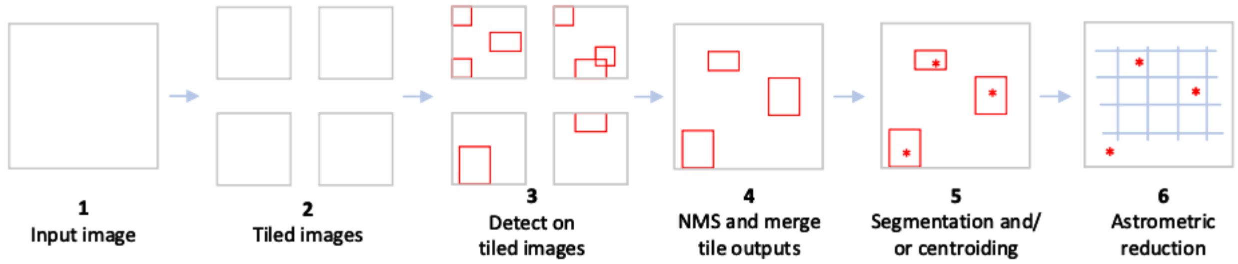

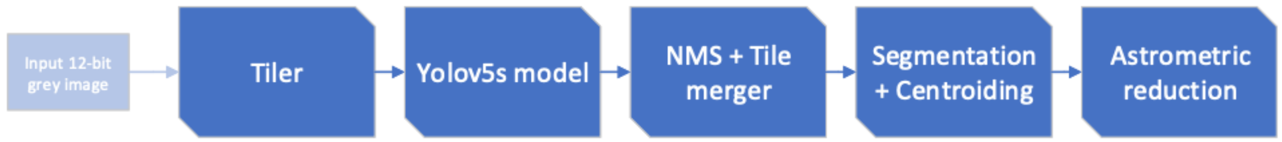

Hybrid Edge-Cloud AI Accelerated Astrometric Reduction Pipeline for Agile Near-Real Time In-Situ SST

Executive Summary

ESA Initial Support for Innovation (EISI) Study

OSIP Campaign: Cognitive Cloud Computing in Space

Affiliation(s): Vyoma GmbH (Prime), Ubotica Technologies Ltd. (Sub 1)

Activity summary:
With the increasing number of resident space objects (RSOs), the ability to accurately track and catalogue these objects becomes more difficult. Space-based Space Surveillance (SBSS) systems can overcome the limitations of ground-based systems by providing a scalable solution and increasing the accuracy of RSO catalogues. However, these systems can be limited by the capacity to downlink the large amount of data generated on-board. This study addresses this issue by reducing the data at the sensor level, through the use of Computer Vision (CV) enabled by onboard Artificial Intelligence (AI) accelerators. Results obtained confirm the feasibility of such approach, with remarkably high detection rates, even at low signal-to-noise ratios.

Publishing Date: 2022-12-15
Contract Number: ESA EISI-I-2022-00365
Implemented as ESA Initial Support for Innovation

Hybrid Edge-Cloud AI Accelerated Astrometric Reduction Pipeline for Agile Near-Real Time In-Situ SST

EXECUTIVE SUMMARY

Version	1.0
Date	15 December 2022
Authors	M. Caceres, J. Salazar, M. Sacchi, D. Rijlaarsdam, L. Buckley, F. Buckley
Document ID	Vy-ASTROREDML-ES
Reference Code	ESA EISI-I-2022-00365

Executive Summary

The ESA Initial Support for Innovation (EISI) study "Hybrid Edge-Cloud AI Accelerated Astrometric Reduction Pipeline for Agile Near-Real Time In-Situ Space Surveillance and Tracking" aims at accelerating the Technological Readiness Level (TRL) maturation of a cost-effective Next Generation (NG) Space-based Space Surveillance (SBSS) mission concept [AD-01].

Devised around a hybrid edge-cloud architecture, and supported by novel Computer Vision (CV) techniques for the different steps of the feature extraction and measurement formation chains, the processing pipeline will be deployed on Commercial Off-The-Shelf (COTS) hardware to accelerate Deep Learning (DL) models both on-board (edge) and on-ground (cloud), enabling a scalable and cost-effective concept of operations (CONOPS).

The exponential growth of the Resident Space Object (RSO) population in Earth's orbit has created huge operational limitations for current ground-based Space Surveillance and Tracking (SST) systems. With the increasing number of satellites, debris, and other objects in space, the ability to accurately track and catalogue these objects becomes more difficult.

One potential solution to this problem is the use of space-based Space Surveillance (SBSS) systems. These systems, which are placed in orbit around Earth, can overcome the limitations of ground-based SST systems by providing a scalable solution and increasing the accuracy of RSO catalogues.

However, even SBSS systems can be limited by the capacity to downlink the large amount of data generated on-board. This creates a need to reduce the data at the sensor level and decrease the latency of processing and delivering Space Situational Awareness (SSA) products.

One way to address this challenge is through the use of Artificial Intelligence (AI)-accelerated Machine Learning (ML) and Computer Vision (CV) technologies. These technologies can help to cost-effectively reduce the amount of data generated on-board and increase the speed of processing and delivering SSA products.

Vyoma's SBSS Mission

Vyoma is building Europe's first commercial Space-Based Surveillance System (SBSS) with the goal of building up an independent high-accuracy debris-object catalogue for the Low Earth Orbit (LEO) regime and improving upon existing object catalogues to provide real-time space domain awareness across all orbit regimes. Ubotica's AI acceleration technology is one of the key enablers that will make our vision a reality.

The system will observe 90% or more of the space population objects greater than 5 cm in high LEO, and 10 cm in LEO objects greater than 35 cm in Geostationary Earth Orbit (GEO). This will provide a measurable improvement on object orbit determination compared to existing systems by increasing the frequency and timeliness of observations, as well as increasing the accuracy of extracted data from images.

In addition, the system will improve the estimation of resident space object properties (such as size, mass, materials, and brightness levels) through photometry and light curve analysis. It will also allow for tasked tracking of objects of interest, particularly in the LEO regime.

Vyoma's SBSS mission viability needs to be approached with a focus on minimising operational costs. This can be achieved by optimising dump operations, either prioritising images with detected objects, or reducing the data on-board. By doing this, the mission can reduce power consumption during data dump contacts, shorten dump contacts, or downlink less often.

Such on-board processing has an impact in the space segment sizing trade-offs. This may involve increasing the power and thermal budgets of the Application and Data Processing Units in favour of less performant and power-hungry Payload Communications Unit. At the same time, the mission can decrease mass storage requirements to reduce overall costs.

On-board processing is also an enabler of higher operational autonomy, reduces complexity in ground operations and infrastructure, leading to cost savings. Additionally, streamlining payload operations such as calibration and on-board software updates will help to optimise the mission and ensure its success.

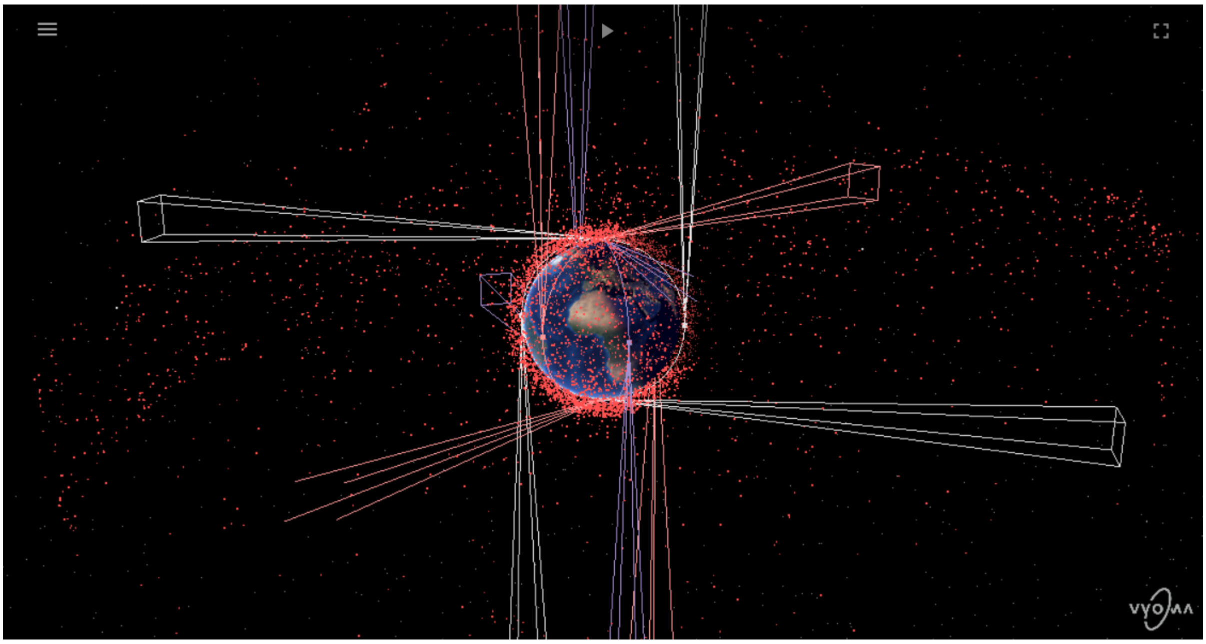

Figure 1: Vyoma SBSS Mission Concept

Ubotica Technologies Ltd. And CogniSAT™

Founded in 2016, Ubotica Technologies provides technical expertise in the areas of Computer Vision and Machine Learning in embedded systems at the Edge. Ubotica is headquartered in Ireland with a team of AI Engineers based in Dublin City University (DCU) Alpha, Glasnevin, Dublin and also has a team of Computer Vision Engineers in Spain based in Universidad de Castilla La Mancha (UCLM), Ciudad Real.

The founders of the company have over one hundred years of combined expertise in the information technology sector and have been instrumental in the success of several companies including Parthus Technologies (silicon IP), GloNav (GPS receivers) and most recently Movidius (low power vision processing), which was acquired by Intel in 2016.

Ubotica has developed Computer Vision and Machine Learning algorithms for several different market segments including Space, IoT, Industry 4.0 and Biomedical. The Intel Movidius Myriad family of Vision Processing Units (VPU) is used to provide Computer Vision and Machine Learning functionality for many of Ubotica's solutions.

Ubotica is leading the race to deploy advanced Artificial Intelligence technologies on board every satellite. CogniSat™, our Hardware and Software platform, is the most comprehensive, adaptable, and power efficient solution for AI on-board satellites, providing the capability to overcome the bottlenecks that have curtailed the Satellite Data Services sector to date.

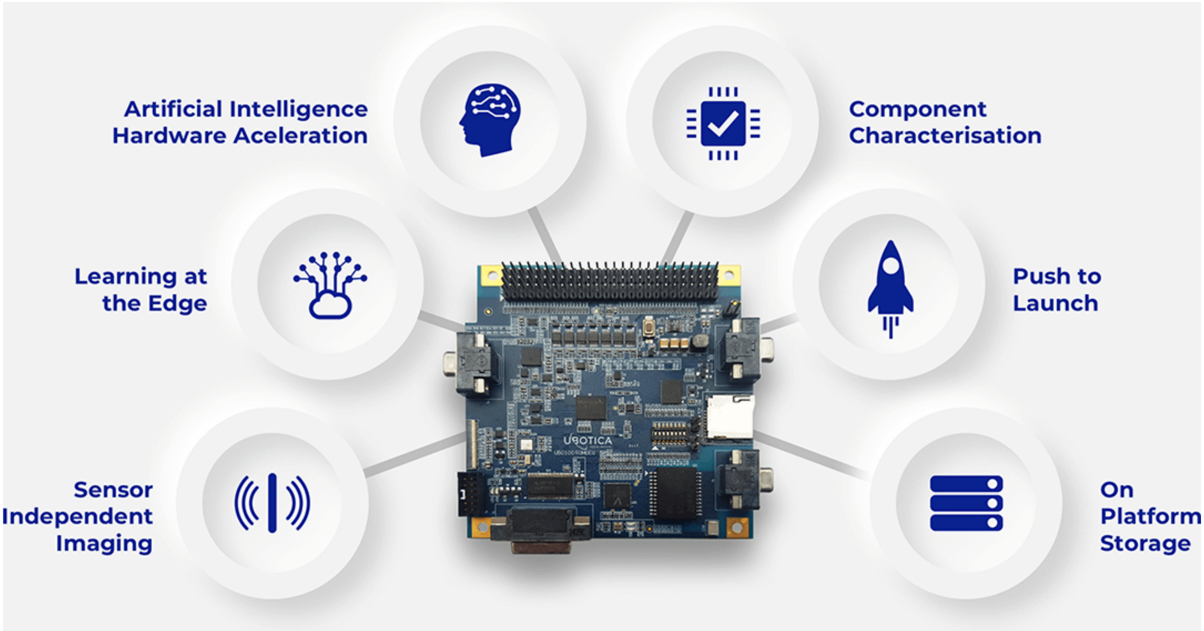

Figure 2: Ubotica's CogniSAT™ On-Board AI Acceleration Platform

Study Objectives

Within this context, the objective of this study is to design and implement a hybrid end-to-end astrometric reduction pipeline that can efficiently and accurately process space-based space surveillance and tracking data. The pipeline will consist of a series of steps that will be performed on both edge and cloud platforms, with the goal of optimally utilizing the available computing and communication resources.

To achieve this, we will first generated a set of synthetic training and validation data that incorporated relevant optical and dynamical models. This data was generated using a physics-based simulator, designed to consider a wide range of operational configurations and scenarios.

Next, we trained data-driven models for the various steps in the pipeline using the synthetic training data and machine learning frameworks that are compatible with the edge and cloud target platforms. We optimized these models for the target acceleration runtime environments, and integrated them into a dedicated test bed for evaluation.

Finally, we evaluated the end-to-end performance of the developed pipeline in terms of relevant key performance indicators, analysed its achievements and shortcomings, and identified improvements, solutions, and opportunities to push the technology forward.

Concept of Operations

The proposed astrometric reduction pipeline follows the common processing strategy of reduce-first, then calibrate.

The first step, image reduction, involves extracting the most relevant features from a raw data frame. In the case of astrometry, this might include detecting streaks left by objects in the field-of-view, as well as detecting and extracting the centroids and total intensities of both objects and the brightest stars in the frame.

The next step, astrometric calibration, involves using these extracted features to identify the portion of the sky field in the background, and estimate the astrometric coordinates of the objects' extracted spatial features (like centres of mass, streak length) in order to form tracklets (angles) and light curves (magnitudes).

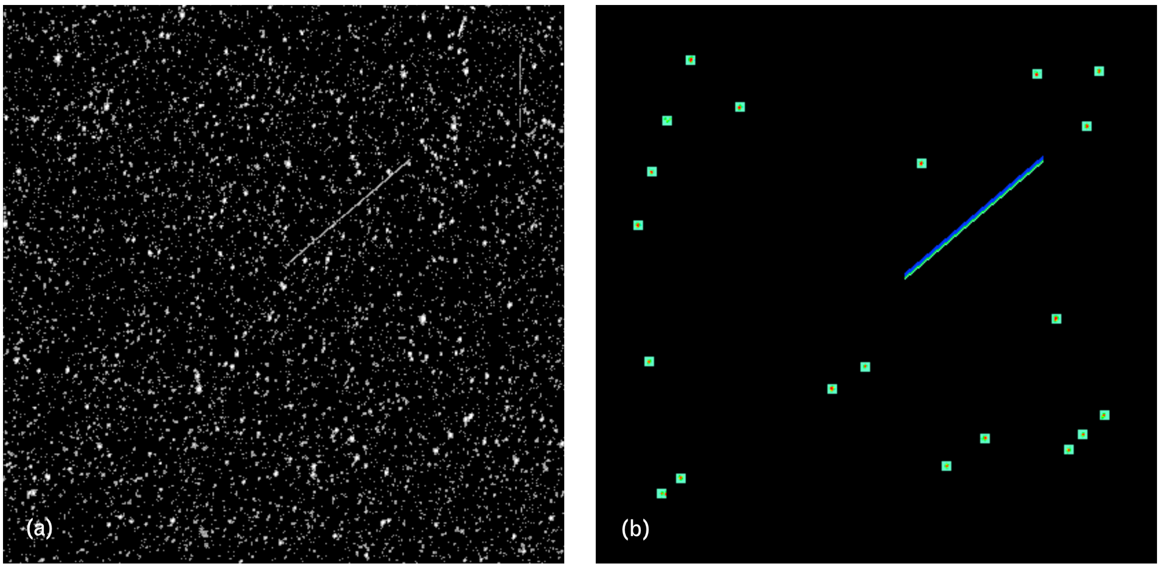

Figure 2: Example raw frame and corresponding visual representation of a reduced frame.

Synthetic Image Generation Framework

Vyoma's comprehensive physics-based framework for the generation of realistic space-based observations is a significant achievement in the field of space observation. The framework is based on two key steps: orbital simulations and photometric synthesis.

Orbital simulations are used to accurately model the trajectories and attitudes of both the observer and target, based on high-accuracy orbital dynamics. This is an essential step in generating realistic space-based observations, as the position and orientation of the observer and target have a major impact on the visibility of objects in space. The process involve simulating the trajectories of both an observer and a target in order to predict times when the target will be visible to the observer. This can be useful for a variety of purposes, including tracking objects in orbit and predicting when they will be visible from a particular location.

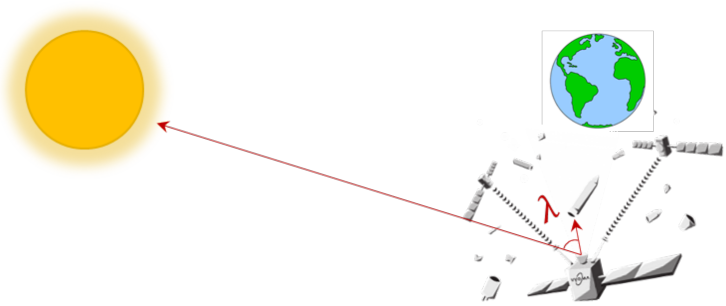

Figure 3: Illustration of Sun phase angle.

Electro-optical rendering is the second step in the process, and involves modelling the visibility of objects based on their brightness and the payload properties of the observing system. This step takes into account factors such as the sensitivity of the payload's detectors and the atmospheric conditions at the time of observation.

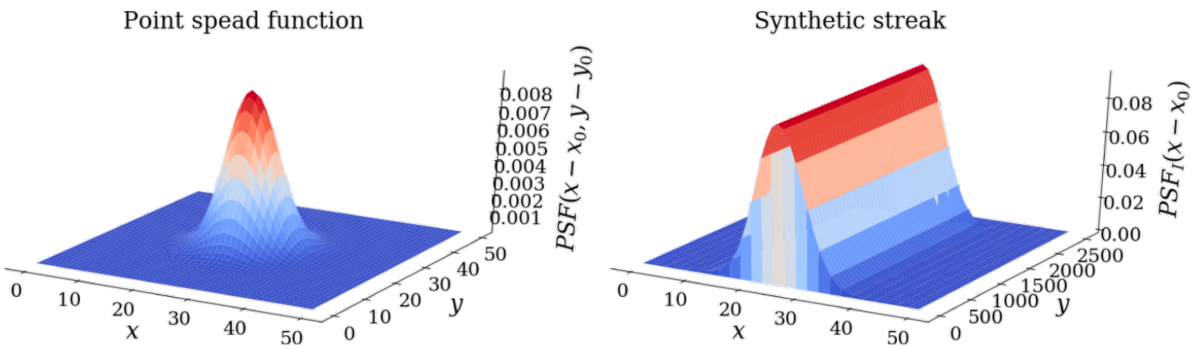

Figure 4: Point spread function and streaks on CCD

The technique used simulates the photometric and astrometric aspects of space-based observations, based on the properties of the objects in visibility, and the above-mentioned payload electro-optical characteristics. The main objective of this technique is to create a self-consistent model of the telescope and detector performance, as well as the photometric properties of the targets being observed. This involves implementing a realistic sky background brightness, detector noise, and image defects, as well as accurately positioning the targets and background stars in the image frame, with a sub-pixel accuracy greater than the one expected to be attained by the feature extraction processing.

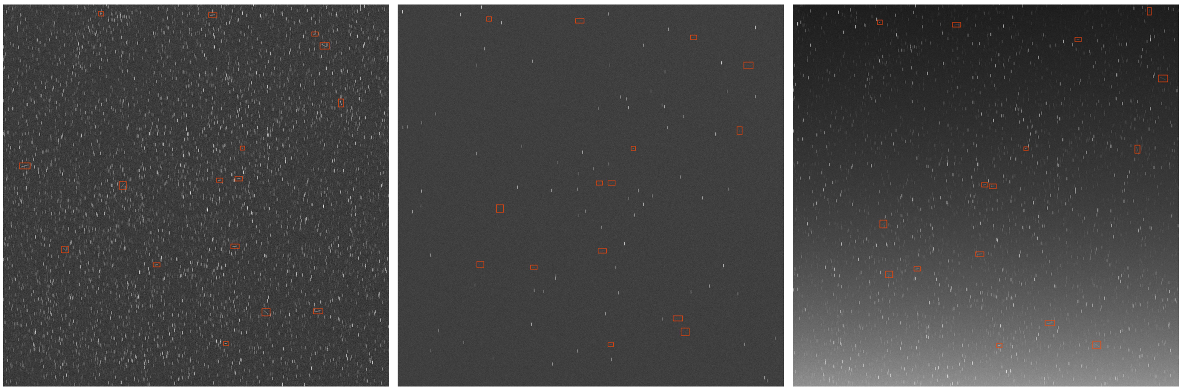

Figure 5: Sample synthetised images with different Galactic background and atmospheric gradient settings

Processing Pipeline

The processing strategy is depicted in the figure below.

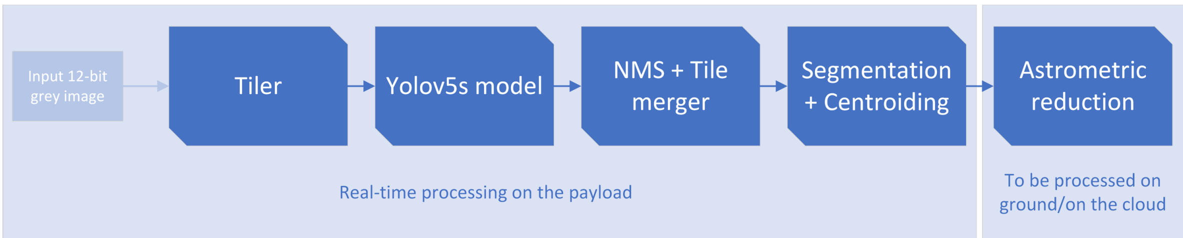

Figure 7: Processing Pipeline Logical Architecture

Tiling and normalisation are important techniques in image processing that allow for the efficient handling of large resolutions. By dividing the input image into smaller, more manageable dimensions, it becomes easier to process the image in a timely manner. However, there is an optimum trade-off between tile size and processing speed, and it is important to find the balance between the two.

For the task of streak detection, the YOLOv5 model has been selected, due to its proven record of reliability and effectiveness due to its state of the art accuracy and inference speed. This model has demonstrated its robustness and versatility in various applications, including SST, and has been tested and customized on different devices to ensure optimal performance.

The NMS (Non-Maximum Suppression) algorithm is a technique used in computer vision to eliminate redundant or overlapping bounding boxes in object detection. It is typically used after object detection algorithms have identified potential objects in an image, but before the final list of detected objects is presented to the user.

The Tile merger or mosaïc'er algorithm is a tool that is used to combine multiple tiles and labels together to form a larger image or mosaic. It takes in a set of tiles and labels and combines them in a way that preserves the integrity of the individual tiles while creating a cohesive whole.

Segmentation is particularly useful for curvilinear streaks, as it allows to accurately estimate the centre of mass and total intensity of these objects. This information is critical for understanding the properties of these streaks and how they evolve over time.

The astrometric reduction is based on Astrometry.net's maturity and versality for solving the orientation of frames according to the visible starfield, while enabling measure accurately the positions of resident space objects detected in space.

The following data flow that illustrates the data transformations at each of the steps:

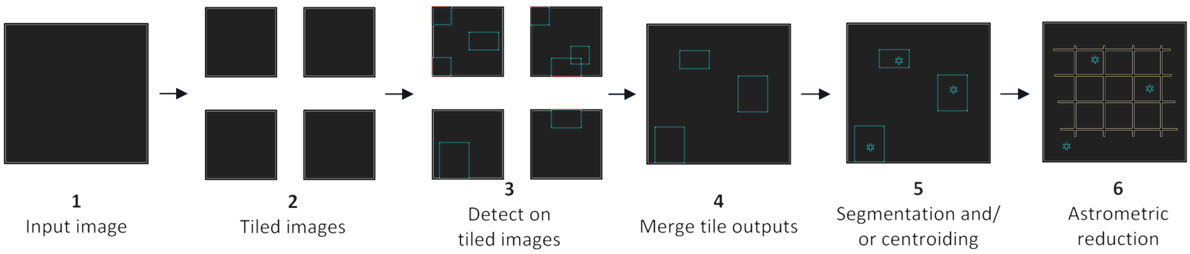

Figure 6: Processing Pipeline Dataflow

Observed Performance

The performance observed on a never seen validation set, with a similar distribution as the training set is reported in the table below.

Table 1: Tasked tracking model detection performance

Recall	Precision	F1-score
0.92	0.88	0.91

As it can be observed, the model detects pretty well resident space objects, even if most of them are just a few pixels in size, as more than 90% of objects were correctly predicted. The number of false positives also is in the same order of magnitude of false negatives, as observed in the precision figure. Overall, the F1-score summarises the satisfactory performance observed.

Another key performance parameter to evaluate is the centroiding error, which determines the accuracy that the model, combined with the segmentation and centroiding approach, can attain before astrometry is performed.

Table 2: Tasked tracking model centroiding performance

	Mean error	Standard deviation
In pixels	0.266	0.349
In arcseconds	1.873	2.454

By employing the geometric centroiding approach, the typical root mean squared error (RMSE) is less than half a pixel, attaining the desired subpixel accuracy, while the same RMSE expressed in arcseconds is slightly above 3 arcsec, which violates the upper limit of the desired accuracy by 3%.

Analysing the performance as a function of the signal-to-noise ratio (SNR), it is clear that there are two regions of performance. Objects below the noise floor (SNR < 1) or just above it (SNR < 1.5) observe a recall of around 80%. However, when the SNR is above 1.5, detection performance jumps to levels well above 90%.

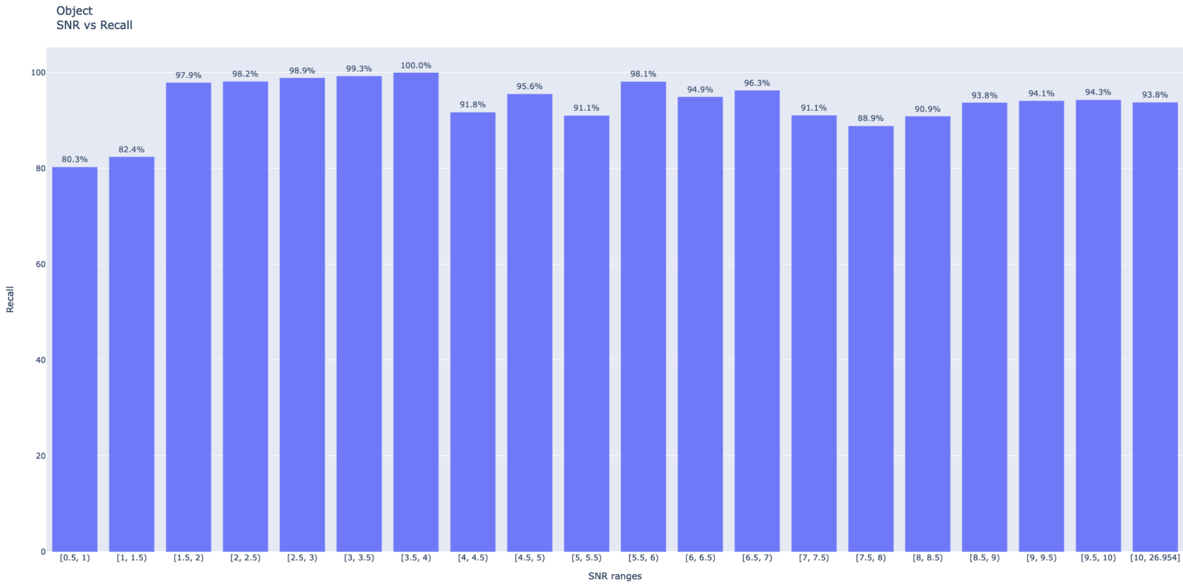

Figure 7: Recall vs. SNR for RSOs

On a similar analysis, the capability of the model to detect stars performs very consistent across all magnitudes it is exposed, and detections are very close to 100%, with some exceptions on bins with very few stars with that corresponding magnitude.

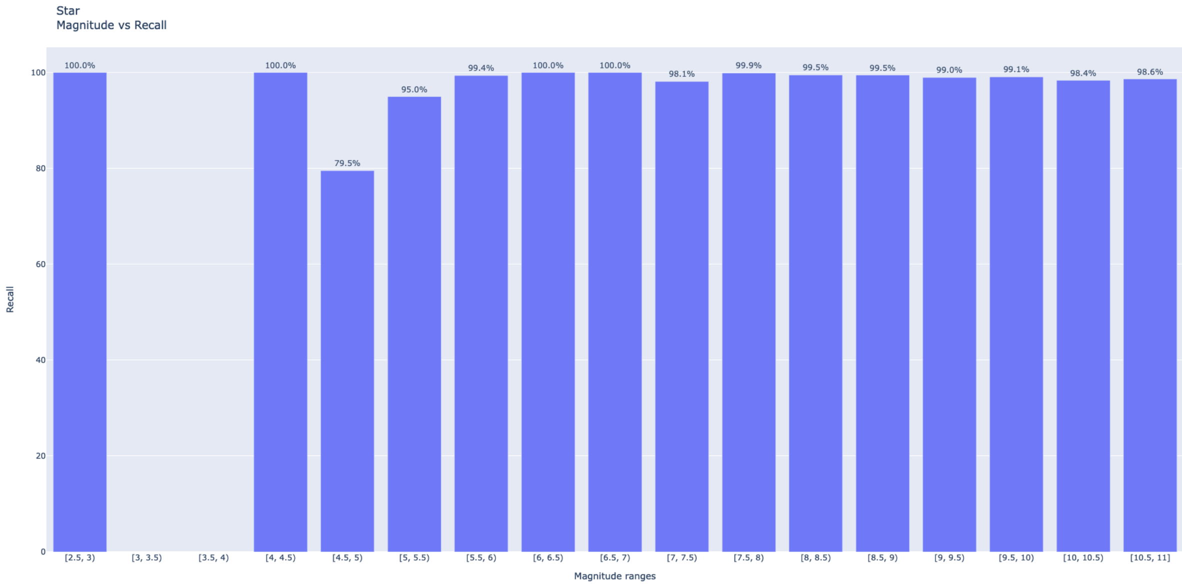

Figure 8: Recall vs. Magnitude for Stars

Conclusions

In conclusion, the objectives set at the beginning of the study have been achieved. An hybrid edge-could astrometric reduction pipeline has been designed, tailored to the specificities of Vyoma's upcoming SBSS mission, enabling a cost-effective way to handle the large amount of data that is expected to be generated on-board, while reducing the latency of SSA products delivery.

The synthetic image generation framework was enhanced by extending its capabilities for SBSS, both in surveillance and tracking observation modes. The framework has been successfully used to generate large datasets for training and fine-tuning deep learning models, representative of the optical payload characteristics of Vyoma's space segment.

The selected YOLOv5s6 model has proven to be a reliable and effective choice for streak detection due to its state-of-the-art accuracy and inference speed, robustness and versatility, and regular updates and extensions to the base code. The model was successfully tailored for the image format and specific features of both datasets, obtaining very impressive and promising detection results and after training and fine-tuning it on both datasets, even in particularly challenging scenarios, like objects below the noise floor.

The fast geometric centroiding approach, proved to achieve the target accuracy that would enable a sustained orbit determination quality increase, when the generated observations feed a cataloguing service.

At the same time, the cloud-native astrometric reduction tailoring observed fast start-up and plate solution times, key aspects for the success of the serverless deployment approach. Nevertheless, implementation delays on the dataset with stars rendered from a real catalogue prevented its formal characterisation and end-to-end astrometry accuracy assessment, in time before the conclusion of the study.

Finally, CogniSAT-XE2™'s development environment used for the validation campaign, allowed to better characterise the performance of the model to be expected on-board. On the bright side, the MyriadX engine proved to be very dependable and versatile, deploying the trained models without loss of detection nor classification performance. While the full frame processing rate attained with the selected model is just 35% of the target established, there are alternatives that could be explored to match achieve the goal.

Overall, the combination of Ubotica's technology and proficiency in edge computing and AI acceleration, together with Vyoma's expertise in SBSS development and ML resulted in a successful formula to advance in Europe's space situational awareness autonomy capabilities. This will have numerous benefits, including increased safety for satellites and spacecraft, sustainability of the orbital environment and operations, as well as improved space situational awareness for all stakeholders.

End of Document