Characterisation of Attitude and Physical Properties of Resident Space Objects for Space Situational Awareness

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PhD Aerospace Engineering UC3M
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- **Resident Space Objects characterisation**
  - ✓ The New Space era ⟶ increasing space traffic
  - ✓ Mitigation of the proliferation of space debris
  - ✓ Holistic characterisation of RSOs
  - ✓ Estimation of attitude, size, shape, optical properties, etc.
  - ✓ Use of ground-based sensors (telescopes, radars) for observations

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- **Applications within Space Surveillance and Tracking (SST)**
  - ✓ Mission analysis and design: Active Debris Removal (ADR), In-Orbit Servicing (IOS)
  - ✓ Improved atmospheric re-entry predictions
  - ✓ Improved collision risk assessments (probability of collision)
  - ✓ Detection of anomalies in operational satellites
  - ✓ Verification of contingency attitude modes

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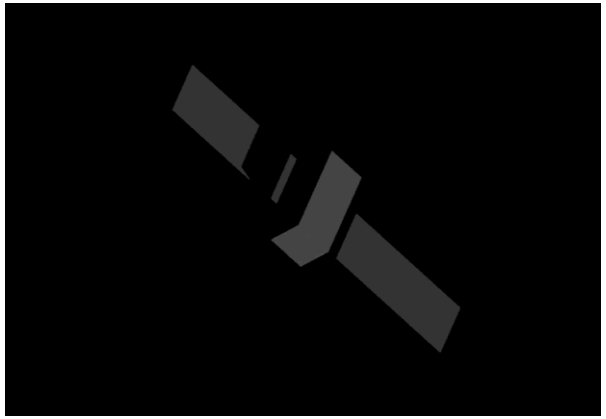
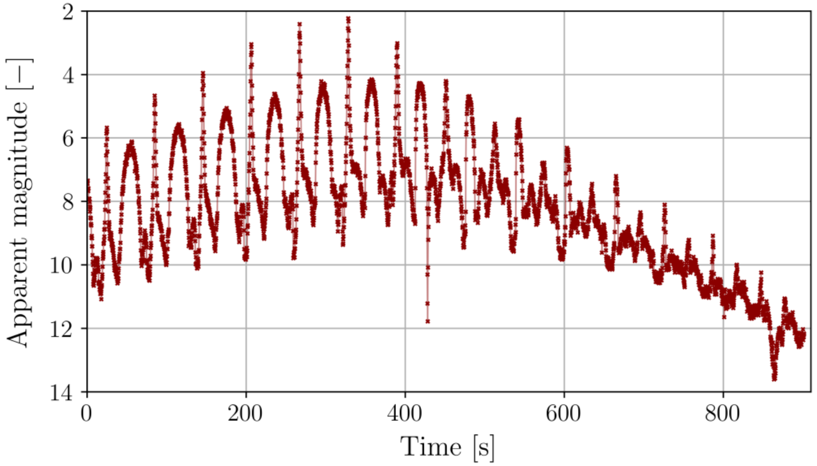
Introduction

- **Light curves**
  - ✓ Temporal variation of photometric intensity measurements
  - ✓ Apparent magnitude:

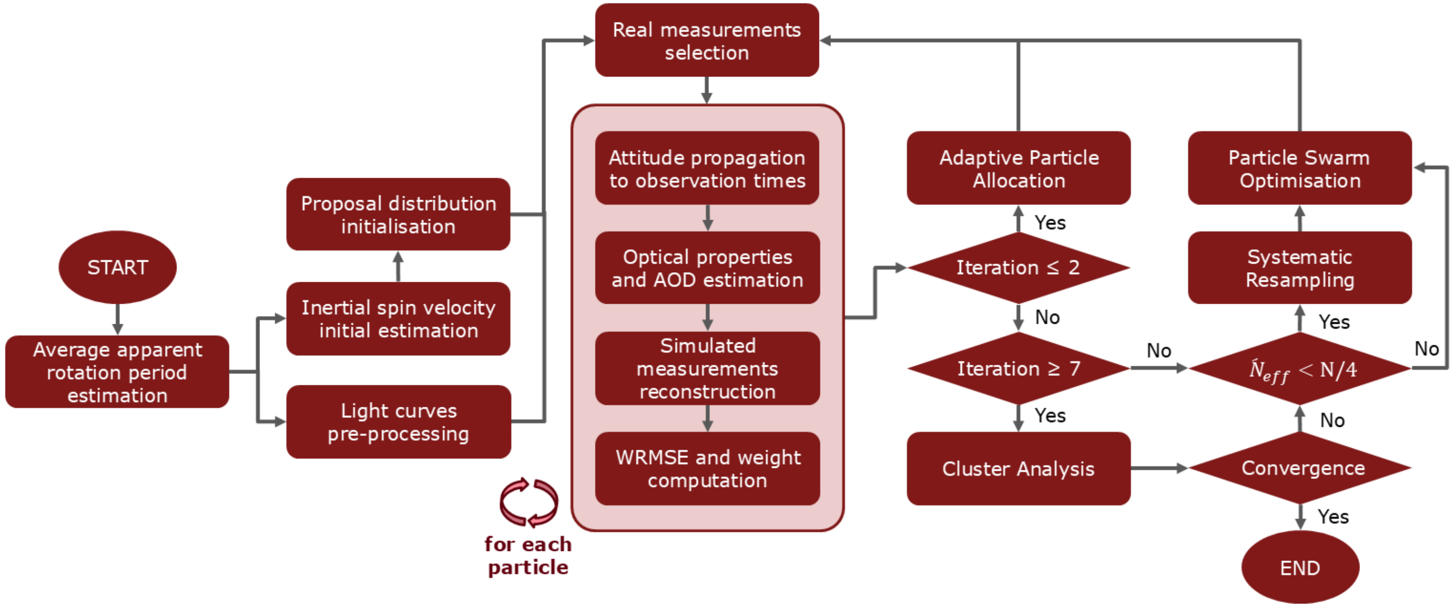
$$m = -2.5 \log\left(\frac{I_o}{I_{ref}}\right) + T_{atm} \qquad T_{atm} = T_{Ray} + T_{O_3} + T_{AOD}$$



- **Research objectives**
  - ✓ Uncontrolled, spin-stabilised space objects with known geometry
  - ✓ Orientation at a reference epoch (yaw, pitch, roll)
  - ✓ Spin velocity: inertial rotation axis (RA, DEC) and period
  - ✓ Solar array orientation
  - ✓ Diffuse reflection coefficients ($k_{d,\Gamma}$)
  - ✓ Aerosol Optical Depth (AOD)



- **Adaptive Importance Sampling (AIS) principles**
  - ✓ Approximation of the unknown target PDF by drawing samples from a proposal distribution
  - ✓ A weighting function quantifies the contribution of each sample in approximating the target distribution
  - ✓ Iterative refinement of the proposal density to match the target distribution

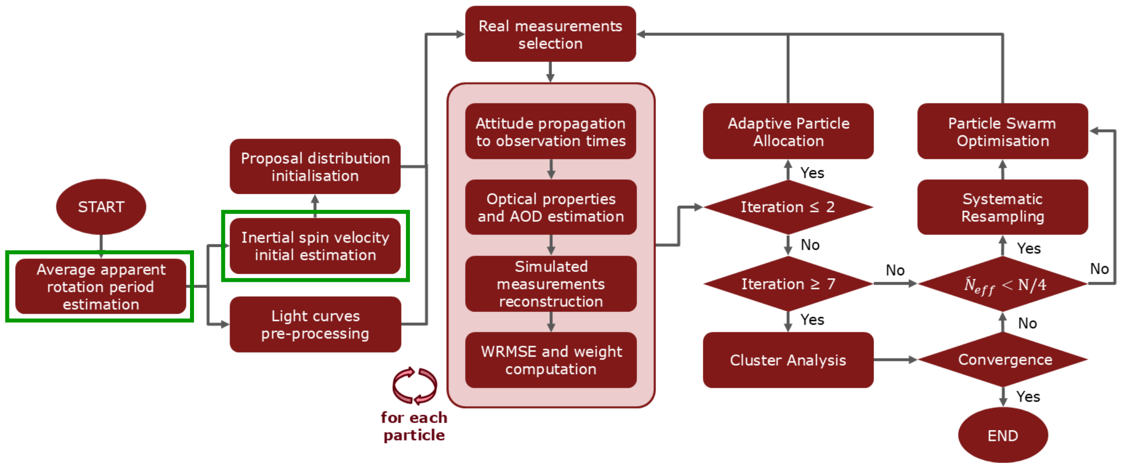


AISwarm-LS method

- **Average apparent rotation period estimation**
  - ✓ Light curve normalisation (range, phase angle, and atmospheric effects)
  - ✓ Generalised Lomb-Scargle (GLS) peridogram

$$y(t_i, f) = \sum_{j=1}^{n_h} \left[a_j \cos(2\pi j f t_i) + b_j \sin(2\pi j f t_i)\right] + \sum_{k=0}^{n_p} c_k t_i^k$$

  - ✓ Applied to the full light curve
- **Initial estimation of the inertial spin velocity**
  - ✓ Observed irradiance is proportional to the illuminated projected area, which is symmetric with respect to the Phase Angle Bisector (PAB)
  - ✓ The light curve pattern repeats when the object returns to the same orientation relative to the PAB
  - ✓ LSM using the Levenberg-Marquardt algorithm



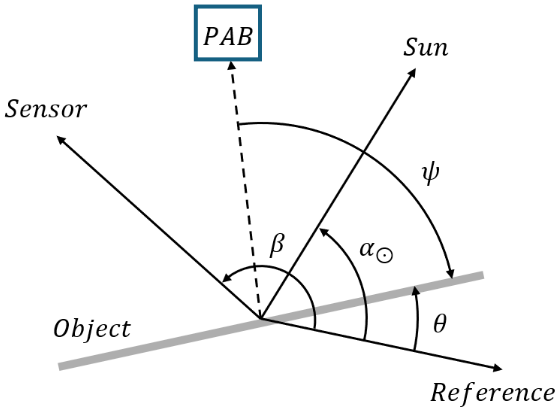
Apparent angular velocity (sliding-window GLS)

Line-Of-Sight angular velocity (known)

$$\omega_{in} = \omega_{app} + \frac{1}{2}\boldsymbol{\omega}_{LOS} \cdot \hat{\boldsymbol{s}}$$

Inertial spin velocity

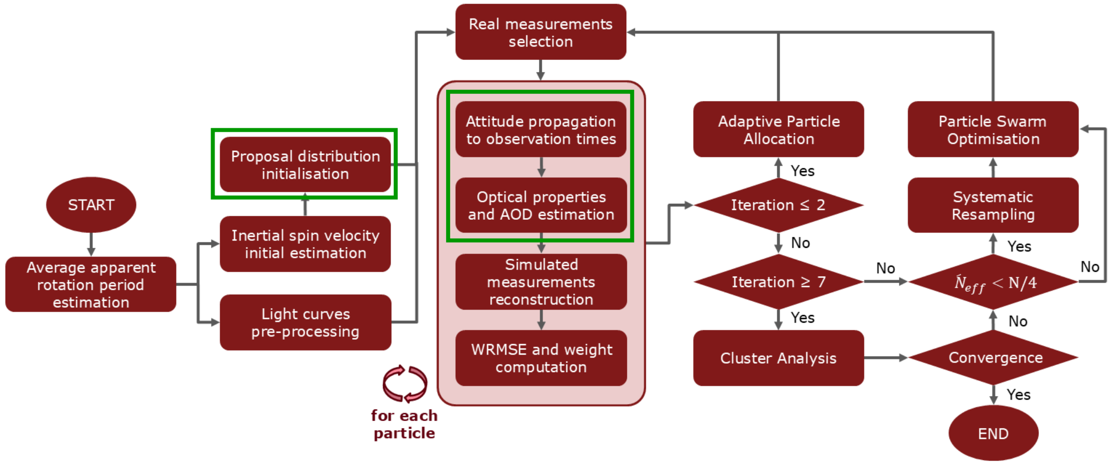
Spin axis (RA, DEC)



AISwarm-LS method

- **Proposal distribution initialisation**
  - ✓ Particle parameters (attitude and solar array)
  - ✓ Uniform distribution (no prior information)
  - ✓ Gaussian distribution (initial estimate)
- **Attitude propagation to observation times**

$$q_B^I(t) = \left[\cos\left(\frac{\omega_{B/I}}{2}t\right)\boldsymbol{I} + \frac{1}{\omega_{B/I}}\sin\left(\frac{\omega_{B/I}}{2}t\right)\boldsymbol{\Omega}\right]q_{B,0}^I$$



- **Optical properties and AOD estimation**
  - ✓ Computationally efficient method (applied to each particle)
  - ✓ Availability of an analytical formulation for $k_{d,\Gamma}$ and AOD
  - ✓ LSM solved with the Levenberg-Marquardt algorithm

$$m = -2.5\log\left(\sum_{\Gamma} C_\Gamma \boxed{k_{d,\Gamma}} + \frac{I_{o,array}}{I_{ref}}\right) + \frac{2.5 m_{air}}{\ln 10}\boxed{AOD} + T_{Ray} + T_{O_3}$$

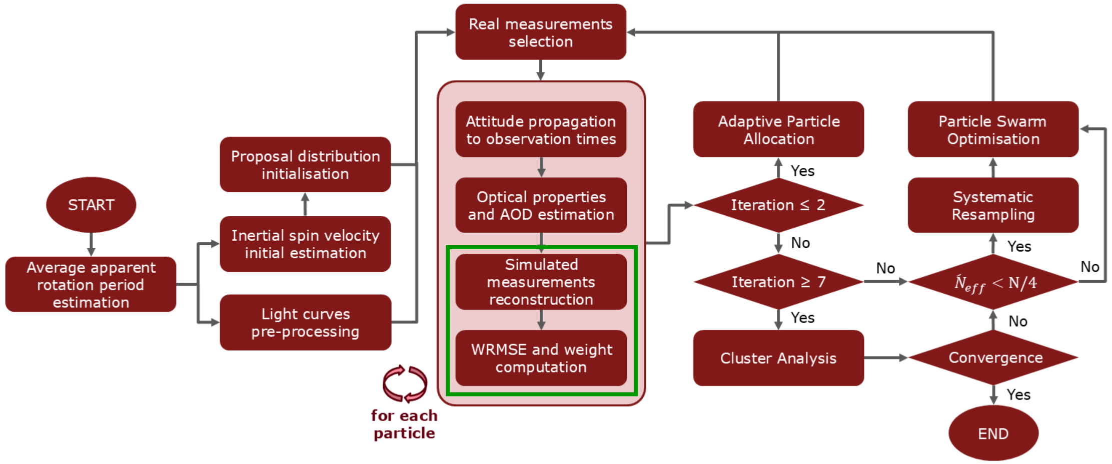
$$C_\Gamma = \frac{I_i}{2\pi r^2 I_{ref}} \underbrace{\sum_{\gamma\in\Gamma} A_\gamma \frac{(\boldsymbol{l}\cdot\boldsymbol{n})_\gamma(\boldsymbol{v}\cdot\boldsymbol{n})_\gamma}{(\boldsymbol{l}\cdot\boldsymbol{n}+\boldsymbol{v}\cdot\boldsymbol{n})_\gamma}}_{\text{Observation geometry}}$$

AISwarm-LS method

- **Simulated measurements reconstruction**
  - ✓ Using the estimated optical and atmospheric parameters
- **Computation of particle WRMSE and weight**
  - ✓ Weights derived by mapping each particle's WRMSE to a probability via a softmax function

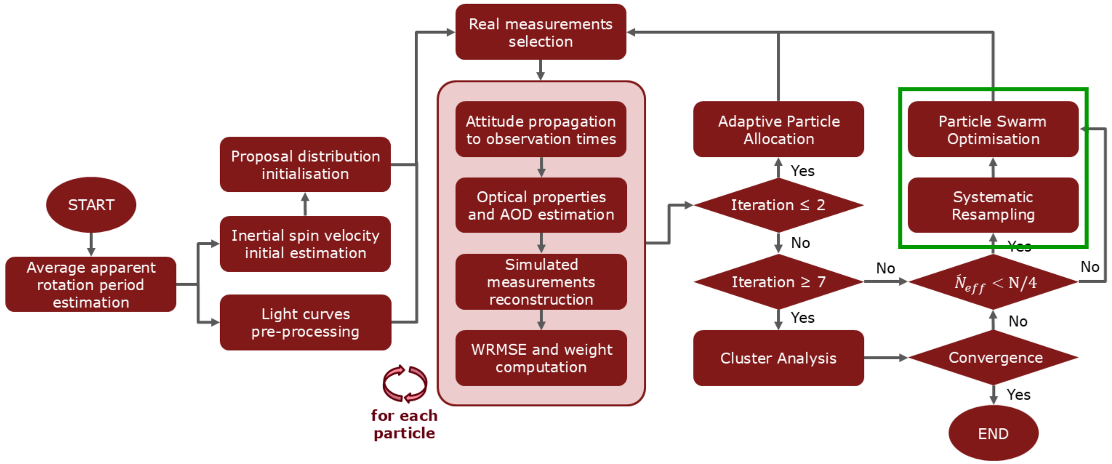
$$\bar{w}_i = \frac{\exp\left(-WRMSE_i^2\right)^{1/T}}{\sum_{i=1}^{N} \exp\left(-WRMSE_i^2\right)^{1/T}}$$

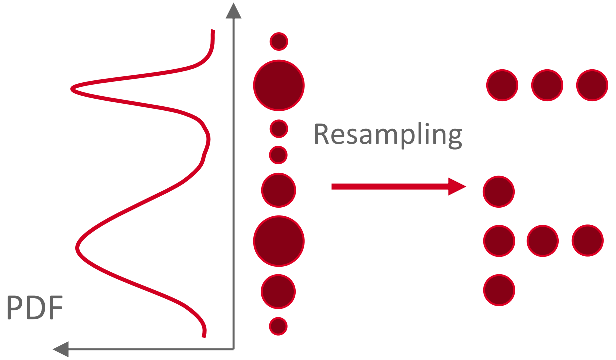
  - ✓ Simulated Annealing (temperature schedule):
    - Flattening of the weight distribution in early stages
  - ✓ - Reduction of the risk of premature convergence to local optima



AISwarm-LS method

- **Systematic Resampling**
  - ✓ Implicit estimation of the target probability distribution (combined with PSO)
  - ✓ Prevents particle degeneracy
  - ✓ Accelerates convergence
- **Particle Swarm Optimisation (PSO)**
  - ✓ Improves particle diversity efficiently
  - ✓ Enables local exploration during early iterations
  - ✓ Accelerates convergence towards global optima as the process progresses





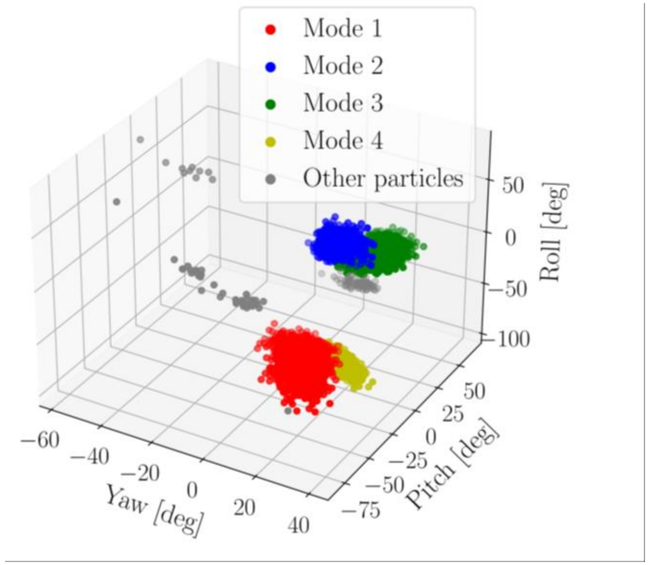
Inertia — Personal best — Global best

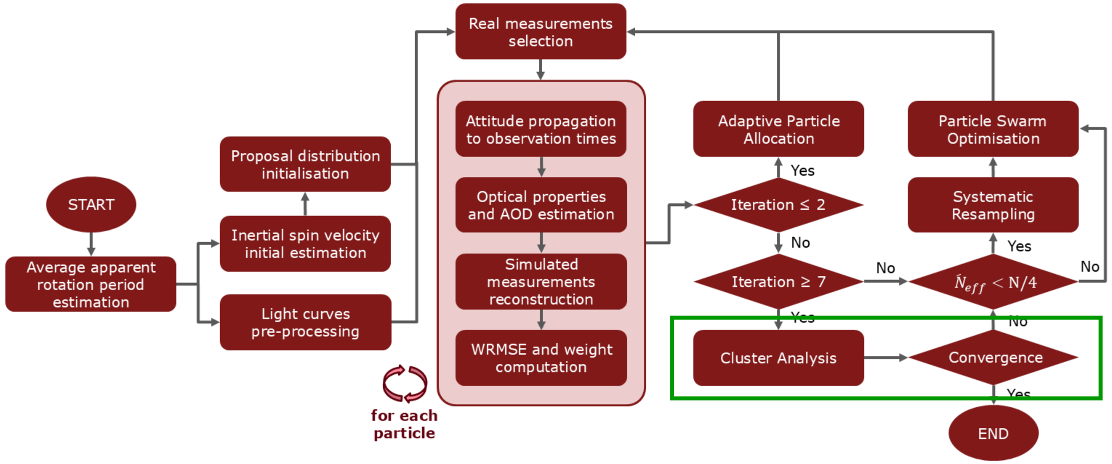
$$v_{i,j}^{k} = w v_{i,j}^{k-1} + c_1 r_1 \left(x_{i,j}^{pbest} - x_{i,j}^{k} \right) + c_2 r_2 \left(x_{j}^{gbest} - x_{i,j}^{k} \right)$$

$$x_{i,j}^{k} = x_{i,j}^{k-1} + v_{i,j}^{k}$$

AISwarm-LS method

- **Cluster Analysis**
  - ✓ Identification of modes in the posterior PDF
  - ✓ DBSCAN algorithm



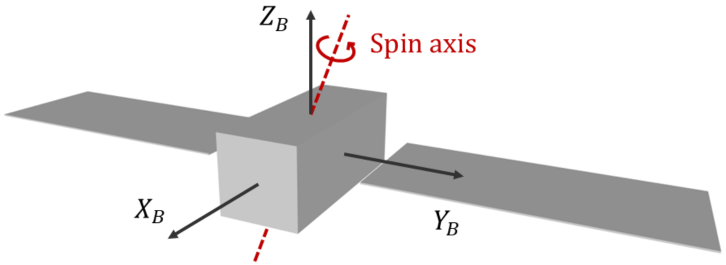


  - ✓ Posterior expected state and covariance

$$\hat{\boldsymbol{x}} = \sum_{i=1}^{N} \bar{w}_i \boldsymbol{x}_i \qquad \boldsymbol{\Sigma} = \sum_{i=1}^{N} \bar{w}_i (\boldsymbol{x}_i - \hat{\boldsymbol{x}})(\boldsymbol{x}_i - \hat{\boldsymbol{x}})^T$$

- **Convergence criteria**
  - ✓ Global: 80% of particles within any cluster
  - ✓ Local: WRMSE < 1.1 and Δ_{WRMSE} < 5%

- **Uncontrolled spin-stabilised satellite**
- **Satellite model**



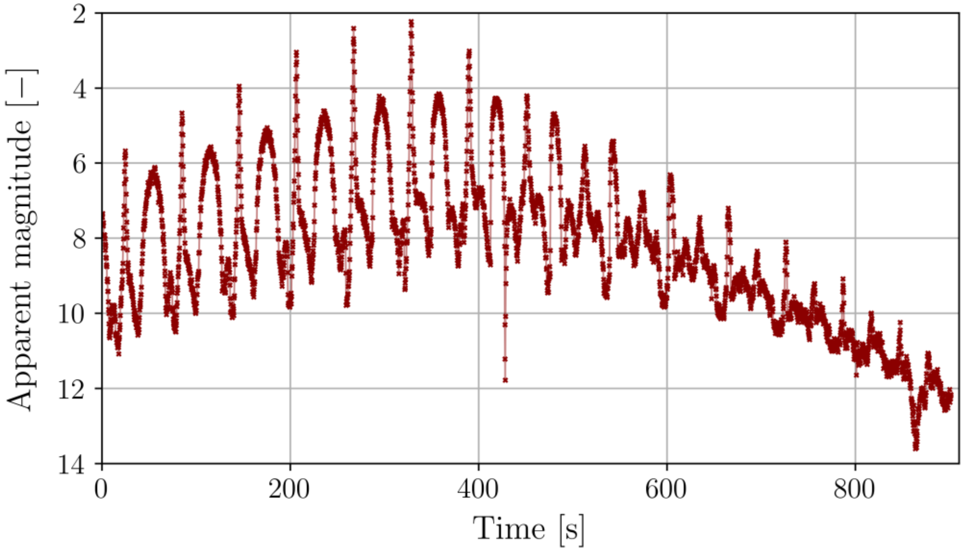
- **Other relevant parameters**
  - ✓ Satellite orbit:

    $e = 0.0, h = 1200 \text{ km}, i = 40 \text{ deg}, RAAN = 0 \text{ deg}$
  - ✓ Solar array: $k_s = 0.1$
  - ✓ Sensor noise: $\sigma_s = 0.1$

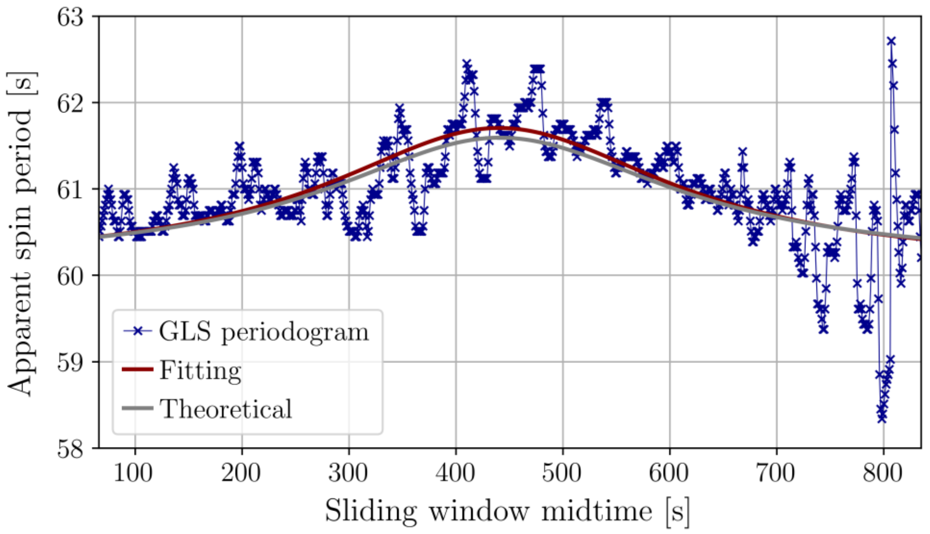
- **Reference parameters**

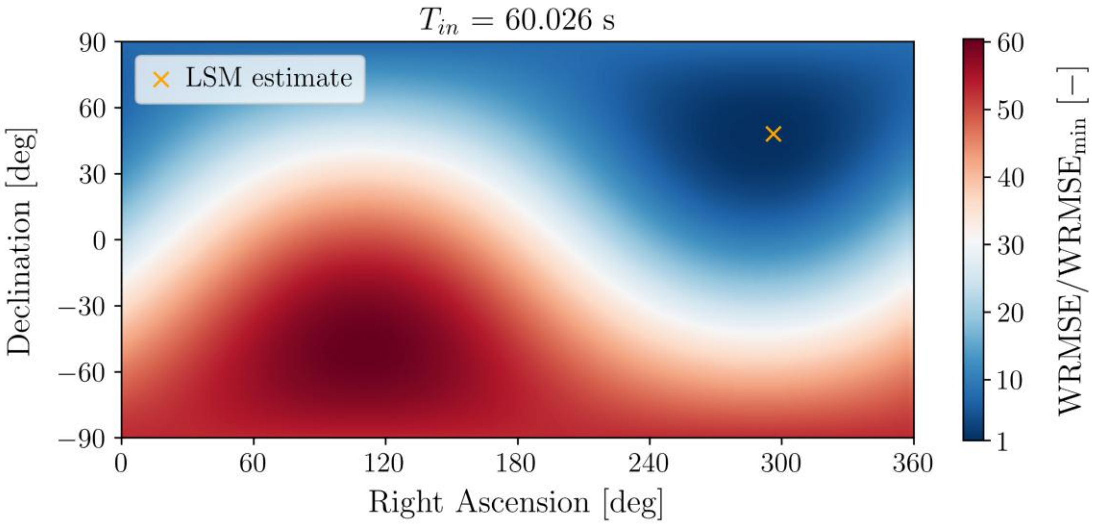
Attitude and solar array parameters	Yaw ψ [deg]	-21
	Pitch θ [deg]	37
	Roll ϕ [deg]	18.5
	Spin axis right ascension α [deg]	307
	Spin axis declination δ [deg]	55.5
	Inertial spin period T_{in} [s]	60
	Solar array β [deg]	80
Optical parameters	$k_{d,\pm X_B}$, $k_{d,SA}$ [−]	0.5
	$k_{d,\pm Y_B}$ [−]	0.15
	$k_{d,\pm Z_B}$ [−]	0.85
Atmospheric parameter	AOD [−]	0.25

- **Reference light curve**



- **Inertial spin velocity initial estimate**
  - ✓ Instantaneous apparent rotation period
  - ✓ Inertial spin velocity parameters





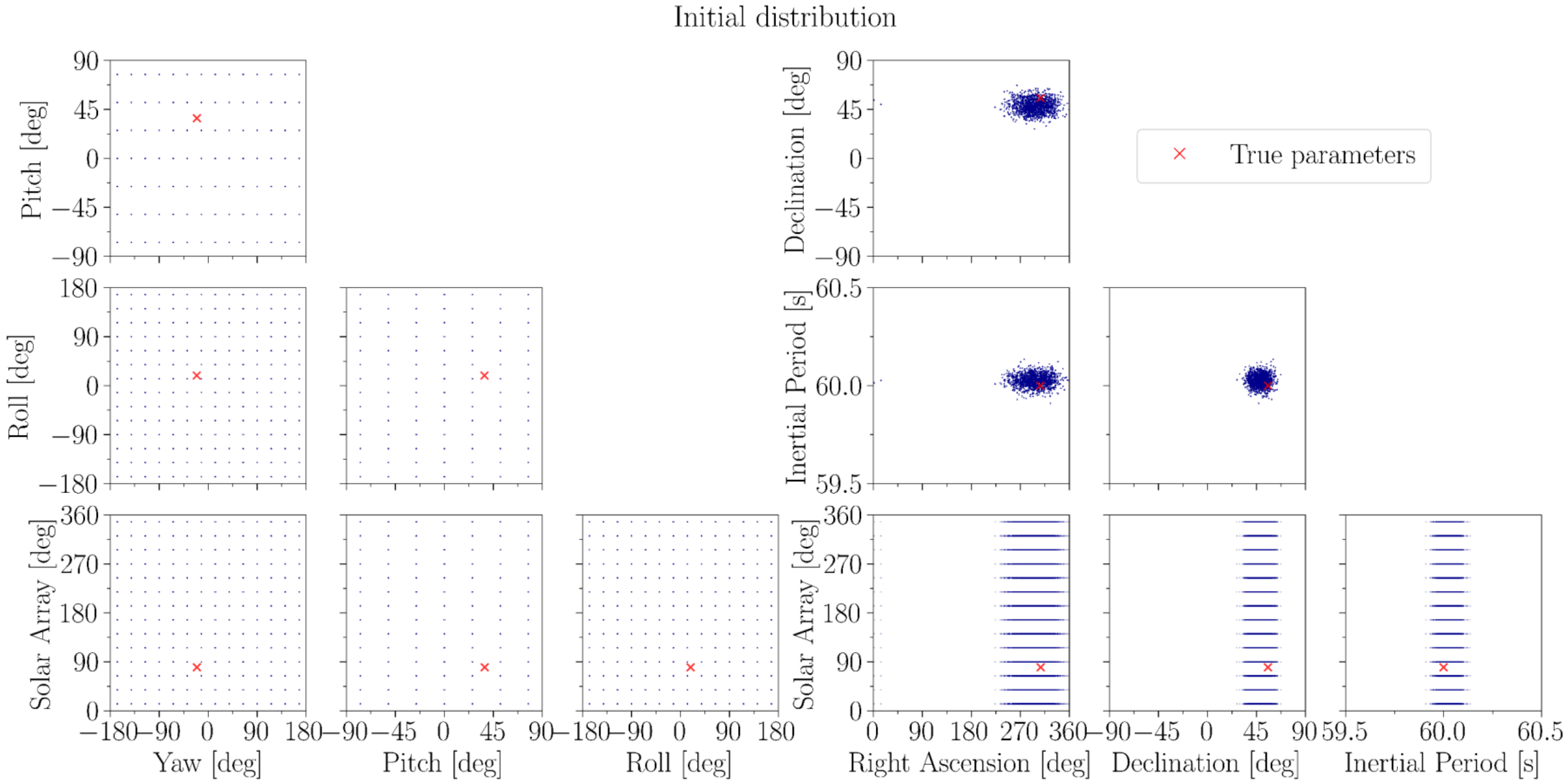
Fitting equation: $c_1 \omega_{LOS} + c_2$

$$\omega_{in} = \omega_{app} + \frac{1}{2} \boldsymbol{\omega}_{LOS} \cdot \hat{\boldsymbol{s}}$$

	Reference	LSM estimate
Spin axis right ascension α [deg]	307	296.074 ± 22.571
Spin axis declination δ [deg]	55.5	48.111 ± 6.293
Inertial spin period T_{in} [s]	60	60.026 ± 0.030

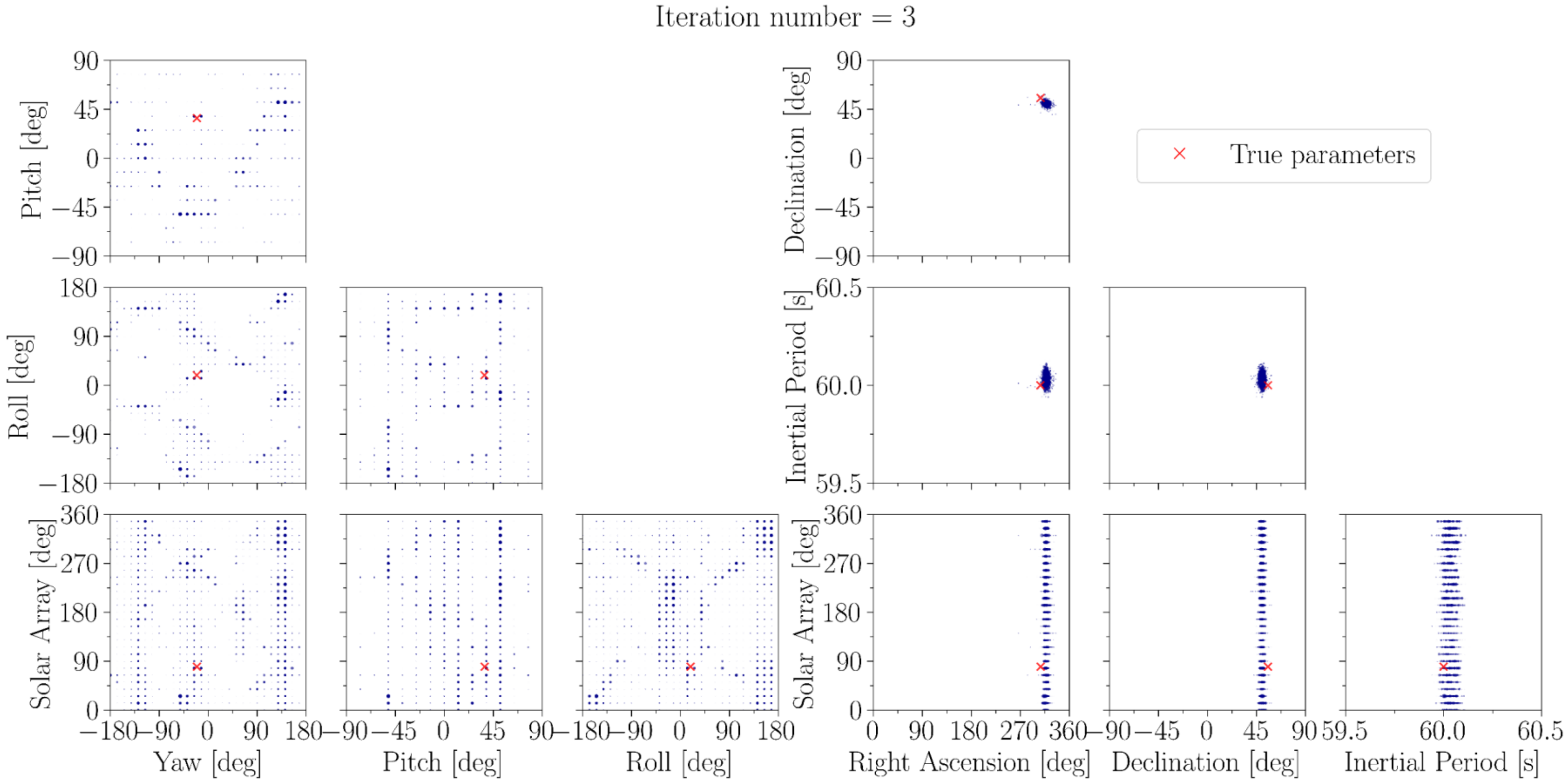
Results

- **AISwarm-LS execution (1/6)**

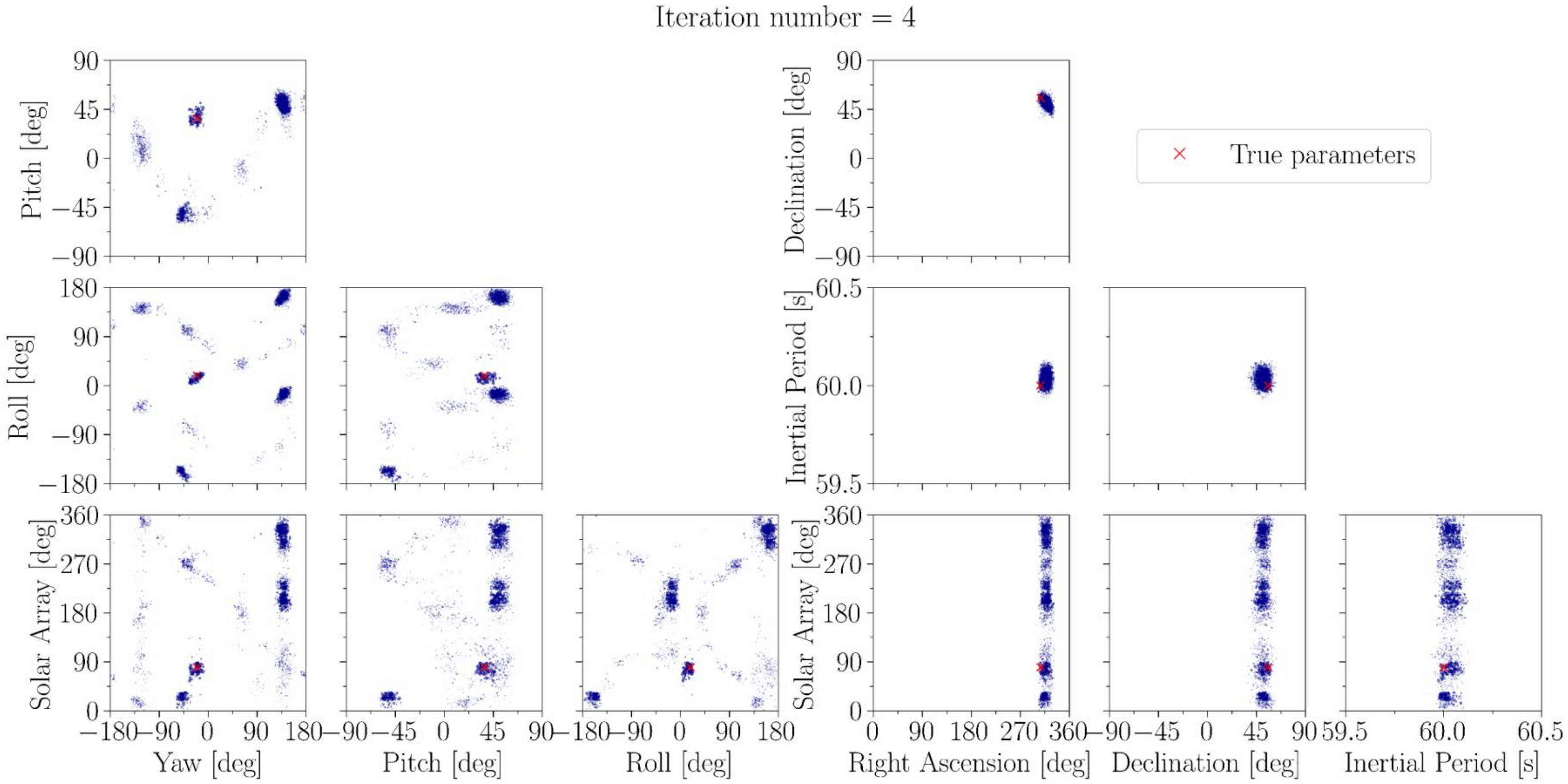


Results

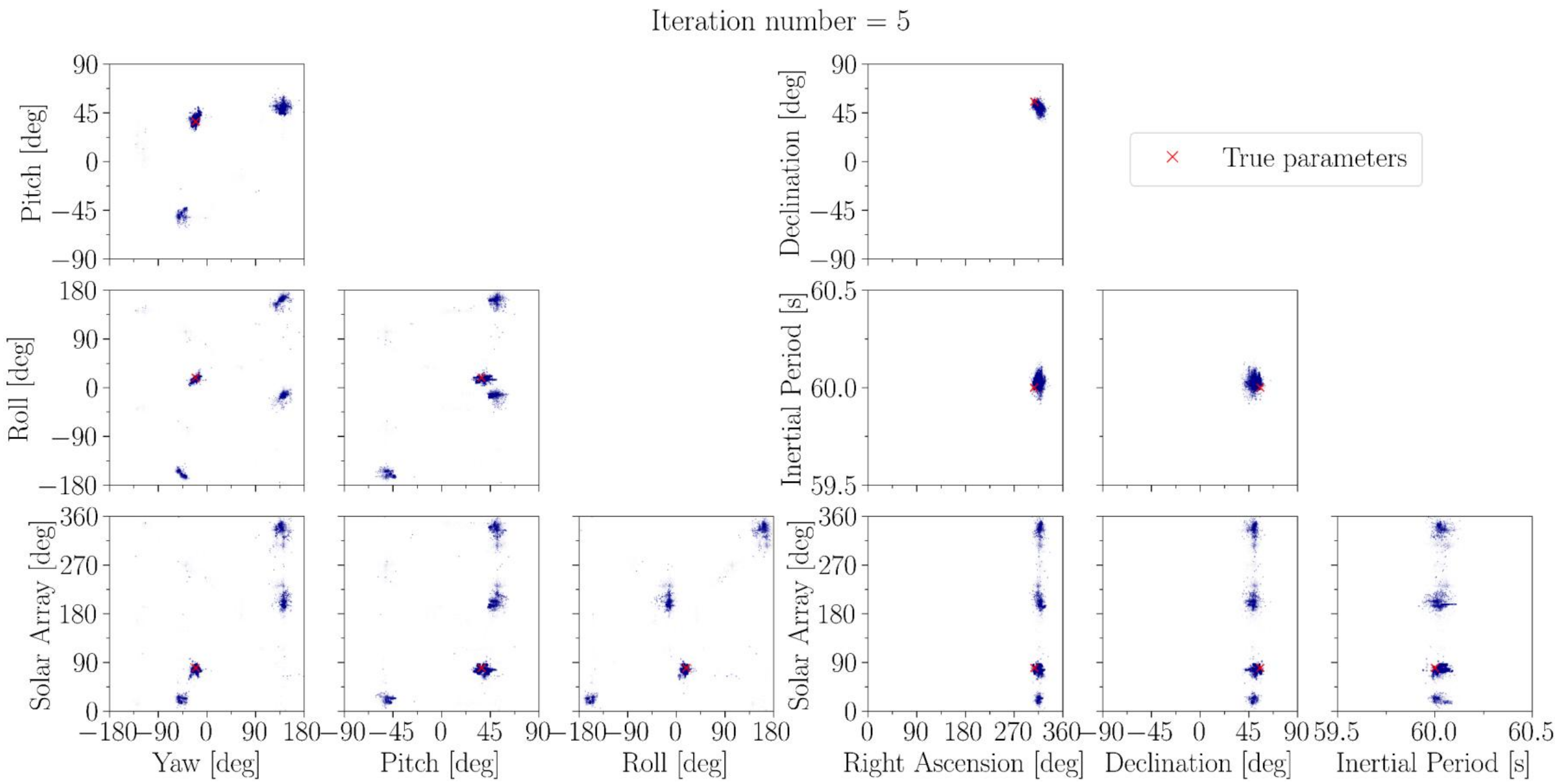
- **AISwarm-LS execution (2/6)**



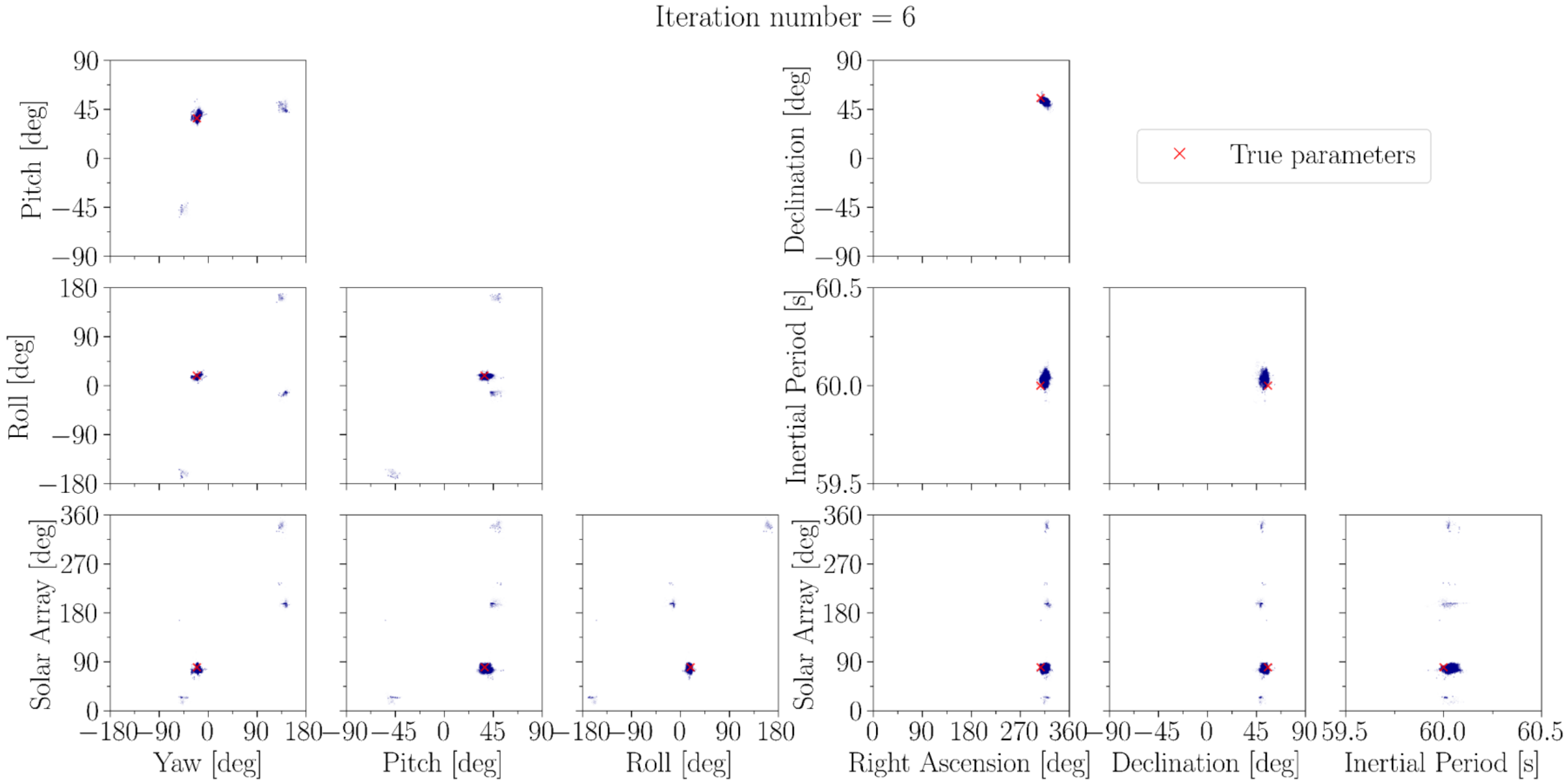
- **AISwarm-LS execution (3/6)**



▪ AISwarm-LS execution (4/6)

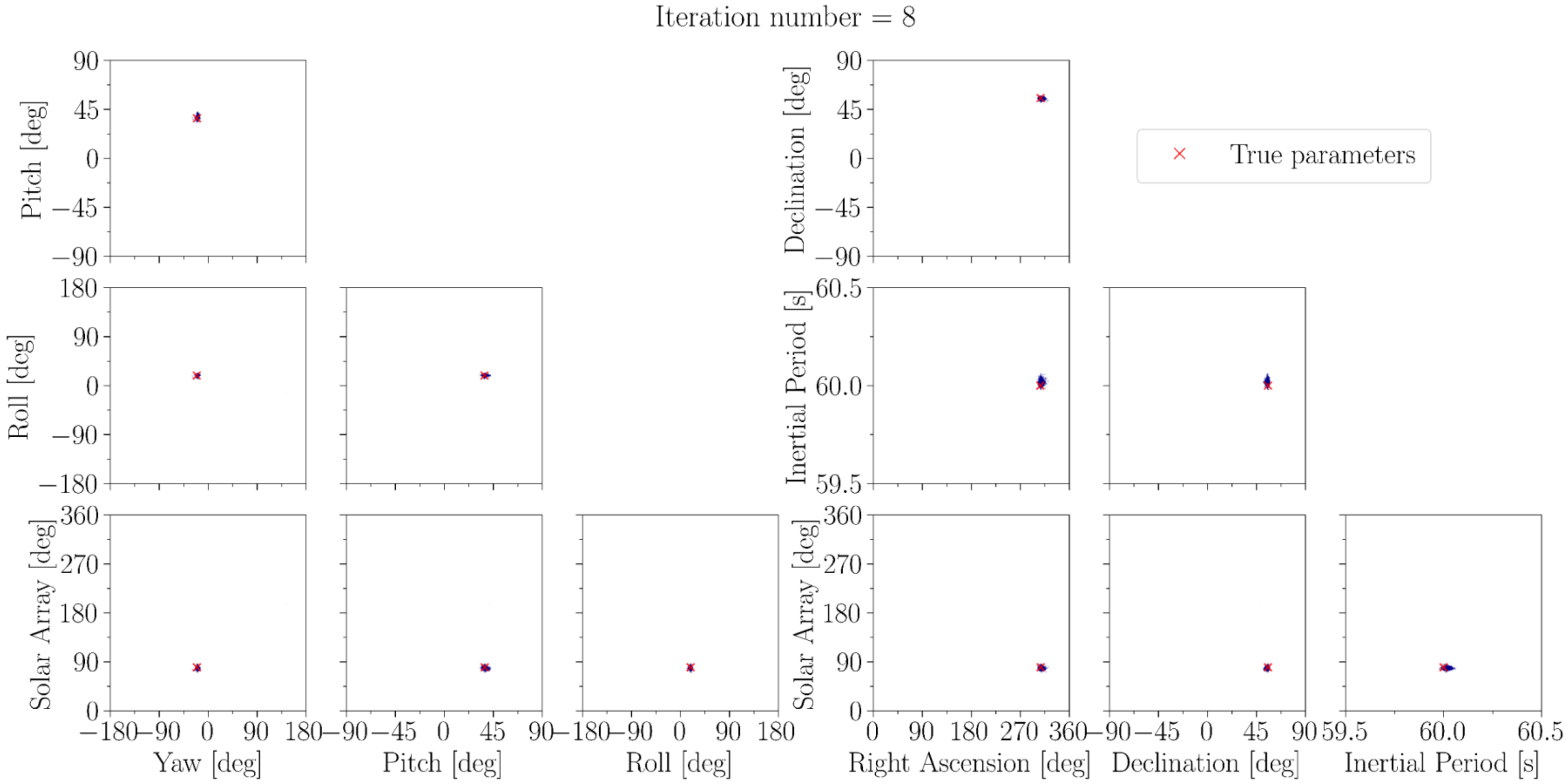


- **AISwarm-LS execution (5/6)**



Results

- **AISwarm-LS execution (6/6)**

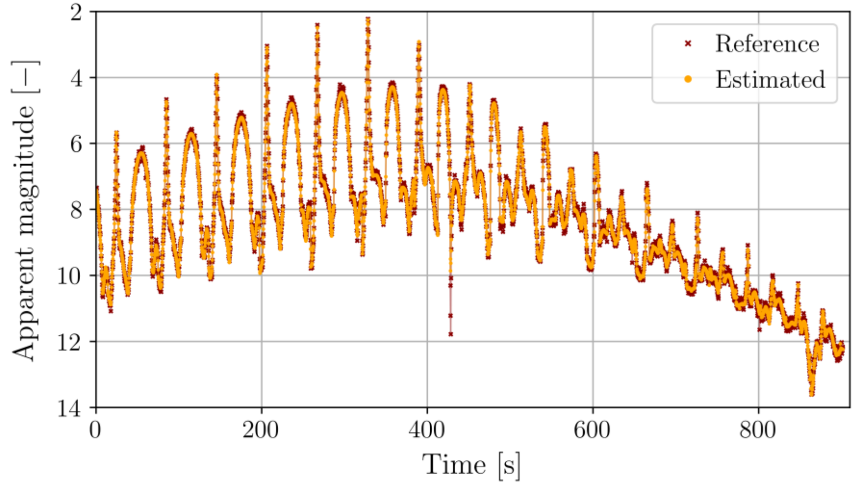


Results

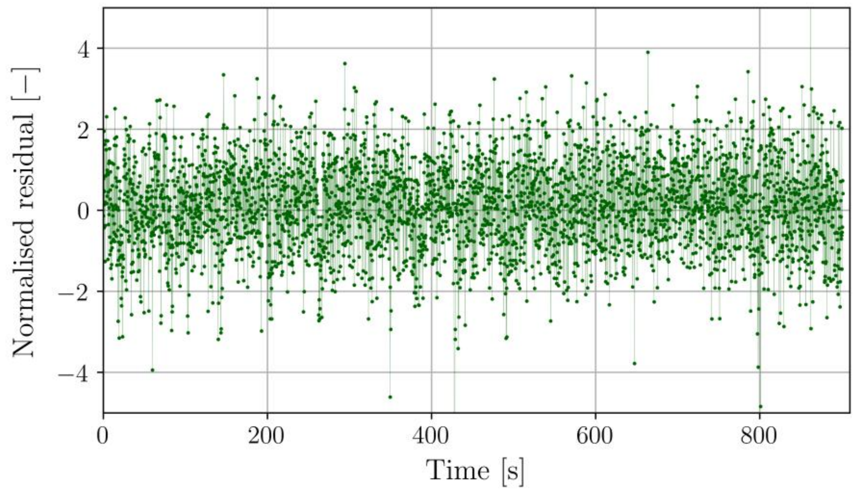
▪ Estimated parameters

		Reference	Estimate
Attitude and solar array parameters	ψ [deg]	-21	-19.629
	θ [deg]	37	37.194
	ϕ [deg]	18.5	18.879
	α [deg]	307	307.969
	δ [deg]	55.5	55.169
	T_{in} [s]	60	60.016
	β [deg]	80	79.462
Optical parameters	$k_{d,\pm X_B}$, $k_{d,SA}$ [−]	0.5	0.476
	$k_{d,\pm Y_B}$ [−]	0.15	0.142
	$k_{d,\pm Z_B}$ [−]	0.85	0.761
Atmospheric parameter	AOD [−]	0.25	0.234
WRMSE [−]		–	1.081

▪ Estimated vs. reference light curves



▪ Relative error



▪ Computational performance

✓ Total time: 119.8 min

- Measurements simulation: 15.4 min/iteration
- Clustering: 7.4 min/iteration

Conclusions and future work

- **Conclusions**
  - ✓ Simultaneous estimation of attitude, solar array orientation and optical properties of uncontrolled space objects
  - ✓ Accounts for atmospheric light extinction, including Aerosol Optical Depth (AOD) estimation
  - ✓ AISwarm-LS method
  - ✓ High accuracy, robustness, and computational efficiency
  - ✓ Designed for computational scalability

- **Future work**
  - ✓ Attitude estimation of tumbling objects
  - ✓ Estimation of the specular contribution to observed irradiance
  - ✓ Integration of RCS measurements from ground-based radar systems
  - ✓ Improvement of computational performance (alternative clustering algorithms)
  - ✓ Application to real observation datasets

- **Journal papers**
  - ✓ J. Rubio, A. de Andrés, C. Paulete, Á. Gallego, and D. Escobar, "Joint Estimation of Attitude and Optical Properties of Uncontrolled Space Objects from Light Curves Considering Atmospheric Effects", Aerospace, vol. 12, no 10, p. 942, 2025.
  - ✓ J. Rubio, A. de Andrés, C. Paulete, Á. Gallego, and D. Escobar, "Attitude Estimation of Uncontrolled Space Objects: A Bayesian-Informed Swarm Intelligence Approach", Advances in Space Research, vol. 77, no. 3, pp. 3791-3814, 2026.
- **Conference papers and presentations**
  - ✓ J. Rubio, A. de Andrés, C. Paulete, Á. Gallego, J. M. Lozano, D. Escobar, and A. Águeda, "A High-Performance and Robust Light Curve Inversion Method for Attitude Monitoring of Three-Axis Stabilised Satellites", in *Proceedings of the Advanced Maui Optical and Space Surveillance (AMOS) Technologies Conference*, Maui, HI, USA, Sep. 2025, p. 138.
  - ✓ J. Rubio, A. de Andrés, C. Paulete, Á. Gallego, and D. Escobar, "Integrated Attitude and Solar Array Orientation Estimation of Uncontrolled, Spin-stabilised Space Objects with Known Geometry", in *Proceedings of the 5th IAA Conference on Space Situational Awareness (ICSSA)*, Tres Cantos, Madrid, Spain, April 2026.

Thank you!
Questions?

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