gendared: THE GENERIC DATA REDUCTION FRAMEWORK FOR SPACE SURVEILLANCE AND ITS APPLICATIONS

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ABSTRACT

Space Surveillance and Tracking (SST) requires the development of observational campaigns to early identify Earth orbiting objects, estimate their orbital elements and monitor the evolution of their trajectories. In this context, The *Generic Data Reduction Framework for Space Surveillance* - ***gendared,*** prototyped initially by GMV in the frame of an ESA Romanian Industry Incentive Scheme project, is intended to be used in order to support the operational reduction of the image data acquired by optical telescopes. ***gendared*** receives as input the raw images taken by the telescope, and generates as output astrometric and photometric data for the target objects detected in the observation images. As of the end of the prototyping phase and the acceptance of the software by ESA, ***gendared*** has been further developed and used in a number of operational and research & development projects.

1 *gendared* PRODUCT

The Space Surveillance is defined as a comprehensive knowledge, understanding and maintained awareness of:

- the population of space objects,
- the space environment,
- the existing threats and risks.

The overall aim of the Space Surveillance programmes is

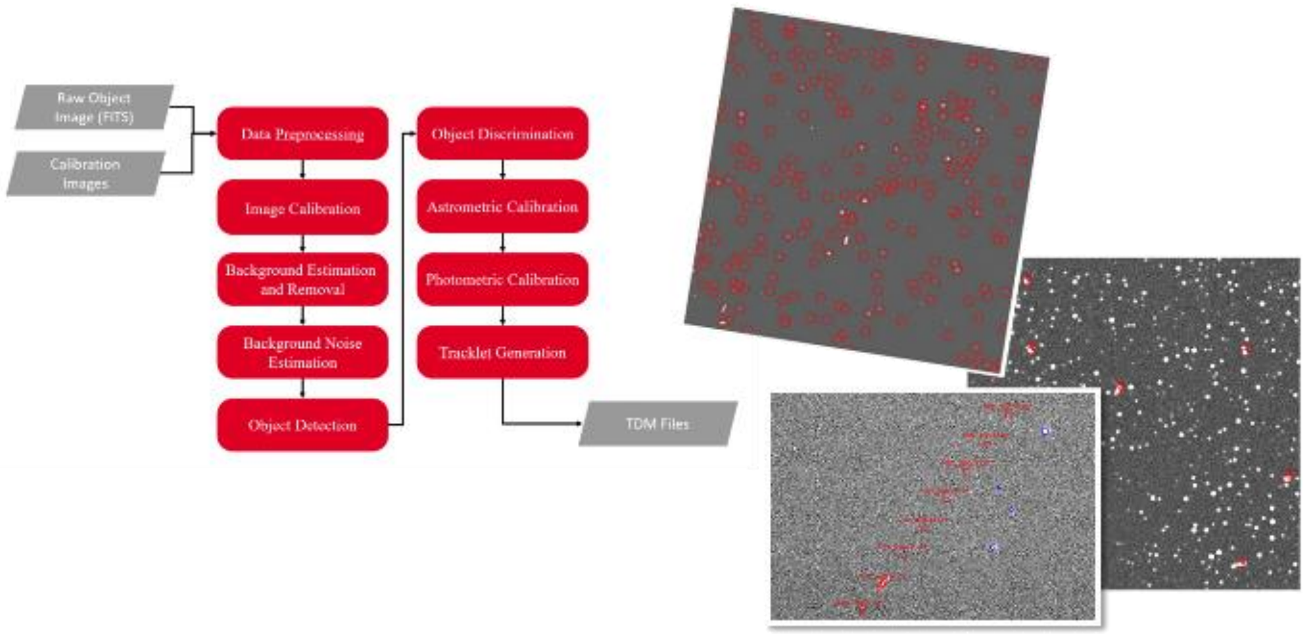

*Figure 1: **gendared** pipeline*

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to support utilisation of and access to space for research or services, through providing timely and quality data, information, services and knowledge regarding the environment, the threats and the sustainable exploitation of the outer space surrounding our planet Earth.

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) optical telescopes, and
- the development of a Data Processing Framework able to process the acquired images, identify potential target objects, correlate object measurements in consecutive exposures according to the observational schema and provide precise measurements of the position and brightness for all retrieved objects.

Considering the increasing interest in Space Surveillance at both European and worldwide levels, a growing number of initiatives are being developed to define new tools or to exploit the existing ones (telescopes) for SST. Nevertheless, it is noted that the observation strategy followed in SST campaigns differs from that used in standard astronomical imagery. In addition, SST requires a quick analysis of the observational data to identify and/or update the orbital data of target objects as soon as possible. Therefore, SST systems must implement an Image Data Reduction Subsystem, able to timely process the continuous exposures taken in automatic and continuous way.

The *Generic Data Reduction Framework for Space Surveillance* (***gendared***) is intended to be used within the Space Situational Awareness system in order to support the operational reduction of the image data acquired during observational campaigns, to collate and deliver astrometric data. ***gendared*** receives as input the raw images taken by the telescope (both observation and calibration images) together with all required additional information (list of images corresponding to the same observation session, defect map), and generates as output astrometric and photometric data for the target objects detected in the observation images.

The key aspects that drove the design and development of such a Generic Framework can be summarised as follows:

- The Image Reduction process shall be fully autonomous and unassisted, able to process incoming images according to a specific logic and not requiring the support of an operator.
- Full Image Reduction process shall be fast enough in order to allow the processing of high image acquisition rates, typically some images per minute, in (near) real time, that is, neither delays nor blockages must occur in the processing of the images taken in a closely continuous acquisition schema.
- Image Reduction algorithms must be able to cope with different acquisition schemas including no tracking, sidereal tracking, precise object tracking and rough object tracking.
- 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.
- The Data Reduction environment shall be 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.

1.1 *gendared* PIPELINE

As described above, the ***gendared*** solution aims the operational processing of image products acquired by Space Surveillance Optical Telescopes. It thus consists of **robust**, **autonomous** and **operational** software.

We summarize here the steps to be executed by the different processors in the ***gendared*** pipeline. A schematic of the ***gendared*** workflow is shown in Fig. 1.

Image calibration: 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 or uneven chip illumination.

Background estimation and noise estimation: The next step is the removal of the image background. The background estimation is used to account for non-instrumental effects, in order to obtain a precise detection of the objects and correctly measure the flux. The main source of background variations is the star glow.

Object detection: In this step, all objects in the images are detected, regardless of object type.

Object discrimination: The detected objects are classified as object of interest / star / cosmic ray.

Astrometry: The astrometric calibration requires the identification and measurement of the position of a set of reference stars in CCD coordinates.

Photometry: The photometric calibration also uses the matching between CCD images and reference stars, and it is based on the relationship between the electrons measured in the CCD and the apparent magnitudes of the stars.

Tracklet generation: After the per-frame processing of a sequence of images, ***gendared*** will generate tracklets, which contain the trajectory of an object of interest identified in multiple images in the dataset. The tracklets are formed as sets of collinear points (centroids) resulted from processing consecutive frames.

analyse the input datasets and generated products and generate quality information.

A high-level view of ***gendared***'s structure is depicted in Fig. 2.

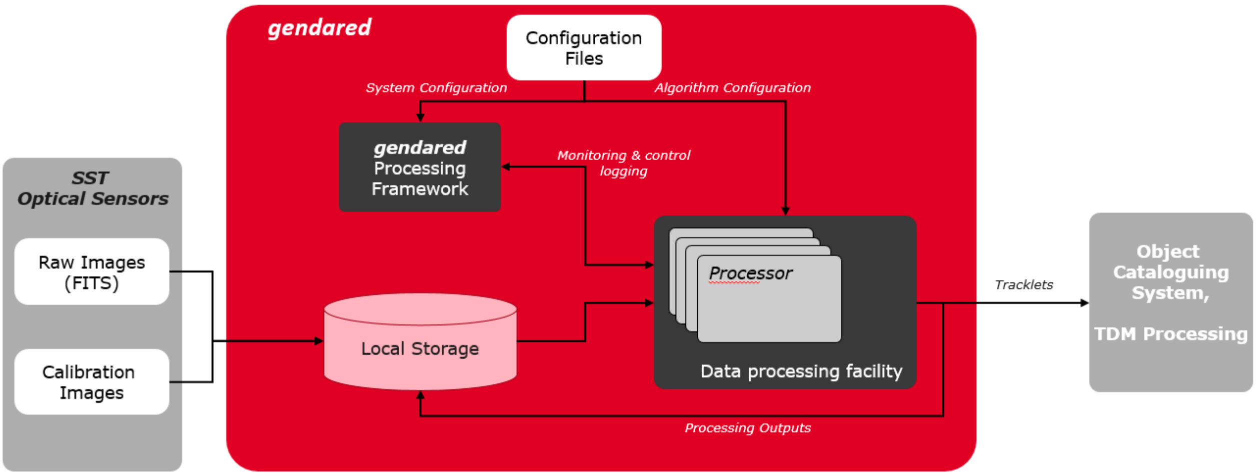

*Figure 2: **gendared** high level structure*

1.2 *gendared*'s MAIN COMPONENTS

gendared's main components are:

- The ***gendared*** framework, containing:
  - The Processing Manager Facility (PMF), in charge of controlling and monitoring how the different components of ***gendared*** run from the SW point of view, and driving the overall processing.
  - The Command Line Interface (CLI) implements the user commands interface that is used by the ***gendared*** user to issue commands and pipeline orders to ***gendared***.
- The ***gendared*** Processing Environment, containing:
  - The Data Reduction Facility (DRF), the component implementing the image reduction process. This component is composed by atomic and self-contained elements each implementing a specific step in the reduction process. The execution of these elements are driven by the Processing Manager Facility in order to build the required pipeline processing.
  - The Product Quality Control (PQC), implementing the functionality to automatically analyse the input datasets and generated products and generate quality information.

1.3 SELECTION of *gendared* NEW ALGORITHMS

The task of accurately detecting and discriminating satellite streaks and stars in images is crucial in order to generate satellite tracks. A lot of methods can be used for this purpose. The most obvious one is to use a **simple threshold technique** on pixel values to build clusters of pixels corresponding to astronomical light sources or artificial satellites. These clusters of pixels are then statistically analysed to obtain their precise position and other geometrical characteristics that will further permit us to classify them into **point-like** and **non point-like** classes.

In function of the observational context, either *satellite-tracking* or *star-tracking*, the point-like class will correspond to either satellites or stars. The star list of sources will serve as input for establishing the **astrometric solution** for the image while the satellite list of sources will be used as input to the **tracklet generation** processor.

As stated previously, the preliminary source list obtained by the image threshold algorithm will be used to classify the sources and detect the class of the strongest sources that correspond to satellite (or star) streaks. When a list of streak images is obtained, it is used to build a **shape**

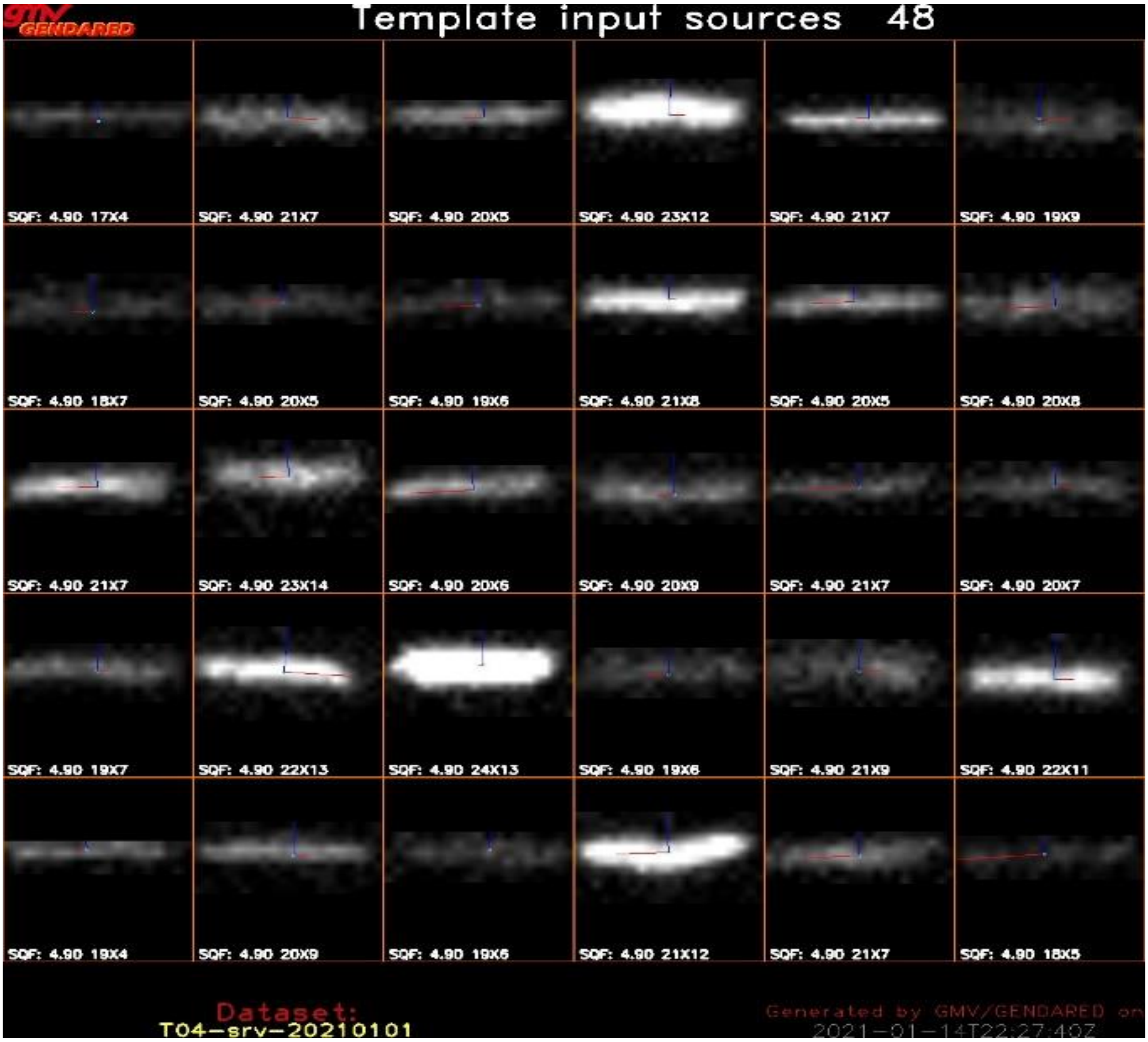

Figure 3: Example of source images used for the shape template creation

image template. This template will then be **cross-correlated** with the images to detect with precision all the matching shapes on the images. An example of source images used for the creation of the shape template is depicted in Fig. 3.

Therefore, a shape template image is built representing the average aspect and relative intensity of the star or satellite streaks present on the images, as shown in Fig. 4. The next step is to **cross-correlate** this template image with our dataset images to **precisely detect the streaks** visible in our images, even the very faint ones if we lower the detection threshold in the correlation image. This method can be applied to both observation modes that we are interested in – sidereal and precise object tracking. An example of detections on satellite-tacking images, where stars appear as streaks and satellites as point-like, is presented in Fig. 5. Fig. 6 further shows an example of detections in survey images, where stars appear point-like and the satellites appear as streaks.

Figure 4: Example of template shape image (21x9 pixels) obtained.

Figure 5: Example of detections on a satellite-tacking images. Stars appear as streaks (purple) and satellites as point-like (yellow).

Figure 6: Example of detections on survey images. Stars appear as point-like (yellow) and satellites appear as streaks (purple).

For the tracklet generation processor, the core idea of the algorithm is to **detect satellites based on their motion dynamics**. To summarize the method, the acceleration vector is computed for each possible triplet of candidate points in 3 successive images. If the amplitude of this acceleration falls below a configurable threshold, this triplet is then considered to be the beginning of a new track. Then, a recursive walk on the following images will be performed to look for new track points that will be accepted in the track if the resulting acceleration vector is similar with the last track's acceleration computed. An example of satellite tracks is shown in Fig. 7.

This algorithm relies on two assumptions that are more or less acceptable. First, it is assumed that the observer is lying at earth's centre and that the satellites are flying on a radius-1 sphere cantered on it. The measurements in the observer's reference frame will of course be more accurate if the object's altitude is high, and less accurate if it is flying low. The second assumption is that the acceleration amplitude is not changing between two observations, this is perfectly true for circular orbits, and is not for elliptic ones. But, even in the case of elliptical orbits, the net acceleration amplitude change between two close-in-time measurements is very low, so that this assumption is more than acceptable.

Finally, in order to obtain the astrometric performance of ***gendared***, the generated measurements from the astrometric reduction process are compared to precise reference orbits compensating for potential time bias and other perturbations. An example of the obtained astrometric performance is shown in Fig. 8.

2 PROJECTS BASED ON *gendared*

2.1 RONOCOPS

This project consists of operational data processing services for Romania's National SST Operational Centre (COSST). Within this project, ***gendared*** is one of the two key SW elements of a fully automated, operational processing chain for SST service provision:

- Configuration of processing pipelines for a variety of Romanian SST optical sensors.
- Continuous monitoring for the receipt of new SST observations, from the several sensors.
- Timely reduction of the FITS images to obtain tracklets (TDM files) with the positions of the objects of interest identified in the observations (either survey or tracking).
- Internal interface with the ***sstod*** SW element for the correlation, validation and upload of TDM files in EUSST DB.

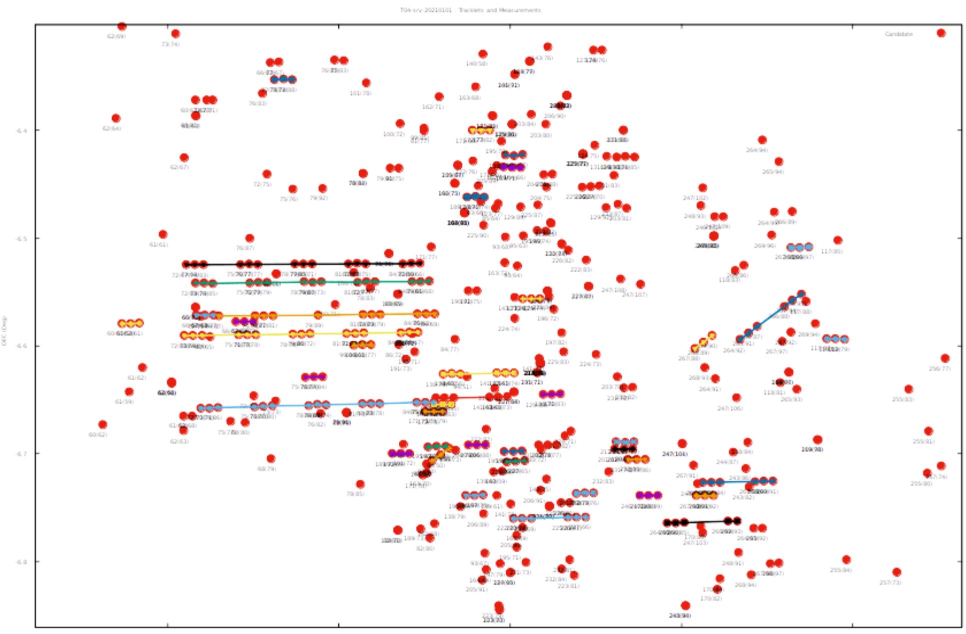

Figure 7: Example of satellite tracks. The high number of false positive point-like sources (red dots) is due

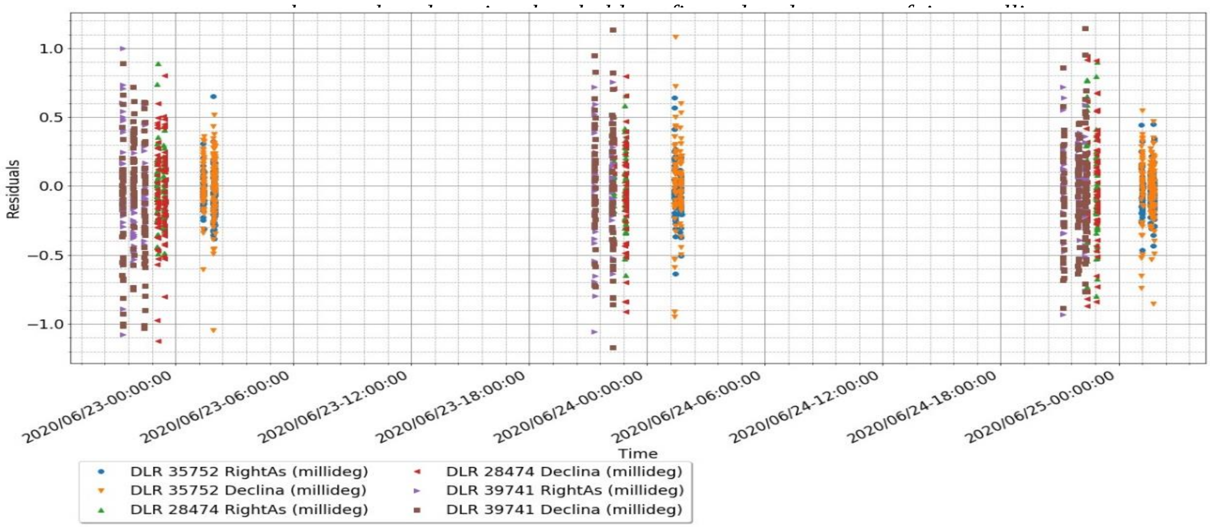

Figure 8: Residuals for NAVSTAR objects - metrics for gendared astrometric performance:

2.2 DLR-ODPS: OPTICAL DATA PROCESSING SOFTWARE

The goal of this project was upgrading ***gendared*** for the operational processing of image products acquired by German Aerospace Centre (DLR) telescopes. This consists of robust, autonomous and operational software in charge of:

- Receiving a continuous and asynchronous flow of data from SST sensors.
- Process received datasets in order to identify objects of interest in the observations, and retrieve accurate measurements of their apparent position and magnitude.
- Generate tracklet information for the identified target objects in appropriate format and send these data to the SST Cataloguing System for further analysis and processing.

2.3 AI4GENDARED

This R&D project aims to upgrade the ***gendared*** framework for SST data reduction with AI algorithms for astronomical image processing. The project involves a consortium led by GMV, with the Faculty of Automatic Control and Computer Science and the Astronomical Institute of the Romanian Academy as partners, with the following objectives:

- Review state-of-the-art AI algorithms and solutions for astronomical image processing, and integrate a selection of the relevant ones into the current ***gendared*** framework.

- Improve ***gendared*** performance by reducing user involvement and computational costs.
- Tailor image detection and multi-frame processing (tracklet generation) pipelines to telescope specifications and characteristics.
- Test and validate the algorithms on real telescope data and representative simulated scenarios.

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We further discuss the technical details to be addressed by AI4GENDARED in order to optimize the processing of large amounts of observational data to be acquired by optical telescopes and facillitate the functioning of the system in an operational environment. Key innovations with respect to current state-of-the-art automatic image detection techniques are addressed.

AI4GENDARED will receive as input the raw images taken by the telescope together with the required additional information, and will generate as output astrometric and photometric data for the target object identified in the observation images.

- **Image Detection.** We propose to use Neural Networks (NNs) to turn the image detection problem into a classification one (e.g., [2]). Artificial Intelligence methods for automatic image detection are a substantial improvement over more traditional iterative techniques, such as those used in [1], [5], [6], [7], [8]. The use of techniques such as principal component analysis (PCA) to compress the redundant information, and unsupervised NNs, will lead to ***algorithm optimization***, ***reduction of computational costs***, and ***conceptual simplification***.

- **Telescope Orientation.** We propose to use Pattern Recognition techniques to solve the problem of incomplete telescope data regarding its orientation with respect to the sky. Such algorithms will use star-maps based on astronomical catalogues, e.g. UCAC4 ([9]) or GAIA ([10]), to train the NN. This will yield to ***configurability***, since the algorithm can be tailored to telescope specifications, as well as ***reduction of computational costs*** and ***increased pipeline autonomy***, since the need for user involvement for telescope information would be significantly reduced.

- **Object Classification.** We propose to use NNs to classify the objects in an image as satellite, star or cosmic rays. Similar classification methods have been used in [3]. This technique will lead to ***true source detection rate improvement*** (i.e., the ratio between the real objects detected and the number of objects from the star catalogue used to validate the results).

- **Tracklet Generation.** We propose to use NNs to identify and predict tracklet patterns, i.e. to connect consecutive images in an observation sequence to generate object tracklets. This will be a significant improvement over iterative algorithms currently used (e.g., [4]), and will lead to ***reduction of computational costs*** and ***increased pipeline autonomy.***

3 CONCLUSIONS AND FUTURE PROSPECTS

The ***gendared*** solution developed by GMV for the operational reduction of astronomical data has proven to be successful and has been developed in several directions under the umbrella of various projects, as discussed in Section 2. Further developments are planned for the ***gendared*** product, including improvements in the detection & discrimination and tracklet generation algorithms, using both AI and traditional methods. In addition, an easier control of the ***gendared*** product is planned through the development of a graphic interface. Further plans include the potential to evolve ***gendared*** as a service, as well as improvements for the tool in the operational context.

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