ADDRESING SPACE DEBRIS-NEO AMBIGUITY: A SOLUTION THROUGH THE ARTSAT INFORMATION PROVISION SERVICE

F. Pallarés-Chamorro[(1)], G. Principe[(1)], A. I. Mediavilla[(1)], J. L. Cano[(2)], M. Fenucci[(1)(3)], E. Brendel[(2)], and F. Gianotto[(2)(4)]

[(1)] Indra-Deimos, 28760 Tres Cantos (Madrid), Spain, Email: {fapallares, gprincipe}@indra.es
[(2)] ESA ESOC / OPS, 64293 Darmstadt, Germany, Email: Juan-Luis.Cano@esa.int
[(3)] ESA ESRIN / PDO / NEO Coordination Centre, 00044 Frascati (RM), Italy, Email: Marco.Fenucci@ext.esa.int
[(4)] Starion group, 00044 Frascati (RM), Italy

ABSTRACT

The increasing presence of space debris in high-energy Earth-bound orbits poses challenges for Near-Earth Object (NEO) monitoring services, as artificial objects, such as detached materials from GEO satellites or interplanetary mission debris, can exhibit trajectories similar to NEOs. This misidentification leads to inefficiencies in planetary defense efforts.

The ArtSat Information Provision Service (ASIPS), developed under the ArtSat initiative by Deimos for ESA, provides a structured solution by offering ephemerides generation, orbit determination, and observation identification services. Additionally, ASIPS includes automated tools such as the NEOCP Identification Service and a priority-based observation system to optimize resource allocation.

ASIPS is implemented through a multi-layered architecture integrating a frontend for user interaction, a business layer for data management, and a computational subsystem incorporating advanced dynamical models, including solar radiation pressure effects, to enhance orbital accuracy. Validation with real-world observations confirms ASIPS's capability to reduce misclassification of artificial objects as NEOs, thereby improving the efficiency of NEO surveillance and planetary defense operations.

1 INTRODUCTION

As human activity in space continues to expand, maintaining awareness and control over space operations becomes essential. Space Situational Awareness (SSA) is a relatively recent concept that encompasses the understanding of the space environment, including the tracking of space objects and monitoring of space weather phenomena. Recognizing its growing significance, both space agencies and private companies have been actively investing in SSA initiatives. The European Space Agency (ESA) has structured its Space Safety Programme around three primary components:

- **Space Weather (SWE):** Focused on detecting and forecasting space weather events to mitigate their potential impact on both space-based assets and ground infrastructure.
- **Space Surveillance and Tracking (SST):** Dedicated to identifying, cataloguing, and predicting the orbits of objects around Earth. The primary goals include preventing collisions between operational satellites and space debris, ensuring safe re-entries, and supporting satellite launches, deployments, and decommissioning.
- **Near-Earth Object (NEO):** Aimed at monitoring celestial bodies that could pose an impact threat to Earth, cataloguing newly discovered objects, and issuing alerts when necessary.

ESA's Space Debris Office and Planetary Defence Office are closely linked to the SSA Programme, particularly in relation to the SST and NEO segments. The Space Debris Office is responsible for cataloguing artificial objects in orbit that may endanger active missions or pose re-entry risks. Meanwhile, the Planetary Defence Office monitors small celestial bodies that pass near Earth, assessing their potential impact probability. Despite their distinct objectives, both offices occasionally encounter the same challenge: distinguishing between artificial objects and natural near-Earth objects.

The increasing accumulation of space debris across various orbital regimes affects high-energy Earth-bound orbits, with sources including scientific research satellites, interplanetary launch vehicles, and the detachment of light materials from objects in the geostationary ring (GEO). The trajectories of these objects often resemble those of NEOs, leading to potential confusion and operational inefficiencies for NEO monitoring services. With advancements in observation techniques, artificial objects, often referred to as "ArtSats", are more frequently being misidentified as NEOs due to their slow velocities near high apogees, which resemble the motion of natural objects rather than artificial satellites. Identifying these objects and determining their artificial origin requires observational resources, diverting time and effort from the primary task of planetary defense.

To address these challenges, the ArtSat initiative, conducted by Deimos under ESA contract, builds upon

Proc. 9th European Conference on Space Debris, Bonn, Germany, 1–4 April 2025, published by the ESA Space Debris Office
Editors: S. Lemmens, T. Flohrer & F. Schmitz, (http://conference.sdo.esoc.esa.int, April 2025)

previous foundational studies [1], [2], [3]; to develop an information service for NEO observers, providing streamlined access to data on artificial objects and satellites with these orbital characteristics. The ArtSat Information Provision Service (ASIPS) offers various services to meet key user and operator needs. Among the primary services are:

- **Ephemerides Generation Service:** Computes ephemerides for selected objects, delivering formatted files to users and operators or automatically saving data in the database.
- **Orbit Determination Service:** Provides accurate orbit determinations for objects based on related observations stored in the database.
- **Observation Identification Service:** Correlates provided astrometric data with objects in the database and reports results to the user or operator.

In addition to these core services, ASIPS includes supplementary functionalities to support its operations. The NEOCP Identification Service monitors the Minor Planet Center's NEO Confirmation Page (NEOCP), automatically analyzing reported observations using the Observation Identification Service. The Priority List Service generates a prioritized list of objects in the database needing observation based on predicted uncertainty evolutions. Additionally, an Observer Scoring Utility ranks observers based on their contributions, encouraging further observational activities.

The ASIPS framework is structured into multiple software layers to support its operations efficiently. The frontend subsystem serves as a direct interface for external users and operators, accessible via a to-be-developed graphical user interface (GUI) on ESA's NEOCC web portal or through a command-line API. The business layer processes user inputs, queries the database, and invokes the computational subsystem. It manages user queries, allows operators to include or remove information from the database, and triggers computational services. The database itself uses different tables to store information on two primary entities: objects, which include identifiers, linked astrometry, and state and covariance definitions; and observers, connected to observatories with specific locations and attributes. The computational subsystem is responsible for performing all necessary mathematical computations. Notably, advanced models addressing solar radiation pressure have been incorporated into the computational subsystem to improve propagation accuracy and enhance the performance of the developed services. These advanced models account for the unique dynamics of light, reflective objects in high-energy orbits.

The components of ASIPS have been validated through real-world scenarios using observations of actual objects historically linked to the challenges addressed by this project. Integration tests have been conducted to ensure the correct functioning of the system across its layers, verifying its operation as a cohesive whole. Ultimately, this study aims to enhance the understanding of misidentifications between artificial objects and NEOs, reducing the unnecessary use of valuable observational resources and improving the efficiency of planetary defense efforts.

2 SW ARCHITECTURE

The high-level architecture for the ASIPS, sketched in Figure 1, is based on the following elements:

- **Frontend subsystem:** This is the presentation layer and establishes the direct interface to the external users or the internal users (the operators) through the GUI or a command line API.
- **Middleware subsystem:** This is part of the business or logic layer and allows processing user-provided inputs and querying the databases to retrieve the necessary information for invoking the computational subsystem. The middleware includes the Algorithm Wrapper Python code, responsible for executing these tasks, selecting the appropriate computational module, and managing data flow in and out of the computational subsystem.
- **Computational subsystem:** This is part of the business or logic layer and is responsible for performing all the necessary computations to populate the ArtSat database (e.g., orbit determination computations) and process user requests, such as ephemerides generation or observation verification. The computational subsystem is structured into several modules developed in FORTRAN, which enables efficient numerical calculations.
- **Databases subsystem:** This is the persistence layer. This would contain all the needed system databases. This is also called ArtSat database.

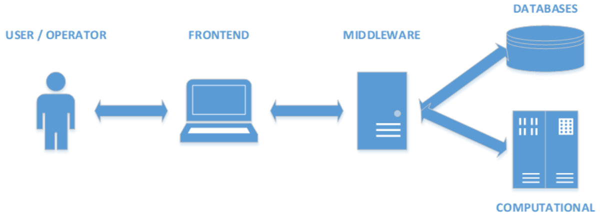

Figure 1. Overall ASIP system architecture.

The context diagram at first level is given by the connections between ASIPS system and external entities such as stakeholders, data sources and data targets (Figure 2). Stakeholders are represented by users and operators. The operators are connected through internal or private network and the users are connected through Internet. In fact, the operator is a registered user, and the applicable profile identifies the specific rights over the system. Moreover, the operator receives an email alarm to activate a communication procedure to Minor Planet Center (MPC) when the NEOCP Identification Service detects that one or more NEOCP objects match any of the objects in the ArtSat database with enough precision. The data sources are the following: objects appearing in the MPC confirmation service from NEOCC; space weather from Celestrak; initial population of objects for the database from space-track; and earth orientation parameters and leap seconds from usno.navy.mil. The reference to NEOCC system is included for clarifying that the LifeRay Frontend from NEOCC will integrate the pages from the ArtSat GUI.

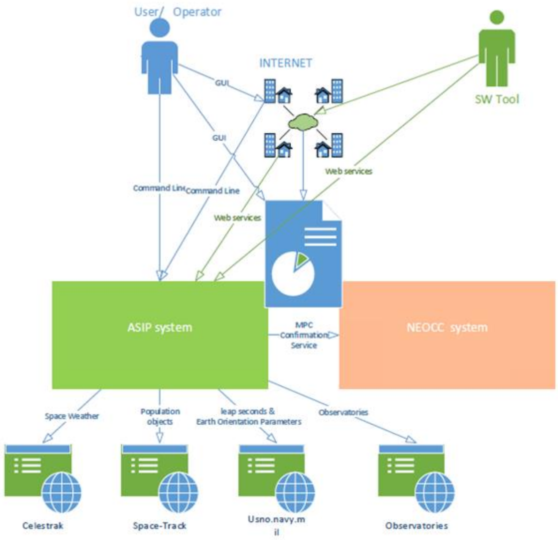

Figure 2. High level view of the system.

Each high-level component has its structure:

- Frontend uses only the middleware
- Middleware uses the database and the computational part
- Computational
- Database

3 DATABASE

The database includes the full list of Earth-orbiting objects of interest. Several utilities have then been developed to manipulate objects in the database and query information about them:

- **Population Query Utility**: which allows users to query general information contained in the database about the ArtSat population.
- **ArtSat Query Utility**: which allows users to query the information contained in the ArtSat database about a given object.
- **New ArtSat Inclusion Utility**: which allows the operators to add new objects to the database, in case such scenario is identified.
- **ArtSat Observations Inclusion Utility**: which allows operators to include new observables of a known ArtSat within the ArtSat database.
- **ArtSat Observations Removal Utility**: which allows operators to remove available measurements within the ArtSat database.

4 COMPUTATIONAL MODULES

The computational subsystem is organized into different FORTRAN modules, which are invoked by the middleware subsystem when needed. This section describes the main modules that form the ASIPS computational core.

4.1 Ephemerides Module

The Ephemerides Module allows users to request observational ephemerides and expected covariance in the plane of the sky for an object in the service database. These ephemerides are computed from a specified observatory or observation point on Earth over a given time interval. The output is provided in both CCSDS OEM format (orbital state format) and RA/Dec format (commonly used in the NEO observer community and linked to the observer site).

TRADE was developed under the scope of another project and is described in [4]. Its functionalities are used to create ephemeris (propagated state vectors and covariances). The numerical propagator and the functions that propagate the covariance matrix embedded in TARDE libraries are used for this purpose. The dynamical model used for the propagation is the one activated during the last OD computation.

TRATO was developed under a contract with the Spanish Centre for Technological Development and Innovation (CDTI), for the project "Aplicación de Nuevas Estrategias de Solo-survey para la Detección y Catalogación de Objetos Espaciales Artificales en Órbita de la Tierra" (ANESS). It is used to convert these ephemerides to topocentric observation angles in RA/Dec format (linked to the observer site and commonly used in the NEO observer community).

4.1.1 Service Operation

To generate the ephemerides, the following information is required from the user:

- **ArtSat Object:** Identified by any of the available database identifiers.
- **Observation Point:** Defined by the user, taken from the MPC database of observatories, or set to the geocenter.
- **Time Interval and Step:** Defines the time span and resolution of the ephemerides.

The service generates an OEM file, and an ephemerides file formatted for the NEOCC portal. It is also used in a daily automatic job to update geocentric ephemerides for the entire ArtSat population, ensuring up-to-date data in the database.

4.1.2 Execution Process

The module is executed through the Algorithm Wrapper and utilized by the ArtSat Ephemerides Generation Service. It operates via a FORTRAN program, which takes an input file containing all necessary information, produces an output file with computed ephemerides, and logs execution details.

The main processing steps are as follows:

1. Read and validate the input file.
2. Retrieve active dynamical model, observation point data, and additional required parameters from the database.
3. Initialize ephemerides generation based on collected data (configure propagator, duration, step size, and observation point).
4. Propagate the state vector and covariance.
5. Compute ephemerides data and errors in the plane of the sky.
6. Generate and report the OEM file.
7. Prepare and store input files for TRATO, ensuring proper conversion to RA/Dec format.
8. Report OEM file, RA/Dec data, and logs.

TRATO processes OEMs using an internal input file prepared by the module, with default sensor parameters ensuring large visibility of the object from the observation point. This guarantees ephemerides generation even if the object is not directly observable from the selected location.

Additionally, this module supports the Automatic Server for regular recalculations of geocentric ephemerides and integrates with the ArtSat Observation Priority List Service to enhance tracking and observation planning.

4.2 Orbit Determination (OD) Module

The Orbit Determination (OD) Module enables operators to perform an accurate orbit determination process for a given object, incorporating user-provided measurements. The associated covariance matrix is also derived and reported. The module accounts for typical perturbations and various object models defined by specific parameters. This service is restricted to operators and not available to external users.

TRADE OD routines are used to fit all the available observations with an orbit minimising residuals. The operator has the possibility to select different dynamical models as described previously.

The OD library uses the numerical propagator embedded in libTRADE.so. The OD functions could be provided in the form of a library, separated from libTRADE.so to allow ESA to use a different OD library in the future. The measurements and the propagator are provided to the library in the form of callback functions.

Orbit determination is provided by an implementation of a non-linear batch least squares algorithm. This algorithm works by fitting a solution (compatible with the selected dynamical model) to the available observations (each of these observations characterised by the time, measurement itself and noise.

All orbit determinations consider the Earth as the central body. However, as the propagator is fully numerical, gravity contributions from other bodies are modelled by adding their masses and distances to the computation of the force over the satellite. This means that even for cases near the boundary of the Hill sphere, the force model is correct.

The orbit determination can be set to work with any orbital elements. However, given the nature of the numerical propagator, it shall work with geocentric Cartesian state vectors. Conversions to other sets of orbital elements may be performed on the outputs.

For each of the different perturbative force models defined, an augmented state vector with the Cartesian orbital elements and extra parameters are determined. In turn, the covariance matrices provided by the algorithm also include the contributions of these extra parameters.

Selection of the most appropriate model is decided by the NEOCC operators when performing the OD process. Initially, the simplest model will be used (gravitational) or the basic SRP model if the solar radiation pressure has a strong signal. As more observations become available, the operator might try fitting a more complex model as the basic SRP one or any of the other two, the time-dependent SRP model, or the complex SRP one. Selection of the final applicable model for a given object is based on a dedicated analysis of the resulting residuals and a trial-and-error approach. To allow this, the Orbit Determination Service can be used in analysis mode if enabled by the operator. This means, in analysis mode, the result will not be saved to the database until the operator decides the result of the OD is satisfactory. An average weighted value of observation residuals and a standard deviation of observation residuals after OD is provided to the operator to allow the assessment of the accuracy of the OD.

The system allows saving pre-computed manoeuvres for an observational arc and to estimate one last manoeuvre if needed. The Orbit Determination Service allows estimating a manoeuvre if the user can provide an initial guess of the delta velocities. Each manoeuvre is estimated by the OD module at least once in the determination process for a given ArtSat. Therefore, the introduction of a manoeuvre could be performed through the OD service as an initial estimate that can be refined by the OD itself. If this has been already determined, it can be selected to be or to not be re-estimated in ulterior OD runs when new measurements are collected. When a new manoeuvre is to be introduced, the previous manoeuvre would be considered as fixed and then just the last one is estimated.

These saved computed manoeuvres are checked every time a propagation of the trajectory takes place, and they are applied to the state vector depending on the initial time and duration of the propagation. For example, if ephemerides are requested in the future and the tool uses the state vector at the end of the observational arc, no manoeuvres shall be considered. If, in the same case, the initial state vector for the propagation was the one at the start of the observations arc, all the manoeuvres shall be included in the propagation.

4.2.1 Service Operation

To perform the OD process, the following input is required:

- **ArtSat Object:** Identified by any of the available database identifiers.
- **Selected Measurements:** List of database measurements to be considered. By default, all non-rejected measurements are included, but the operator can manually exclude specific data.
- **OD Reference Epoch:** Defines the epoch for the orbit determination process.
- **Object Model Code:** Specifies the model parameters for orbit determination.
- **Initial Guess Solution:** Provides an initial estimate of the state vector and covariance.
- **Additional Model Parameters:** Includes estimated or assumed parameters with their associated covariance if applicable.
- **OD Configuration Parameters:** Includes configuration parameters required to define the OD execution, such as the maximum number of iterations and the count of convergence iterations.

The OD Module retrieves relevant data from the ArtSat database and processes it. The computed orbit solution is provided to the operator and stored in the database. If the OD process is conducted for a new object, an initial orbit solution is required to integrate it into ASIPS.

4.2.2 Execution Process

The module is executed via the Algorithm Wrapper within the ArtSat Orbit Determination Service. It operates through a FORTRAN program, which processes an input file, generates an output file with the computed OD solution, and logs execution details.

The primary steps involved in the OD process are:

1. Read and validate the input file.
2. Load selected observations from the database.
3. Retrieve initial state vector and dynamical model if processing an existing object.
4. Configure the dynamical model and determine an initial state vector if processing a new object.
5. Initialize the OD process by configuring the propagator and required parameters.
6. Perform an initial OD run to evaluate residuals and classify observations as accepted or rejected.
7. Conduct a refined OD run using only the accepted observations.
8. Compute final residuals and generate a detailed OD report.
9. If not in analysis mode, save the OD solution in the database.
10. If manoeuvre estimation is enabled, incorporate the estimated manoeuvre into the OD state vector before saving.
11. Report the OD results and log the process.

4.2.3 Orbit Determination Algorithm

For the sake of completeness, here a brief description of the algorithm used for OD is given. For a given initial condition of a space object, with state X_{t_0} associated with covariance P_{t_0}, and for an available arc observation, *Batch Least-Squares* (BLS) algorithm provides the best estimate at the epoch state,

$$\hat{X}_{t_0} = X_{t_0} + \delta x_{t_0} \tag{1}$$

This is carried out in an iterative process by solving a Normal equation,

$$\delta x_{t_0} = (A^T W A)^{-1} A^T W b \tag{2}$$

where A is the partial derivative matrix, W is the weighting matrix and b represents the residual vector.

The partial derivative matrix, A, is usually composed of the observation matrix, H, and the state transition matrix Φ,

$$A = \frac{\partial \alpha(t)}{\partial X(t)} \frac{\partial X(t)}{\partial X_{t_0}} = H_{t,t} \Phi_{t_0,t} \tag{3}$$

The A matrix is approximated by using finite differencing. The technique is independent of any propagation method.

4.3 Observation Identification Module

The Observation Identification Module allows external users to verify whether a set of measurements obtained from a given observation point correspond to any object in the service database. Additionally, it enables users to provide observations of a specific targeted object in the database. In the Space Surveillance and Tracking (SST) field, this process is commonly referred to as ‘correlation.’

In general, any ArtSat orbit is affected by a certain level of uncertainty (more or less, depending on the orbit dynamics, the number of observations available, and on the time from the last observation). Such uncertainty typically shows a secular increase, mostly due to the errors in the knowledge of the orbital period and a periodic evolution due to the orbit's eccentricity. This situation remarks the need to have periodic re-observations of the objects to keep the uncertainties within established boundaries that will avoid them to be lost.

The above situation makes the identification problem become a statistical one, like the orbit determination problem. The information available to facilitate the identification is based on the expected object position in the sky using right ascension and declination celestial coordinates, obtaining an angular deviation; and on the expected object motion, based on the scalar angular path travelled by the object from the observer's point of view from one observation and the following, obtaining an angular path deviation. The obtained residuals are normalized and combined into a correlation index as a metric of how distant the true object and the expected one are.

The correlation process included in TRADE library is based on the comparison of actual and predicted measurements, using the computation of the minimum measurement residual. This procedure allows a great reduction in computation time with respect to other methods based on pure orbital determination.

4.3.1 Service Operation

To perform observation identification, the following information is required from the user:

- **Observer Information:** Details about the observer submitting the measurements.
- **Set of Obtained Measurements:** The observational data to be analyzed.
- **Correlation index threshold:** The threshold set for an ArtSat object to be considered as possible correlation candidate.

The service produces a scoring report that lists only the objects demonstrating some level of compatibility with the provided measurements. Each identified object is assigned a fitting parameter, allowing users to assess which object best matches their observations.

By default, external users' observations are not automatically included in the database. Instead, these measurements are preserved in a dedicated repository and require review and approval by NEOCC operators before inclusion. The approval process is conducted using the ArtSat Observations Inclusion Utility, serving as a precautionary measure to prevent the erroneous inclusion of spurious data from external sources.

4.3.2 Execution Process

The binary is called by the Algorithm Wrapper and is used by the Observation Identification Service and NEOCP Identification Service. The FORTRAN program includes the following command line parameters: an input file with all input information, an output file with all output data, and a log file with all logging information. The main steps performed by the module are summarized below:

1. The first step is to read and validate the input file.
2. If the user selects to load observatory from the database, load the data from the database.
3. Load observations from file. Collect celestial coordinates for each observation.
4. Compute observed angular path travelled between pairs of observations.
5. Load all ArtSat objects from the database.
6. Start a pre-processing loop in all loaded ArtSats.
7. Collect reference epoch, state, and state covariance. Discard ArtSats with a newer reference epoch than the first observation epoch.
8. Start a processing loop for all considered ArtSats.
9. Start a loop in observed observations.
10. Propagate each ArtSat state and state covariance to the observation epoch.
11. Compute expected celestial coordinates and their covariance for the observation epoch.
12. Compute the angular deviation metric between observed and expected celestial coordinates.
13. Compute expected angular path travelled and its variance for the current and next observation epochs.
14. Compute the angular path deviation metric between observed and expected angular path travelled.
15. Update the correlation index. If the correlation index exceeds the threshold, discard and exit ArtSat processing.
16. Repeat the process for all observations.
17. Repeat the process for all considered ArtSats.
18. Sort the ArtSat candidates in correlation index ascending order.
19. Prepare the report.
20. Candidates report and log are generated.

4.3.3 Observation Matching Algorithm

The implemented procedure follows a chronological processing for the measurement. For every object in the catalogue, the expected measurements are pre-computed.

These expected measurements are compared against the actual processed measurements, i.e., against those for all the objects with expected measurements-to-come passing a filter. Differences between current measurements and expected measurements-to-come for that object are then computed for celestial coordinates and angular path. The expected state covariance for each object at observation times is used to compute an expected covariance in the angular deviation and angular path deviation, which are then used for the normalization of both computed deviations. Finally, a correlation index is computed combining the two metrics. The chronological approach allows the algorithm to update the correlation index with each angular deviation and angular path deviation for each observation. Therefore, the processed object is immediately discarded in the computational process once the updated correlation index exceeds the defined threshold. Then, among all objects passing this correlation filter, the algorithms search for the candidate with the minimum correlation index.

The comparison between current observations and the computed observations from all the catalogued objects is a not trivial computational task. For this reason, objects whose reference epoch in the database corresponds to a later time than the first observation to be correlated are discarded since the observations are assumed to belong to an outdated object. It is very important to set a low-enough correlation index threshold, which allows the quick discarding of objects whose expected observations are far away from the ones to be analysed.

Whereas the correlation algorithm provided in TRADE is a simple one and it is already available and the motion direction in the plane of the sky is already analysed from the celestial coordinates comparison, it is possible the identification could fail to work in cases of just a few measurements, if no comparison is done between the expected angular path shift of the objects and the observed angular path in the plane of the sky between each pair of observations. Hence, this service uses algorithms from TRADE supported by a check on the angular path displacement of the object between each observation.

Angular deviation. To get the figure of merit related to the angular error, for each observation O_i, and epoch $t_i, i = 1, \dots, m$, the following steps are followed:

1. **Compute expected celestial coordinates and its covariance matrix.** The expected position vector is transformed into right ascension and declination angles through pertinent reference frame rotation and angular considerations. The concrete transformation is defined through vectorial function f. The Jacobian matrix for this function, $J_{\alpha,\delta}$, is computed numerically and used for the transformation of the state covariance matrix into a celestial coordinate's covariance matrix.

$$\alpha_{exp_i}, \delta_{exp_i} = f(r_i) \tag{4}$$

$$U_i = J_{\alpha,\delta} \Sigma_i J_{\alpha,\delta}^T \tag{5}$$

2. **Compute Eigenvalues and Eigenvectors of celestial coordinates uncertainty ellipse.** The 1-σ uncertainty ellipse is defined using the eigenvalues and eigenvectors of the covariance matrix in the celestial coordinates space. The eigenvalues represent the lengths of the semi-axes of the ellipse, and the eigenvectors indicate the directions of these axes.

$$\Lambda_i, V_i = \mathrm{Eigen}(U_i) \tag{6}$$

3. **Project the deviation in the eigenvector reference system.** Project the error between real and computed observations into this reference system, scaling the obtained distance by the corresponding eigenvalue. This step facilitates the determination of the error along the axes of the uncertainty ellipse in terms of the number of standard deviations.

$$P_i = \sqrt{\Lambda_i^{-1}} \left(V_i^T \begin{bmatrix} \alpha_i - \alpha_{exp_i} \\ \delta_i - \delta_{exp_i} \end{bmatrix} \right) \tag{7}$$

4. **Compute the modulus of the number of σ along both directions.** This provides information about the angular error in terms of number elliptical radii related to the 1-σ uncertainty ellipse.

$$M_i = \left| |P_i| \right| \tag{8}$$

Finally, calculate the average to obtain the observation deviation index for the entire set of observations.

$$I_{\alpha,\delta} = \frac{1}{m} \sum_{i=1}^{m} M_i \tag{9}$$

Angular path deviation. To obtain the figure of merit related to the angular path error for each observation pair $\{O_i, O_{i+1}\}$ and epochs $\{t_i, t_{i+1}\}$, where $i = 1, \dots, m-1$, these steps are followed:

1. **Compute observed angular path.** Computed from the celestial coordinates of the pair of observations, which define their observed celestial coordinates.

$$\cos \Omega_i = \cos(\delta_i) \cos(\delta_{i+1}) \cos(\alpha_i - \alpha_{i+1}) + \\ + \sin(\delta_i) \sin(\delta_{i+1}) \tag{10}$$

2. **Compute expected angular path and its variance.** Through the definition of the extended state χ_i which collects the position-velocity states for both time instants $\{t_i, t_{i+1}\}$, the expected travelled angular path is expressed as function f of this extended state and computed. Its variance is computed through the numerical computation of the Jacobian matrix for this transformation J_{Ω}, and the covariance matrix for the extended state vector, Ξ_i, formed as a block matrix using the state vector covariance matrices for the first time instant and the following, considering them correlated through the dynamical equations.

$$\Omega_{exp_i} = f(\chi_i) \tag{11}$$

$$\sigma_{\Omega_i}^2 = J_{\Omega} \Xi_i J_{\Omega}^T \tag{12}$$

3. **Derive the error in angular path in terms of number of standard deviations.** Aids in determining a normalized, non-dimensional description of the error.

$$N_i = \frac{1}{\sigma_{\Omega_i}}\left(\Omega_i - \Omega_{exp_i}\right) \tag{13}$$

Finally, calculate the average to obtain the observation pairs deviation index for the entire set of observations.

$$I_\Omega = \frac{1}{m-1}\sum_{i=1}^{m-1} N_i \tag{14}$$

Correlation index. Utilizing the computed indices, calculate an overall error index for the set of observations by employing a weighted function. This function assesses the fitting of the data to the current ArtSat trajectory. The selection of weights should be determined through a validation process, wherein the algorithm is tested with real observations from known ArtSats.

The definition of the weighted index is part of the work to be performed in the implementation of the service.

$$I = w_{\alpha,\delta} I_{\alpha,\delta} + w_\Omega I_\Omega \tag{15}$$

5 DYNAMICAL CONSIDERATIONS

Deimos software is reused for this project. Existing software derived from validated versions of source code is integrated into the project.

The reused astrodynamics code is based on the Deimos TRADE tool [4]. This tool is used for the specific purpose of performing orbit determination for operational satellites in GEO. The scope of this project is different, and therefore, TRADE shall not be used nor provided as-is. Instead, the TRADE functionalities shall be extracted and included in the form of a dynamic link library (libTRADE.so).

The stand-alone TRATO tool is used to compute the topocentric ephemeris (in RA/Dec). In this case, the TRATO tool is provided in the form of a self-contained executable, with its interfaces modified to be machine-friendly (as it shall not be used directly by any operator).

In addition to the above, the following assumptions are taken:

- Database objects are assumed as Earth-bound objects (in the extreme case, objects in L1/L2 could be considered if the propagation of their orbits is performed in an Earth-centred reference system).
- By default, database objects are considered non-operational, meaning ASIPS cannot autonomously detect or account for manoeuvres. However, if an operator manually provides an initial estimation of a potential manoeuvre’s delta velocities, the OD service can refine this estimate and incorporate it into the object's data in the database.
- The OD solution to be offered to external users are based on an analysis performed offline by the operators to determine which solution best fits the set of observations.
- Object uncertainties are treated through linear models (linear covariance applied to express the uncertainties).
- New observations are assumed in the TDM format and in the MPC 80-column format.

The ASIPS computational subsystem is based on several dynamical models and basic functions, which are identified in the following subsections.

5.1 Orbit propagation function

This function allows propagating orbit and covariance with model parameters from database. TRADE libraries are used for this purpose. TRADE propagator is based on the numerical integrations of the dynamic contributions, detailed in the following sections.

The modification of TRADE software includes the capability to choose between different dynamical models, developed for ASIPS.

5.1.1 Numerical Integrator

The numerical integration function solves the equations of motion of a given satellite. Numerically, it means to solve the following type of equation:

$$\dot{y}(t) = f(y, t) \tag{16}$$

with the initial conditions being expressed as state vectors and being f given by the dynamical model function.

There are several schemes for integrating these kinds of equations (equations of motion). The integration scheme proposed for the satellite dynamics function is the Runge-Kutta Fehlberg 7/8 method, a single-step numerical integrator with variable step size.

5.1.2 Dynamical Contributions

One of the key features of the ASIPS is the possibility to simulate the motion of objects in space in highly perturbed non-gravitational trajectories. This is certainly required due to the own nature of the ArtSat population of objects. Some of them present a high degree of interaction with non-gravitational contributions, such as the ones induced by solar radiation pressure.

Regarding the purely gravitational interactions, these are based on the possibility to include the gravitational effects from all the planets, the Sun, the Moon, and the extension in harmonics of the Earth gravitational field.

In this section all these contributions to the objects motion are described. These contributions are ultimately grouped to define several dynamical models, described in section 5.2.

Earth Gravity Field Model

The gravitational field in the vicinity of a celestial body may be described in several ways. Since planetary bodies are not perfectly symmetrical and their mass is not uniformly distributed, the representation of the gravitational field would require an infinite set of orthogonal functions.

For the ASIPS, the Earth gravity field is modelled through EGM 96 model, which uses a spherical harmonics expansion up to degree and order 360. This allows for a detailed representation of gravitational variations caused by Earth's shape, mass distribution, and anomalies.

Third Body Perturbation

To compute the third body perturbations affecting the satellite dynamics, it is necessary to calculate the positions of the perturbing celestial bodies with respect to the satellite at a given epoch.

Planetary and lunar ephemerides recommended for the IERS standards of 2003 are the JPL Development Ephemeris DE405. The Celestial Body State Vectors function computes the ephemeris of Solar System planets at a given epoch. They are calculated using the JPL DE 405 ephemerides model.

The third body objects involved in the executions processes performed by ASIPS are selectable.

Atmospheric drag

Atmospheric drag refers to the aerodynamic drag forces that act on a solid object falling through the atmosphere.

$$D = \frac{1}{2} C_d \rho A V^2 \tag{17}$$

where:

- D: stands for the atmospheric drag.
- C_d: stands for the drag coefficient.
- ρ: stands for the atmospheric density.
- A: stands for the area A on which the drag coefficient is based.
- V: stands for the velocity.

The MSISE model describes neutral temperature and density in Earth's atmosphere from the surface to the thermosphere, with successive versions incorporating additional data. While not ideal for specialized tropospheric studies, it is useful for analyses spanning multiple atmospheric layers. The NRLMSISE-00 model, used in TRADE, is an improved version of MSISE-90, enhancing accuracy through accelerometer data and the inclusion of ionized oxygen (O^+) contributions and UV occultation measurements.

Since some ArtSat objects may not interact with the atmosphere in a large time span, this contribution can be switched off.

Constant Aligned Solar Radiation Pressure

The SRP acceleration depends on the object-Sun relative position at the given epoch within the simulation period and on the object physical characteristics (mass, cross section area, reflective coefficient).

$$\vec{a}_{SRP} = \overline{s_P} \frac{d_{earth}^2}{d^2} fr_{sun} C_R \vec{u} \tag{18}$$

where:

- $\overline{s_P}$: radiation pressure at mean Earth distance from the Sun, $4.56 \times 10^{-9} \mathrm{kg\ km/(m\ s)^2}$.
- d_{earth}: mean Earth distance from the Sun.
- d: object distance from the Sun.
- fr_{sun}: fraction of visible Sun seen from the object.
- $\vec{u}$: unit vector defining Sun-object direction.
- C_R: reflective area-to-mas ratio parameter.

$$C_R = A_s \frac{c_R}{m} \tag{19}$$

- A_s: object's cross section area.
- c_R: object's reflective coefficient.
- m: object's mass.

This contribution adds one extra parameter: C_R.

Time-dependent Aligned Solar Radiation Pressure

For the models including a time dependency in the SRP, the variation of the cross-section area from Eq. 19 is proposed to be approximated as a constant area A_0, plus a basic sine wave modulation as follows:

$$\Delta A(t) = A_{sin} \sin(\omega t) + A_{cos} \cos(\omega t) \tag{20}$$

where:

- A_{sin}, A_{cos}: are area amplitudes.
- ω: is the frequency.

Hence,

$$A_s(t) = A_0 + \Delta A(t) \tag{21}$$

The overall area modulation amplitude, $\bar{A}$, and phase, ϕ, can be obtained from these parameters:

$$\bar{A} = \sqrt{{A_{sin}}^2 + {A_{cos}}^2}$$

$$\phi = \tan^{-1} \frac{A_{cos}}{A_{sin}}$$

This contribution adds four extra parameters: A_0, A_{sin}, A_{cos} and ω.

Misaligned Solar Radiation Pressure

For the models adding an out-of-line contribution of the SRP, its impact on perpendicular directions to sun direction is proposed to be estimated by surface-to-mass

Table 1. List of proposed dynamical models and associated contributions.

Model / Contribution	*Earth Gravity Field, Third body* and *Atmospheric drag*	*Const. Aligned SRP*	*Time-dep. Aligned SRP*	*Misaligned SRP*	No. Param.
Gravitational	Configurable				6
Basic SRP	Configurable	✓			7
Time-varying one-dimensional SRP	Configurable		✓		10
Constant three-dimensional SRP	Configurable	✓		✓	9
Complex SRP	Configurable		✓	✓	12

ratio for each direction. Hence, Eq. 18 is modified considering the new areas and new SRP directions:

$$\vec{a}_{SRP_y} = \overline{s_P} \frac{d_{earth}^2}{d^2} f r_{sun} C_{R_y} \vec{u}_y \quad (22)$$

$$\vec{a}_{SRP_z} = \overline{s_P} \frac{d_{earth}^2}{d^2} f r_{sun} C_{R_z} \vec{u}_z \quad (23)$$

This contribution adds two extra parameters: C_{R_y} and C_{R_z}.

5.2 Dynamical Models

To ensure sufficient flexibility in ASIPS, the dynamical contributions are combined in various ways to create different dynamical models. While the Earth's gravitational field, third-body perturbations, and atmospheric drag are configurable across all models, the primary differences lie in the specific SRP contributions adopted for each one.

- **Gravitational model:** Typically characterized by position and velocity or the osculating orbital elements at a given epoch, representing a six-parameter object model.
- **Basic SRP model:** Incorporates the *Constant Aligned Solar Radiation Pressure* contribution and introduces one additional parameter to model the simplest SRP effect.
- **Time-varying one-dimensional solar radiation pressure model:** Accounts for the *Time-dependent Aligned Solar Radiation Pressure* contribution, requiring four additional parameters.
- **Constant solar radiation pressure with constant out-of-line contribution model:** Considers both *Misaligned Solar Radiation Pressure* and *Constant Aligned Solar Radiation Pressure*, adding three extra parameters.
- **Complex SRP model:** The most advanced model, combining *Time-dependent Aligned Solar Radiation Pressure* and *Misaligned Solar Radiation Pressure*, increasing the total number of additional parameters to six.

A summary for the different models is shown in Table 1.

6 RESULTS

A series of tests have been carried out to validate the modules involved in the ASIPS. Here below, some of them are presented, and their results are reported.

6.1 Orbit Determination validation

6.1.1 GEO object

Several real GEO objects were used for the initial validation of the OD module, providing a robust test case for integrating new algorithms with existing tools like TRADE and TRATO. This subsection presents the results for a non-operational GEO object, using 602 observations from 5 different sensors nearly uniformly distributed along 13 consecutive days, with just 4 periods of more than 1 day without observations.

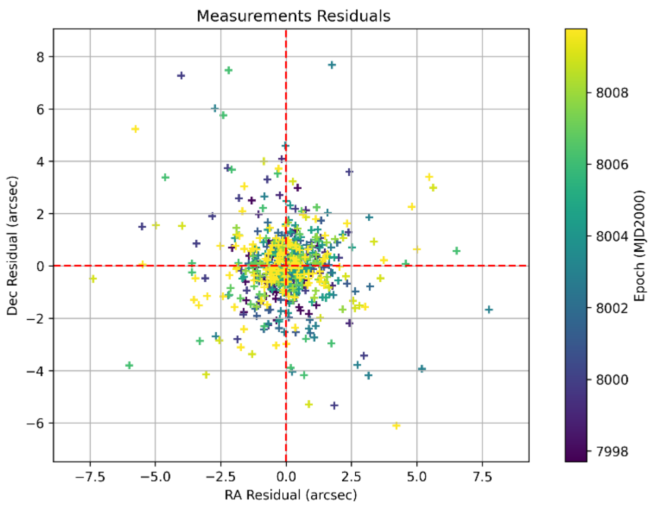

Figure 3. GEO object OD residuals.

The Basic SRP dynamical model with an extra parameter was used and produced a solution with a uniform distribution of residuals (Figure 3). The mean and standard deviation of the residuals are as follows:

$$\mu_{res} = 1.464 \text{ arcsec}$$

$$\sigma_{res} = 2.399 \text{ arcsec}$$

6.1.2 ArtSat object

The ArtSat Spektr-R has also been used for the OD validation. A reference state estimation external to the service was propagated to the initial observation time, T_0, serving as the initial state for the OD process. The classical orbital elements of this initial state highlight the distinctive characteristics of the orbit of this type of object:

$$a_0 = 195626 \text{ km} \quad (T \sim 7.0 \text{ days})$$

$$e_0 = 0.807641$$

$$i_0 = 52.680°$$

$$\Omega_0 = 308.951°$$

$$\omega_0 = 355.639°$$

$$\theta_0 = -167.431°$$

A set of real observations for this object was used in the analysis. This dataset consists of three observation batches:

- Batch 1: 344 observations on the night of T_0.
- Batch 2: 120 observations on the night of $T_0 +$ 5 days.
- Batch 3: 116 observations on the night of $T_0 +$ 17 days.

Due to the complexity of orbit determination for this type of orbit, a thorough analysis was performed. Several combinations of observation batches and dynamical models were studied to achieve a satisfactory validation.

Model 1 – Batch 1

This is the simplest case studied for this object, where only the first batch of observations was used for OD. The resulting OD solution produced uniformly distributed residuals for the astrometry of the observations used (Figure 4). The mean and standard deviation of the residuals are as follows:

$$\mu_{res} = 0.236 \text{ arcsec}$$

$$\sigma_{res} = 0.302 \text{ arcsec}$$

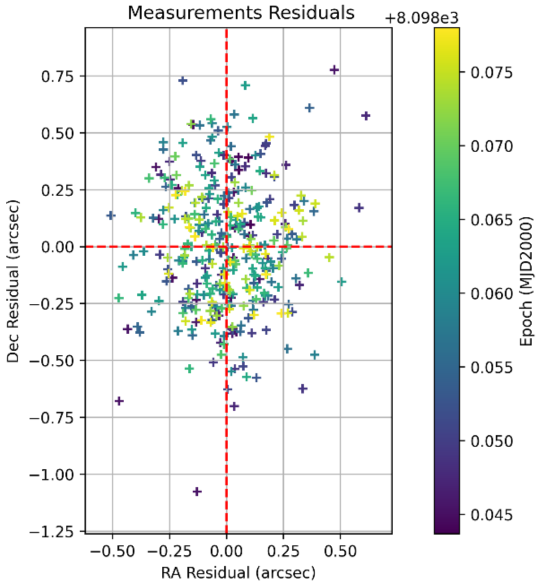

Figure 4. Spektr-R OD residuals, Model 1, Batch 1.

Model 5 – Batches 1, 2, and 3

This represents the most complex case studied for this object, incorporating all three batches of observations. Given the extended time intervals between observation windows and the particular orbital characteristics, the OD solution exhibited a trend in the astrometric residuals (Figure 5). The behaviour emerges after a slow convergence to local minima in the OD optimization process and may result from a misalignment between the implemented approach, derived from TRADE's GEO OD algorithms, and the actual dynamics of these objects.

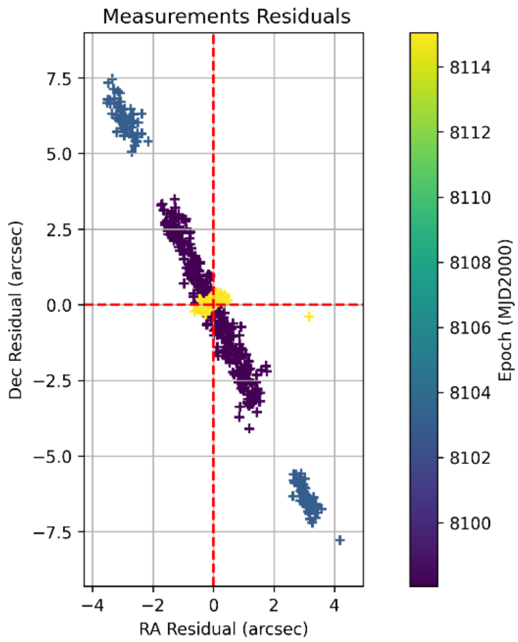

Figure 5. Spektr-R OD residuals, Model 5, Batches 1, 2 and 3.

The mean and standard deviation of the residuals are:

$$\mu_{res} = 2.51\,\text{arcsec}$$

$$\sigma_{res} = 3.46\,\text{arcsec}$$

6.2 Observation Identification validation

The observation identification service algorithm was tested using multiple cases with different sets of observations corresponding to known real ArtSat objects. In these analyses, each observation set was processed with a reduced list of candidate objects, ensuring that the correct object was included. The goal of the analysis was threefold:

1. To verify that the algorithm properly filters out objects that are too far from the given observations based on the correlation index threshold.
2. To determine whether the algorithm correctly identifies the target object by assigning it a low correlation index.
3. To analyze the correlation indices assigned to the remaining candidate objects.

The initial set of candidate objects consisted of four ArtSats and two GEO objects:

- **Spektr-R** (2019-040A) – Epoch: 2022-03-04.
- **DSCOVR booster** (2015-007B) – Epoch: 2022-02-07.
- **Chandra** (1999-040B) – Epoch: 2022-04-03.
- **INTEGRAL** (2002-048A) – Epoch: 2022-01-04.
- **GEO object 1** – Epoch: 2021-11-23.
- **GEO object 2** – Epoch: 2021-12-01.

The initial state and covariance for all these objects were generated *a priori* using the OD module of the ASIPS, incorporating real observations available for each object.

Spektr-R observations identification.

A total of 116 observations from 2022-03-21 were used in this validation case. The observation identification service successfully discarded Chandra, as its reference epoch was after the observation epoch; and the two GEO objects, whose correlation indices exceeded the configured threshold of 3×10^3.

The results of the correlation index analysis are presented in Table 2. The algorithm successfully assigned the correct object (Spektr-R) a low correlation index, placing it in second position. However, the initial data available for the INTEGRAL object, combined with its propagation, led to a significant increase in its state covariance estimation over time. Consequently, this resulted in large expected errors for the computed observations used in the correlation process.

Notably, as described in Section 4.3.3, the algorithm normalizes observation deviations using these expected errors. When the expected errors are large, they systematically lower the overall correlation index, potentially leading to false positives. This effect caused the INTEGRAL object to receive the lowest correlation index due to an inaccurate state estimation, which reduced its score.

Table 2. Spektr-R observations identification.

Position	Object	Correlation Index
1	INTEGRAL	9.08
2	**Spektr-R**	$\mathbf{11.26}$
3	DSCOVR booster	27.90
-	GEO 1	5.55×10^5
-	GEO 2	1.17×10^6

Chandra observations identification.

In this case, 19 observations from 2022-04-03 were used. The observation identification service again successfully discarded the two GEO objects, as their correlation indices exceeded the 3×10^3 threshold.

The results, presented in Table 3, show that the algorithm correctly identified Chandra as the most likely candidate, assigning it a significantly lower correlation index than the other objects.

Table 3. Chandra observations identification.

Position	Object	Correlation Index
1	**Chandra**	$\mathbf{2.55 \times 10^{-2}}$
2	Spektr-R	2.05
3	DSCOVR booster	59.10
4	INTEGRAL	1969.92
-	GEO 2	1.68×10^6
-	GEO 1	1.75×10^6

7 CONCLUSIONS

The increasing challenge of distinguishing artificial objects from Near-Earth Objects (NEOs) has highlighted the need for improved identification and tracking solutions. The ArtSat Information Provision Service (ASIPS), developed under the ArtSat initiative, addresses this issue by providing a structured and automated approach for managing artificial objects with high-energy Earth-bound orbits.

The system has been designed to integrate seamlessly with existing planetary defense and space situational awareness infrastructures. Its core services: Ephemerides Generation, Orbit Determination, and Observation Identification; offer critical functionalities that enhance the efficiency of NEO monitoring efforts. Additionally, supplementary tools such as the NEOCP Identification Service and the Observer Scoring Utility contribute to improved prioritization and engagement within the observer community.

The ASIPS computational framework incorporates advanced orbit propagation models that account for non-gravitational perturbations, particularly solar radiation pressure, improving the accuracy of trajectory predictions for light-reflective objects.

The results obtained confirm that ASIPS could help ESA NEOCC infrastructure reducing observational resource waste by minimizing false NEO detections. Furthermore, the correlation index methodology introduced in the Observation Identification Service has proven to be an effective metric for object classification, ensuring accurate association of observations with known artificial objects. However, its reliability depends on the accuracy of state estimations over time. If estimation uncertainties grow excessively (resulting in large covariances), the correlation index may be artificially reduced, increasing the risk of false positives. Therefore, careful consideration must be given to maintaining accurate orbit determinations to preserve the robustness of the identification process.

Looking ahead, future developments could focus on enhancing ASIPS's automation capabilities, integrating more accurate orbit determination techniques designed for these high-energy orbits, and developing more efficient computational algorithms. Collaboration with international SSA initiatives, integration of new products such as Aegis software [5], and increased data-sharing efforts will be crucial in further refining the system's performance and ensuring its long-term impact on space surveillance and planetary defense.

ASIPS represents a step forward in mitigating the growing ambiguity between space debris and NEOs, supporting both planetary defense strategies and the sustainable use of Earth's orbital environment.

ACKNOWLEDGEMENTS

This work was funded by ESA under the project S1-PD-06.2 - *Software development for NEO observational activities.*

AI USE DISCLOSURE

This manuscript was prepared with the assistance of AI technology to improve readability, grammar, and language clarity. Specifically, *ChatGPT* was used to refine sentence structure and enhance readability. No AI-generated content was used for original research, data analysis, or conceptual contributions. Additionally, the authors reviewed and verified any figures or illustrations modified using AI tools to ensure accuracy and compliance with ethical standards. The authors take full responsibility for the integrity and correctness of the content presented in this work.

REFERENCES

[1] J. L. Cano, M. Ceccaroni, L. Faggioli, R. Jehn, D. Koschny, S. Lemmens, F. Letizia, S. Löhle, J. Martín and M. Micheli, "ESA's Activities on the Boundaries between NEO and Debris Detection," *1st NEO and Debris Detection Conference, ed. T. Flohrer, R. Jehn, & F. Schmitz (ESA Space Safety Programme Office Publishing),* vol. 470, 2019.

[2] J. L. Cano, N. Sánchez-Ortiz, M. Micheli and J. N. Torres, "Identification of SST community support to reduce false positives in the identification of NEO imminent impactors," *1st NEO and Debris Detection Conference,* p. 7, 2019.

[3] F. Pallarés-Chamorro, "Analysis of the Population of Artificial Objects Detected by the NEO Community," La Sapienza University of Rome, Rome, Italy, 2022.

[4] N. Sánchez-Ortiz, R. Domínguez-González, J. Nomen, S. Pessina and M. Klinc, "Satellite flight dynamics activities supported by optical observations, lessons learnt from operational experience," *8th European Conference on Space Debris,* p. 53, 2021.

[5] M. Fenucci, L. Faggioli, F. Gianotto, D. B. Cioci, J. L. Cano, L. Conversi, M. Devogèle, G. D. Girolamo, C. Drury, D. Föhring, L. Gisolfi, R. Kresken, M. Micheli, R. Moissl, F. Ocaña, D. Oliviero, A. Porru, P. Ramirez-Moreta, R. Rudawska and F. Bernardi, "The Aegis orbit determination and impact monitoring system and services of the ESA NEOCC web portal," *Celestial Mechanics and Dynamical Astronomy,* vol. 136.6, p. 58, 2024.