Detection and Study of Space Debris with TNG and SiFAP2 within the IDL Project

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In this poster, we present the development of an integrated system with tools for Space Situational Awareness (SSA) within the Interoperable Data Lake (IDL) project. Among system's capabilities, we report a proof-of-concept study on optical debris detection using SiFAP2, an ultra-fast optical timing instrument installed at the Telescopio Nazionale Galileo (TNG).

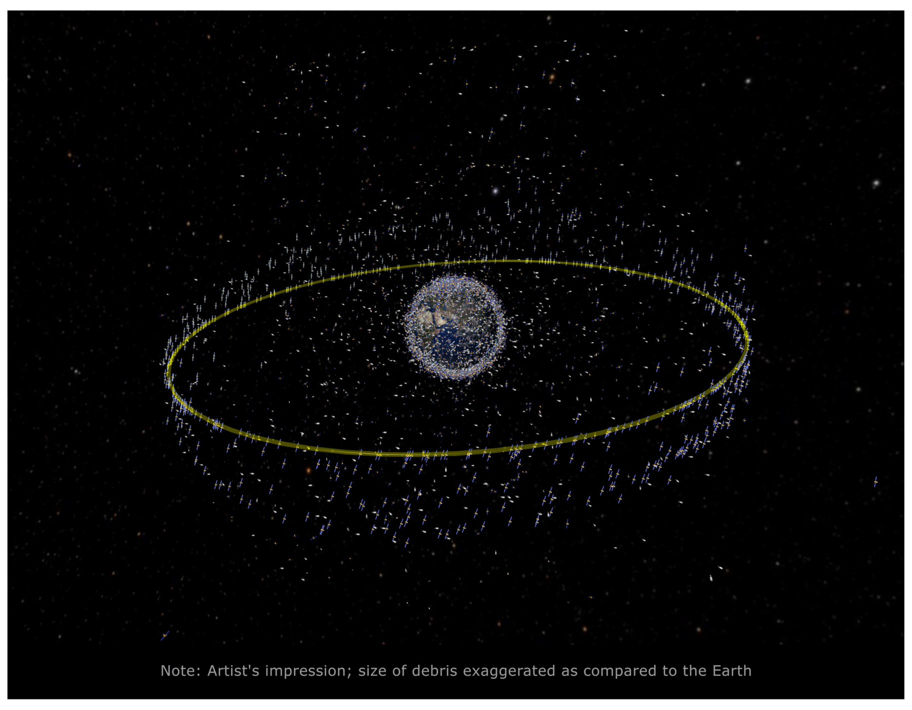
We implemented a dedicated data-processing pipeline, based on Two-Line Element (TLE) sets propagated via the SGP4 model, to schedule observation sessions and to measure orbital objects transits with high precision.

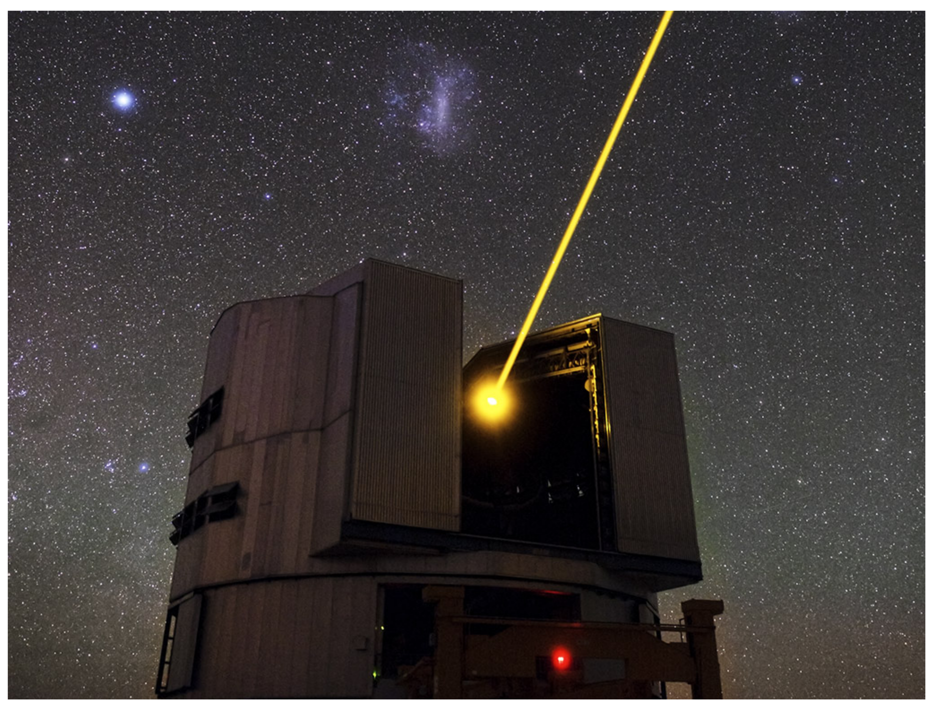
Observational campaigns conducted in February, March and September 2025 targeted a curated set of orbital objects based on their trajectory accuracy, visibility, altitude and physical characteristics. Across three sessions, out of 20 detection attempts, 7 successful transits were confirmed, demonstrating the feasibility of optical debris monitoring with SiFAP2 despite its narrow field of view and a limited orbital propagation precision.

The results validate the methodology of correlating optical signals with predicted passes and open opportunities for debris morphology studies, as well as for *a posteriori* analyses of previous optical campaigns using deterministic and machine learning techniques to distinguish astrophysical signals from noise generated by artificial object transits.

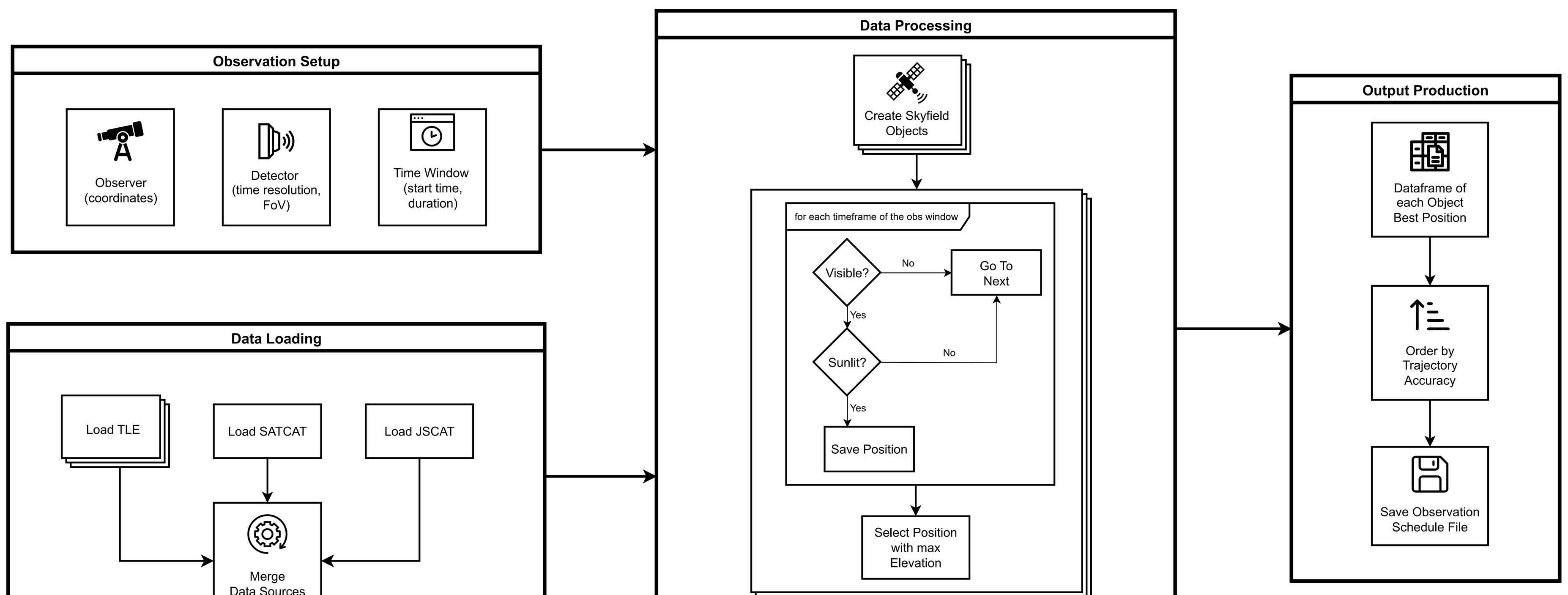
1. Introduction

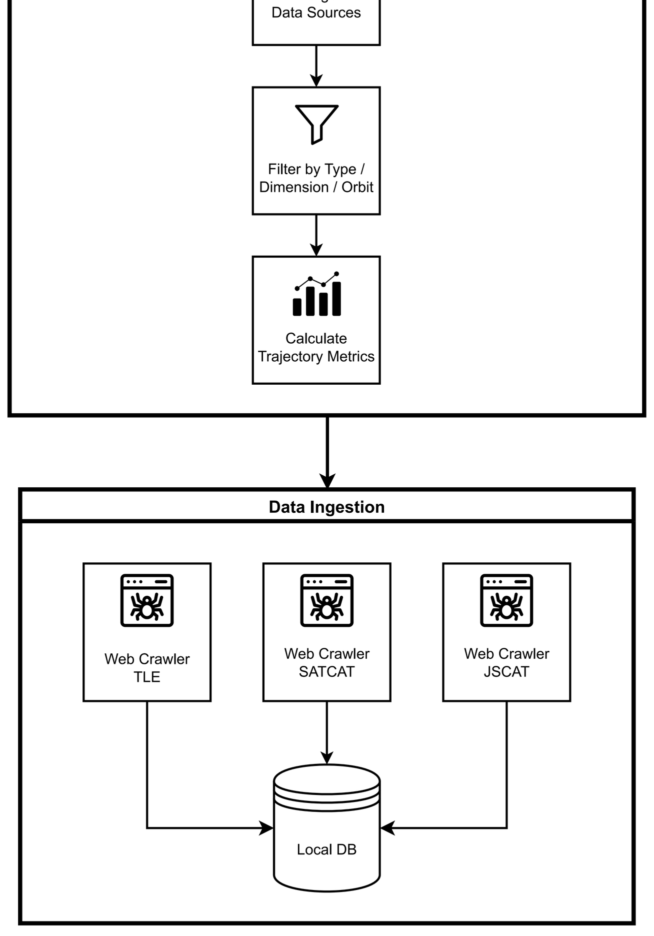
- **Space Situational Awareness (SSA)** is a ESA initiative to detect, track and forecast the trajectory and behaviour of near-Earth orbiting objects
- Development of a software tool to **schedule observation sessions** as module of an integrated system implemented for the IDL project and as activity of ICSC Spoke 2
- Tests conducted with the **Telescopio Nazionale Galileo (TNG)** and the **SiFAP2** detector, a sub-millisecond photon counter





2. Methodology





Trajectory Accuracy Metrics built using TLE database

1. RMSE [km]

$$\mathrm{RMSE} = \sqrt{\frac{1}{3}\left[(x_n - x_{n-1})^2 + (y_n - y_{n-1})^2 + (z_n - z_{n-1})^2\right]}$$

2. Relative Error [%]

$$\epsilon_{\mathrm{rel}} = \frac{||\vec{r}_n - \vec{r}_{n-1}||}{||\vec{r}_n||} \times 100$$

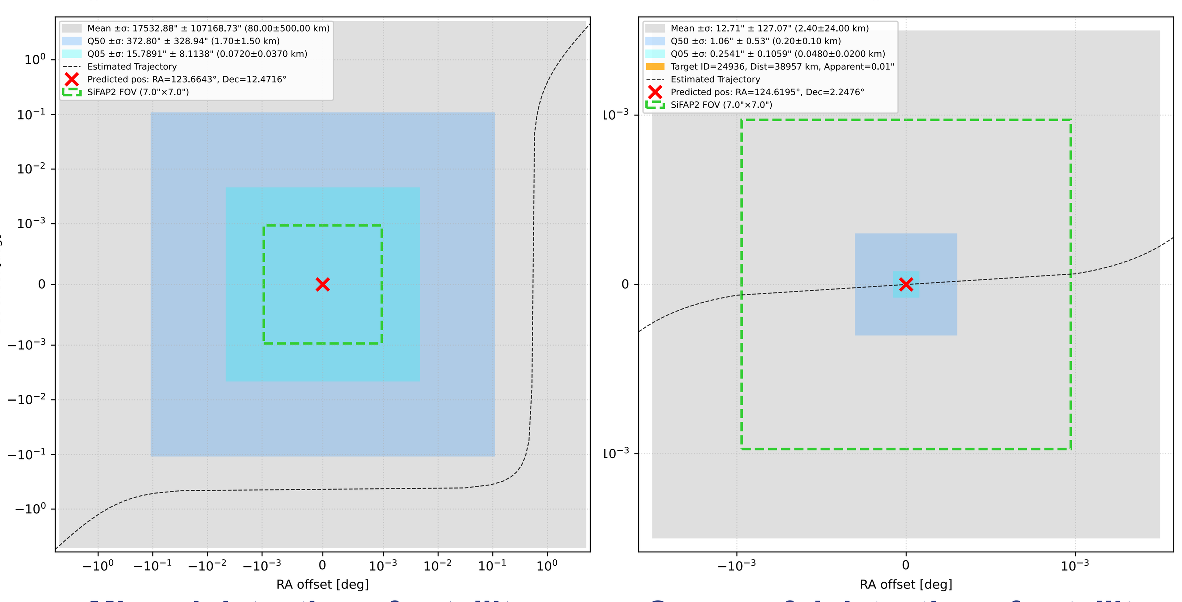
3. Angular Error [arcsec]

$$\theta_{\mathrm{err}} = \arccos\left(\frac{\vec{r}_n \cdot \vec{r}_{n-1}}{||\vec{r}_n|| \cdot ||\vec{r}_{n-1}||}\right) \times \frac{180}{\pi} \times 3600$$

4. Error Over Time [km min^{-1}]

$$\mathrm{EOT} = \frac{||\vec{r}_n - \vec{r}_{n-1}||}{\Delta t}$$

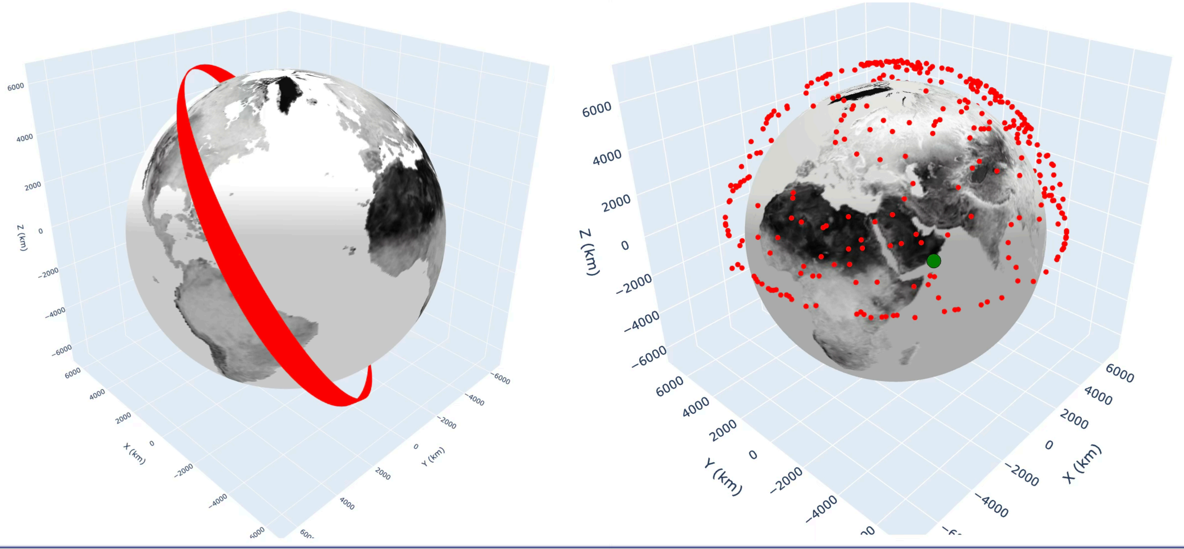
Logarithmic Visualization of Orbital Uncertainty vs SiFAP2 FoV



Missed detection of satellite ISTSAT-1

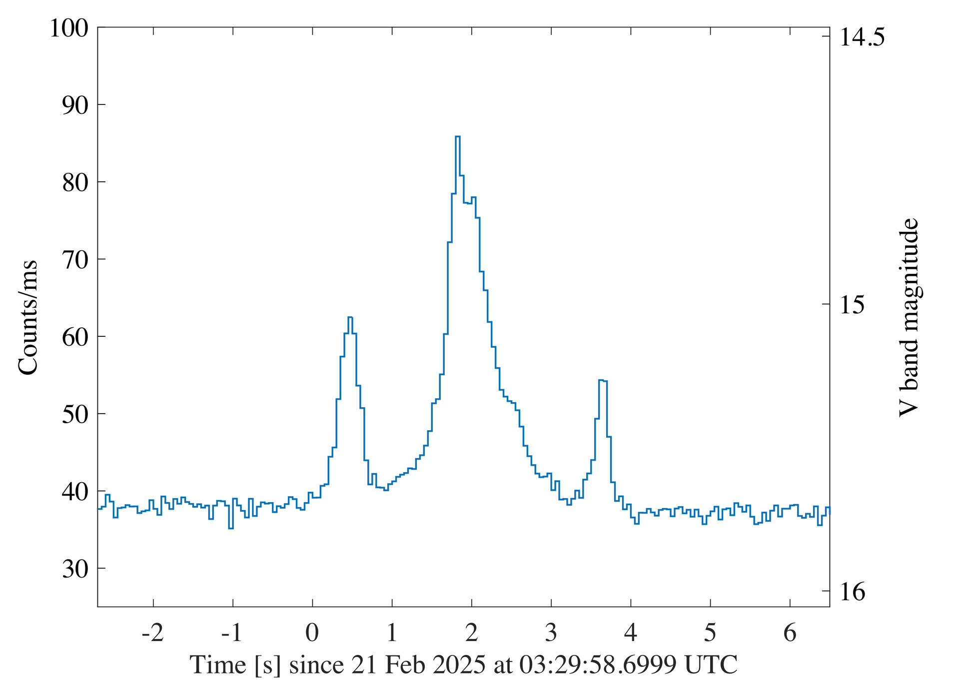
Successful detection of satellite AMC-3

Examples of trajectory forecast and past positions reconstruction

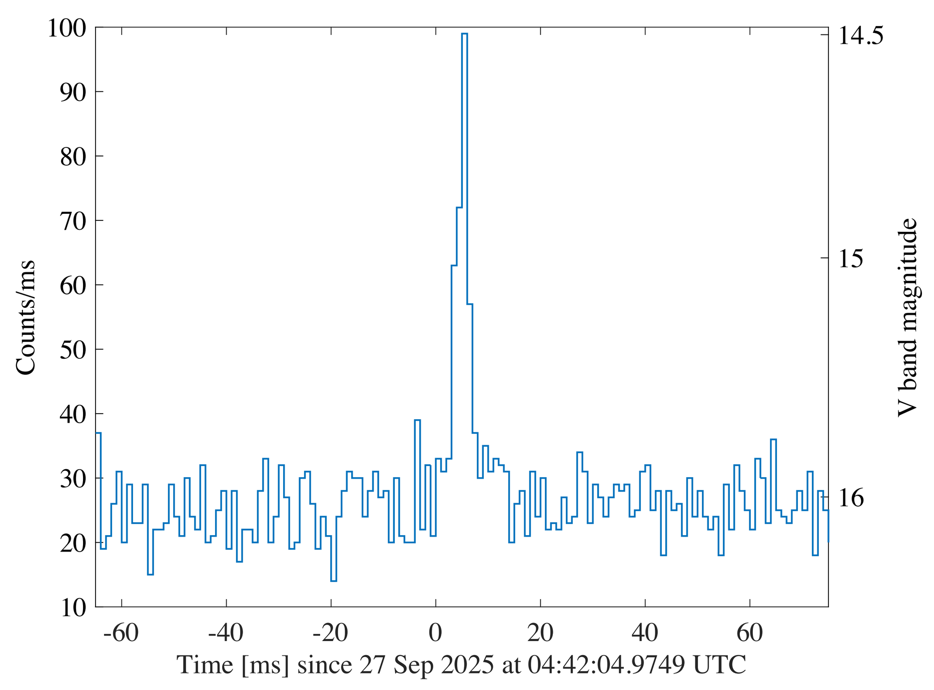


3. Results

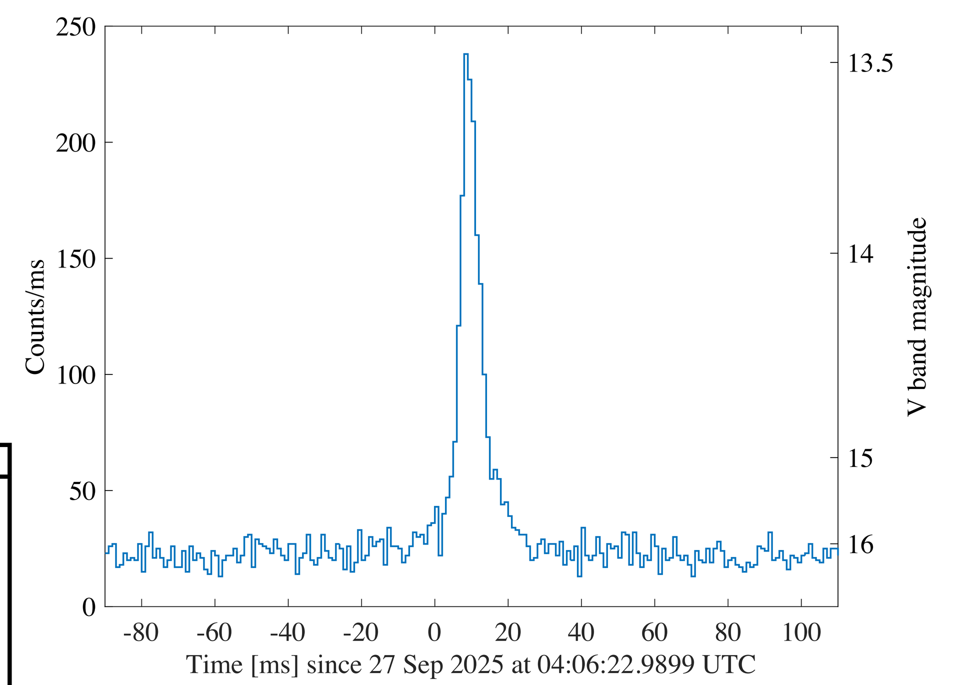
- **3 tests** conducted in February, March and September 2025
- **7 out of 20 target detections (~35% success rate)**
- Detected objects of **various types and dimensions**, and in **every orbit**, from lower LEO (550 km) to GEO (36000 km)



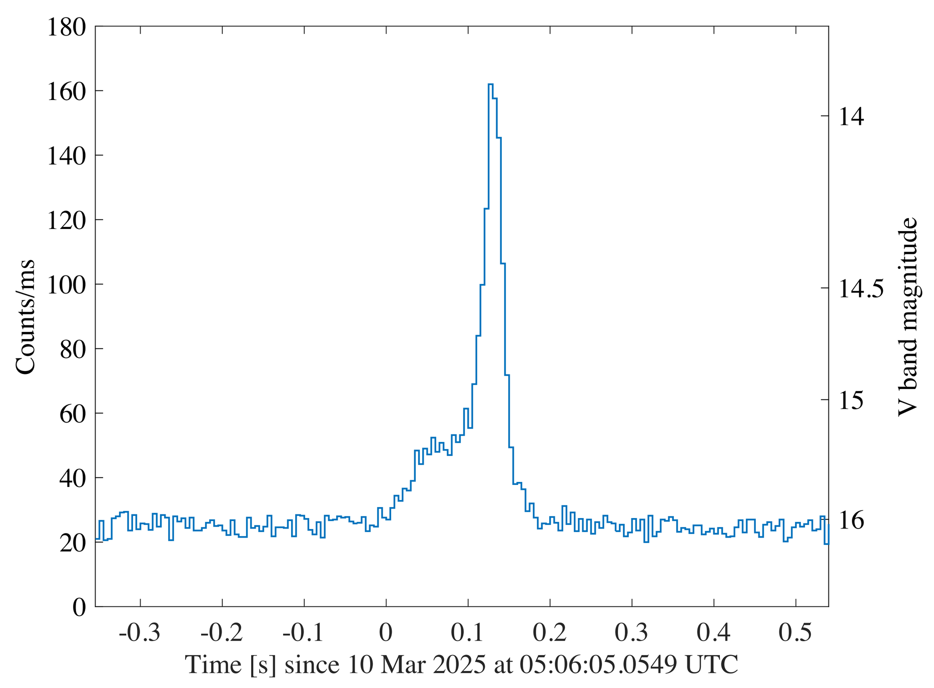
Detection of satellite AMC-3, GEO, 2.6 m x 1.8 m, Box + 2 Pan



Detection of satellite YAOGAN-30M, lower LEO, 0.5 m x 0.5 m, Box + 2 Pan



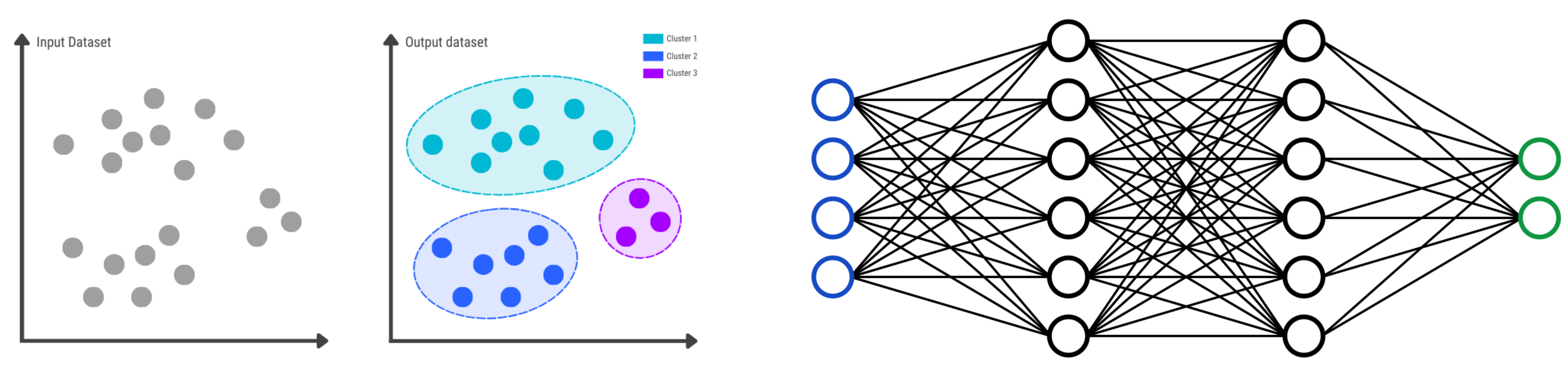
Detection of satellite COSMOS-1752, LEO, 0.8 m x 0.8 m, Poly



Detection of debris DELTA-2 R/B, MEO, 6.0 m x 2.4 m, Cyl

4. Next Steps

- ***A posteriori* analysis** of previous campaigns to verify the correspondence of optical signals with artificial transits
- **Signal classification** using unsupervised (**clustering, anomaly detection**) and supervised (**neural networks**) ML models, leveraging **physical** and **morphological properties**



- Development of a **simulator to study hardware and software solutions** to improve debris detection campaigns

5. Conclusions

Demonstrated the capability for **ultra-fast temporal measurements of space debris**, detecting objects **down to ~10 cm class (CubeSats)**, even **at low orbits**, where the uncertainty grows, thanks to a **optimized target selection** based on trajectory accuracy metrics.

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