EUROPEAN OPTICAL NETWORK: OPERATIONAL SERVICES FOR GEO OPERATORS

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ABSTRACT

The European Optical Network (EON) activity, initiated under the ESA Space Safety Programme, has successfully transitioned from a conceptual framework to an operational system. To meet this goal, cataloguing and data provider centric services have been built into OKAPI:Orbits' Aether Space Situational Awareness software solution. The paper focuses on the critical aspects of tracking data processing, orbit determination, GEO neighbourhood debris awareness and conjunction risk assessment as part of the journey and experiences in making the backend fully functional.

EON integrates a network of automated sensors, both existing and newly deployed, to provide comprehensive optical observations and data products aimed at enhancing spacecraft safety and mission success. The project leverages advanced software services for handling data requests, scheduling observations, processing acquired data, and delivering high-quality data products with a high level of process automation.

The consortium, comprising Sybilla Technologies Sp. Z., OKAPI:Orbits GmbH, Vyoma GmbH, and Aristotle University of Thessaloniki, has focused on three main system streams: sensor upgrades and deployment, software service development, and system integration and operations.

Sensor upgrades have been a pivotal component, with efforts directed towards enhancing the existing Panoptes-Solaris network and integrating additional sensors to improve network resiliency and redundancy. At the time of writing, the network comprises a total of 44 sensors around the world, ensuring continuous and uninterrupted data flow. The tracking data is processed and used for ephemeris and service provisioning, with a strong emphasis on sensor calibration to maintain high data quality.

The software services developed within the activity support various functionalities, including data requests, processing, and delivery of data products. The system's user interface isolates users from the hardware components, providing a seamless experience for satellite operators, service providers, and other stakeholders interested in space traffic management (STM) and space surveillance and tracking (SST).

A significant achievement is the development of robust algorithms for automated orbit determination and neighbourhood determination of objects in proximity to GEO satellites. These algorithms enable precise tracking and prediction of object trajectories in the vicinity of our assets, facilitating accurate conjunction risk assessments.

The paper discusses the challenges encountered during the activity, including the integration of diverse sensor systems, the development of interoperable software services, and the coordination among international consortium partners. Lessons learned from these experiences have been instrumental in refining the system and enhancing its operational capabilities.

In conclusion, the European Optical Network represents a significant milestone in commercial European space situational awareness and space traffic management. The successful operationalization of EON demonstrates the potential of automated sensor networks and advanced data processing techniques in ensuring the safety and sustainability of space activities.

Keywords: SST; SSA; Cataloguing; GEO.

1. ABBREVIATIONS

API Application Programmatic Interface

CDM Conjunction Data Message

EON European Optical Network

GEO Geostationary Orbit

GTO GEO Transfer Orbit

GUI Graphical User Interface

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IOD Initial Orbit Determination

OD Orbit Determination

OEM Orbit Ephemeris Message

OMM Orbit Mean-Elements Message

OPM Orbit Parameters Message

PoC Probability of Collision

SSA Space Situational Awareness

SST Space Surveillance and Tracking

STM Space Traffic Management

TCA Time of Closest Approach

TDM Tracking Data Message

TLE Two Line Elements

2. INTRODUCTION

The European Optical Network (EON) project began in 2022 to establish an independent European infrastructure for Space Situational Awareness (SSA) and Space Surveillance and Tracking (SST). The project involves both software and hardware upgrades. The consortium includes Sybilla Technologies Sp. z o.o., **OKAPI:Orbits** GmbH, Cilium Engineering Sp. z o.o., Vyoma GmbH, NTT DATA Romania S.A., Aristotle University of Thessaloniki, Libre Space Foundation, AstroTech KFT, and Astros Solutions [1].

The project consists of multiple components, including sensor upgrades and the integration of new sensors. **OKAPI:Orbits** primarily contributed to software development, focusing on service integration and operations. The software processes measurements and generates an object catalogue, which supports scheduling new measurements and providing services to satellite operators. The project mainly targets satellite operations in the geostationary (GEO) region.

Services are provided to various user groups, including satellite operators, sensor operators, public entities, and service providers. **OKAPI:Orbits**' SSA platform, **OKAPI:Aether** was enhanced to support these services. The platform ingests pre-processed Tracking Data Messages (TDMs) and performs Orbit Determination (OD) and propagation, generating a catalogue predicting object positions up to 10 days in advance. For sensor operators, the system provides tracking priorities and assists the scheduling with improvement predictions, while satellite operators receive insights into potential close approaches with other satellites and debris.

This paper details the provided services and presents results and learnings from the process of turning it into an operational system.

3. SOFTWARE CAPABILITIES

As part of the EON project, software was developed to connect hardware with various user groups. Users can access multiple services via dedicated Application Programmatic Interfaces (APIs). This document focuses on services for GEO satellite operators.

3.1. Architecture

The EON architecture has a scheduling agent creating a plan for measurements that is then executed by the sensors. Measurements are processed by **OKAPI:Aether** in the form of TDMs. The results are stored in the catalogue, which serves as the basis for all the offered services. The loop to the scheduling agent is closed this way, so the current catalogue status can be used to plan new measurements.

At the core of this stands the **OKAPI:Aether** platform. Apart from catalogue maintenance, it provides services to satellite operators. This includes conjunction assessment, the tracking of the satellite, and the tracking of nearby, potentially dangerous objects.

3.2. User interface

OKAPI:Aether offers different options for users to interface with the platform. All functionalities are accessible via an API. This allows the operator to integrate functionalities into their own software. In addition to that, a Graphical User Interface (GUI) shows an overview over all satellites of a user and any upcoming and historical conjunctions. The neighbourhood of each satellite and possible collision avoidance manoeuvres are also displayed.

3.3. Cataloguing

OKAPI:Aether automatically processes raw TDMs uploaded to the database in CCSDS format [5]. TDMs of known objects are grouped together by the observed object. A batch is created from all unprocessed TDMs for a given satellite. To fill the optimal OD fit span, older, already processed measurements can be loaded from the database. Additional data, like satellite parameters, if available, improve modelling accuracy. The initial orbit is retrieved from previous OD results or public catalogues. If no information is available, an initial orbit determination is performed instead. OD settings are chosen per orbit group, defining optimal values for configuration parameters such as OD interval and perturbation model. The OD relies on a robust weighted batch least squares algorithm with outlier rejection and is able to fuse measurements from multiple sensor types.

Figure 1 displays TDMs for selected GEO objects provided by different sensors. Measurements can be uploaded using the API. Orbit determination results are stored in the database following the CCSDS OEM and OMM formats. OEMs are used for accurate ephemeris information while the less accurate OMMs are useful when a fast access to less accurate data is needed. Interpolated orbital states enable quick position and velocity access without full propagation. This catalogue supports downstream services, including sensor tasking to improve tracking quality. Ephemerides can be retrieved from the database via API request. It is also possible to request an independent orbit determination that does not interact with the catalogue.

The data quality process consists of the realistic assessment of uncertainties, which is crucial for services provided based on the catalogue. There are several factors that introduce difficulties in this process. A major factor making orbit determinations difficult are unknown manoeuvres performed by tracked satellites. If they are not properly modelled, trying to fit an orbit to measurements before and after a manoeuvre will not result in an accurate orbit. To deal with this, **OKAPI:Aether** can detect manoeuvres based on residuals in the measurements and adjusts the fit span to provide an accurate orbit determination. Figure 2 shows the process detecting a manoeuvre and adapting.

An accurate estimation of uncertainties is important to understand catalogue quality and provide accurate services like Collision Probability assessments. The accuracy of an uncertainty is assessed through comparing ephemerides from different sources or of different age. The uncertainty is propagated to another epoch and comparing it to an ephemeris determined at that epoch. Calculating the Mahalanobis distance [4] between propagated and determined ephemeris allows to make a statement on the accuracy of the uncertainty. By aggregating a large number of such comparisons, a statement on the general accuracy of the uncertainty can be made.

A high rate of measurements, that are not independent from each other, un-modelled biases or uncertainties can lead to an underestimation of the uncertainty of an ephemeris. To avoid these issues, different techniques are employed. The impact of inconsistent measurement rates is kept in check through undersampling of TDMs. Based on historic orbit comparisons, scaling factors are determined for the uncertainty of different groups of objects.

OKAPI:Aether is operational since 2020 and is able to provide services to any satellite operating in GEO based on a growing network of ground based sensors. This Section gives an overview over some of the available services for satellite operators. Measurements are created from more than 44 sensors that are distributed worldwide. These are used to perform orbit determinations and create OEMs.

For a well maintained catalogue, regular updates of objects of interest are necessary. The health of the catalogue is regularly monitored based on uncertainty size and time since last observation. Figure 3 shows a snapshot of the health of the neighbourhood catalogue of prioritized objects. During the observed time frame, around 100 were maintained in the catalogue with sufficient quality. Further objects were catalogued with lower quality.

3.4. Cataloguing of Fragmentation Events and uncatalogued objects

Fragmentations, from collisions or explosions, are a significant contribution to the space debris environment [3]. In case of such an event, objects need to be found and orbits determined quickly to mitigate the risk from collisions with uncatalogued objects. A goal of the EON project is to develop the capability to catalogue objects originating from fragmentations. The main difficulty lies in the problem that no prior orbit information is available to perform the initial tracking.

OKAPI:Aether is capable of performing an Initial Orbit Determination (IOD) if no orbit is given. For measurements that are classified as `UNKNOWN` by the sensor operator, new IDs are assigned and the objects are catalogued. Once catalogued, new measurements can be correlated to these objects to keep the orbit well tracked.

3.5. Neighbourhood Awareness

GEO satellites operate within a relatively narrow range of inclinations and semi-major axes, making awareness of nearby objects crucial for conjunction risk assessment and manoeuvre planning [2].

OKAPI:Orbits implemented a *Neighbourhood screening service*. Satellite operators define a “neighbourhood” around their satellite, triggering alerts when objects enter this region. It is defined by an extended screening volume in each spatial direction. Using a larger screening volume increases the long term awareness of a satellites surroundings. The system can operate with any available ephemeris information, including public catalogues as well as catalogues created from processed measurements. Each new ephemeris triggers a one-vs-all screening for user satellites, while observations of non-customer objects trigger a one-vs-few screening of the new ephemeris versus the active satellites.

As a result, operators receive a list of predicted neighbourhood crossings, including time of closest approach (TCA) and component-wise distances. Priority tracking is assigned to objects frequently entering neighbourhoods. If an object poses a collision risk, a Conjunction Data Message (CDM) is generated for further assessment. Figure 4 illustrates a satellite’s neighbourhood with surrounding objects. Screening a satellite’s neighbourhood allows for a 10 day look ahead and increased awareness for objects that

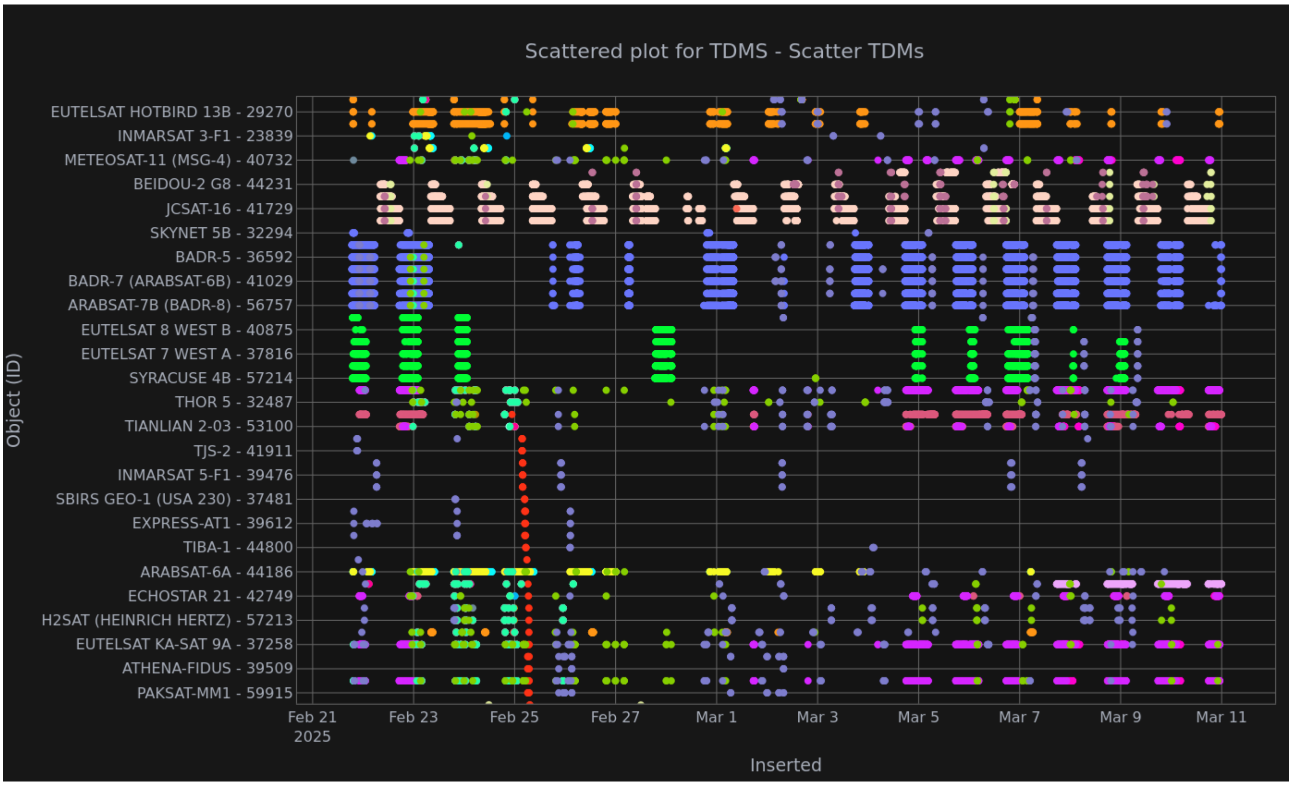

Figure 1. Incoming TDMs in the database for selected satellites.

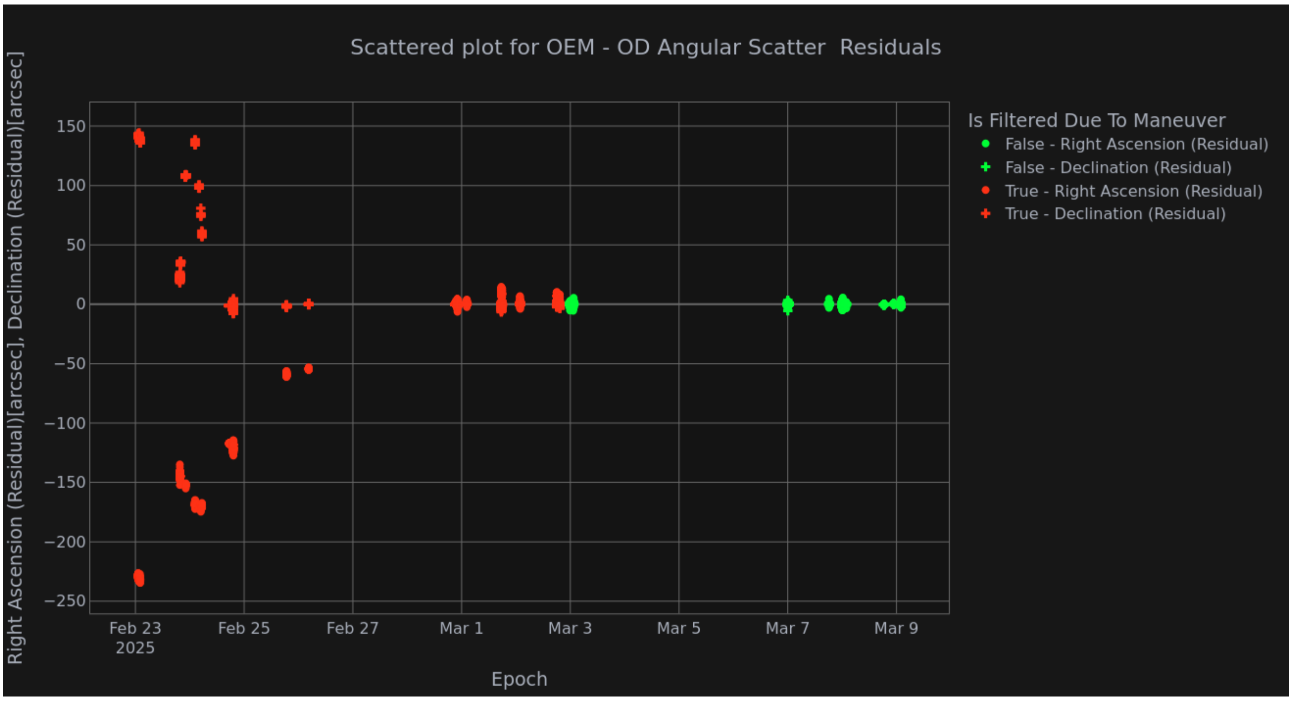

Figure 2. Manoeuvre detected in the OD process.

could pose a threat in the future. This gives the satellite operator a longer preparation and reaction time. It also allows for dedicated tracking of potentially dangerous objects.

3.6. Conjunction Assessment

OKAPI:Aether assesses conjunction risks and computes mitigation strategies. It ingests CDMs from space-track or

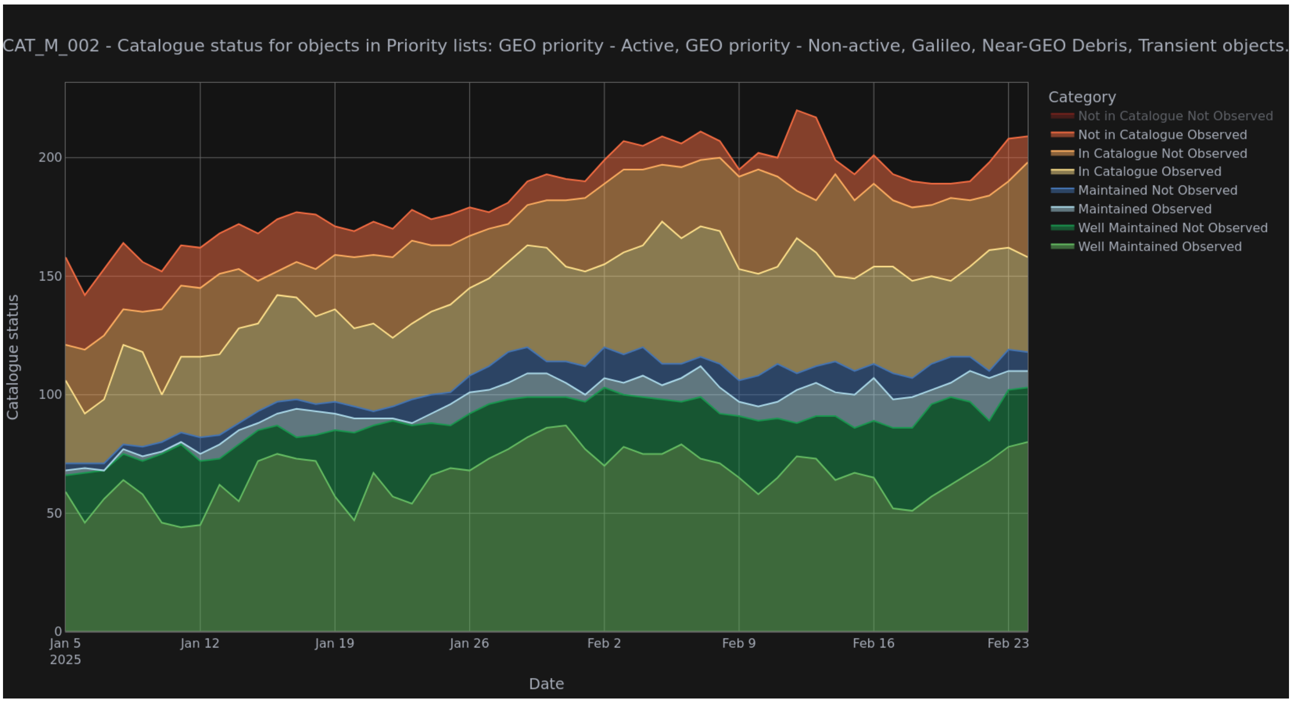

Figure 3. Number of objects in the EON catalogue by maintenance status.

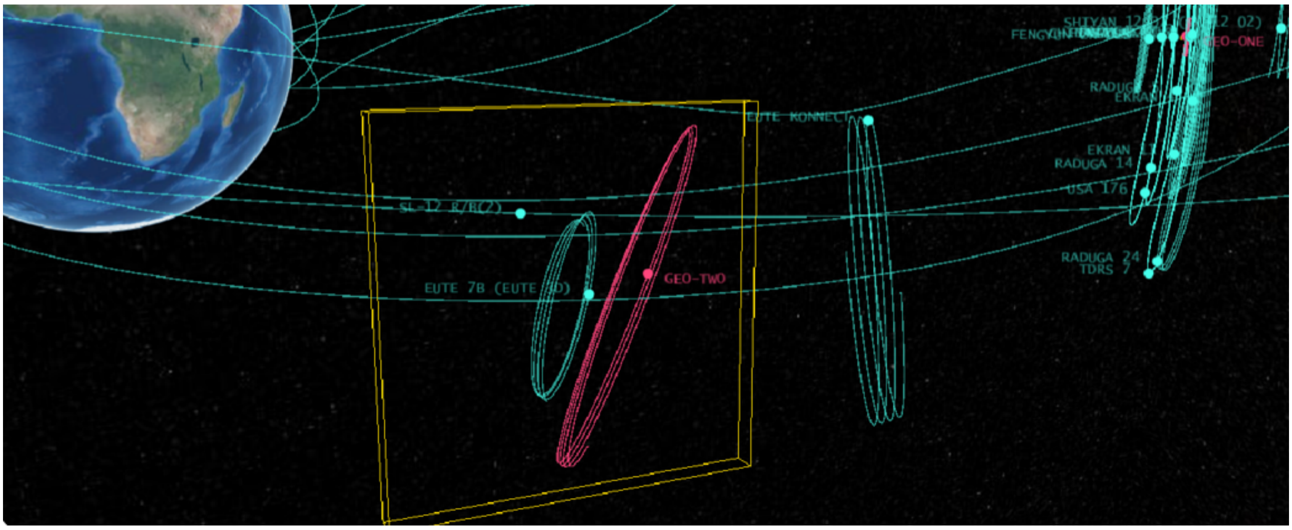

Figure 4. View of a GEO neighbourhood.

internally detected events from the neighbourhood screening. Any available ephemeris from user provided data or tracking data is used to reprocess the conjunction and create additional CDMs. Data quality and covariance realism is monitored to provide trustworthy Probability of Collision (PoC) estimations. Conjunctions are analysed based on miss distance, Mahalanobis distance, and collision probability.

Operators receive a prioritized list of conjunctions, categorized as critical, observe, or non-critical. Risk thresholds are user-defined, based on total or per-component miss distance or collision probability. For critical events, manoeuvre recommendations are generated that ensure a safe miss distance and collision probability. Many satellites have strict constraints related to the station keeping requirements of the satellites and limits like the maximum thrust and thrust duration. **OKAPI:Aether** can take these constraints into account to provide manoeuvres that are actionable.

All information related to a conjunction event is collected and summarized for satellite operators. Positions of primary and secondary objects and their uncertainties are evaluated at TCA. This data can be taken from space-track data, taken from the CDM, or calculated based on ephemerides from the catalogue. From this, miss distances (total and split by component) and collision probability are calculated. Whenever new ephemerides become available, the event is updated. A time series of information and current status is provided to the user via the GUI of **OKAPI:Aether**. Figure 5 shows this view for a simulated conjunction event where both data from space-track and data from the catalogue are available.

For critical events, collision avoidance manoeuvres are provided to the operator. Based on the desired limits for miss distance or collision probability, the satellites propulsion system and additional constraints like station keeping or maximum thrust durations manoeuvres are determined. The orbit after the manoeuvre is screened against the catalogue to avoid any secondary conjunctions. Different manoeuvre strategies are provided for the user to select one that fits their needs.

3.7. Manoeuvre Confirmation

OKAPI:Aether allows operators to verify manoeuvre execution. Operators upload Orbital Parameter Messages (OPMs) with planned manoeuvrers, which are compared to observation-based orbits. Residual analysis between planned and observed states determines manoeuvre success.

4. SUMMARY

Software and hardware components developed and improved during the EON Project have now become operational. A global network of telescopes is regularly acquiring measurements of objects mainly in the GEO region. This data is processed by the software component developed by **OKAPI:Orbits** creating an independent catalogue of neighbourhood objects affecting GEO satellites. To close the loop to the measurement creation, tracking priorities are set based on the current quality of catalogued orbits as well as interference of objects with operational spacecraft. Based on the catalogue, additional services are provided to satellite operators to increase awareness of surrounding objects, screening for conjunctions and providing options for collision avoidance manoeuvres.

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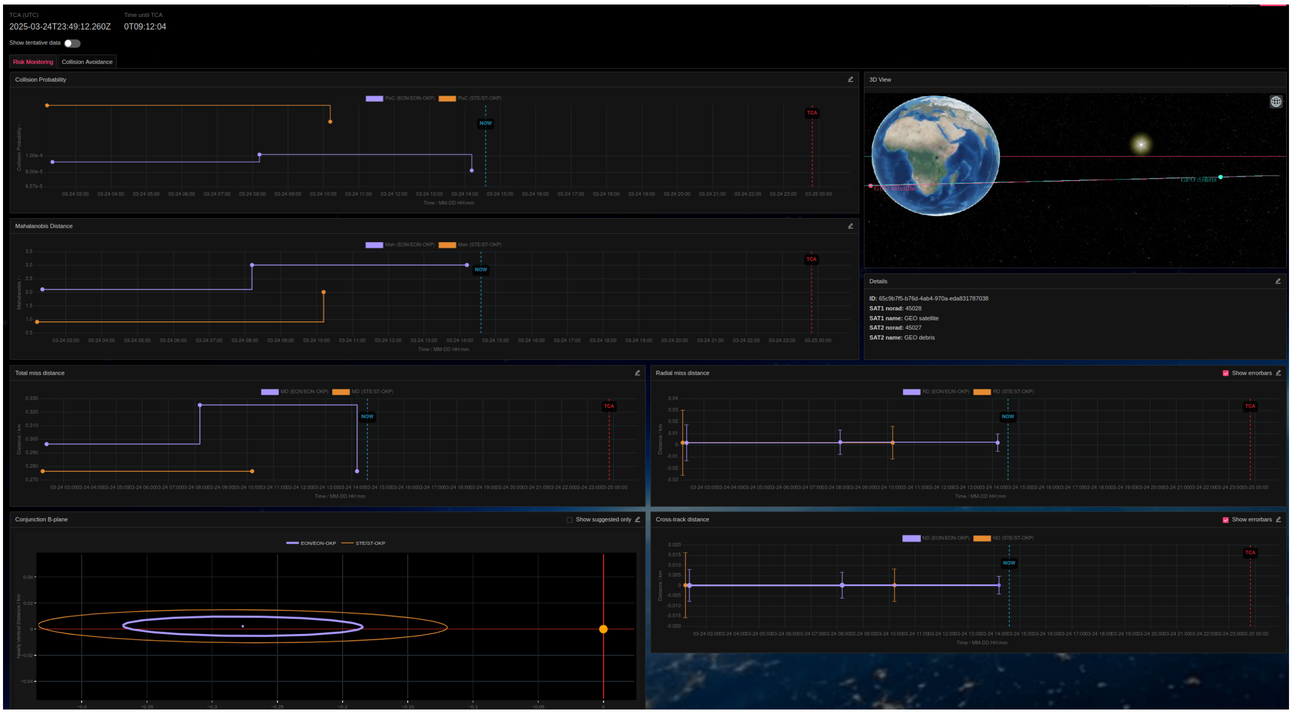

Figure 5. View of a conjunction.