Multi-sources data correlator for commercial services
ESR – Executive Summary Report

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1.0	02/09/2024	First version issued for external release
1.1	10/10/2024	Version after Final Review

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Acronyms and abbreviations

API	Application Programming Interface
BLS	Batch Least Squares
CCSDS	Consultative Committee for Space Data Systems
CRD	Consolidated laser Ranging Data format
DB	Database
ESA	European Space Agency
ESOC	European Space Operations Center
ESR	Executive Summary Report
FTP	File Transfer Protocol
GEO	Geostationary Orbit / Geosynchronous Equatorial Orbit
GODOT	General Orbit Determination and Optimisation Toolkit
gRPC	Google Remote Procedure Call
HTTP	Hypertext Transfer Protocol
IOD	Initial Orbit Determination
LEO	Low Earth orbit
LUPI	Length of Update Interval
MSDC	Multi-Source Data Correlator
OD	Orbit Determination
OEM	Orbit Ephemeris Message
OPM	Orbit Parameters Message
ODM	Orbit Data Message
POE	Precise Orbit Ephemeris
REST	Representational State Transfer (convention for programming APIs over HTTP)
SDLR	Satellite Debris Laser Ranging
SP	Special Perturbations
SLR	Satellite Laser Ranging
STM	Space Traffic Management
TC	Track Correlation
TDM	Tracking Data Message

1.Introduction

1.1 Purpose of the Document

This document is the **Executive Summary Report** (ESR), Doc.-No. **NEU-MSD-FR**, produced for the MSDC project. It represents one of the deliverables of the "**Multi Multi-sources data correlator for commercial services**" project, ESA Contract No. **4000141190/23/NL/GLC/cb**.

The ESR is produced for business purposes and summarises the project context, the approach taken, the results, and the findings of the project.

1.2 Document Structure

The document is structured as follows:

- Chapter 2 provides the context, and introduces the object and activities;
- Chapter 3 presents the conclusions for data analysis and literature review;
- Chapter 4 describes the high-level design;
- Chapter 5 presents the prototype specification;
- Chapter 6 demonstrates the performance of the MSDC demo model
- Chapter 7 draws conclusions

2. Context, Objective, and Activities

The activity is inserted in the ESA GSTP *Assessments to Prepare and De-Risk Technology Developments* framework to de-risk the development of a multi-sources data correlator (MSDC) demo model for a commercial STM service. Starting from a TRL 3 and targeting a TRL 7, the activity aims to develop a demo model demonstrating the element performance for the operational environment after which continued operation, improvement, and parallel injection of the MSDC into present-day and future pilots is envisaged. Eventually, the MSDC will prove full functionality after its integration into the Neuraspace sensor network, once it is up and running.

2.1 Objective

The objective of the activity is:

To develop a multi-source data correlator (MSDC) demo model for a commercial STM service.

In order to consider this achieved we have the following requirements:

- Ingest and combine tracking data from multiple sensor types (telescope, radar and laser)
- Correlate measurements with intended target
- Perform orbit determination with all available data sources
- Provide a high accuracy propagation of spacecraft trajectory
- Perform orbital updates automatically on track ingest in a manner compatible with Neuraspace's STM platform in order to maintain a catalogue of selected objects of interest

The MSDC, once operational, will allow to generate the necessary information to:

- Identify and catalogue the near- and deep-space environment in orbit;
- Provide the necessary information for conjunction analysis assessment;
- Provide manoeuvre recommendations to avoid collisions;
- Validate manoeuvre recommendations.

Furthermore, the catalogue will enable other services such as fragmentation, manoeuvre detection, and re-entry analysis.

2.2 Activities

The approach to de-risk the development of the MSDC included the following activities: data analysis, high-level design, algorithm development and testing, and operation and performance evaluation.

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3.Data Analysis

From our review of near-earth dynamics and space weather, we concluded both Orekit and GODOT support the main perturbations associated with the trajectories of space objects around Earth. The major differences arrive when comparing implementations for drag and solar radiation pressure, where the cross-section is perpendicular to the along-track and sun directions, which depend on how the satellite shape and attitude are being modelled: canon-ball model, through the use of a simple n-plate model such as the box and solar array model Orekit), or more complex models (GODOT).

Regarding space weather and atmospheric density models, we compared the NRLMSISE-00 using freely available space weather data against the JB2008 using space weather provided by SET. No clear benefit was found both from the literature review and from the Neuraspace assessment. Also, the NRLMSISE-00 model is implemented in both low-level flight dynamics frameworks, while JB2008 is only supported by Orekit. As such, we plan to use the NRLMSISE-00 in the scope of the MSDC activity.

Then we identified several IOD and OD algorithms and strategies. IOD strategies to be implemented in the future will depend on the typologies of sensors and network used, while the selection of OD algorithms may be limited to constraints such as timeliness and frequency of the data batches being received, performance objectives and will come down to the computation framework chosen.

While reviewing the literature for the correlation processes involved in building a catalogue as the one proposed in the MSDC, we have identified several correlation techniques for both track and orbit-to-orbit correlation. Unfortunately, the literature on correlation methods for this application is not direct and concise to definite results, and the definition of preliminary correlation (and manoeuvring) thresholds that was expected to be derived from literature could not be met with reference values found in the literature (other than those found for specific cases).

Finally, we evaluated the relevant standards for the exchange of tracking messages (CCSDS TDM and ILRS CRD), along with the practices, tracking performances and procedures found among data providers and different typologies of sensor systems identified for integration into the MSDC, namely on-ground radar, optical passive and SLR/SDLR infrastructure.

4.High-Level Design

4.1 Neuraspace Space Object and Orbit Databases

Neuraspace Space Object and Orbit Databases are sourced from different origins, most importantly Space-track, Discos and directly from the Satellite Owners/Operators. The data from multiple sources is curated and merged into Neuraspace's Platform via the relevant REST APIs, in particular Space Objects and Orbits API. These APIs are later widely used for internal consumption by the platform. Through the acquisition of tracks, it is expected that new data will progressively be added and updated, either with new orbital data or even with new space objects.

From the perspective of the Space Objects Database, the current implementation of Neuraspace Space Objects API (and database) includes mechanisms for change requests and versioning of data. These mechanisms allow Neuraspace to manage and keep candidate versions of space-object data, which only become effective throughout the platform after subsequent validation. At this stage, these mechanisms are considered sufficient for dealing with the potential incorporation of new space objects.

From the perspective of the Orbital positioning of a space object, Neuraspace's Platform follows the concept of Orbital Data Series. An Orbital Data Series is a segregation of orbital data by its origin and determination method. This approach allows Neuraspace to be able to distinguish and incorporate different data sources, whichever those data sources may be. The component Orbital Data Processor is the one responsible for selecting from the many data sources and choosing the most accurate representation of a space object's orbit. At this stage, it is expected that Neuraspace will create a new Orbital Data Series which will reflect the data acquired from sensors.

4.2 Track Normalization Process

The track normalization process is a key part of the overall process for TC/OD. It is responsible for processing input files by archiving them and converting the tracks measurements contained within the files onto a uniform track data model which would then be stored by the Tracks API. Finally, this process would also be responsible for ensuring data lineage exists for the relation between original files, tracks and updated orbital states.

4.3 Track Correlation and Orbit Determination Processes

The Track Correlation process is the process by which a track/set of tracks becomes correlated with a space object, or by which a track's relationship with a space object becomes verified. To establish the correlation, tracks which were already associated with space objects have their association validated, while if this correlation is missed from the track, it will have to be established or a new space object created.

In the first stage, this relation is verified through the comparison of the measurements on the tracks with filtered orbits of possible candidates at the time of track acquisition. If the space object identified in the track matches the candidate space objects, then the track status would be considered as "Correlated", otherwise it will go into the status of "Waiting Correlation" or "Not Correlated".

5. Prototype Specification

5.1 Track Ingestion

Neuraspace expects to receive data from several sources in the longer term and has therefore designed its data ingestion and storage to be extensible to many types of data. The initial version covers: optical passive and radar tracks via CCSDS TDMs and laser ranging tracks via ILRS CRDs.

5.2 Track Correlation

We currently expect all incoming data to be pre-tagged with a high level of accuracy (our initial data sources will be tracking telescopes, laser ranging systems and radars operating in tracking mode that follow an object upon a previous estimate for the object within a small field-of-view) and therefore the track correlation step is simply a confirmation of the initial tag plausibility.

5.3 Base Catalogue

The key feature of the Neuraspace catalogue is that it can maintain several data series for each object, each containing ephemeris from a different source. For example, one data series could consist of ephemeris pulled from the US SP catalogue. Another could contain ephemeris created by Neuraspace as a result of an orbit determination process. A third could be operator-provided ephemeris data, etc. The accuracy and availability of each series is determined by the source of the data, with more up-to-date information being added whenever available. This system allows Neuraspace to make use of the best available data, whilst simultaneously providing reliability to gaps in any single data source.

5.4 Orbit Determination

When the orbit determination process is triggered, observations will be gathered for a defined time interval. An appropriate initial state is obtained from the catalogue and a batch least squares (BLS) fit is performed.

The batch least squares method was decided upon for a number of reasons:

- It is more robust to poor initial states than a sequential estimator
- It is more resilient to large gaps in data than a sequential estimator

- It offers the possibility to fit additional parameters such as the drag and SRP coefficients (this is crucial for tracking debris where these are unlikely to be available)
- No process noise tuning is required
- Only a rough state estimate is required for initialization
- No convergence period/ monitoring of convergence is required
- Outlier determination (e.g. for incorrectly tagged tracks) is easy

6. Performance

This section demonstrates the performance of the MDSC demo model in terms of numerical propagation accuracy and OD capability for a commercial STM service. several case studies have been analysed to demonstrate Neuraspace's platform capability. For the sake of brevity, only the most significant are reported.

6.1 Numerical Propagation Accuracy

As part of demonstrating Neuraspace's platform capability as a multisource correlator for a commercial STM service, the accuracy of the dynamical model used in the numerical propagation is validated against precise orbit ephemerides of Sentinel-1B (altitude of ~700 km) and Sentinel 6 Michael Freilich (altitude of ~1350 km).

6.2 Sentinel 6 Michael Freilich OD Campaign

For the Sentinel 6 case study, 3 different OD campaigns are computed with tracking data dated from September 23rd to 26th of 2023. The first relies upon a series of optical measurements (RADEC angles) delivered as TDMs by the Deimos' ANTSY telescope, while the second exploits public laser ranging measurements provided in CRDs by about a dozen different ILRS stations. The third OD campaign incorporates observations from Deimos's ANTSY telescope and ILRS stations, thereby performing a combined OD and fusing angular and ranging measurements from multiple sources.

Figure 1 shows the residuals of the successfully processed measurements for the individual OD campaigns. The overall observation window covers roughly 92 hours (slightly less than 4 days), starting from September 23, 2023, up to the first half of September 26, 2023.

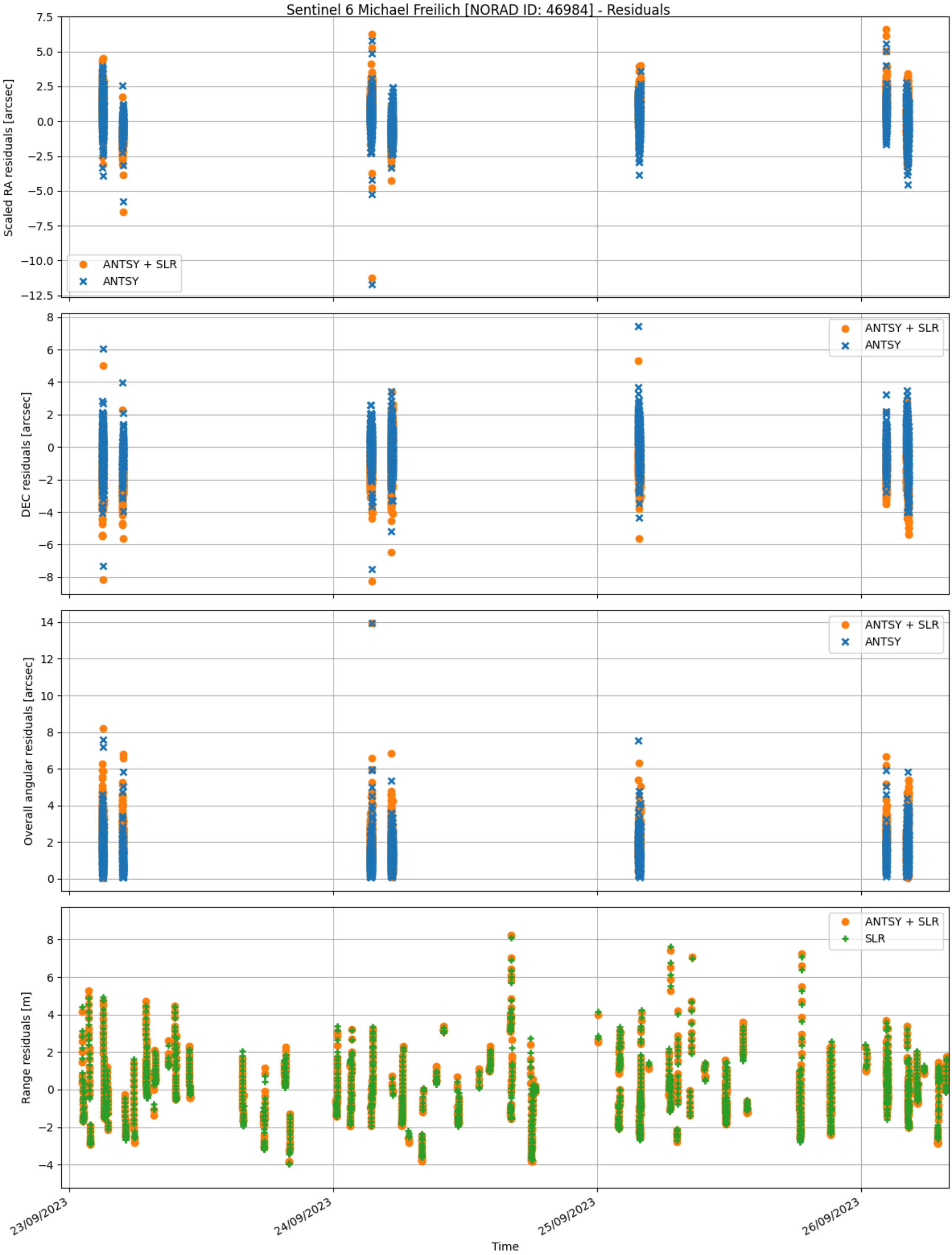

Figure 1: Residuals for the 3 OD campaigns; Sentinel 6 case study. *First (from top)*: Scaled RA residuals. *Second*: DEC residuals. *Third*: Overall angle. *Fourth*: Range residuals.

The resulting estimates from the OD campaigns are evaluated against precise predictions from CPFs published by the ILRS. Specifically, estimated states are numerically propagated for 72 hours after the last available observation, then the propagated states are compared against states obtained by interpolating the CPFs. Results are presented in Figure 2, where position and velocity errors are plotted. According to the errors, using SLR range measurements from ILRS produces better estimates than just relying on optical observations from the Deimos' ANTSY optical telescope, as expected since they are used to produce their orbital predictions.

We observe in the plots of Figure 2 below that the inclusion of the optical data does not improve the prediction. This is not concerning for 2 reasons:

- The huge volume of much more accurate laser measurements overwhelms the contribution from the optical measurements. In a more realistic scenario, we would have far fewer laser measurements and the optical would then make a useful contribution. This is further investigated by verifying the effectiveness of data fusion when only 1 SLR station is considered. Results show how optical measurements improve the laser measurements estimate, thereby proving the benefit of exploiting data fusion.
- The accuracy reached by the predicted orbit (~40 m and ~0.3 m/s after 3 days of numerical propagation) is comparable with errors between CPF files.

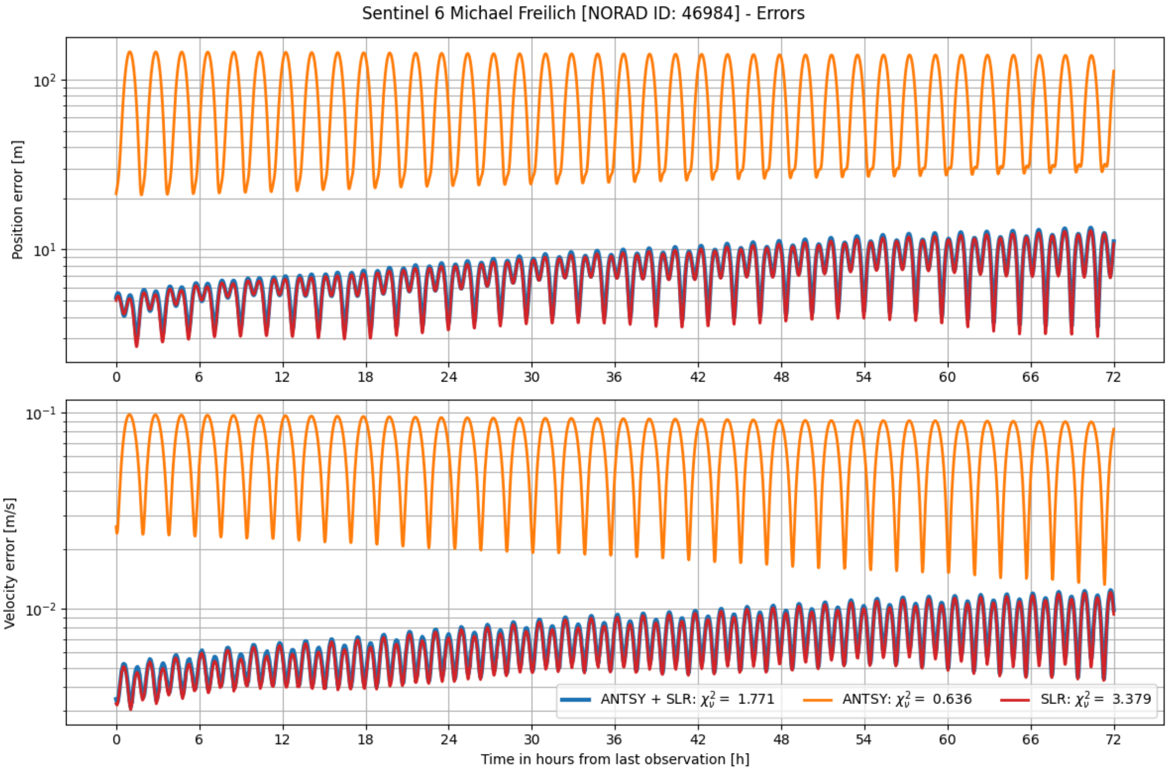

Figure 2: Errors computed against CPF predictions for the 3 OD campaigns simulated; Sentinel-6 case study. In the legend, the reduced chi-squared statistics χ_ν^2 for each OD campaign are reported. *Top*: Position error. *Bottom*: Velocity error.

6.3 Summer Debris Campaign

The summer debris campaign proposes the OD capability demonstration for 30 large targets in the LEO orbital regime. Optical and laser ranging measurements are exploited. The former was collected by Deimos' ANTSY telescope and the latter by DiGOS's Borowiec SLR station. Specifically, the Deimos telescope tracked 27 different objects for a total of 99 tracks, while the DiGOS SLR station tracked 9 different objects for a total of 13 tracks. Overall, observations were carried out for 3 subsequent nights, from 11 to 13 August 2023.

Out of the 30 debris targets, 22 were successfully processed while others were filtered from this analysis because of the small amount of passes acquired; objects with less than 3 pass acquisitions during the campaign were excluded. Their average residuals computed from optical (i.e., RADEC angles) and laser ranging measurements are presented in Figure 3. The reduced chi-squared metric χ^2_ν is reported as well. In Figure 3, debris are identified by their NORAD ID.

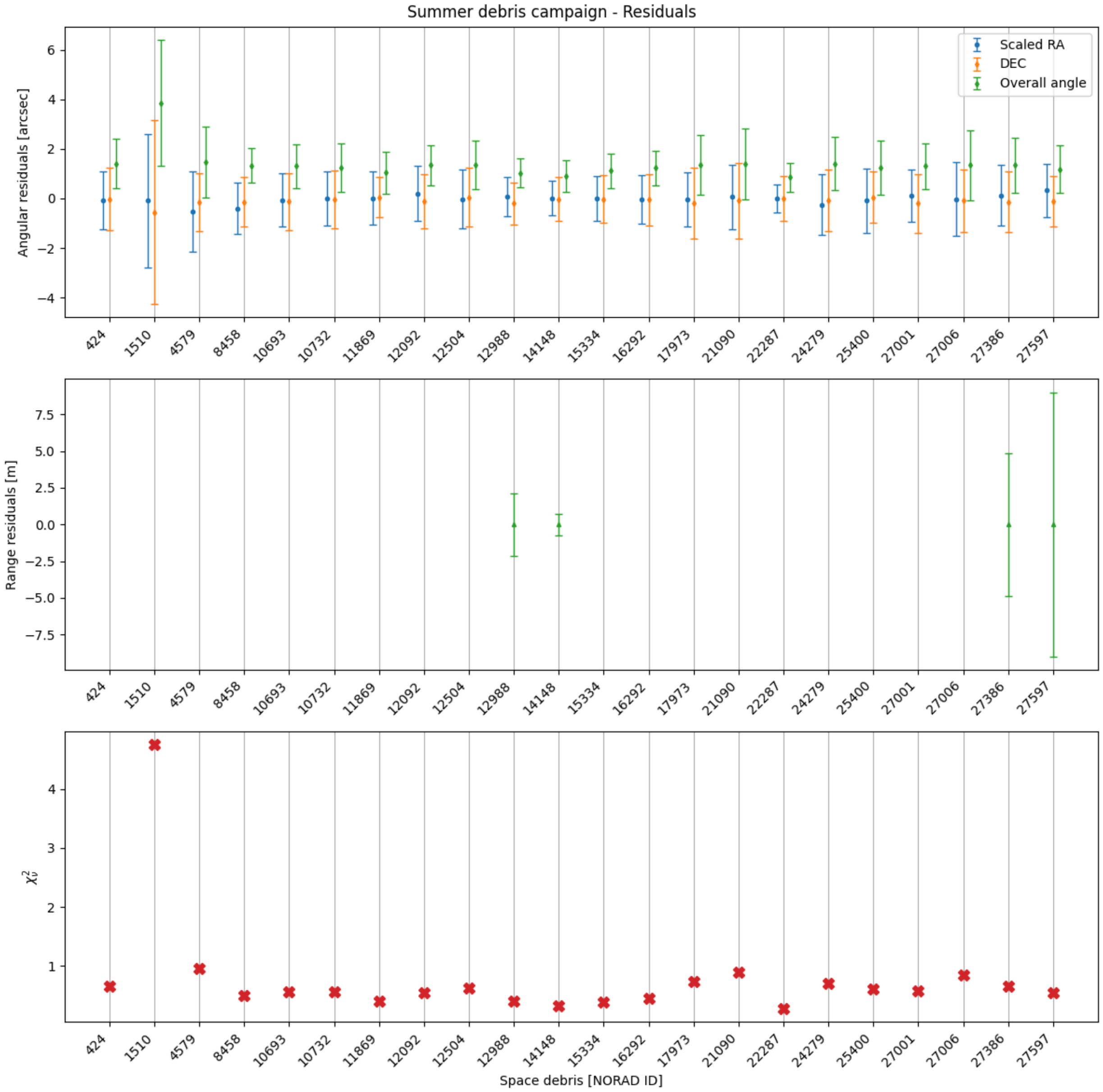

Figure 3: Average residuals for the summer debris campaign. *Top*: Angular (RADEC) residuals. *Middle*: Range residuals. *Bottom*: reduced chi-squared statistics χ^2_ν.

6.4 EISCAT Experiment Campaign

As part of the EISCAT Experiment Campaign, five targets have been selected to be followed:

- CRYOSAT 2 (NORAD 36508)
- Hai Yang 2D (NORAD 48621)
- Sentinel-3A (NORAD 41335)
- Sentinel-3B (NORAD 43437)
- Stella (NORAD 22824)

The experiment lasted 5 days, from the 10th to the 14th of June, 2024, with approximately 2 hours of observation per day scheduled to follow the pre-selected targets. The sensor used to perform the observations was the EISCAT's UHF radar. Only the results for Sentinel-3B are presented in this section.

The evolution of the position error for Sentinel-3B over approximately 1 revolution period after the last measurement epoch is shown in Figure 4. Furthermore, data fusion with optical measurements by OurSky's telescopes has been performed. The evolution of the position error of the resulting OD solution is shown in Figure 5. In this case, an improvement of the OD solution is observed when performing data fusion. Indeed, the minimum and maximum errors decreased and the optical measurements were able to improve the radar-only OD solution.

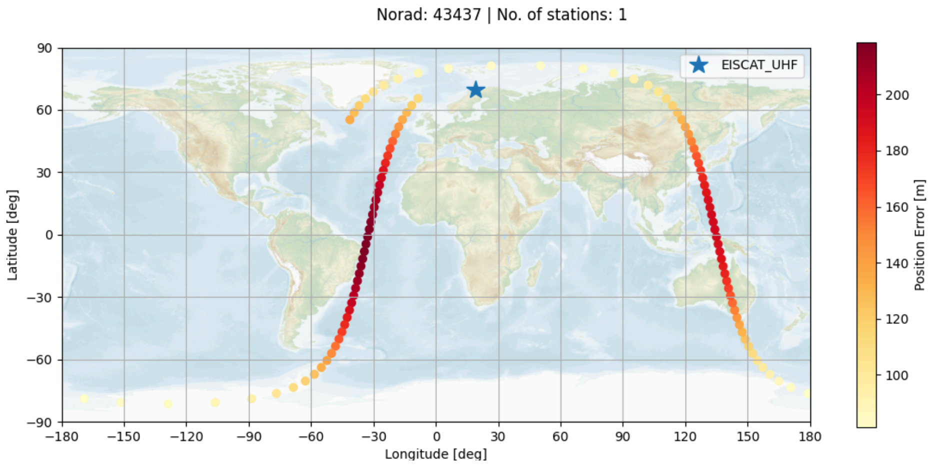

Figure 4: Position error evolution over the groundtrack of approximately 1 orbit after the last measurement epoch. OD product of Sentinel-3B for EISCAT data comprising radar measurements from the EISCAT's UHF radar (represented with a star in the plot).

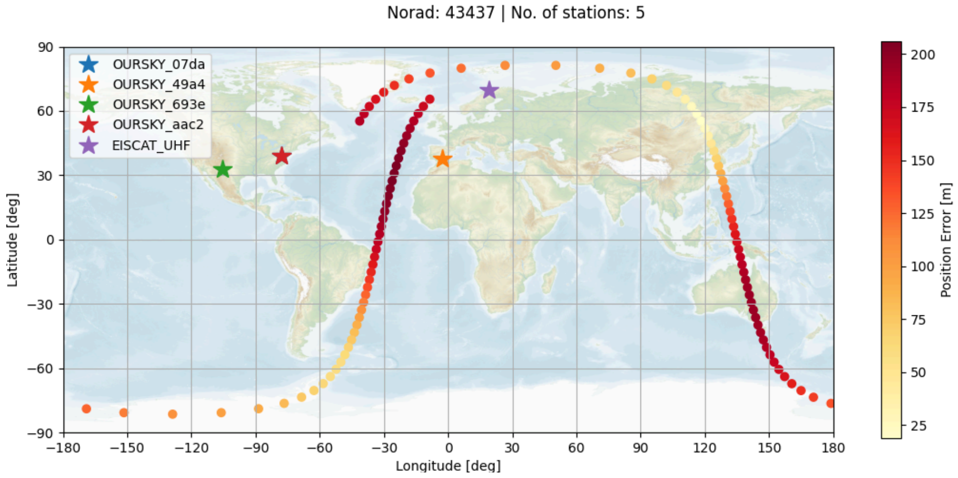

Figure 5: Position error evolution over the groundtrack of approximately 1 orbit after the last measurement epoch. OD product of Sentinel-3B fusing EISCAT data comprising radar measurements from the EISCAT's UHF radar (represented with the purple star in the plot) and OurSky optical measurements from multiple telescopes (represented with stars in the plot, two stars overlapped).

7.Conclusions

The activity has de-risked the development of an MSDC demo model for a commercial STM service. The MSDC has demonstrated the ability to use optical, laser and radar measurements of spacecraft both individually and in combination to provide an accurate orbit determination solution. Key capabilities such as high accuracy orbit propagation, rapid processing of TDMs and successful handling of asynchronous received data has been validated. This has been done using an architecture compatible with Neuraspace's SaaS platform, paving the way for it to be made available to operators.

Data from laser stations was shown to be fitted to metre level accuracy, consistent with the size of the spacecraft. An optical telescope very similar to the one that Neuraspace has now installed in Beja, Portugal demonstrated accuracy. Finally an experimental radar capability was demonstrated in conjunction with EISCAT. Results were promising although there remain some calibration issues to work through. The radar results are particularly exciting as radar does not suffer from the same weather and lighting restrictions that we find with optical telescopes.

With all of these sensors a primary limitation was shown to be the use of a single ground station and as a consequence an under-determination of the full orbit. This highlights one of the key benefits of data fusion, the ability to take different measurements at several points in the orbit, thus offsetting the weaknesses of the other sensors and improving overall accuracy. This improved accuracy was highlighted in the report.

The MSDC demo model TRL level has been successfully increased from 3 to 7 with demonstration and evaluation of the prototype in an operational environment. Therefore, the objective of the project is considered achieved. Next steps for Neuraspace include adding tracking and orbit determination in its SaaS offerings. This will support the original objective of maintaining a catalogue of accurate trajectories for our operators in order to support both operational needs as well as conjunction analysis and space traffic management. Indeed the tracking and orbit determination functionality has already been deployed to support customers during the risky Launch and Early Operations Phase (LEOP) to provide accurate ephemeris to operators to cover the gap between launcher separation and regular inclusion in the space-track catalogue, thuse ensuring spacecraft are not lost, becoming dangerous debris. In sum:

- The project successfully de-risked the development of an MSDC demo model, achieving the primary objective for a commercial STM service.
- The MSDC demonstrated accurate orbit determination using a combination of optical, laser, and radar measurements, validating key capabilities.
- Integration with Neuraspace's SaaS platform confirmed the system's readiness for operator use, with a TRL level increase from 3 to 7.
- Promising radar results provide a valuable alternative to optical telescopes, unaffected by weather and lighting conditions.
- The tracking and orbit determination functionality has already been successfully deployed, ensuring spacecraft safety and enhancing Neuraspace's STM offerings.

7.1 Identified Improvements

The following improvements were identified throughout this project and will be further analysed by Neuraspace and incorporated into its development roadmap:

- Regarding fit span, a LUPI-style algorithm is planned to be implemented.
- A sequential estimator will be added alongside the BLS so that the two techniques can be used in a complementary manner to provide the benefits of both.
- IOD strategies to be implemented in the future based on the typologies of sensors and network used.
- Expand the current selection of methods with the consider parameters technique to represent the uncertainty in unstable parameters such as the drag force.
- Monitor the accuracy of each data series, enabling us to select from those with the best historical accuracy and covariance consistency.
- Provide feedback to EISCAT regarding the conjectured phase ambiguity in the radar measurements and hopefully solve the issue, thereby improving the accuracy of the computed OD solutions for production code purposes.