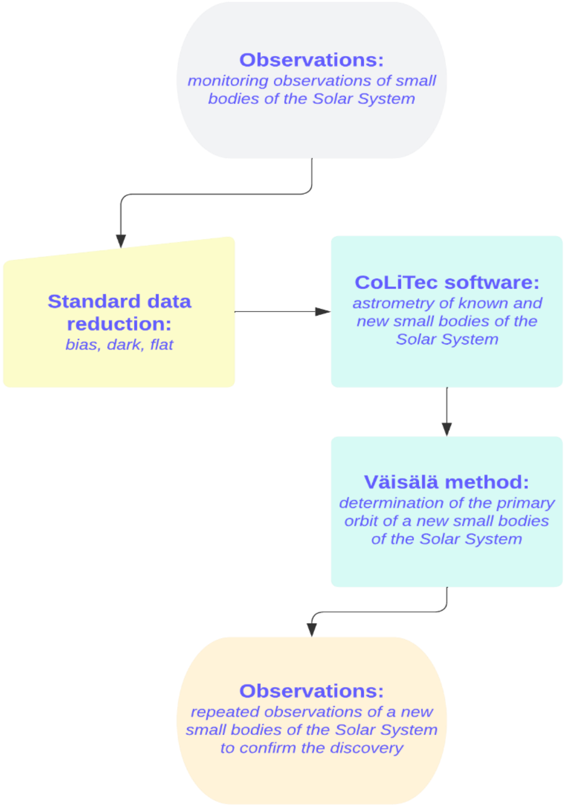


Figure 1: Architecture of a processing pipeline for data mining of the primary orbits and discovery of the new Solar System objects using the CoLiTec software and classical Väisälä method

4. Results

4.1. CoLiTec software

The created algorithm to determine a primary orbit and discoveries of the SSOs using the Väisälä algorithm works in combination with the CoLiTec software (https://colitec.space) [26]. The specific functional features related to the mathematical method for determining the primary orbits and discovery of asteroids in the CoLiTec software are:

- automated frame calibration [9];
- cosmetic frame correction;
- track-and-stack feature;
- brightness equalization [2];
- background alignment;
- astronomical image filtering [27];
- determining the contours of objects [28];
- fully automated robust method of the astrometric reduction [1];
- fully automated robust method of the photometric reduction [23];
- support of the multi-threaded processing;
- On-Line Data Analysis System (OLDAS) for managing the processing pipeline;
- transferring of astronomical data with intermediate storage [29];

More extended details about the CoLiTec software are presented in these works and research [30, 31, 32]. The high-level processing pipeline with the developed modules and implemented methods of the CoLiTec software is presented in the Figure 2.

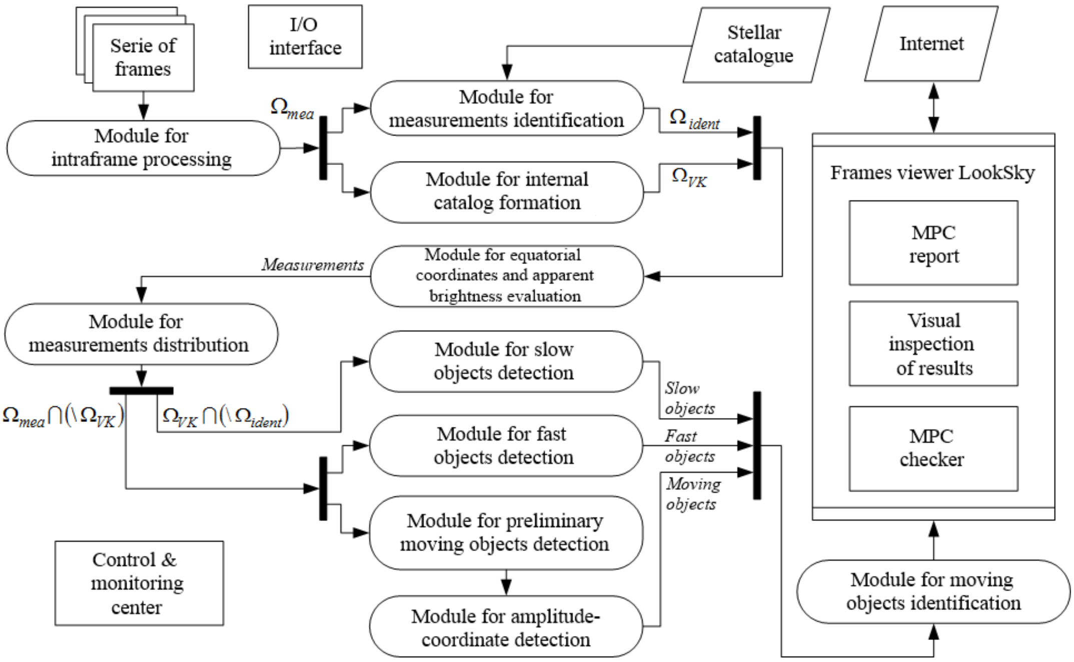


Figure 2: The high-level processing pipeline of the CoLiTec software

The CoLiTec software is installed at the different telescopes at the various observatories in Ukraine and around the world:

- OMT-800 and AZT-3 telescopes installed at the Odesa-Mayaky observatory [33];
- SANTEL-400AN telescope installed at the ISON-NM observatory;
- ISON-Uzhgorod [34];

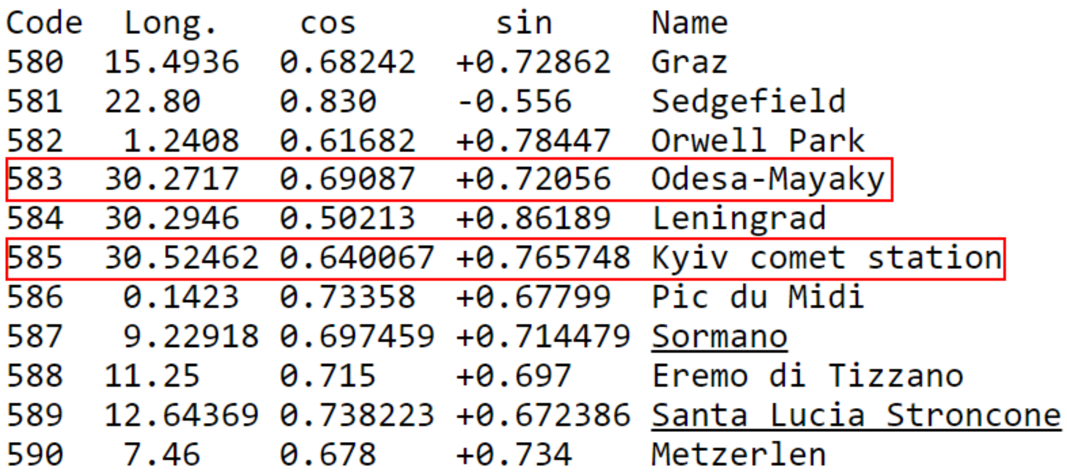
- VNT and Celestron C11 telescopes installed at the Vihorlat Observatory [23];
- PROMPT-8 telescope installed at Cerro Tololo observatory [35];
- NARIT (National Astronomical Research Institute of Thailand) [36];
- AZT8 and Takahashi BRC-250M telescopes.

All listed above telescopes installed at the observatories have an official identifiers received from the Minor Planet Center (MPC) (https://minorplanetcenter.net) – MPC code from the International Astronomical Union (IAU) (https://iau.org).

4.2. Odesa-Mayaky (observatory) [code: 583]

Astronomical observations were made on the OMT-800 telescope installed at the Mayaky observational station of the Astronomical Observatory of the Odesa I. I. Mechnykov National University.

The official MPC code of the Odesa-Mayaky station is 583 (see Figure 3) [37]:



Code	Long.	cos	sin	Name
580	15.4936	0.68242	+0.72862	Graz
581	22.80	0.830	-0.556	Sedgefield
582	1.2408	0.61682	+0.78447	Orwell Park
583	30.2717	0.69087	+0.72056	Odesa-Mayaky
584	30.2946	0.50213	+0.86189	Leningrad
585	30.52462	0.640067	+0.765748	Kyiv comet station
586	0.1423	0.73358	+0.67799	Pic du Midi
587	9.22918	0.697459	+0.714479	Sormano
588	11.25	0.715	+0.697	Eremo di Tizzano
589	12.64369	0.738223	+0.672386	Santa Lucia Stroncone
590	7.46	0.678	+0.734	Metzerlen

Figure 3: The official MPC codes of the Odesa-Mayaky observatory and the Kyiv comet station

The 0.8-m main hyperbolic mirror is installed at the OMT-800 telescope and has a useful focus ratio as *f = 1/2.7*. The FLI ML09000 CCD-camera is used as an image CCD-detector along with a 4-lens field corrector for a primary focus, which allows receiving the field of view (FOV) as *58.6′×58.6′* and the scale of image as *1.15* arcseconds per pixel.

During the astronomical observations at the OMT-800 telescope and research after processing the results, the next new asteroids were firstly discovered:

- 2017 BC94 (MPS 766258);
- 2017 QX33 (MPS 813479);
- 2017 RV12 (MPS 817137);
- 2017 QJ36 (MPS 817122).

During the astronomical observations at the OMT-800 telescope and research after processing the results, the next lost SSOs were found again:

- 2012 FN61 = 2010 VP219 (MPS 441842);
- 2017 AB8 = 2014 OD380 (MPS 525811).

4.3. Kyiv comet station (observatory) [code: 585]

Astronomical observations were made on the AZT-8 telescope installed at the Kyiv comet station of the “Lisnyky” observational station of the Taras Shevchenko National University of Kyiv.

The official MPC code of the Kyiv comet station is 585 (see Figure 3).

The installed AZT-8 telescope is a telescope-reflector. The FLI PL4710 CCD-camera (63.5 mm) was used as an image CCD-detector, which allows receiving the FOV as *16.2′×16.7′* and the scale of image as *0.948* arcseconds per pixel.

During the astronomical observations on the Kyiv comet station and research after processing the results, the new asteroid 2017 SV39 (MPS 828365) was firstly discovered and the next lost SSOs were found again:

- (536266) = 2007 HU101 = 2015 CX48 = 2017 ST39 (MPS 891037);
- (540584) = 2000 WN134 = 2007 XY37 = 2010 RD162 = 2015 DH168 = 2017 TS7 (MPS 23003).

5. Conclusions

We present a processing pipeline for data mining of the primary orbits and discovery of the new Solar System objects using the CoLiTec software and classical Väisälä method. The literature review showed the benefits and disadvantages of the existing methods and algorithms. So, we made a decision to improve such algorithms for the better accuracy and quality of detection of the new or lost SSOs. The first step of such computational algorithm is to perform the observations and the standard data reduction. It was performed in scope of the common mathematical methods for the astronomical image processing and numeric analysis [38] implemented in the CoLiTec software. It includes inverse median filtration, calibration using the master frames, object detection, etc. Then the orbit parameters, like the right ascension and declination, were determined for a certain moment. After receiving the two observations of an investigated object at different times, the classic Väisälä method is applied. The created algorithm is implemented as a processing pipeline that contains a cooperation between the CoLiTec software pipeline and a special implemented plugin based on the general Väisälä algorithm. Such a plugin is realized as a console application based on the programming language Delphi. The CoLiTec software was selected among another astronomical software tools for astrometric reduction like Astrometrica [39] as the more accurate software with more precise measuring of positional coordinates of celestial objects.

The created mathematical method was verified in practice based on the classical mathematical models [40] and fuzzy clustering data arrays with omitted observations [41] as well as statistical modeling [42]. With help of the developed processing pipeline, the several new SSOs (Main-belt asteroid 2017 AB8 (2014 OD380), Mars-crossing asteroid 2017 QX33, Main-belt asteroid 2017 RV12) were firstly discovered and some of the lost SSOs were found again during the astronomical observations at the Kyiv comet station and the Odesa-Mayaky observatory.

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