

Design of an AI-Based Framework for Optical Detection and Characterization of Space Debris

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ABSTRACT

The growing number of space debris orbiting the Earth represents a critical challenge for both space operations and ground-based astronomy. The continuous increase in the population of artificial objects in orbit not only raises concerns for the safety and sustainability of space activities, but also introduces significant complications for astronomical observations, where debris and satellite passages can affect data quality and scientific output. In this context, this work presents the design of an AI-based software framework aimed at detecting, classifying, tracking, and physically characterizing space debris from wide-field optical observations. The framework is conceived as an integrated and modular pipeline that follows the main stages of the Space Situational Awareness (SSA) workflow, providing a scalable structure for data processing and analysis.

Starting from the management of observational data, including object tracks and light curves, the framework progressively integrates AI-based techniques with classical image-processing, photometric, and astrodynamical methods. The proposed processing chain addresses object detection and classification, photometric characterization, orbit determination from Very-Short Arcs (VSAs), measurement correlation and catalogue association, and preliminary conjunction assessment. Photometric information is exploited to investigate rotational behaviour, approximate shape indicators, and effective-size constraints, while astrometric measurements provide the basis for preliminary orbit reconstruction and subsequent refinement through multi-arc correlation.

A distinctive aspect of the proposed design is its hybrid AI-physical approach, in which data-driven techniques complement physically based methodologies rather than replace them. This architecture is particularly intended to support the progressive characterization of faint and potentially uncatalogued objects, for which individual observations may provide limited information. In addition, the framework establishes a connection between SSA and observational astronomy by exploiting detected tracks, orbital information, and catalogue data to identify astronomical observations potentially affected by satellite or debris passages.

Keywords: Space Debris, Space Situational Awareness, Artificial Intelligence, Optical Observations, Very-Short Arcs, Detection, Tracking, Initial Orbit Determination, Photometric Characterization

1. INTRODUCTION

The increasing number of artificial objects orbiting the Earth represents a major challenge for the safety and long-term sustainability of space activities. The continuous deployment of new spacecraft, together with fragmentation events and the accumulation of non-functional objects, has progressively increased the density of the near-Earth orbital environment. The consequences of this evolution have long been recognized, particularly in relation to collision-driven debris generation and the consequent growth of the orbital debris population.¹ Current space-surveillance catalogues contain tens of thousands of tracked objects, while a significantly larger population of smaller debris remains untracked or insufficiently characterized.² Improving the capability to detect, identify, track, and characterize these objects is therefore a fundamental objective of modern Space Situational Awareness (SSA).

Ground-based optical observations represent an important component of current and future space-surveillance capabilities, providing angular and photometric measurements of Resident Space Objects (RSOs). Wide-field optical systems are particularly attractive because they enable large-area surveys and the detection of faint objects over extended regions of the sky.³ An example is represented by the FlyEye telescope, developed to

provide very wide-field monitoring capabilities relevant to astronomical and space-surveillance applications.⁴ The increasing availability of such observations therefore provides new opportunities for detecting potentially uncatalogued objects and extracting information beyond their apparent position.⁵

At the same time, the growing population of artificial objects represents an increasing challenge for ground-based astronomy. Satellite and debris passages can produce trails and other artefacts in astronomical images, affecting data quality and scientific exploitation, particularly in wide-field surveys. The impact of satellite constellations on astronomical observations and possible mitigation strategies has already received significant attention within the astronomical community.⁶ Space surveillance and observational astronomy therefore address two complementary aspects of the same observational problem: artificial objects represent targets to be detected and characterized for space-safety purposes, while their signatures can constitute sources of contamination in astronomical datasets.

The increasing amount and complexity of observational data make Artificial Intelligence (AI) and Machine Learning (ML) attractive tools for supporting these analyses. Deep Learning approaches have been investigated for the classification of space objects from photometric light curves,⁷ while light-curve analysis has demonstrated its potential for space-debris characterization and classification.⁸ AI-based techniques have also been investigated for object identification and segmentation in optical images.⁹ Such approaches can complement conventional image-processing and photometric techniques, particularly when large and heterogeneous datasets must be processed.

A similar hybrid perspective is relevant to orbit reconstruction. Optical ground stations may provide only short observational arcs for newly detected objects, making Initial Orbit Determination (IOD) particularly challenging. Previous studies have investigated AI-based methodologies for orbit determination from very-short or too-short arcs, combining optimization, machine-learning, and physics-informed approaches with conventional orbital dynamics.^{10,11} These studies motivate the integration of data-driven and physically based methodologies rather than the replacement of established astrodynamical techniques.

However, detection, classification, physical characterization, and orbit reconstruction are often addressed as separate processing problems. Wide-field optical observations can instead provide heterogeneous but complementary information, including images, angular tracks, photometric measurements, light curves, orbital solutions, and catalogue information. A common architecture in which these products can progressively contribute to the characterization of an observed object is therefore particularly relevant for faint and potentially uncatalogued objects, for which individual observations may provide limited information.¹²

In this context, this work presents the design of a modular AI-based software framework for the detection, tracking, classification, and physical characterization of space debris from wide-field optical observations. The proposed architecture follows the main stages of an SSA processing chain, integrating observational-data management, AI-assisted detection and characterization, photometric analysis, orbit determination from Very-Short Arcs (VSAs), measurement correlation and catalogue association, and preliminary conjunction assessment. A hybrid AI-physical methodology is adopted throughout the framework, combining data-driven techniques with classical image-processing, photometric, and astrodynamical approaches. In parallel, SSA-derived information is connected with astronomical observations to identify datasets potentially affected by artificial object passages. The objective of the present work is to define the methodological architecture and the processing modules that will support its progressive implementation and validation.

2. FRAMEWORK ARCHITECTURE

2.1 Overall Architecture

The proposed framework is conceived as a modular software architecture for organizing and progressively processing information extracted from wide-field optical observations of artificial objects. Its structure follows the main logical stages of a Space Situational Awareness (SSA) processing chain, connecting observational data management with object detection, physical characterization, orbital analysis, and SSA products.

The general architecture is illustrated in Fig 1. Wide-field optical observations constitute the primary input and can include raw or pre-processed images, detected tracks, photometric measurements, light curves,

and the corresponding observational metadata. A common data infrastructure is introduced to organize these heterogeneous products and preserve the information required by the subsequent processing modules.

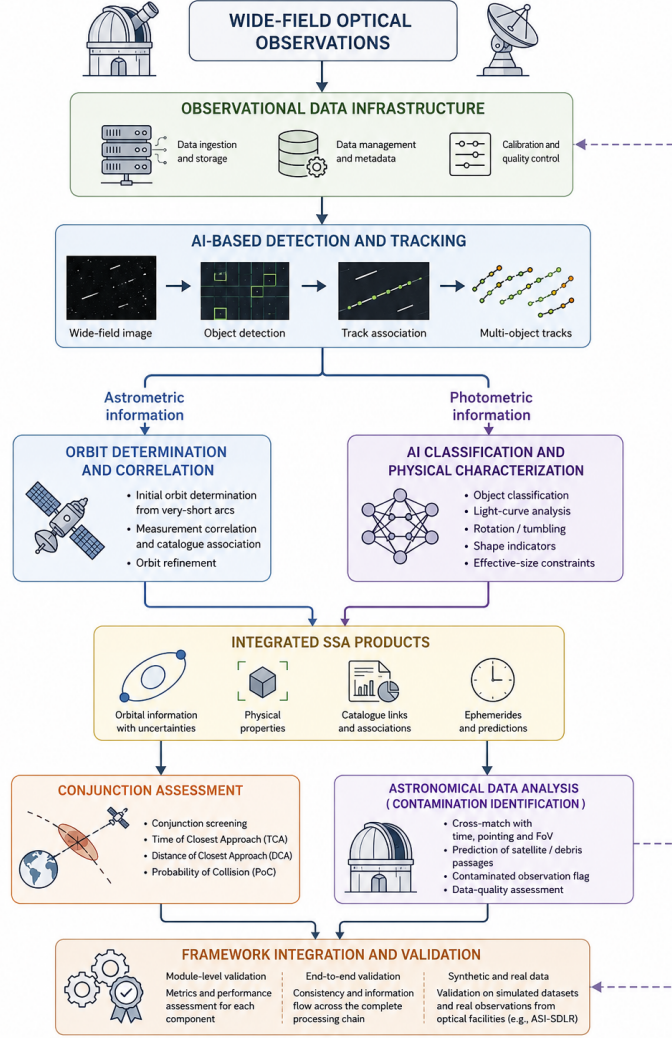


Figure 1. Architecture of the proposed AI-based framework. Wide-field optical observations are organized within a common data infrastructure and processed to extract astrometric and photometric information. AI-based characterization and physically based orbital analysis provide complementary information that is progressively combined to generate SSA products and support both conjunction assessment and the identification of contamination in astronomical observations.

After the object detection and tracking, the processing chain separates into two complementary branches. Astrometric information, derived from the apparent motion of the detected object, provides the input for Initial Orbit Determination (IOD), measurement correlation, and catalogue association. In parallel, photometric measurements and light curves are exploited for object classification and physical characterization. The information generated by the two branches can subsequently be combined to progressively improve the description of the observed object and generate higher-level SSA products.

A central characteristic of the architecture is the adoption of a hybrid AI–physical methodology. AI-based techniques are introduced where data-driven approaches can support automation, scalability, and the extraction of information from complex observational datasets, while classical image-processing, photometric, and astrodynamical methods provide physical constraints and solutions. The individual modules are designed to

be independently developed, tested, and refined while preserving a common processing logic and standardized exchange of information.

The framework also establishes an interface between SSA and observational astronomy. Information derived from object detections, orbital reconstruction, and catalogue association can be exploited to identify astronomical observations potentially affected by satellite or debris passages. Conversely, wide-field astronomical observations can provide additional measurements of artificial objects. This bidirectional interaction extends the proposed architecture beyond conventional space-surveillance applications and enables the same observational information to contribute both to space-object characterization and to astronomical data-quality assessment.

2.2 Observational Data and Data Infrastructure

The first layer of the proposed framework is dedicated to the ingestion, organization, and synchronization of observational data. Since optical observations can generate heterogeneous information products depending on the sensor, acquisition strategy, and processing level, a common data infrastructure is required to support the exchange of information among the different processing modules.

The primary inputs consist of wide-field optical images and the associated observational metadata. After the detection and tracking processes, these observations can provide two complementary categories of information: astrometric measurements describing the apparent motion of the detected object and photometric measurements describing its brightness evolution. When the required calibration, timing, and pointing information is available, image-plane coordinates can be converted into angular measurements, while photometric measurements can be organized into light curves for subsequent characterization.

The data layer is therefore conceived to manage raw or pre-processed images, object tracks, angular and photometric measurements, light curves, and the corresponding metadata.

External catalogue information and simulated datasets can also be incorporated into the same infrastructure. Catalogue data can support object identification and measurement correlation, whereas synthetic observations provide controlled datasets for the development and validation of individual modules, particularly for AI-based techniques requiring representative labelled data.

2.3 AI-Based Detection, Tracking and Classification

The detection of artificial objects represents the first processing stage of the proposed framework. Starting from sequences of optical images, this module is intended to identify candidate Resident Space Objects (RSOs), distinguish them from the observational background, and reconstruct their apparent motion across the field of view. This task is particularly relevant for wide-field observations, where artificial objects may exhibit different apparent brightness, angular velocities, and morphological signatures.

Both conventional image-processing techniques and AI-based approaches can be considered for object detection. Classical methods may rely on image pre-processing, background estimation, thresholding, and the identification of connected or streak-like features, whereas data-driven methods can learn relevant image features directly from representative datasets. Deep Learning architectures have already demonstrated their applicability to optical RSO detection and image segmentation, including U-Net-based approaches developed for star-sensor imagery.⁹ These results provide a methodological basis for investigating similar approaches in the wide-field observational scenario considered here.

After the detection process, candidates identified in consecutive images are associated to reconstruct an object track, as schematically illustrated in Fig.2. Depending on the available calibration and observational metadata, the resulting image-plane coordinates can be converted into angular measurements, while the intensity associated with each detection provides the corresponding photometric information. Each track can therefore provide both astrometric measurements for subsequent orbital analysis and photometric measurements for light-curve generation and object characterization.

AI-based techniques can also support a first classification of the detected objects. Rather than relying exclusively on the morphology of individual detections, the framework is intended to exploit complementary information associated with the observation, including image features, apparent motion, and photometric evolution. The

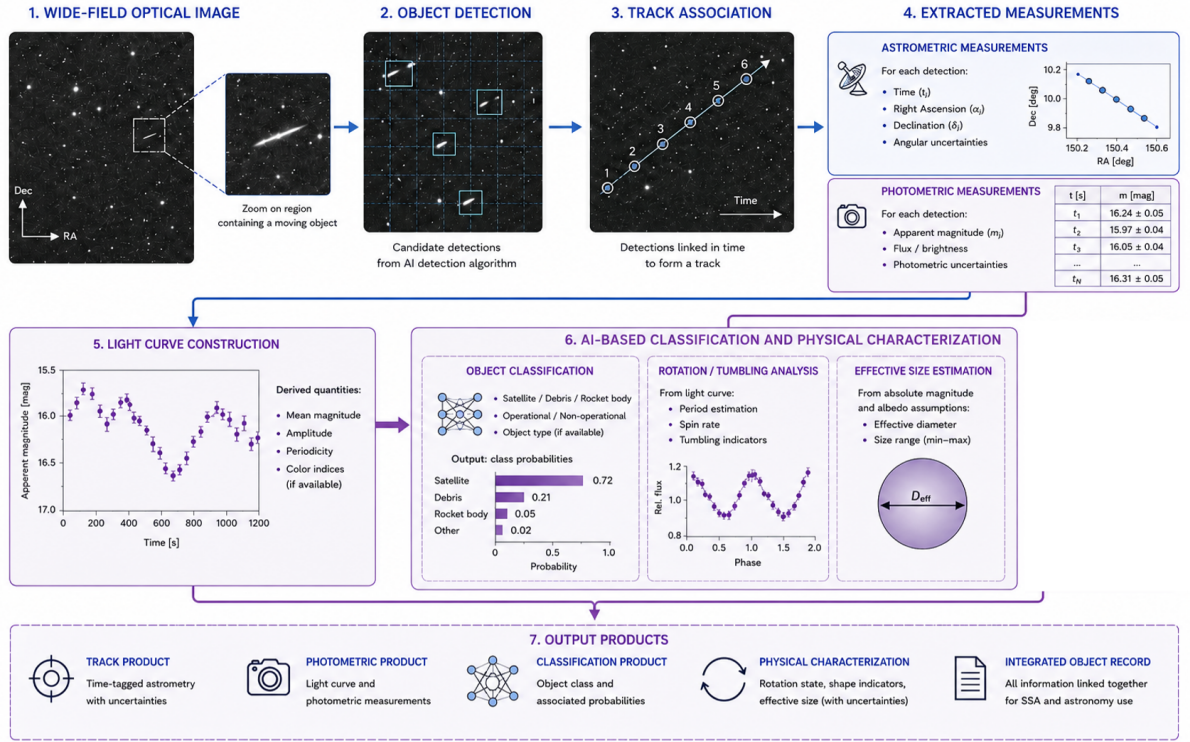


Figure 2. Processing workflow from wide-field optical images to object detection, track reconstruction, and AI-assisted characterization. Astrometric and photometric measurements provide complementary information for subsequent orbital analysis and for light-curve-based classification and physical characterization.

objective is to investigate the discrimination among broad classes of artificial objects, such as payloads, rocket bodies, and debris, while also distinguishing artificial objects from astrophysical sources and image artefacts. Previous studies have demonstrated the potential of photometric light curves for RSO classification using Deep Learning⁷ and for space-debris characterization and classification.⁸

The module is therefore conceived as a progressive processing stage rather than as a single AI model. Detection provides candidate object signatures, temporal association reconstructs their tracks, and the resulting observational information supports subsequent classification and characterization. This modular organization also enables AI-based and conventional approaches to be independently evaluated and combined according to the characteristics of the available observations.

For faint and potentially uncatalogued objects, a reliable classification may not be possible from a single passage. The module therefore preserves the observational products required by subsequent stages of the framework, allowing classification to be progressively refined as additional photometric and orbital information becomes available.

2.4 Photometric Analysis and Physical Characterization

In addition to astrometric information, optical observations provide photometric measurements describing the temporal variation of the brightness of an observed object. The resulting light curves can contain information related to its physical and dynamical properties, as schematically illustrated in Fig.2. Their use for space-object classification and characterization has already been investigated through both data-driven and physically motivated approaches.^{7,8}

Within the proposed framework, photometric measurements extracted during detection and tracking are organized into light curves and analysed to identify periodic or quasi-periodic brightness variations. When

the observational conditions and available time series are sufficiently informative, these signatures may provide estimates or constraints on characteristic rotational periods and possible tumbling behaviour.

Light-curve variability can also provide information related to object geometry. However, the measured brightness depends simultaneously on object shape, attitude evolution, illumination and observation geometry, and surface reflection properties. The framework therefore does not assume that a unique geometrical reconstruction can be obtained from an individual optical passage. Instead, photometric information is intended to support the extraction of approximate shape indicators or broad shape classes that can complement the object-classification process. Deep Learning techniques are of particular interest in this context, given their demonstrated applicability to space-object classification from light-curve measurements.⁷

Similar considerations apply to object size. Observed brightness cannot be directly converted into a unique physical dimension without assumptions or additional information concerning illumination geometry, reflective properties, and object attitude. Size estimation is therefore treated as a model-dependent characterization problem, in which photometric measurements can be combined with observational and orbital information to derive effective-size indicators or ranges of compatible values.

This module reflects the hybrid philosophy of the overall framework. Data-driven techniques can support the identification of patterns in heterogeneous light curves, while simplified photometric models can provide physical constraints and assist the interpretation of AI-derived outputs. The resulting characterization products, including object-class information, rotational indicators, approximate shape information, and effective-size constraints, can be progressively refined as additional observations become available and combined with the astrometric and orbital information associated with the same object.

2.5 Initial Orbit Determination from Very-Short Arcs

Once an artificial object has been detected and tracked across a sequence of optical images, the resulting angular measurements can be exploited to obtain a preliminary estimate of its orbital state. This is particularly challenging for Very-Short Arcs (VSAs), where the limited angular displacement and the absence of direct range information result in a poorly constrained Initial Orbit Determination (IOD) problem.

Within the proposed framework, the IOD module receives the angular measurements associated with a detected track, together with the corresponding acquisition times and observer information. Its objective is to derive a physically consistent preliminary orbital solution that can support object identification, correlation with additional observations, and subsequent orbit refinement. Since the duration and quality of the available arcs may vary significantly, the module is conceived to accommodate different orbit-determination strategies rather than relying on a single algorithm.

Classical IOD techniques provide the physical basis for orbit reconstruction, but their applicability becomes increasingly challenging when the observational arc contains insufficient information for a well-conditioned estimate. Previous work has investigated the use of optimization and AI-assisted methodologies for Initial Orbit Determination from too-short arcs.¹⁰ More recently, physics-informed approaches have been explored for the same problem, incorporating the governing dynamical equations directly into the learning process.¹¹ These studies provide the methodological basis for considering hybrid approaches in which orbital dynamics constrain the estimation process while data-driven techniques support the reconstruction of the orbital state.

The proposed module therefore considers classical orbital mechanics, optimization-based algorithms, and AI-assisted techniques as complementary methodologies. Depending on the available measurements, these approaches can be independently evaluated or combined to obtain preliminary orbital information. The objective at this stage is not necessarily to derive a definitive high-accuracy orbit from a single VSA, but to generate a physically consistent initial solution that can enable subsequent correlation with orbital estimates relative to the same detected object and refinement.

This aspect is particularly relevant for potentially uncatalogued objects. As illustrated in Fig.3, orbital information derived from individual arcs can support the search for compatible observations acquired at different epochs. Successful multi-arc correlation progressively extends the observational time span and provides additional information for orbit refinement. IOD and measurement correlation are therefore treated as interconnected components of the proposed framework, linking image-derived angular tracks with catalogue association and higher-level SSA analyses.

2.6 Measurement Correlation and Catalogue Association

The preliminary orbital information derived from an individual observational arc can be exploited to determine whether the detected object is already known and whether observations acquired at different epochs can be associated with the same RSO. Within the proposed framework, measurement correlation therefore addresses two complementary problems: catalogue association and multi-arc correlation.

Catalogue association compares the observed track and the available orbital information with existing catalogued objects. A successful association links the observation to a known RSO and can provide additional information for its interpretation and characterization. Conversely, the absence of a reliable association may indicate a potentially uncatalogued object and motivate the search for compatible observations acquired at different epochs.

Multi-arc correlation is particularly relevant when individual passages provide VSAs that are insufficient to accurately constrain the orbital state. Candidate associations can be evaluated by assessing the dynamical compatibility of different observational arcs. Once multiple arcs are associated with the same object, the extended observational time span can be exploited to refine the orbital solution, following the progressive process illustrated in Fig.3.

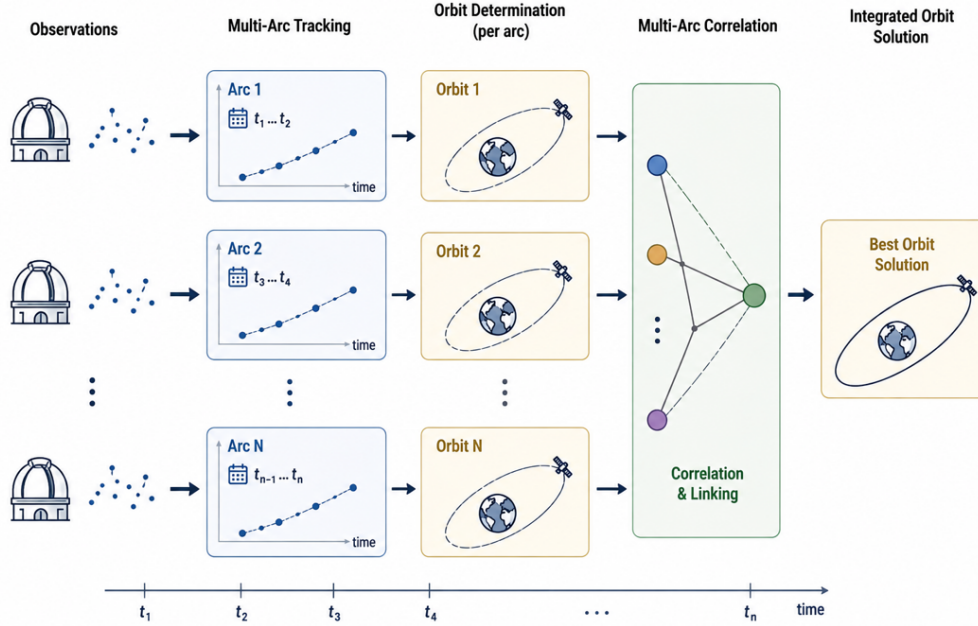


Figure 3. Schematic representation of the proposed VSA orbit-determination and multi-arc correlation process, from individual observational arcs to a progressively refined orbital solution.

The correlation module is conceived to accommodate conventional astrodynamical criteria together with future AI-assisted methodologies. Physically based approaches provide interpretable measures of orbital compatibility, while data-driven techniques may support the screening and ranking of candidate associations when large numbers of observations are processed. The resulting associations and refined orbital information provide the basis for catalogue maintenance and subsequent higher-level SSA analyses.

2.7 Conjunction Assessment and SSA Products

The progressive reconstruction and refinement of the orbital state enables the generation of higher-level SSA products. Within the proposed framework, conjunction assessment is considered as a downstream capability

whose applicability depends on the quality of the orbital information obtained through the previous processing stages.

When sufficiently reliable orbital solutions are available, object trajectories can be propagated over a selected time interval to identify potential close approaches. Preliminary conjunction assessment can provide quantities such as the Time of Closest Approach (TCA) and the corresponding Distance of Closest Approach (DCA). When appropriate information on orbital uncertainties is available, the analysis can be extended to the estimation of the Probability of Collision (PoC).

The framework does not assume that orbital information derived from every newly detected object or individual VSA is immediately suitable for collision-risk assessment. Preliminary solutions may require additional observations, multi-arc correlation, and orbit refinement before higher-level SSA products can be considered sufficiently reliable. Conjunction assessment therefore represents a progressive capability of the architecture, becoming applicable as the knowledge and associated uncertainty of the observed object improve.

2.8 Identification of Contamination in Astronomical Observations

The increasing population of artificial objects in Earth orbit represents a growing challenge not only for space safety but also for observational astronomy. Satellites and debris crossing the field of view during an exposure can generate trails or other artificial signatures that affect image processing and the scientific exploitation of astronomical datasets, particularly in wide-field surveys. The impact of satellite trails on astronomical observations and the corresponding need for mitigation strategies have already been investigated in the context of major survey facilities.⁶

The proposed framework addresses this common observational domain through a bidirectional interaction between SSA and astronomy, as illustrated in Fig.4. From the SSA perspective, wide-field astronomical observations represent a potential additional source of measurements of artificial objects. Once an artificial signature is detected and distinguished from the astronomical background, the corresponding track can provide astrometric and photometric information that can be processed by the detection, characterization, and orbital-analysis modules. Astronomical datasets can therefore contribute complementary observations of catalogued objects and potentially provide detections of previously uncatalogued objects.

In the opposite direction, SSA-derived information can support the analysis of astronomical datasets. Detected tracks, catalogue information, and reconstructed or predicted orbital information can be compared with the acquisition time, pointing direction, and field of view of an astronomical exposure to determine whether an artificial object was detected or expected to cross the observed region.

The output of this analysis is conceived primarily as a diagnostic product rather than as an automatic image-restoration procedure. Astronomical observations can be flagged according to the presence of detected or predicted artificial-object passages and associated, when available, with object identification and characterization information. These products can subsequently support data-quality assessment and the development of dedicated mitigation procedures.

The interaction between SSA and astronomy is therefore inherently complementary: astronomical observations can provide additional measurements for space-object detection and characterization, while SSA products can provide contextual information for identifying and assessing artificial contamination in astronomical datasets. The same artificial-object signature can consequently be treated either as a valuable measurement for SSA or as a potential source of contamination for astronomy, depending on the scientific objective of the analysis.

3. VALIDATION STRATEGY AND EXPECTED CAPABILITIES

The modular structure of the proposed framework enables the individual processing components to be developed and validated independently before their integration into the complete pipeline. The validation strategy is therefore conceived as a progressive process, starting from controlled synthetic datasets and subsequently moving toward real optical observations and integrated end-to-end testing.

Synthetic observations provide a controlled environment in which object properties, orbital states, observing geometries, brightness levels, and acquisition conditions can be defined a priori. They can therefore support

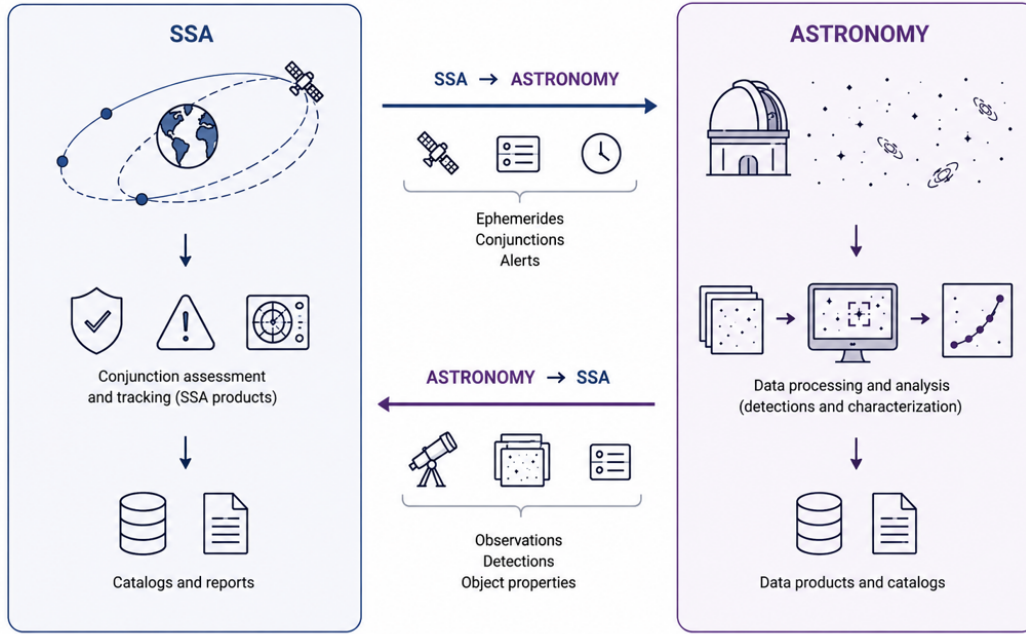


Figure 4. Schematic representation of the bidirectional interaction between SSA and observational astronomy, where SSA-derived information supports the assessment of artificial-object contamination, and astronomical observations provide complementary measurements for space-object detection and characterization.

both the development of AI-based components and the quantitative evaluation of the individual modules against known reference information. Detection and tracking can be assessed in terms of object identification and trajectory reconstruction, classification through comparison with reference classes, and photometric characterization through the recovery of simulated physical indicators. For the IOD module, reconstructed orbital information can be compared with the reference trajectories used to generate the observations, with particular attention to the dependence on arc duration and angular-measurement quality.^{10,11}

A second validation level is based on real observational datasets. Such observations are required to assess the robustness of the proposed methods under realistic instrumental effects, variable observing conditions, and imperfect calibration. Data from optical facilities and dedicated space-debris sensors, including observations from the ASI Space Debris Laser Ranging (SDLR) facility at the Space Geodesy Centre in Matera, can provide representative scenarios for testing selected components of the processing chain. Wide-field astronomical observations can additionally be used to evaluate the framework in fields containing both astrophysical sources and artificial moving objects.

The final validation level concerns the integration of the individual modules. In this phase, the objective is to verify not only the performance of each component but also the consistent transfer of information throughout the pipeline: detected tracks should provide astrometric and photometric measurements for orbital and physical characterization; preliminary orbital information should support catalogue association and multi-arc correlation; and progressively refined SSA products should enable higher-level analyses and the assessment of astronomical observations.

The expected outcome of this process is a quantitative assessment of the feasibility, capabilities, and limitations of the proposed architecture. Particular attention will be devoted to faint and potentially uncatalogued objects, for which the combination of multiple observational and analysis products may provide information unavailable from individual measurements alone. The comparison of AI-based and classical methodologies on both simulated and real observations will progressively identify the most suitable approaches for the different processing stages and provide the basis for subsequent integration and extension of the framework.

4. CONCLUSIONS

This work presented the design of a modular AI-based framework for the detection, tracking, and characterization of space debris from wide-field optical observations. The proposed architecture integrates observational-data management, AI-assisted detection and characterization, photometric analysis, orbit determination from Very-Short Arcs, measurement correlation, and higher-level SSA products within a common processing environment. Rather than relying on a single methodology, the framework combines data-driven techniques with classical image-processing, photometric, and astrodynamical approaches, allowing the individual modules to be progressively developed and integrated.

A distinctive aspect of the proposed framework is the connection established between SSA and observational astronomy. Wide-field astronomical observations can provide complementary measurements for the detection and characterization of artificial objects, while SSA-derived tracks, catalogue information, and orbital products can support the identification and assessment of satellite and debris contamination in astronomical datasets. The same artificial-object signature can therefore represent either a valuable measurement for SSA or a source of contamination for astronomy, highlighting the potential benefit of addressing both domains within a common architecture.

Future activities will focus on the progressive implementation and validation of the individual modules using synthetic and real optical observations, followed by their integration into the complete processing chain. Particular attention will be devoted to assessing the capabilities and limitations of the hybrid AI-physical approach for faint and potentially uncatalogued objects. This process will provide the basis for evaluating the feasibility of the proposed architecture and for its future extension toward more advanced SSA and astronomy-oriented applications.

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