中国科学院云南天文台
YUNNAN OBSERVATORIES,CHINESE ACADEMY OF SCIENCES

Attitude Estimation of Falcon 9 Rocket Body Based on Automatic Differentiation

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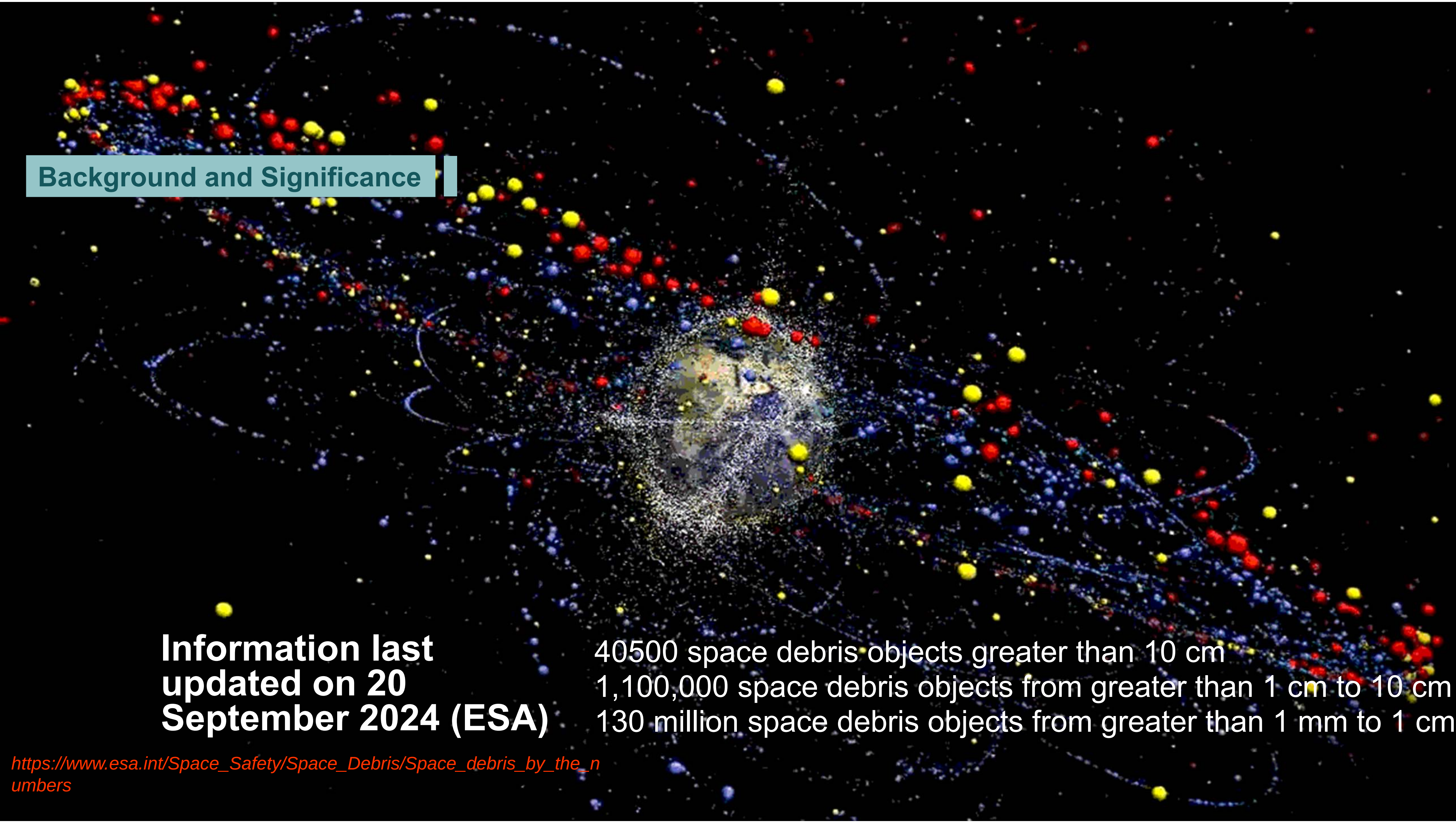


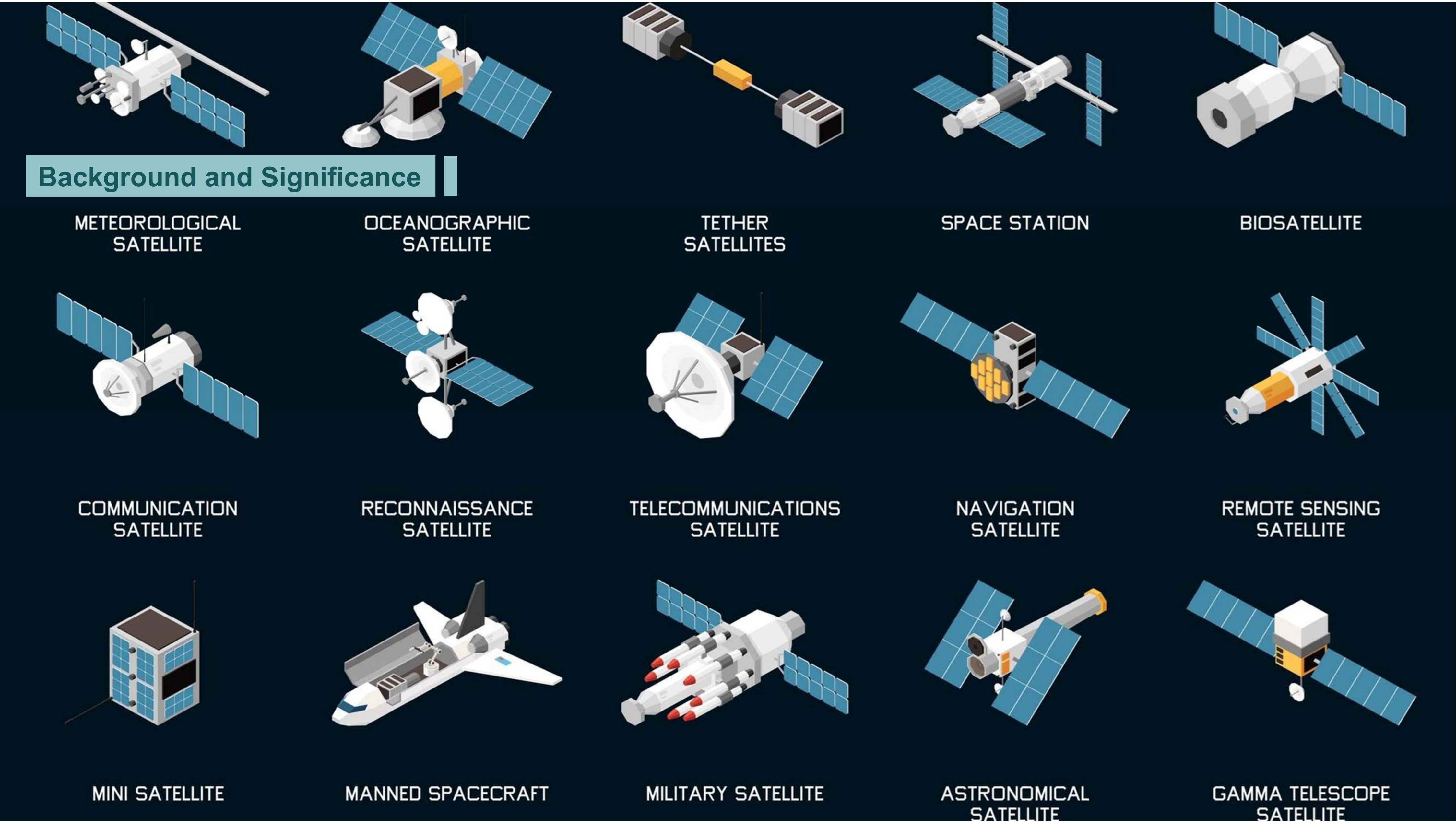
Background and Significance

Information last updated on 20 September 2024 (ESA)

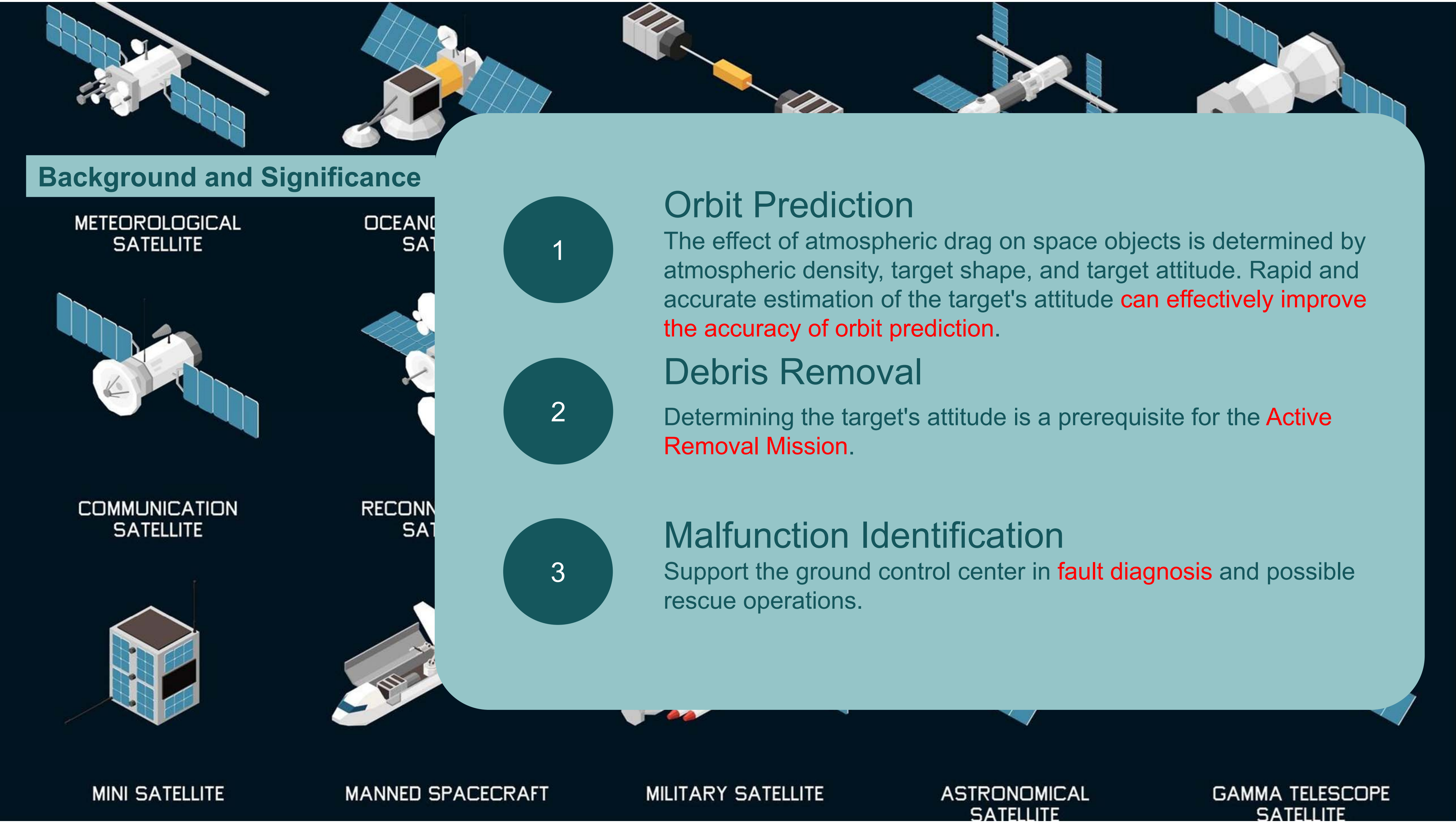
40500 space debris objects greater than 10 cm
1,100,000 space debris objects from greater than 1 cm to 10 cm
130 million space debris objects from greater than 1 mm to 1 cm

https://www.esa.int/Space_Safety/Space_Debris/Space_debris_by_the_numbers

Background and Significance



Background and Significance



1

Orbit Prediction

The effect of atmospheric drag on space objects is determined by atmospheric density, target shape, and target attitude. Rapid and accurate estimation of the target's attitude can effectively improve the accuracy of orbit prediction.

2

Debris Removal

Determining the target's attitude is a prerequisite for the Active Removal Mission.

3

Malfunction Identification

Support the ground control center in fault diagnosis and possible rescue operations.

Main Research Content

Research Goal

The light curves indicate a space object's attitude. How can we quickly and accurately estimate the attitude parameters?

Innovation

Automatic Differentiation (AD) is used to efficiently compute derivatives of complex photometric functions in attitude estimation.

Main Conclusion

AD enables rapid convergence of initial parameters to a stable solution in about 50 iterations, achieving an MSE reduction to three decimal places.

Data Collection

Photometric measurements of the target are conducted using the 1.2m telescope system at Yunnan Observatories.

Laser ranging of space debris was conducted in September 2023.

YNAO 1.2m Telescope System

System Overview:

1. 1.2m Telescope
   - Cassegrain design with a field of view of 3′ × 3′.
   - The coated mirror has high reflectivity for 532 nm and 1064 nm light.
   - Primarily used for laser ranging.
2. 30cm Telescope
   - Refracting telescope with a field of view of 36′ × 36′.
   - Limiting magnitude of 13.
   - Mainly used for photometric measurements of space targets.

Main Applications:

1. Lunar laser ranging
2. Laser ranging of space debris
3. Photometric measurements of space targets

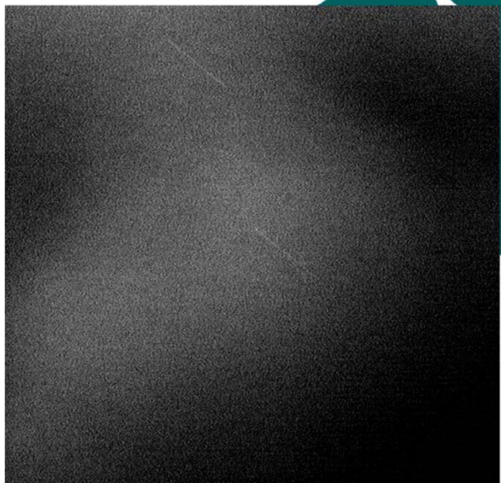
Research Methodology

Data Processing

The method of machine learning is applied to the pre-processing to improve the efficiency of contamination image judgment.

1. **CNN** Convolutional Neural Network
2. **ResNet-18** Residual Network-18
3. **lightGBM** Light Gradient Boosting Machine
4. **SVM** Support Vector Machine

Stellar contamination



Cloudy contamination

Contamination	Model	Training Set	Test Set
stellar	CNN	0.9389	0.9221
	CNN with stamp images	1.0000	1.0000
cloudy	ResNet	0.8000	0.8000
	lightGBM	1.0000	0.9995
	SVM	0.9753	0.9712

Note. The accuracies of the lightGBM model shown above are very high, but this model has weak generalization ability.

Hui Li et al 2024 Res. Astron. Astrophys. 24 045025
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Research Methodology

Photometric model

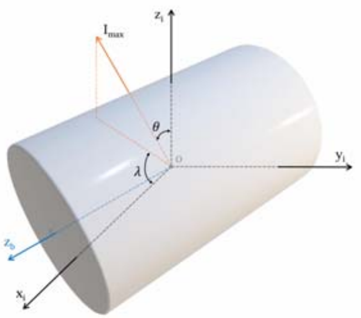
Analyze the target's shape, attitude, and slant range to establish a photometric model.

$$dE_s = \frac{E_{0,V}}{\pi r^2}\rho_{d,s} cos\theta_i cos\theta_o ds$$

Illumination at the observation station from the surface element dS scattering sunlight.

$$E_s = \frac{E_{0,V}}{\pi r^2}\int_S \rho_{d,s} cos\theta_i cos\theta_o ds \qquad E_s = \frac{E_{0,V}}{\pi r^2}\sum_{j=1}^{N}\rho_{d,j}A_{e,j}$$

Integrate the illumination, or sum up the illumination from each part.



$$A_p = Acos\alpha_p cos\beta_p$$

Equivalent area of the top and bottom surfaces.

$$A_s = \int_S cos\theta_i cos\theta_o ds$$

Equivalent area of the cylindrical surface.

$$= \int_S sin\alpha_s cos\psi \cdot sin\beta_s cos(\psi - \gamma) \cdot h\frac{d}{2}d\psi$$

$$= (dh) \cdot \frac{1}{4} sin\alpha_s sin\beta_s[sin\gamma + (\pi - \gamma)cos\gamma]$$

Su, X., Tang, R., Li, R. et al. (2021). Research on estimating the rotation state of the upperstage of falcon 9 rocket by using lightcurve. doi:10.14005/j.cnki.issn1672-7673.20200722.002.

Parameter Search

An innovative approach using Automatic Differentiation is introduced to improve search speed and accuracy in parameter optimization.

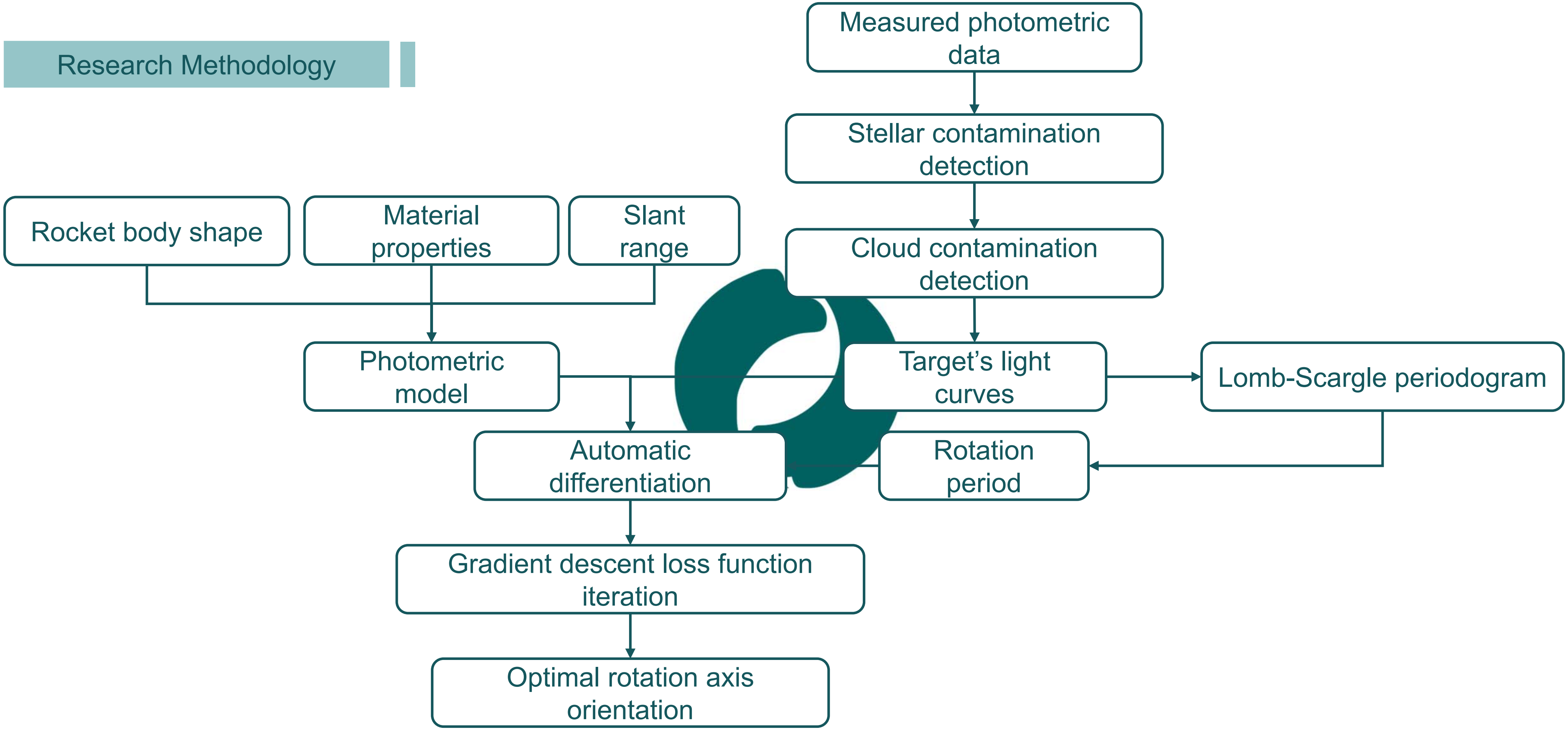
JAX Quickstart

Open in Colab | Open in Kaggle

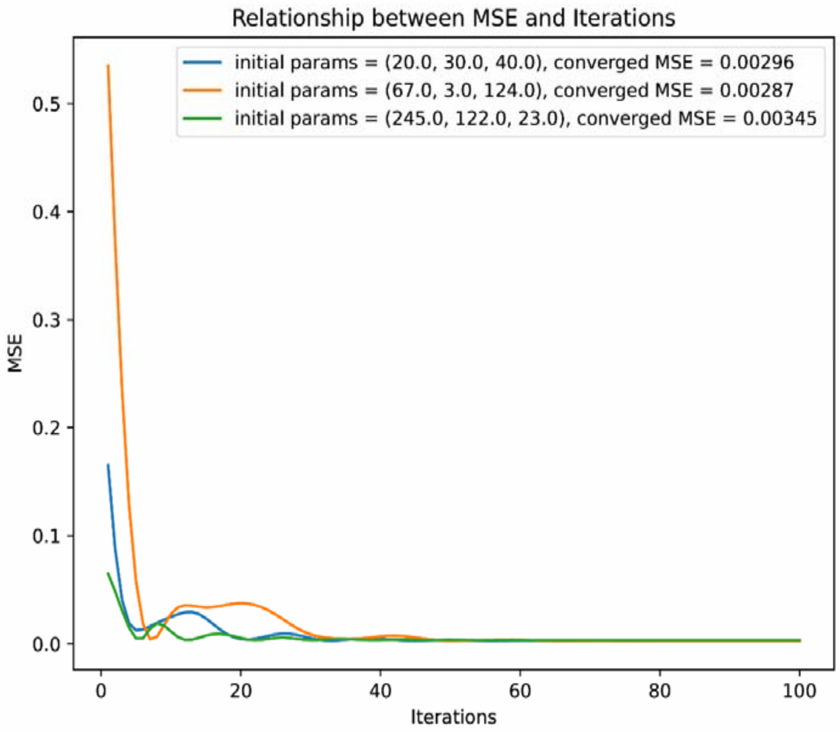
JAX is NumPy on the CPU, GPU, and TPU, with great automatic differentiation for high-performance machine learning research.

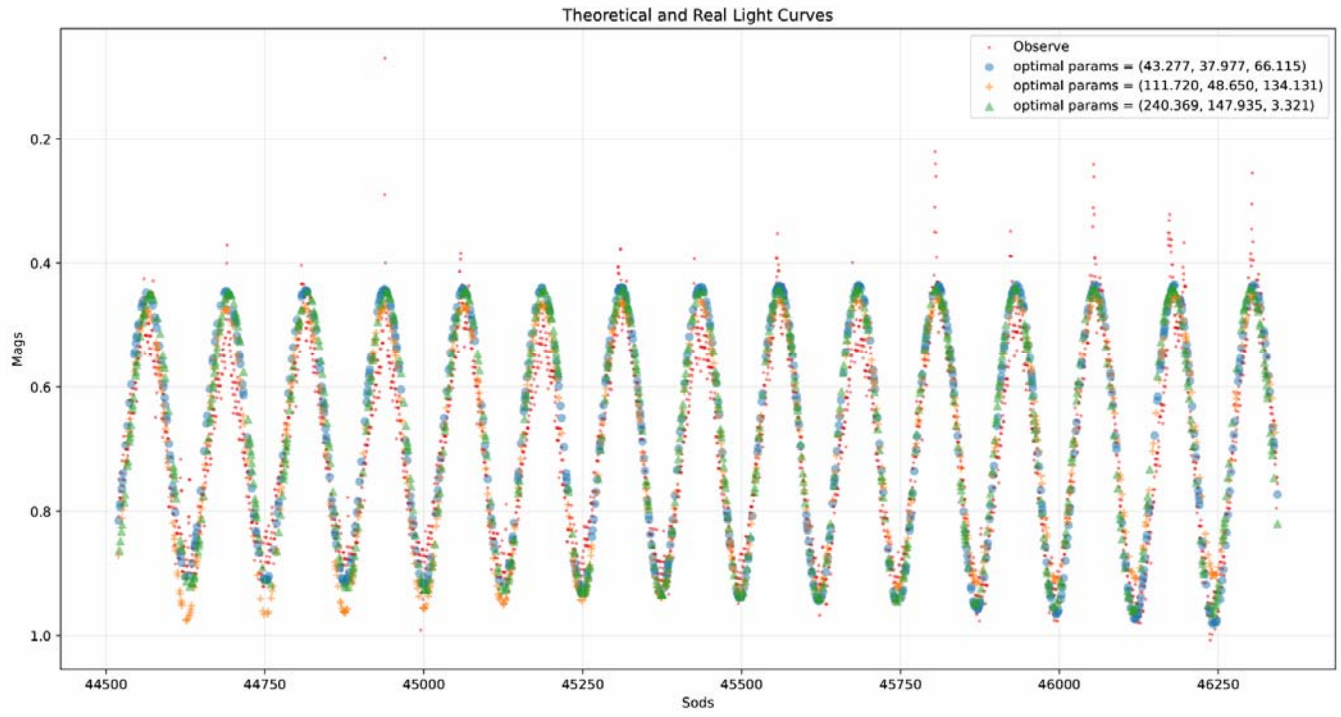
With its updated version of Autograd, JAX can automatically differentiate native Python and NumPy code. It can differentiate through a large subset of Python's features, including loops, ifs, recursion, and closures, and it can even take derivatives of derivatives of derivatives. It supports reverse-mode as well as forward-mode differentiation, and the two can be composed arbitrarily to any order.

Research Methodology



Research Results

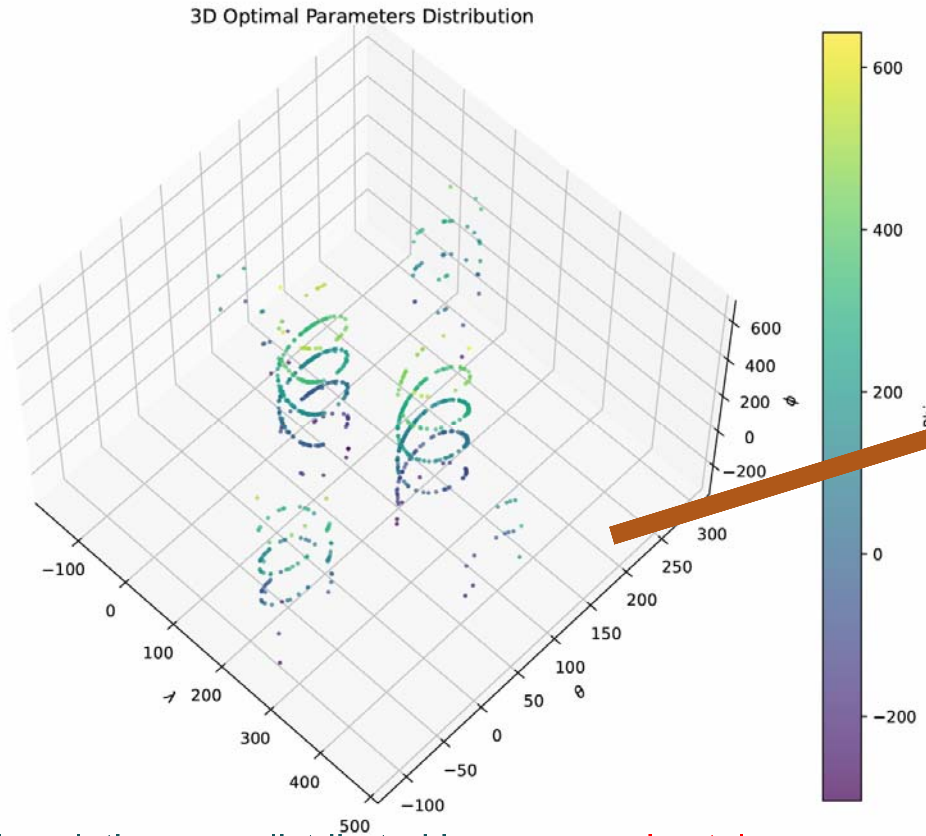


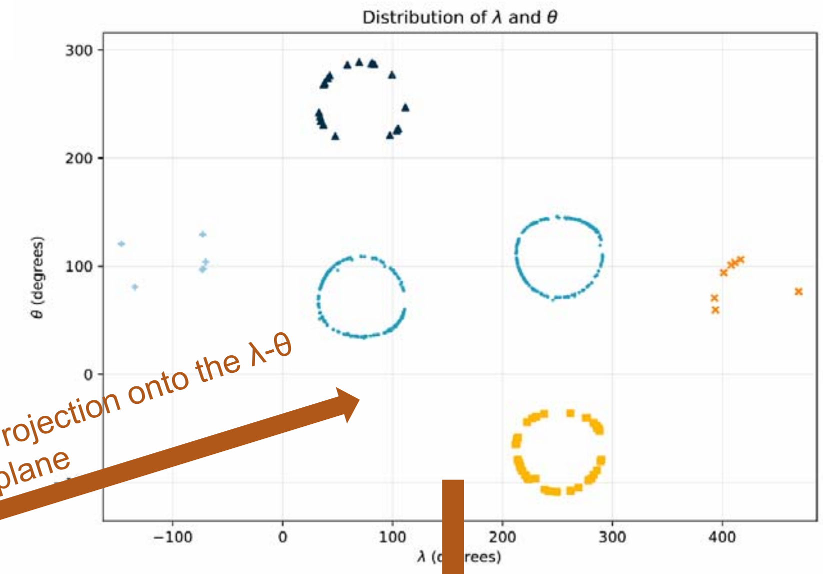


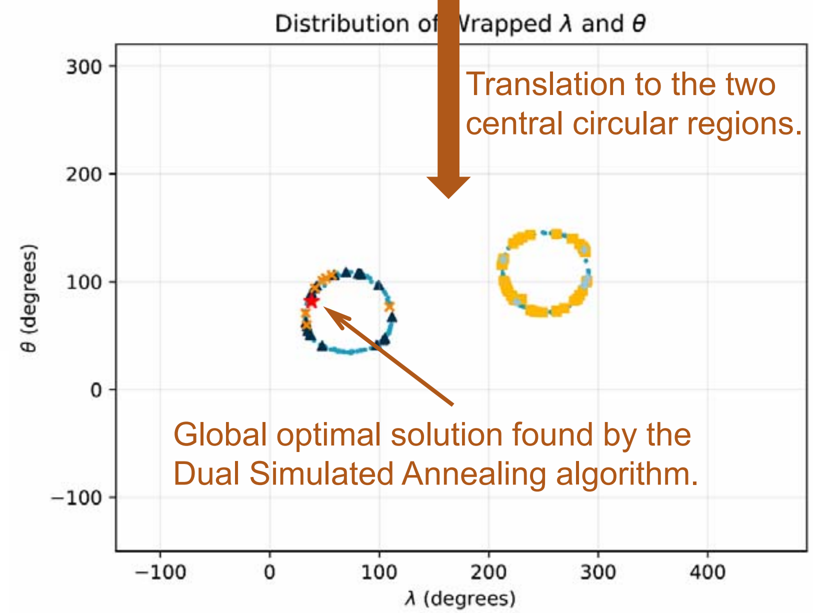
Parameters search with three different sets of initial values converges to optimal parameters within about 50 iterations (around 10 seconds).

Due to simplicity of the assumed model, multiple parameter combinations can fit well the theoretical light curves to the measured data.

Research Results







All possible solutions are distributed in an approximately circular pattern on the λ-θ plane.
This circular distribution arises from the relationship between initial phase and the orientation of the rotation axis.
The two circular distributions are mirror images. Reversing the rotation axis orientation of one will yield the other.

Research Results

1. Automatic Differentiation offers fast convergence and low computation time in parameter optimization.

2. We also applied Dutomatic Differentiation for estimating parameters involving voxel reflectivity, providing valuable guidance for selecting empirical reflectivity values.

Date	Initial $\rho_1,\ \rho_2,\ \rho_3$	Optimal $\rho_1,\ \rho_2,\ \rho_3$	MSE
2019-12-13	0.340, 0.010, 0.010	0.326, 0.054, 0.048	0.002
2022-03-10	0.340, 0.010, 0.010	0.333, 0.244, 0.149	0.003
2024-05-23	0.340, 0.010, 0.010	0.339, 0.012, 0.143	0.006

3. The Dual Simulated Annealing algorithm performed similarly to Automatic Differentiation in optimization speed, quickly finding global optima. However, it is less effective than AD in finding multiple solutions caused by symmetry.

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THANKS!
谢谢