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## Advanced Debris Analysis Techniques Enabled by Rich Persistent Datasets

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## **Advanced Debris Analysis Techniques** **Enabled by Rich Persistent Datasets**

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### **Abstract**

Recent events in Geosynchronous Earth Orbit (GEO), including two probable breakup events in summer 2017, illustrate the potential risks of hazardous debris on orbit. Historically, distinguishing among the many types of negative events that may befall a satellite on orbit (and which may all be grouped together under the category of anomalies) has been challenging, due to a lack of observation data of sufficient volume and quality to support analyses capable of disambiguating these occurrences. As a result, there is limited opportunity to examine these incidents and extract lessons that may support future space traffic management objectives.

However, the events of summer 2017 provided extensive data to multiple observers, including the ExoAnalytic Global Telescope Network (EGTN). The significant volume of collected imagery and derived products can be used to interrogate the events in depth and potentially to ascertain future methods of mitigating the relevant risks. In both cases, staring sensors were pointed at the objects, and thousands of frames were collected during the immediate period surrounding the two very different events. Because the sensors used were persistent, there was a stream of relevant data bracketing the time of interest. Because the data collection architecture used captures and stores raw imagery at large scales, the data stream was rich enough to support primary analysis of astrometric and photometric data as well as secondary analysis of the child objects, including attempts to account for impact and kinetic energy conserved through the event. Additionally, because the sensors were elements of a global network, there was an existing detailed pattern of life for the objects, and data from before the breakup was available for comparison, and deviations were notable on an almost real-time basis.

Taken together, these facts show the importance of a robust persistent SSA sensor network, and how to utilize the data to develop advanced alerts for other satellites operating nearby. This paper describes the data collected, explains the analyses performed and others that may be possible with additional advancement, and uses the two events as case studies for the future.

### **Introduction**

The very act of placing a new object into the space traffic population is an example of a debris-generating event. It is unrealistic to expect that throughout the launch, separation, mission, and

disposal of a space object, no debris will be generated. Great efforts have been dedicated to the establishment of effective guidelines which help to stave off the rate at which debris grows. In fact, every active space object, unless de-orbited, will conclude its mission and transition to the inactive debris population. Space Traffic Management concerns the preservation of safety to assure continued operations in space. Nonetheless, incidents will occur in space, and when they do, the ability to study them in detail and provide lessons learned to future members of the traffic population should be available to provide for later benefit from such incidents. It is this learning process that facilitated standard of safety that air traffic management enjoys today. For this reason, we present here two events which may serve as case studies for deep space traffic management. These events include the AMC-9 spacecraft, which experienced an anomaly on 17 June 2017 and a subsequent long-duration event on 01 July 2017; the Telkom-1 spacecraft, which experienced a high-energy, short-duration event in conjunction with a thruster firing anomaly.

Although a high level of detail is available due to in-depth observations having been detected by the EGTN and others [8, 9], there is no reason to think these are the first or only such events to have occurred in the GEO neighborhood to date. [6, 7]. As noted in [7], there are other indications of possible fragmentation of GEO satellites (based on detection of changes in their TLEs), although it is not certain that data provided through these TLEs alone would be of sufficient grade to detect fragmentation events, nor that the events observed were not simply propellant venting.

The two events considered most likely to have been breakups in GEO are described in some detail in References 6 and 7, and a more recent breakup event on 4 Jun 2014 is under additional investigation by other parties. Although this paper will confine itself to a brief overview of the events and analyses surrounding AMC-9 and Telkom-1, in-depth analysis of a range of GEO events using tools developed to utilize rich datasets will be the subject of future work.

On 17 Jun 2017, AMC-9 (NORAD ID 27820) began exhibiting signs of somewhat anomalous behavior. Notably, while AMC-9 had been displaying excellent stationkeeping and a steady lightcurve, it began displaying deviation. Initial indications were in the form of lightcurve differences, although astrometric differences became apparently shortly thereafter. After internal monitoring noted the behavior, the EGTN focused additional resources on monitoring AMC-9. This monitoring not only collected some imagery of the initial anomaly, but also extensive imagery of the energetic events which occurred two weeks later, on 01 July 2017.

Figure 1 shows the deviations, collecting photometric data from a long period of observation before the anomaly (in red) and following (in yellow). The pattern shown in red, a hemispherical curve across the solar phase angle with a sharper spike near the center (zero solar phase angle) is characteristic of sun-tracking active RSOs. Figure 2 shows the initial anomaly as it occurred.

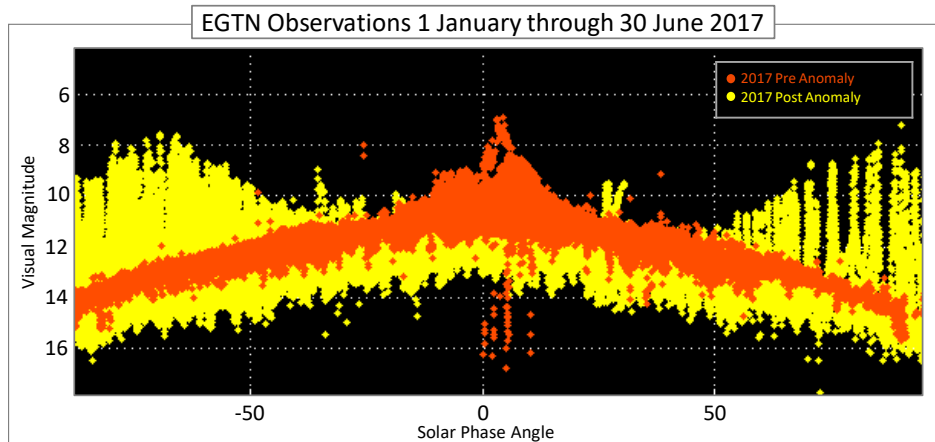


Figure 1. AMC-9 photometric data prior to anomaly (red) and after anomaly (yellow).

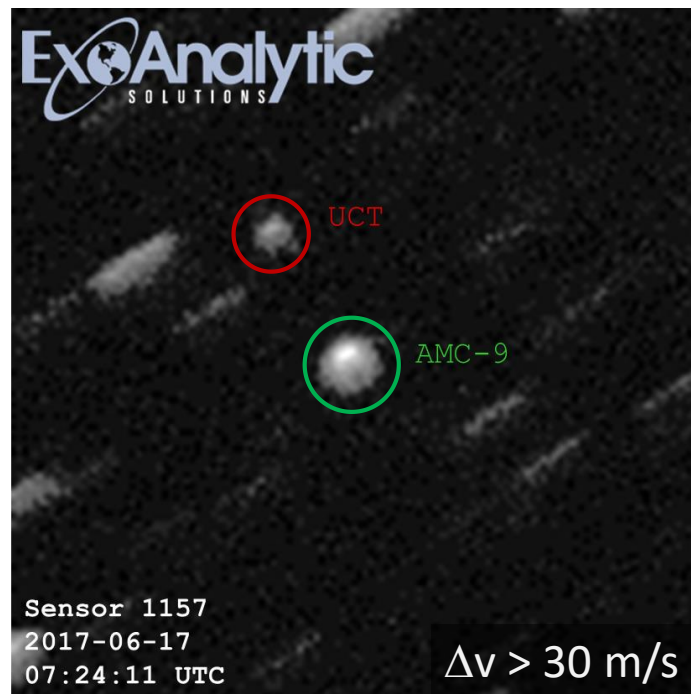


Figure 2. Imagery showing the 17 June 2017 anomaly.

Additionally, a separate object in close proximity to AMC-9 was noted. Figure 3 shows this object's lightcurve on a plot with AMC-9's lightcurve. Notably, the object is dimmer than AMC-9 (indicating most likely a smaller size, although nearly any object in GEO is smaller than a large communications satellite), and is displaying a sinusoidal lightcurve, possibly indicative of some rotational motion.

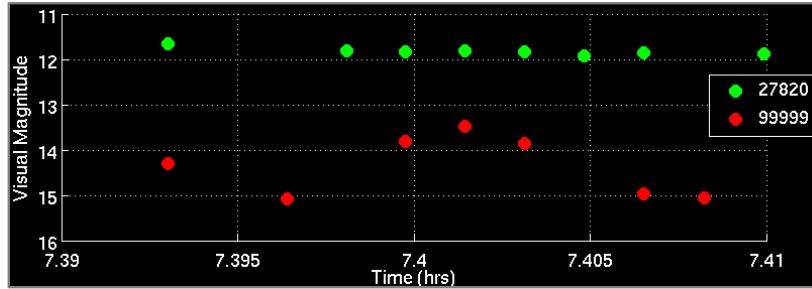


Figure 3. Lightcurves from the 17 June 2017 anomaly, showing a child UCT and the parent object (AMC-9).

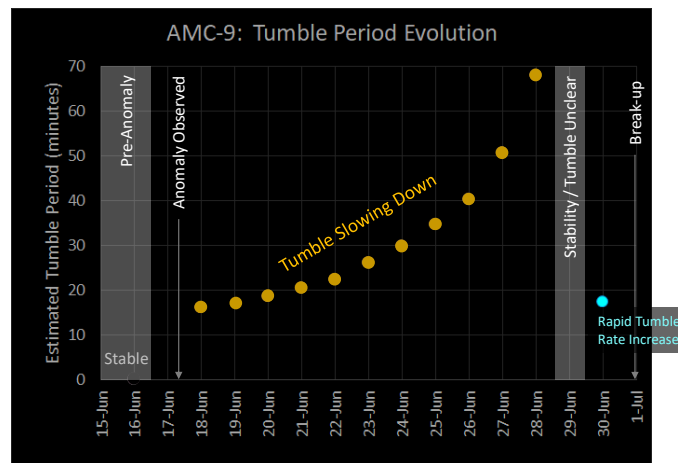


Figure 4. AMC-9 apparent tumble rate from 17 June 2017 to 01 July 2017.

As seen in Figure 4, AMC-9 experienced periodic spikes in its photometrics, indicating an ongoing tumble. The tumble period slowed from sixteen minutes to 68 minutes over two weeks, although the data from a short time later indicate a highly-energetic event on 01 July 2017, seen here as a rapid increase in apparent tumble rate. The 01 July 2017 event also included the generation of multiple tracks that dispersed from AMC-9, as seen in Figure 5.

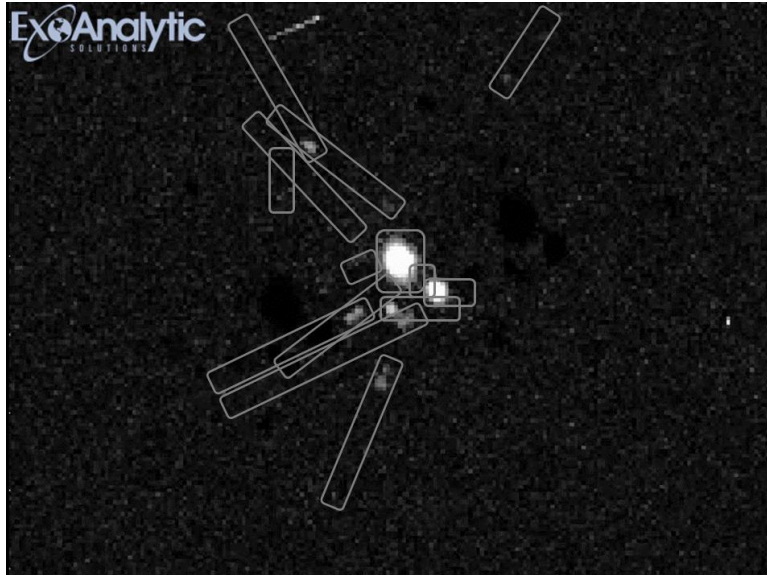


Figure 5. Screenshot of AMC-9 video, with dispersion tracks highlighted.

Figure 6 summarizes the analysis performed on the tracks, showing emission of track particles as a function of time (left), and tracks in 2-D space (right). Note that the 2-D tracks are projections of 3-dimensional paths, and the apparent recurving behavior of some tracks is due to this. Note also the way the reframing of this rich dataset enables two conclusions: all particle tracks were not emitted at once, but over a period of time corresponding to roughly  $\frac{1}{4}$  orbit; and that the particle tracks show no obvious directional preference.

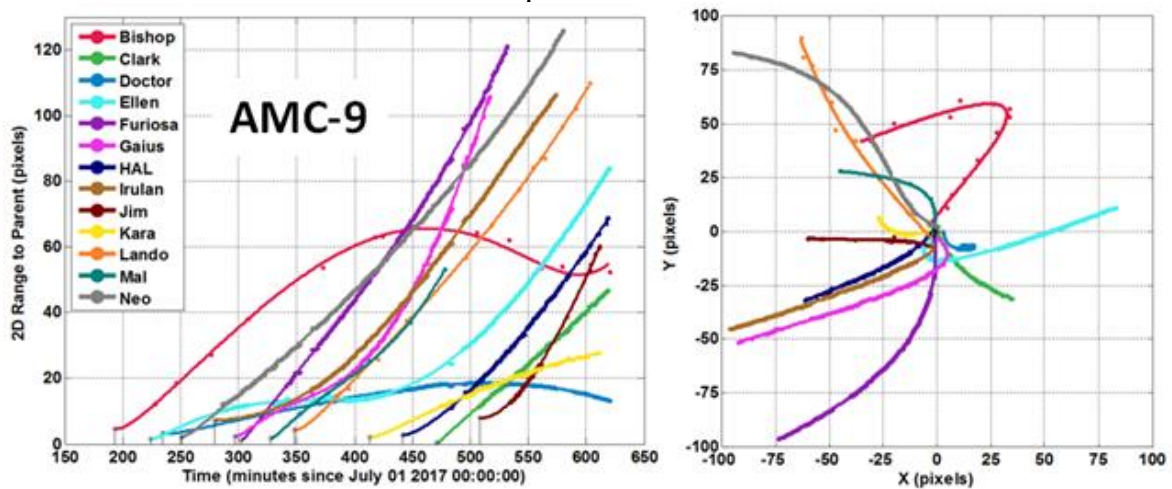


Figure 6. Time-axis (left) and 2-D (right) views of the AMC-9 event on 01 July 2017.

### Telkom-1 Event

Another event occurred involving the Telkom-1 satellite on 25 August 2017. As seen in Figure 7, all the apparently emitted fragments were seen to have nearly cotemporaneous times of closest approach to the main Telkom-1 body, indicating that a single catastrophic moment may have been the ultimate proximate cause. Additionally, the tracks emitted show a clear directional preference,

with the cone of emission covering roughly one hemisphere. In fact, as seen in Figure 9, the data collected may well have captured a fluid plume being emitted as the event occurred.

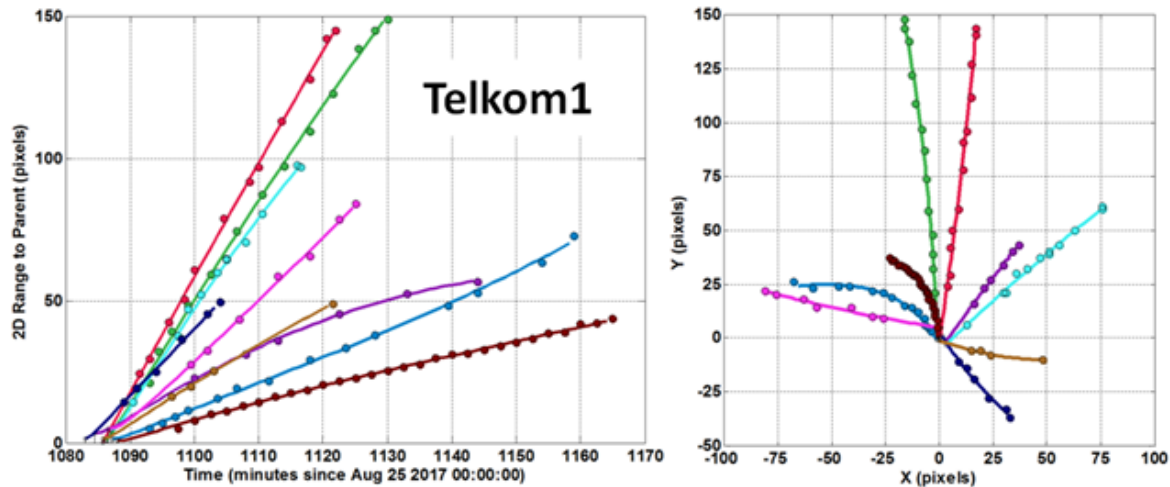


Figure 7. Time-axis (left) and 2-D (right) views of the Telkom-1 event on 25 August 2017.

At first impression the rich data for Telkom-1 may well be consistent with a rupture event in a pressurized vessel onboard the vehicle.

The events are described in additional detail in [3], and simple narratives may be tentatively applied to two of the events. For instance, the evidence in the case of AMC-9 indicates that some sort of instability in the lightcurve occurred, and that stability was being gradually returned to a state approximating that which had prevailed before the initial 17 June 2017 anomaly. A period of increased deviation from an apparent return to stability appeared on 01 July 2017, followed by a dispersion of signals from the main body of AMC-9. The most straightforward explanation for this sequence of phenomena is that AMC-9 underwent some kind of anomaly which caused a tumble to occur. The tumble was being brought under control slowly, possibly by the application of slightly degraded maneuvering or pointing capability, and then a second compounding anomaly occurred, which produced increased or worsened stability and tumble, and created a field of debris which was physically dispersed by the tumble effects.

The Telkom-1 event seems even more straightforward. The existence of a plume-like field near the main body of Telkom-1, combined with the roughly-hemispherical dispersion of signals from the main body over a very short period of time (which occurred approximately during a maneuver window), seem to credit the explanation that a pressure vessel ruptured as a result of some internal failure during a period of increased use or stress on vehicle systems.

### Analysis Techniques

This section describes a few key technologically-enabled methods for assessing incidents and events on orbit. Fundamental techniques which support a basic level of knowledge and more-developed techniques which permit the extraction of deeper insight are described briefly.

Rich persistent datasets are those which cover multiple aspects of a given observation subject (the term 'rich' here refers to a breadth of coverage), potentially including multiple view angles or solar

geometries, multiple wavebands, or variety in some other characteristic; and without significant gaps in coverage (i.e., with coverage at every possible window or with gaps in coverage substantially shorter than the typical timescale on which a major change might occur). Rich persistent datasets are thus interesting because they provide insight into (potentially) multiple patterns of life of a signal over (potentially) multiple temporal cycles of relevance.

### Instrument Proliferation

Accordingly, one of the best techniques for obtaining rich persistent datasets is simple proliferation of collection instruments. Much as a wide variety of telescopes types might permit the collection of a rich dataset on a given target, a wide variety of sites might permit the collection of a persistent dataset on a given target. Today there are multiple distributed global networks from which the future Space Traffic Management authorities of the world could obtain relevant, timely, and useful information on observed space objects.

### Frame-Stacking

Preserving the raw frames of collected observations allow for various trade-offs to be possible with over-sampled data. Aggregating data collected in straightforward ways, such as stacking imagery presuming the trajectories of space objects, allows for post-processing methods to enhance the information collected. Often this can result in an increase in sensitivity, resolution, or in the quality of the information and context that can be inferred.

Figure 8 shows stacked frames from the Telkom-1 event. The large dot in Telkom-1's location is seen to be accompanied by a few tracks which lead away, plus a cloud of pixels which separates, expands, and fades. The dim tracks and the pixel cloud, highlighted further in Figure 9, are visible in part due to the frame-stacking conducted as part of the analytic process.

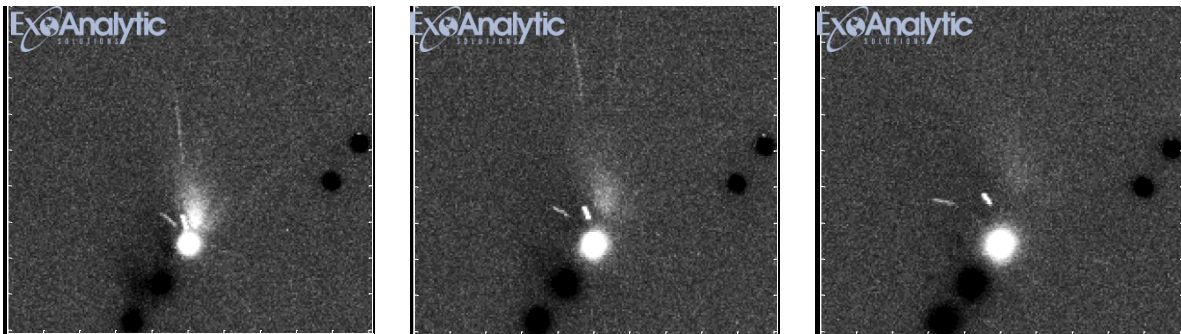


Figure 8. Screenshot sequence showing the Telkom-1 event (at approximately 20-minute intervals). Note the apparent fading in and out of tracks and the spray of pixels resembling a dissipating plume.



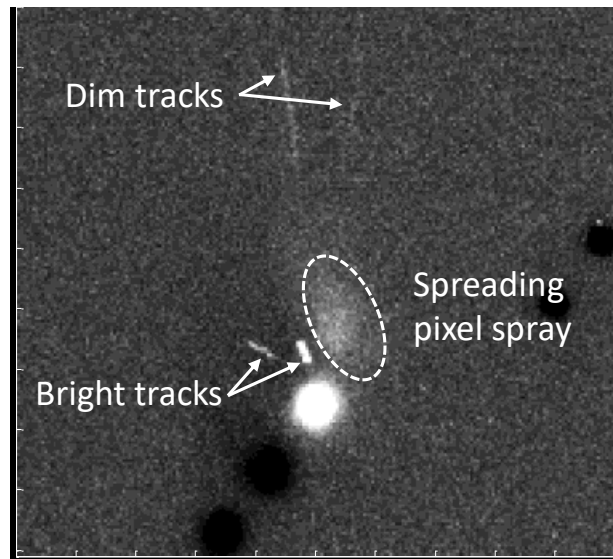


Figure 9. Expanded view of Figure 8 center image, showing tracks and pixel spray.

#### Momentum Impulse Transfer Events (MITEs)

MITEs refers to the art applied to the detection of very small impulses as exhibited by RSOs. It is described in detail in [4], and consists of comparing the trajectory of an RSO based on a long period of frequent observations with the predicted trajectory based on an advanced orbit propagation tool. ExoAnalytic has a customized orbit propagation tool that accounts for higher-order perturbations, as well as solar photon effects and shadowing effects. More advanced applications of the technique compare ballistic trajectories (accounting for known environmental effects) with actual trajectories, and then comparing residuals to assess where the orbits cross, indicating where an impulse of some kind occurred. This technique in itself may be used to detect and characterize very small or minor anomalies (for instance, a slightly-uncalibrated lag in thruster valve response), and serves a broader purpose in anomaly investigation.

For example, AMC-9 displayed multiple MITEs after its apparent debris dispersion event, likely meaning that it was either still attempting to perform a detumbling or other stabilization, or that it was offgassing in some other way.

#### Lightcurve Assessment

While MITEs techniques rely heavily on astrometric data, photometrics provide another avenue of investigation. Lightcurves have traditionally been assessed for many purposes, but the data from a single lightcurve is a different (lower) order of magnitude in value than a series of time-distributed lightcurves indicating a pattern of life. This may be used to produce early warnings of anomalous behavior. Furthermore, as seen in Figure 10, lightcurve data can allow tumble rates to be estimated, given sufficiently rich data. The difference in spikes in photometric data are analogized to the time period between recurring times when a highly-reflective element of the RSO is pointed at the sensor. The sheer volume of data collected again serves to fill in gaps in the pattern of life of the RSO, even to such an extent that anomalous patterns of life can be comprehended.

- Number of Observations: 8,807
- Photometric Summary: Tumbling, ~16:05 minute period

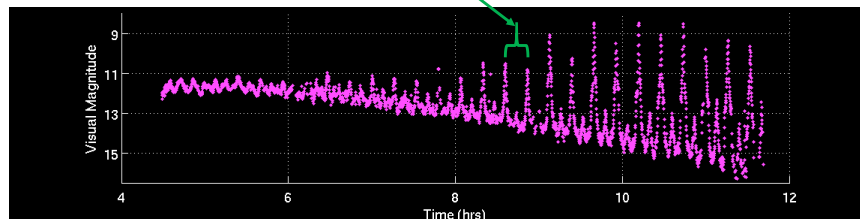


Figure 10. AMC-9 apparent tumble rate assessment.

More advanced methods of lightcurve analysis may include detailed fingerprinting over the course of an entire season or even year, obtaining multiple solar phase angle aspects on a given RSO and thereby obtaining photometric information corresponding not only to short-term but also to longer-term cycles of behavior by said RSO.

#### Energy Methods: Invisible Impactor Limit

A simple energy-based method involves the estimation of maximum possible impact energy deliverable by an unseen impactor, to assess whether an event incorporating energetic dispersion of pieces from an RSO may have been caused by an unseen impactor or was more likely generated using energy stored inside the RSO in some way.

As a simple first look at this method, we can examine the anomaly affecting Telkom-1 and whether it may likely have been the result of an invisible impactor. Notably, no visible impactor was observed approaching Telkom-1 in the period before the anomaly (nor departing the region around Telkom-1 afterward).

Figure 9 shows the Telkom-1 energetic event, with a field of bright pixels moving rapidly away from the main bright body of Telkom-1 and dimming. It is most probable that this imagery represents a set of particles of various sizes (note particularly the singular points of light moving up and to the left, most likely corresponding to larger pieces).

Impact mechanics studies indicate that a highly energetic event (such as the explosion of an artillery shell) produces a fragment distribution with many more small particles than larger particles, and from [1], we see that catastrophic breakup is thought to occur at greater than 40 J of kinetic impact energy per total g of impactor plus target. Given that there is an apparent particle distribution visible in the imagery, it seems reasonable that some partially-catastrophic event occurred. While Telkom-1 was severely affected, it was not utterly destroyed. However, given that modern communications satellites have extensive physical structure (incorporating, at a minimum, a central bus, multiple solar array wings, and several large protruding antennas), it seems highly possible that only some subset of the structure was damaged, and most of the probable fragmentation may have contained to some subset of the major structures. (This is not perhaps as unlikely as it seems – consider that on Earth, an aircraft ingesting FOD in flight may sustain catastrophic engine failure and even undergo engine shutdown, but then is often more than capable of gliding to a safe landing, as physical impact effects, debris shedding, and even energy

releases such as aviation gasoline fires do not necessarily cross the physical interface between the engine and the wing or body as easily as they spread within the engine itself.)

As such, it is possible that Telkom-1 had a subassembly of some kind destroyed, leaving the main body relatively intact. If we assume that the subassembly underwent catastrophic fragmenting failure, we can assess the likelihood that this was caused by an unseen impactor versus an internal failure. If Telkom-1 had been reduced to fragments in its entirety, we could similarly apply the same analysis to the entire vehicle.

Given the limitation of 40 J of impact KE per gram of impactor plus target, we may write the following:

$$KE_{total} = 40 \frac{kJ}{kg} * (m_{target} + m_{impactor}) = 0.5(m_{target} + m_{impactor})V_{impact}^2$$

From this, we can derive the necessary impact velocity if we know the masses of the target segment and the impactor.

The mass of the impactor may be estimated by assessing what the maximum mass of said impactor could be if the impactor were invisible. The main equation [2] driving this assessment is:

$$M_v = -26.7 - 2.5 \log(A_{cross} \rho F(\varphi)) + 5.0 \log(r)$$

where

$M_v$	Visual magnitude
$A_{cross}$	Cross-sectional area
$\rho$	Reflectivity coefficient
$F(\varphi)$	Phase angle function
$r$	Range to observer

We may set the visual magnitude at the (conservative) lower limit for an impactor which would have been expected to be visible to our sensors: 19. Additionally, we may relate the cross-sectional area to the impactor mass using volume and density equations, as follows:

$$m_{impactor} = \rho_{mass} Vol = \rho_{mass} \frac{4}{3} \pi \left(\frac{d}{2}\right)^3 = \rho_{mass} \frac{1}{6} \pi (d)^3, \text{ where } d \text{ is the invisible impactor's diameter. As } A_{cross} = \pi \left(\frac{d}{2}\right)^2 = \frac{\pi}{4} d^2, \text{ we may write } m_{impactor} = \rho_{mass} \frac{\pi}{6} \left(\sqrt{\frac{4A_{cross}}{\pi}}\right)^3.$$

Rearranging and substituting, we see that

$$m_{impactor} = \rho_{mass} \frac{\pi}{6} \left( \sqrt{\frac{4 * \left( \frac{10^{\left( \frac{M_v + 26.7 - 5.0 \log(r)}{-2.5} \right)}}{\rho F(\varphi)} \right)}{\pi}} \right)^3$$

Substituting for the limiting visual magnitude of 19 and a range of 37,700 km, we simplify as:

$$m_{impactor} = \rho_{mass} \frac{\pi}{6} \left( \sqrt{\frac{4 * \left( \frac{10^{(-3.1274)}}{\rho F(\varphi)} \right)}{\pi}} \right)^3 = \rho_{mass} \frac{\pi}{6} \left( \sqrt{\frac{4 * \left( \frac{0.0007458}{\rho F(\varphi)} \right)}{\pi}} \right)^3$$

For this assessment, the feasibility of a dark impactor causing the event will be based on the necessary impact velocity, with lower velocities being more feasible. Accordingly, we will assume the largest, heaviest, dimmest possible invisible impactor. For the solar geometry at the time of the event (approximately 0700 UTC on 17 June 2017, or around midnight in the US Pacific timezone, where the primary observer systems were located), the solar phase angle was very nearly 180 degrees. From [2], the reflectivity function for a diffuse sphere is described by:

$$F(\varphi) = (2/(3\pi^2))[(\pi - \varphi)\cos\varphi + \sin\varphi]$$

At this geometry (roughly stellar opposition), this term collapses to approximately 0.2122. We may additionally set a very low reflectivity threshold of 0.05 (most are much higher; 0.2 is closer to typical), and select a high density of 2700 kg/m<sup>3</sup> (solid aluminum) to analyze the case of a powerful but dim impactor.

Accordingly,

$$m_{impactor} = 2700 \frac{\pi}{6} \left( \sqrt{\frac{4 * \left( \frac{0.0007458}{0.01061} \right)}{\pi}} \right)^3 = 2700 \frac{\pi}{6} (0.02677) = 37.847 \text{ kg}$$

And, from prior equations, we can see that the impacting velocity needed is approximately 539.74 m/s. This relative velocity is approximately 17.5% of GEO orbital velocity, and seems an unlikely impacting speed. It is most likely that an impact from a near-GEO object would have a relative speed within 1% of GEO orbital speed (for nearly co-orbital objects), or be approximately twice the orbital speed (for counter-orbitals). Although unique geometries and combinations of different object materials, sizes, and vectors that might provide this sort of impact cannot be ruled out, it seems unlikely that an invisible impactor generated this anomaly, and as no visible impactor was observed before or after the event, the most well-supported conclusion is that the event was

precipitated by the release of an internal energy store. This does not conflict with the intuitive assessment produced by watching the video of the event.

An additional assessment of this possibility relied on a Monte Carlo simulation model, which assessed 10,000 possible orbits for a randomly-evaluated invisible impactor that could have delivered the necessary kinetic energy upon a collision to create the resulting effect visible upon Telkom-1. The model was run multiple times, and no combination of parameters resulted in a probability over about 1%. Accordingly, we assess the chances of this energetic event stemming from an impact between some invisible impactor in a GEO-crossing orbit and Telkom-1 as less than 1%. The odds of a visible impactor having hit Telkom-1 without being observed by the sensors that watched Telkom-1 undergo the event are equal or lower, and therefore we may safely state that the primary source of energy for this event was initially onboard Telkom-1.

Philosophically similar evaluation of the AMC-9 event can be conducted on the basis of assuming that the primary result of a collision was the generation of a rotational state in the AMC-9 satellite. If we estimate the tumble rate of AMC-9 based on the ~16-minute period of peaks in the lightcurve initially following the anomaly, and assume an invisible impactor, we may use similar Monte Carlo methods to determine that the likely closing velocity range for an invisible impactor is between 0.1 and 1 m/s, and probably in the range of 0.2-0.3 m/s with AMC-9.

This relative velocity may very sensibly be attributed to a piece of debris in a nearly co-orbital condition, but the likely narrative for this to be the case is still complicated. The suggested narrative would then be that an impactor of approximately the low tens of kg in mass, and less than 0.3 m on a side, drifted into AMC-9 at a low velocity and with such geometry as to graze a distal surface, causing a spin to be generated. This would explain the apparent lack of an immediate catastrophic fragmentation event (seen in the EGTN-collected imagery) and the owner/operator's assessment that damage was not crippling, if it were to incorporate the scraping of a small and non-essential strip of material from AMC-9, or perhaps impart a spin to the invisible impactor such that it briefly turned and reflected enough sunlight to appear as a separate object. In this story, a piece of debris essentially bounces off AMC-9 lightly enough to avoid shattering parts of it, but hard enough to set both AMC-9 and the piece of debris temporarily spinning. While the piece of debris tumbled away and is perhaps lost somewhere in the UCT catalogue now, AMC-9 attempted to correct itself and suffered further issues on 01 July 2017, most likely the result of some other compounding effect.

At any rate, while this is a plausible case, it is not compelling, and we cannot state that there is a convincing assessment that the energy needed to impart to AMC-9 its ascribed motion came from an external source. Accordingly, an internal source is still deemed possible. However, much additional further analysis is required in order to evaluate possible causes of the anomaly.

The broader point that this analysis method matches well with the intuitive assessment of Telkom-1's energetic event as an internally-caused failure indicates the relative validity of the method.

#### Energy Methods: Fragment Size Distribution

While some conclusions can be made using observation data of the character available from persistent, rich datasets, there may be additional techniques still to be applied, albeit they are

consequently still in their infancy. The in-depth tracing and tracking the number, estimated size, and apparent motion of fragments or possible fragments produced by an event is such a technique.

The assessment of dispersed object size is such a technique. Although direct assessment of size is not always possible from nonresolved imagery, we may take the established relationship between object brightness and size and set rough limits on size from observed brightness.

A figure showing the approximate brightness distribution of AMC-9 dispersed tracks is below.

<u>Num</u>	<u>Temp ID</u>	<u>Vmag</u>	<u>Apparent motion</u>
0	Anakin	12.6	Center
3	Doctor	15.3	E
4	Ellen	17.9	E
8	Irulan	17.9	SSW
13	Neo	18.5	NW
7	HAL	18.7	SW
2	Clark	18.8	S
5	Furiosa	18.8	SSW
6	Gaius	18.8	SW
9	Jim	18.9	SW
10	Kara	19.5	N
11	Lando	19.6	NW
1	Bishop	19.7	NNE
12	Mal	19.7	NW

Figure 11. AMC-9 dispersing tracks characterization.

Brightness is estimated for each individual object (numbered and named; Object 0/Anakin is AMC-9's main body), as it varied somewhat throughout the dataset. The direction of motion is given for convenience.

Figure 12 shows the brightness of fragments (except the main body of AMC-9) in a distribution, from dimmer (left) to brighter (right). The solid blue line shows available data, and the dotted black line is an estimate of the data curve as it should appear for objects dimmer than the EGTN can typically detect.

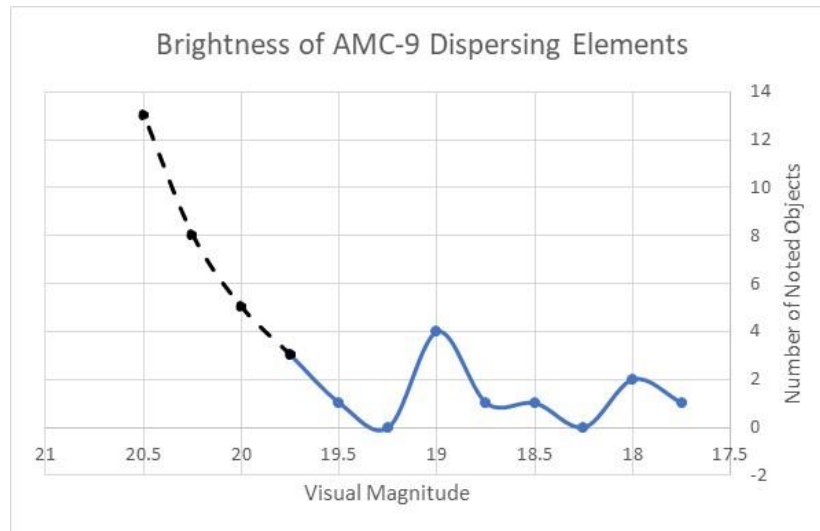


Figure 12. AMC-9 dispersing tracks brightness distribution.

The curve bears a distinct resemblance to the shape of a shell fragment size curve for a structured shell. Classically, there should be many very small fragments and fewer larger fragments, with a near-logarithmic distribution. The data on the left Figure 13 show such a distribution for a simple shell (roughly a pure cylindrical shape). The data on the right, however, show a similar fragment size distribution for a shell with a structured shape (a sectioned cylinder). Note that the existence of structure on the fragmenting body results in bumps in the fragment size distribution curve.

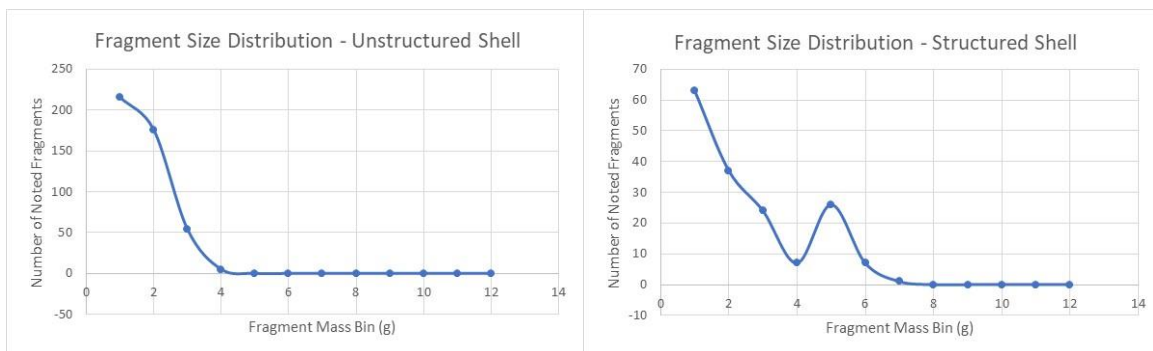


Figure 13. Shell fragment size (by mass) distributions for a simple cylindrical shell (left), and structured shell (right). The figures recapitulate data from Tables VII and VIII (and Figs. 4 and 5) from Reference 5.

The brightness distribution shows an interesting possible similarity to the fragmentation of a structured shell as described in [5], providing some evidence that a structured or shaped element of AMC-9 (possibly an outer physical segment), and not the main body, was the source of the various dispersing tracks observed.

Intriguingly, if we generalize that structure results in multimodal fragment distributions, we can presume that the dispersing track brightness distribution should also follow a multimodal pattern, and accordingly a structure-mediated partial breakup is a reasonable description of what may have occurred when AMC-9 experienced an on-orbit anomaly.

### **Importance of Data Management and Classification**

One paradigm advanced in the trade publications recently is the ‘data lake,’ wherein all sources of data pertinent to SSA are combined into one extremely large body, and thereby effectively pooled together. The driving logic seems to be that if small ponds of data are valuable, surely a larger lake is more valuable, much in the same way that an aquatic environment gains complexity as it grows in size (witness the fact that sharks are not distributed evenly in all small streams and springs around the world, but are typically found only in bodies of water above a certain volume). The insights afforded by the rich datasets used in this paper support the belief that more data is better, but we ought to distinguish between more data from all sources globally and from well-understood and well-managed sources.

However, there are two drawbacks to the uncautious grouping of all data into a global lake. The first is the possible negative effect of low-quality or inaccurate data, a small amount of which may contaminate much larger sets of better data (the lake analogy is perhaps apt here, as the negative effects of small amounts of pollutants upon drinking water have been attested since antiquity and publicized since at least 1962, wherefore we may perhaps call this the Carson Effect, to which data lakes are vulnerable).

The other is the dilution of valuable data by other data, a factor to which an SSA data lake (by the nature of the concept, including data amounts exceeding the ability of any single entity to handle, process, and utilize efficiently) may well be particularly vulnerable. If a data lake includes substantial amounts of data from multiple sources, it is likely to include multiple duplicate perspectives of less-interesting events, and the simple effect of sorting through all the data thereby encompassed to arrive at a usable depiction of a news-worthy occurrence may well consume sufficient time and resources that the data lake will actually serve to reduce the value of good data by dilution, thereby achieving the precise opposite of its intention. We may term this the Faelivrin Effect, after the literary description of an event wherein a valuable opportunity to prevent a catastrophic loss was missed due to inattention in the face of a dangerously distracting preoccupation, much to the later detriment of all concerned. Equally may we suggest that the pursuit of a data lake concept, while motivated by appropriate concern, is perhaps an *ignis fatuus* given the resources and attention it would consume in the face of a rapidly-changing and potentially quickly-compounding situation at the GEO belt today.

### **Policy Implications**

We present these case studies in this forum to initiate meaningful discussion regarding the policy implications of such events. The events observed and discussed in this paper represent a change, at least for deep space traffic, in that it is now possible to review observation data in addition to owner/operator telemetry during experienced anomalies and take steps toward attributing cause, provide sufficiently accurate and timely alerts to other stakeholders in deep space traffic, and record important lessons learned for the benefit of future space operations. While the public descriptions of these events represent sufficient reporting for present-day standards, we should carefully consider what is required to meet the full objectives of space traffic management. Going beyond the state-of-the-art capabilities in Space Situational Awareness which seek to understand the current state of observed objects and predict their evolution with the intent of preventing conjunctions or other incidents, Space Traffic Management solutions require members of the traffic population, observers, and traffic managers to be well coordinated in order to skillfully



direct active traffic, avoid hazards, provide timely and sufficiently accurate warnings, and, in the case of incidents like the ones presented here, provide the most informative assessment possible.

There is significant opportunity afforded by the fusion of owner/operator information with persistent, real-time observation data. Historically, these pieces of information have been analyzed as independent data streams, one attempting to infer variations in state of the system being observed, the other with limited information about the outside environment. It is critically important that we exploit this opportunity to obtain the highest-fidelity model of any active space traffic member, such that we can enable the highest-precision control of its motion during its mission, and understand as clearly as possible the model that should be used most effectively to track it when it becomes part of the inactive debris population. Being able to do these two things well will be increasingly important as the active and inactive space traffic populations grow.

### **Summary**

Some important techniques for utilizing large, rich SSA datasets were discussed in this paper, and given specific application to the cases of AMC-9 and Telkom-1, both of which experienced significant anomalies and major energetic events in the summer of 2017. These techniques rely on a foundation of proliferated and persistent coverage, the generation of patterns of life and the ability to detect deviations therefrom, and application of close analysis to track energy and mass from remote observations, as far as technological limits permit.

The use of these datasets and techniques has allowed the creation of narratives for the AMC-9 and Telkom-1 events. It is most probable that Telkom-1 experienced a short-duration catastrophic failure of an internal energy-storage component (a propellant tank rupture seems intuitively likely). The fact that this event occurred in close association with a maneuver and the visual observation of what seems to be a small, dispersing cloud associated with the event provide further confirmation.

The AMC-9 event is more complicated, although it also seems more probable to have been generated by internal effects. The precise nature of the initial anomaly and separation event on 17 June 2017 is still unclear, although there is not unambiguous evidence as to its having been the result of either an external impact (from a rather small object in a near-matching orbit) or the result of an internal cause of some kind. However, the mass dispersion of multiple tracks in all directions, over a sustained fraction of an orbit, following an apparent gradual decrease and then sudden increase in visible tumble rate of AMC-9, strongly indicates some kind of inadvertent magnification of a negative effect that resulted in the possible disintegration of some small and possibly peripheral element of AMC-9. While more specific conclusions would benefit greatly from comparison to onboard telemetry, for the present we suggest additional analysis, which might include calculation of initial orbit vectors for each dispersing track, as a way to continue investigating what may have occurred when AMC-9 experienced an anomaly.

The development of methods for detailed energy and mass tracking are pursued in recognition of the fundamental conservation of mass, momentum, and energy laws, rather than from a signals processing standpoint. Approximate analogues are frequently used in other investigations of incidents (witness the FAA/NHTSA's standard method of assembling all parts of a crashed aircraft

inside a hangar), and the intense level of data collection and knowledge of behaviors (particularly how certain patterns of lightcurve behavior typically correlate to physical behavior) comprising the other methodology described in this paper enable at least some level of mass, momentum, and energy tracking. These methods are inherently data-intensive, and are best used with knowledge of the proximate predecessor events and immediate consequences of an anomaly as key enablers in investigation.

However, the traditional avenues of acquiring such knowledge are two: mandated capture and storage of data most likely to be relevant to such an investigation (e.g., ADS transponders and CVRs) per regulation by government authorities; and placing investigators physically at an incident site as promptly as possible following the incident. The first avenue is not mandated for space vehicles at this time, and data that are collected (transmitted telemetry) may not serve this role in RSO anomaly investigations. The second avenue is not plausible for the GEO environment, which has never been visited by a human (save for those in passing transit to or from lunar orbit), and is currently not a sphere in which the general public or even civil government bodies may have much expectation of remotely operating surveillance systems. Accordingly, overwatch from other locations must be the primary method of supporting investigations in the GEO neighborhood for the present. This means that advancing methods of analysis of overwatch, as well as strengthening the mature techniques of overwatch, is a critical component of any possible capability to investigate GEO RSO anomalies in the near future, and a worthwhile subject for further research.

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