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Rocket Body Tumbling Assessment Through Radar, Optical Telescope, and Imaging

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Abstract

The tumbling of intact derelicts, especially rocket bodies due to their typically larger aspect ratio, creates challenges for active debris removal (ADR) solutions. However, it is unclear how quickly (i.e., tumble rate) and in what modes (i.e., flat spin, end-over-end, or multi-axis) rocket bodies might be tumbling. This parameter is important for prioritizing ADR targeting sequences.

This project captures measurements on rocket bodies using four diagnostic measurement modes. The four diagnostic measurement modes include (1) ground-based optical telescope approximations of the objects' tumble rates/modes, (2) variations of ground-based S-band radar cross-section (RCS) data, (3) imagery from a space-based earth observation system performing non-Earth imaging, and (4) time history of positional uncertainty derived from ground-based radar measurements.

The characterization of the objects' tumble rate can be used to both assess difficulty of ADR grappling/detumbling processes and examine correlation to positional uncertainty that will directly affect probability of collision calculation integrity. The challenging need to measure these different dynamic modalities over a short timeframe is balanced by examining several potential targets.

Processes developed in this activity may be used as a prototype for high confidence tumble rate assessment for objects in LEO and other space object characterization tasks.

Keywords: space object characterization, space situational awareness, active debris removal

1. Background

Space situational awareness (SSA) and space domain awareness (SDA) efforts must be refined with measurement diversity and ability to scale as the LEO space population continues to grow dramatically in number of objects and number of countries operating.

Specific events will likely become more complicated and difficult to characterize quickly. This reality served as a catalyst to assemble the team for this study effort. The ability to detect interesting situations then quickly apply ubiquitous radar measurements (time series positional uncertainty and radar cross-section, RCS), light curves from ground-based optical telescopes, and non-Earth imaging (NEI) by space-based assets of space objects brought to bear in the same timeframe provides a unique characterization capability.

This effort shows how we can integrate tasking of these different measurement modes and assess an object's attitude and tumble characteristics.

The specific use case for this effort is to test the hypothesis that the positional uncertainty of rocket bodies (RBs) in LEO are affected by their tumble rate. Specifically, it is conjectured that RBs will have low positional uncertainty if they are either very stable or tumbling very quickly. Conversely, if an RB is tumbling slowly (i.e., 0.5 to 2 °/min) about the minimum dimension axis (i.e., tumbling end-over-end), then it is anticipated that the positional uncertainty will be worse (i.e., larger). The goal of simultaneous measurements of RBs is to provide a wealth of information to determine their dynamic state unambiguously which, in turn, provides valuable information to debris remediation companies trying to prioritize derelict hardware for active debris removal (ADR) missions.

This ability to task, acquire, and integrate information from a variety of collection sources to characterize space objects has many other applications to include breakup forensics, payload mission status, object identification, etc.

The capabilities of each of the participants are provided before results are presented.

2. MAXAR Capabilities

MAXAR's fleet of electro-optical imaging satellites are capable of capturing resolved focused non-earth imagery (NEI) of spacecraft in a variety of orbits. The only limitations being range, relative rates, and angular separation from the sun. Focus can be achieved for objects down to a range of about 50 km, resulting in a Space Sample Distance (SSD, or "resolution") of about 2.5 - 3 cm depending on which spacecraft is used. For close encounters, high angular rates may limit collection feasibility. The imaging spacecraft cannot aim its imaging sensor too close to the sun; and from an image quality/interpretability standpoint, a larger angular separation between target and sun provides for better illumination. Therefore, the encounter geometry could provide for multiple sequential images as well, which creates a time-series that can be analyzed to characterize a target's stability and to extract an approximate rotational rate and spin axis (whether uniform or complex). The time separation between images will dictate the maximum rotational rate that can be detected; if the target rotates more than 180° between images, it may become indeterminant as to which direction it's rotating and at what rate.

Given an accurate estimate of the target's orbit obtained from open-source providers such as LeoLabs, a prediction can be made as to when upcoming imaging opportunities will be feasible. Once an encounter is identified, the imaging spacecraft is tasked in such a way as to track the relative motion of the target to ensure no smearing occurs. Note that the MAXAR satellites employ a line-scanning (push-broom) methodology as opposed to being a full-frame imager.

The rotation about the imaging spacecraft's boresight can also be customized to any orientation to increase the success of the collection. For example, one could scan along the direction of the relative motion to minimize the required body rates, or alternatively, the scan could proceed along the target's orbit track in order to minimize the impact from uncertainties in its position (or to obtain coincident imagery of co-orbital objects in close proximity). The focus setting can be changed for each scan as well to maximize image quality.

Once the imagery is produced, an analyst is then able to perform several mensuration assessments knowing the orbit of both observer and target, along with knowledge of the observer's inertial attitude. Projections of target-centric directions to the Sun, Nadir, and Velocity Vector are possible, which provide a sense for how the target is flying. Target size estimates can be made knowing the range to the target and the SSD of the image.

To estimate the target's "relative" orientation with respect to the image frame, the analyst may employ several techniques. One is to model the target in a 3D orbitology application such as Systems Toolkit (STK). The user can manipulate a model within the visualization software until it approximates the captured image. Another approach involves assigning arbitrary body axes along identifiable features of the target; for example, assigning Z-body to the long axis of a rocket body. The orientation of these axes is then measured in the image frame. These angles can then be fed to an evolutionary estimator to iterate on candidate inertial orientations until the resulting body axis directions match those that were measured. Finally, once an estimate is made of the individual target attitudes (assuming a multi-shot collection), a calculation can be made to determine the target's inertial rotation rate and spin axis knowing the time interval between images.

3. University of Bern Capabilities

The Astronomical Institute of the University of Bern (AIUB) operates several telescopes at the Swiss Optical Ground Station and Geodynamics Observatory in Zimmerwald. Routine photometric observations are made using the 1-meter ZIMLAT telescope and a Spectral Instruments 1100 CCD camera mounted at the 4-meter focal station. The 2048 x 2048 pixels of the sensor cover a FoV (field of view) of 26.4' x 26.4'. The exposure time for LEO objects is usually 0.1 seconds. Together with the readout time of the CCD sensor this leads to a sampling rate of 1 frame per second (fps). For light curves with higher temporal resolution the Oxford Instruments Andor Zyla 5.5 sCMOS camera is used. It is mounted at the 5.6 m focus of the 0.8-meter ZimMAIN telescope. The 2560 x 2160 pixel CMOS sensor covers a FoV of 10.2' x 8.6' and it can acquire subframes at a frame rate of more than 100 fps. The ephemerides of the RBs are generated using two-line element sets (TLEs) and simplified general perturbations (SGP) propagators. The observation window for LEO objects is typically 3-12 min and during the observation the changing elevation and phase angle can lead to trends in the light curve.

At the beginning of a photometric observation series a full frame is acquired to locate the object. Then a series of sub-frames spanning 200 by 200 pixels is acquired. The image-processing pipeline automatically computes the centroid and the total intensity of the object for each sub-frame. The mid-exposure modified Julian date and the relative magnitude are then stored in a text-based file. The acquired light curve is checked for anomalies such as clouds or bright streaks using the raw frames as a reference. If the light curve features a periodic pattern a phase-diagram reconstruction method is used to recover the apparent period that minimizes the dispersion of the measured relative magnitudes. In practice, periods of a few seconds to a few hundred seconds can be detected in this way.

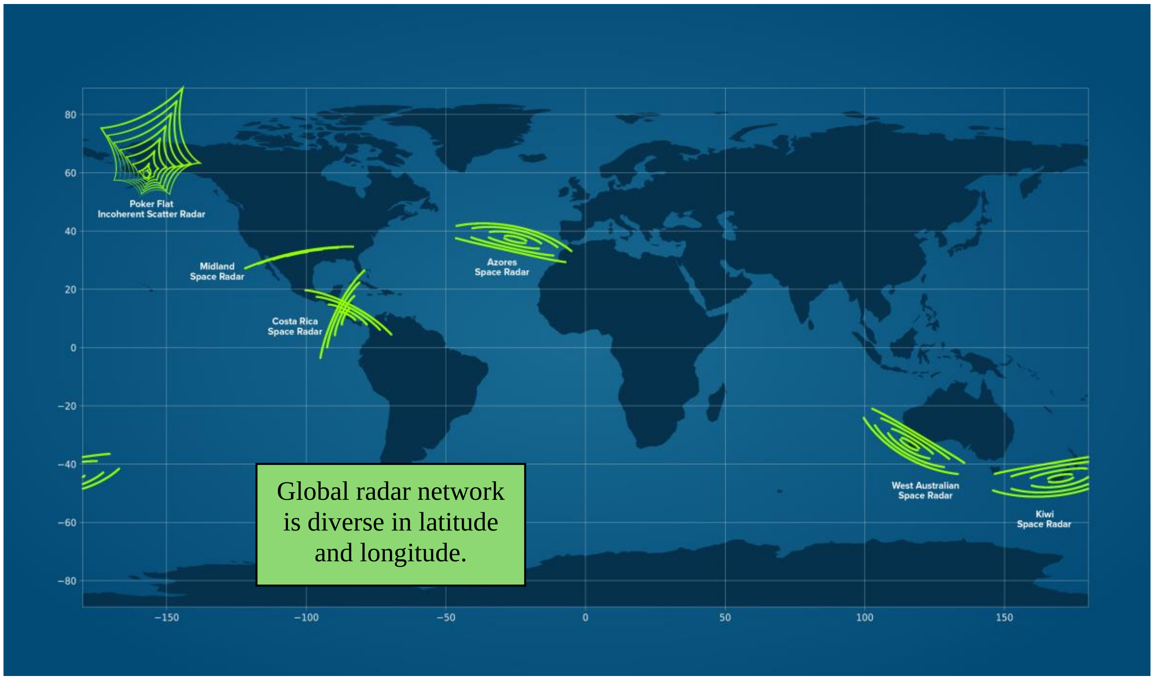
4. LeoLabs Capabilities

LeoLabs operates a global network of radars with 10 radars at six sites on four continents, as shown in Figure 1. These one dimensional (1-D) phased array radars can take detailed measurements on 800 to 900 objects per hour resulting in millions of measurements daily and on the order of 100,000 state vectors generated daily for the ~23,000 objects in the LEO catalogue. It takes only five minutes for the system to create a new state vector for an object after it crosses any of the radars. This information is used to update relevant Conjunction Data Messages, identify orbital maneuvers, and many other features of SSA/SDA. The typical LEO space object has its orbital state updated four times a day, however, some space objects have a much higher revisit rate, as high as 12 times a day due to object altitude, inclination, size, and tasking priority. Frequent update rate and modern orbit determination software results in epoch positional uncertainty values for intact objects in LEO on the order of 15 to 30 m.

Radar measurements also include a determination of radar cross-section (RCS) which is a depiction of the radio frequency (RF) signal returned from the space object. While it is often assumed that RCS is a direct measurement of the physical cross-section of a space object, it is not. RCS is loosely correlated to the physical cross-section due to fluctuation whereby a very small change in orientation can change the signal return from an object. [1] In addition to fluctuation, the material makeup (e.g., metallic vs composite or polymer), object shape (e.g., flat, convex surface, or concave surface), geometry of object pass over the radar (e.g., range, elevation angle, and object's track relative to the center of the transmit beam), and variations in the radar performance parameters (e.g., system noise, transmitter gain, etc.) affect RCS values. [1] As a result, the RCS value requires a series of quality control checks that include minimum signal to noise ratio of 15 dB, at least three measurements per tracklet (i.e., per single radar pass), and 50 tracklets before a statistical physical cross-section can be determined by using the median of the 50 or more RCS values. However, the large amounts of RCS data acquired by LeoLabs allows a time series representation of a space object's RCS by aggregating sufficient measurements to potentially examine an object's dynamic physical cross-section, and thus attitude, relative to the radar, however, this is only effective for very stable objects (i.e., keep same orientation over time).

5. Simultaneous Tasking Approach

The process by which the three investigators for this measurement campaign cooperated exemplifies the restrictions on the measurement modes for these three modalities. LeoLabs radar data is ubiquitous and continuous so did not drive the synchronization of efforts; 24/7 service provides flexibility. MAXAR's space-based assets can predict quantitively the optimum opportunities for taking a sequence of images of a resident space object, interestingly leveraging the state



Global radar network is diverse in latitude and longitude.

Fig. 1 LeoLabs operates 10 radars at six sites around the word; eight of the radars are S-band one-dimensional phased array radars.

vectors of both objects as produced by LeoLabs. The University of Bern optical observations from the ground are highly affected by both weather and sun angle which can both change significantly over short time scales. Starting this collective process in the dead of winter when cloud cover is common in Switzerland, limited the number of opportunities for joint simultaneous measurements. However, as late Spring and early summer rolled around there were more and more chances for joint measurements. As a result, the tasking process evolved into following the MAXAR imaging schedule.

6. Results

The first observation made by all parties was of a CZ-2D RB (SATNO 53878) on 16 March 2024. From open-source reporting [2], a CZ-2D RB has a mass of 4,000 kg, length of ~6 m, and diameter of ~3 m. MAXAR calculations estimates the length to be ~10 m and diameter ~3.5 m. Figure 2 portrays how the four sets of observation data were merged to assess the dynamic state of this RB. The upper lefthand quadrant shows the NEI from MAXAR which shows the object to not be gravity-gradient stabilized. As a matter of fact, in MAXAR's experience in monitoring rocket bodies in orbit, they are more likely to conform to a minimum drag orientation with the smallest cross-section in the velocity vector. Though in this case, it was interially stable and traveling more broadside into the velocity vector.

The lower left quadrant is the light curve taken by the University of Bern on the same day as the MAXAR image but just a few orbits later. This light curve shows a small variation in the relative magnitude over time indicating a stable object orientation. The CCD light curve was collected with 0.1 sec exposure time and 1 Hz frame rate.

The lower righthand quadrant displays the time series RCS taken by LeoLabs with the vertical dashed line indicating the time of the MAXAR image. The distribution of RCS has small variation over time indicating a stable orientation. This one CZ-2D RB is about 11% larger in average RCS than the total ensemble of 23 CZ-2D RBs on-orbit hinting that it is oriented with the maximum physical cross-section pointing toward the earth as MAXAR's assessment suggests.

The upper right quadrant of the figure depicts the positional uncertainty over time for this RB. The positional uncertainty at epoch is also stable supporting the assertion that the RB is either very stable or tumbling very quickly. It is not believed that the positional uncertainty distribution can differentiate between a stable RB versus a quickly tumbling RB.

However, since the other three measurements point toward a stable orientation for this CZ-2D RB, this data set suggests that this RB is not tumbling, and with all else equal, it would be a good candidate for retrieval since it does not pose a grappling challenge.

Further, a sequence of NEI frames (Figure 3) clearly shows that the RB is stable. Scrutinizing the sequence of

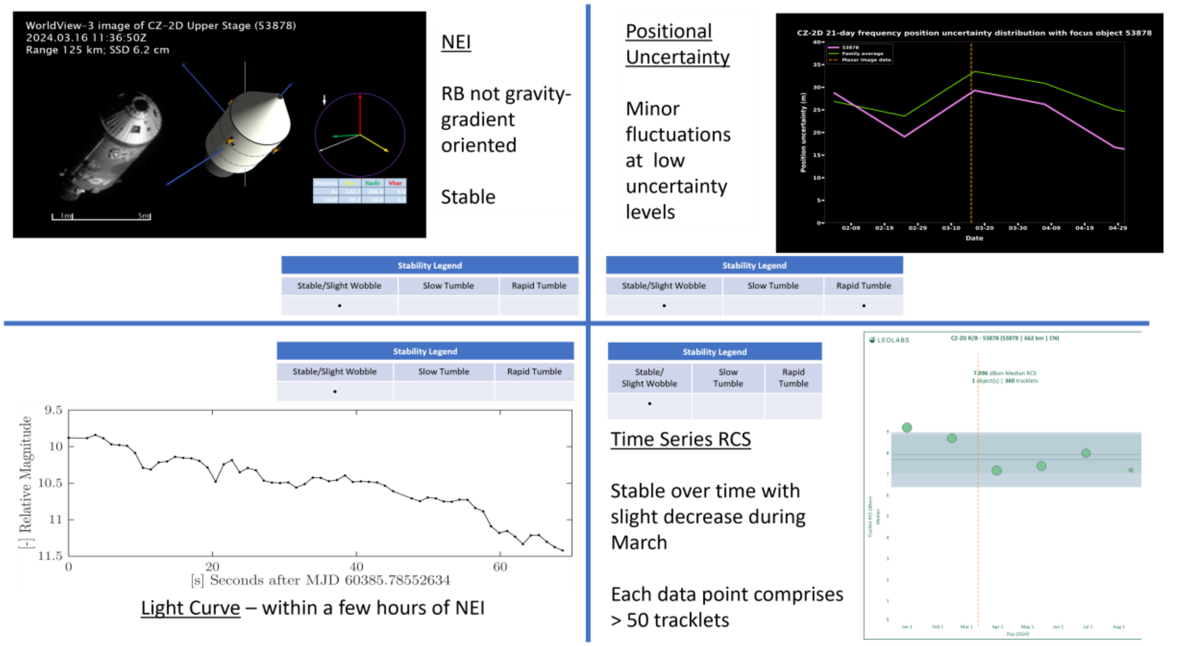


Fig. 2. The near-simultaneous observation of a Chinese RB by space-based NEI, ground-based telescope, and ground-based radar supported the observation that this massive derelict was in a slow wobble and thus a viable target for ADR.

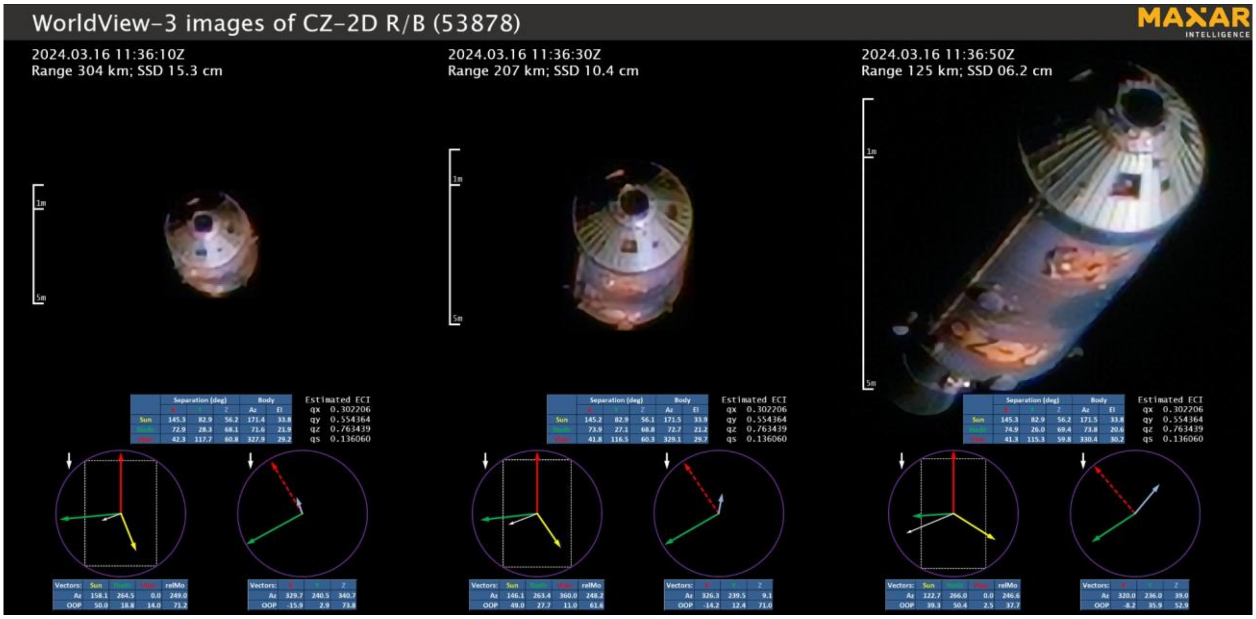


Fig. 3. A time series of NEIs for SATNO 53878 depicts the small tumble rate of this object very clearly. Please note that the axes below the actual images must be considered as these axes adjust for the change in perspective for the individual images.

the images from Maxar for this RB is very illustrative of its dynamics. Figure 3 shows a series of three images over time. It is important to note that the apparent movement in the three images must be considered relative to the coloured reference frames below each image and should not be interpreted as the dynamics of the RB.

The reference frame on the left under each image is for target relative to the Earth and Sun. The axes on the right are for the target with the Z-axis representing the long dimension of the RB. However, neither of these directly informs the stability of the RB.

The table and matrix above these two reference frame depictions are the Earth Centered Inertial (ECI) quaternions. The change in the ECI over time directly characterizes the tumble/wobble rate of the RB. For this example, the quaternion does not change at all throughout this sequence, so it is stable.

A second cooperative collection was completed on 24 August 2024 of a Chinese CZ-4C RB (SATNO 41728) that resides around 650 km altitude. From a technical paper [2], the RB is reported as 2,000 kg in mass and ~6 m long with a diameter of ~3 m. MAXAR estimates the RB to be 5.4 m in length and 3.0 m in diameter. Figure 4 shows all the measurements made by the team for this collection.

The University of Bern was able to capture a 2-minute light-curve of using the CMOS sensor on the 80cm Telescope at 20:05 UTC on 23 August. The exposure time was 0.01 sec and the frame rate was 20 Hz. The solid line on the curve is the Savitzky-Golay value filtered with order 3 and window size 101. The light curve indicates a stable object. Further, the RCS for 41728 was almost exactly the same as the ensemble of 47 CZ-4C RBS currently on-orbit indicating that all of these RBs may indeed be oriented in a similar fashion.

LeoLabs collected positional uncertainty measurements and RCS values over time for this RB. The results indicate a stable object as the positional uncertainty and the RCS variation are both small.

MAXAR took 13 scans on 25-Aug from 02:27-02:31Z, with SSDs from 10-6 cm. The single NEI in Figure 4 portrays the orientation of the RB relative to the Earth as the nose of the RB “pointing at the Earth”. However, the sequence of NEIs in Figure 5, including five of the images, provides the insight into the stability of the RB. It is wobbling about the long axis. More specifically, the RB is rotating very close to orb rate (within about 10%), which is 0.061 deg/sec for this object. Interestingly, the two exhaust cones then align with the Y-Z plane. As it turns out, the nose cone is a bit under 20 degrees off-nadir during this sequence and since the RB is pitching at orbital rate, it remains in this orientation throughout the orbit (nose almost down and rotating about nadir).

7. Conclusions

This examination of RBs by four independent but near-simultaneous measurements provide a high confidence evaluation of the dynamic states of these objects. This information at scale (i.e., for all potential intact derelicts being considered for ADR) could be very useful for operationalizing ADR soon. However, the utility of this sort of collaborative effort goes well beyond debris remediation. This type of activity could be used for diagnostic (i.e., determining state of recently launched object), forensic (i.e., provide insight into the state of a recently failed space system), verification (i.e., prove an entity's claim about the state of a space object), and many more possibilities. As the LEO space environment continues to get more cluttered and competitive this sort of insight may be used to improve space safety and defuse space security situations.

References

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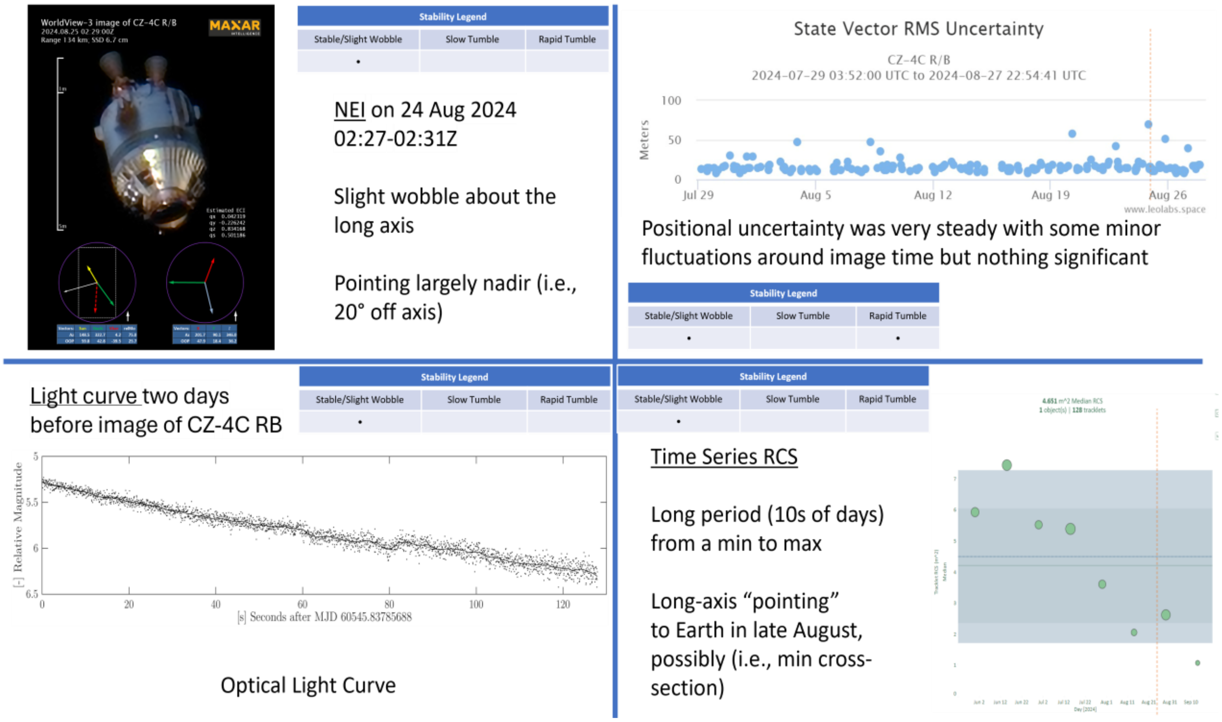

Stability Legend		
Stable/Slight Wobble	Slow Tumble	Rapid Tumble
•		

NEI on 24 Aug 2024 02:27-02:31Z

Slight wobble about the long axis

Pointing largely nadir (i.e., 20° off axis)

Positional uncertainty was very steady with some minor fluctuations around image time but nothing significant

Stability Legend		
Stable/Slight Wobble	Slow Tumble	Rapid Tumble
•		•

Stability Legend		
Stable/Slight Wobble	Slow Tumble	Rapid Tumble
•		

Stability Legend		
Stable/Slight Wobble	Slow Tumble	Rapid Tumble
•		

Time Series RCS

Long period (10s of days) from a min to max

Long-axis "pointing" to Earth in late August, possibly (i.e., min cross-section)

Fig. 4. A cooperative collection on SATNO 41728 indicates a very stable dynamic with the RB generally "pointing at the Earth (i.e., smaller projected area to Earth observers) at the observation time.

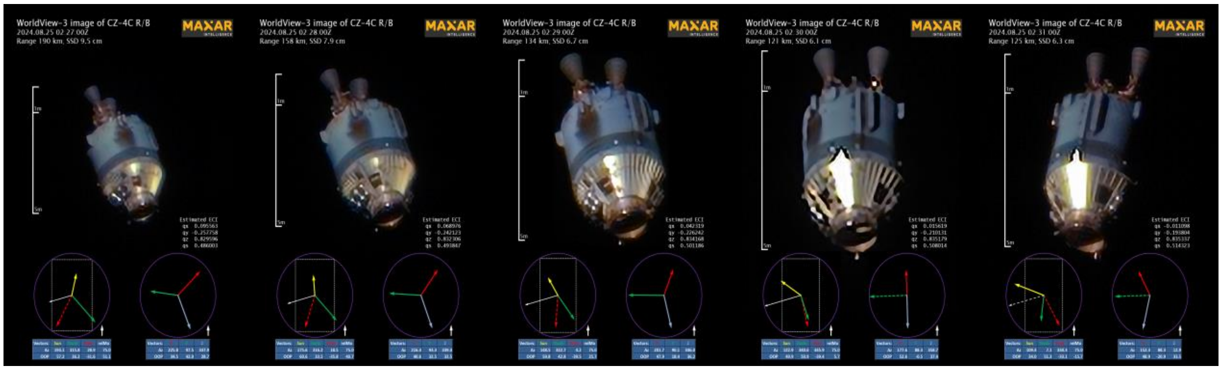

Fig. 5. A sequence of NEIs of SATNO 41728 reinforces the assessment that this RB has a short period, low amplitude wobble about the long axis while traveling in a gravity-gradient orientation.