Multi-Sources Data Correlator for Commercial Services – Final Presentation

ESA Contract No. 4000141190/23/NL/GLC/cb

08 October 2024

Outline

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01 – Introduction

Introduction

This document is the **Final Presentation** (FP), Doc.-No. **NEU-MSD-FP**, 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 FP introduces the project context, describes the approach taken to achieve the activity's objectives, discusses the results, and summarises the findings of the work in the form of a slide deck to be used for slideshows.

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02 – Context & Objectives

Context

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- Activity 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 TRL 3** and **targeting TRL 7**, demonstrate the **MSDC performance** for the **operational environment** after which continued operation, improvement, and parallel injection of the MSDC into present-day and future pilots is envisaged.

- **MSDC** will prove full functionality after **integration** into the **Neuraspace sensor network**.

Objective

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

The MSDC 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

The catalogue will enable other services:

- Fragmentation
- Manoeuvre detection
- Re-entry analysis

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03 – Activities

Activities

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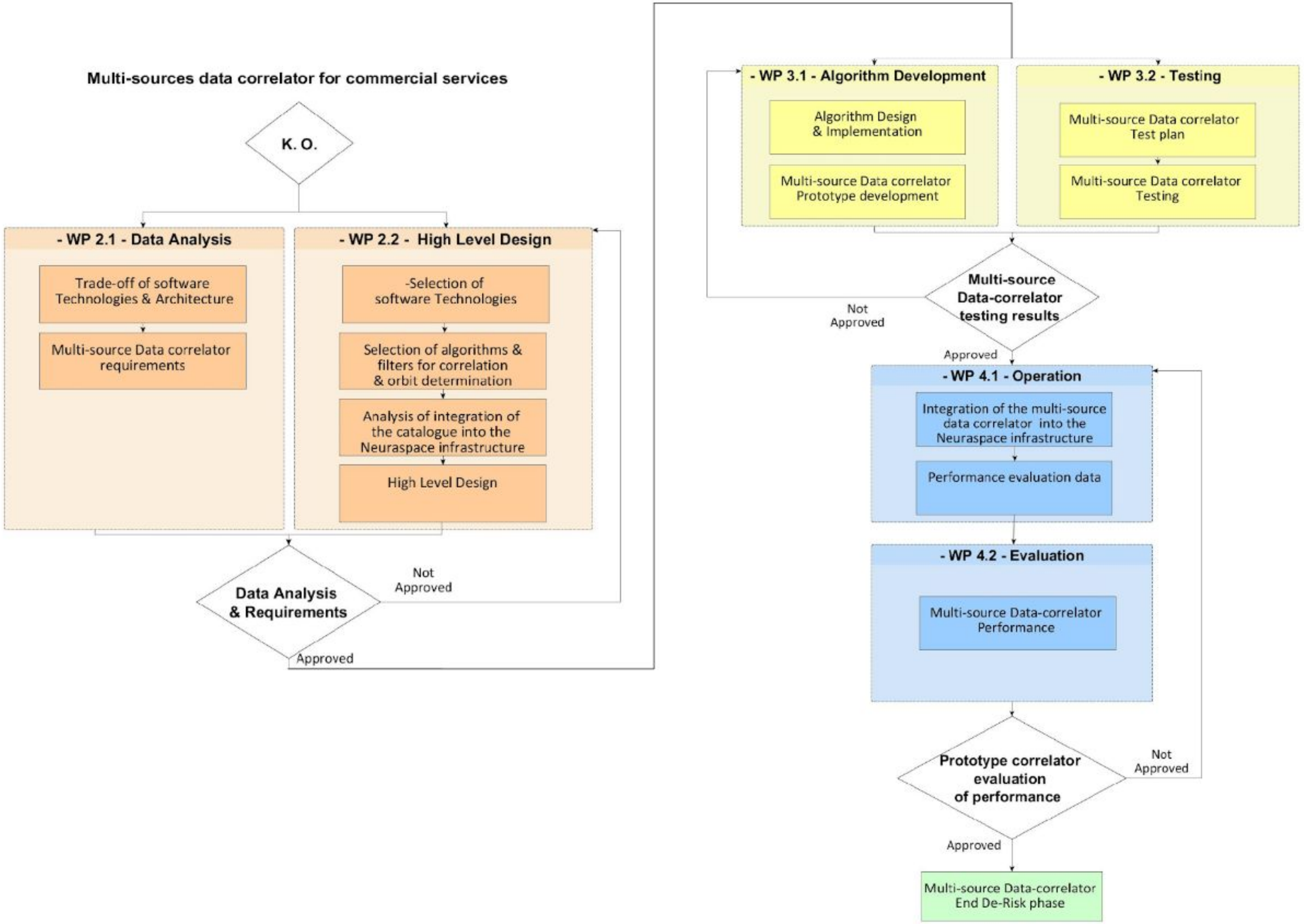
- **Data analysis**: Literature review on the orbital dynamics and perturbations. Characteristics of each orbital regime are studied as well as a comprehensive investigation of space weather sources, data, and atmospheric models. Extensive literature review on correlation and orbit determination algorithms, sensor measurements and applied corrections. Identification and analysis of algorithms and software technologies used for correlation, orbit determination and prediction.

- **High-level design**: Definition of the high-level software elements participating in the MSDC, the context in which they exist, their role and responsibilities, and how they interface and interact.

- **Algorithm development and testing**: Definition, design, and implementation of correlation algorithms. Testing of the algorithms and overall data-correlator. Definition and analysis of performance metrics within the testing environment.

- **Operation and performance evaluation**: Usage of MSDC prototype and performance evaluation under real conditions.

Work Logic



Multi-sources data correlator for commercial services
K. O.
- WP 2.1 - Data Analysis
Trade-off of software Technologies & Architecture
Multi-source Data correlator requirements
- WP 2.2 - High Level Design
-Selection of software Technologies
Selection of algorithms & filters for correlation & orbit determination
Analysis of integration of the catalogue into the Neuraspace infrastructure
High Level Design
Data Analysis & Requirements
Not Approved
Approved
- WP 3.1 - Algorithm Development
Algorithm Design & Implementation
Multi-source Data correlator Prototype development
- WP 3.2 - Testing
Multi-source Data correlator Test plan
Multi-source Data correlator Testing
Multi-source Data-correlator testing results
Not Approved
Approved
- WP 4.1 - Operation
Integration of the multi-source data correlator into the Neuraspace infrastructure
Performance evaluation data
- WP 4.2 - Evaluation
Multi-source Data-correlator Performance
Prototype correlator evaluation of performance
Not Approved
Approved
Multi-source Data-correlator End De-Risk phase

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04 – Data Analysis

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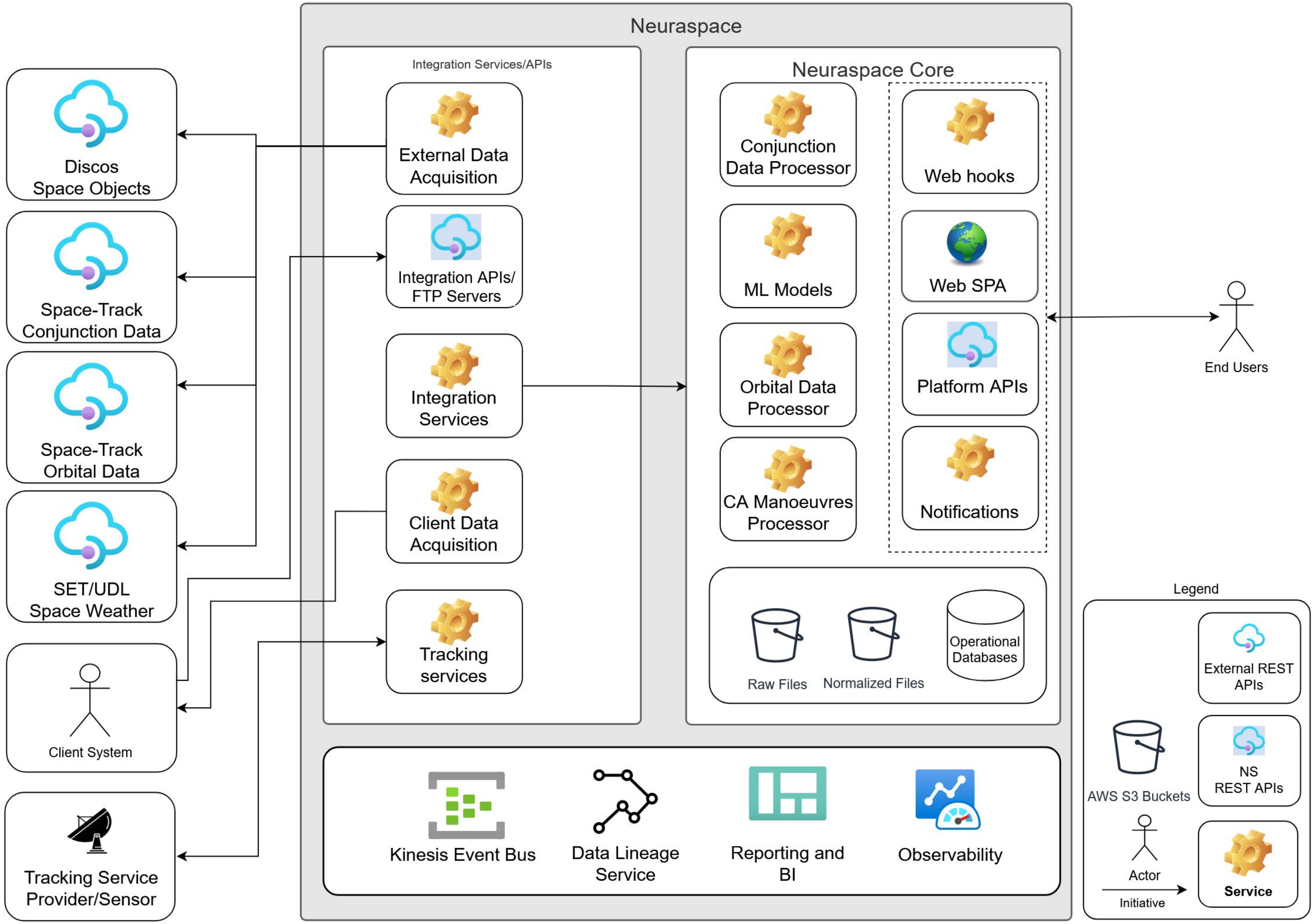
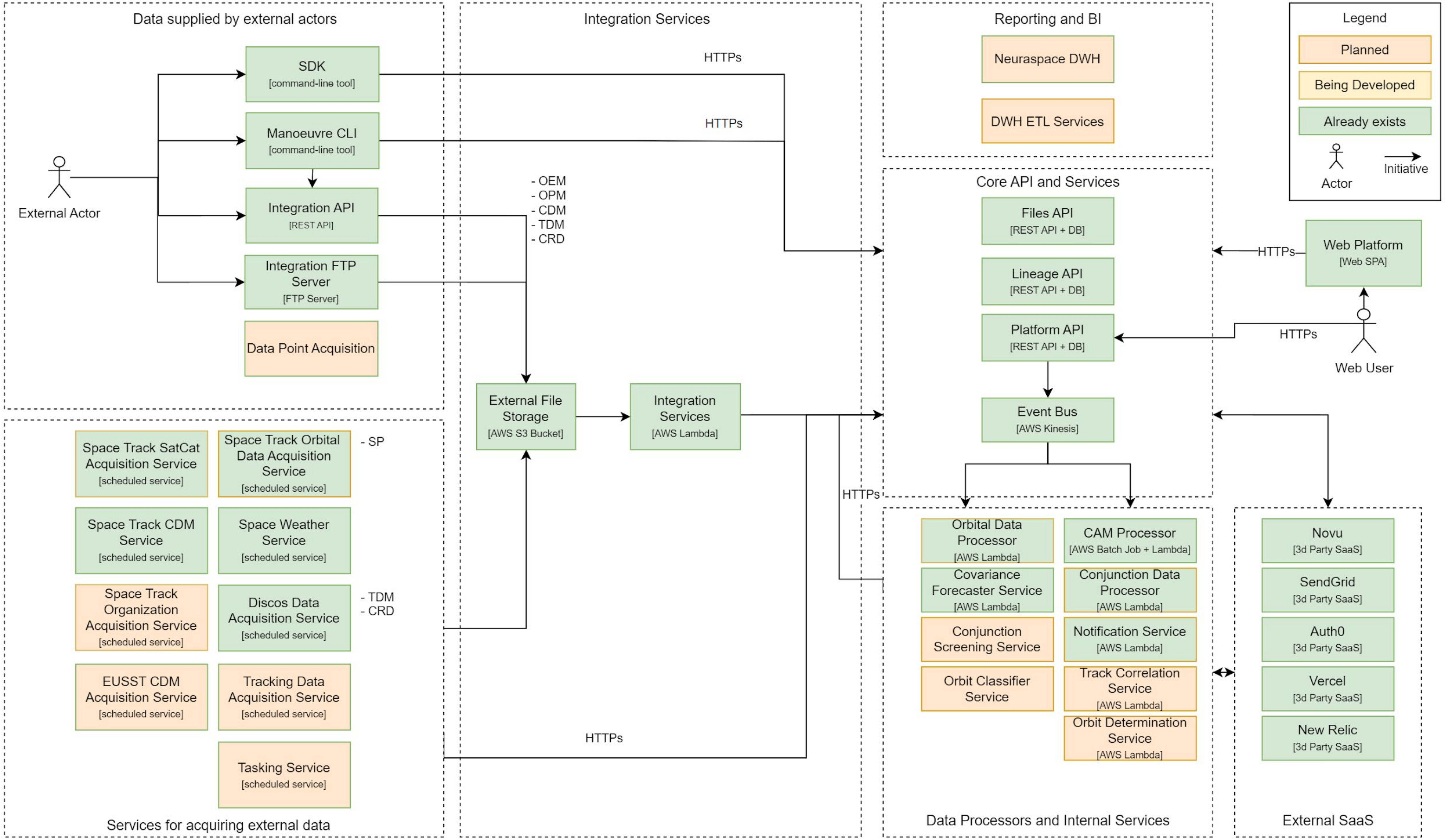
05 – High-Level Design

Architecture – Simplified View



Architecture – Detailed View



High-Level Design

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Processes and components covered by the high-level design:

- **Space object catalogue**
- **Track normalization process**
- **Track correlation and orbit determination**

HLD – Space Object Catalogue

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Neuraspace's **Space Object** and **Orbit Databases** are sourced from:

- Space-track
- Discos
- Directly from Satellite Owners/Operators

Data from multiple sources is curated and merged into Neuraspace's Platform via the relevant REST APIs, in particular Space Objects and Orbits API.

The **Space Objects Database** includes mechanisms for:

- Change requests
- Versioning of data

These allow to manage and keep candidate versions of space-object data, which only become effective throughout the platform after subsequent validation.

Regarding **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.

The **Orbital Data Processor** is responsible for

- **Selecting** from the many **data sources**
- **Choosing** the **most accurate representation** of a space object's orbit

This allows to distinguish and incorporate different data sources, whichever those data sources may be.

HLD – Track Normalization Process

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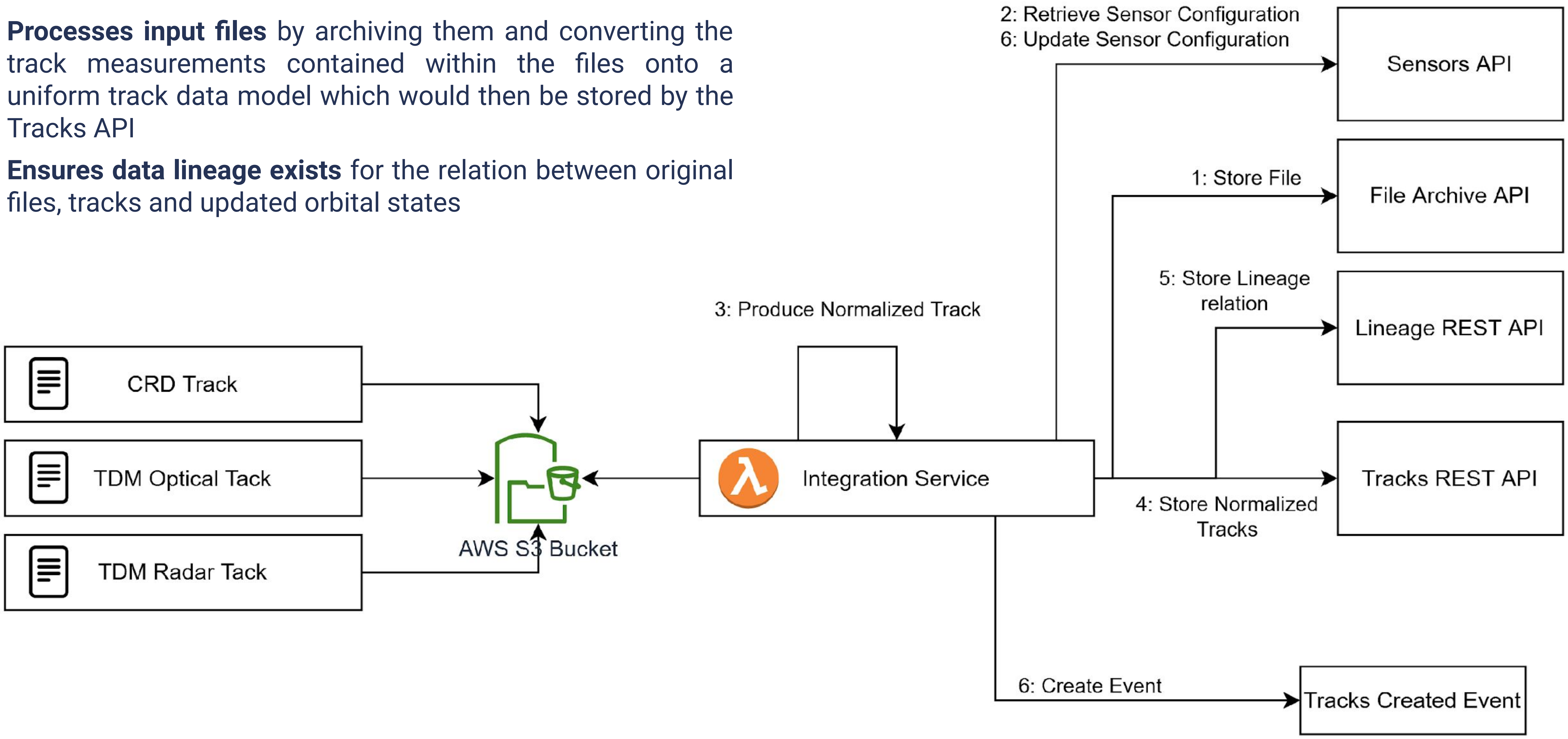
The **track normalization**:

- **Processes input files** by archiving them and converting the track measurements contained within the files onto a uniform track data model which would then be stored by the Tracks API
- **Ensures data lineage exists** for the relation between original files, tracks and updated orbital states



HLD – Track Correlation & Orbit Determ.

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Track correlation is the process by which:

- A track/set of tracks becomes correlated with a space object
- a track's relationship with a space object becomes verified.

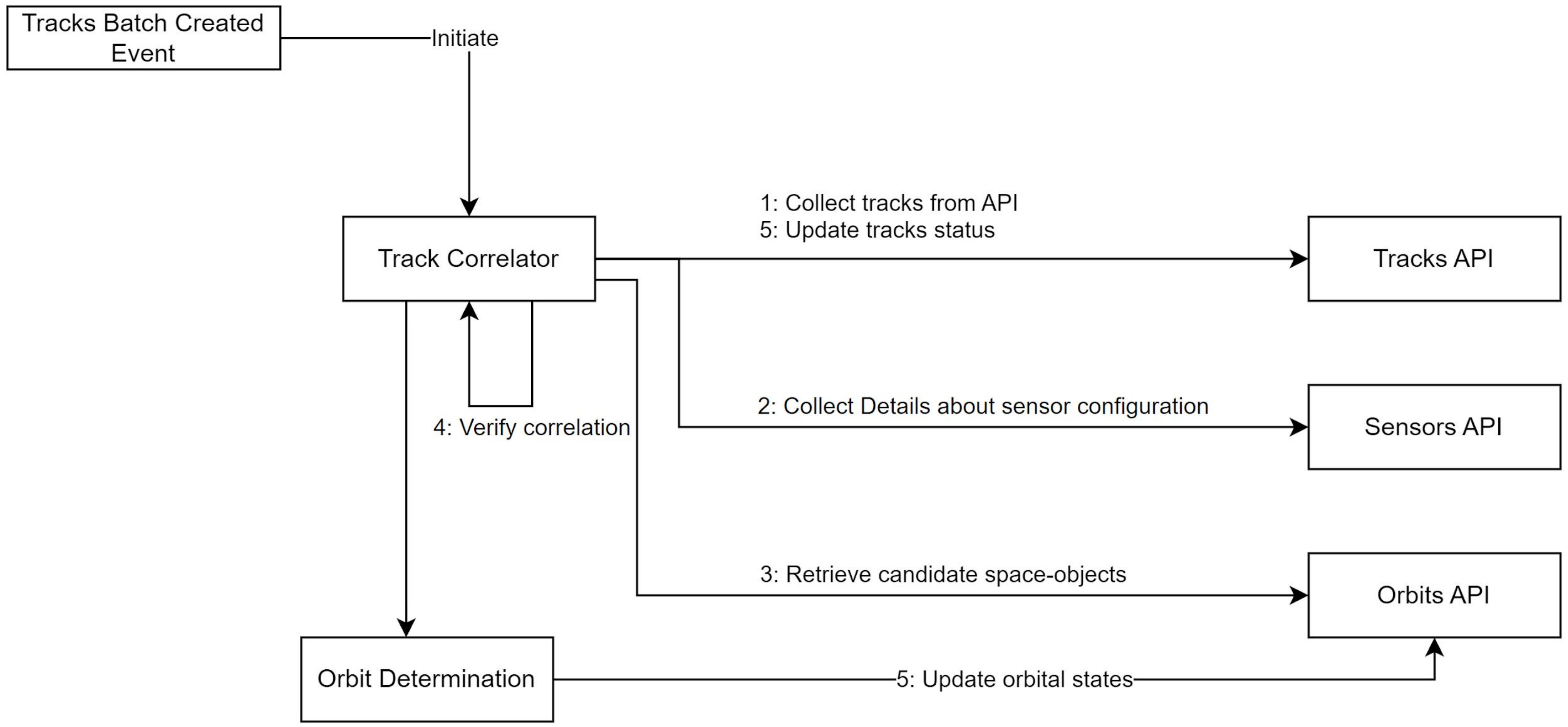
To establish the correlation, tracks which were already associated with space objects have their association validated, while if this correlation is missed from the track, it will have to be established or a new space object created. The relation is verified through the comparison of sensor configuration at the time of track acquisition.

Track Correlation Status (depending if track does/does not match candidate space object)

- Correlated
- Waiting Correlation
- Not Correlated

Potential application of several filters based on:

- Radar Cross Section and minimum Visual Magnitude;
- Right Ascension and Declination (RADEC) section;
- Apogee and Perigee or altitude filters;
- Range-rate vs. expect radial speed (radar)
- Expected angular speed and angle of motion vs. catalogue



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06 – Prototype Specification

Track Ingestion

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Data sources

- Optical tracks via TDMs
- Radar tracks via TDMs
- Laser Ranging tracks via CRDs

Procedure

- Parsing of the file
- Normalisation based on track type (e.g., unit and frame conversion to simplify OD process)
- Storage of the measurements

Ground station configurations are added manually as they are expected to be updated infrequently

Track Correlation

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1. All incoming data pre-tagged with a high level of accuracy → Track correlation step is a confirmation of the initial tag

2. We are looking for confirmation of correlation → State uncertainty is disregarded

3. Measurements are simulated using the ephemeris (from any data series, e.g., SP catalogue, previous OD) we wish to correlate against

4. Comparison of simulated to observed measurements, obtaining a residual. The root mean square residual is then used as the correlation metric requiring thresholds definition.

5. When both range and range rate are available we normalise the range rate delta by the ratio of the sigmas to give a pseudo-meter value.

6. If an object is miss tagged but somehow does not exceed the correlation threshold then it can be rejected by the outlier rejection at the OD stage. (We have more risk of rejecting useful data than of accepting incorrectly tagged data which could corrupt our solution. Hence we have deliberately avoided choosing thresholds which are too tight.)

Track Correlation – Optical Observation

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Correlation metric used with optical measurements (RADEC angles) is

$$d_{opt} = \frac{1}{N}\sum_{i=0}^{N}\sqrt{\left(\frac{RA_{i,real} - RA_{i,synt}}{W_{RA}}\right)^2 + \left(\frac{DEC_{i,real} - DEC_{i,synt}}{W_{DEC}}\right)^2}$$

Weights (W_{RA} and W_{DEC}) can either empirical or chosen to be the sigmas of the measurements, since they are self-correcting for different setups.

To ensure no wraparound errors occur we use (from trigonometric identity)

$$RA_{i,real} - RA_{i,synt} = arcsin\left(sin\left(RA_{i,real}\right)cos\left(RA_{i,synt}\right) - cos\left(RA_{i,real}\right)sin\left(RA_{i,synt}\right)\right)$$

Base Catalogue

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Characteristics

- The catalogue maintains several data series for each object, each containing ephemeris from a different source.
- The accuracy and availability of each series are determined by the source of the data, with more up-to-date information being added whenever available.
- Composite data series can be created.
- Implemented hierarchy based on the data source, preferring operator ephemeris to the SP catalogue.
- Data contains a lineage record, enabling the source data to be identified.
- Thanks to the open-ended nature of the base catalogue, there is significant potential for further additions depending on the data available.
- This system allows to make use of the best available data, whilst simultaneously providing reliability to gaps in any single data source.

Initialisation & Maintenance

1. Pull data from external sources by referring to the appropriate data series.
2. Maintain our independent catalogue by obtaining ephemeris for correlation and initial OD states from our own independently determined data series.
3. If a gap appears in our data, fall back to an external data source to repair the issue.

Orbit Determination

Procedure

- Triggering of orbit determination process
- Gathering of observations for a defined time interval
- Retrieval of appropriate initial state from the catalogue
- Execution of batch least squares (BLS) fit

Rationale behind selection of BLS method:

- More robust to poor initial states than a sequential estimator
- 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
- No process noise tuning is required
- Only a rough state estimate is required for initialization
- No convergence period / monitoring of convergence is required
- Simple outlier determination (e.g. for incorrectly tagged tracks)

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07 – Performance

Numerical Propagation Accuracy 2/3

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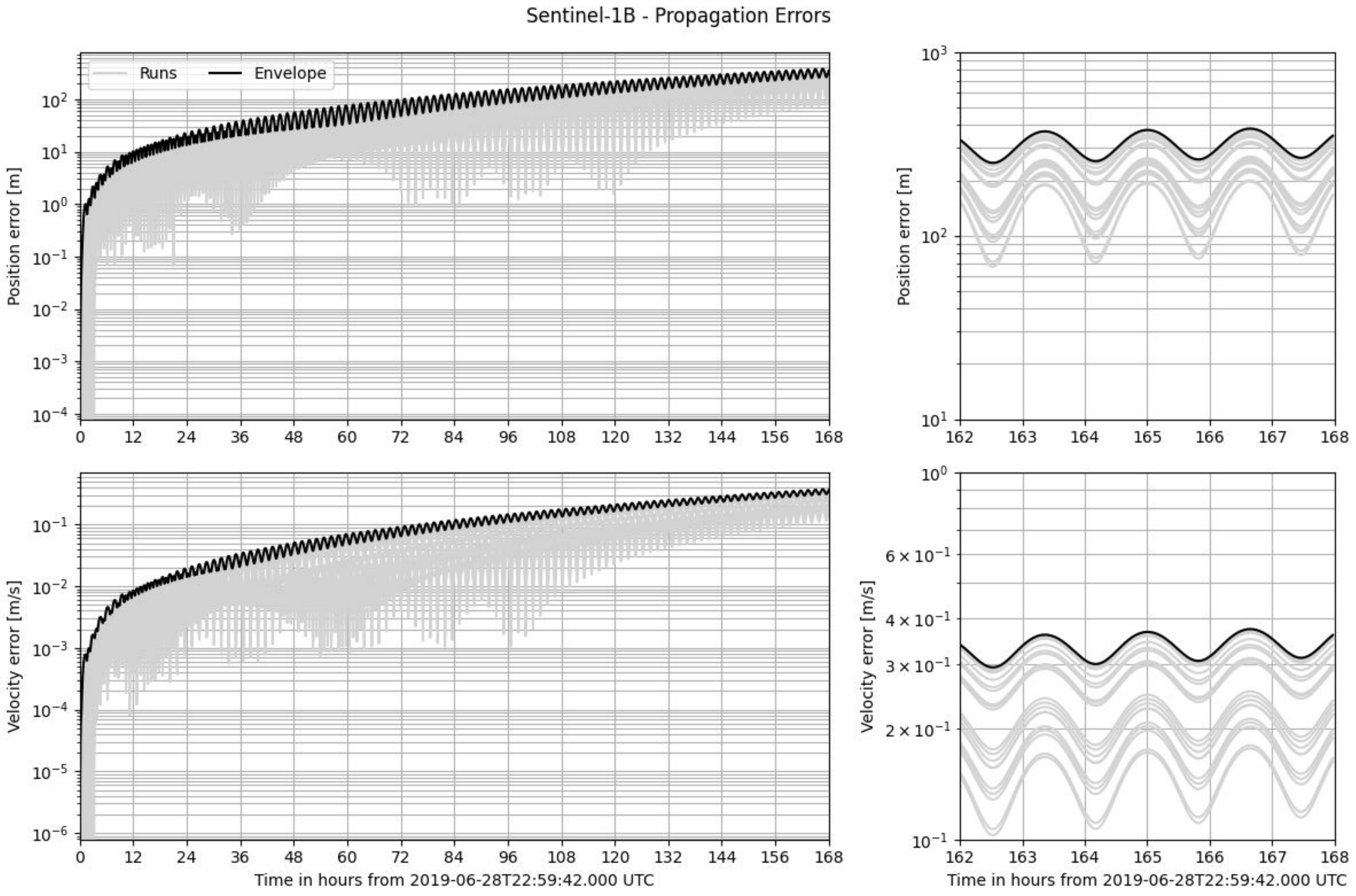
Accuracy of the dynamical model used in the numerical propagation is validated against POE of:

- Sentinel-1B (altitude of ~700 km)
- Sentinel 6 Michael Freilich (altitude of ~1350 km)

Methodology

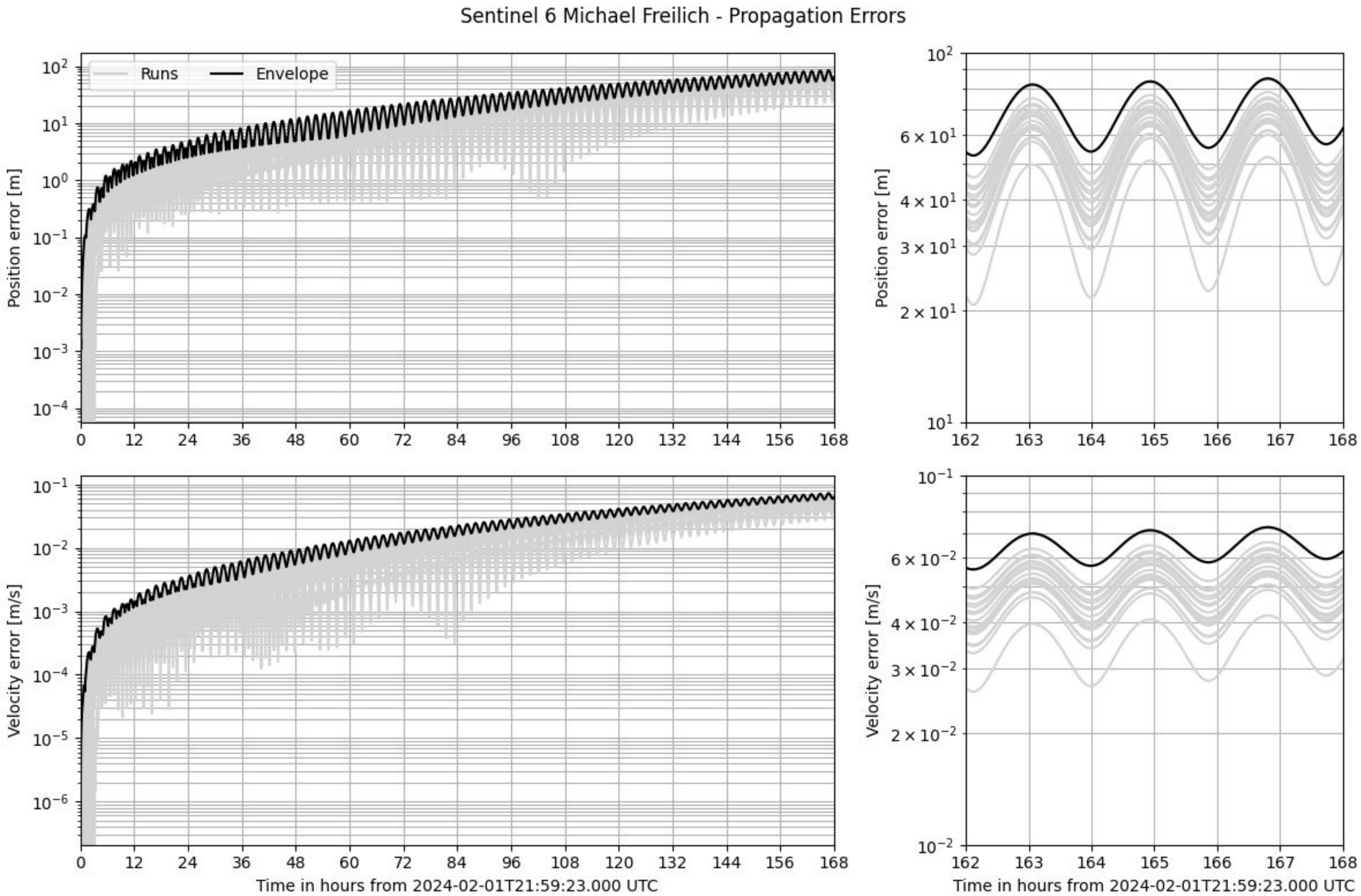
- 20 state vectors are sampled every 10 minutes from the precise ephemerides
- Sampled states are propagated up to 7 days (168 hours) after the first sample epoch
- Finally, position and velocity errors of the numerically propagated solution are computed against POE

Numerical Propagation Accuracy 1/3



Propagation errors for Sentinel-1B. Top-left: Position errors. Top-right: Magnification of position errors at final epoch. Bottom-left: Velocity errors. Bottom-right: Magnification of velocity errors at final epoch.

Numerical Propagation Accuracy 2/3



Propagation errors for Sentinel 6 Michael Freilich. Top-left: Position errors. Top-right: Magnification of position errors at final epoch. Bottom-left: Velocity errors. Bottom-right: Magnification of velocity errors at final epoch.

Sentinel 6 & LARES OD Campaigns

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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
- The second exploits public laser ranging measurements provided in CRDs by about a dozen different ILRS stations.
- The third incorporates observations from Deimos's ANTSY telescope and ILRS stations, thereby performing a combined OD and fusing angular and ranging measurements from multiple sources.

Inclusion of the optical data does not improve the prediction (see next slides). **This is not concerning** for 2 reasons:

1. 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.

2. The accuracy reached by the predicted orbit (~40 m and after 3 days of numerical propagation) is comparable with errors between CPF files.

Deimos' ANTSY Telescope characteristics.

Angular accuracy	1.5 arcsec
Geolocation	
Longitude	4.408 W deg
Latitude	38.543 N deg
Altitude	1115.0 m

Sentinel 6 OD Campaign – Results

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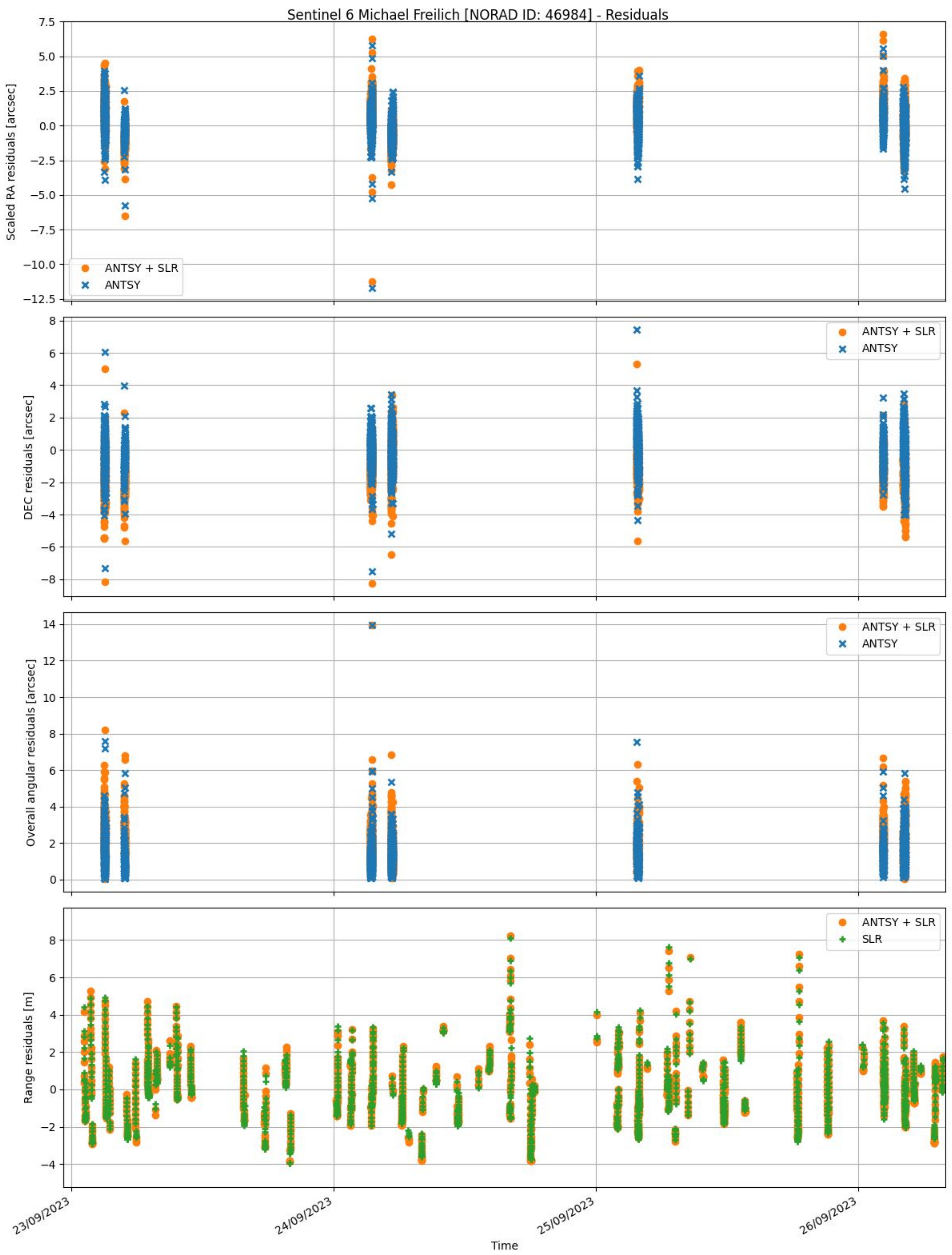
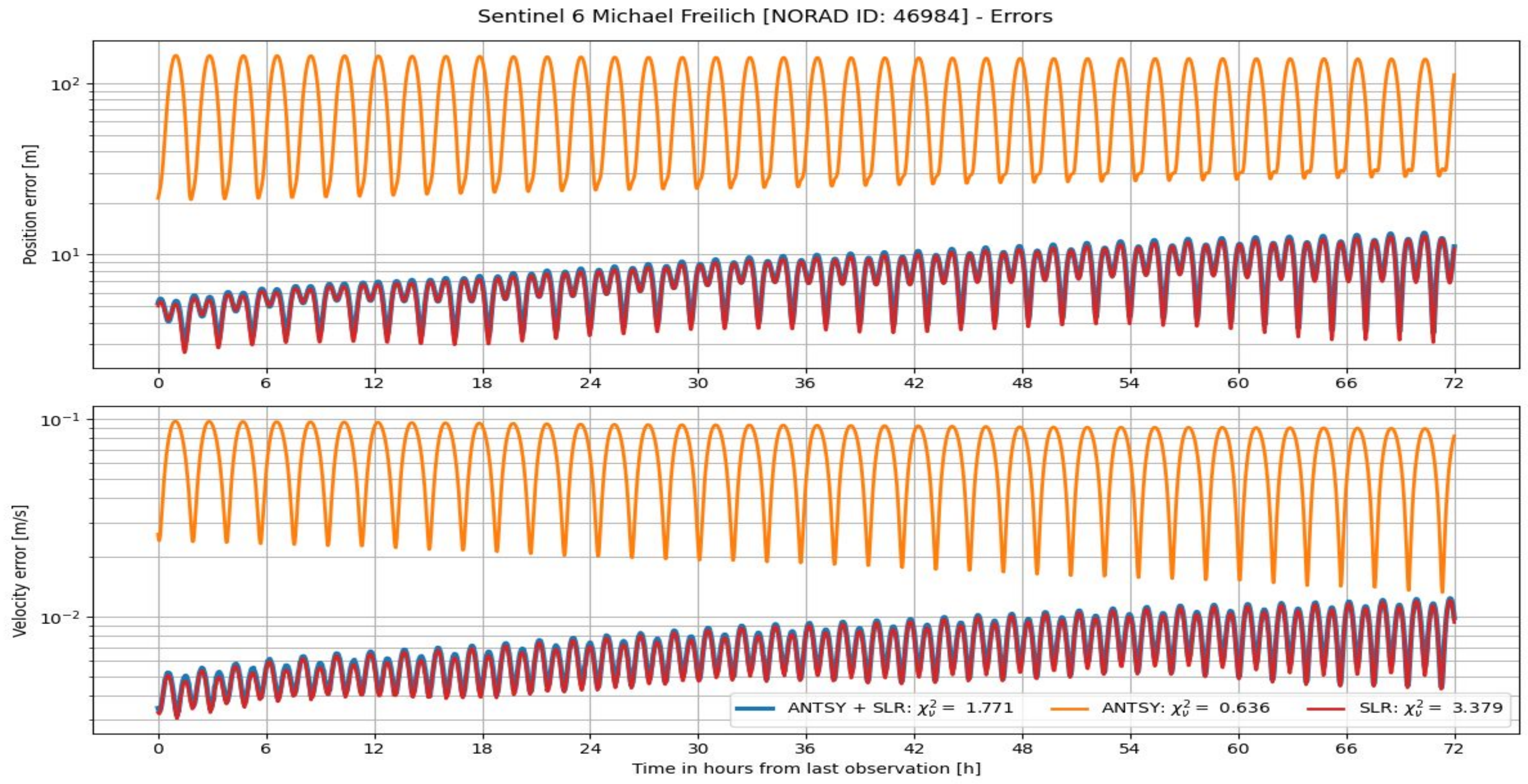
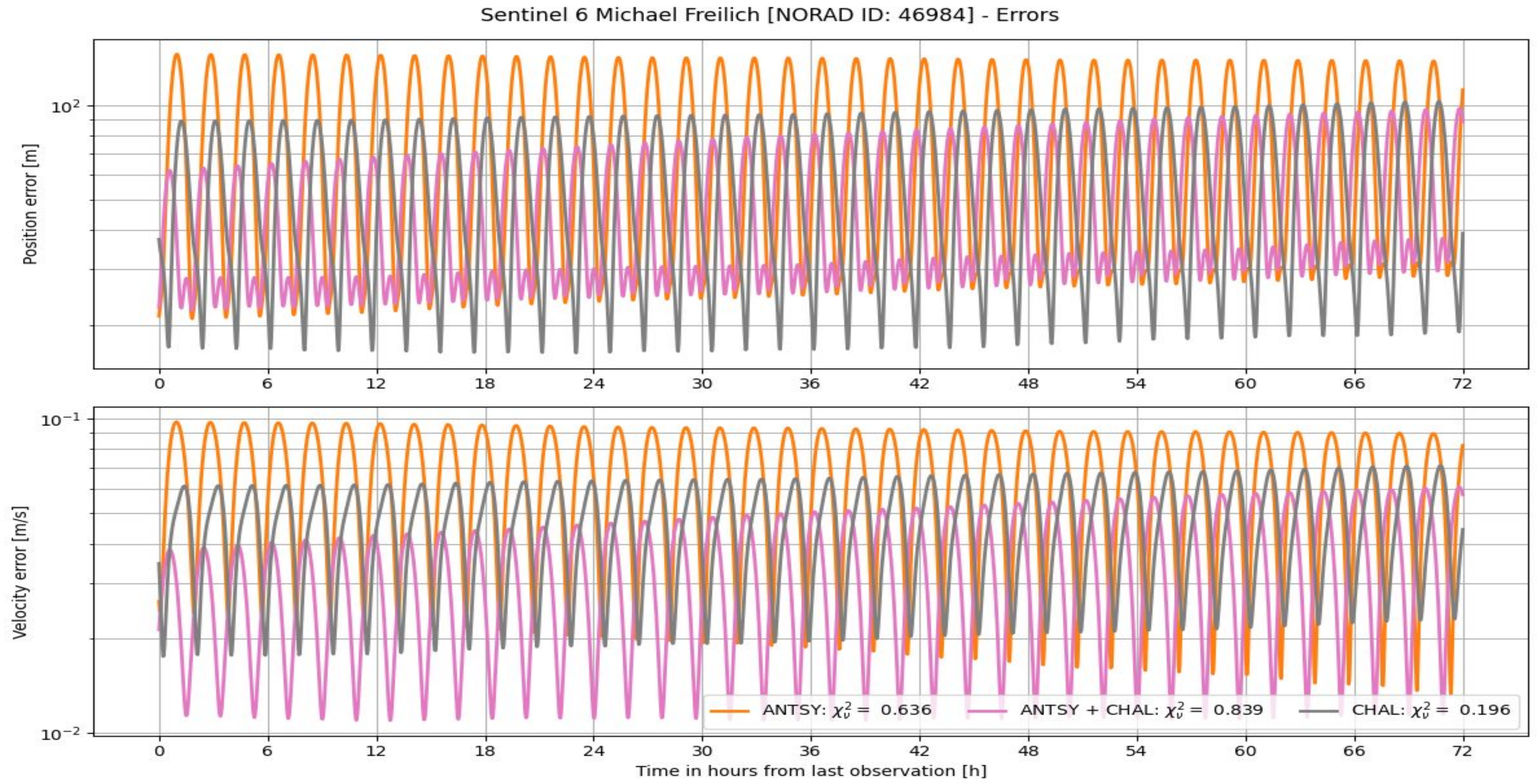


Residuals for the 3 OD campaigns; Sentinel 6 case study. First (from top): Scaled RA residuals. Second: DEC residuals. Third: Overall angle. Fourth: Range residuals.



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



Errors computed against CPF predictions showing the benefit of data fusion; Sentinel-6 case study. In the legend, the reduced chi-squared statistics for each OD campaign are reported. Top: Position error. Bottom: Velocity error.

Sentinel 6 OD Campaign – Results

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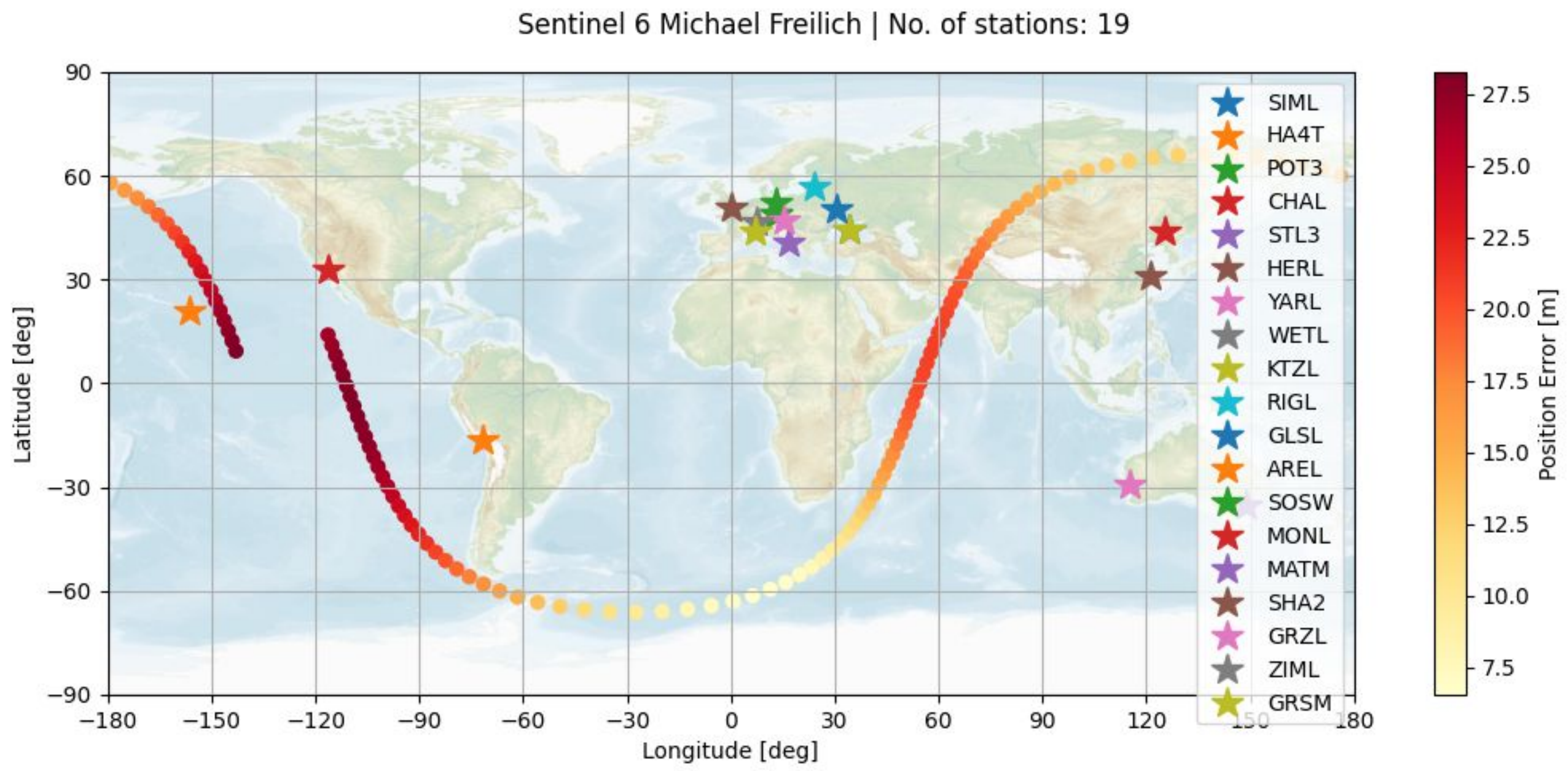
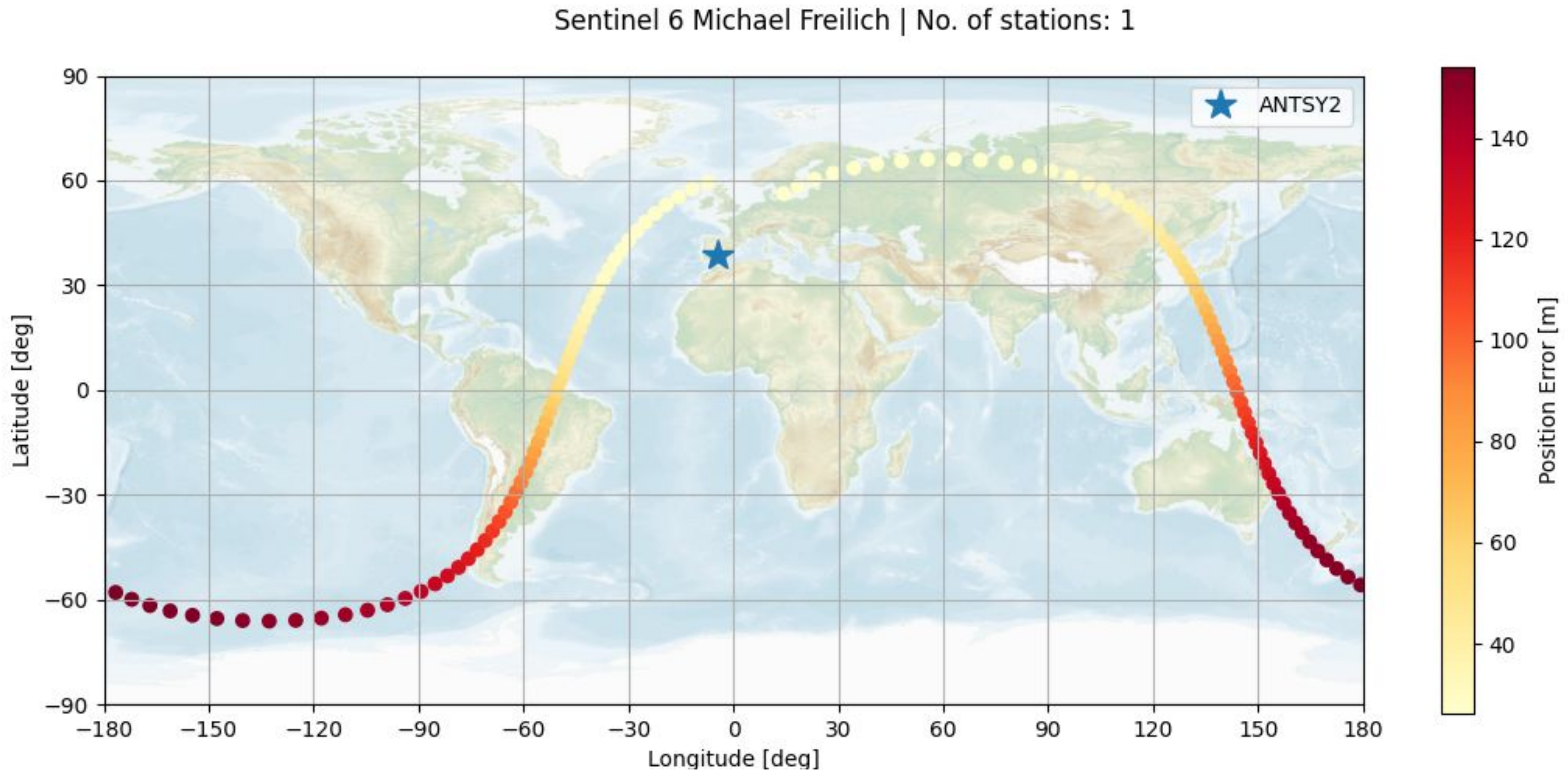
- **Positioning error** is consistently **below 30 m** when using **ISLR data**
- measurements produced by **19 different stations**



- **Position error** is bounded roughly **between 20 and 160 m** when using **Deimos data**
- Measurements produced by **1 telescope**



Sentinel 6 OD Campaign – Results

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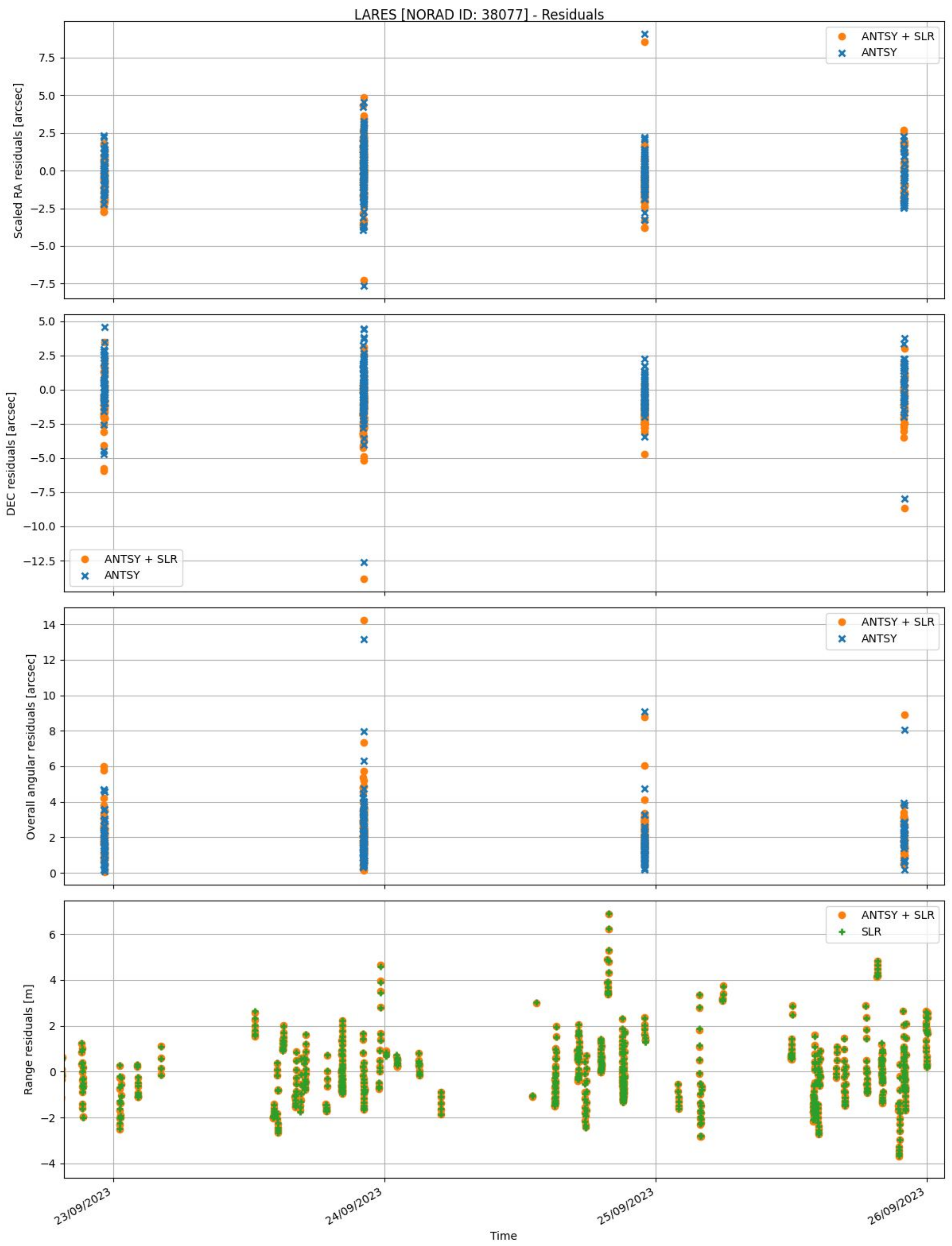
Space object name	Sentinel 6 Michael Freilich
NORAD ID	46984
Orbital regime	LEO
TLE used to initiate OD	`1 46984U 20086A 23264.55737190 -.00000063 00000-0 -83899-5 0 9994` `2 46984 66.0423 51.2912 0007847 268.1978 91.8138 12.80929823132292`
Observation period	23/09/2023–26/09/2023
Observation span	92.52 h
No. of passes	Deimos' ANTSY optical telescope: 7 ISLR stations: 51
ANTSY	
Reduced chi-squared	0.636
No. of processed measurements	Angular: 2047
Rejection rate measurements	Angular: 0.05 %
Scaled RA residual	Average ± 1-sigma: 0.013 ± 1.186 arcsec RMS: 1.185 arcsec
DEC residual	Average ± 1-sigma: -0.159 ± 1.196 arcsec RMS: 1.206 arcsec
Position error Δr (against precise CPF)	21.300 m
Velocity error Δv (against precise CPF)	0.026 m/s

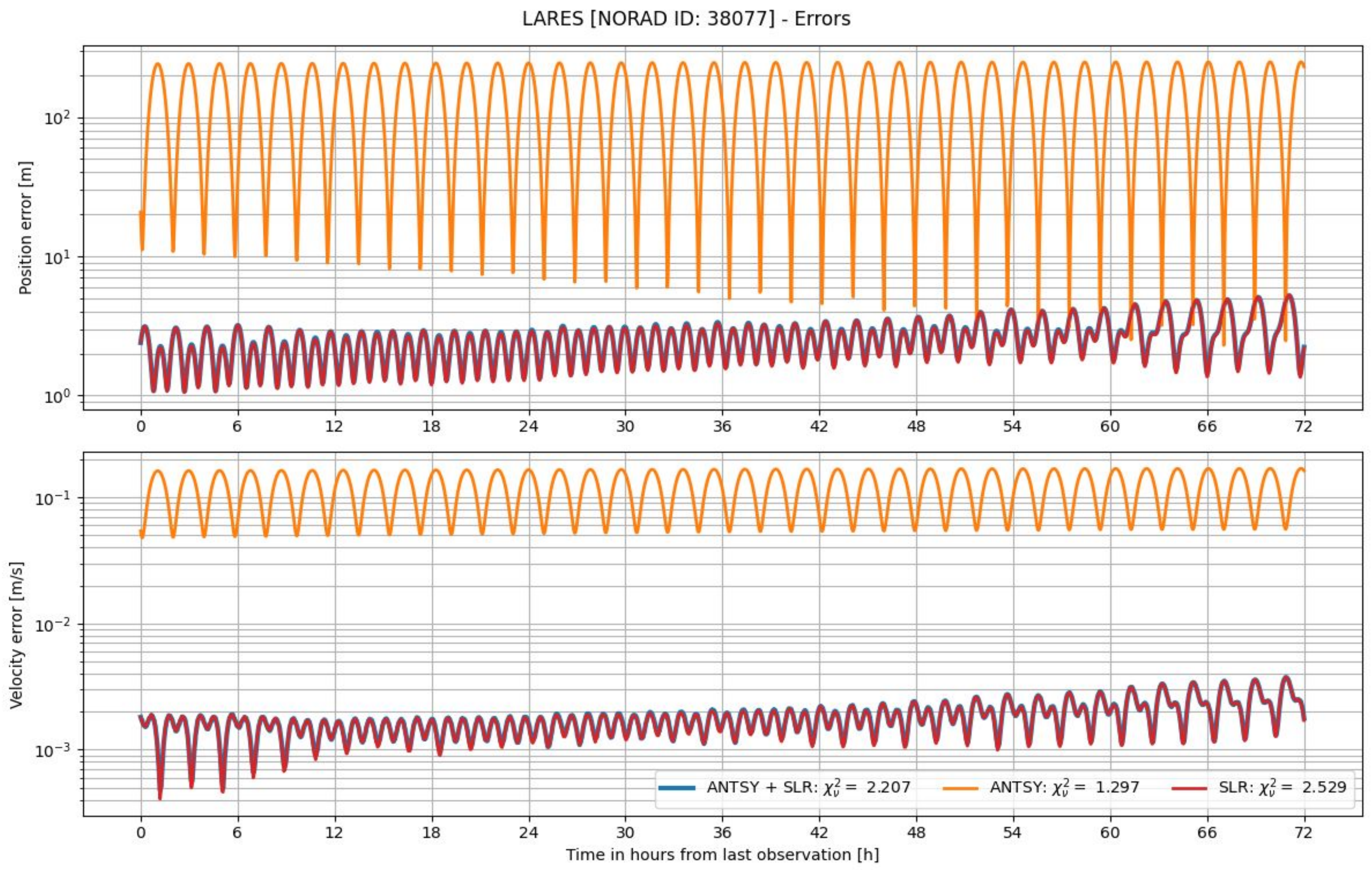
SLR	
Reduced chi-squared	3.379
No. of processed measurements	Range: 1522
Rejection rate measurements	Range: 0.00 %
Range residual	Average ± 1-sigma: 0.000 ± 1.926 m RMS: 1.925 m
SLR ground station biases	AREL: 0.528 m CHAL: 5.658 m GLSL: 5.781 m GRSM: 2.541 m GRZL: 3.761 m HA4T: 1.473 m HERL: 3.992 m KTZL: 3.299 m MATM: 4.195 m MONL: 0.775 m POT3: 3.842 m RIGL: 2.383 m SHA2: 4.666 m SIML: 4.406 m SOSW: 2.775 m STL3: 2.895 m WETL: 3.684 m YARL: 4.794 m ZIML: 2.649 m
Position error Δr (against precise CPF)	5.008 m
Velocity error Δv (against precise CPF)	0.003 m/s

ANTSY + SLR	
Reduced chi-squared	1.771
No. of processed measurements	Angular: 2047 Range: 1522
Rejection rate measurements	Angular: 0.05 % Range: 0.00 %
Scaled RA residual	Average ± 1-sigma: 0.557 ± 1.425 arcsec RMS: 1.530 arcsec
DEC residual	Average ± 1-sigma: -1.116 ± 1.304 arcsec RMS: 1.716 arcsec
Range residual	Average ± 1-sigma: 0.000 ± 1.934 m RMS: 1.933 m
SLR ground station biases	AREL: 0.639 m CHAL: 5.713 m GLSL: 5.732 m GRSM: 2.630 m GRZL: 3.598 m HA4T: 1.410 m HERL: 4.145 m KTZL: 3.323 m MATM: 4.266 m MONL: 0.794 m POT3: 3.933 m RIGL: 2.479 m SHA2: 4.544 m SIML: 4.467 m SOSW: 2.775 m STL3: 2.809 m WETL: 3.766 m YARL: 4.803 m ZIML: 2.634 m
Position error Δr (against precise CPF)	13.877 m
Velocity error Δv (against precise CPF)	0.006 m/s

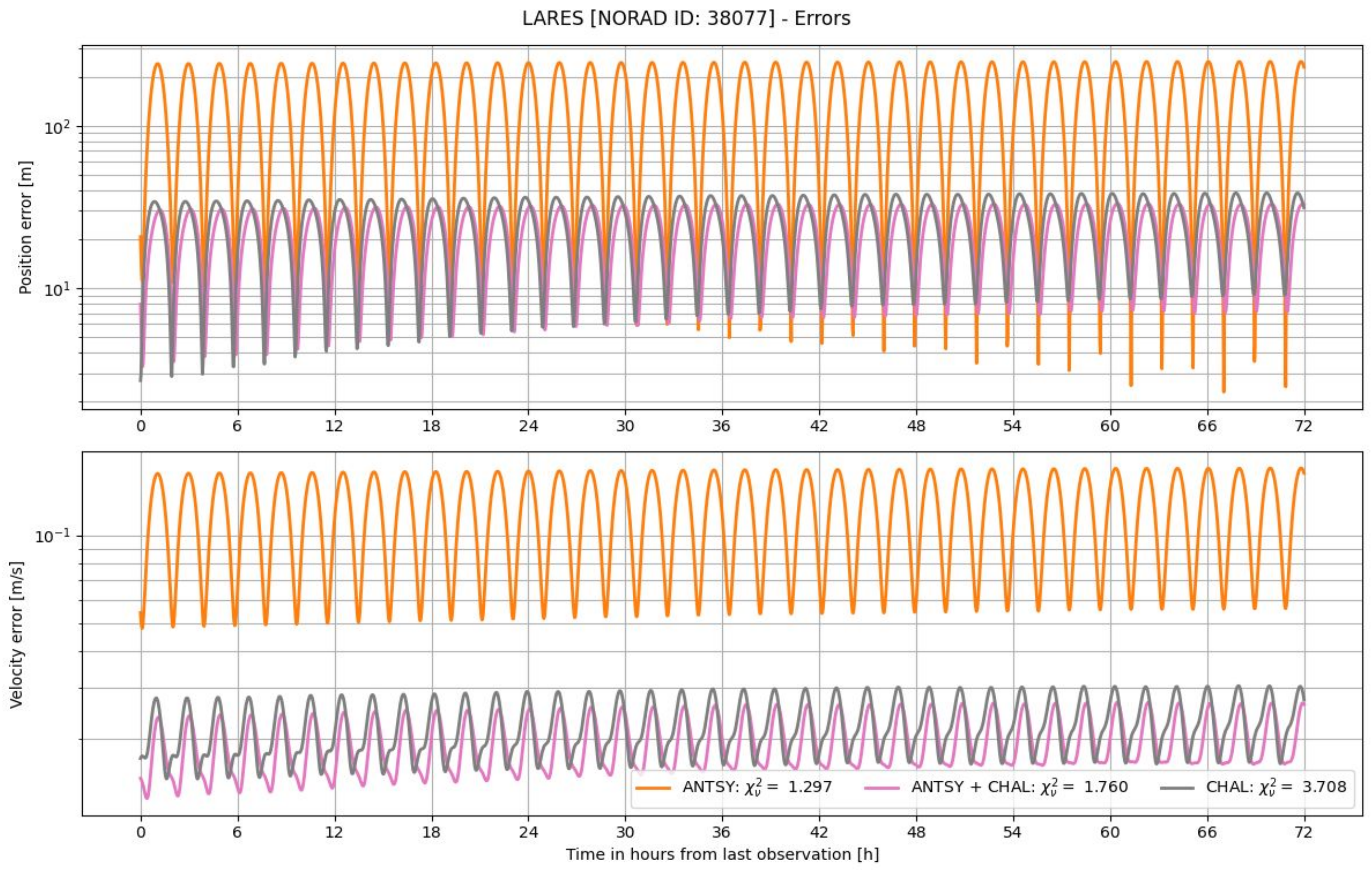
LARES OD Campaign – Results



Residuals for the 3 OD campaigns simulated; LARES case study. First (from top): Scaled RA residuals. Second: DEC residuals. Third: Overall angle. Fourth: Range residuals.



Errors computed against CPF predictions showing the benefit of data fusion; LARES case study. In the legend, the reduced chi-squared statistics for each OD campaign are reported. Top: Position error. Bottom: Velocity error.



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

LARES OD Campaign – Results

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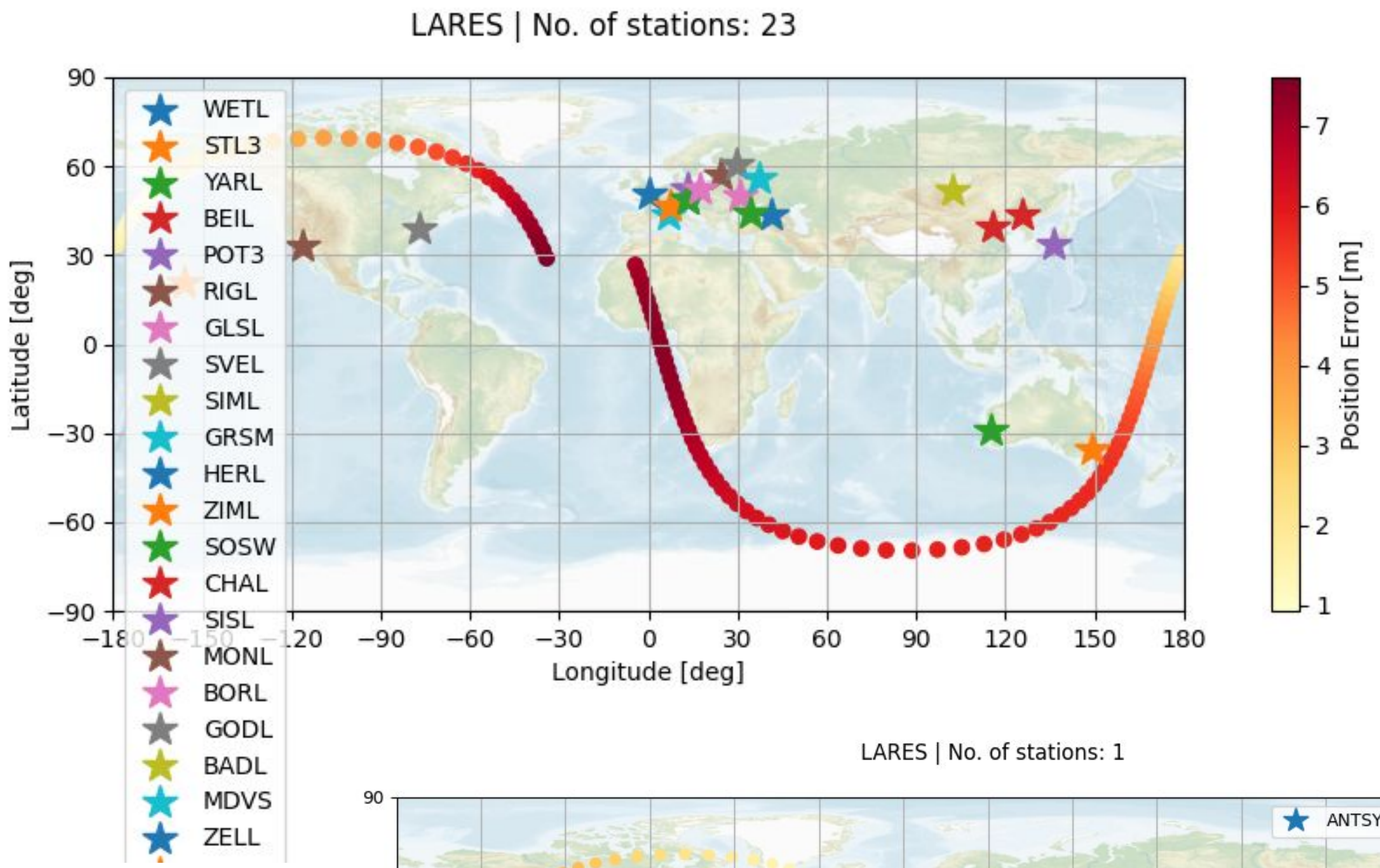
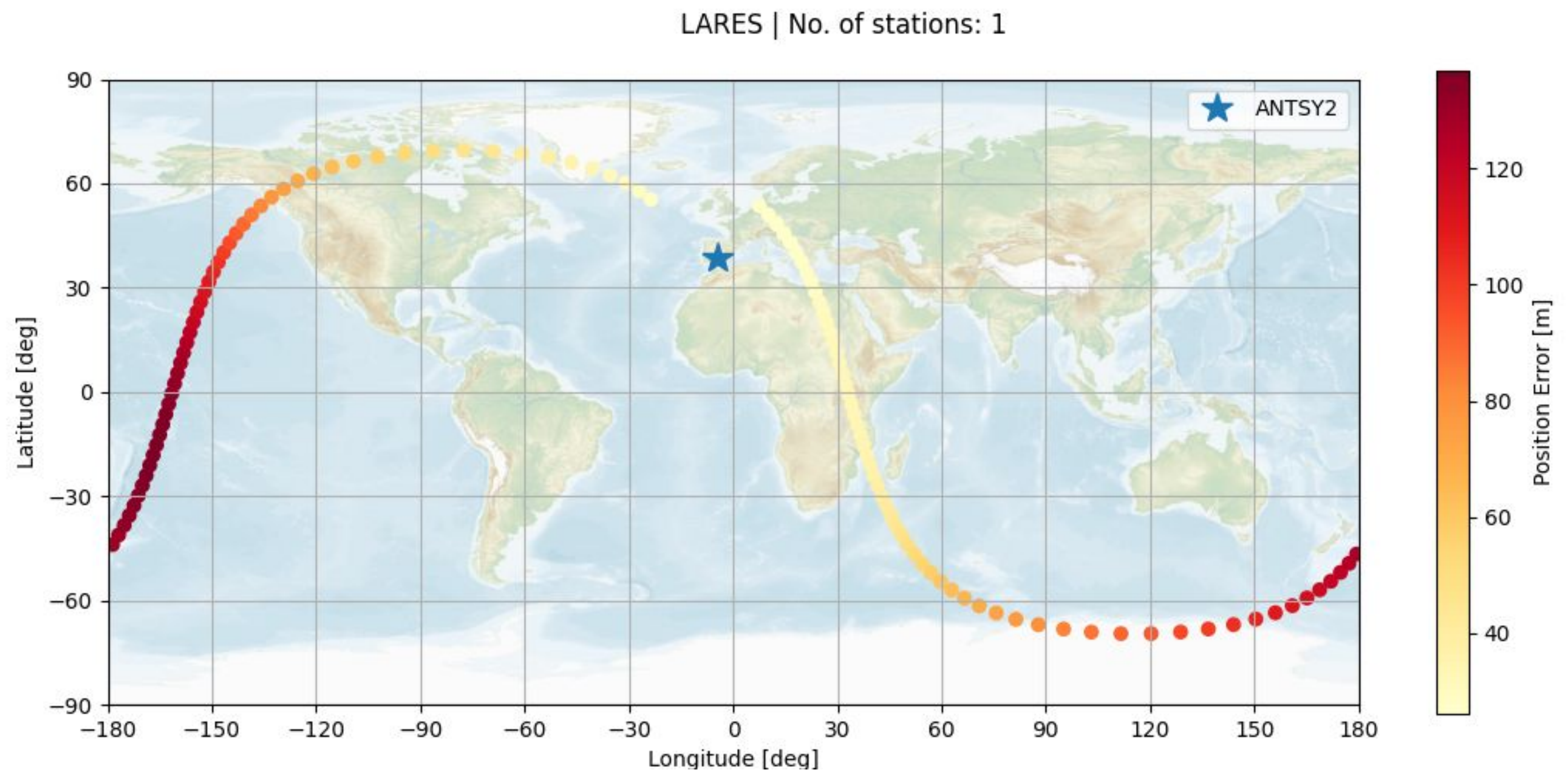
- **Positioning error** is consistently **below 10 m** when using **ISLR data**

- Measurements produced by **23 different stations**



- **Position error** is bounded roughly **between 20 and 180 m** when using **Deimos data**

- Measurements produced by **1 telescope**



LARES OD Campaign – Results

Space object name	LARES
NORAD ID	38077
Orbital regime	LEO
TLE used to initiate OD	1 38077U 12006A 23264.90481623 -.00000044 00000-0 -36337-4 0 9990 2 38077 69.4905 199.1054 0011508 266.1559 93.8151 12.54931308531695
Observation period	23/09/2023–26/09/2023
Observation span	95.79 h
No. of passes	Deimos' ANTSY optical telescope: 4 ISLR stations: 43
ANTSY	
Reduced chi-squared	1.297
No. of processed measurements	Angular: 252
Rejection rate measurements	Angular: 0.00 %
Scaled RA residual	Average ± 1-sigma: -0.126 ± 1.627 arcsec RMS: 1.628 arcsec
DEC residual	Average ± 1-sigma: 0.009 ± 1.772 arcsec RMS: 1.769 arcsec
Position error Δr (against precise CPF)	20.748 m
Velocity error Δv (against precise CPF)	0.054 m/s

SLR	
Reduced chi-squared	2.529
No. of processed measurements	Range: 870
Rejection rate measurements	Range: 0.00 %
Range residual	Average ± 1-sigma: 0.000 ± 1.579 m RMS: 1.578 m
SLR ground station biases	BADL: 3.777 m BEIL: 5.710 m BORL: 5.185 m CHAL: 5.688 m GLSL: 4.983 m GODL: 1.131 m GRSM: 4.408 m HA4T: 1.071 m HERL: 4.547 m KTZL: 4.731 m MDVS: 4.039 m MONL: 2.110 m POT3: 4.663 m RIGL: 4.543 m SIML: 4.972 m SISL: 3.454 m SOSW: 3.646 m STL3: 3.077 m SVEL: 3.780 m WETL: 4.316 m YARL: 4.535 m ZELL: 4.049 m ZIML: 4.583 m
Position error Δr (against precise CPF)	2.418 m
Velocity error Δv (against precise CPF)	0.002 m/s

ANTSY + SLR	
Reduced chi-squared	2.207
No. of processed measurements	Angular: 253 Range: 870
Rejection rate measurements	Angular: 0.00 % Range: 0.00 %
Scaled RA residual	Average ± 1-sigma: -0.144 ± 1.689 arcsec RMS: 1.691 arcsec
DEC residual	Average ± 1-sigma: -1.216 ± 1.788 arcsec RMS: 2.159 arcsec
Range residual	Average ± 1-sigma: 0.000 ± 1.579 m RMS: 1.578 m
SLR ground station biases	BADL: 3.803 m BEIL: 5.771 m BORL: 5.221 m CHAL: 5.696 m GLSL: 4.987 m GODL: 1.170 m GRSM: 4.445 m HA4T: 1.072 m HERL: 4.553 m KTZL: 4.706 m MDVS: 4.037 m MONL: 2.120 m POT3: 4.652 m RIGL: 4.564 m SIML: 4.951 m SISL: 3.479 m SOSW: 3.656 m STL3: 3.064 m SVEL: 3.804 m WETL: 4.321 m YARL: 4.524 m ZELL: 4.042 m ZIML: 4.613 m
Position error Δr (against precise CPF)	2.389 m
Velocity error Δv (against precise CPF)	0.002 m/s

BeiDou DW 11 & IRNSS-R1F OD Campaigns

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- OD campaign using optical observations provided by the State Space Agency of Ukraine (SSAU)
- Measurements originate from two optical telescopes: OES30 and OES50.
- Dataset corrected for aberration and converted to EME2000
- No theoretical sigmas or time bias were provided, thus the first was arbitrarily chosen according specification of the telescopes and the time bias was assumed to be null.

OES30 telescope characteristics.

Angular accuracy	1 arcsec
Geolocation	
Longitude	30.603 deg
Latitude	50.608 deg
Altitude	113.0 m

OES50 telescope characteristics.

Angular accuracy	0.5 arcsec
Geolocation	
Longitude	26.721 deg
Latitude	48.848 deg
Altitude	355.0 m

BeiDou DW 11 – Results

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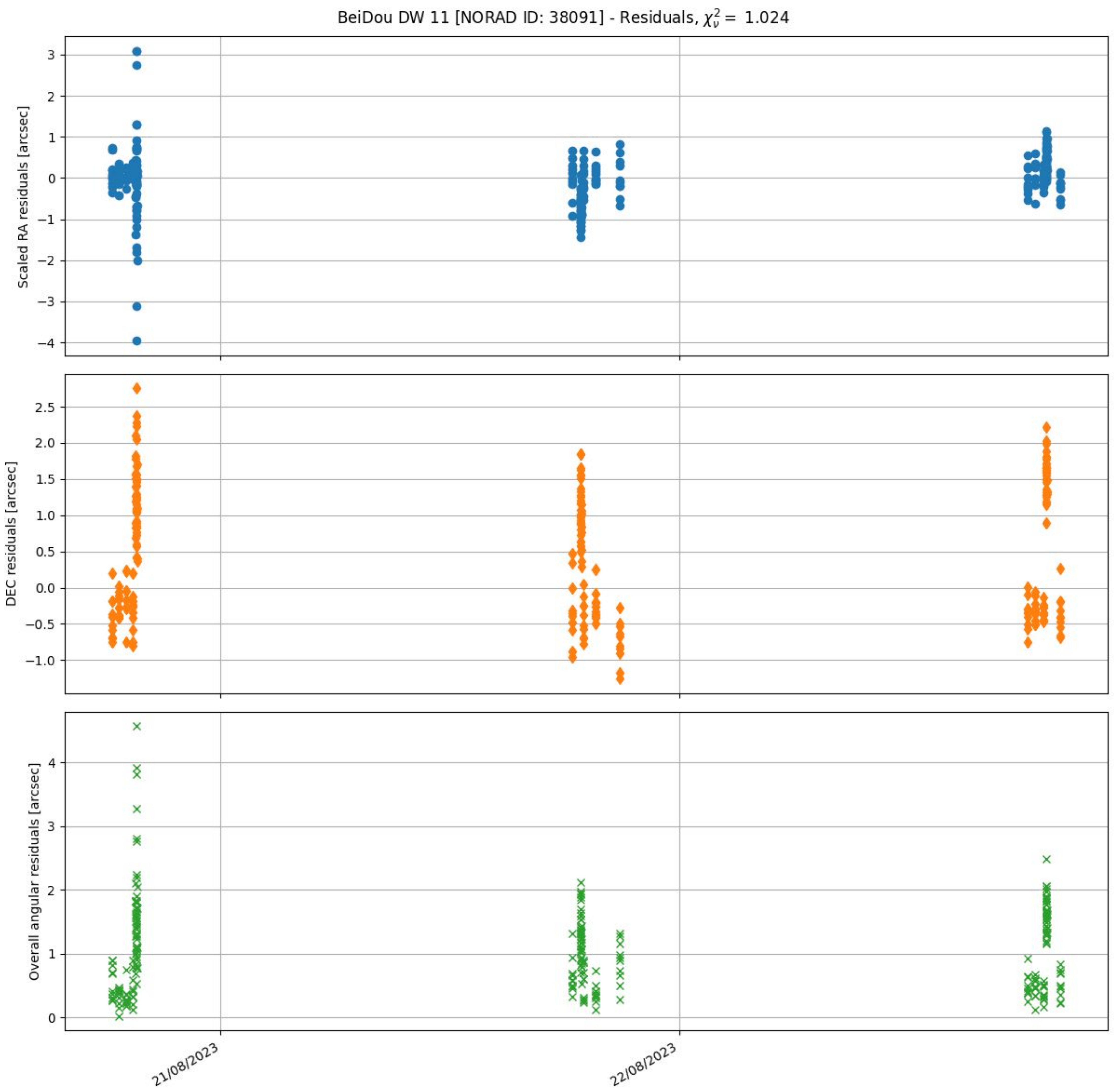
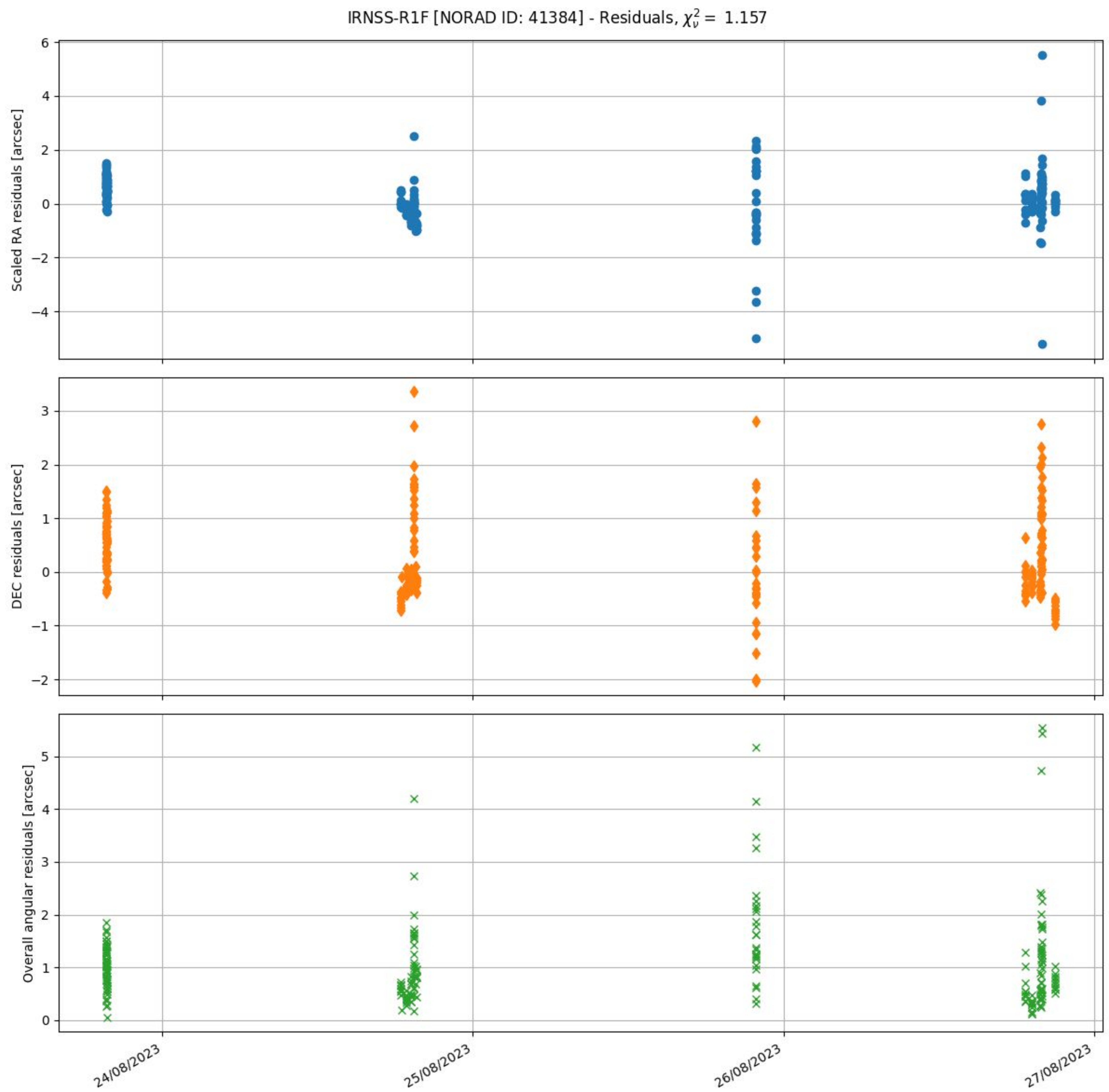


Residuals for the OD campaign using SSAU measurements; BeiDou DW 11 case study. Top: Scaled RA residuals. Middle: DEC residuals. Bottom: Overall angle.

The overall observation window covers roughly **50 hours, from 20 to 23 August 2023**

Space object name	BeiDou DW 11
NORAD ID	38091
Orbital regime	GEO
TLE used to initiate OD	1 38091U 12008A 23234.77609855 .00000066 00000-0 00000+0 0 9994 2 38091 1.6779 68.1891 0002121 165.8669 74.8595 1.00269235 42151
Observation period	20/08/2023–22/08/2023
Observation span	49.67 h
No. of passes	OES30: 3 OES50: 3
No. of processed measurements	Angular: 251
Rejection rate measurements	Angular: 0.00 %
Reduced chi-squared	1.024
Scaled RA residual	Average ± 1-sigma: -0.042 ± 0.716 arcsec RMS: 0.715 arcsec
DEC residual	Average ± 1-sigma: 0.493 ± 0.904 arcsec RMS: 1.028 arcsec
Position error Δr (against TLE)	3510.893 m
Velocity error Δv (against TLE)	0.056 m/s

IRNSS-R1F – Results



Residuals for the OD campaign using SSAU measurements; IRNSS-R1F case study. Top: Scaled RA residuals. Middle: DEC residuals. Bottom: Overall angle.

The overall observation window covers slightly more than **73 hours**, **from 23 to 26 August 2023**

Space object name	IRNSS-R1F
NORAD ID	41384
Orbital regime	GEO
TLE used to initiate OD	1 41384U 16015A 23238.96366814 .00000154 00000-0 00000-0 0 9994 2 41384 2.9156 130.2175 0018180 177.0272 46.9392 1.00266776 27386
Observation period	23/08/2023–27/08/2023
Observation span	73.34 h
No. of passes	OES30: 4 OES50: 2
No. of processed measurements	Angular: 214
Rejection rate measurements	Angular: 0.00 %
Reduced chi-squared	1.157
Scaled RA residual	Average ± 1-sigma: 0.189 ± 1.035 arcsec RMS: 1.050 arcsec
DEC residual	Average ± 1-sigma: 0.302 ± 0.834 arcsec RMS: 0.885 arcsec
Position error Δr (against TLE)	2033.311 m
Velocity error Δv (against TLE)	0.234 m/s

Summer Debris Campaign

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- OD capability demonstration for 30 large targets in LEO orbital regime.
- Optical (Deimos' ANTSY telescope) and laser ranging (DiGOS's Borowiec SLR station) measurements
- Deimos telescope tracked 27 different objects for a total of 99 tracks
- DiGOS SLR station tracked 9 different objects for a total of 13 tracks
- observations were carried out for 3 subsequent nights, from 11 to 13 August 2023

Outcome

- Out of the 30 debris targets, 22 were successfully processed
- Others were filtered because of the small amount of passes acquired

Summer debris campaign observation statistics.

	No. of different objects	No. of tracks	Median no. of measurements per track	Median span (s)
Deimos(1 telescope)	27	99	140	429
DiGOS (laser ranging)	9	13	10	147

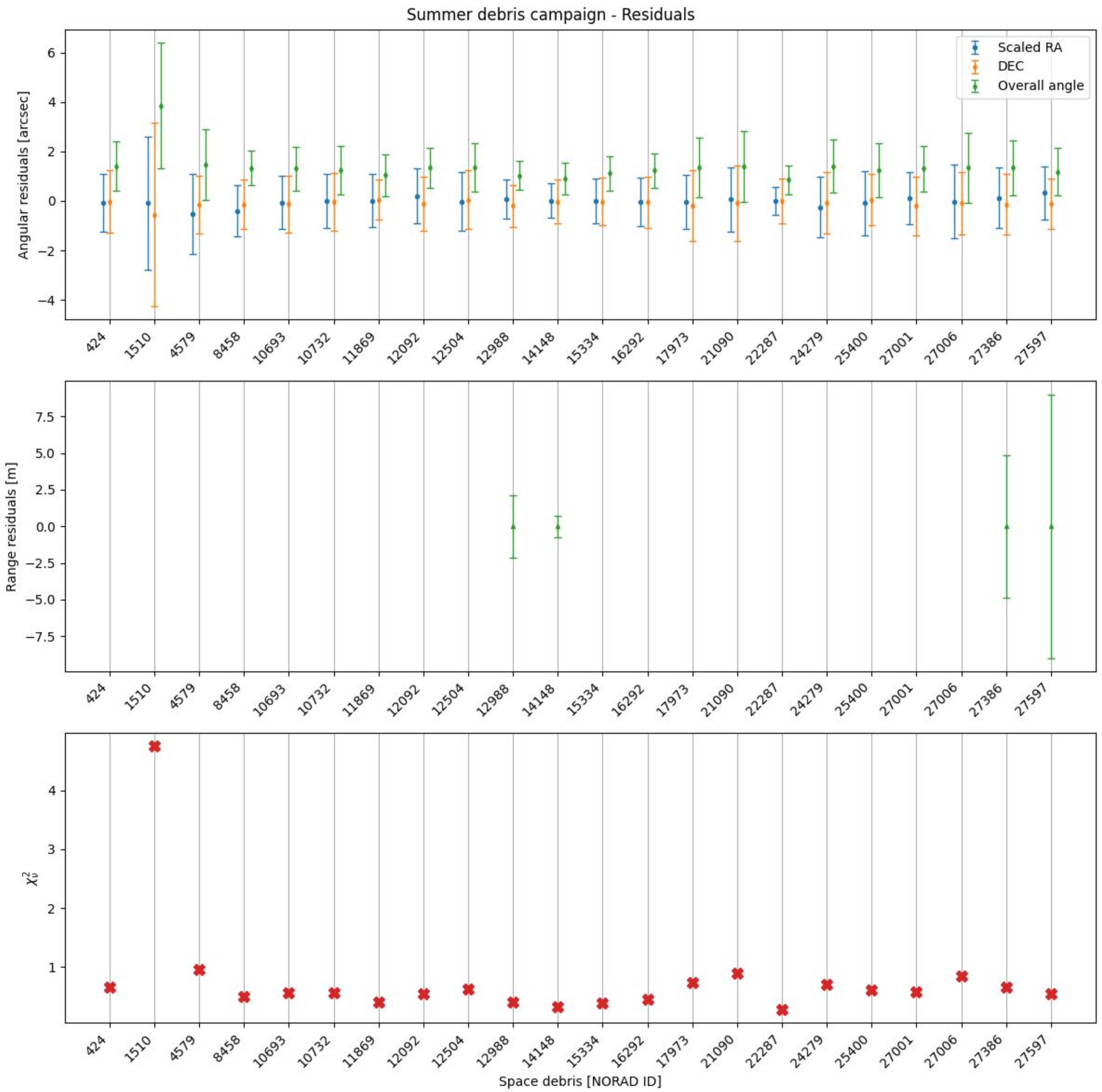
Deimos' ANTSY Telescope characteristics.

Angular accuracy	1.5 arcsec
Geolocation	
Longitude	4.408 W deg
Latitude	38.543 N deg
Altitude	1115.0 m

DiGOS' Borowiec SLR station characteristics.

Range accuracy	5.0 m
Geolocation	
Longitude	17.075 E deg
Latitude	52.277 N deg
Altitude	122.615 m

Summer Debris Campaign



Average residuals for the summer debris campaign. Top: Angular (RADEC) residuals. Middle: Range residuals. Bottom: reduced chi-squared statistics.

Rejection rates

NORAD ID	Rejection Rates	
	Angular	Range
424	0.00 %	-
1510	0.22 %	-
4579	0.26 %	-
8458	0.00 %	-
10693	0.00 %	-
10732	0.00 %	-
11869	0.00 %	-
12092	0.00 %	-
12504	0.00 %	-
12988	0.00 %	0.00 %
14148	0.00 %	0.00 %
15334	0.17 %	-
16292	0.00 %	-
17973	0.27 %	-
21090	0.12 %	-
22287	0.00 %	-
24279	0.24 %	-
25400	0.00 %	-
27001	0.00 %	-
27006	0.43 %	-
27386	0.29 %	0.00 %
27597	0.00 %	0.00 %

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EISCAT Experiment Campaign

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Five targets selected:

- ~~CRYOSAT 2 (NORAD 36508)~~ → Omitted because of not enough accurate radar measurements
- ~~Hai Yang 2D (NORAD 48621)~~ → Omitted because of not enough accurate radar measurements
- Sentinel-3A (NORAD 41335)
- Sentinel-3B (NORAD 43437)
- Stella (NORAD 22824)

Table 8: EISCAT's UHF radar characteristics (range and range rate accuracy estimated).

Estimated Range accuracy	50.0 m
Estimated Range rate accuracy	20.0 m/s
Geolocation	
Longitude	19.2257799 deg
Latitude	69.5865577 deg
Altitude	100 m

- The experiment lasted 5 days, from the 10th to the 14th of June, 2024
- Approximately 2 hours of observation per day scheduled
- Observations performed with EISCAT's UHF radar.

EISCAT Exp. – Methodology

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The experiment was executed as follows:

1. Neuraspace carried out a preliminary analysis to propose EISCAT a list of potential targets and observation slots.
2. EISCAT received the list of potential targets and observation slots, reviewed it, and approved it.
3. Neuraspace prepared pointing information for all targets within the scheduled observation hours to send before any observation slots (pointings were generated the day before to be more accurate). For each target, the pointing information included:
   i. The most recent TLE
   ii. A list of pointing data, each structured to contain the epoch, the azimuth, the elevation, the range, and the pointing duration.
4. Neuraspace sent the pointing information to EISCAT.
5. EISCAT performed the radar observation and sent the obtained measurements to Neuraspace.
6. Neuraspace produced OD solutions.

EISCAT Exp. – Considerations

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- The geolocation altitude value provided by EISCAT for their UHF radar is accurate to 10s of meters.
- Range rate measurements are not very accurate
- The time tagging of range and range rate measurements is precise to ~1 ms level, which may account for errors in OD solutions in the order of ~10 m
- Additional inaccuracies in measurement time tagging are present
- An additional 1 s of bias in all measurement epochs (of currently unknown source) has been observed and was accounted for in producing OD solutions
- By inspecting range and range rate residuals, it looks like measurements are affected by phase ambiguity

EISCAT Exp. – Time Tagging Inaccuracies

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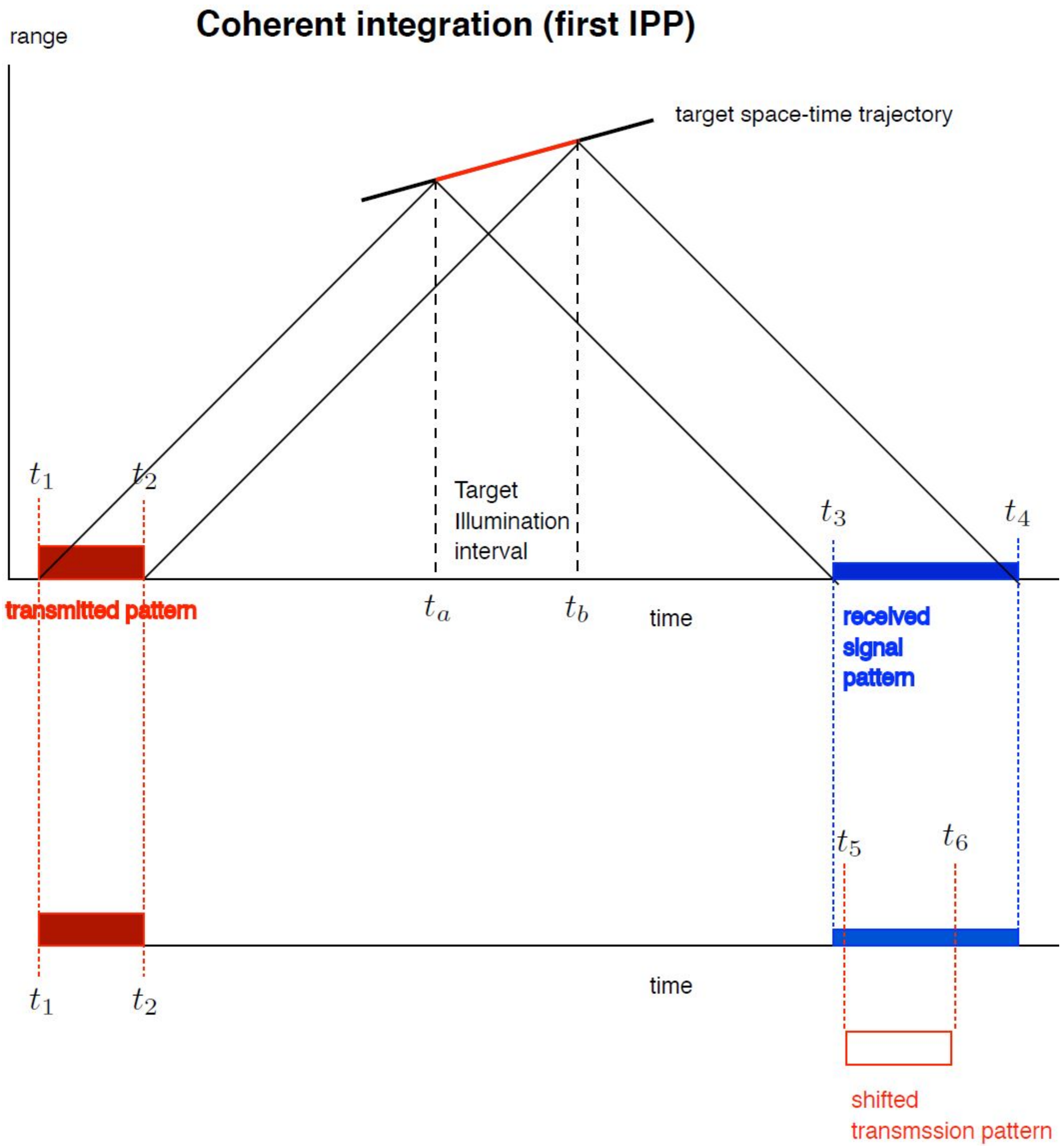

Schematic representation of the Match Function (MF) method analysis used by EISCAT to time tag measurements. The MF method analysis uses the data of ten interpulse periods (IPP), each 20 ms long, to compute one single data point (called hit) in the hitlist files. Hitlist data points have a time stamp with 10x20 ms = 200 ms granularity. That timestamp is attached to the hit by using the UTC start time of the ~200 ms long reception data segment used in the analysis of that hit. The MF method is essentially a matching exercise. In the reception data, one searches the time-shifted, doppler-shifted replica of the transmission. The best-matching time shift is used to compute the range, and the best-matching doppler-shift gives directly the doppler-shift. With a single pulse coherent MF method, the range the analysis would give would be the range Ra = (ta - t1) * c that the target has at the time ta, but that range Ra then is the range for the time ta = (t1 + t3) / 2, not the range at "hit time-stamp time" t3. Note how the interval between the received patterns changes from pulse to pulse, due to the target motion, but this is not taken into account by the MF method.

EISCAT Exp. – Phase Ambiguity

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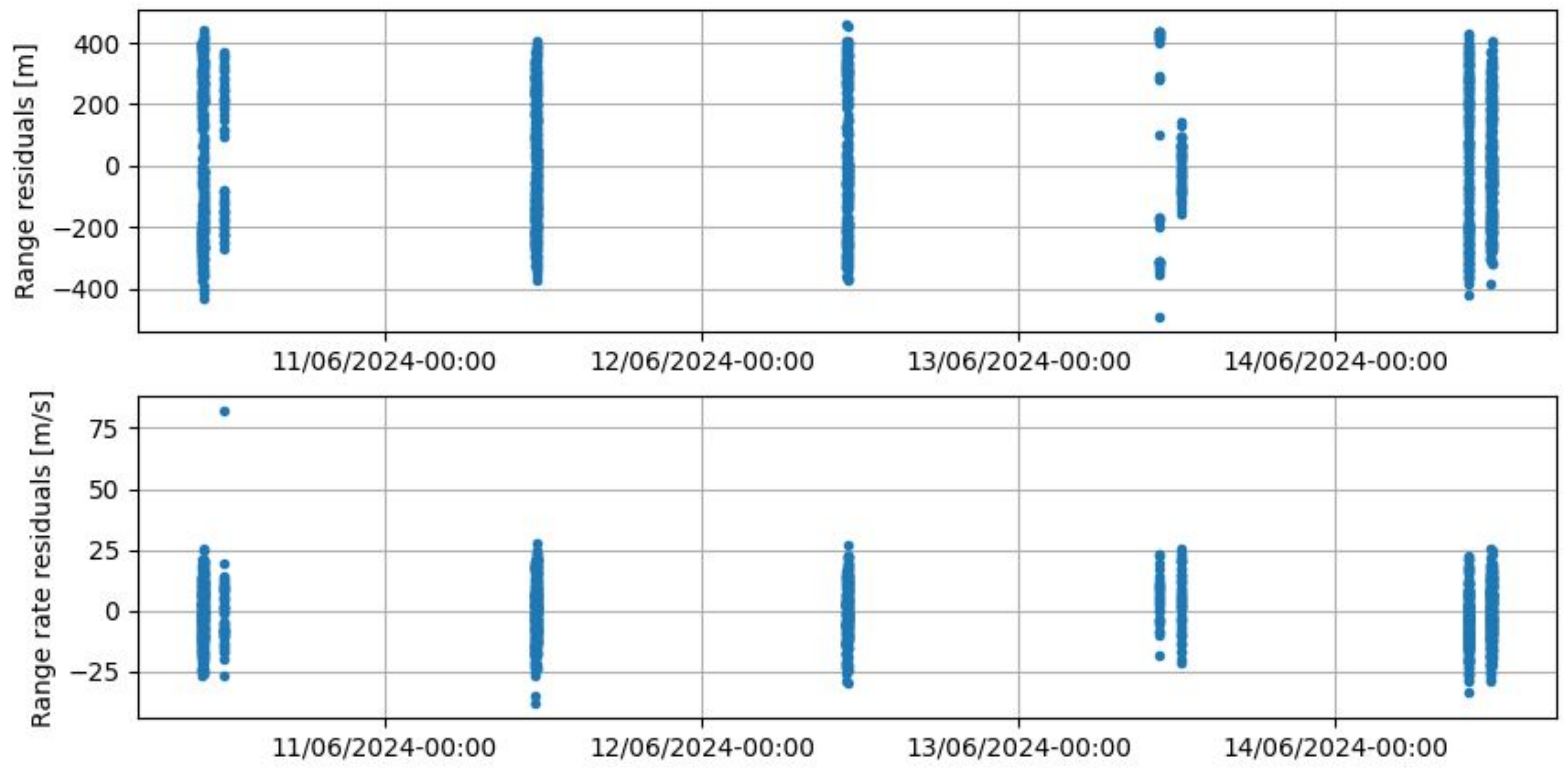
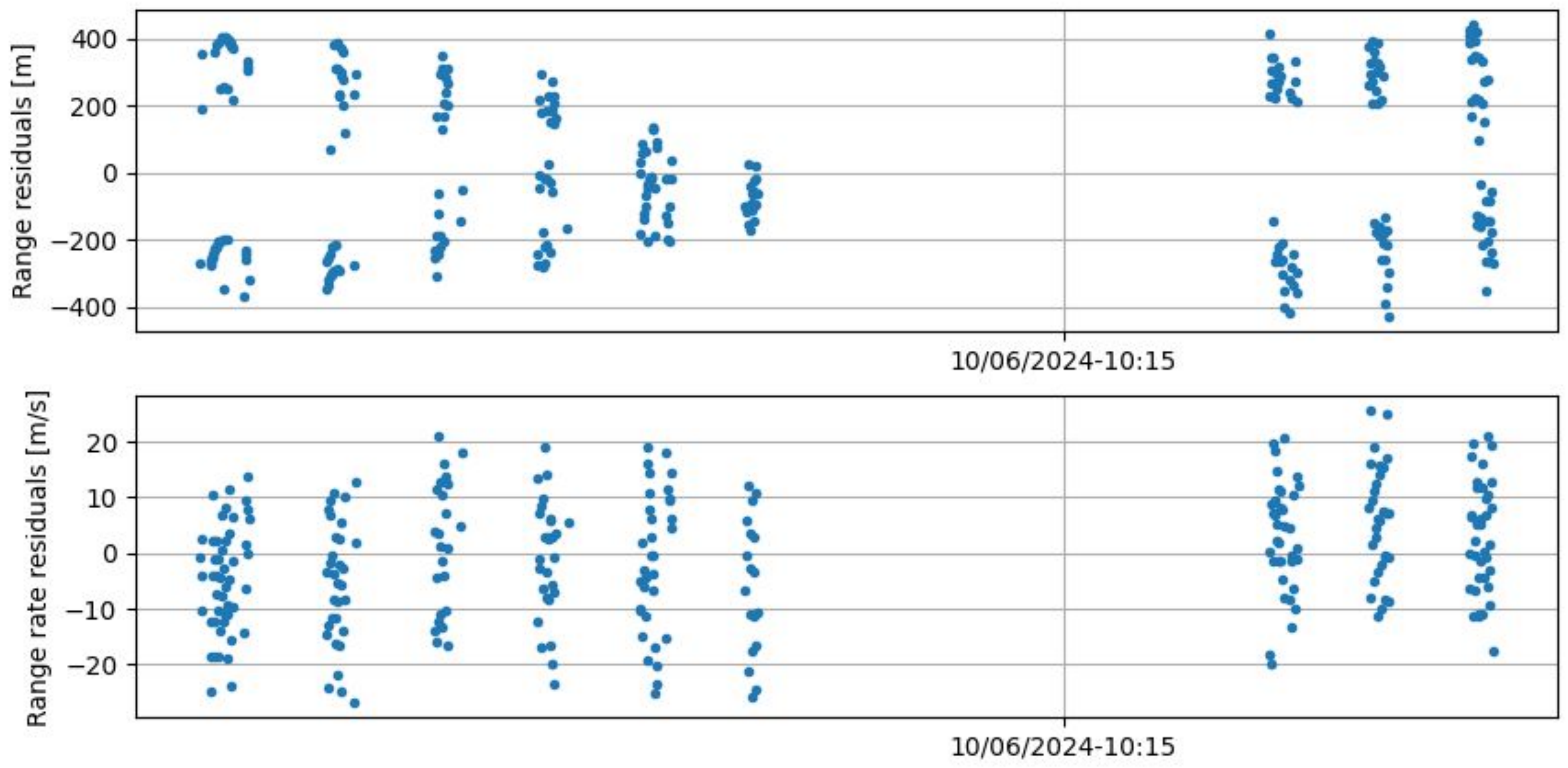
- By inspecting range and range rate residuals, it looks like measurements are affected by phase ambiguity
- Range residuals appear to follow the same trend but on different levels
- By solving such phase ambiguity, which will not be considered optional for production code purposes, accuracy of the computed OD solutions is expected to improve dramatically
- Give feedback on this problem to EISCAT and iterate with them to solve it

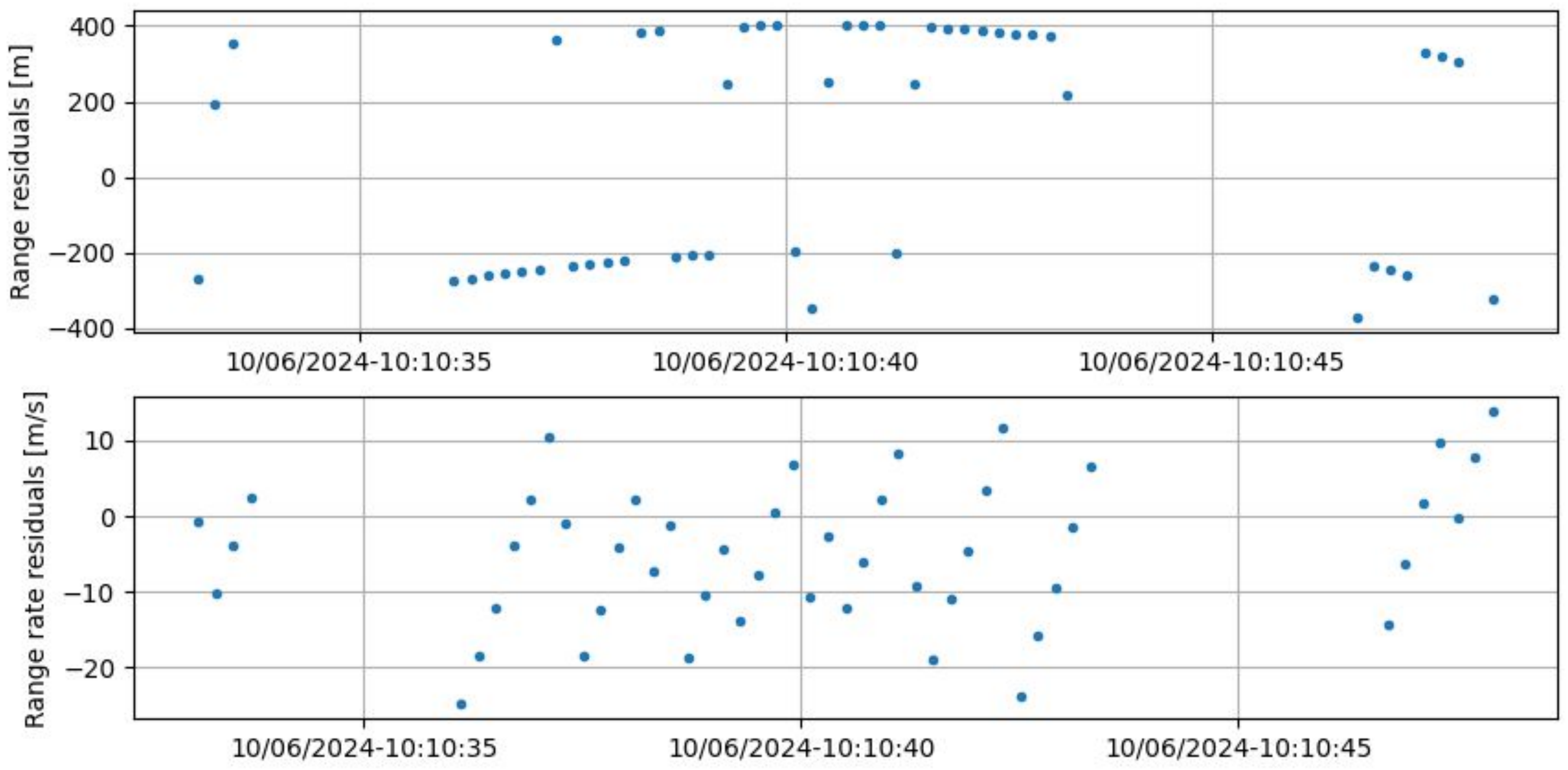
Example of range and range rate residuals of EISCAT's radar measurements; Sentinel-3B.



Full residuals collection.



First pass residuals.



Magnification of first ~50 residuals. Possible phase ambiguity on range residuals.

EISCAT Exp. – Sentinel-3A

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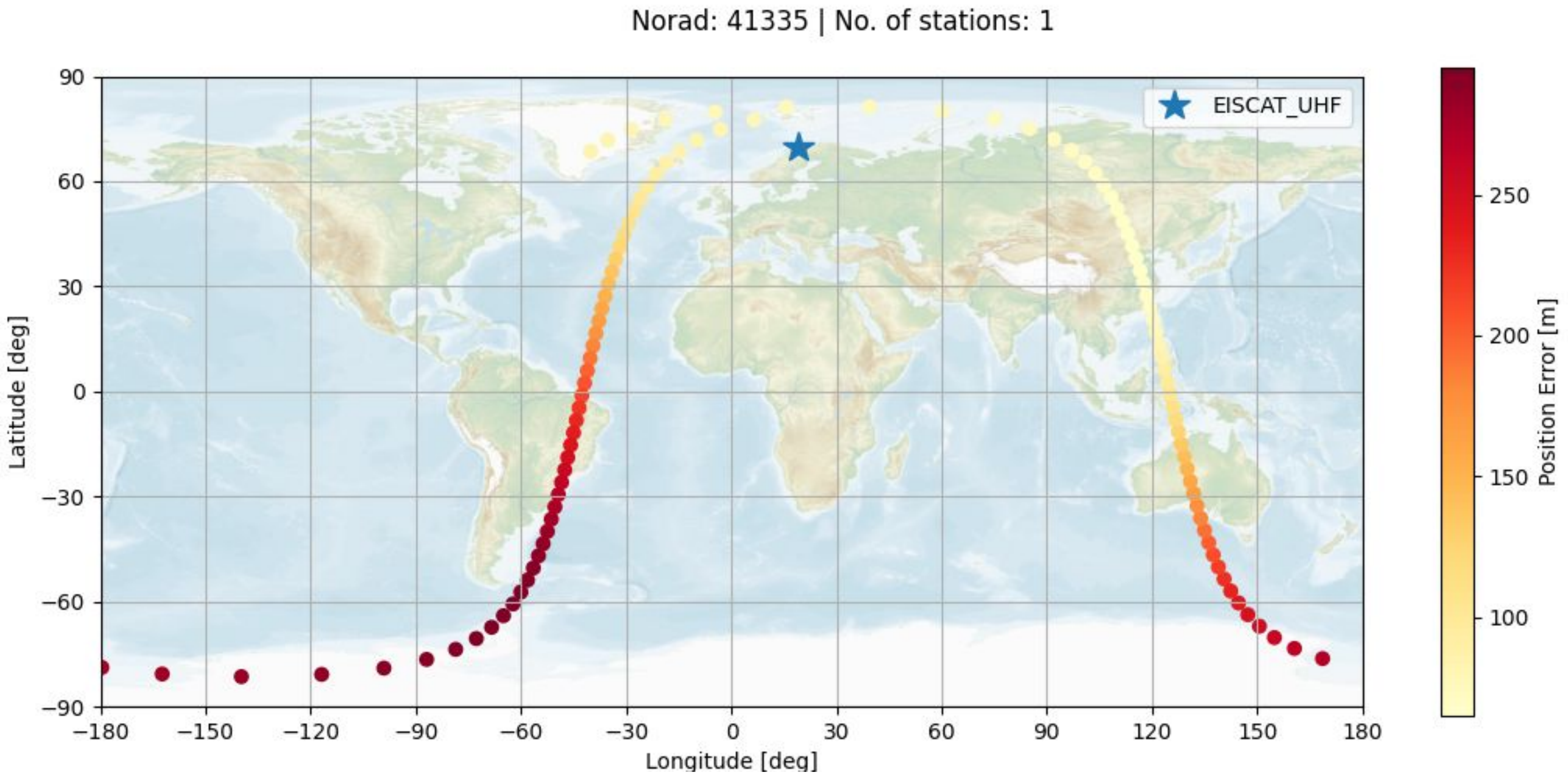
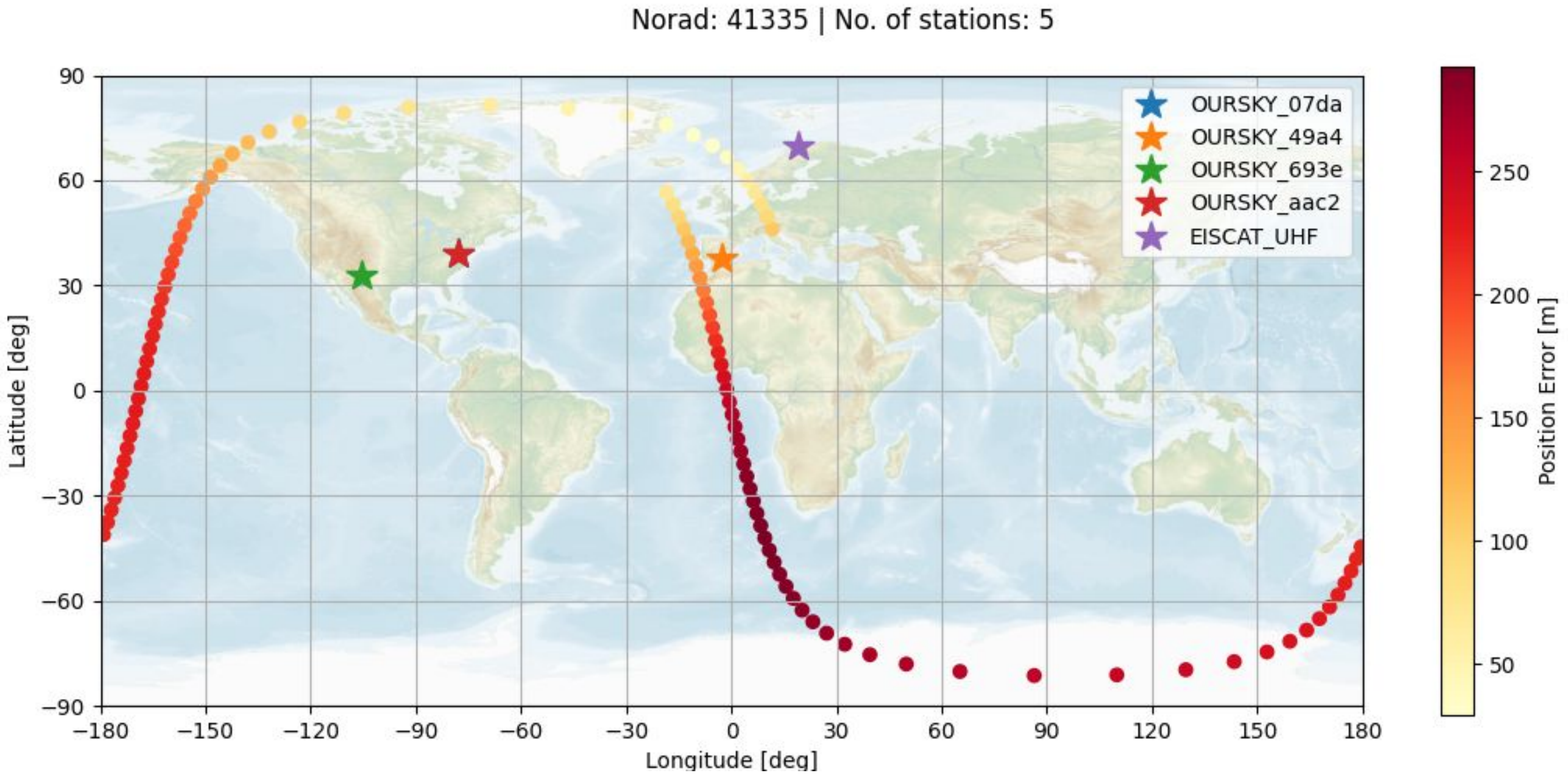
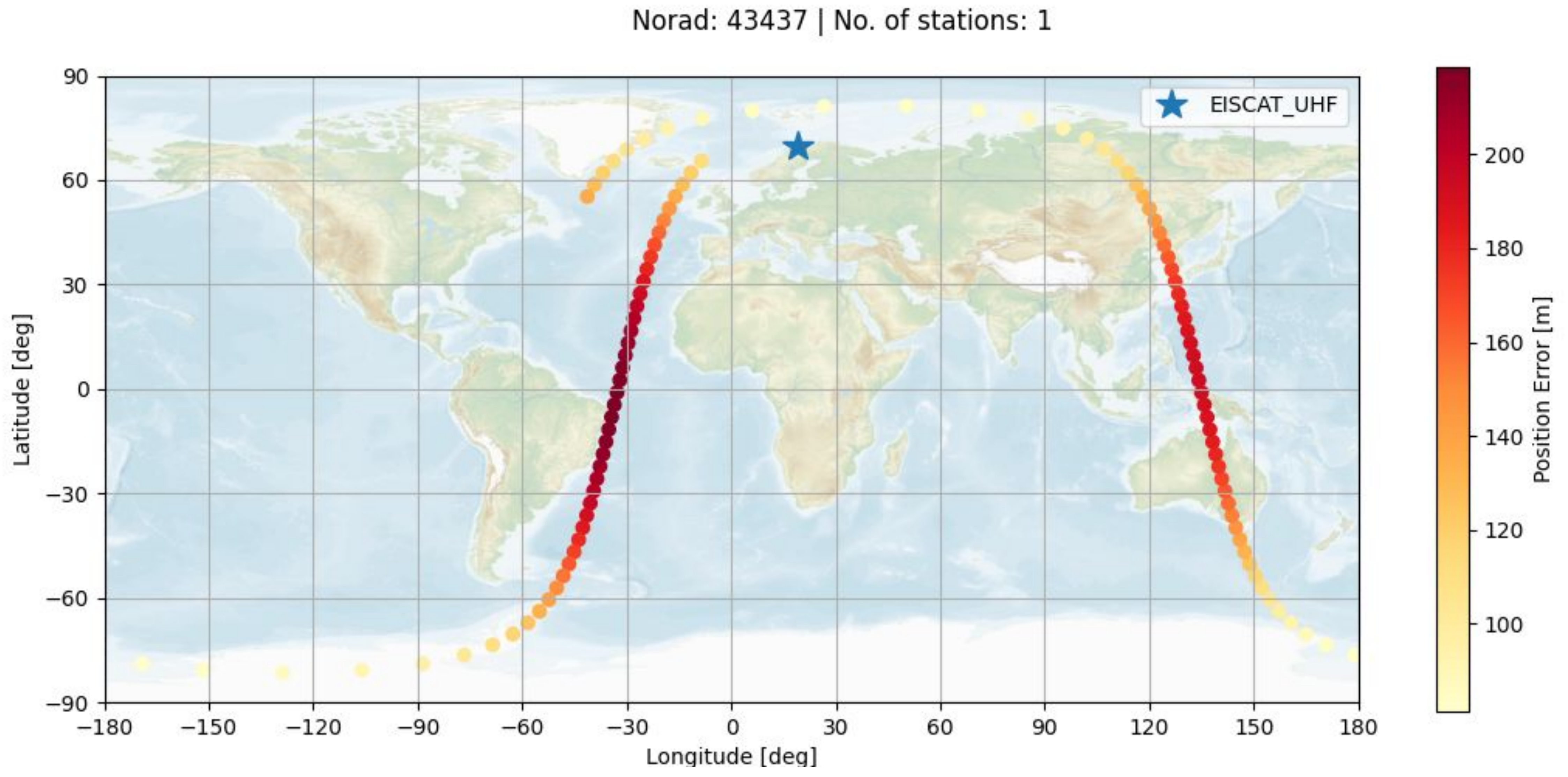


Space object name	Sentinel-3A
NORAD ID	41335
Observation period	10/06/2024–14/06/2024
No. of measurements	Total: 3358 Used: 3354
Reduced chi-squared	8.2
Position error Δr (against EOF)	Min: 65 m Max: 295 m
Velocity error Δv (against EOF)	Min: 0.069 m/s Max: 0.224 m/s

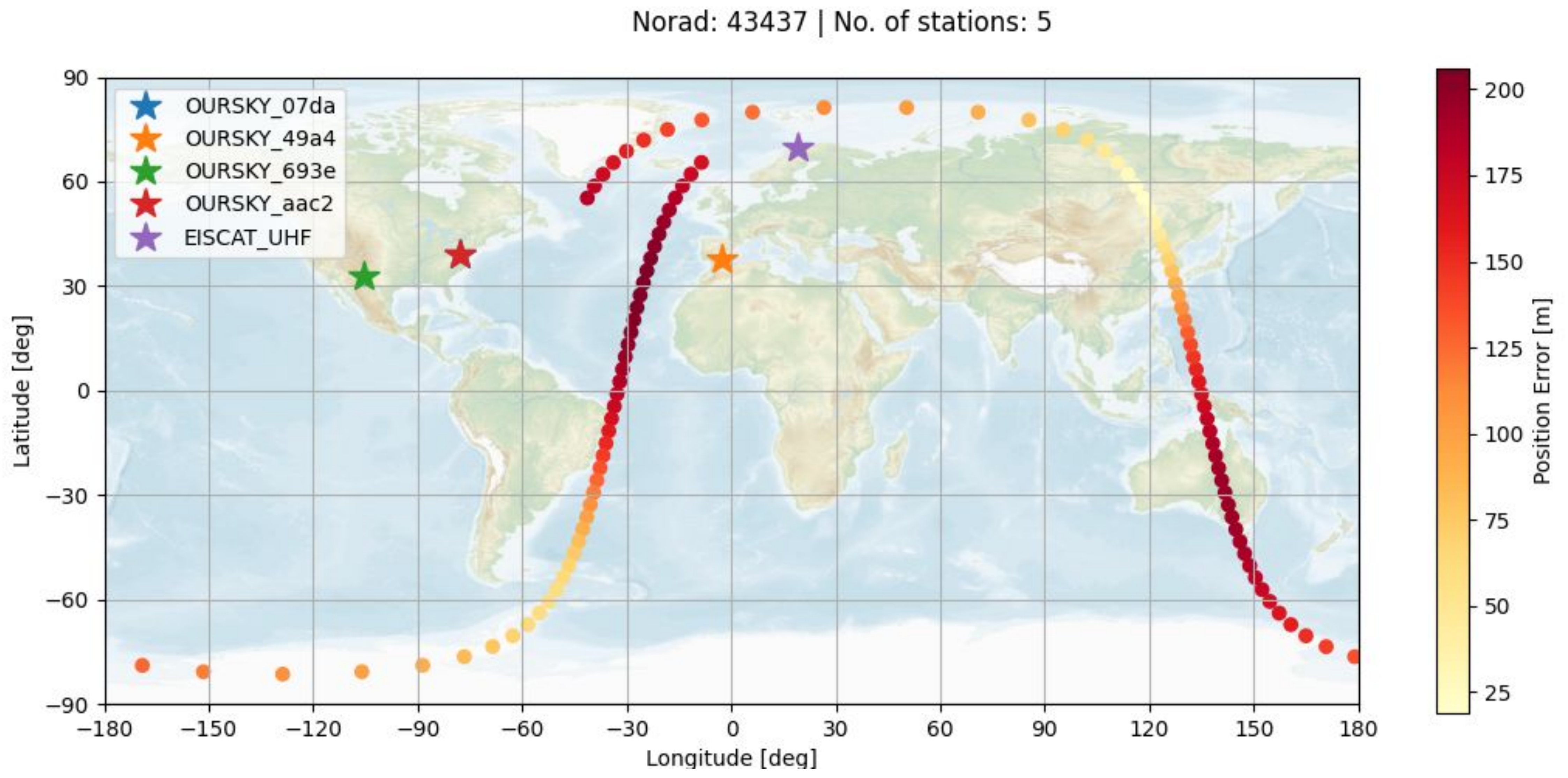


Space object name	Sentinel-3A
NORAD ID	41335
Observation period	10/06/2024–14/06/2024
No. of measurements	Total: 3568 Used: 3514
Reduced chi-squared	8.1
Position error Δr (against EOF)	Min: 32 m Max: 332 m
Velocity error Δv (against EOF)	Min: 0.129 m/s Max: 0.312 m/s

EISCAT Exp. – Sentinel-3B



Space object name	Sentinel-3B
NORAD ID	43437
Observation period	10/06/2024–14/06/2024
No. of measurements	Total: 2968 Used: 2966
Reduced chi-squared	10.0
Position error Δr (against EOF)	Min: 81 m Max: 218 m
Velocity error Δv (against EOF)	Min: 0.066 m/s Max: 0.153 m/s



Space object name	Sentinel-3B
NORAD ID	43437
Observation period	10/06/2024–14/06/2024
No. of measurements	Total: 3180 Used: 3149
Reduced chi-squared	10.4
Position error Δr (against EOF)	Min: 28 m Max: 199 m
Velocity error Δv (against EOF)	Min: 0.017 m/s Max: 0.198 m/s

EISCAT Exp. – Stella

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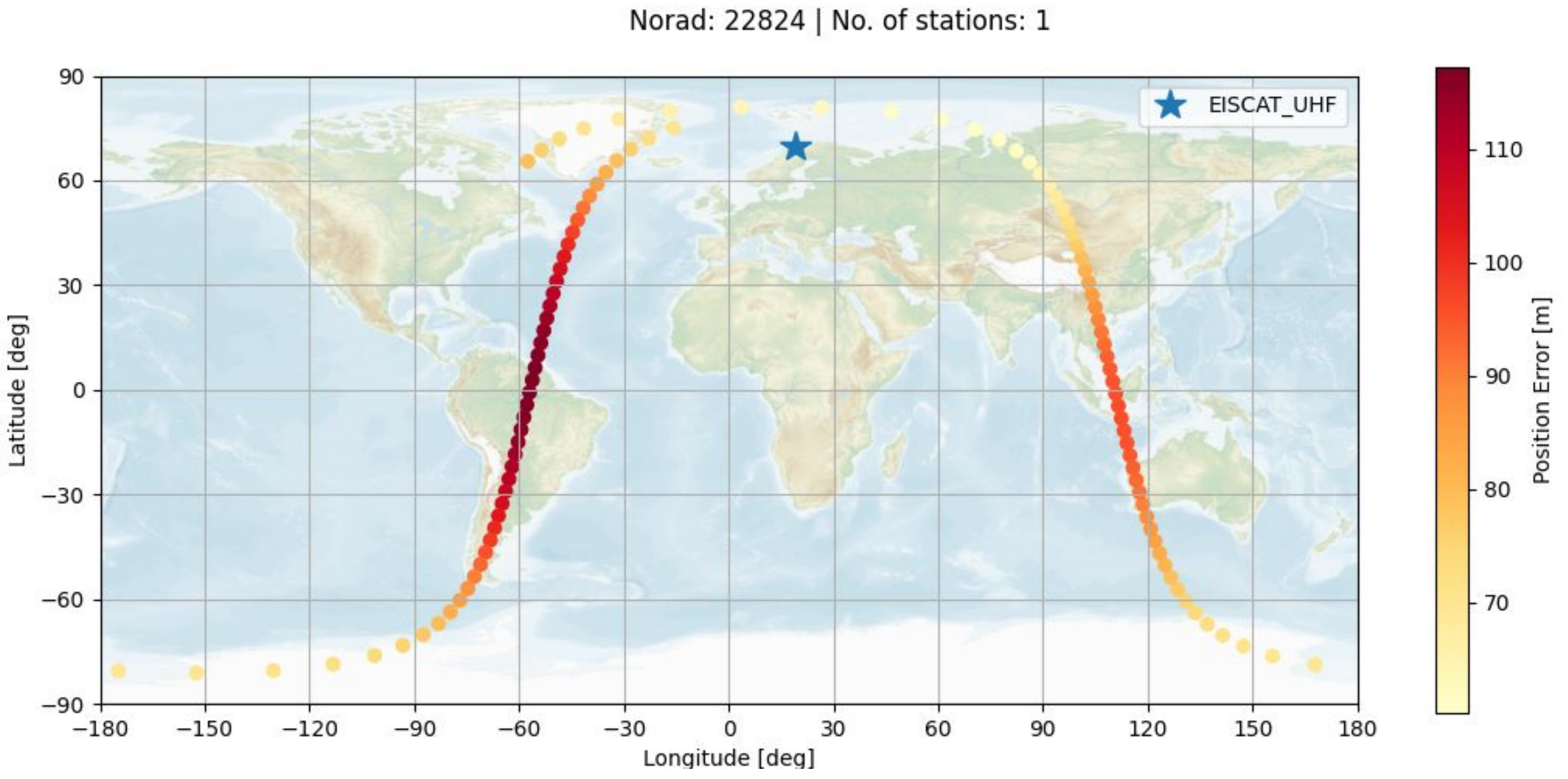
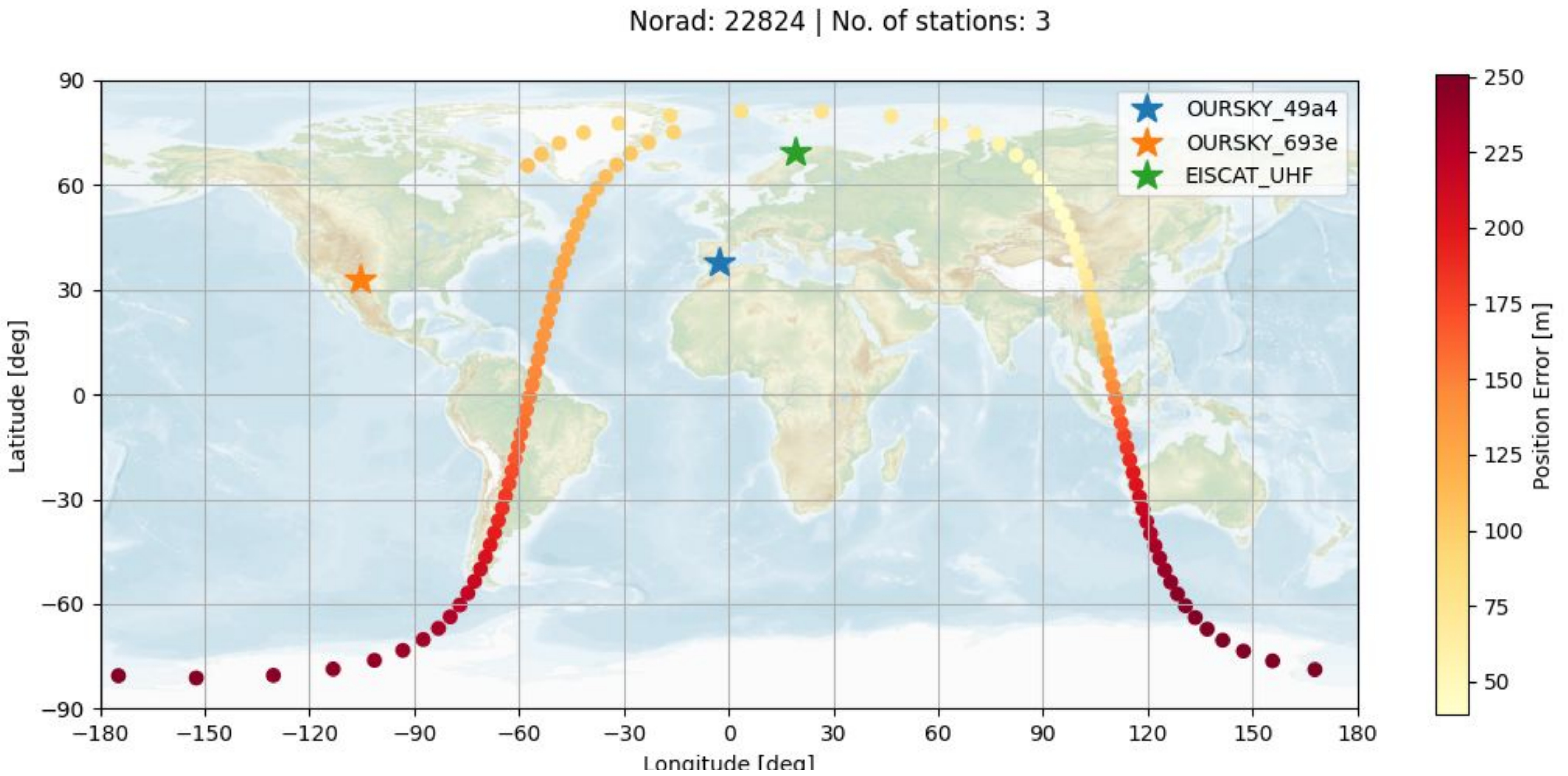


Space object name	Stella
NORAD ID	22824
Observation period	10/06/2024–14/06/2024
No. of measurements	Total: 1208 Used: 1208
Reduced chi-squared	4.4
Position error Δr (against EOF)	Min: 62 m Max: 114 m
Velocity error Δv (against EOF)	Min: 0.046 m/s Max: 0.084 m/s



Space object name	Stella
NORAD ID	22824
Observation period	10/06/2024–14/06/2024
No. of measurements	Total: 1517 Used: 1517
Reduced chi-squared	3.8
Position error Δr (against EOF)	Min: 39 m Max: 252 m
Velocity error Δv (against EOF)	Min: 0.072 m/s Max: 0.207 m/s

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08 – Conclusions

Conclusions

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- The project successfully de-risked the development of an MSDC, achieving the primary objective.
- Demonstrated accurate orbit determination using a combination of optical, laser, and radar measurements
- Promising radar results provide a valuable alternative to optical telescopes, unaffected by weather and lighting conditions.
- Integration with Neuraspace's SaaS platform confirmed the system's readiness for operator use
- MSDC prototype model TRL successfully increased from 3 to 7

↓

<u>Project Objective Achieved</u>

Identified Improvements

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- LUPI-style algorithm to be implemented for estimating fit span
- Sequential estimator and consider techniques to be added alongside BLS
- IOD strategies to be implemented based on the typologies of sensors and network used
- Accuracy of each data series to be monitored
- Conjectured phase ambiguity in radar measurements to be solved with EISCAT

Recent Developments

- Installation and calibration of Neuraspace's first telescope in Beja, Portugal
- Next telescope to be installed in Chile in October 2024

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