GENERIC DATA REDUCTION FRAMEWORK FOR SPACE SURVEILLANCE

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ABSTRACT

Space Surveillance and Tracking (SST) of both natural and man-made objects requires the development of observational campaigns to early identify Earth orbiting objects, estimate their orbital elements and monitor the evolution of their orbits. This implies the deployment of an observation network based on on-ground (and potentially space-based) instruments, and the development of a processing tool able to process the acquired data.

This paper aims to present the development of a Generic Data Processing Framework for Space Surveillance, intended to process the observational data to be acquired by autonomous robotic optical telescopes focussed in the surveillance, cataloguing and monitoring of Earth Orbiting Objects.

These activities are being developed as part of ESA's GENDARED project, financed under the Romanian Industry Incentive Scheme, aiming at supporting the participation of Romania in ESA SST activities.

1 INTRODUCTION

Space junk is now one of the principle threats to orbital satellite systems, with more than 700 000 dangerous debris objects estimated to orbit Earth and having the potential to damage or destroy space-based infrastructure. Due to very high relative orbital velocities, centimetre-sized debris can seriously damage or disable an operational spacecraft, and collisions with objects larger than 10 cm can lead to catastrophic break-ups, creating more space debris in Earth orbits.

Space Surveillance and Tracking (SST) of both natural and man-made objects requires the development of observational campaigns to early identify Earth orbiting objects, estimate their orbital elements and monitor the evolution of their orbits. This implies the deployment of an observation network based on on-ground (and potentially space-based) observations, and the development of a processing tool able to process the acquired data.

The Generic Data Reduction (GENDARED) Framework for Space Surveillance is intended to process the observational data to be acquired by autonomous robotic optical telescopes focussed in the surveillance, cataloguing and monitoring of Earth Orbiting Objects. The framework is intended to be fully independent and unassisted, able to process incoming images according to a specific logic, and not requiring the support of an operator. It will be able to identify potential target objects, correlate object measurements in consecutive exposures according to the observational schema, and provide precise astrometric and photometric measurements for all retrieved objects. The following sections will present the capabilities of the GENDARED framework, the processing to be orchestrated by the framework and a CCD image simulator that was developed to test the capabilities and performance of the processing algorithms to be implemented.

2 GENDARED FRAMEWORK

Being integrated with the telescope infrastructure, GENDARED will receive as input the raw images (both observation and calibration images) acquired during an observation session, together with all required additional information, and will generate as output astrometric and photometric data for the target objects detected in the observation image, which will be sent to the SST system for further processing. All the information needed for the processing at image level will be included in the Flexible Image Transport System (FITS) header of the images. In addition to the information at image level, GENDARED will require information at sequence level describing the set of individual images composing the observation of a target object, and therefore the list of images that must be processed in order to retrieve the measurements for the specific object. GENDARED will generate tracklets,

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consisting of tracking data for one target object detected in the processed exposures, at multiple epochs contained within a specified time range, and will connect to the SST back-end through a virtual private network (VPN), enabling a secure and encrypted connection for transferring the files.

The Image Reduction algorithms will be able to cope with different acquisition schemas including staring (for GEO), sidereal tracking and precise object tracking. The full Image Reduction process shall be fast enough in order to allow the processing of high image acquisition rates, typically several images per minute, in near real time, in order to not have delays or blockages in the processing of the images taken in a closely continuous acquisition schema.

The Data Reduction environment is designed in a modular way to easily allow adding or updating specific data reduction processes to ensure the improvement and evolution of the processing algorithms. It is defined as a chain of sub-processing elements connected in series, where the output of one of the elements is used as input for the next processing step. That is, the Image Reduction process shall be designed as a Pipeline. Each sub-processing element is in charge of a specific step from the Image Reduction process. This schema gives great advantages, including:

- Each reduction step is implemented as an atomic, independent and complete reduction process, focussed on the considered reduction aspects and ignoring the rest of the processing. Composing the pipelines from stand-alone and independent processes will enable the GENDARED framework to process in parallel multiple input datasets.
- Easy development and integration of the sub-processing elements by the Scientific Teams, strongly decoupled from the development of the GENDARED components in charge of their orchestration. The GENDARED operator will be able to design the pipelines to be applied for the processing of the input datasets acquired using a specific observational strategy by defining the sub-processing elements to be applied and their dependencies (order).
- The whole Data Reduction process, composed by a set of sub-processing steps, can be easily updated just installing new versions of selected processing elements implementing improved and accurate processing algorithms. This strategy minimises the potential impact on the remaining reduction process (pipeline) given that the new processing element complies with the required interfaces (input data from previous processing element, output data for the next processing element).

The Image Reduction process will be fully autonomous and unassisted. GENDARED will behave autonomously for the entire time of its activity, from the receiving of the input datasets until the sending of the generated tracklets to the SST back-end, and will act according the system configuration and events. GENDARED will be data-driven, it will monitor the arrival of new input datasets, will determine the pipeline to be applied for the processing of the received input datasets and will schedule them for execution according to a configurable priority criteria (by injection time, by observational strategy) and according to the free computational resources.

The Data Reduction environment shall be configurable in order to allow the operator to easily define and/or modify the behaviour of the processing to fit specific instrumental and observational characteristics. All configurable parameters, such as instrumental characteristics (pointing, orientation, tacking mode, spectral response, quantum efficiency, …) and processing configuration (algorithm parameters, thresholds, options, …) shall be read from the input images (when available) and configuration files.

GENDARED will provide a Human Machine Interface (HMI) to be used for the control, configuration and monitoring of the framework. Through the HMI, the GENDARED user will be able to visualise:

- the configuration parameters,
- the list of input datasets received and scheduled for processing and the ones that are currently being processed,
- the available resources in terms of disk space, RAM memory and CPU usage,
- the logged events,
- the warnings and errors occurred during the processing,

Also, through the use of the HMI, the user will be able to:

- modify the configuration of the framework, including the system parameters and parameters used by each sub-processing element.
- command the processing of a particular input dataset. The operator will be able to start, stop, resume and abort the processing of a particular input dataset.
- design the pipelines to be applied for the processing of the input datasets acquired using a specific observational strategy by defining the sub-processing elements to be applied and their dependencies (order),

The HMI will have an identity management and authentication system that is capable to manage user identities and authenticate users. GENDARED shall support multiple user types with different privileges (capability to issue commands to GENDARED).

3 GENDARED PROCESSING

After the acquisition of the astronomical images, the objects within the image need to be detected and their position and brightness need to be measured. An effective strategy algorithm for astronomical image reduction needs to satisfy the following requirements (not an exhaustive list):

- It must be able to cope with large variation in image background and noise
- It should be able to detect faint objects
- Must obtain precise astrometric and photometric measurements

The automatic algorithms in charge of detecting the objects in the astronomical images include different steps that can be categorized in four main classes:

- Image calibration,
- Image transformation,
- Image subtraction and segmentation,
- Astrometric and photometric measurements and calibrations.

A study on the state-of-the-art automatic image processing strategies was executed in order to identify the most used and successful image processing algorithms. The following sections will describe the processing steps to be implemented for the processing of images acquired during sidereal tracking, precise object tracking and staring.

3.1 Sidereal tracking processing

CCD images acquired during sidereal tracking contain point-like images for all stars in the field of view, and trailed-shaped images for orbiting objects. The strategy that is intended to be implemented for GENDARED is inspired by the one proposed in [1]. The considered technique implies the detection and removal of every feature in the image that is not a streak, leaving just the target objects in the image. In the end, an image from which all the non-streak components (sensor artefacts, background, noise and stars) are eliminated will be obtained. The last step is the identification of the streaks that are left in the image. The general process is described in Figure 1.

Raw images taken with a CCD camera are calibrated to correct for non-data elements that are found in each raw data frame, such as bias offset, bias structure, dark current, uneven chip illumination, and "dust donuts", through the use of master frames.

The first component that will be eliminated from the image is the background signal. The detection of satellites streaks in astronomical images requires a good algorithm for the removal of the image background. If the background is not adequately removed, a part of the relevant signal can be removed together with the background, or the remaining part of the background may degrade the estimation of the residual noise. A good estimation of the background can improve the performances of the detection algorithms. The removal of the background is realised through an iterative procedure ([1]). The first step is a blind polynomial fit on the image columns (due to the linear profile of the background) after eliminating all the saturated stars. After truncating all the brighter objects with respect to the first estimation (using a certain threshold) another polynomial fit is executed on the image columns. The process is repeated one more time, obtaining a good estimation on the image background. Because faint horizontal bright bands may still be present in the image, a polynomial fit is executed also on the image rows.

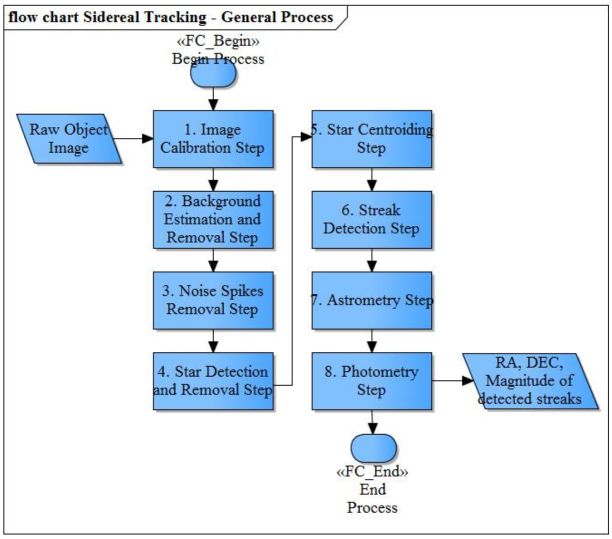

Figure 1. Sidereal Tracking per-frame processing steps

As was described, the background estimation procedure requires the detection and elimination of saturated stars as a pre-requisite step for the first polynomial fit on the image columns. The detection of saturated stars starts with the detection of all the saturated pixels in the object image. Starting from a single saturated pixel, a region growing algorithm ([6]) is applied to determine the contiguous saturated pixels that will be assigned to the star. The purpose of the region-growing algorithm is to partition the saturated pixels corresponding to a saturated star from the rest of the image. For each saturated star that is detected, we compute the aspect ratio in order to determine if the star is bleeding. If the ratio is much different from 1, the star is considered to be “bleeding”, and is useless for further processing. For the removal of the saturated stars a combination of the central mask and peripheral-crown erasing processes is used. All the pixels within the circular mask centred at the centroid of the star will be set to zero. The peripheral-crown erasing process implies the computation of the median from the values of all the pixels having the same distance w.r.t. the centroid of the star and its subtraction from the initial intensities. The radius of the circular mask (being also the inner radius of the annulus) and the outer radius of the annulus will have to be fine-tuned in order to fit the telescope infrastructure and the observation conditions.

Having a background free image, the next step will be the elimination of noise spikes. The process of eliminating these artefacts employs a filter shaped like a Greek cross ([1]) centred on each pixel from the image and a thresholding step for the validation of the detection. The method is able to take into account the occurrence of consecutive events and to remove more than 99% of the noise spikes.

The process of star elimination is also an iterative process. After removing the saturated stars as a pre-requisite step for the background estimation process, the next steps are the detection and removal of bright and faint stars.

The process for the detection of the bright stars uses a double-gate type filter ([1]). The idea is to use statistical indicators like the mean and standard deviation to prove that there is a star in the inner window of the filter, and that the outer window contains only background signal. In order to alleviate the erasing of a satellite streak (in this case the sensitivity of the outer window is reduced due to the presence of a high number of background pixels) the outer window of the filter is divided in several sub-windows.

The shape of the star profile in a CCD image is a combined result of the optical transfer function, the degradation due to the atmospheric transmission and turbulence and the blooming effect. The dimension of the inner window needs to be selected taking into account all these factors. The outer window will be composed of a certain number (depending on the dimension of the inner window) of 3x3 sub-windows. The double-gate filter is centred on each pixel and then the mean and the local noise standard deviation are used to verify that a bright object is detected in the inner window, and that the outer window contains only background signal, in order to avoid erasing a bright streak.

The erasing process is similar with the one used for erasing saturated stars. The erased stars are copied in a separate image in order to obtain a clean star image to be used for the astrometric and photometric calibration.

The detection of faint stars uses the same approach as for the detection of bright stars. The only differences are in the size of the inner window (which need to be chosen according to the factors that affect the image of the star) and the conditions used to validate that a faint star is located in the inner window and that the outer windows only contain background signal.

Once the background, the noise spikes and all the stars are removed, the only components left in the image are the streaks from the target objects, the residue and the noise.

The algorithm for the streak detection is similar with the one described in [2]. It implies the usage of filters with different lengths and orientation to be convolved with every pixel of the image in the idea of obtaining the highest answer for the best matching filter. The filter is constructed by considering the streak as a moving Gaussian PSF. For each pixel, steps of few pixels and few degrees are used for incrementing the length and the orientation of the filter. The streaks are detected with a thresholding step.

The last steps are the astrometric and photometric calibrations for the detected objects. In order to find the astrometric solution for the star mask that has been created during star removal, a star catalogue has to be used. The most comprehensive star catalogue is UCAC4. Stars from the region of the sky in the image frame have to be queried from the catalogue, up to a maximum magnitude (which is dependent on the instrument used) and corrected for their proper motion up to the epoch of the observation. Also, the effects of precession, nutation and aberration have to be accounted for each star.

After computing the estimated pixel position for the Astrometric Reference Stars in the image, we can search for the stars with the highest magnitude. The searching process will look for stars in the neighbourhood of the predicted position. The search radius must assure that the reference star was located within it, according to the estimated error in the pointing. If the radius is large enough to hold several stars, the choice will use additional information, such as the brightness (total number of electrons from the object in the CCD). The next steps will be to fit a low order polynomial between the computed standard coordinates and the measured coordinates in the CCD frame, and to compute the plate constants by applying a Least Squares method to the data retrieved for the Reference Stars. Then, the accurate position of the satellite streak can be obtained by computing the standard coordinates using the previous polynomial fit, and converting them to equatorial coordinates.

If at least 5 stars from the image have had their correspondents identified in the star catalogue, calculating the apparent magnitude of the satellite streak is straightforward, provided the stars are isolated (no other stars contaminate their vicinity) and they are not saturated. The process implies the computation of the flux of each star and of the streak and then the difference in the magnitude between the streak and each star. The apparent magnitude of the streak will be taken as the mean value from the streak comparison with each reference star.

3.2 Precise Object Tracking and Staring processing

The precise object tracking or staring observational strategies can be applied for known objects in order to update the observation database and their orbital elements. As opposed to sidereal tracking, this acquisition methodology produces a point-like image of the target object in a trailed star background. The strategy that is intended to be implemented for GENDARED is inspired by the one proposed in [1] and [3]. The image calibration, background estimation and the noise spikes removal steps are similar with the ones presented for sidereal tracking.

The star detection and removal process is presented in [3] and [4] and implies an iterative convolution and clipping method. The star streaks are all alike and are very similar to a 'rectangle function'. As a pre-requisite step to the iterative process we determine the streak length and orientation by applying the Fast Fourier Transform on the background free image and then the Radon transform [5]. The maximum value of the Radon transform applied on the modulus of the Fast Fourier Transform indicates the orientation of the streak s_θ. The zeroes (or the minimum and maximum) of the Radon transform profile in the direction of the streak orientation allow the computation of the expected streak length s_l. Having the streak length and orientation, we can generate a convolution kernel $Z(s_\theta, s_l)$ by considering the streak as a moving Gaussian PSF. The iterative process for the star detection implies the convolution of the background free image I_k^{-B} with the obtained filter:

$$\Lambda_k = I_k^{-B} \otimes Z(s_\theta, s_l) \qquad (1)$$

The convolved image contains convolution peaks which indicate where the streaks are. The next step in the iterative process is a clipping process, which selects the minimum between the pixel intensity in the background free image and the double of the corresponding value in the convolved image:

$$I_{k+1}^{-B} = \min\left(I_k^{-B}, 2\Lambda_k\right) \qquad (2)$$

Once the iterative process converges towards a stable solution, a binary extraction mask is created by clipping the final convolved image w.r.t. the noise level σ_n:

$$M^s = \begin{cases} 1, & \text{if } \Lambda_N > \sigma_n \\ 0, & \text{if } \Lambda_N < \sigma_n \end{cases} \qquad (3)$$

The clean star map containing only the detected stars is obtained by multiplying the background free image with the generated extraction mask. The clean star image is generated by subtracting the clean star image from the background free image.

For the detection of the target objects in the clean star image we can use the algorithm for the detection of saturated stars to generate a new image containing only the pixels identified to have an intensity over a specific threshold.

4 GENDARED SIMULATOR

In order to test the capabilities and performance of the processing algorithms to be implemented in the frame of GENDARED project, a CCD Image Simulator (CIS) was implemented in order to generate realistic CCD astronomical images.

The main characteristics and functionality of the GENDAREC-CIS is summarized in the following items:

- Configuration of the instrumental setup, including the telescope parameters (e.g. aperture and optical transmission), CCD parameters (e.g. pixel size, quantum efficiency, plate scale, ...), sky background brightness, observation parameters (e.g. seeing, centre FOV coordinates, ..),
- Simulation of a stellar FOV using as input a text file containing a list of stars with position (Right Ascension (RA) and Declination (DEC)) and magnitude,
- Simulation of stellar-tracks for moving objects, read from an input file containing, for each object, the initial and final position (RA, DEC) and magnitude,
- Simulation of images (including both stars and moving objects) acquired by telescopes in sidereal tracking or any other tracking (defined by RA and DEC angular speeds),
- Simulation of all contributions to the final signal in the CCD, including bias level, dark current, sky background, celestial objects (both, stars and moving objects),

- Simulation of all contributions to noise (at pixel level) in the CCD, including read-out noise, noise related to the dark current signal, noise related to the sky background signal, noise related to the objects signal,
- Simulation of a final image including all contributions for both signal and noise
- Simulation of a set of consecutive acquisitions, to obtain the track of a moving objects in different locations according the acquisition time (start and stop of the observation)

The bias signal and read-out noise introduced during the reading of the CCD are provided as input parameters to the simulator. The signal introduced due to thermal mechanisms is modelled by a configurable parameter, the dark current, defined as the number of electrons created by thermal effects per pixel and per second, which is another input parameter.

The simulator uses for the generation of stars in the FOV a text file, provided as input, containing the magnitude and position (right ascension and declination in degrees) of the stars, extracted from a Guide Star Catalogue. The stellar field is simulated by convolving the total signal of the stars, derived from its magnitude, with the instrumental PSF in the CCD location computed according a nominal astrometric transformation. The generation of the stellar field implies the computation of the total number of electrons produced in the CCD due to star brightness given the star magnitude, the exposure time, the telescope aperture and the quantum efficiency, the computation of the position of the star in the CCD image and the convolution of the total signal of the object with the PSF.

The PSF of a point-like source of light in the CCD is dominated by the seeing, and has been modelled as a 2-dimensional Gaussian distribution, with the standard deviation being computed using the seeing (the blurring of a punctual source of light due to atmosphere turbulence, measured as the full with half maximum (FWHM) of the distribution of the blurred light). A discrete PSF is then computed in a super-sampled grid (11 times the resolution of the CCD) up to a width of 4σ . The super-sampled grid allows the location of the light distribution in the CCD pixel with an accuracy of about 1/10 pixel.

The simulator uses for the generation of moving objects a text file, provided as input, including the position of the object at the beginning and ending of the exposure. The moving objects are simulated by convolving the total signal of the object derived from its magnitude, with the instrumental PSF along the track of the object in the CCD. The generation of the images from moving objects includes the computation of the total number of electrons produced in the CCD due to the object brightness, the computation of the initial and ending position in the CCD of the object given the celestial coordinates, and the convolution of the partial signal in each point on the track that is obtained by splitting the track according to the PSF grid (11 times the CCD grid).

A final simulated image is computed by adding noise to the total signal per pixel of the CCD. The noise added at pixel level follows a Gaussian distribution with the standard deviation equal to the total noise computed for a corresponding pixel. The final step implies the adding of cosmic ray events in the final simulated image. Cosmic Rays (CR) are spread randomly in the CCD with the following characteristics: random length up to 5 pixels (not homogeneous distribution), random direction, random signal (from 0.4 to 1.3 CCD saturation level), number of CR depending on the exposure time.

The simulator allows the generation of images assuming that the telescope moves with respect to the celestial frame at fixed angular speed in both RA and DEC axis. Note that sidereal tracking is a special case, with RA and DEC angular speeds equal to zero. Stars are simulated by convolving the elongated PSF in the coordinates of the star in the CCD computed at the beginning of the exposure (using the RA and DEC of the centre of the FOV at the beginning of the exposure). The PSF is rotated using the position angle computed from the RA and DEC angular velocities. Moving objects are simulated as in sidereal track mode, but the final position of an object is computed by taking into consideration the RA and DEC angular velocities.

In the following figures a set of images generated using the GENDARED simulator are presented. Figure 2 presents a simulated CCD image acquired during sidereal tracking, including three moving objects of different magnitude. Figure 3 presents the same three objects, but this time the image was simulated to be acquired during GEO tracking for one of the objects.

By comparing the two images one can observe the transformation of the point-like star images into trailed shape images and the transformation of the streak from sidereal tracking into a point like image corresponding to the GEO tracking.

The images of the three moving objects are also generated in the case of precise object tracking, as presented in Figure 4.

Figure 5 through Figure 9 demonstrates the capabilities of the simulator to generate a sequence of CCD images acquired in a close acquisition schema. The images are acquired with a 10 seconds exposure and with a 5 seconds time interval between them. The sequence of frames present the movement of three orbiting objects (marked with green).

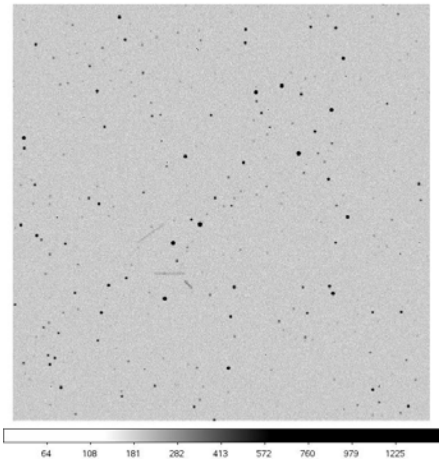

Figure 2. Simulated CCD image - Sidereal Tracking

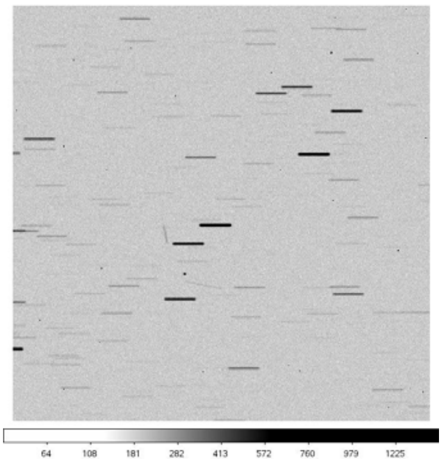

Figure 3. Simulated CCD image - GEO Tracking

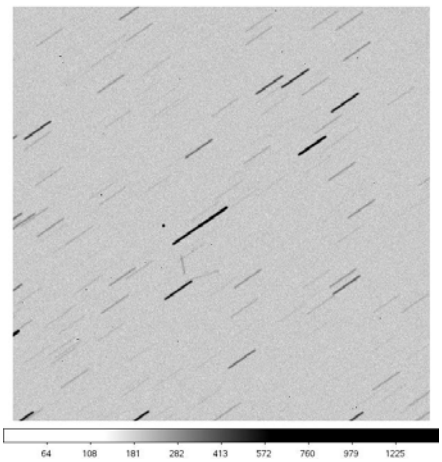

Figure 4. Simulated CCD image - Precise Tracking.

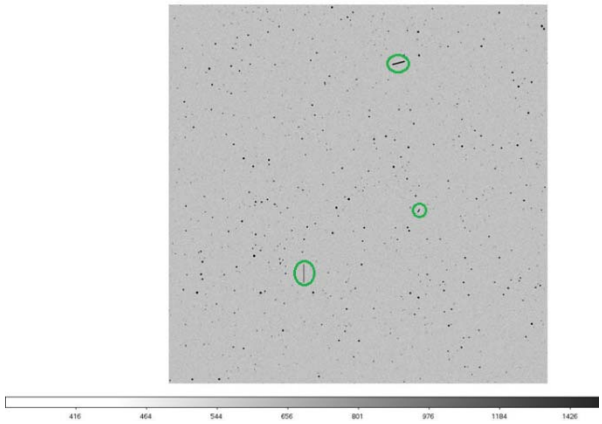

Figure 5. Simulated sequence of images - frame 1

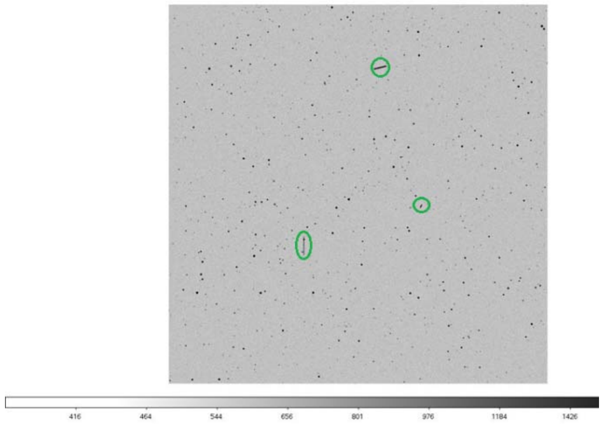

Figure 6. Simulated sequence of images – frame 2

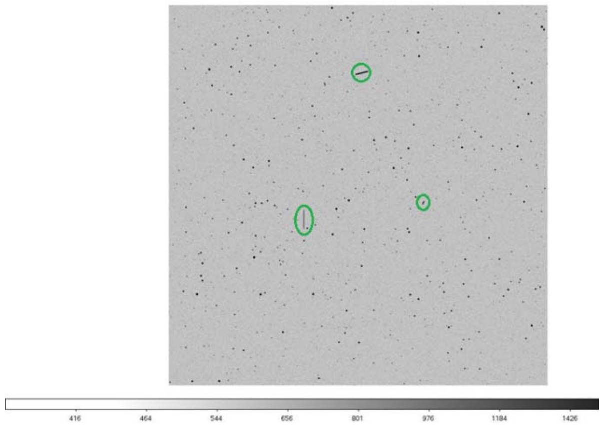

Figure 7. Simulated sequence of images - frame 3

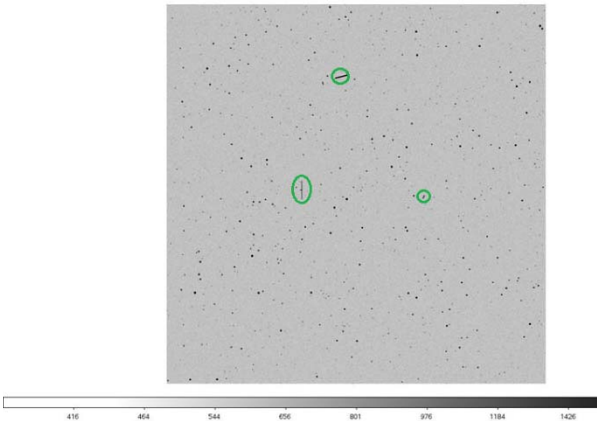

Figure 8. Simulated sequence of images - frame 4

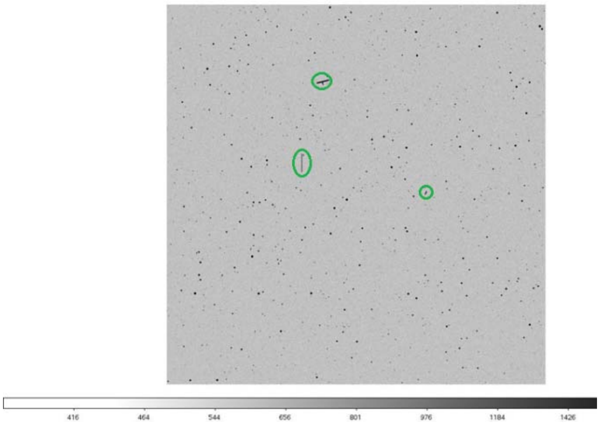

Figure 9. Simulated sequence of images - frame 5

The GENDARED simulator is also capable of simulating blooming effects for saturated stars. Figure 10 presents on the left hand side a CCD image simulated with blooming effects deactivated (in this case the surplus electrons are clipped at the saturation level) and on the right hand side a CCD image that presents blooming effects for three saturated stars. The blooming effect is implemented in the GENDARED simulator as an equal distribution on the vertical direction of the surplus of electrons for each saturated pixel.

Figure 11 and Figure 12 demonstrate the capabilities of the GENDARED simulator to generate realistic CCD images. In this scope, a real CCD image acquired with the telescope infrastructure available from BITNET-CCSS was selected (Figure 11) and was regenerated using the simulator (Figure 12). The noticeable differences include the appearance of random cosmic ray events in the simulated image, and the differences in the magnitude of the generated stars, which is due to the difference in the filters that were used to acquire the real image and the images and the filters used during the building of the GSC star catalogue.

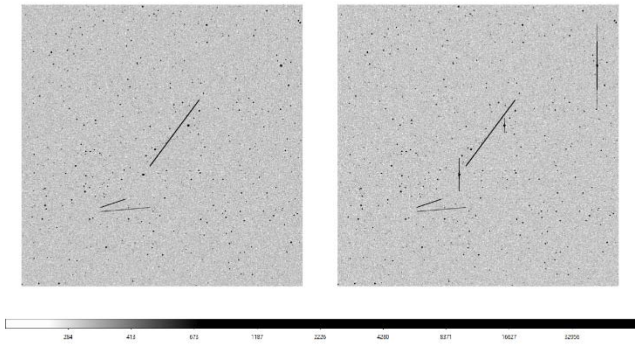

Figure 10. Simulated CCD image with blooming deactivated (left) and with blooming activated (right)

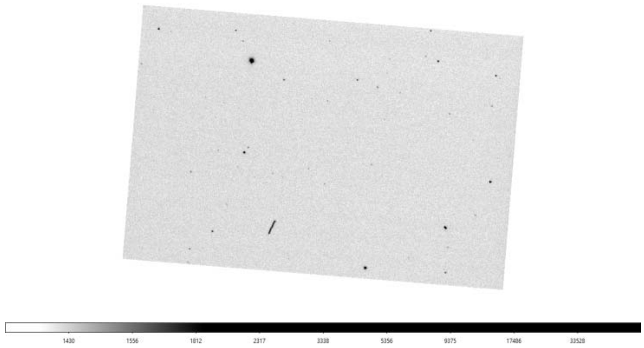

Figure 11. Real CCD image

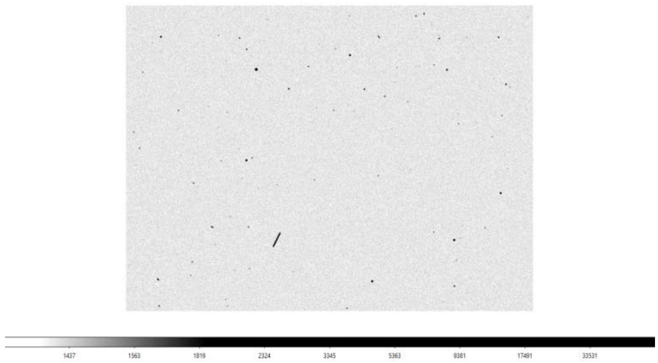

Figure 12. Simulated CCD image

5 CONCLUSIONS

The paper presents the functionalities to be implemented by a framework intended to process the observational data to be acquired by autonomous robotic optical telescopes focussed in the surveillance, cataloguing and monitoring of Earth Orbiting Objects and the full automatic processing to be orchestrated by it.

The GENDARED framework will be fully independent and autonomous for the entire time of its activity, being able to monitor for the reception of new input data from the telescope infrastructure, to automatically process the data and to securely transfer the obtained astrometric and photometric data for the detected target objects to the SST back-end.

The Data Reduction environment is designed in a modular way, as a chain of sub-processing elements, each one being responsible for a specific step in the reduction process. Composing the pipelines from stand-alone and independent processes will enable the GENDARED framework to process in parallel multiple input datasets. Also, the whole Data Reduction process can be easily updated just by installing new versions of selected processing elements implementing improved and accurate processing algorithms.

Through the use of the HMI, the GENDARED operator is able to monitor the full activity of the framework and the status of the processing, to define the behaviour of the processing by modifying the configuration of the framework and the design of the pipelines to be applied for the processing of the input data, and is also able to control the processing of particular input datasets (start, stop, resume and abort the processing).

In the near future, after the implementation of the framework, results on the capabilities of GENDARED will be provided.

The paper also presents the capabilities of the GENDARED simulator implemented for the generation of realistic images to be used for testing the capabilities and performance of the processing algorithms to be implemented in the frame of GENDARED project. The simulator allows the configuration of the full instrumental setup (including telescope parameters, CCD parameters and observation parameters), the simulation of all contributions to the final signal and noise in the CCD image, and the simulation of sets of consecutive images acquired in a close acquisition schema with any kind of traking (defined by RA and DEC angular speeds of the FOV).

6 REFERENCES

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