Expanding Pattern-of-Life Capabilities on Passive Radio Frequency Datasets

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ABSTRACT

In today's increasingly congested and contested satellite communications (SATCOM) radio frequency (RF) signal environment, it is crucial to monitor, track, and characterize the behaviors of space-based assets to support Space Domain Awareness (SDA). Historically, SDA has relied on orbital state estimation of assets based on optical and radar measurements. While these phenomenologies offer distinct advantages, they are also subject to significant limitations. In this paper, we discuss the use of RF measurements to develop a pattern-of-life for space objects that enable the user to observe not only the orbital state but also the behavior of the spacecraft payload, which is crucial for the SDA mission.

The ability to perform optical observations is constrained by weather conditions and time-of-day limitations, while radar observations require significant transmit power to effectively observe objects in Geosynchronous Orbit (GEO), which poses logistical, regulatory, and environmental concerns. Additionally, these phenomenologies focus only on the orbital state of an object, and do not provide any insight into the behavior or operation of the spacecraft payloads.

In contrast, RF offer unique advantages over these traditional phenomenologies. RF measurements can be collected for objects emitting RF energy regardless of weather or time-of-day constraints. In addition to enabling orbital state estimation, RF measurements also allow the observation and characterization of the spacecraft payload. RF characterizations of downlinked signals (e.g., power, frequency, modulation type, data rate, etc.) can be conducted at regular intervals. While individual RF observations can offer immediate insights into the current state of payloads, their real value emerges when these measurements are accumulated over time to establish a pattern-of-life. SDA systems can then identify deviations from the expected behavior to flag significant and meaningful events and provide indications and warnings of potential issues long before they could be observed by using traditional phenomenologies.

Prior work in RF-based pattern-of-life analysis [1] has solely focused on univariate analysis of raw RF metrics over time (such as analyzing bandwidth utilization of a spacecraft over time). This paper seeks to expand on that work by conducting multivariate analysis on multiple raw RF metrics, as well as examining derived RF metrics. Specifically, this paper will define, present and analyze four distinct RF metrics, each of which contributes uniquely and meaningfully to the SDA mission.

The first section will examine how GEO satellites utilize their assigned bandwidth. Abrupt and unexpected changes in bandwidth utilization are often indicators of changes in real-world political, economic, or military events. The paper will first explore several examples of nominal bandwidth utilization, followed by instances of abrupt changes in bandwidth usage, and analyze their potential implications for SDA.

The second section will focus on the behavior of carriers, utilizing a multivariate approach that integrates multiple raw RF metrics to draw more comprehensive conclusions than can be achieved with any single metric in isolation. We will demonstrate how this multivariate approach allows us to understand behavior of payloads. By analyzing modulation type, data rate, time of day, and other RF metrics we can predict future operations and identify unexpected carrier activity, which might indicate technical issues or malicious activities. Additionally, multivariate pattern-of-life approach will be applied to find instances of Electromagnetic Interference (EMI) on satellites, including an example that was captured on a commercial satellite used by Russia during the Russia/Ukraine conflict.

The third section will introduce the first RF-derived metric: maneuver detection. While difference of arrival methods for maneuver detection have been well researched [2] [3], this paper will seek to leverage these results as inputs to a pattern-of-life detection model. Specifically, analysis of the time intervals between maneuvers, the duration of each maneuver, and the orbital elements will enable classification of nominal station-keeping, relocating, and rendezvous

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and proximity operation (RPO) maneuvers. We will demonstrate how the multivariate pattern-of-life approach can effectively identify instances where satellites come into proximity, providing valuable insights into potential close encounters and enhancing the overall SDA mission. This will be supported by a real-world example of a Russian satellite performing aggressive station-keeping maneuvers to drift uncomfortably close to a communications satellite.

The final section examines Very Small Aperture Terminal (VSAT) networks, showing how RF characterizations can track self-reported terrestrial or maritime positions. By integrating maritime self-reported geolocations with Automatic Identification System (AIS) beacon data, it becomes possible to reconstruct vessel locations, historical movements, and route patterns. This combined approach offers a detailed view of maritime activity and supports more accurate path and behavior analysis.

To perform pattern-of-life analysis on these datasets, this paper will build upon prior work [1] and enhance it by evaluating up to 45 outlier detection algorithms which includes 12 deep learning methods as provided by PyOD 2 [4]. The best performing of these algorithms will be applied on real-world data and integrated into a system that can autonomously alert operators of suspicious behavior on an object's payload.

In this paper, we explain how pattern-of-life applied to RF data offers substantial value to the SDA mission. Using these pattern-of-life capabilities, operators and analysts can achieve a multifaceted understanding of satellite operations. This includes pinpointing the precise location of satellites in real-time, monitoring the operational status and behavior of their payloads, and analyzing the IP traffic they manage. We apply these pattern-of-life models to real-world datasets to identify events relevant to SDA missions. By integrating these insights, SDA operators and analysts can make informed decisions, anticipate potential issues, and respond swiftly to emerging threats.

1. RADIO FREQUENCY OVERVIEW

Before discussing multivariate anomaly detection, several RF terms and concepts are important to understand.

- *Transponder*: A satellite communication unit that receives data from a ground antenna and then transmits that data to a different ground antenna. Satellites will typically have dozens of transponders, with each on a different portion of the RF spectrum. Transponders are defined by their frequency range, beam connectivity, and polarization.
- *Carrier*: A signal that a transponder emits. Carriers are modulated signals that carry data between ground stations. A transponder supports one or more carriers.
- *Payload Usage*: For every RF capture of a transponder with bandwidth b_t, there are n detected carriers, each with a bandwidth b_c.

  The Payload Usage can then be defined as $\frac{\sum_{i=0}^{n} b_{c,i}}{b_t}$

  (Note that this formula does not take guard bands between carriers into account.) Fig. 1 displays a transponder wherein all traffic stops and causes the payload usage to drop to 0.

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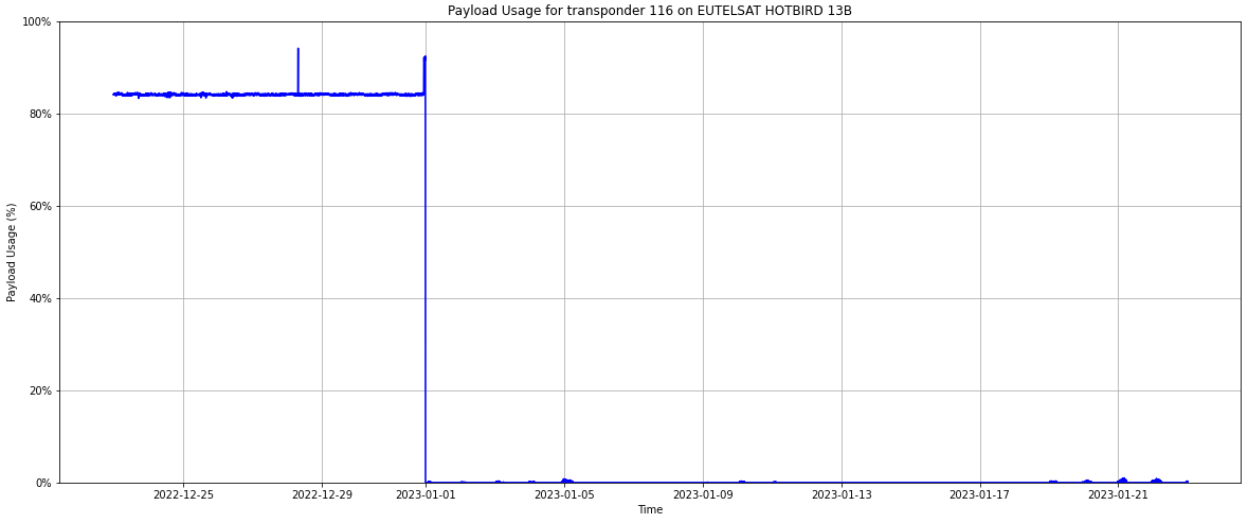

Fig. 1. Payload Usage Plot for Transponder 116 on Eutelsat Hotbird 13B wherein All Traffic Stops on 2023-01-01

- *Waterfall*/*Spectrogram*: For a transponder, this visualizes the RF spectrum using three dimensions: Frequency (typically in MHz), Time, and Power (typically in dBW). The terms "waterfall" and "spectrogram" are generally interchangeable terms. In this work, we will refer to these diagrams as waterfalls for the sake of consistency. Waterfalls are like heatmaps that give an analyst an at-a-glance view of payload behavior over time for an entire transponder. Fig. 2 shows a waterfall that has 7 distinct carriers, with each carrier designated by a horizontal bar. (Note that for clarity, the x-axis is time, the y-axis is frequency, and the color is power level per the color scale to the right of the plot in Fig. 2)

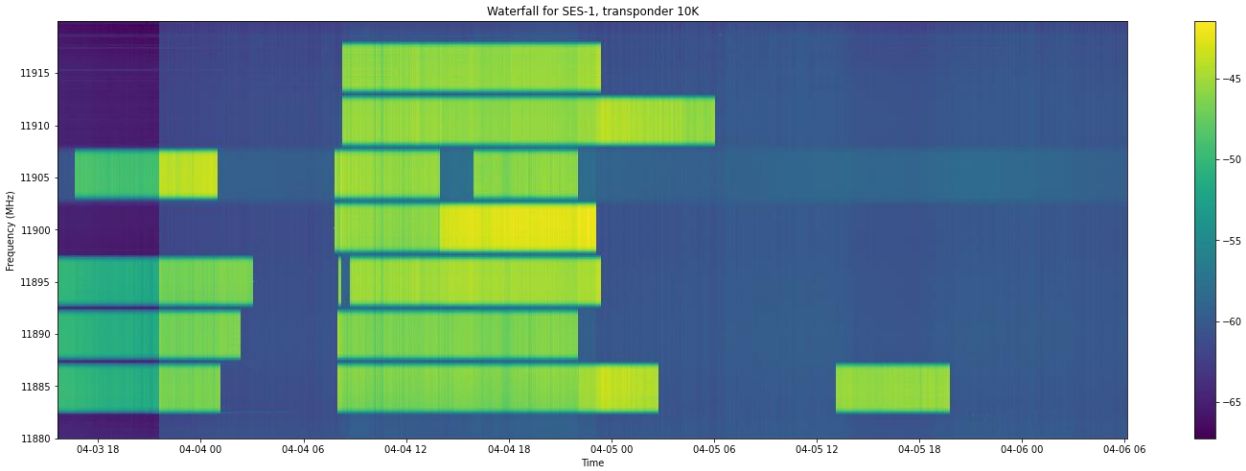

Fig. 2. Waterfall Plot of Transponder 10K on SES-1

- *Power Spectral Density (PSD):* Another way to visualize RF data. The x-axis is the RF frequency, and the y-axis is the signal power (typically in decibel watt (dBW)). This can give an RF analyst an at-a-glance view of instantaneous payload behavior for a transponder. Fig. 3 displays the PSD for an SES-1 transponder with 7 carriers at a particular instance of time.

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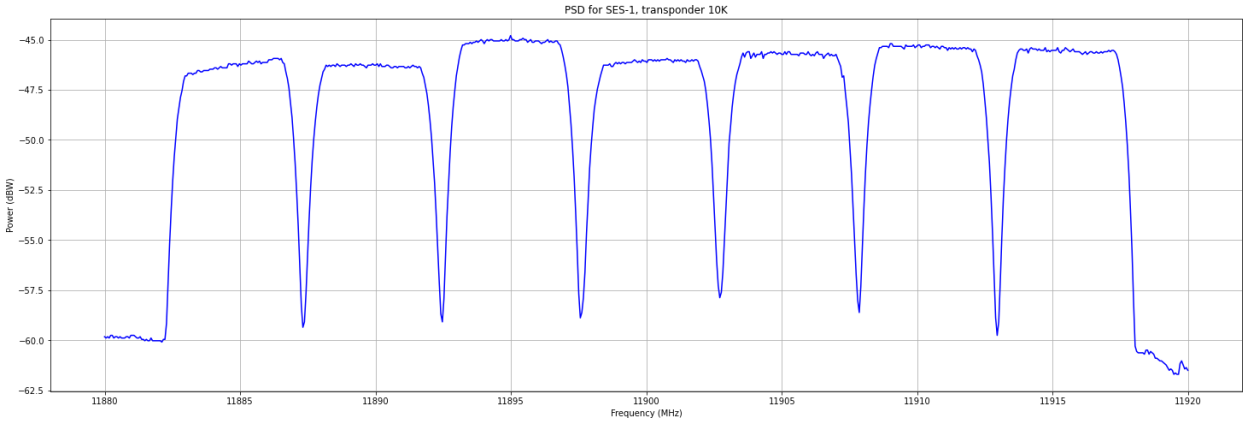

Fig. 3. PSD for SES-1, Transponder 10K on SES-1 with 7 Carriers

When transponder and carrier information is known, it can be visualized as shown in Fig. 4.

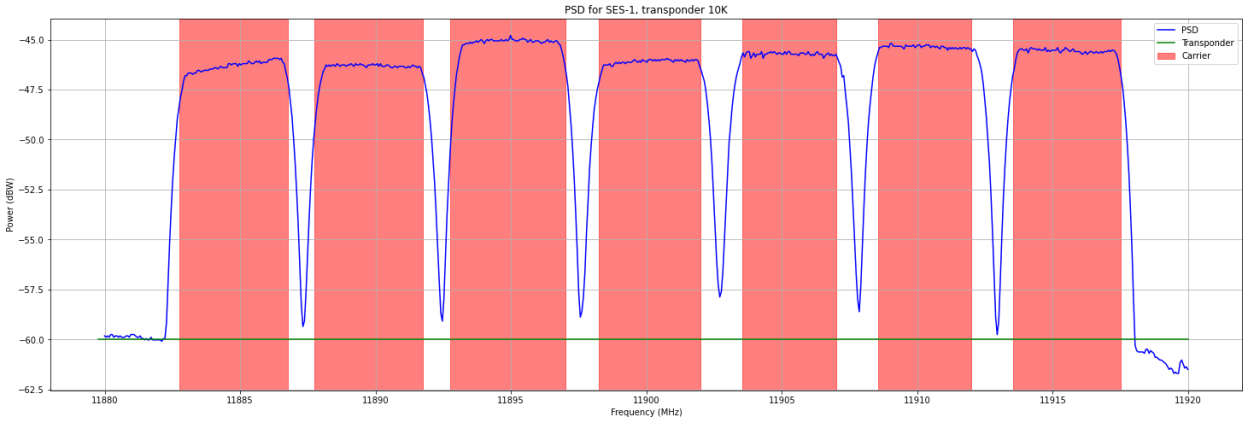

Fig. 4. PSD of a Transponder with Transponder (green) and Carriers (pink) Highlighted

- *Symbol*: For encoded carriers, the modulation process encodes bits of data into distinct RF states called symbols. The modulation type determines how many bits of information are contained in each symbol. For example, a carrier with modulation type 8PSK will encode every 3 bits into a single RF symbol. This knowledge is used by DSP algorithms in models, for example, to convert a stream of symbols back to the original transmitted message.
- *Symbol Rate*: The transmission rate in symbols per second. This is usually represented in kilosymbols per second (ksps) or megasymbols per second (msps).
- *Carrier-to-Noise (C/N) Ratio:* Higher ratios indicate better reception quality and in general, higher communications accuracy and reliability.

For a carrier, this is defined as $\frac{Power_{Carrier}}{Power_{Noise}}$

- *Energy per Symbol-to-Noise Density (Es/N0) Ratio*: Es/N0 is similar to C/N, with the exception that it measures the normalized ratio of the power of the symbol to noise. This metric is of particular importance because it is determined on the receive side after the signal is demodulated.
- *Interference*: There are many different kinds of carrier interference, but in this work we refer to it as one signal transmitted atop another, rendering the original transmission unusable.
- *Ephemerides:* Using passive RF ranging techniques, the orbital elements that describe a satellite's position and motion can be estimated with high accuracy. In this work, we focus on the following key parameters:

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- Period: The time required to complete one orbit.
- Eccentricity: A dimensionless parameter describing the deviation of the orbit from circularity, where 0 denotes a perfect circle and values approaching 1 indicate increasingly elongated ellipses.
- Inclination: The angle between the orbital plane and the Earth's equatorial plane, which determines the ground track coverage.
- Longitude: The geographic coordinate of a GEO satellite's sub-point on Earth, defined in the Earth's geodetic coordinate system and independent of the ascending node.

2. PATTERN-OF-LIFE ANOMALY DETECTION TECHNIQUES

Prior work in this area has primarily focused on univariate analysis of raw RF metrics, which, while useful to the SDA mission, remain limited in scope. For example, a carrier's power level may deviate from nominal for many benign reasons when viewed in isolation. However, if multiple metrics simultaneously depart from expected behavior, the likelihood of a true anomaly increases. To capture this richer context, we apply multivariate analysis and data fusion techniques to extract additional value from RF metrics.

PyOD provides over 50 models for anomaly detection. In this work, we present results only from the top-performing models. Because our datasets are unlabeled and our goal is to capture general patterns of life, we define "best" models as those that generalize well across domains (e.g., a model effective on orbital elements should also perform well on carrier metrics with minimal adjustment) and require relatively few training parameters.
The first three examples in this paper apply multivariate analysis. Specifically, we apply the following techniques:

- Matrix Profile: A python library that efficiently computes the matrix profile [5], a vector that stores the z-normalized Euclidean distance between any subsequence within a time series and its nearest neighbor. While developed for the univariate analysis case, the library was extended to work for multivariate datasets. In this work, we applied this extension so that subsequences of multiple RF metrics are compared together, allowing anomalies to be detected only when the joint behavior across metrics is unusual.
- Variational Autoencoder (VAE): PyOD implements VAE, in which input samples are mapped into a latent space parameterized by a mean (μ) and variance (σ^2). Training is performed on fixed-length windows, with the model learning to compress and reconstruct the multivariate input. Poor reconstruction quality is interpreted as evidence of an anomaly.
- LUNAR: PyOD implements a graph neural network approach for outlier detection called LUNAR. Unlike traditional density-based methods such as Density-Based Spatial Clustering of Applications with Noise (DBSCAN), which rely on fixed formulas and thresholds, LUNAR represents each data point as a node in a graph and learns adaptive edge weights to identify anomalies dynamically.
- Custom transformer: A transformer-based autoencoder was implemented in PyTorch that minimizes the mean squared reconstruction error (MSE). Inspired by the success of transformers in large language models, this approach leverages attention and self-attention mechanisms to capture complex multivariate relationships and to identify which time steps are most relevant for reconstruction.

Finally, we present a data fusion example that integrates AIS maritime beacon geolocations with self-reported positions from VSAT networks to highlight anomalies detectable only when multiple data sources are combined.

3. PAYLOAD USAGE ANALYSIS

Our first analysis examines the payload usage of multiple transponders on Intelsat-33e. As defined in Section 1, a transponder with no traffic has a payload usage of 0%, while a fully utilized transponder reaches 100%.

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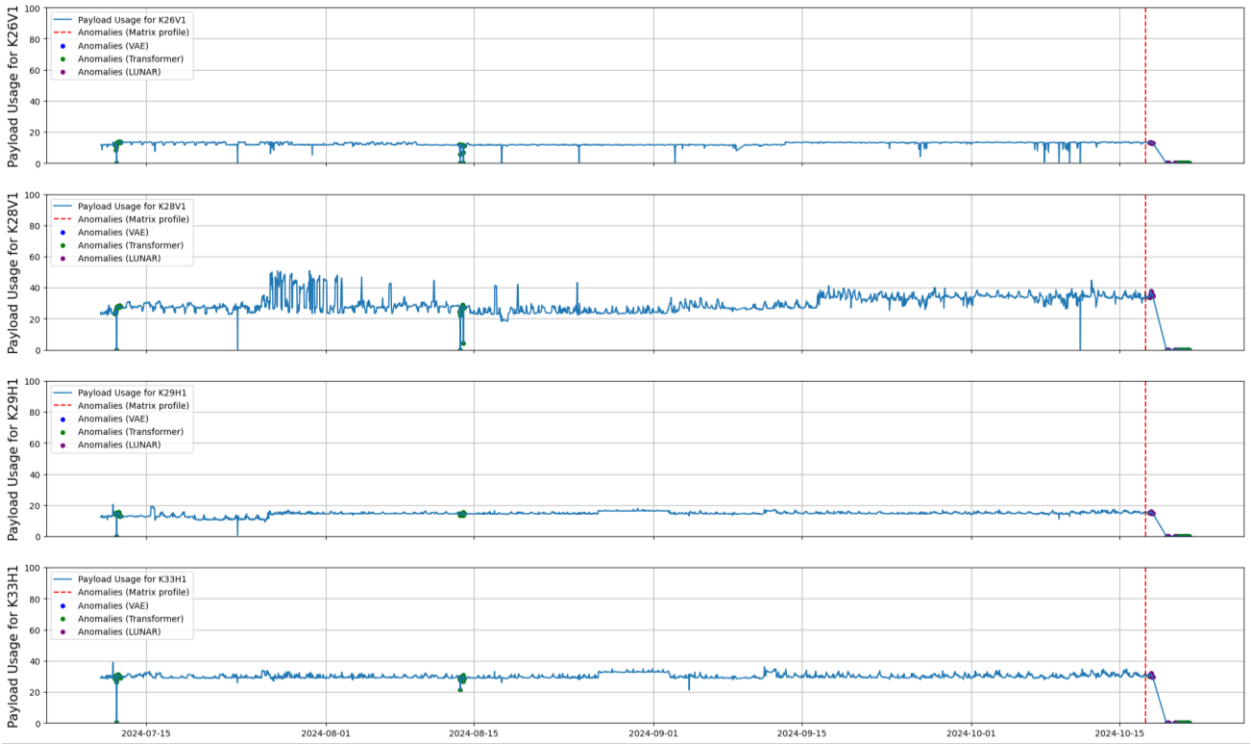

Fig. 5. Payload Usage Multivariate Analysis on Intelsat-33e showing abrupt drop in traffic on 2024-10-16

Over the four-month observation period, transponder subsequences appear largely consistent, with one striking exception on October 19, 2024. (Note that due to the selection in window sizes, some of the anomalies get detected a few days before the 19th). While it is not uncommon for a single transponder's payload usage to fluctuate independently of external events, it is highly unusual for all four transponders to exhibit a simultaneous and abrupt drop in traffic.

This anomaly aligns with the reported breakup of Intelsat-33e in orbit [6]. Notably, the anomaly was evident in the RF metrics immediately, whereas other phenomenologies did not confirm the breakup until several hours later.

The spectrogram in Figure 6 visually corroborates this finding, showing a sharp decline in power beginning on October 19th.

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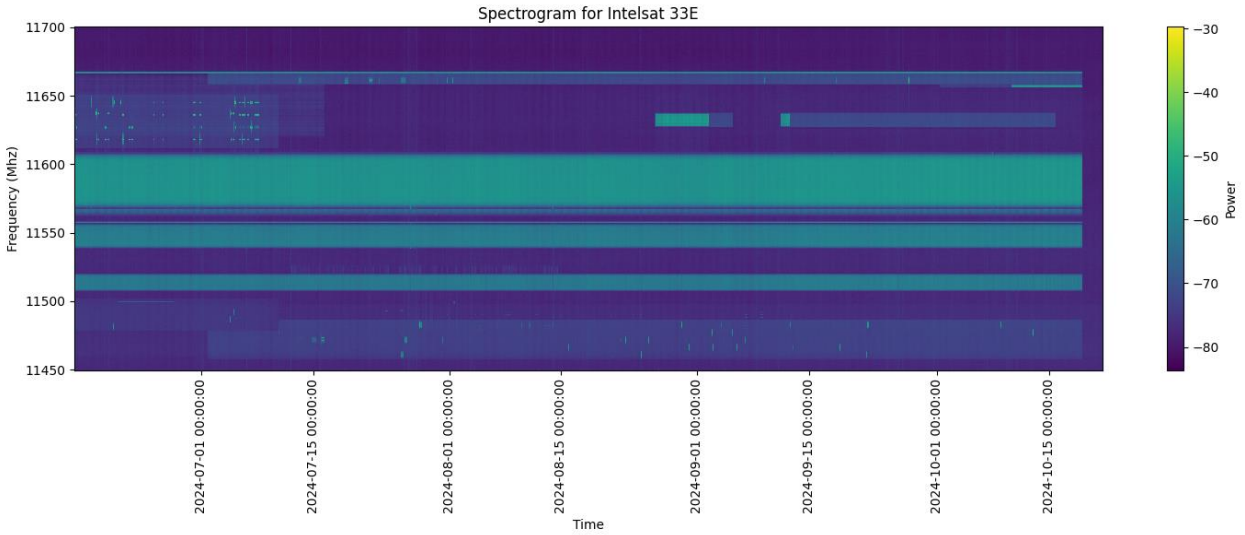

Fig. 6. Spectrogram of Intelsat-33e showing abrupt drop in traffic on 2024-10-19

4. CARRIER ANALYSIS

Our second analysis focuses on the carrier centered at 11060 MHz on Yamal 401, a Russian communications satellite, examining its behavior over time. Around July 15, 2023, multiple anomaly detection methods consistently flagged unusual activity.

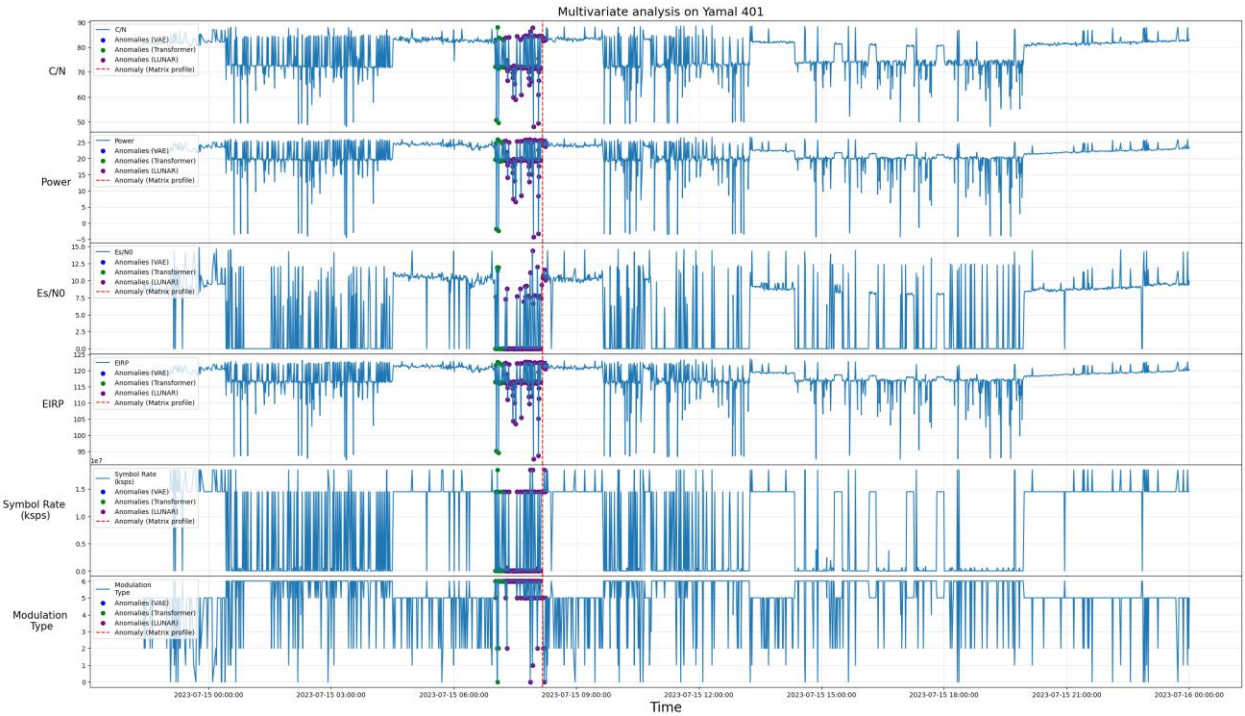

Fig. 7. Multivariate analysis on carrier data for Yamal 401 with multiple anomalies detected

To better characterize these anomalies, we analyze the corresponding power spectral densities (PSDs). Prior to the anomaly, the PSDs appear nominal, showing no unusual features.

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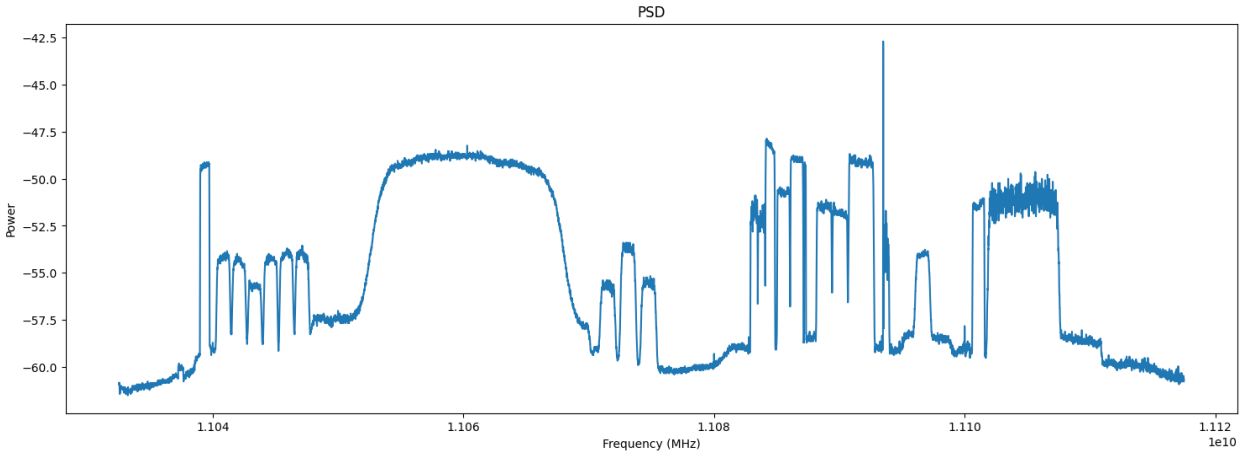

Fig. 8. Nominal PSD for YAMAL 401

During the anomaly windows, however, the PSDs reveal the presence of a high-powered carrier transmitted directly on top of the nominal carrier at the center frequency.

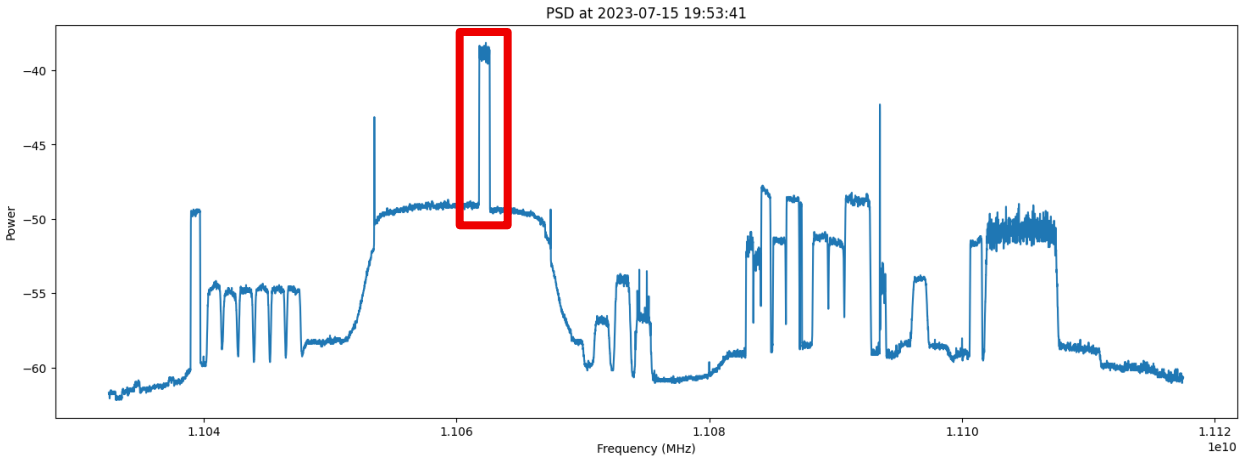

Fig. 9. Yamal 401 PSD with the Sweeper Highlighted in Red

Looking at the waterfall, we can see that the interferer recurs over time. This is a type of interferer known as a sweeper, which is a low bandwidth high power carrier being transmitted atop the original carrier. Such interference effectively renders the underlying carrier unusable for data transmission.

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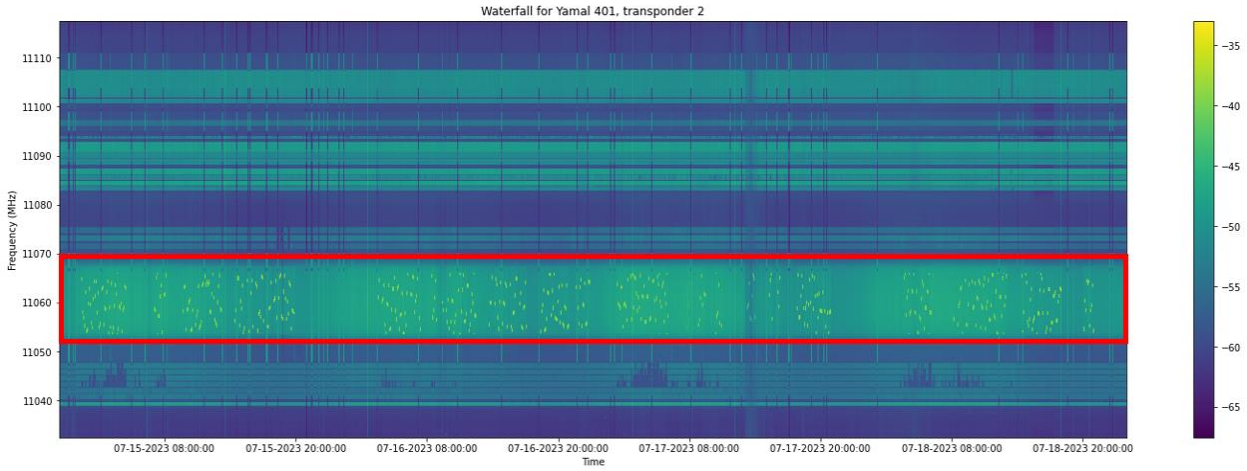

Fig. 10. Waterfall for Yamal 401, Transponder 2 with Interference Highlighted in Red

5. ORBITAL ELEMENT ANALYSIS

Previous work has demonstrated that highly accurate ephemerides can be derived from passive RF collections [3][4]. Here, we focus on Luch Olymp 2, a geosynchronous Russian satellite publicly described as a data relay platform. Independent analysts believe that Luch Olymp 2 is a cover for a classified Russian satellite that is part of the Olymp-K program managed by the Federal Security Service, or FSB, intelligence agency or the Russian military. Despite its designation as a data relay platform, Luch Olymp 2 has been observed conducting aggressive maneuvers that place it in close proximity to other geosynchronous satellites [7].

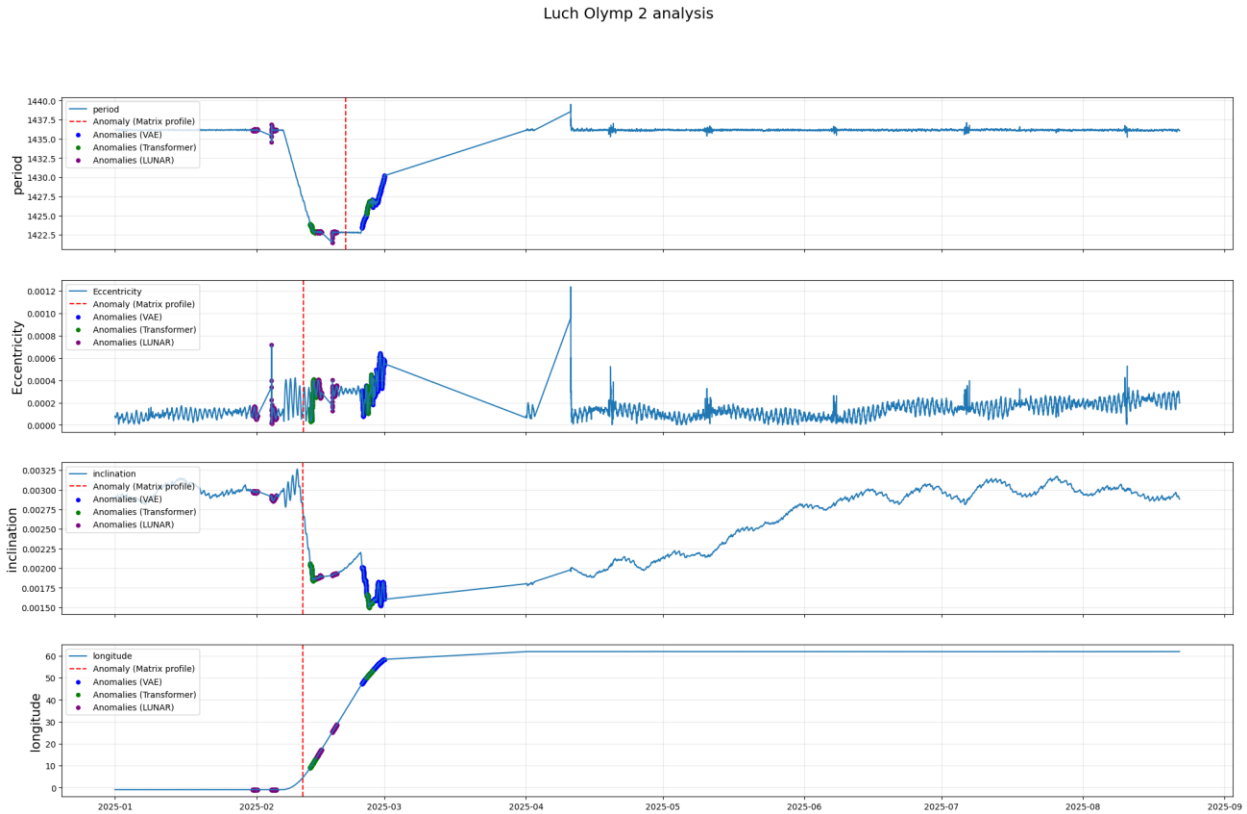

Fig. 11. Multivariate analysis on Luch Olymp 2 Orbital Elements

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From the beginning of 2025 through February, the satellite's orbital elements remained nominal. During this period, Luch Olymp 2 occupied the 1° W orbital slot, co-located with Intelsat 10-02, which is known to host commercial SATCOM leases supporting operations in the Ukraine conflict.

In February, multiple anomalies were detected. The data indicates that Luch Olymp 2 executed aggressive maneuvers toward the 60° W slot, bringing it into close proximity with Intelsat 39. Intelsat 39 is known to support payloads for Myanmarsat-2, which provides communications for the Ministry of Transport and Communications of Myanmar. Satellite operators can apply multivariate analysis to proactively address satellites like Luch Olymp 2 that maneuver aggressively near their assets, rather than merely reacting after the fact.

6. VSAT NETWORK

VSAT networks are a primary means of delivering broadband connectivity to ships or rural areas via geostationary satellites. Because vessels are continuously in motion, VSAT terminals typically self-report their positions, enabling satellite and network operators to maintain accurate beam alignment and reliable service. When this information is fused with AIS beacon data, it becomes possible to associate network activity with specific vessels.

The hub is situated in Iran, and analysis revealed an extensive maritime network with multiple vessels self-reporting their positions. By overlaying the VSAT and AIS datasets, we were able to resolve individual ships, including their names, origins, and destinations.

Fig. 12 and Fig. 13 show an example of overlaying AIS tracks with the self-reported geolocations from VSAT terminals to identify a container ship.

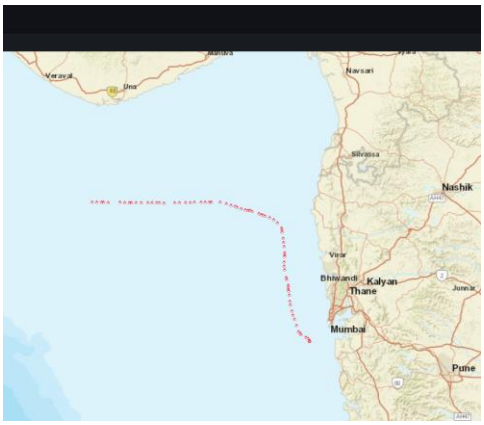

Fig. 12. Data fusion to identify vessels –self-reported geolocations

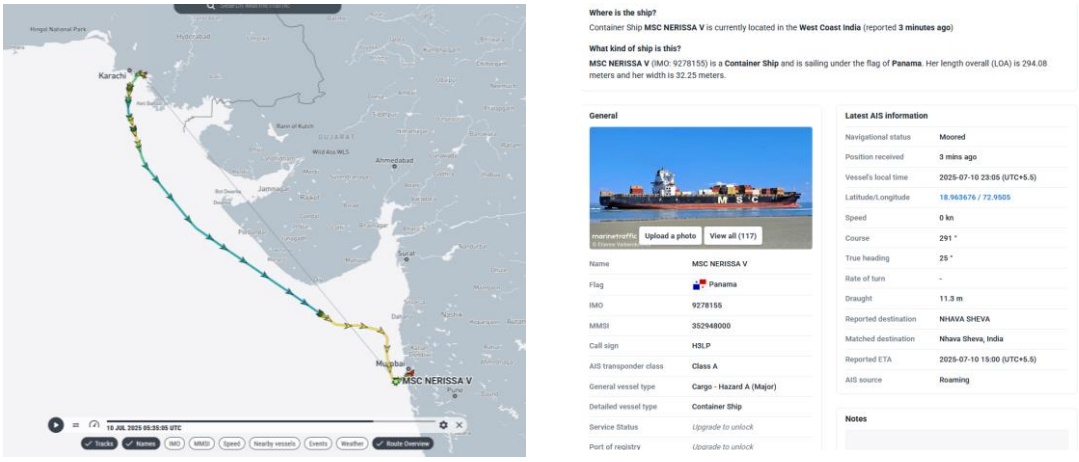

Fig. 13. Data fusion to identify vessels – from left to right: AIS track and AIS profile of ship

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Fig. 14. Data fusion to identify vessels – from left to right: self-reported geolocations, AIS track

Fig. 14 shows data fusion identifying a carrier vessel called Yue Dian 56 has been anchored for about a month at a Chinese harbor.

While this work is in its infancy, future applications include being able to identify when ships turn off their AIS beacons but keep their VSAT networks on, which allows for sustained custody of a ship.

7. CONCLUSION

In this paper, we explained how pattern-of-life applied to RF data offers substantial value to the SDA mission. Using these pattern-of-life capabilities, operators and analysts can achieve a multifaceted understanding of satellite operations. This includes pinpointing the precise location of satellites in real-time, monitoring the operational status and behavior of their payloads, and analyzing the positions of maritime networks reported by VSAT networks. We apply these pattern-of-life models to real-world datasets to identify events relevant to SDA missions. By integrating these insights, SDA operators and analysts can make informed decisions, anticipate potential issues, and respond swiftly to emerging threats.

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