Assessment of Real-World Incident Types and Rates in Geosynchronous Orbit

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Abstract
As technology for imaging space objects advances and proliferates, anomalous events on orbit become increasingly visible. ExoAnalytic Solutions operates a global telescope network performing persistent Space Situational Awareness (SSA) for space objects, utilizing over 300 telescopes stationed across several dozen observatories. This network has captured multiple events during which geosynchronous satellites apparently underwent unexpected issues.

The databody amassed by the global telescope network, containing hundreds of potentially-interesting events and more than a dozen major events. These exist among more than a billion total recorded observations, allowing large-scale and automated analysis of the overall event types and rates. This can serve as the basis of an on-orbit event type taxonomy, supporting detailed approaches to mitigation of root causes and final effects, and enabling rapid initial categorization of events (particularly those occurring in close proximity).

This paper reviews notable major events in the past 5 years, presenting summary analyses of their likely courses and causes when supported by the data. This review leads to a taxonomic structure sorting the reviewed events. Theoretical predictions of event rates, derived from review of available literature on component failures and space environment effects, will be compared to observed event rates. Differences between predicted and observed/actual event rates are of particular interest.

Relevant insights regarding the implications of observed event rates will be discussed with a view to providing actor-specific guidance for future space traffic authorities. Particular emphasis is placed on traffic safety and forensic analysis. The relationship between event rates and methods of incident forensics and attribution will be examined, and suggestions for further data collection fully to validate useful models will be given.

Keywords: STM, SSA, Orbital Debris, Incident Forensics, Satellite Anomalies

I. Introduction

Although widespread public reporting of the relevant facts is not commonplace, a small number of interesting events occur on orbit in the geosynchronous ("GEO") neighborhood every year. While there are somewhat fewer conjunctions than in other orbital regimes (when measured by cataloged debris population), they nonetheless do appear to occur with sem-regular frequency. Additionally, close approaches (up to and including docking) occur with increasing regularity.

Finally, one particular class of interesting event, the “incident”, occurs. An “incident” may generally be defined as the undesirable (but not necessarily unanticipated or unpredicted) occurrence of a behavior that negatively impacts a satellite’s mission capability. Incidents range from mundane (such as lower-than-expected power levels) to catastrophic (such as the rapid disassembly of a vehicle), and may have causes ranging from exposure to the space environment to inadvertent MMOD (micrometeorite orbital debris) strikes.

This paper is interested in categorizing incidents and working to understand them using ground-based imagery. As such, it presents a taxonomy of event types, describes a small number of actual incidents detected in the past 5 years by ExoAnalytic sensors, and makes an initial assessment regarding whether the number of incidents observed, on the one hand, approximately matches the number of incidents expected, on the other hand, based on statistical reliability models. Finally, it suggests paths-forward toward an improved understanding of the risk environment at GEO, in order to prepare for 1) a fast-approaching era of space commerce, and 2) the space traffic management requirements and capabilities such an era will require.

II. Suggested Taxonomy of Events

In a broad sense, on-orbit events occur on a daily basis. In the GEO belt, there are hundreds of Resident Space Objects (RSOs), many of which have missions that support maintaining a stable and unexciting orbital slot (i.e., orbiting, usually with a low or effectively zero inclination, continuously over the same portion of the Earth). However, the presence of orbital perturbations means that on any given day at least a few satellites are undergoing housekeeping procedures, including small station-keeping maneuvers that allow them to:

- Adjust their position in their assigned slot (the smallest of these are typically around 0.1 degrees wide; 0.5 degrees is more typical);
- Dump accumulated excess from a momentum wheel; or
- Slightly alter the rate at which they are moving within their orbital slot

These events, while they can be observed and whose regularity is often leveraged to generate pattern-of-life characterizations, are quotidian and typically among the most anticipated and controlled occurrences on orbit. As such, this paper relegates them to a single category.

More interesting events fall into four additional categories:

1. Those resulting in loss of mission access;
2. Those resulting in loss of satellite stability;
3. Those resulting in departure from the orbital slot; and
4. Those resulting in loss of satellite structural integrity

These events, roughly ordered in increasing degree of negative impact, range from the nearly-invisible to the dramatic, and all represent an unanticipated and undesirable departure from expected spacecraft behavior. Such events are separately categorized as “incidents”. In these cases, partial or full recovery from an incident is possible. A sixth category of event, referred to in this paper as a "shenanigan", is a departure from expected behavior that is anticipated, planned, and desired (at least to some of the parties operating the satellite).

At first glance, it may be hard to distinguish a shenanigan from an incident, although typically a shenanigan entails a degree of control over the entire event that is not present in an incident. A loose analogy may be made to the distinction between aircraft crashes (incidents) and stunt flying (shenanigans): the former is unplanned and undesirable, while the latter (as frighteningly spontaneous and daring as it may look) is deliberate. (Additionally, the latter does occasionally lead to the former, despite the best of intentions.)

More aggressive (but still common) behaviors–such as changing inclination, altering orbits, and inserting to a slot after launch–are not explicitly considered here, as they are not unanticipated, uncontrolled, or undesirable. These might be considered shenanigans that occur rarely in the lifetime of an individual vehicle but not uncommonly in the GEO neighborhood as a whole.

Figure 1 below offers a simple taxonomy focused on GEO incidents.

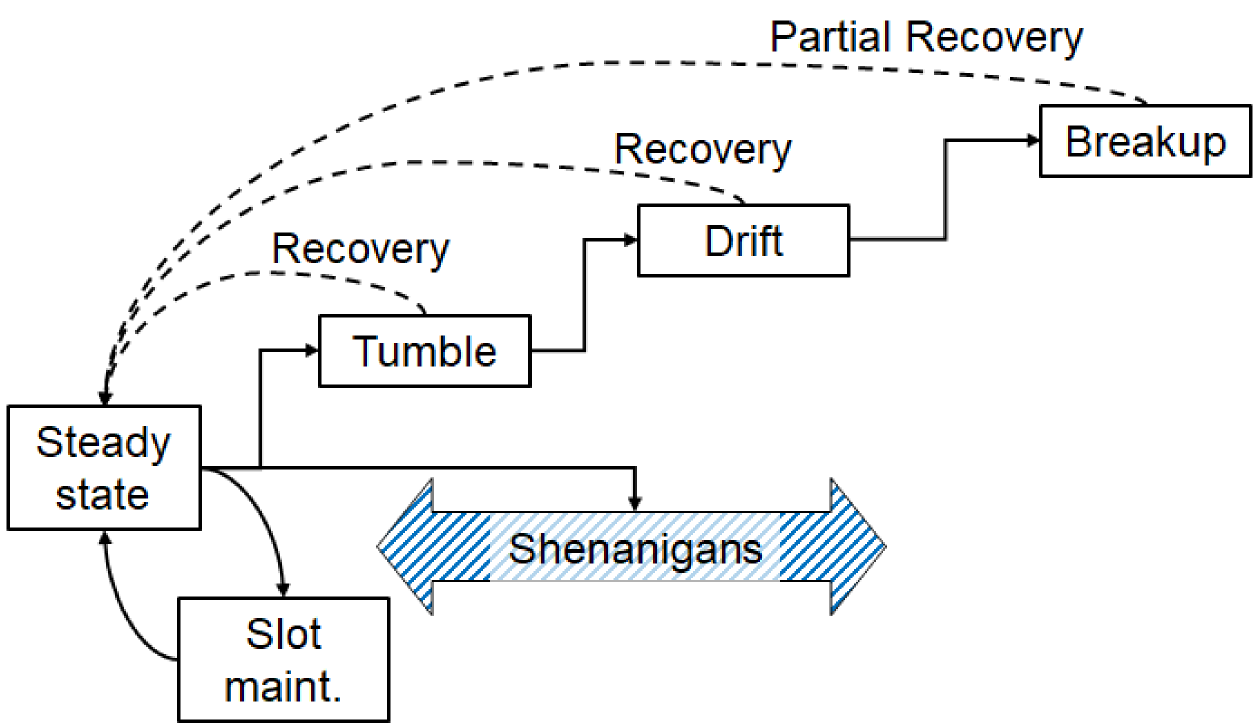

Figure 1. Suggested taxonomy of events at GEO, showing paths by which steady state behavior may diverge (temporarily or permanently).

Note that recovery paths to steady-state exist; however, the path from a breakup event can only (even in the best of cases) be a partial recovery.

Figure 1 shows how the typical and expected steady-state behavior of a GEO satellite may diverge–either into small maneuvers that make up slot maintenance; into shenanigans (including, for the purposes of this paper, such life events as launch, changing orbits, and retirement); and into several states of incident. There is one additional lowest state of incident: those resulting in a loss of mission access, perhaps due only to antenna-pointing anomalies, transient loss of power, or even minor software upsets. These are generally not visible to external optical or infrared sensors, and are elided from the figure in the interests of simplicity.

This leaves three primary categories of incident:

- "Tumble" - a loss of three-axis stability
- "Drift" - a departure from designated orbital slot
- "Breakup" - a loss of structural integrity

These categories of incident are useful because they represent successively higher levels of concern. Furthermore, lower categories may occur in isolation but higher ones are often compound–that is, a tumble may be corrected or may eventually develop into a drift, and a breakup event can generally (although not always) be expected to be associated with tumbling and drifting as well.

Tumbling

Loss of stability events are those where the RSO no longer operates with 3-axis stability; instead it begins to tumble along one or more axes. Detecting this behavior is generally feasible with optical sensors; if a spacecraft begins tumbling, it will generally show changes in its lightcurve (photometric signature) that reflect this, and the tumble rate can be estimated.

Drifting

Departure from an orbital, in a drift, means a satellite leaves the confines of its assigned slot (usually a box-like station less than one degree wide along the GEO belt). Detecting this drift is typically straightforward for optical sensors: the spacecraft will move across a steady progression of longitudes over time. Notably, most spacecraft drift at small residual rates within their boxes (slot maintenance addresses these residual drifts periodically); departing from a slot usually means a marked increase in drift rate, usually associated with an input of energy or uncorrected perturbations that effectively alter the shape (perigee and apogee) of the near-circular orbit most GEO satellites use. (In somes cases, the inclination of the satellite is also altered noticeably.)

Breakup

Loss of structural integrity refers to the sudden separation of elements of the satellite from the central body. One fixed entity becomes multiple discrete entities. This is almost never a part of a typical satellite's lifecycle, and so it is generally an unambiguous indicator of an incident. (This assessment does not apply to the deployment of spacecraft from a launch vehicle, which is a life event.)

The appearance of bright child objects near a satellite is a clear sign of loss of structural integrity, and optical sensors persistently observing GEO can easily capture any child objects above a certain visual magnitude (closely correlated with size).

Figure 2 shows the taxonomy from Figure 1 as it relates to alteration in the collision/debris risk generated by each type of incident (note the steep rise for a breakup event) and a table of alarm levels for each type of incident, together with an assessment of the indicators present and the analytical tool categories by which each type of incident may be analyzed.

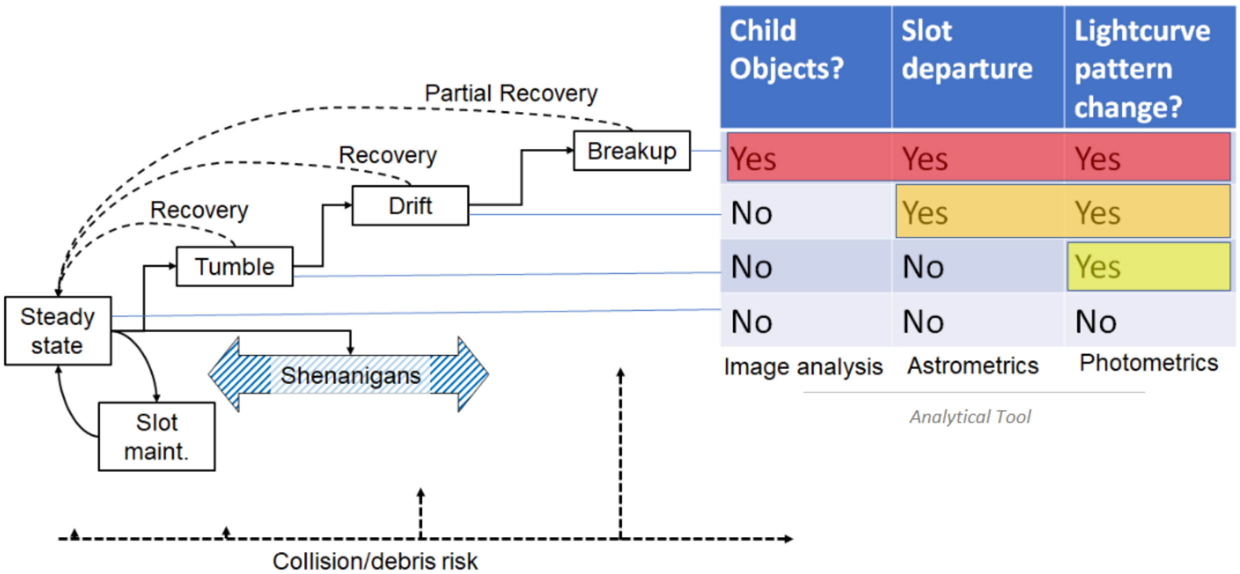

Figure 2. Amplification of taxonomy of events in GEO, showing an assessment of relative risk level and an alarm level table, with yellow, orange, and red highlighting steadily-higher levels of alarm.

III. Collected Events and Analyses

This section presents a list of events captured by ExoAnalytic sensors since 2017. The events on this list were initially curated for internal R&D use; this list does not represent an exhaustive categorization of every event observed or analyzed by ExoAnalytic. In fact, in operational practice ExoAnalytic typically addresses a dozen or more alerts (each of which may indicate a new event) on a daily basis. Instead, this paper seeks to develop a taxonomy for which the list of major events shown below is intended to be illustrative.

Table 1. List of illustrative GEO events since 2017.

Date	Affected RSO (SSCID)	Description	Type
2017-06	AMC-9 (27820)	On-orbit breakup	Loss of structural integrity
2017-08	TelKom-1 (25880)	On-orbit breakup	Loss of structural integrity
2018-12	TJS-3 (43874)	Deployment of child objects (AKM) after launch	Shenanigan/life event
2019-03	Galaxy-11 (26038)	Transfer to new slot/Child object deployment mid-drift	Shenanigan/life event
2019-04	IntelSat-29E (41308)	On-orbit breakup	Loss of structural integrity
2020-02	MEV-1 (44625)	Docking, repositioning	Shenanigan/life event

2020-03	VeneSat-1 (33414)	Sudden drift	Slot departure/Loss of stability
2020-06	Cosmos 2473 (37806)	Tumble and drift	Loss of stability/Slot departure
2020-12	JDRS-1 (47202)	Close approach	Shenanigan/life event
2021-02	MEV-2 (46113)	Docking, repositioning	Shenanigan/life event
2021-06	Measat-3 (29648)	Tumble and drift	Loss of stability/Slot departure
2021-12	SJ-21 (49330)	Docking	Shenanigan/life event
2022-01	COMPASS-G2 (34779)	Docking, repositioning	Shenanigan/life event

Of these 13 selected events, 7 are identifiable as shenanigans. Interestingly, three of these shenanigans are related to the operation of a servicing vehicle, in order to reposition/refurbish an existing on-orbit vehicle: MEV-1, MEV-2, and COMPASS-G2 (which was approached and moved by SJ-21). [9]

Note that, per the caveats above, it is emphatically not the case that all shenanigan events have been captured in this list, although it is somewhat more likely that all incidents have been. Accordingly, we can split out the non-shenanigan events and separate them into another table.

Table 2. List of GEO incidents.

Date	Affected RSO (#SSCID)	Incident Type	Assessed Cause
2017-06	AMC-9 (#27820)	Loss of structural integrity	Uncertain
2017-08	TelKom-1 (#25880)	Loss of structural integrity	Pressure vessel failure
2019-04	IntelSat-29E (#41308)	Loss of structural integrity	Similar to AMC
2020-03	VeneSat-1 (#33414)	Slot departure/loss of stability	Uncertain but likely non-external
2020-06	Cosmos 2473 (#37806)	Loss of stability/Slot departure	Uncertain but likely non-external
2021-06	Measat-3 (#29648)	Loss of stability/Slot departure	Uncertain but likely non-external

In addition to indicating the type of incident, Table 2 has a column listing the present candidate for root cause, based on ExoAnalytic's internal analyses. In most cases, no public analysis of the incidents or final determination of cause or course of events has been published, other than in prior work by ExoAnalytic. The following subsections briefly describe the observed incidents from the list in Table 2, including short narratives supported by material from deeper analyses.

AMC-9

In late June/early July 2017, AMC-9 underwent an on-orbit breakup. At various points during the course of the incident, AMC-9 displayed indicators of tumbling, drifting, and separation of multiple child objects. A number of analytical techniques, detailed in other publications, were utilized to assess the incident. While the final assessment remains somewhat ambiguous, AMC-9 underwent a loss of structural integrity, due most likely (but not incontrovertibly) to an internal failure which created cascading problems. However, By the end of the incident, child object separation was clearly visible, as seen in Figure 3. [7-8]

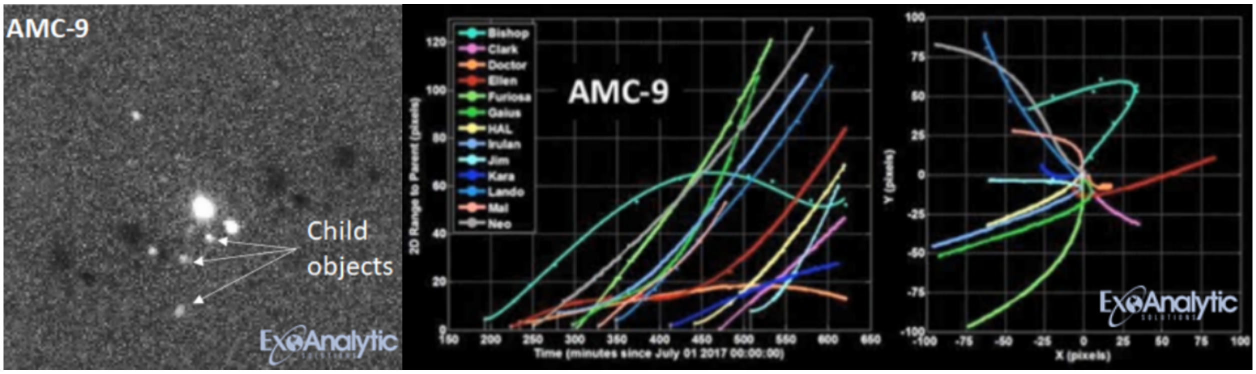

Figure 3. Details of AMC-9 incident, including still image, timeline, and fragment directionality plot.

TelKom-1

In August 2017, TelKom-1 underwent an on-orbit breakup as well. Because TelKom-1 generated a visible plume as well as child objects, and because the timeline shows a very rapid event and other analyses indicate low probability of invisible impactors, TelKom-1 is assessed to have experienced the rupture of a pressure vessel, with catastrophic consequences. [7-8]

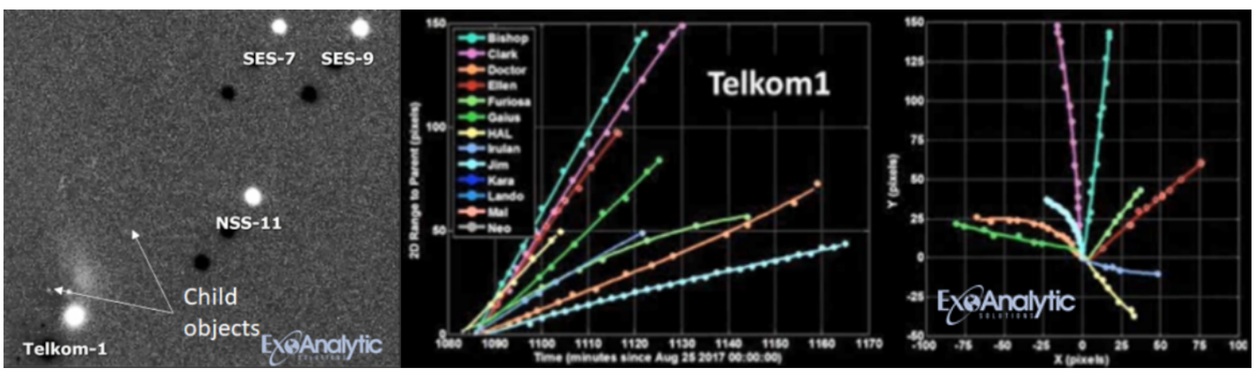

Figure 4. Details of TelKom-1 incident, including still image, timeline, and fragment directionality plot.

IntelSat-29E

In April 2019, IntelSat-29E began displaying behavior similar to that observed during the AMC-9 incident, including the generation of multiple child objects. Accordingly, a final assessment of this incident is likely to match that of the AMC-9 incident: not incontrovertible, but probably an internal failure that cascaded to some extent, resulting in the observed effects. Full publication of IS-29E analyses may be forthcoming in future papers.

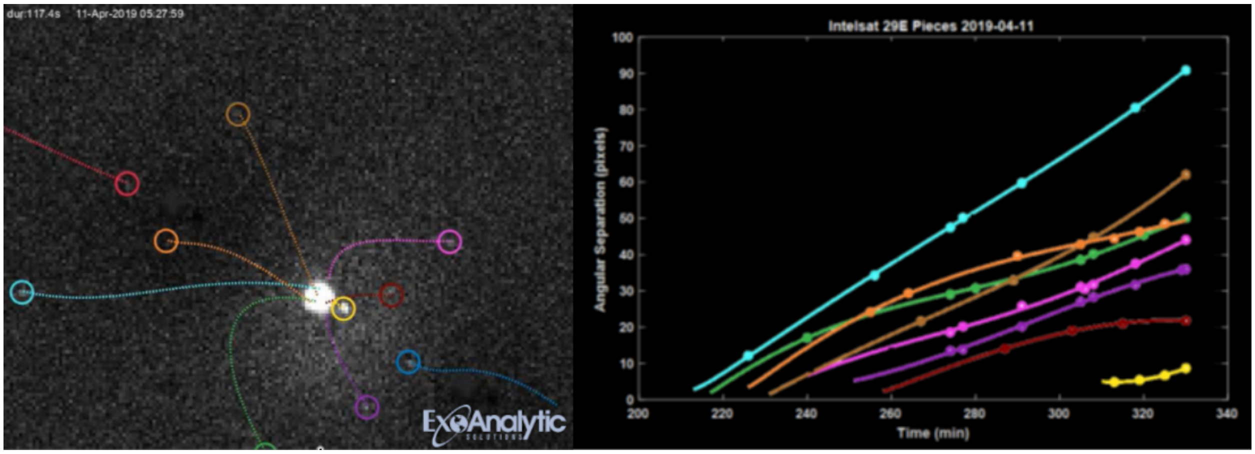

Figure 5. Still frame and timeline plot from IS-29E incident. Note the presence of multiple child objects and the comparatively-wide temporal spread of child object separation times.

VeneSat-1

VeneSat-1 held a steady orbit at approximately 78 West (longitude 282) in February and early March 2020, with a lightcurve indicative of consistent three-axis stability.

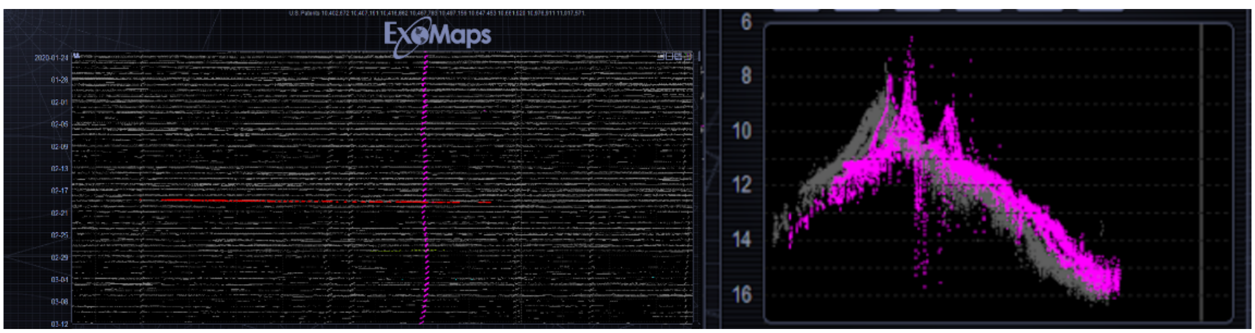

Figure 6. Steady orbit (left) and lightcurve (right) for VeneSat-1.

On the night of 13 March 2020, however, an apparent rapid maneuver occurred, resulting in relative motion to the east, followed by a reversal of direction. This sudden change occurred at around 0700 UTC. Following this event, at around 1000 UTC, the stable lightcurve that had previously held began to “smear” in brightness, indicating a likely tumble. The next day, 14 March 2020, VeneSat-1 had begun drifting west at approximately 3.6 deg/day, and was showing a lightcurve that strongly implied dynamic instability (tumbling).

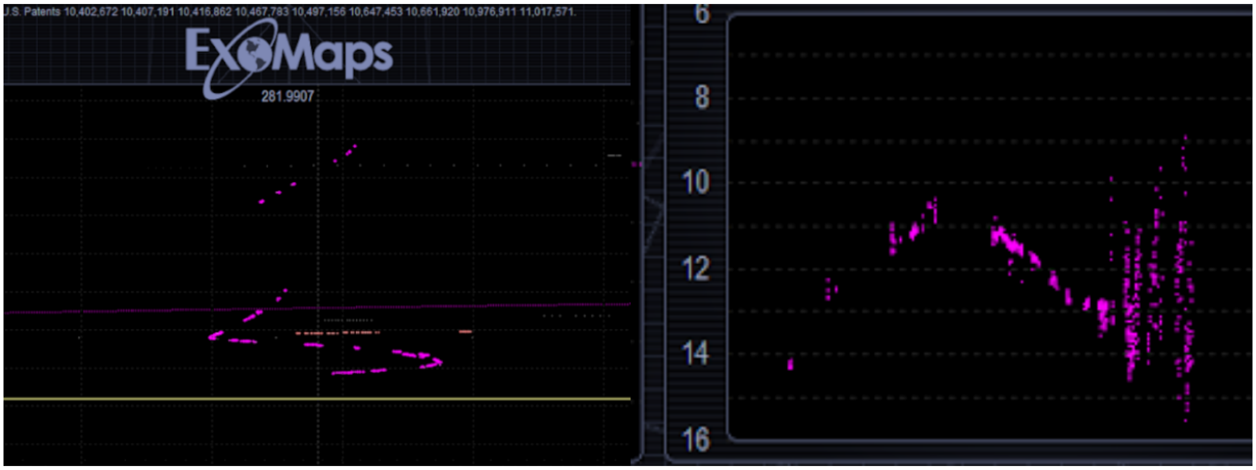

Figure 7. Sudden motion (left) and sudden lightcurve smearing (right) for VeneSat-1. Note the left image also shows the previous night's (nominal) orbit above the flattened S-curve of the eventful orbit.

There is no directly visible evidence of child object generation by VeneSat-1, however. Additionally, the double reversal of direction of motion, prior to the observation of an unstable lightcurve, suggests that an external impact (which would impart momentum and motion in one direction primarily) is an unlikely explanation.

Cosmos 2473

Cosmos 2473 was steady and stable at 13.5 W Longitude through late May 2020 and early June 2020. Lightcurves prior to 18 June indicate stable attitude control; however, this stability gradually decreases, and by the night of 21-22 June, the lightcurve showed a "smearing" pattern generally characteristic of reduced stability. Figure 8 compares the two different lightcurves.

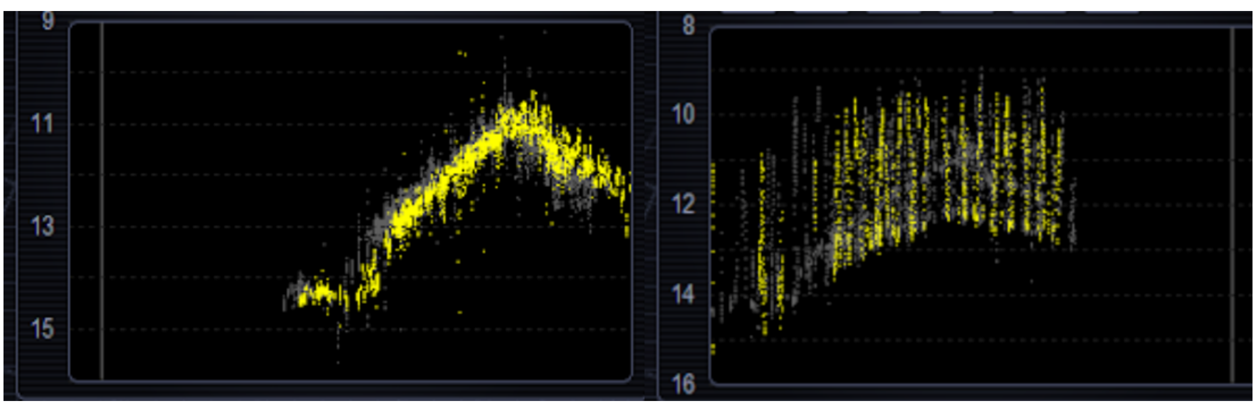

Figure 8. Lightcurves typical of before 18 June (left), and from 21-22 June (right).

A slow westward drift began around the night of 24 June; by 24 September 2020, Cosmos 2473 was at 14.5 west (longitude 345.5) and showing a slow drift rate of about 0.01-0.02 deg/day. However, this drift rate was not steady, as Figure 9 shows.

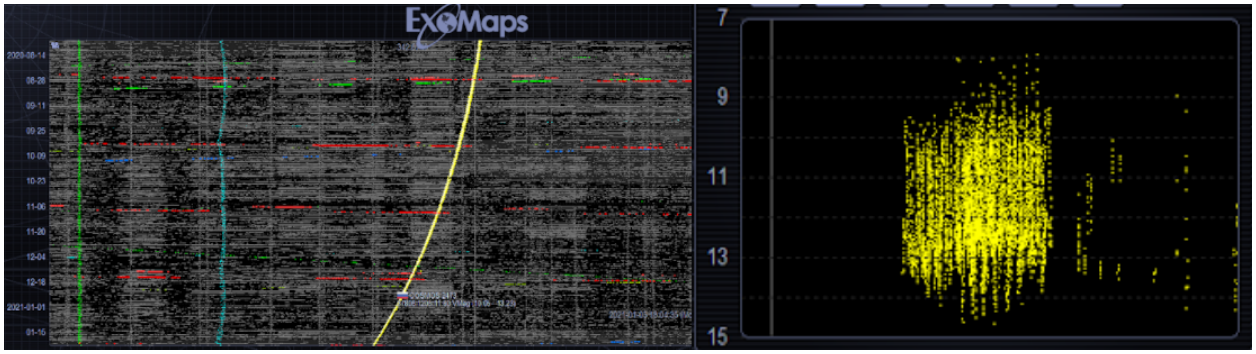

Figure 9. Smooth parabolic path, indicative of accelerating drift west (left), and smeared lightcurve (right) for Cosmos 2473, over the latter part of 2020 and into 2021.

By roughly 19 January 2022, Cosmos 2473 was at approximately longitude 275.7 and drifting at about 0.33 deg/day. No apparent evidence of child objects was noted.

MeaSat-3

Through May and June 2021, MeaSat-3 was in a stable, steady slot around longitude 91.5, with a mostly-unremarkable lightcurve.

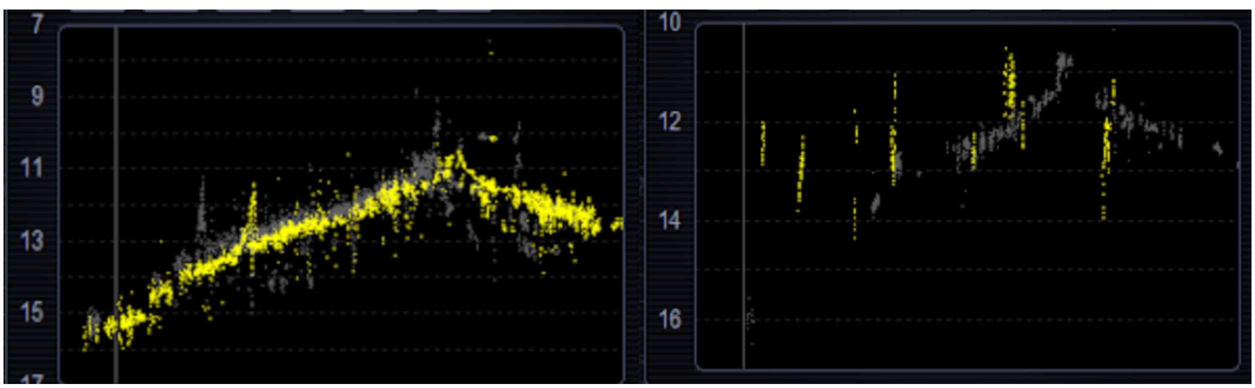

Figure 10. Baseline lightcurve for MeaSat-3 (left) and transient lightcurve (right).

On 21 June 2021, the lightcurve began to show smearing spikes, and by 22 June 2021, a westward drift became apparent, as seen in Figure 11.

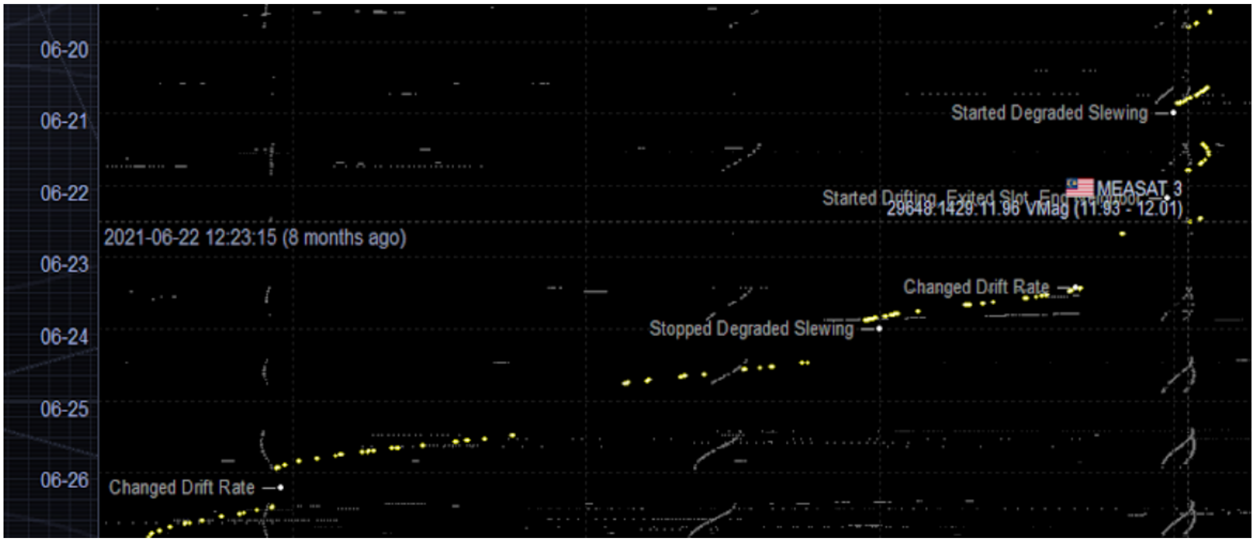

Figure 11. Westward drift for MeaSat-3.

Interestingly, the lightcurve shows evidence of a much more stable configuration on the night of 25 June, prior to a series of changes in drift and inclination occurring from 25 June to 30 June.

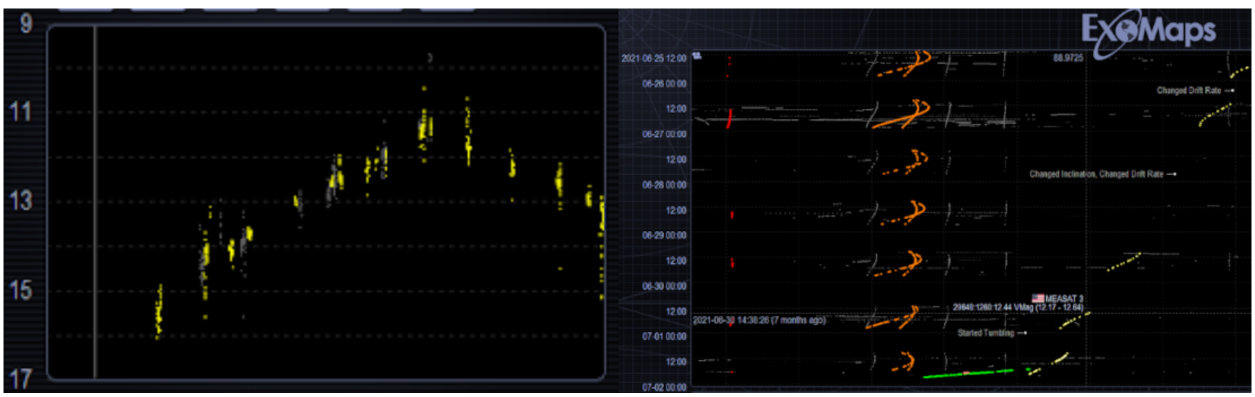

Figure 12. Lightcurve from 25 June 2021 (left), and orbital motion between 25 June and 01 July (right).

However, as shown in Figure 12 (demarcated as text generated via automated system alerts), the spacecraft showed signs of beginning to tumble again on the night of 30 June, and after this the lightcurve smeared out again. While it seems possible that these changes represent a failed recovery attempt, there are no obvious indications of external impacts nor child objects. MeaSat-3 is currently drifting at approximately 1.7 deg/day, near longitude 78.

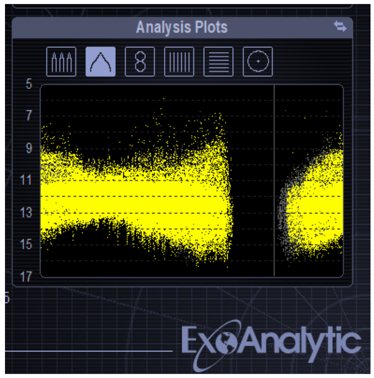

Figure 13. Smeared lightcurve from MeaSat-3 (amalgamated/typical through July and August of 2021).

IV. Review of Event Rates

Risk Analysis

Academic technical literature tends to discuss reliability in theoretical terms; this may be due to the fact that detailed empirical information on spacecraft reliability is likely inaccessible and/or proprietary, and accordingly remains unpublished. However, some general principles of reliability are widely understood. Spacecraft typically show a bathtub- or U-shaped failure pattern: any vehicle that survives infancy may be expected to make it near or past the far end of its typical lifetime. Many large and capable geosynchronous satellites continue to perform effectively several years beyond the end of their original service lifetimes.

A standard model for reliability can be found in the form of a Weibull distribution. This family of curves, supported by empirical studies, models the decay in reliability over time of a satellite. A single such distribution can be characterized by the following equation when expressed as a function of time: [1]

$$f(t)[\lambda, k] = \frac{k}{\lambda}\left(\frac{t}{\lambda}\right)^{k-1} e^{-(t/\lambda)^k}$$

A "bathtub" distribution of failure probabilities is a combination of three such distributions with differing parameters:

- An "infant mortality" failure probably that peaks towards $t = 0$
- A "wearout mortality" failure probably that peaks towards $t = F$
- A "floor mortality" failure probability that represents a constant probability across time

For the purposes of a simple analysis in this paper, one source notes that large GEO spacecraft have a reliability of about 91% (or 0.91) over 5 years. Similarly, another source notes that LEO spacecraft have a reliability of 95% (or 0.95) over 5 years. As such the value of 91-95% (or 0.91-0.95) over 5 years may be taken as a range of reliability. [1,2]

Note that CubeSat data is excluded in this analysis; CubeSats experience high rates of extreme infant mortality, and are not manufactured in the same manner (or from the same components pools) as major commercial GEO satellites. Data on individual component reliability, while available, may not be useful either, as major commercial GEO satellites also tend to be built with internal redundancy and backup components, meaning that individual component failures do not necessarily lead to spacecraft incidents, even if accurate estimation of the number of individual components aboard a typical spacecraft can be made. [3,4]

Note that there is a potential significant confounding factor: many spacecraft for which failure is anticipated in the near future (whether due to known old age or to internal vital signs from telemetry data) are moved to one of the graveyard orbits (a substantial distance above or below the GEO belt itself) and passivated before failing completely. Incidents which seem to originate in GEO itself, such as those listed in Table 2, are (in contrast) likely unexpected. Most spacecraft anticipating obsolescence are moved to a graveyard orbit before a failure can occur. Passivation can include deliberate actions to minimize potential energy of satellite systems (despinning attitude controls, depressurizing propellant tanks, etc.), reducing the potential for unintended energetic events. Of the spacecraft events listed in Table 2, none occurred in a graveyard orbit after such retirement activities took place.

One source lists 538 satellites in GEO orbit, as of 21 July 2021. Rounding to 540 to account for growth, and assuming that all satellites were in similar phases of life (which is known to be an inaccurate assumption, but is used here to achieve a broad estimate), we might surmise that 5% of this population (or 27 satellites), would show failures over the course of 5 years. This is approximately the amount of time spanned by the data in Table 2. Of course, this value does not accurately account for the actual distribution of lifetimes, the total extension beyond expected lifetime that very often occurs, and the fact of retirement before failure that often occurs preemptively to a failure [5].

The difference between a) the ~27 theoretically expected incidents, and b) the 6 listed observed incidents is interesting. Unfortunately, without access to telemetry and satellite operations records, it is difficult to assess whether these incidents were anticipated in any way by satellite operators, or why retirement of the satellite did not occur before the incident. However, some analyses can suggest whether each incident is more likely attributable to an obvious singular external cause (i.e., a debris impact). Of the incidents in Table 2, none can be unambiguously attributed to an impact.

The course of evolution of the AMC-9 and IS-29E events suggest that these incidents were not primarily impact failures, although it is possible that they were chains of larger events partly exacerbated or triggered by very small debris impacts. The TelKom-1 incident was very likely not a debris-triggered failure. Insufficient data exists to answer these questions for Cosmos, VeneSat, and Measat, although child objects were not observed in any of these cases.

Insights

In summary, there are some possible indications (based on initial apparent mismatches between projected and observed events) that simple baseline models of spacecraft reliability do not necessarily apply to the active GEO population. A strict but simple interpretation of reliability rates would lead to an expectation of approximately 27 major incidents over 5 years; a more-informed interpretation that accounts for a predictive and protective retirement process would lead to an expectation of few-to-no incidents over 5 years. As recorded in this paper, an intermediate number of 6 major incidents does not consort well with either of these interpretations.

There are multiple possible explanations, which need not be mutually exclusive:

- More complex models of GEO satellite reliability, likely with particular attention paid to precursors that indicate impending events or incidents, may be highly desirable for more accurate assessments of risk than are simple reliability curves over time. It is doubtless the case that such tools already exist within the confines of corporate or government institutions; open publication of such tools or models – and/or their standardization by relevant regulatory authorities – might substantially benefit space traffic management efforts.
- Significantly more failures may occur than are regularly observed and detected. These may be misinterpreted as "hiccups" in satellite operations that are never fully resolved, assumed to be the natural result of "aging" on-orbit hardware, or simply dismissed without additional direct evidence of failure. Or failures may occur outside of times and locations where data collection is prevalent (e.g., due to illumination constraints).

Future Data Collection

Among the most straightforward suggestions to improve knowledge of the actual rates and impacts of incidents among spacecraft operating at GEO is the recognition that there is no replacement for increased prevalence and utilization of persistent space situational awareness sensor systems and improved automated alert and change detection tools and algorithms. This variety of ongoing growth in capability may be considered foundational for better understanding of all events on orbit and for the eventual deployment of a space traffic management regime.

To support further improvements, a detailed fault taxonomy, accounting for the expected distribution of the incident types outlined in this report, should be used to resolve and improve the parameters of supporting models. These models can be adjusted to determine what the relative distribution of incidents should be. This would enable improved risk and reliability processes for space traffic management stakeholders.

Additionally, a means of sharing and reviewing incident analyses is highly desirable. While incidents do occur, they are often not reviewed in depth, particularly not by military, intelligence, and commercial satellite operators. While third parties can offer some insight, full validation of incident forensics narratives and root cause assessments would be best achieved by review of external data and telemetry in concert with one another.

Finally, the tools of incident forensics, both for external data collection and analysis, should be further developed. These actions, taken together, would constitute a notable step forward in support of a future global space traffic management regime, which would ensure flight safety for all the elements of critical infrastructure already in place or soon heading to orbit.

V. Implications for Incident Forensics

While a nascent field, STM has a strong legacy in analogies to air traffic management and relevant safety mechanisms [6]. One particular mechanism that remains relatively unexplored, directly applicable to the taxonomy and events outlined in this paper, is incident forensics. For example, the National Transportation Safety Board (NTSB) has well-established processes for investigating aviation accidents [10].

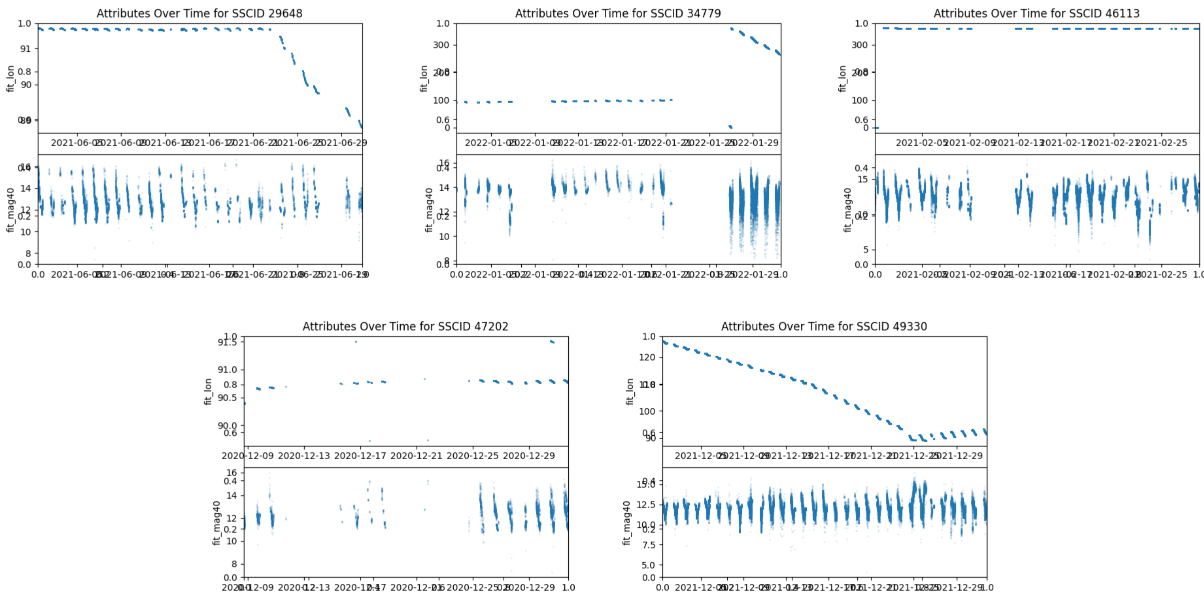

Figure 14. One month's worth of observation data (fitted longitude on top, fitted magnitude on bottom) for five separate satellites listed in Table 1: Where's the incident?

Automation

While crewed spaceflight is important, the vast majority of resident space objects are semi-autonomous systems. The SSA networks (both telescopes and radars) that monitor these systems are also highly automated, particularly as such networks evolve into highly-distributed architectures. As data inputs grow, the need to automate forensics and other analysis of these streams also becomes more important. For one incident referenced earlier in this document alone (49330), the ExoAnalytic Global Telescope Network (EGTN) has over 195,000 individual observations spanning a single month (December 2021).

What does automated incident detection and forensic analysis mean? From the point of view of a ground observer, an incident is an event in the lifecycle of a Resident Space Object (RSO) which is interesting and possibly unexpected. Incidents may be of several types, and may have internal or external root causes. Automated review of indicators readily visible to electro-optical (EO) telescopes from GEO satellites, particularly longitude and visual magnitude, can facilitate automated incident detection (Figure 15).

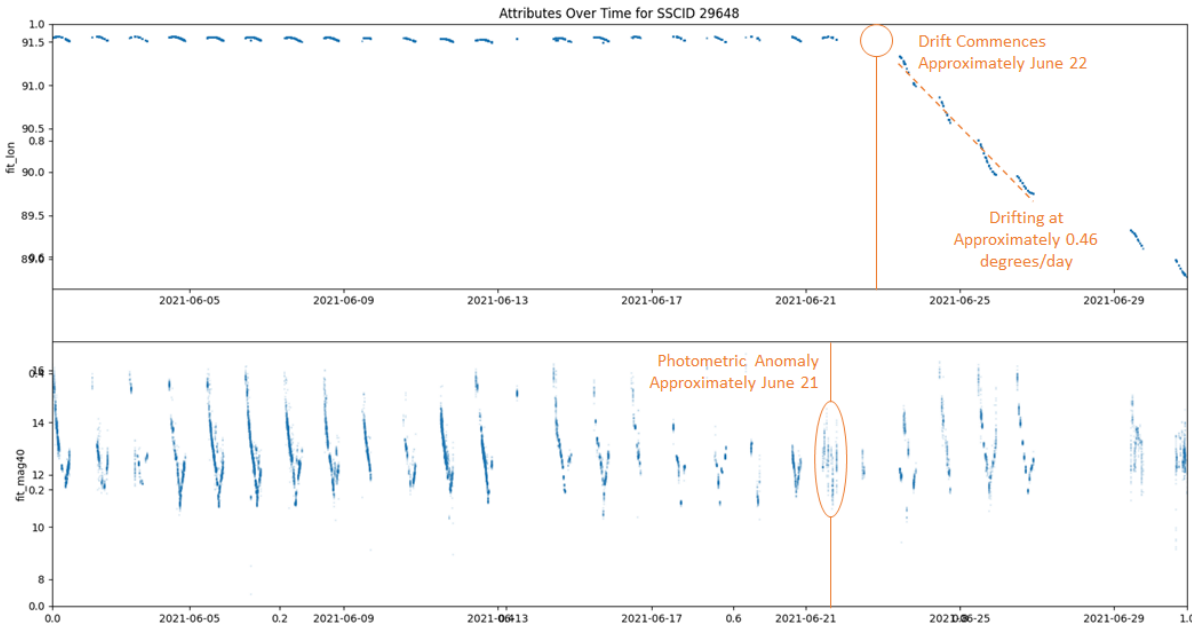

Figure 15. A detailed deep-dive into a month of observing 29648, including photometric anomalies, drift anomalies, and drift rate approximation.

Flight Safety

A fundamental goal of spacecraft incident forensics is the analysis of the evolution of the event in order to determine whether the root cause was internal (due to onboard events or events originating in the command and control system), external (due to an external impact or action), or some combination. The two metrics illustrated in Figure 15 present, over the course of a month for the satellite MeaSat-3 (29648), a key mechanism for triggering flight safety warnings from external (third-party) observations, regardless of internal or external root cause. Additional parameters (such as changes in velocity vectors) can be computed from "sliding windows" of batched statistical orbit fits, informing what energy exchange mechanisms may be involved to further pinpoint the magnitude and risk of ongoing events.

Investigation

The total set of potential incidents that can occur with an RSO is not yet definitively captured; an exhaustive taxonomic description of space incidents is not necessarily possible from empirical evidence alone. Some categorization is possible from what has been observed, as illustrated in this paper. However, allowances should be given for future evolution of such a taxonomy by the space traffic management community. For example, how will incident forensics differ as the portfolio of cislunar missions undergoes significant expansion in the future decade (Figure 16)?

Cislunar Missions (cumulative)	By Year
1	2020
8	2021
15	2022
18	2023
23	2024
24	2025
27	2027
28	2029
30	202X

Figure 16. Several dozen cislunar missions are planned over the next decade. How will STM incident taxonomies and forensics evolve with new operations and experiences?

VI. Summary

A brief assessment of incidents, which may rise in frequency due the future growth of on-orbit populations, was provided in this paper, including an empirically-derived incident taxonomy based on readily observable metrics and change detection events. Incident rates were compared to theoretical models, with a gap observed between expected and observed probabilities. Specific incidents were summarized and presented, before implications for incident forensics were projected.

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