



AFRL-AFOSR-JP-TR-2024-0030

Machine-learning SSA Frameworks for Photometric Light Curves of Low Earth Orbit Resident Space Objects

**Melrose Brown
University of New South Wales-NEW NCAGE Code
HIGH STREET
KENSINGTON, NSW, ,
AU**

**12/18/2023
Final Technical Report**

DISTRIBUTION A: Distribution approved for public release.

Air Force Research Laboratory
Air Force Office of Scientific Research
Asian Office of Aerospace Research and Development
Unit 45002, APO AP 96338-5002

REPORT DOCUMENTATION PAGE

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

1. REPORT DATE 20231218		2. REPORT TYPE Final		3. DATES COVERED	
				START DATE 20200930	END DATE 20230329
4. TITLE AND SUBTITLE Machine-learning SSA Frameworks for Photometric Light Curves of Low Earth Orbit Resident Space Objects					
5a. CONTRACT NUMBER		5b. GRANT NUMBER FA2386-20-1-4034		5c. PROGRAM ELEMENT NUMBER	
5d. PROJECT NUMBER		5e. TASK NUMBER		5f. WORK UNIT NUMBER	
6. AUTHOR(S) Melrose Brown					
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of New South Wales-NEW NCAGE Code HIGH STREET KENSINGTON, NSW AU				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AOARD UNIT 45002 APO AP 96338-5002			10. SPONSOR/MONITOR'S ACRONYM(S) AFRL/AFOSR IOA		11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-AFOSR-JP-TR-2024-0030
12. DISTRIBUTION/AVAILABILITY STATEMENT A Distribution Unlimited: PB Public Release					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT The final report was received 6 months late and represents a very disappointing discussion of an extremely poor effort all round. In this report it was noted that yet more people left the program, and that the telescope originally planned for obtaining real world data was never fully operational and did not ever seem to give any worthwhile data. Meanwhile the backup telescope (Falcon Telescope Network node) was also under repair for large amounts of time, so little was done to collect real light curves. More disappointing was the lack of progress on the modeling side which should have benefited from the additional time allocation. A few light curves were generated but little by way of publishable science was gained. All of the publications made were either reporting of operations or literature reviews of light curve methodologies and plans for future work. My recommendation would be that we should not fund this group in the future.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT		18. NUMBER OF PAGES
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U	SAR		6
19a. NAME OF RESPONSIBLE PERSON GEOFFREY ANDERSEN				19b. PHONE NUMBER (Include area code) 703-588-8442	

Standard Form 298 (Rev. 5/2020)
Prescribed by ANSI Std. Z39.18

Annual Report for AOARD Grant Annual Report for AOARD Grant FA2386-20-1-4034

“Machine-learning SSA Frameworks for Photometric Light Curves of Low Earth Orbit

Resident Space Objects”

Name of Principal Investigators (PI and Co-PIs):

Dr Melrose Brown – Melrose.brown@adfa.edu.au

Assoc. Prof Andrew Lambert - a-lambert@adfa.edu.au

Dr Rizka Purwanto - r.purwanto@unsw.edu.au

Dr Chris Capon - no longer with UNSW

- University of New South Wales, Canberra
- School of Engineering and IT
- Northcott Drive
- Canberra
- ACT 2600
- Phone: +61 2 5114 5129

Period of Performance: 09/30/2022 – 03/28/2023

Personnel Changes

Dr Chris Capon left the group in December 2022 to pursue the role of CEO within his company Nominal Systems. Dr Rizka Purwanto left the group in March 2023 to take up a tenure track position at the Singapore campus of Monash University, but remains with UNSW in an adjunct capacity.

VIPER and Falcon Telescopes

Further delays in the optical campaign have been incurred in Q4 2022 and Q1 2023. A mechanical failure in the VIPER mount system has damaged an important part of the camera system. Temporary repairs to VIPER were made in Q2 2023, however the field of view has been reduced until a full replacement of the affected components can be acquired. The UNSW Canberra node of the Falcon Telescope Network has also been under repair since Q3 2022, with several other nodes in the network currently offline due to a large-scale upgrade of the hardware across the network.

Light curves for the UNSW Canberra M2-A, M2-B and M2 Pathfinder satellites were collected throughout the project and have supported the validation of the RayMAN light curve simulation tool. A larger database that covers a greater range of pass geometries, spin states, and lighting (such as entering or leaving eclipse, sky brightness close to twilight or dawn), and weather conditions to train the machine learning algorithms.

Space Object Shape Identification

Synthetic Data Generation

Dr Chris Capon has developed the RayMAN simulation software and Dr Rizka Purwanto has developed the machine learning (ML) framework since filling the vacant ML post-doctoral position in June 2022. Synthetic data generation has been a larger task than initially anticipated. The GPU resources available to Dr Capon in the desktop PC used to develop RayMAN for the project have been stretched by the ML training data requirements. ML data generation is ongoing, with an estimated total run time of 7 months to generate the complete dataset. In parallel, Dr Capon has been working to port the code onto UNSW Canberra's new space domain awareness AI/ML server, featuring 8xNVIDIA A100 (80Gb) GPU cards that was commissioned Q3 2022. The work porting the code for production use was expected to be completed by Q2 2023, however Dr Capon's departure from the group in December 2022 leaves some remaining work to have the containerized code able to run autonomously for long periods without expert intervention.

During the synthetic data generation process, three types of geometric shapes: cubes, plates, and the combination of both. During every data generation, we randomise the object's length to obtain a heterogeneous dataset with sufficient variety. We generate 20,000 objects with various materials for each shape: 10,000 objects made of aluminium and 10,000 objects made of solar cells. Each object is passed as an input to the RayMAN simulation software. To generate the light curve data, the rendering and simulation process takes at least roughly 5 minutes per object, or around 208.3 days roughly to complete the simulation with 60,000 objects (which consist three different geometric shapes and two different materials).

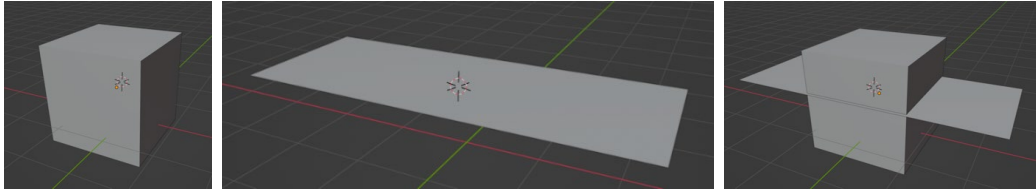


Figure 1 Blender Objects

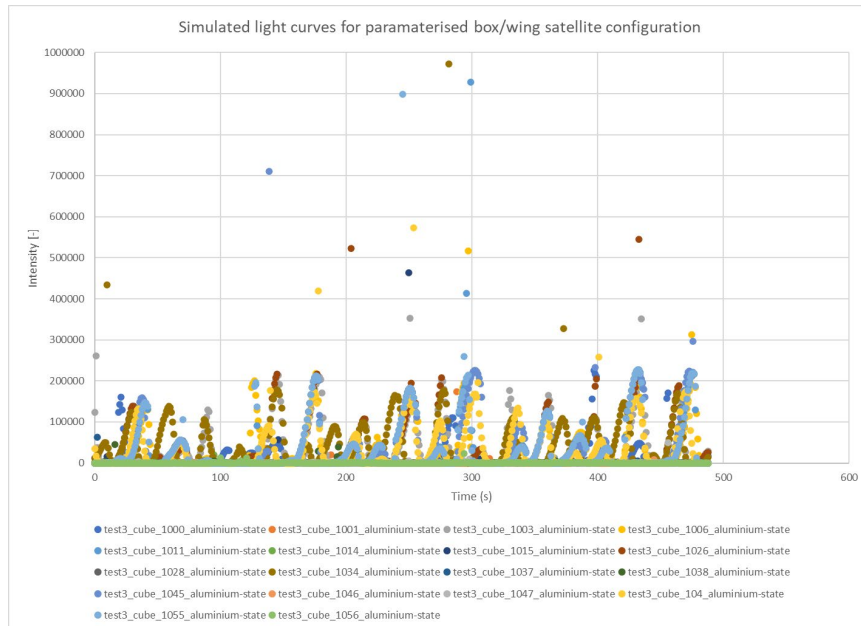


Figure 2 Sample of the simulated light curve output from RayMAN for different paramaterised box/wing configurations

The simulated light curve generation is ongoing, however preliminary results for approximately 3500 cases has been extracted and processed. An example of the data is shown in Figure 2.

Light Curve Data Collection and Analysis

As a preliminary work, we collected some light curve data with the VIPER telescope to observe the light curve data characteristic of different space objects. The light curve data was collected between 11-24 January 2023.

The plot in Figure 3 shows the light curve data of a sample of satellites, namely Cosmos 1603 (NORAD #15333U), Cosmos 2242 (NORAD #22626U), ALOS (NORAD #28931U), and SL-16 R/B (NORAD #17974U). To assess how distinguishable each object is, we measure the similarity of each pair of light curve series by measuring the cosine similarity, Pearson

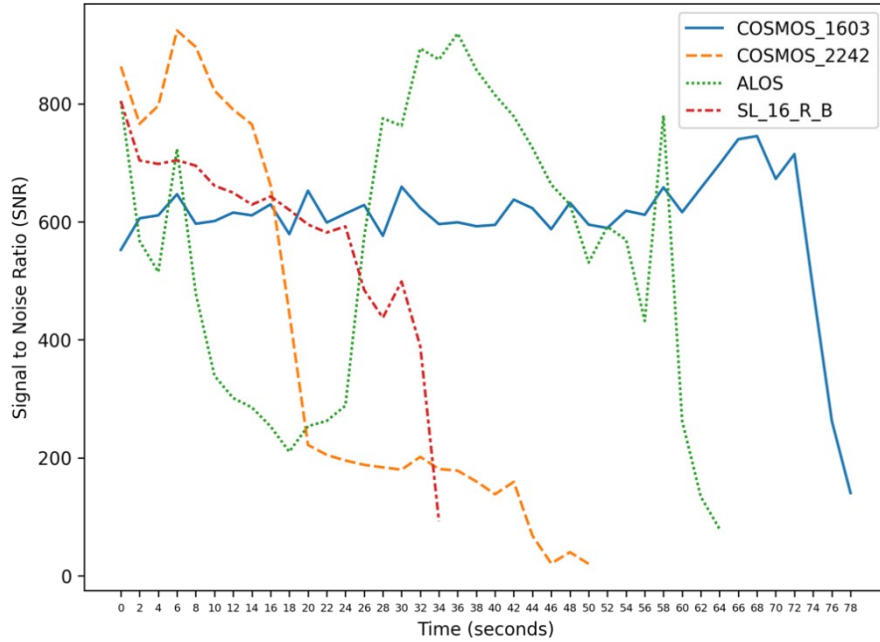


Figure 3 Light Curve Data

similarity, and Dynamic Time Warping (DTW) distance between each pair. The cosine and Pearson similarity value measures the closeness between two time-series data, thus a higher value closer to 1 would indicate that two time-series data are similar to each other. Meanwhile, similarity between two light curve data would be indicated by a DTW distance closer to 0.

Table 1 Cosine similarity between each light curve data

	COSMOS_1603	COSMOS_2242	ALOS	SL_16_R_B
COSMOS_1603	1.0	-0.09913	-0.285014	-0.08905
COSMOS_2242	-0.09913	1.0	-0.350029	0.726364
ALOS	-0.285014	-0.350029	1.0	-0.441235
SL_16_R_B	-0.08905	0.726364	-0.441235	1.0

Table 2 Pearson similarity between each light curve data

	COSMOS_1603	COSMOS_2242	ALOS	SL_16_R_B
COSMOS_1603	1.000000	-0.099130	-0.285014	-0.089050
COSMOS_2242	-0.099130	1.000000	-0.350029	0.726364
ALOS	-0.285014	-0.350029	1.000000	-0.441235
SL_16_R_B	-0.089050	0.726364	-0.441235	1.000000

Table 3 Dynamic Time Warping (DTW) distance between each light curve data

	COSMOS_1603	COSMOS_2242	ALOS	SL_16_R_B
COSMOS_1603	0.0	724.685614	1007.176944	427.591263
COSMOS_2242	724.685614	0.0	1324.275524	423.854921
ALOS	1007.176944	1324.275524	0.0	1209.021264
SL_16_R_B	427.591263	423.854921	1209.021264	0.0

For sanity checking, we checked that the cosine and Pearson similarity measures between identical objects are 1, and the DTW distances between identical satellites are 0. Otherwise, there might be some issues in our data or algorithm and further checking might be required. As shown in Table 1-3, most objects are quite distinctive to each other. Interestingly, Cosmos 2242 and SL-16 R/B light curves are found to be quite similar to each other, based on all the three metrics (cosine similarity, Pearson similarity, and DTW distance). Based on the plot in Figure 12, while Cosmos 2242 and SL-16 R/B light curves have different lengths, there are similar trends observed in both light curves, with consistent decreasing light intensities over time. The use of deep learning on a larger number of data would help in automatically capturing these patterns, and “signatures” in each light curve data, that would be useful to perform space object characterisation.

Preliminary Extension Work – Radio Frequency (RF) Spin Characterisation

Preliminary work has begun to investigate using the change in signal to noise ratio from a satellite’s RF transmissions to provide additional information on the spin characteristics of the UNSW Canberra M2-A, M2-B, and M2 Pathfinder satellites. The preliminary work assumes a single omni-directional UHF antenna transmitting from a single face of the spacecraft. The null in the antenna beam pattern creates a variation in received signal strength that correlates to the spin characteristics of the spacecraft. The work, pioneered by Dr Edwin Peters, is novel and offers the potential to detect changes in satellite spin characteristics day or night and in all

weather conditions.

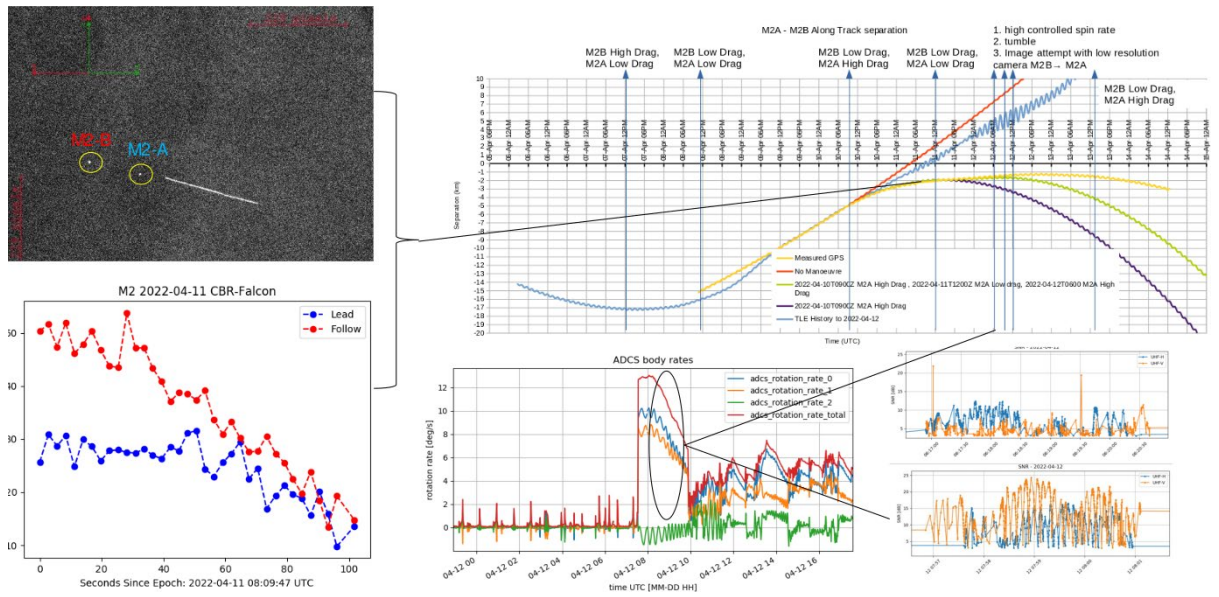


Figure 4 Summary of Results from the Sprint Advanced Concept Training 22-2 space domain awareness exercise (Brown, Smith et al. 2020). RF spin stability analysis results are shown in the bottom right corner of the figure.