Stability Analysis of LEO Rocket Bodies

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ABSTRACT

The Center for Space Situational Awareness Research (CSSAR) at the United States Air Force Academy (USAFA) is participating in a study led by LEOLabs to determine the stability of certain rocket bodies in low-earth orbit (LEO). This paper presents initial results of observations taken by CSSAR faculty and cadets. Observations of 19 rocket bodies (R/Bs) were taken over a four-month period from November 2022 to February 2023; of these, 5 R/Bs appear to be stable while 13 appear unstable or partially unstable. Seven R/Bs were observed more than once and only one of them (SL-8-07426) exhibited both a stable attitude and an unstable attitude. For the unstable R/Bs, we applied a two-term model where the first term accounted for long-term, non-periodic trends in the light curve, whereas the second term was a Fourier series to account for superimposed periodic variations. Using this model, we were able to determine the synodic or apparent period of rotation. Our observations showed R/Bs with fast rotation (11 seconds) and long, slow rotation (968 seconds)

1. INTRODUCTION

Space Domain Awareness (SDA) helps the United States Space Force monitor and respond to potential threats to U.S. space assets, such as orbital debris, space launches, and space traffic. By clearly understanding the space domain, the Space Force can ensure the continued ability to operate in and through space, supporting military and national objectives. An increasing number of satellites are being launched into orbit each year, making it more crucial to track them to ensure the safety and success of United States space operations. As of 23 August 2023, the public space catalog stands at a total of 27,836 objects, of which 11,281 (~41%) are payloads, 2,343 are rocket bodies (~8%), 13,698 (~49%) are debris, and 514 (~2%) awaiting an assignment [1]. One can see that the majority of the space catalog is composed of rocket bodies and debris; objects which for the most part do not have maneuvering capability, thus making them vulnerable to collisions.

Three basic collisions can occur: 1) a large object colliding with another large object (large-on-large), 2) a small object colliding with a large object (small-on-large), and 3) a small object colliding with a small object (small-on-small). Of the three, a large-on-large collision will generate more debris which could lead to a cascading effect known as the Kessler Syndrome [2]. Efforts across the broader space community have recognized the need to control the growth in space debris. For LEO, active debris removal (ADR) technology is one approach to controlling the growth of space debris. Various approaches and concepts for LEO ADR, rely on de-orbiting large objects like the rocket bodies. As the Earth's upper atmosphere expands due to solar activity, rocket bodies in very low LEO should eventually reenter the earth's atmosphere and burn up. For higher orbiting LEO rocket bodies however, to cause them to decay in the Earth's atmosphere would require a technical solution. Regardless, reentry of LEO rocket bodies through either natural forces or ADR technology, requires some understanding of their attitude profile.

One project led by LeoLabs uses academic telescopes to observe LEO rocket bodies (R/Bs) to determine their tumble rates. Besides USAFA, participating universities include the University of Warwick (Coventry, UK), Sapienza University of Rome (Rome, Italy), and the University of Bern (Bern, Switzerland). This paper presents only the USAFA portion of the larger study.

2. APPROACH

The goal of this project is to provide an estimation of a rocket body's stability and period of rotation. Hypotheses include:

- Difficulty in maintaining reliable and highly accurate positional uncertainty (e.g., 10-20 m) of slowly tumbling LEO R/Bs compared to rapidly tumbling or very stable R/Bs at higher altitude orbits
- Higher L/D R/Bs are more likely to be gravity-gradient-stabilized compared to lower L/D R/Bs
- R/Bs at lower altitudes are less likely to be gravity-gradient-stabilized
- R/B dynamics will not change over time except when the R/B goes to lower altitudes
- Higher L/D R/Bs more likely to change over time and altitude compared to lower L/D R/Bs

A set of five types of R/Bs were chosen for this study because 1) they pose the greatest debris-generating potential in LEO, 2) they span much of the LEO regime in altitude, thus providing a statistically significant sample size, and 3) they span a range of length-to-diameter (L/D) ratios (see Table 1).

Table 1. List of rocket bodies observed in this study.

Type	Length (m)	Diameter (m)	L/D Ratio
SL-14	2.58	2.25	1.2
CZ-4C	6.24	2.9	2.15
SL-8	6	2.4	2.5
SL-16	11	4	2.75
Delta 2	5.89	1.7	3.46

At USAFA, we used a 16-inch (0.4-meters), f/8.2 Ritchey-Chrétien telescope (USAFA-16) to image the R/Bs as they passed overhead during 1-3 hours after sunset. Using an R-filter, we collected images as we rate-tracked a rocket body. Rate tracking a LEO space object results in star streaks but allows one to use aperture photometry techniques to determine the brightness of the object. Fig. 1 is an example of four different R/Bs images taken on 9 December 2022.

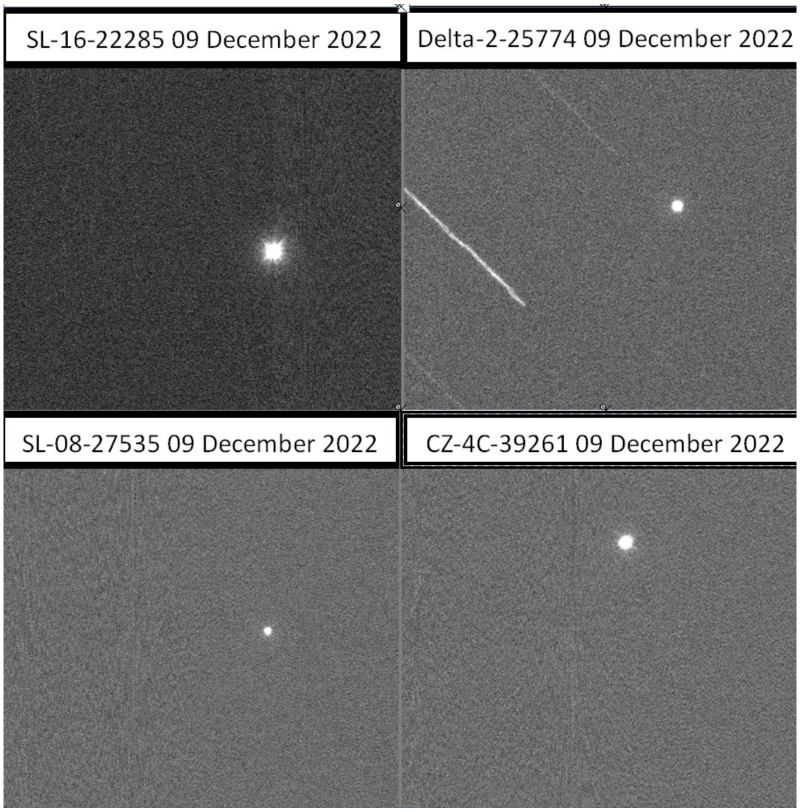

Fig. 1: Raw images of rocket bodies observed 09 December 2022

These observations were conducted on six nights, 08 November 2022, 02 December 2022, 09 December 2022, 01 February 2023, 02 February 2023, and 10 February 2023 which produced a total of 2,312 images of 28 passes consisting of 19 different rocket bodies. These R/Bs consist of the following types: SL-14, CZ-4C, SL-8, SL-16, or Delta 2. We applied aperture photometry techniques to determine the flux (counts/second), which was then used to calculate the R/Bs's instrument magnitude. Using calibration stars, the instrument magnitude of the R/Bs was then converted to an apparent magnitude using code developed by previous USAFA cadets [3]. Finally, we plotted the apparent magnitude of each R/B as a function of time producing a light curve which then allowed us to visually determine whether the rocket body was stable or unstable. Fig. 2 shows three light curves illustrating a stable attitude (top left), a partially unstable attitude (top right), and an unstable attitude (bottom). The stable attitude R/B was a Delta-2 R/B (Satnum 25774) observed soon after dusk on 8 November 2022. The partially unstable R/B was a SL-8 R/B (Satnum 27535) observed on 9 December 2022. Finally, the example of an unstable attitude was a SL-14 R/B (Satnum 18340) observed on 2 December 2022.

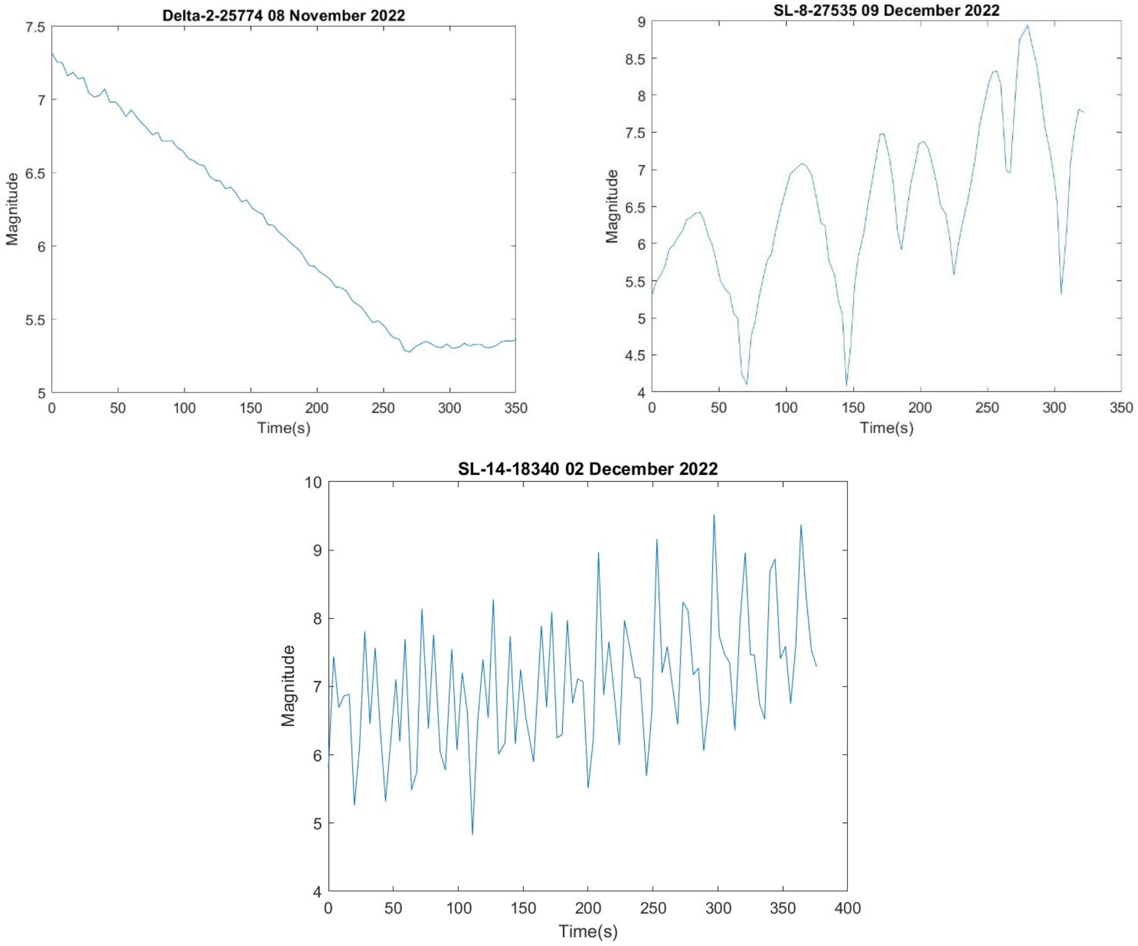

Fig. 2: The magnitude versus time graphs of the stable Delta-2-25774 (Top Left), the partially unstable SL-8-27535 (Top Right), and the unstable SL-14-18340 (Bottom)

3. RESULTS

The first step in our analysis was to visually inspect the resulting light curve for a given R/B to determine whether it was stable or unstable. Out of the 26 R/B light curves, visually, 9 exhibited a stable profile while 17 were unstable (see Table 2). If a R/B was unstable or partially unstable, we determined the synodic or apparent period of rotation using an approach developed by the Air Force Research Laboratory for the NASA Image satellite [4]. Equation (1) in [4] had two terms, a polynomial term to account for long-term non-periodic trends in the magnitudes and a second Fourier series to account for superimposed periodic variations (see equation below).

$$F'(t) = \left[\sum_{m=0}^{M} a_m t^m\right] + \left[\sum_{n=1}^{N} b_n \cos(n\omega t) + c_n \sin(n\omega t)\right] \qquad \text{Eqn (1)}$$

Using test data from [4], we are confident that our implementation of the Fourier series approach is correct. Fig. 3 shows the FFT of the partially unstable SL-8-27535 (left plot) and the unstable SL-14-18340 (right plot). The frequency found from the Fourier transform is then used to generate a synthetic light curve which is then compared to the original R/B light curve by aligning as many of the peaks and the troughs. Fig. 4 presents the fitted light curve (green trace) to the original signal (blue trace).

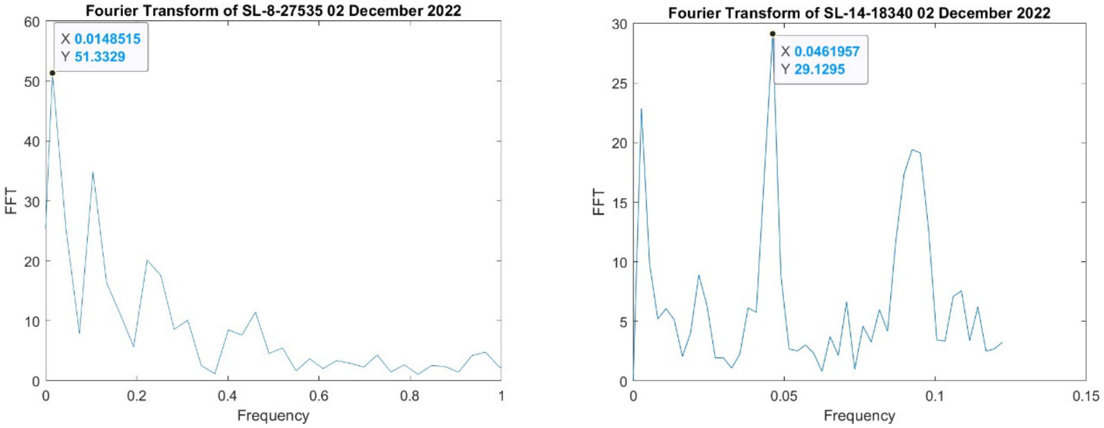

Fig. 3: Fourier Transforms of the SL-8-27535 (Left) and the SL-14-18340 (Right).

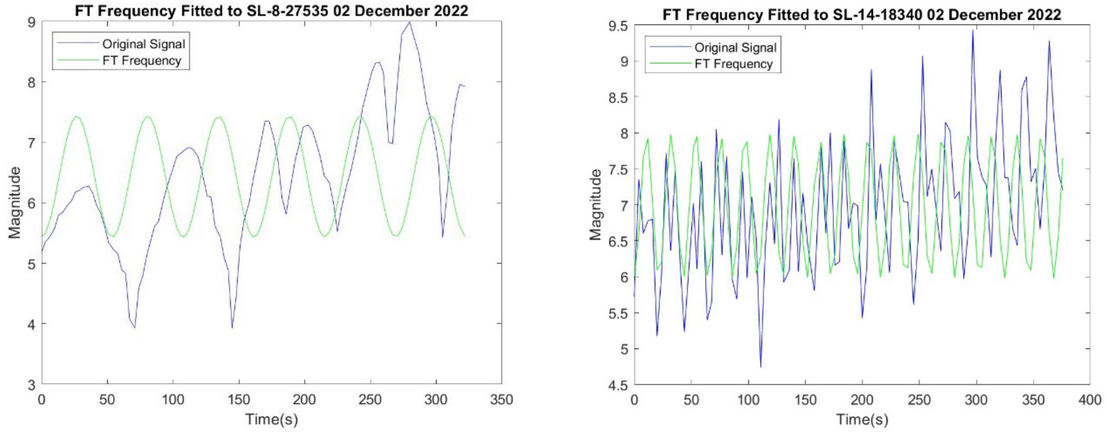

Fig. 4: Frequency Fitted Graphs of the SL-8-27535 (Left) and the SL-14-18340 (Right).

Table 2 displays all 26 observations taken over a four-month period (November 2022 – February 2023) of 19 distinct R/Bs. Of those 19 R/Bs, 5 appear to be stable,13 appear unstable, and 1 exhibit both attitudes. The rows that are color-coded indicate that the R/B was observed on multiple nights. Any row that is not color-coded means that the R/B was only observed once during the four-month period. The one R/B (SL-8-07426) that exhibit both attitudes is colored coded yellow and is an example of the same R/B appearing to be stable one night and then unstable months later. This is very evident in Fig. 5 and was also seen in a previous study [6].

Table 2: Rocket Body Synodic Periods

Date (yyyymmdd)	Rocket Body	Stability	Synodic Period(s)
20221108	CZ-4C-39261	Stable	N/A
20221202	CZ-4C-39261	Stable	N/A
20221209	CZ-4C-39261	Stable	N/A
20221202	CZ-4C-48341	Stable	N/A
20221202	CZ-4C-52201	Unstable	192
20230202	CZ-4C-52201	Unstable	488
20221108	Delta-2-25774	Stable	N/A
20221209	Delta-2-25774	Stable	N/A
20230202	SL-08-05707	Stable	N/A
20221108	SL-08-07426	Stable	N/A
20230202	SL-08-07426	Unstable	200
20221108	SL-08-03577	Unstable	968
20221108	SL-08-04255	Unstable	840
20230210	SL-08-27466	Unstable	808
20221209	SL-08-27535	Unstable	115
20221202	SL-08-27819	Unstable	424
20230210	SL-08-28381	Unstable	648
20230201	SL-08-28421	Unstable	472
20230210	SL-08-36520	Unstable	165
20221202	SL-14-18340	Unstable	22
20221209	SL-14-18340	Unstable	11
20221108	SL-14-20306	Stable	N/A
20221209	SL-16-22285	Unstable	520
20230201	SL-16-23705	Unstable	78
20230202	SL-16-23705	Unstable	243
20221209	SL-16-28353	Unstable	488

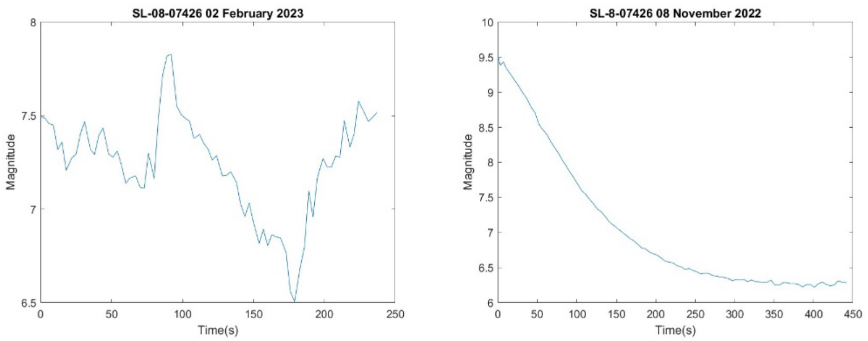

Fig. 5. Observations of SL-8-07426 taken 3 months apart showing very different light curves.

4. CONCLUSION AND FUTURE WORK

This study was an initial attempt to observe and characterize the spin dynamics of different classes of rocket bodies in low earth orbit that impose a higher probability of collision with other large resident space objects. Observations of 19 R/Bs were taken over a four-month period from November 2022 to February 2023; of these, 5 rocket bodies appear to be stable while 13 appear unstable or partially unstable. Seven R/Bs were observed more than once and only one of them (SL-8-07426) exhibited both a stable attitude and an unstable attitude. For future work, not only are more observations required, but we need to take the next step and determine the absolute period of rotation. Additionally, more analysis is required to determine why an R/B can be observed to have a stable attitude and then months later exhibit an unstable attitude. This phenomenon was seen in this study as well as in a previous study [6].

5. ACKNOWLEDGEMENTS, DISTRIBUTION, AND DISCLOSURE

We want to acknowledge the support of the Air Force Office of Scientific Research.

DISTRIBUTION STATEMENT A: Approved for public release: distribution unlimited. PA#: USAFA-DF-2023-559

6. REFERENCES

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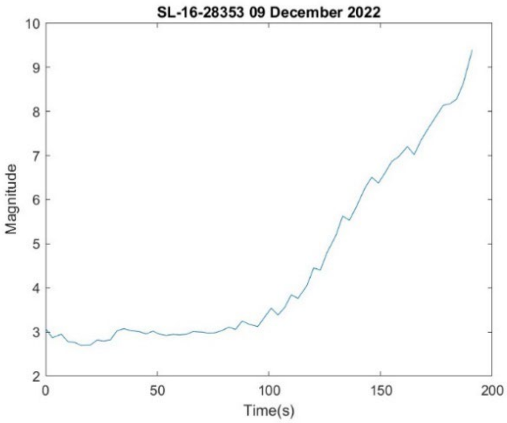
7. APPENDIX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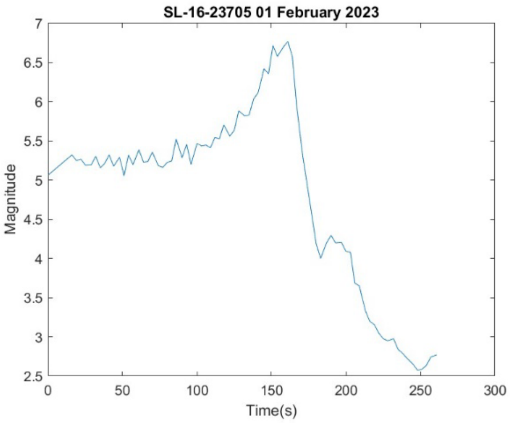
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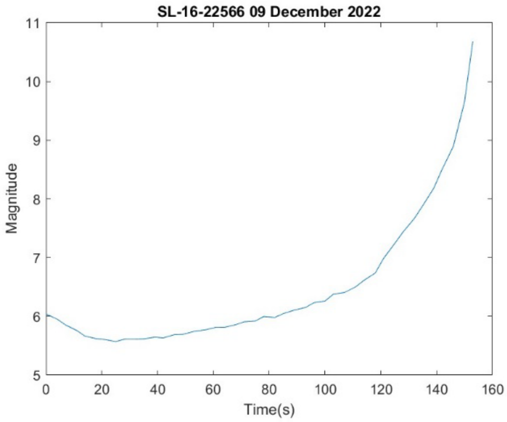
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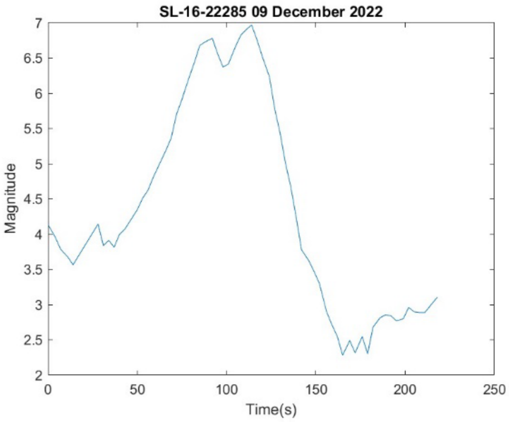
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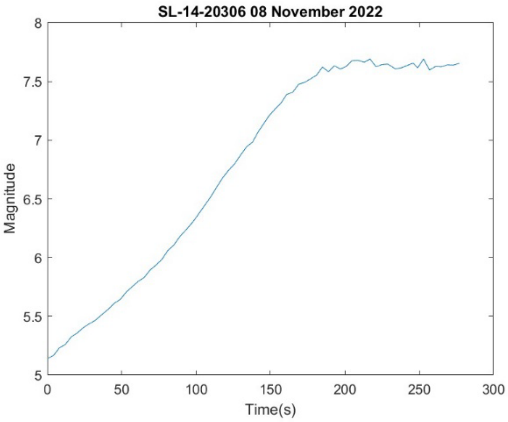
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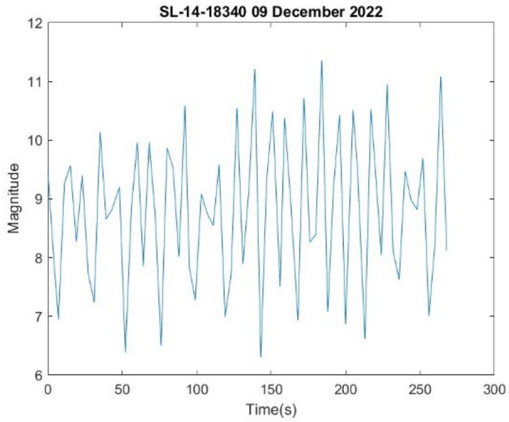
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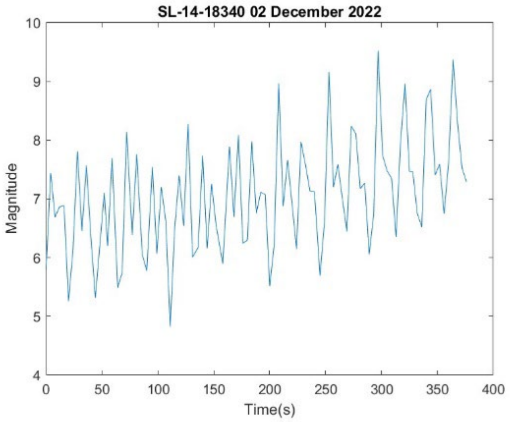
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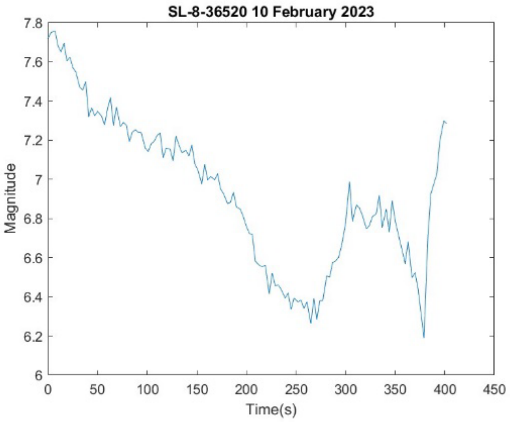
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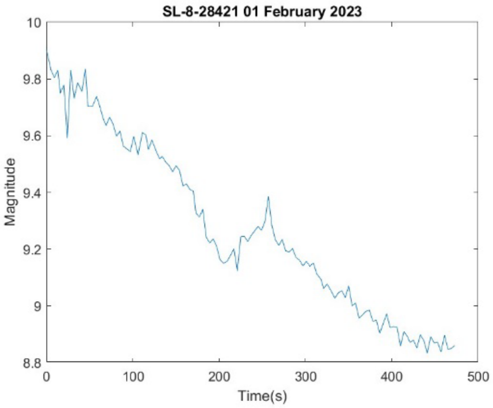
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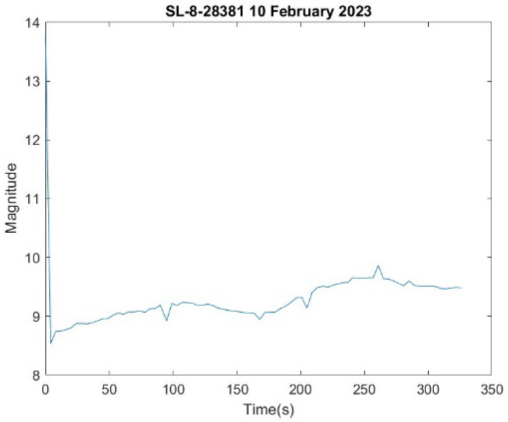
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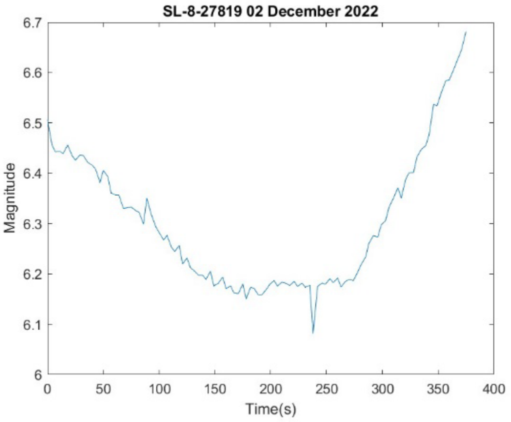
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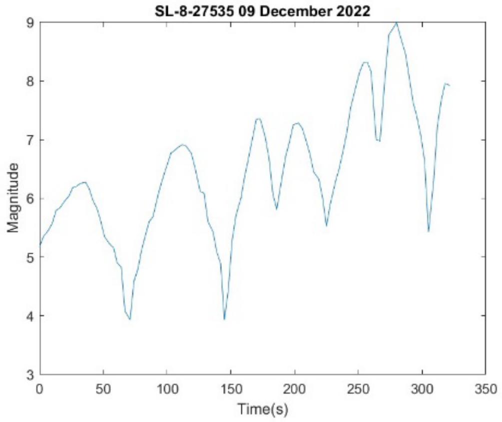
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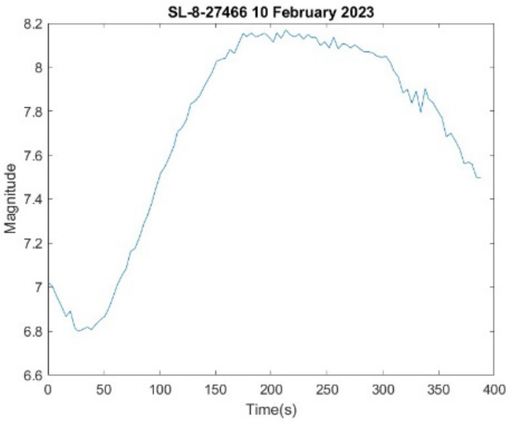
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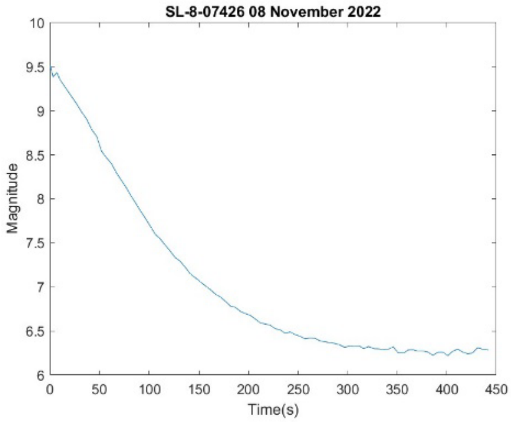
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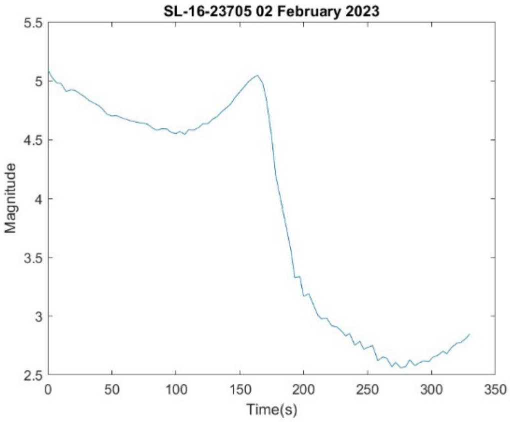
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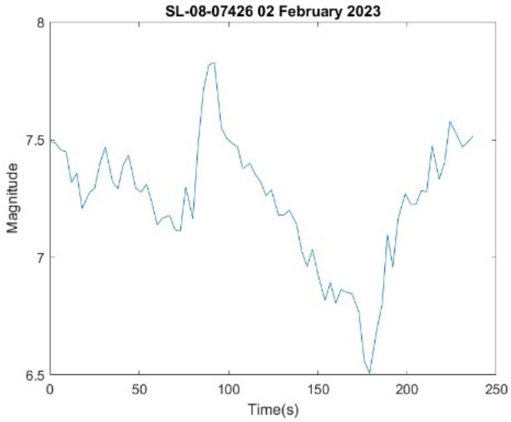
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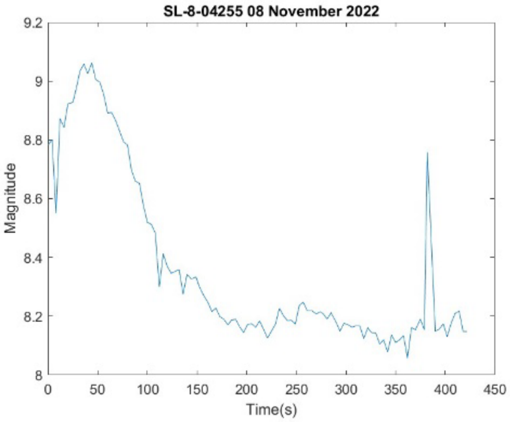
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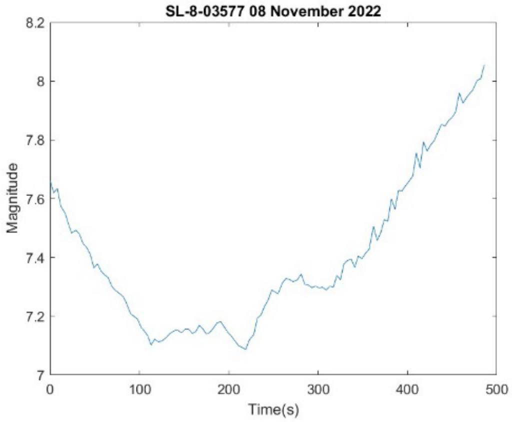
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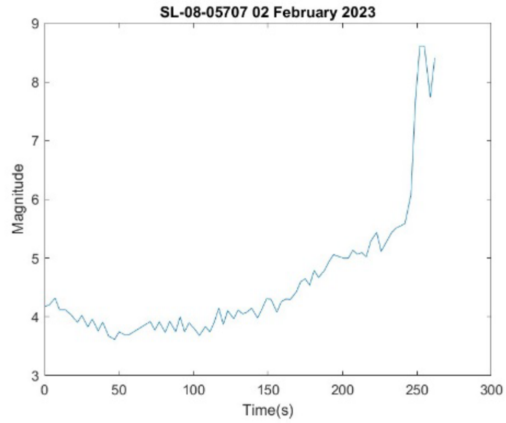
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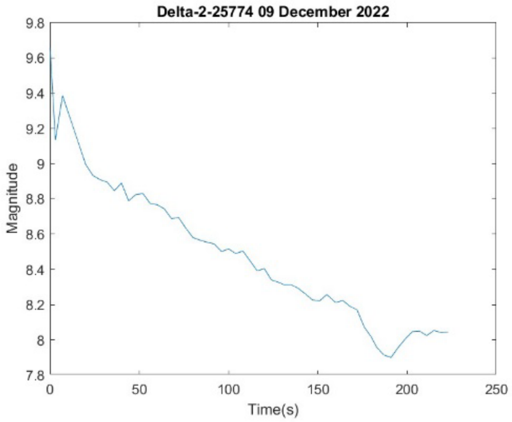
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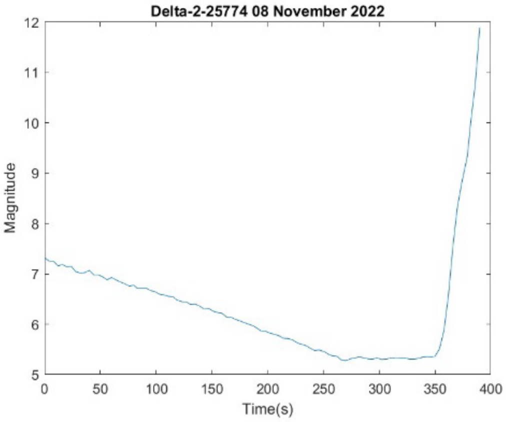
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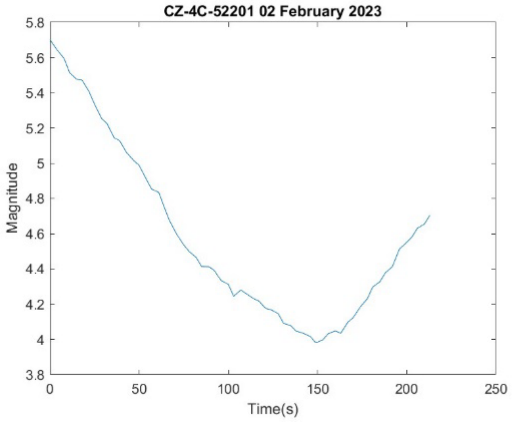
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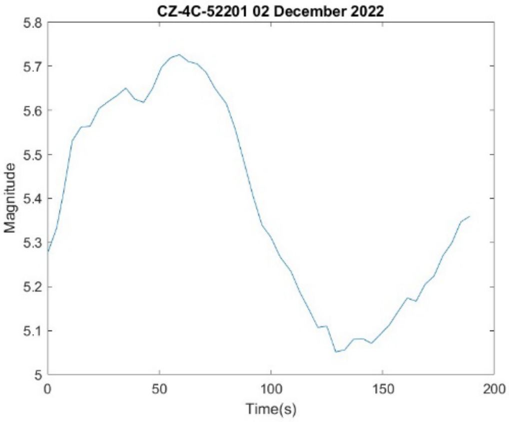
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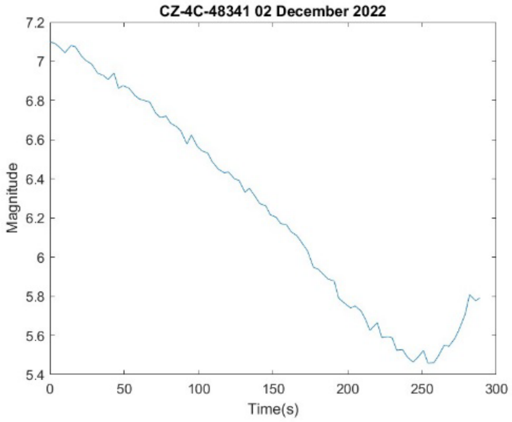
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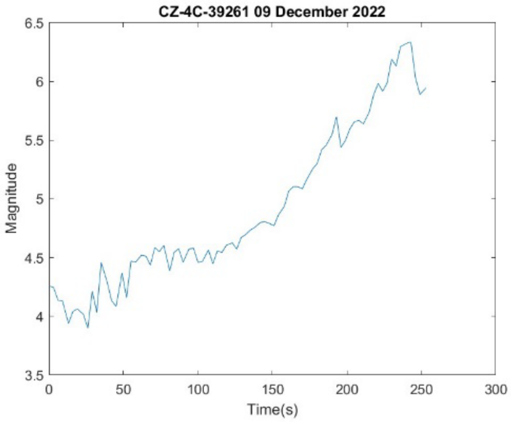
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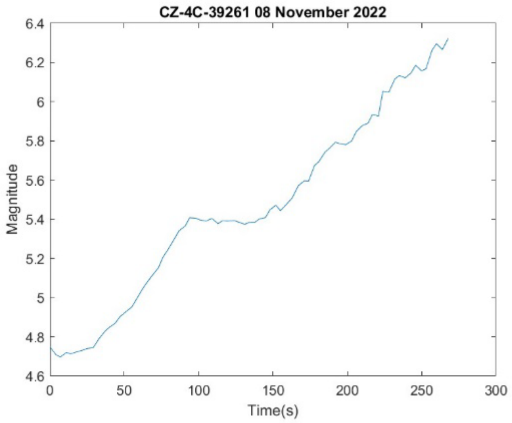
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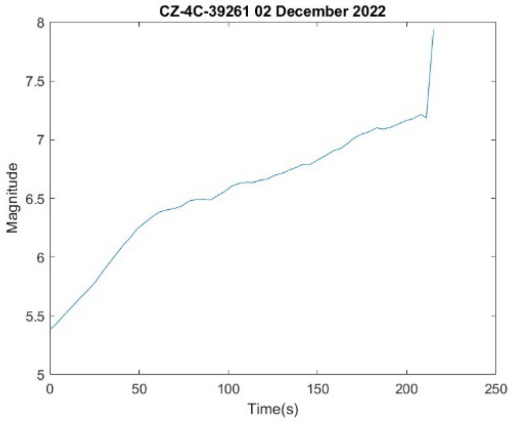
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