Methods for Orbiting Objects Characterization and Space Traffic Management

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Agenda

- Introduction
  - Objectives and applications
  - Photometric measurements
- Methodology
  - Previous considerations
  - Proposed Bayesian inference method
- Results
- Conclusions and future work
- Achievements

Introduction

Objectives and applications

- **Resident Space Objects (RSOs) characterisation**
  - New Space era ⟶ increasing space traffic
  - Mitigate the proliferation of space debris
  - Holistic characterisation of RSOs
  - Estimate attitude, size, shape, optical properties, etc.
  - Use ground-based sensors (telescopes, radars) for observations

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- **Applications in the context of Space Surveillance and Tracking (SST)**
  - Mission analysis and design, e.g. Active Debris Removal (ADR)
  - Improve atmospheric re-entry predictions
  - Refine collision probability computations
  - Verify contingency attitude modes

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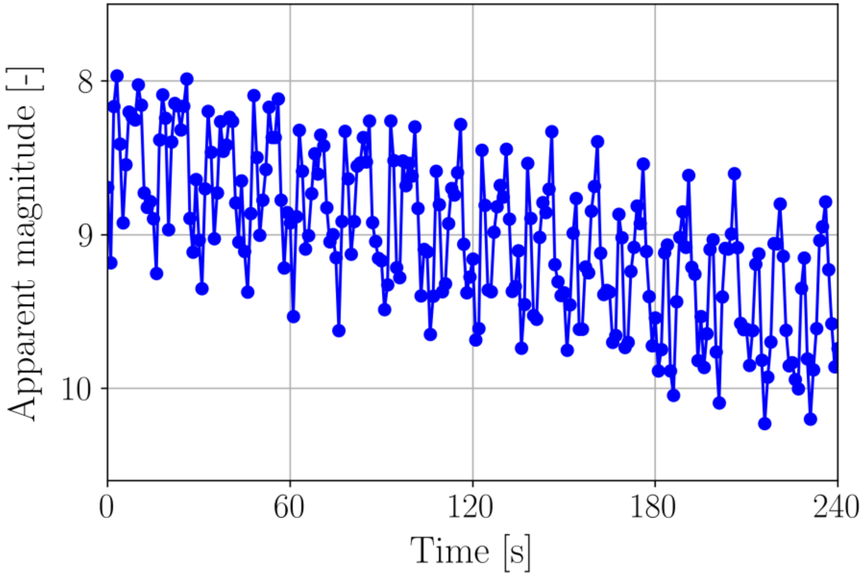
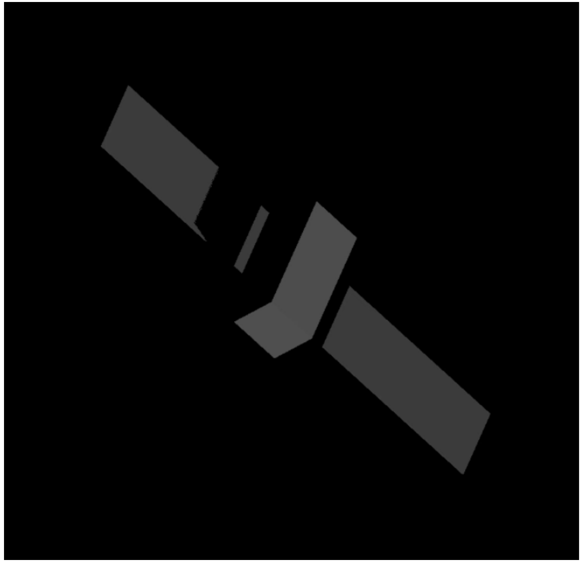
Photometric measurements

- **Light curves**
  - Photometric measurements obtained with ground-based telescopes
  - Apparent magnitude: $m = -2.5 \log\left(\frac{I_o}{I_{ref}}\right)$





Methodology

Previous considerations

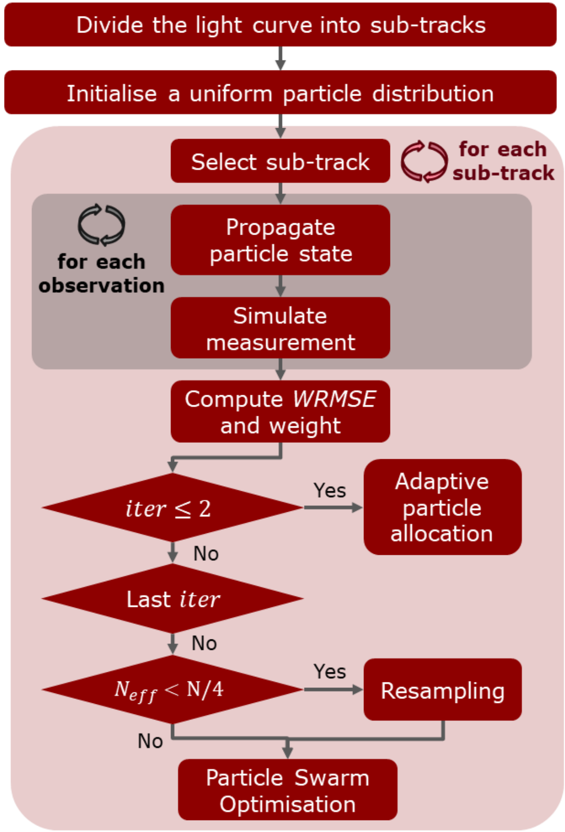
- **Typical assumptions in light curve inversion for attitude estimation**
  - Knowledge of the RSO’s shape, size and surface optical properties
  - Knowledge of the Aerosol Optical Depth (AOD)
- **Challenges of the light curve inversion problem**
  - Ambiguities in measurements
  - Nonlinear measurement model
- **GMV’s previous experience**
  - Least Squared Method (LSM)
  - Unscented Kalman Filter (UKF)
    - Reliance on an initial estimate
    - Tendency to converge to local minima

Proposed Bayesian inference method

- Based on **Adaptive Importance Sampling (AIS)**
  - Approximate the unknown target PDF by drawing samples from a proposal distribution.
  - Iteratively refine the proposal density to match the target distribution based on the weights of the samples
- **Batch processing of real measurements (sub-tracks)**
  - Update particle weights according to the WRMSE

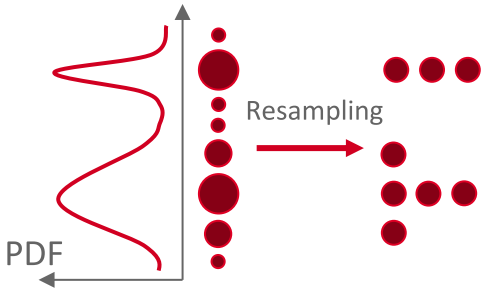
$$w(\boldsymbol{x}_i) = \ell\left(\{z_j\}_{j=1}^{M} \middle| \boldsymbol{x}_i\right) = \exp\left(-WRMSE_i^2\right)$$

  - Advantage: reduce the occurrence of local optima
- **Adaptive particle allocation**
  - Move particles with higher WRMSE to regions of higher probability
  - Advantage: refine the initial proposal distribution



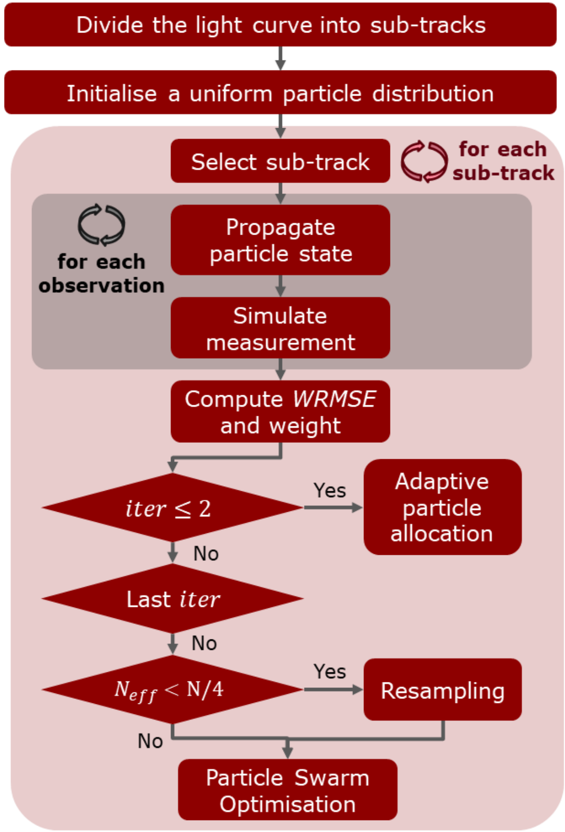
Proposed Bayesian inference method

- Particle update based on combination of two methods:
  - **Resampling**
    - Prevent particle degeneracy
    - Robust and faster convergence (in combination with PSO)



  - **Particle Swarm Optimisation (PSO)**
    - Estimate the target PDF implicitly, avoiding the computational expense of explicitly computing it at each iteration.
    - More efficient solution than conventional methods employed in particle filters to enhance particle diversity, e.g. adding artificial noise, thus allowing a faster convergence.

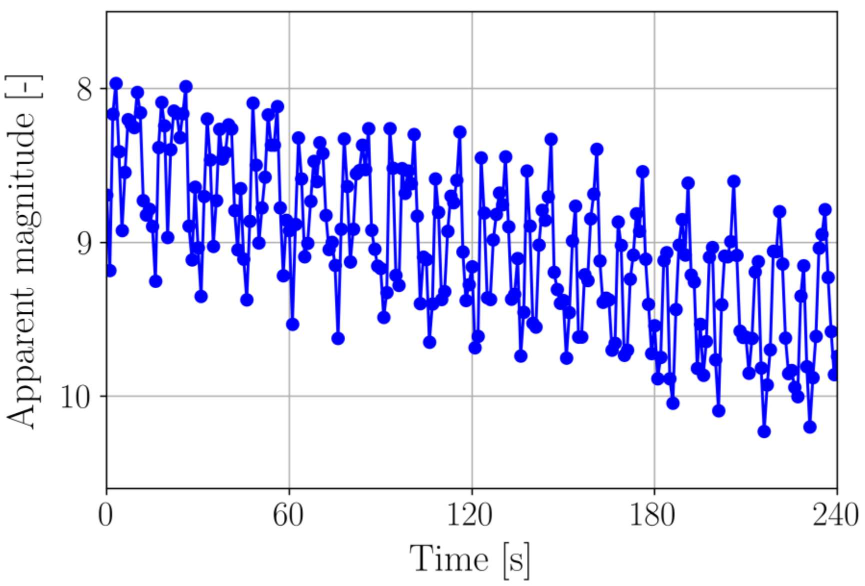
$$\boldsymbol{v}_k^i = w\boldsymbol{v}_{k-1}^i + c_1 r_1(\boldsymbol{x}_{pbest}^i - \boldsymbol{x}_k^i) + c_2 r_2(\boldsymbol{x}_{gbest} - \boldsymbol{x}_k^i)$$
$$\boldsymbol{x}_k^i = \boldsymbol{x}_{k-1}^i + \boldsymbol{v}_k^i$$

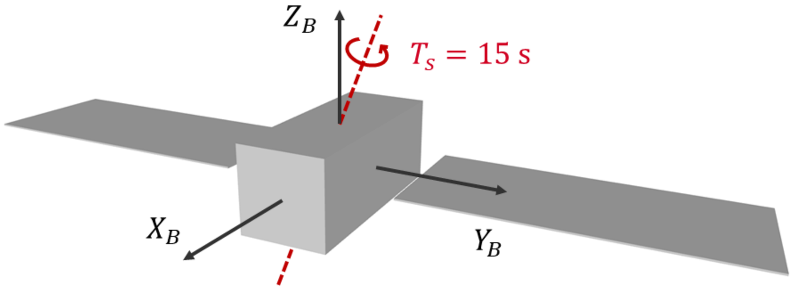


Results

Results

- Test case
  - **Spinning attitude law parameters**: platform and spin rotation axis orientation, and spin angular velocity
  - **Assumptions:** known geometry, optical properties and Aerosol Optical Depth (AOD), and $T_{inertial} = T_{apparent}$





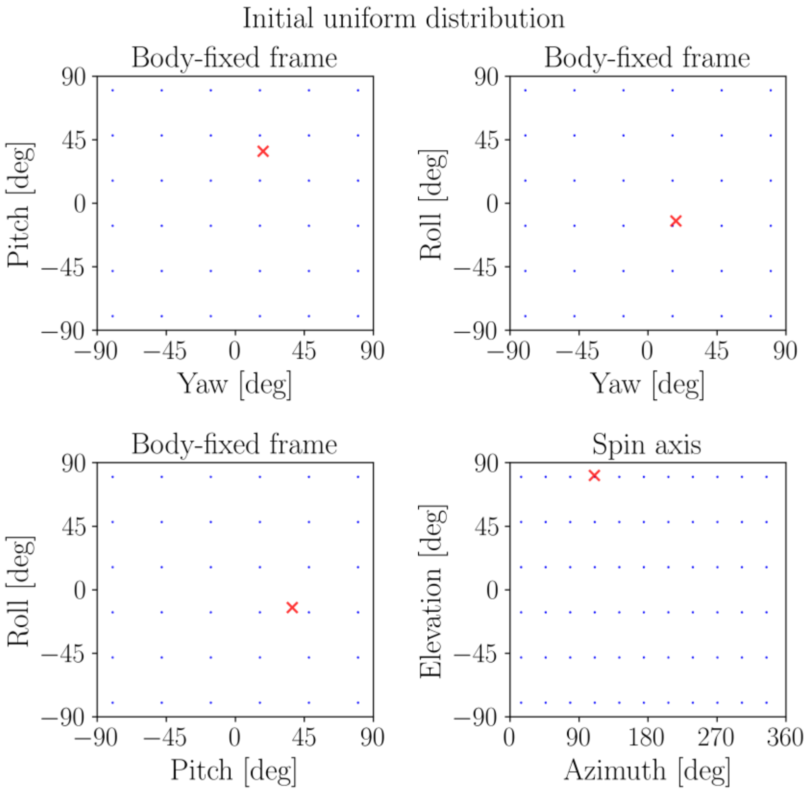
Sensor noise: $\sigma = 0.1$

Attitude: $\boldsymbol{x}_{ref} = [18,\ 37,\ -12.5,\ 110,\ 81]$ deg

platform (18, 37, −12.5) — spin axis (110, 81)

Results

- **Filter execution**



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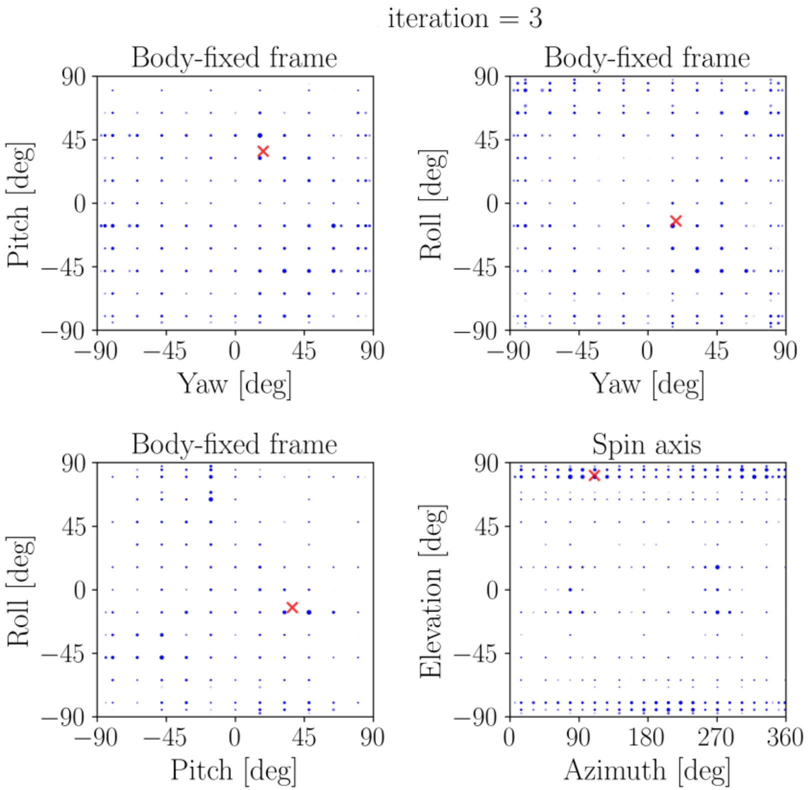

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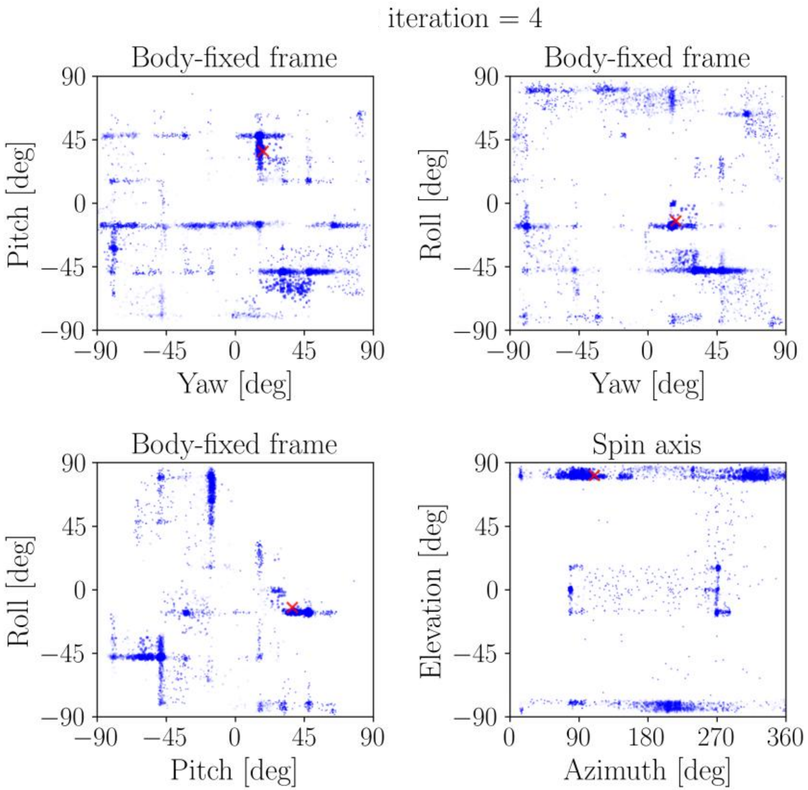

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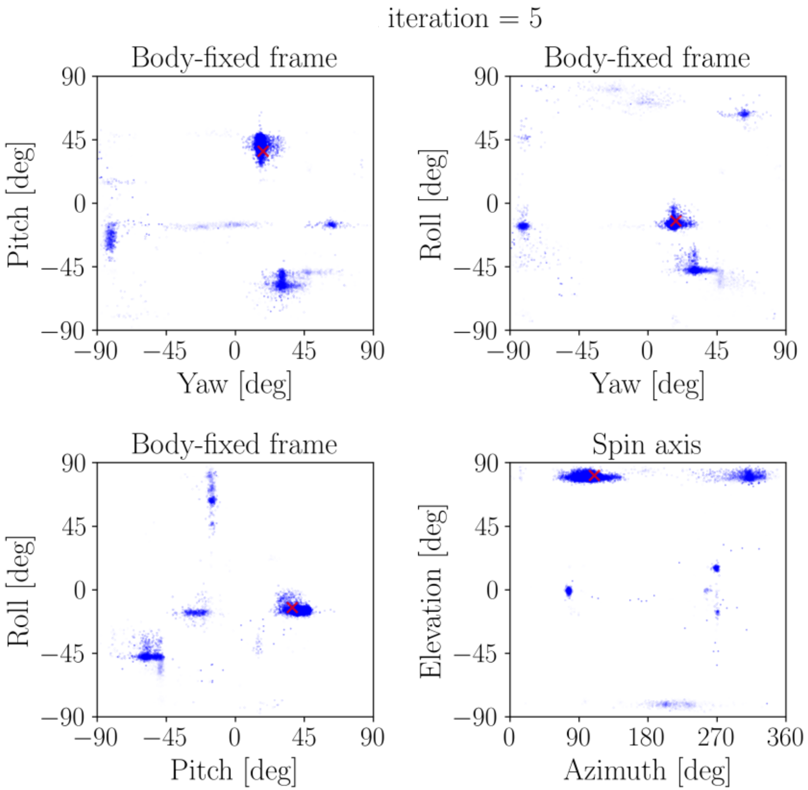

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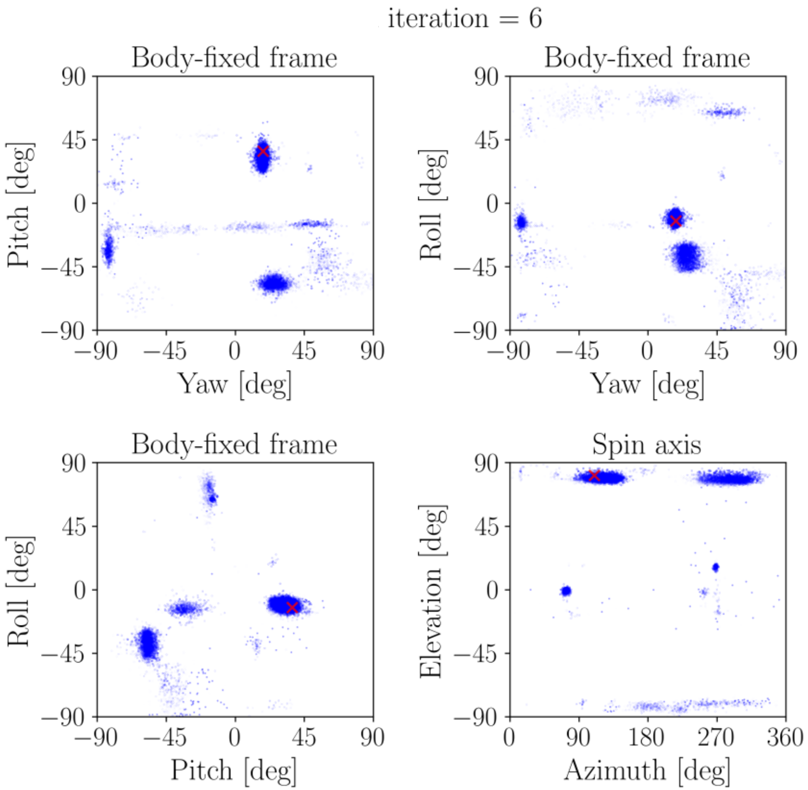

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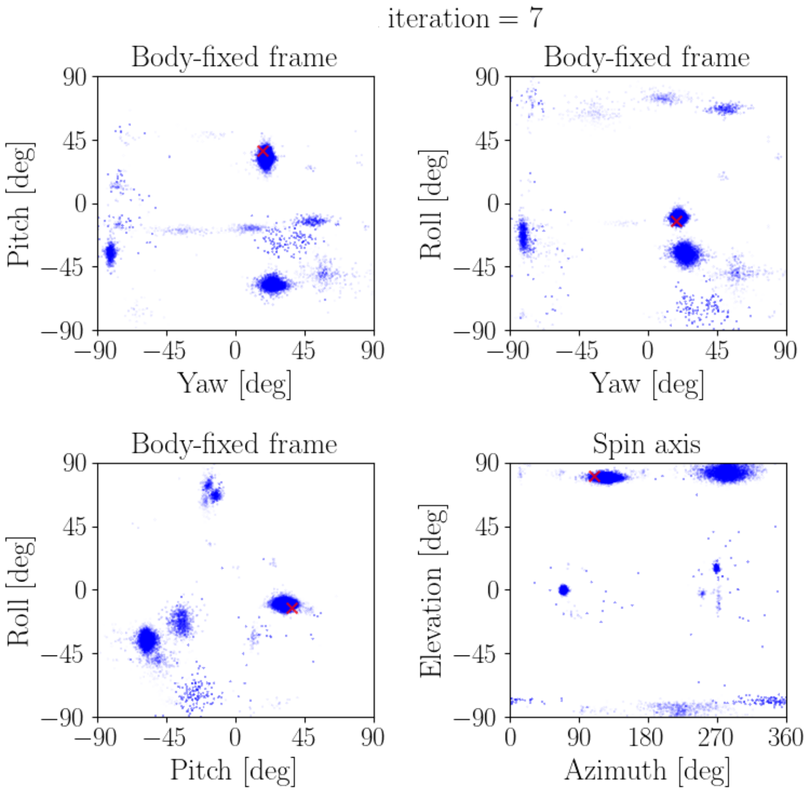

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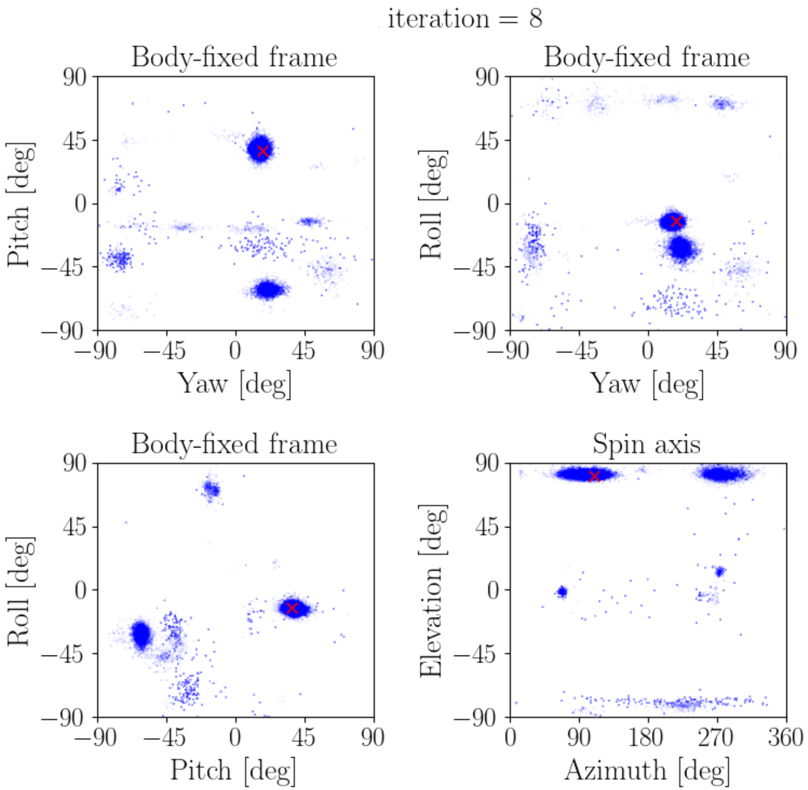

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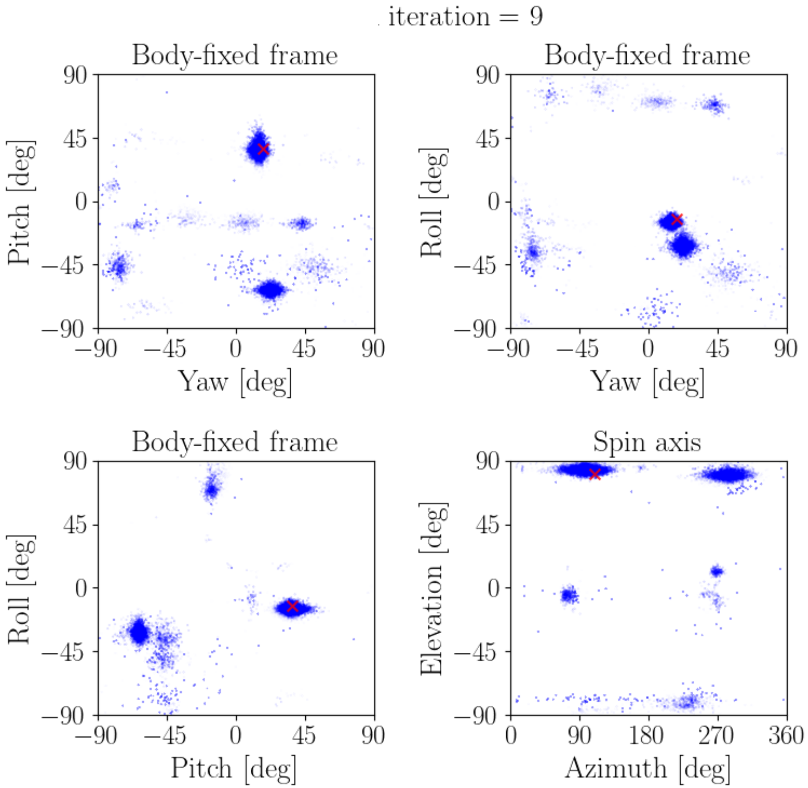

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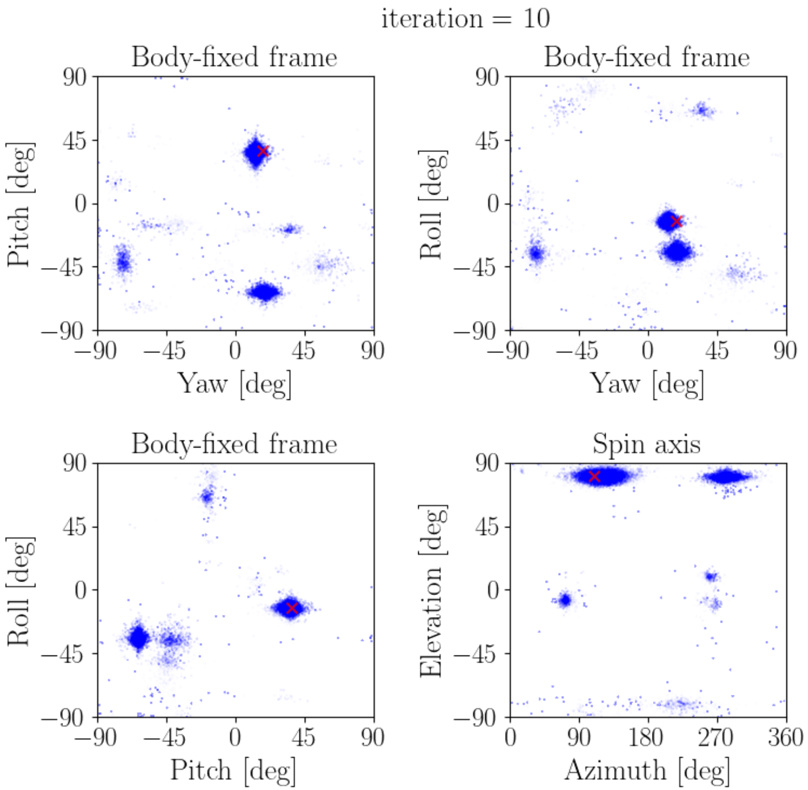

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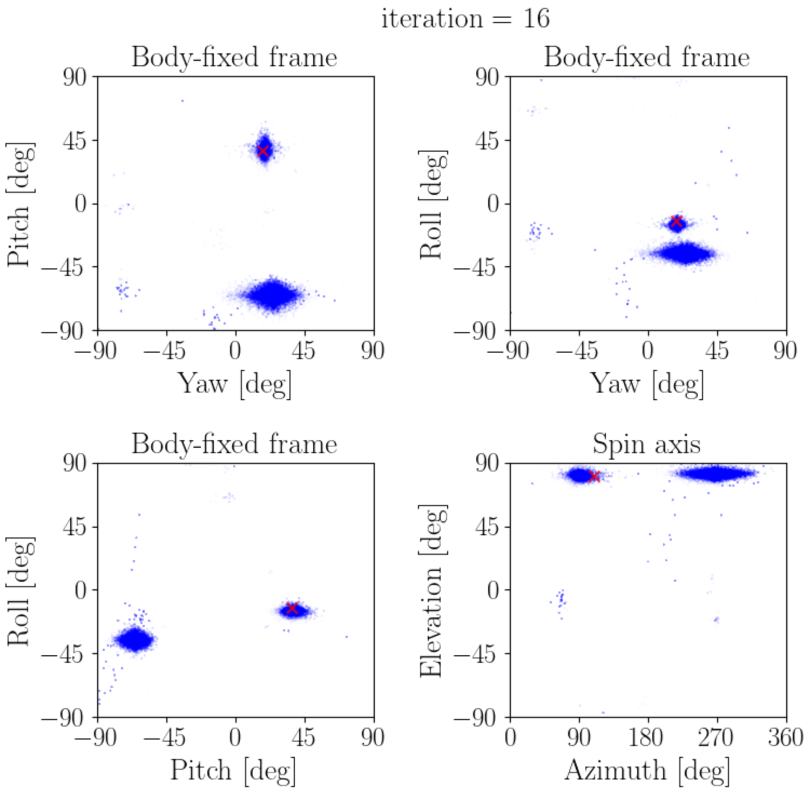


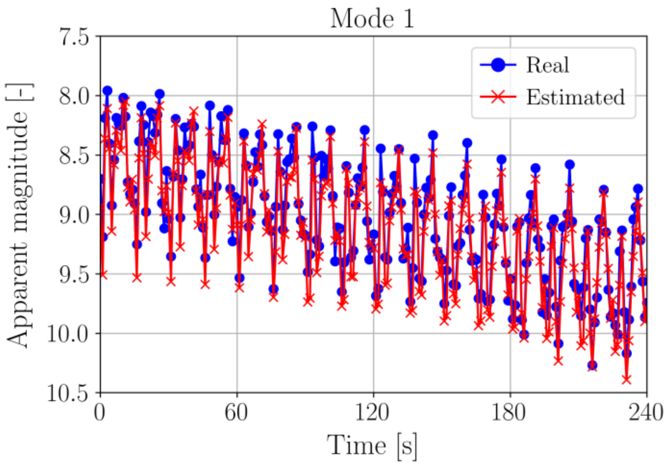
Results

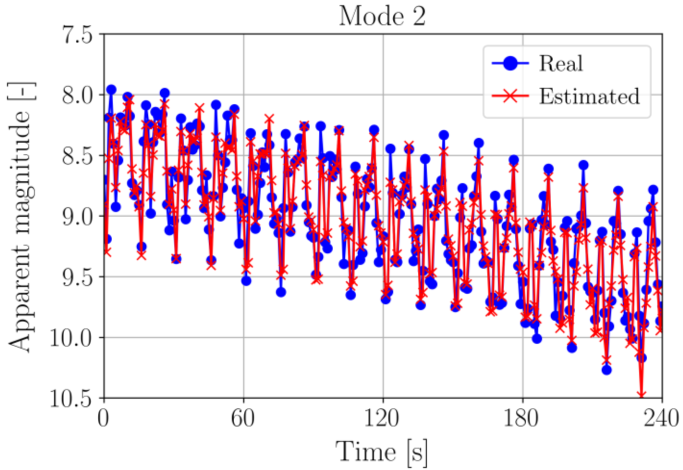
■ **Post-processing of the posterior PDF**

- Cluster analysis to identify the modes of the posterior PDF
- Density-Based Spatial Clustering of Applications with Noise (DBSCAN)
- Analysis of PDF modes to identify the most probable attitude

	Mode 1	Mode 2
Yaw [deg]	18.89 ± 2.33	24.90 ± 4.95
Pitch [deg]	38.83 ± 3.54	-64.95 ± 3.27
Roll [deg]	-14.86 ± 1.84	-35.71 ± 2.33
Azimuth [deg]	93.93 ± 8.85	269.63 ± 12.93
Elevation [deg]	81.05 ± 1.87	82.12 ± 1.59

$$x_{ref} = [18,\ 37,\ -12.5,\ 110,\ 81]\,\text{deg}$$





Conclusions and future work

Conclusions and future work

- **Conclusions**

  - Understand the challenges of light curve inversion for attitude estimation
  - Identify the limitations of traditional estimation methods (LSM, UKF, sequential particle filters, etc.)
  - Develop a robust, accurate and computationally efficient Bayesian inference method

- **Future work**

  - Improve the accuracy of the estimation
  - Estimate the RSO’s optical properties and the AOD together with the attitude
  - Analyse three-axis stabilised satellites (higher measurement ambiguity)
  - Extend analyses using real light curves

Achievements

Achievements

- **Conference papers and presentations**
  - J. Rubio et al., “*Attitude Estimation of Inactive Resident Space Objects from Photometric Measurements Using Particle Filtering*”, ESA’s Clean Space Days 2024, ESTEC, Noordwijk, The Netherlands, October 2024.
  - J. Rubio, F. Biondi, D. Escobar, and P. Di Lizia, “*Fair Shared Collision Avoidance Manoeuvre for Active vs Active Conjunctions*”, 75th International Astronautical Congress (IAC), Milan, Italy, October 2024.
  - J. Rubio et al., “An Accurate and Efficient Particle Filtering Method for Attitude Estimation Using Photometric Measurements”, 9th European Conference on Space Debris, Bonn, Germany, April 2025.
  - J. Rubio et al., “A High-Performance and Robust Light Curve Inversion Method for Attitude Monitoring of Three-Axis Stabilised Satellites”, Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS), Maui, HI, USA, September 2025. (Abstract accepted).
- **Journal papers**
  - J. Rubio et al., “Attitude Estimation of Uncontrolled Space Objects: A Bayesian-Informed Swarm Intelligence Approach”, Advances in Space Research, under revision.

Thank you

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