Photometric and Other Analyses of Energetic Events Related to 2017 GEO RSO Anomalies

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ABSTRACT
This paper addresses significant anomaly events affecting Resident Space Objects (RSOs) in Geosynchronous Earth Orbit (GEO), two of which occurred during the summer of 2017. The paper details the progress of the events, pulling from multi-frame imagery to illustrate observable phenomena. It also addresses the importance of possessing such content-rich data by detailing the additional opportunities for deep analysis and root-cause assessment offered by the presence of content-rich datasets rather than sparse datasets.

1. Introduction

Enhanced orbit determination (OD) and photometric analysis of deep space resident space objects (RSOs) enabled by coordinated collection from multiple observers is essential for Space Situational Awareness (SSA) and Space Traffic Management. OD models directly impact propagated orbit accuracy, which then drives collision avoidance (COLAs) and impels responses to potential collisions. To improve the accuracy, detail, and timeliness of RSO tracking and characterization, ExoAnalytic Solutions built and operates the ExoAnalytic Global Telescope Network (EGTN): a network of 170+ ground-based telescopes at 23 sites on 5 continents (and Hawai'i) that annually collects 80+ million correlated astrometric and photometric measurements of active and inactive RSOs in geosynchronous Earth orbit (GEO) and the near-GEO region.

Precision OD analysis reveals occasional momentum impulse transfer events (MITEs) with detectable in-track velocity as small as 1 mm/s [1]. In several cases, observed MITEs are accompanied by unexpected features coincident in the photometry data. Using automated change detection routines, these coincident astrometric and photometric feature sets can be used to invoke enhanced analysis of collected imagery. In the summer of 2017 this approach resulted in the detailed analysis of two break up events in GEO. Exploiting the collection redundancy inherent to the EGTN enhanced visual representation of observed events is achieved through multi-sensor frame-stacking. In this way, multiple fragments produced by the events are made apparent, including detections approaching 20th visual magnitude. In stark contrast to analysis approaches which discard information contained in optical imagery by reducing collected frames immediately to apparent detection reports, the analysis approach described here enables an enhanced understanding of events in the GEO neighborhood, including information suitable for tipping and cueing of follow-up sensors as well as indications and warnings which may be provided to neighboring RSOs in a matter of minutes.

This paper will describe the approach used to 1.) rapidly identify astrometric and photometric features within properly associated detection histories, 2.) visually inspect the raw imagery used to generate the identified features, and 3.) perform frame stacking to enable enhancement of the signal to noise ratio of the local neighborhood in order to enable significantly more detailed analysis of observed events. The paper closes with the framing of a few potential policy questions bearing on operations in the GEO belt that this approach illuminates.

2. Extracting Direct Enhanced Visual Evidence from Autonomously-Detected Events

Astrometric analysis can be conducted simply by assessing the motion of a visible RSO in terms of right ascension (RA) and declination (DEC) over a period of time. Data collected by means of visible imagery provides photometric assessment in terms of visual magnitude (Vmag) as well, such that three streams of data (RA, DEC, and Vmag) are collected from RSOs on a continual basis.

If the RA and DEC data streams are sufficiently rich, OD can be conducted on it at a relatively rapid cadence. However, there is a certain lag time during which data sufficient to perform OD (meaning data collected while the RSO traverses some significantly sufficient fraction of its orbit). However, identifying the sudden change in metric values (state vector history) that is apparent in RA and DEC data streams depends on how frequently OD is performed. This inherently lags the identification of a photometric feature, such as an unexpected dip or peak in brightness or other atypical variation. Autonomous extraction of these features may be used to alert a user to perform additional OD at higher cadence to improve watch over an RSO of interest.

This high-cadence OD can then enable fairly direct evidence that an observed event incorporated some momentum exchange or impulse. While simple orbital mechanics can answer this question, direct imaging performed during the event provides an opportunity for re-investigation of the imagery in order to discern additional context. To this end, having a high-coverage, high-persistence observer network enables multiple opportunities for coordinated observation which result in this type of enhancement opportunity.

Other potential enhancement opportunities include frame stacking, multi-point photometry which may enable multi-axis rotational assessment or precise pointing determination, and even possibly super-resolution. For these reasons, the sorts of SSA analysis afforded via a system which maintains raw photons enable an explosion of insight that may match the size and complexity of forthcoming small satellite constellations and will enable ongoing operations in the increasingly complicated and crowded (by both active satellites and debris) GEO neighborhood.

The ability to observe these relevant data streams constantly provides unique insight into on-orbit behavior. When coupled with a precise model of orbital forces (including solar radiation pressure), these data allow recognition of the very small orbital changes, as described in [1, 2]. Some changes as small as 0.5 mm/s were recognized in the case of multiple retired rocket bodies [3].

These data, when collected at a rate of hundreds to thousands of datapoints per day, permit novel alternative visualizations. Fig. 1 shows these. On the left is a large dataset of photometric data, and on the right astrometric data. The photometric data shows a characteristic shape wherein a sharp peak of brightness is seen at a narrow band around a centered solar equatorial phase angle. This is a consequence of increased reflectivity from sun-pointing elements of the RSO. The astrometric data shows some sub-patterns of drift, but overall indicates that the RSO remains solidly within a given latitude-longitude box.

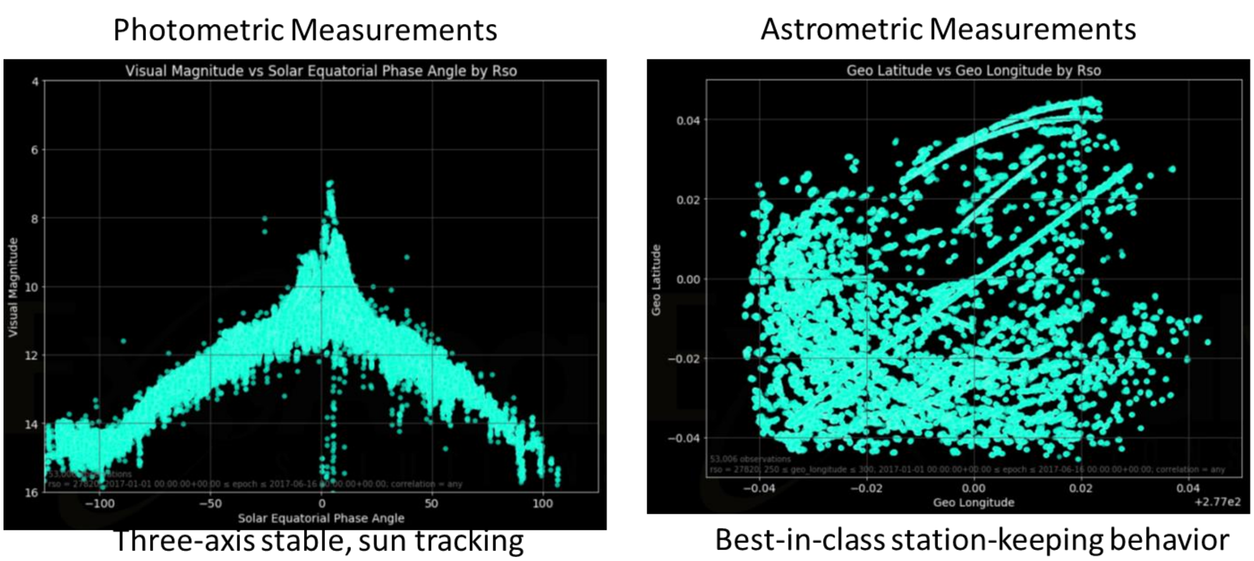


Fig. 1. Example of data.

In both cases, although outlier data are visible, the patterns are clear. When patterns of life such as those seen here are present, deviation from these patterns, especially for any significant period of time, becomes equally clear.

Events such as large orbital maneuvers and even changes in overall RSO rotation can easily be noticed. Once deviation from established norms has occurred, it can be recognized by very simple automated algorithms, which then alert humans. This process has the advantage of permitting machine attention to perform persistent vigilance over a large fleet of RSOs, while still using human attention and insight to analyze any deviations. This can be done within just 5-10 minutes given the system architecture used here.

Once human attention has been triggered, further fine analytical techniques may be deployed. Among these is frame-stacking, wherein a series of frames taken close in time are registered and stacked such that dim objects and tracks can be enhanced, allowing more insight into events that transpire on orbit. The presence of multiple datapoints is a unique enabler for this process as well, and can even be used to pin down times of occurrence to within the time lapse between two specific collected images.

3. Analysis Methods Applied, Including Frame Stacking

Primary analysis of astrometric and photometric data collected on an active RSO benefits greatly from strong information on prior patterns of life. Most active satellites in GEO have very long durations of periodically stable operations, with characteristic timescales on the order of their orbital period or greater. This is driven by their primary mission of continuous provision of a service to their clients on the ground over which they are positioned.

For this reason, a statistical and periodic analysis of the astrometric and photometric data collected can be used to define many features associated with the satellite's translational and rotational dynamics. Spacecraft attitude variations are more rapidly apparent in photometry data collected by optical systems than variations in translational dynamics (e.g due to maneuvers or other impulsive events). For this reason, a simple anomaly indicator algorithm may be used to identify characteristic periods in a photometric signal and define typical values and variance. Should new data be collected that fail to fall within these bounds, an anomaly flag may be reported, which prompts an analyst to perform additional review to determine if there is indeed a visually-apparent anomaly associated with the observed spacecraft. This rapid follow-up analysis is useful in the timely discrimination of routine station-keeping maneuvers from potential anomalous or even debris-producing events; the latter require additional effort to mark and begin keeping custody of new members of the debris population which would otherwise go unnoticed.

If automated versions of these algorithms are used, human attention can be attracted in the range of minutes or low tens of minutes, and thus responses to anomalous events can be initiated extremely rapidly. The use of additional astrometric primary analysis techniques dependent upon orbit determination mean that confidence in the effects and nature of an anomalous event will grow over hours or days, but appropriate initial alerts may be issued immediately.

In addition to these primary analyses, the enhanced data can also be used to conduct secondary analyses. It is a feature of rich datasets that they enable multitudinous additional analyses, and so this paper will not propose to provide an exhaustive explanation of secondary analyses made possible, instead confining the discussion to a few select instances.

For example, a key secondary analysis could include attempts at accounting for all conserved physical properties through an energetic event. If an object with an approximately-known mass is tracked through an event that results in separating tracks of multiple child objects, it may be assumed that the mass of the child objects plus the depleted parent object totals the original parent, minus whatever was lost in the energetic event. Similarly, if reliable orbit tracks on the child objects can be obtained, then their aggregate kinetic energy may be compared to the kinetic energy of the original parent object.

In either case, allowances should be made for loss of mass and energy to invisibly-small child objects. The final tally of mass and kinetic energy will likely show some percentage of unaccountable loss [4]. However, it can also be expected that the remainder of the tally will show important insights in certain cases. For instance, if the total apparent mass of the child objects seems to be exceptionally close to or even exceeding the original parent object's mass, it is reasonable to presume a high probability of the energetic event's cause being an impact by some other (potentially unseen) object, the mass of which became visible only after the event.

Additionally, an observer may expect some dissipation of stored energy from the RSO (provided it was not in a fully-retired state prior to the energetic event), in the form of propellant expenditure (e.g., from a stuck-on thruster) or perhaps pressurized fluid dissipation (e.g., from a propellant tank rupture). If the aggregate kinetic energy of the child objects can be seen to exceed the original parent object's kinetic energy, then it is likely that one of these sources bled energy into the child objects. If accurate information on remaining delta-V or propellant tank pressurization state is available, it may be feasible to determine which bleed event occurred (the potential energy stored in a substantial amount of propellant greatly exceeds that of a pressurized tank, for example).

4. Analysis of 2017 GEO RSO Anomalies

The GEO RSO anomaly which is the primary focus of this paper is the anomaly sequence experienced by the AMC-9 communications satellite in June and July of 2017, culminating in an apparent energetic event generating multiple child objects on 01 July 2017.

The geosynchronous RSO designated AMC-9 (NORAD ID 27820) experienced a series of anomalies in mid-summer 2017 which caused it to cease offering service as a communications system. The ultimate cause of these anomalies is still the subject of ongoing analysis, but the known facts are described according to the timeline in Fig. 2.

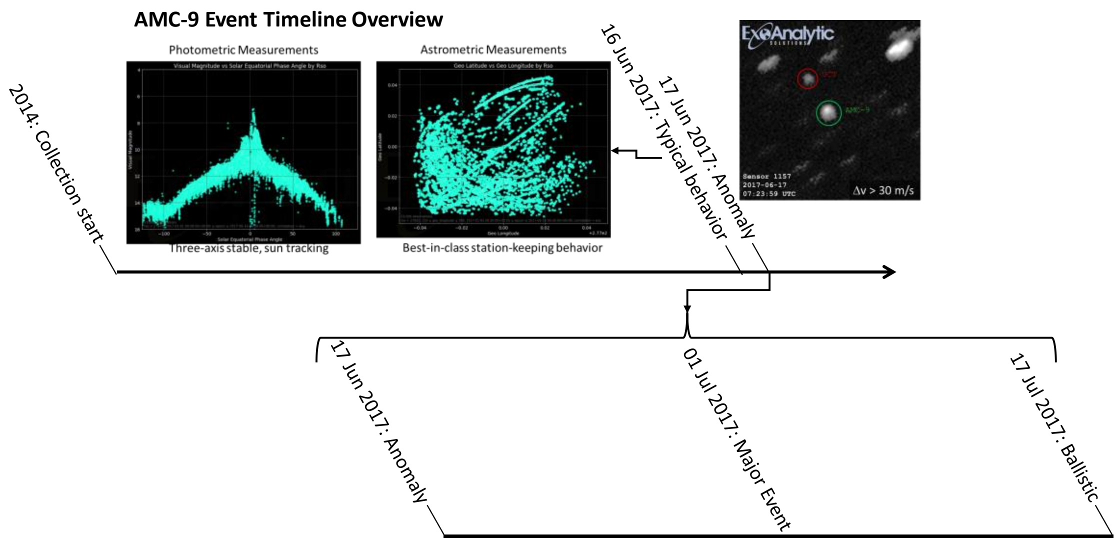


Fig. 2. Overall AMC-9 timeline.

AMC-9 had been behaving very typically for a communications satellite (with best-in-class stationkeeping performance) from at least early 2014 until 16 Jun 2017, and then it experienced an anomaly on 17 Jun 2017, followed by a major energetic event approximately two weeks later on 01 July 2017, before gradually settling into a pattern of purely ballistic behavior (indicating no station-keeping) around 17 July 2017. This period is called out in additional detail in Fig. 3.

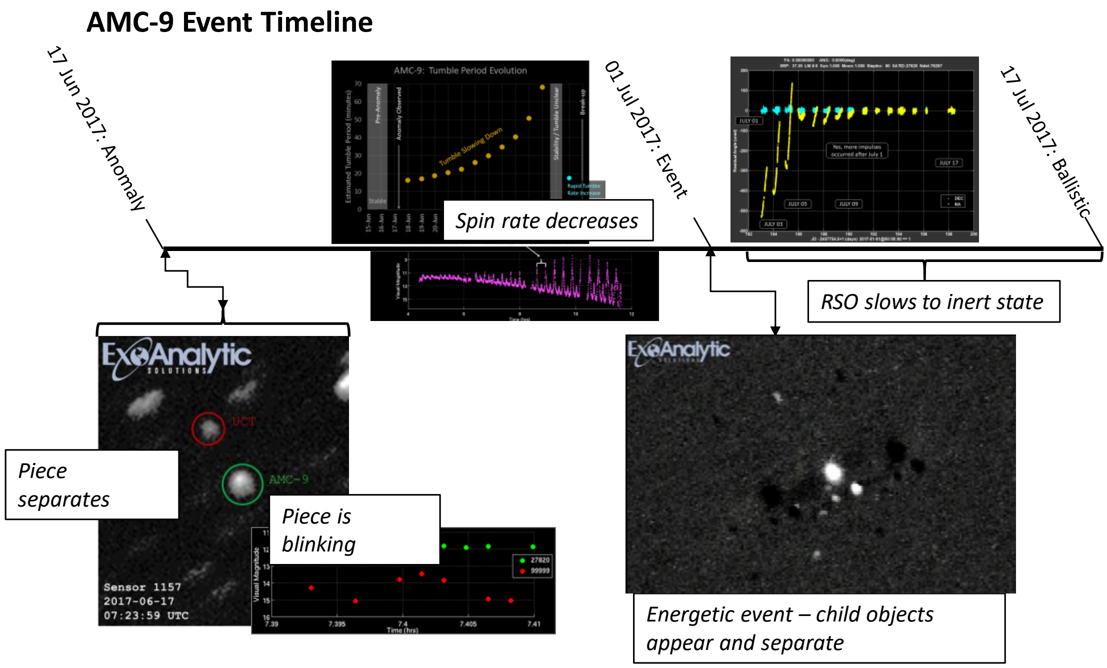


Fig. 3. AMC-9 timeline detail.

Early indications of an event affecting AMC-9 were visible in the photometric data stream. Fig. 4 shows the variation in photometric data captured.

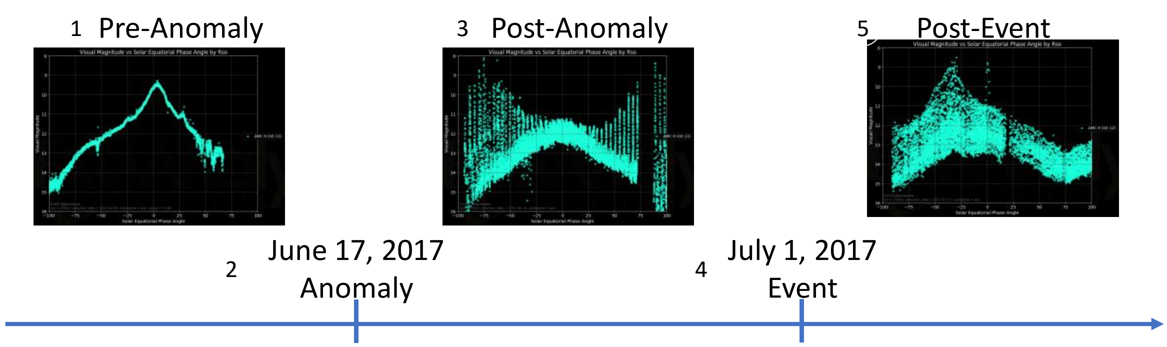


Fig. 4. AMC-9 photometric data prior to anomaly, after anomaly, and after energetic event.

As is shown, AMC-9 displayed the characteristic sharp central spike of a sun-tracking object before the anomaly. After the initial anomaly on 17 June 2017, it began to display different behavior, indicative of a tumble. After the apparent energetic event and break-up on 1 July 2017, it began exhibiting a photometric fingerprint indicative of a different rotational behavior mode, apparently a rotation around an axis not pointed at the sun.

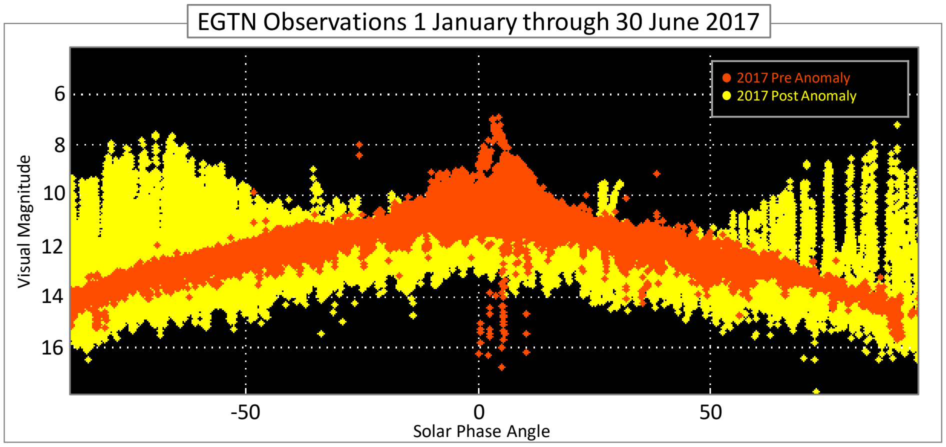


Fig. 5. AMC-9 photometric data prior to anomaly (red) and after anomaly (yellow).

As can be seen more clearly when the data before and after the anomaly are overlaid in Fig. 5, there was some substantial change in AMC-9's pattern of life on 17 June 2017.

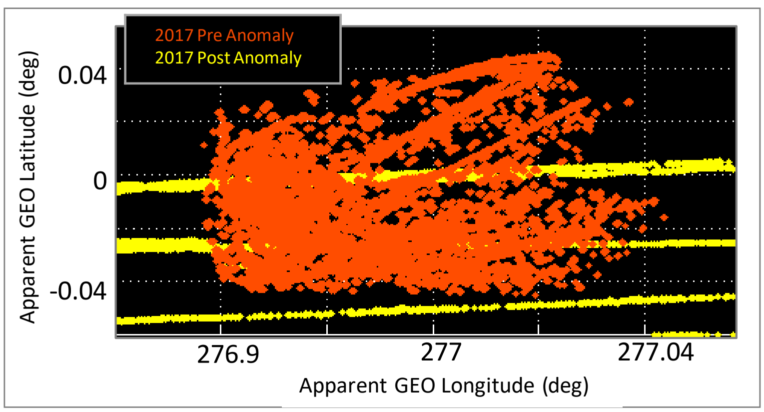


Fig. 6. AMC-9 station-keeping astrometric data prior to anomaly (red) and after anomaly (yellow).

Similarly, as seen in Fig. 6, a change was apparent in the astrometric data shortly thereafter, as AMC-9 apparently began drifting in its orbit. The yellow streaks show it crossing orbits rather than maintaining station inside its assigned box, as had previously been the case. The accuracy with which AMC-9 kept station prior to the anomaly was notable, and the post-anomaly behavior hints at the severity of the event.

In addition to the summary data, specific images collected during the event's duration are also available, and can be viewed directly for context and human awareness, or for thorough in-depth analysis. Fig. 7 and Fig. 8 illustrate some of this capability.

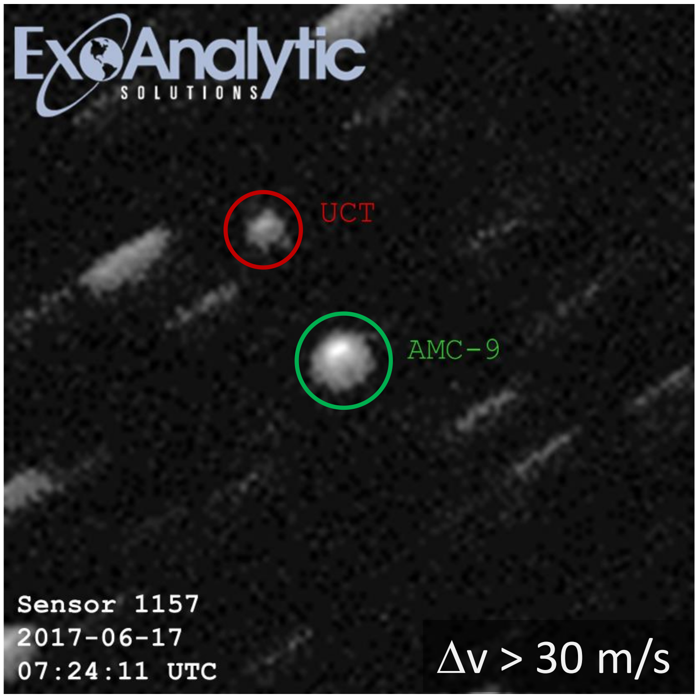


Fig. 7. Imagery showing the 17 June 2017 anomaly.

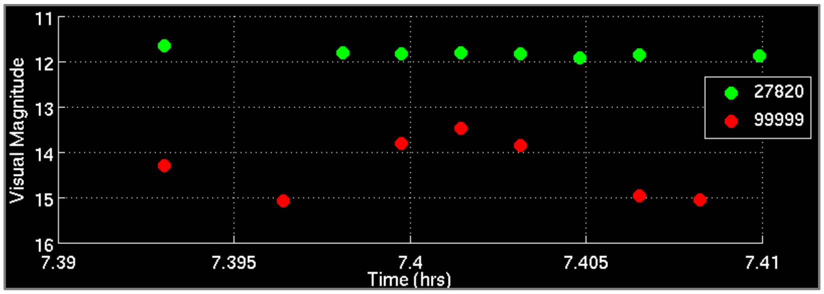


Fig. 8. Imagery showing the 17 June 2017 anomaly, tracking a child UCT and the parent object (AMC-9).

The UCT (Un-Correlated Track) in Figure Fig. 7 shows an object in close proximity to AMC-9, and the photometrics presented in Fig. 8 show that UCT object to be varying in brightness. The appearance of this child object in concert with its relatively uncontrolled behavior indicate it likely is not a self-contained object, and the temporally-corresponding anomalous behavior exhibited by AMC-9 lead to the conclusion that the child object separated from the parent object for some reason.

The approximate narrative of the events can be summarized as the following sequence:

- AMC-9 behaved typically for a GEO communications satellite until mid-2017.
- On 17 June 2017, AMC-9 experienced an anomaly. This anomaly caused AMC-9 to cease functioning as a working communications satellite; ExoAnalytic observed a large and blinking UCT apparently separating from AMC-9 at a delta-V of >30 m/s. This was calculated by determining an orbit for the UCT and then comparing the difference in orbital velocity at the time of closest approach.
- Following this separation event, AMC-9's photometrics indicated an ongoing spin or tumble.
- From 17 June 2017 to 01 July 2017, AMC-9 apparently slowed its spin rate from one rotation every sixteen minutes to one rotation every hour (approximately).
- On 01 July 2017, AMC-9 experienced a rapid increase in spin rate and a large number (13 or more) of other UCTs were observed apparently separating from AMC-9.
- After 01 July 2017,C-9 gradually slowed to an apparently astrometrically inert state over the course of several days, ending in a state of ballistic behavior by 17 July 2017.

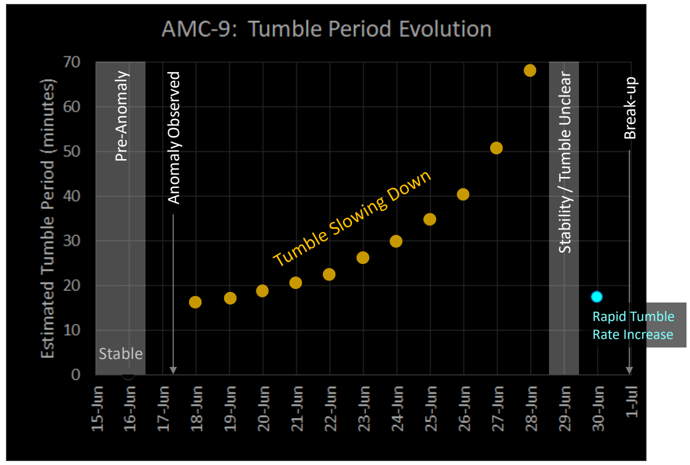


Fig. 9. AMC-9 apparent tumble rate from 17 June 2017 to 01 July 2017.

As seen in Fig. 9, AMC-9 experienced periodic spikes in its photometrics, indicating an ongoing tumble. The tumble period slowed from 16:05 to 68:02 until 29 June 2017. The data from a short time later indicate a highly-energetic event (most likely a breakup) on 01 July 2017, seen here as a rapid increase in apparent tumble rate.

Fig. 10 details how tumble rates are 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.

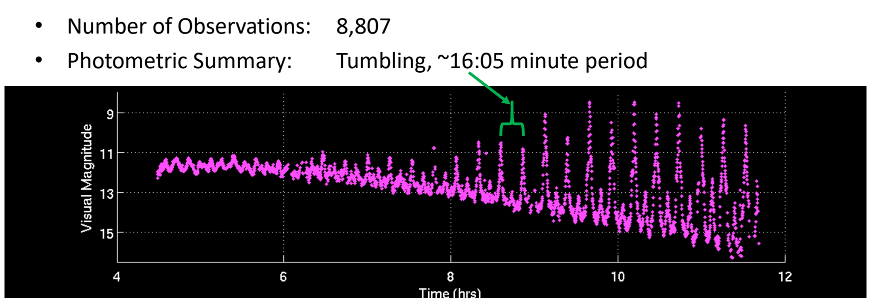


Fig. 10. AMC-9 apparent tumble rate assessment.

5. Metric and Photometric Conclusions from Enhanced Data

This section of the paper describes conclusions about the anomaly events due to the enhanced visual representation afforded by a global network of coordinated observers who may frame stack at will. The presence of this rich dataset also provides the opportunity to perform additional in-depth secondary analyses.

Fig. 11 shows some of the child objects that were tracked with advanced processing methods. It is a single frame from a longer data sequence, showing an overall view of the tracks created when objects appeared nearby and began departing from AMC-9's location.

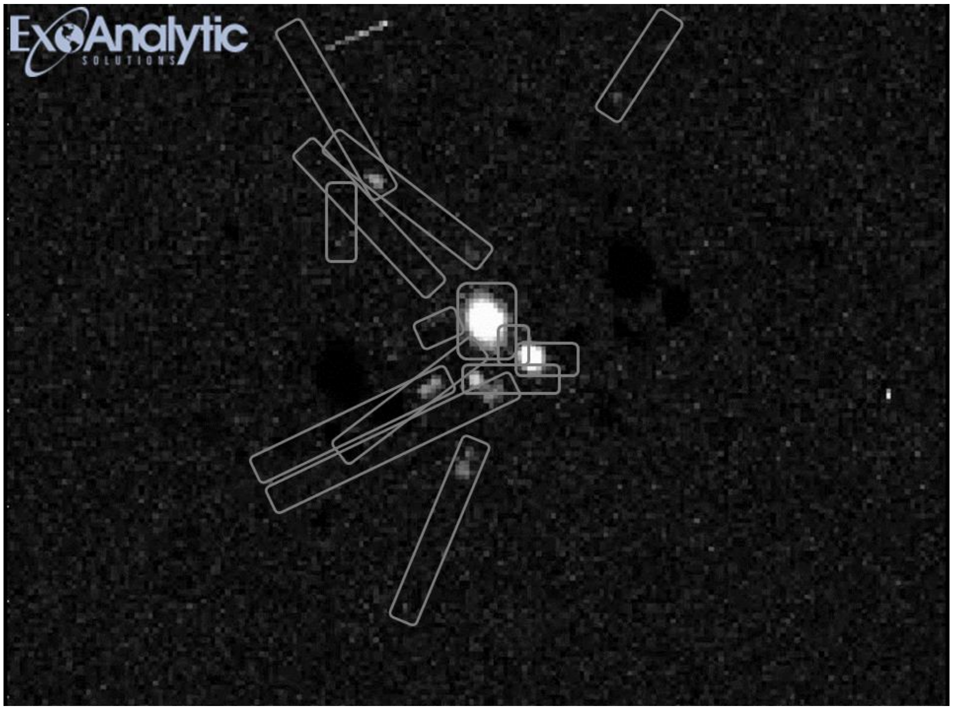
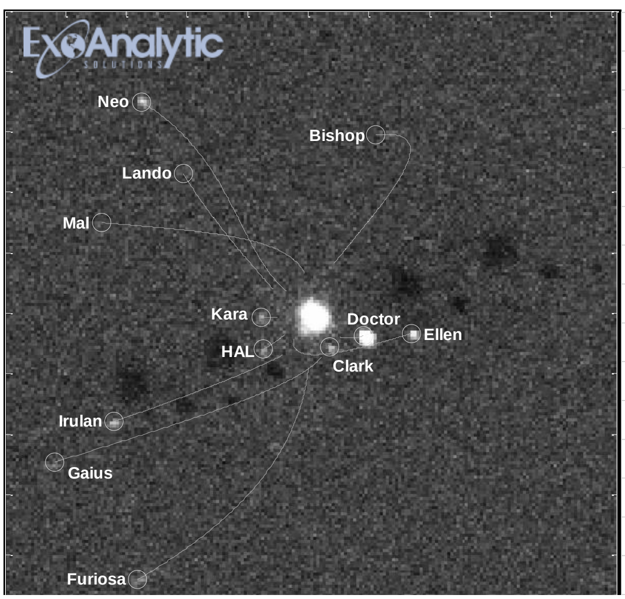


Fig. 11. Screenshot of AMC-9 video, with location regions overlaid post-hoc.

Fig. 12 provides additional context and lays out an image of all the apparent tracks near the main body of AMC-9. To tabulate these fragments, each is given a unique temporary ID name. Overlaid on the figure below are the approximate paths each fragment follows on the focal plane, together with the temporary ID name and an approximate Vmag (note Vmag may vary between any two frames, and the numbers used are just a snapshot illustrative of overall brightness variation).



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

Fig. 12. AMC-9 and child objects named, with paths marked.

The table on the right in Fig. 12 lists all main objects noted. The object assigned the temporary ID of Anakin is likely the main body of the AMC-9 vehicle, and the other objects are referenced to it. In the table portion of Fig. 12, the columns show a number (assigned roughly clockwise from top right in the frame), a temporary ID name (assigned alphabetically), and an assessment of apparent direction of 2D motion on the focal plane, as further marked in the track seen in the left part of the figure.

For additional context, Fig. 13 shows multiple screenshots from the AMC-9 dataset. Note the gradual dispersion of child objects from the center object.

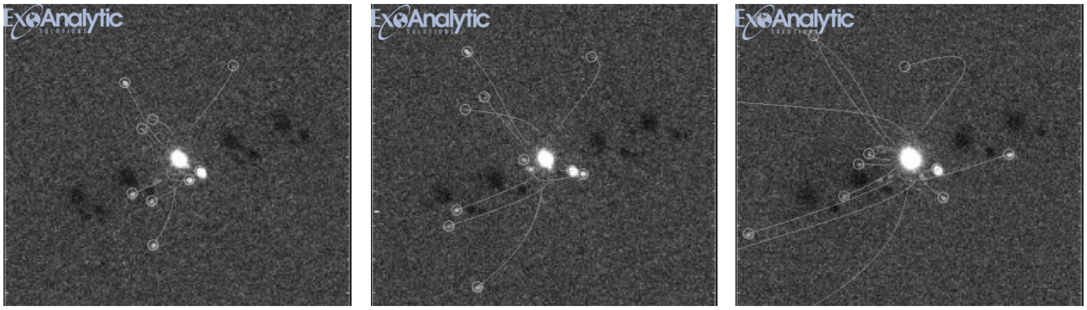


Fig. 13. AMC-9 video sequence of still frames.

The data also, however, include temporal information. This allows the figure below to be created, which shows time in the vertical (Z) axis. The dispersion of the child objects in 2-D across the focal plane is shown in the X and Y axes.

Of note is the fact that some objects are apparently emitted at times occurring sequentially. Note also that all the tracks are arcs, indicating that over the time shown (roughly ¼ orbit) no re-crossing occurred.

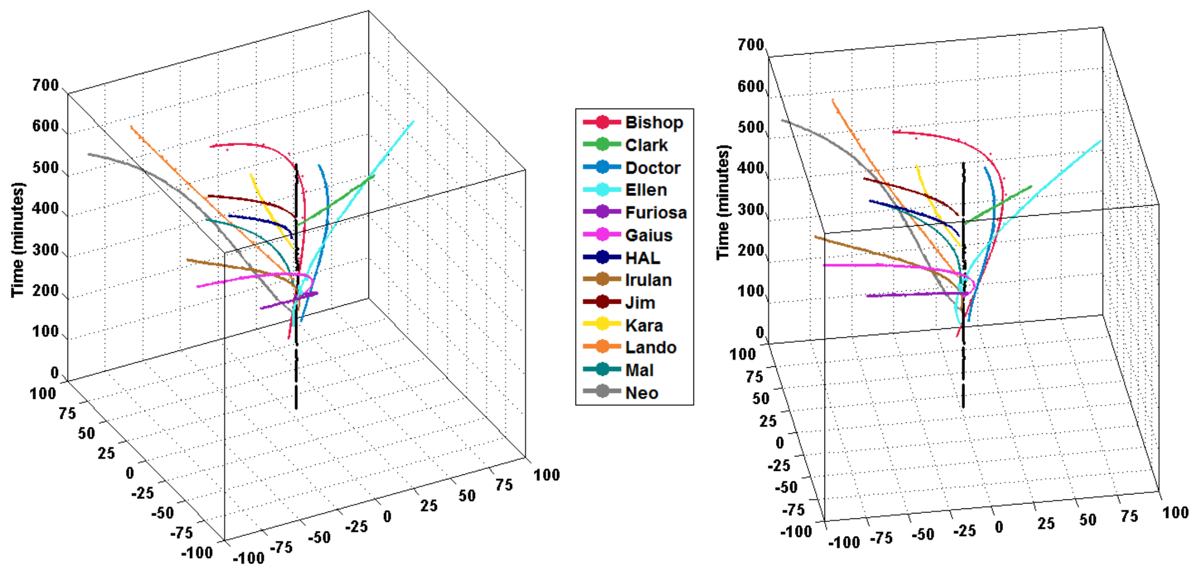


Fig. 14. Time-axis view.

Notably, the behavior of the fragments in being emitted over time and in arcing generally away from the main body of AMC-9 is evidence for some ongoing event rather than a single catastrophic moment. Possible explanations for this sort of occurrence may include a stuck thruster.

This type of behavior may be contrasted to another event, which occurred to the Telkom-1 satellite on 25 August 2017. Fig. 15 shows a single frame and overlaid tracks from this event. Once again, as seen in Fig. 16, the first nearly-immediate indications of an event in progress were in photometric data.

However, in the case of Telkom-1, 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. In fact, as seen in Fig. 17, the data collected may well have captured a fluid plume being emitted as the event occurred.

Although the imagery available from the Telkom-1 event can provide many of the same insights that this paper introduces for AMC-9, the analysis that provided them has not yet been applied in full to the Telkom-1 event, and thus it is not presented in such depth in this paper. Future work will detail this event more fully, and in fact there is significant additional work planned to be done on both events to glean more accurate insights.

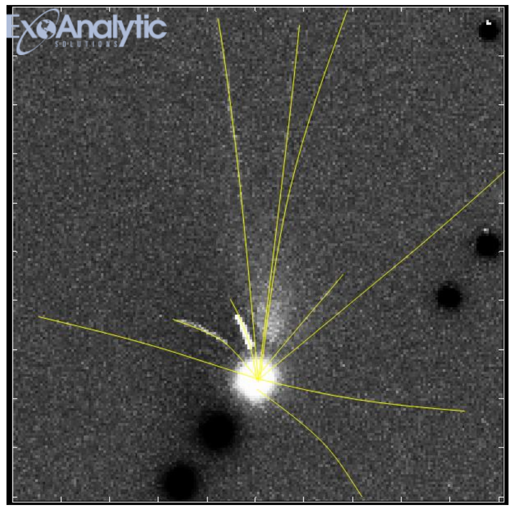


Fig. 15. Screenshot showing Telkom-1 event, with tracks of 10 pieces radiating from the center.

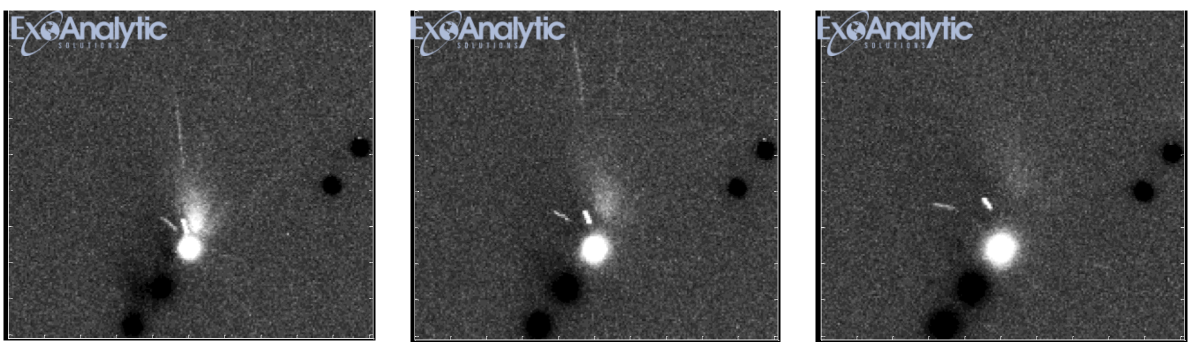


Fig. 16. Screenshot sequence showing the Telkom-1 event (at approximately 20-minute intervals). Note the apparent fading in and out of tracks and the spray of pixels resembling a dissipating plume.

Fig. 18 shows a detailed comparison of the fragments tracked from the AMC-9 energetic event on 01 July 2017 (top) and the Telkom-1 energetic event (28 August 2017). The figures on the left show time on the horizontal axis and distance on the focal plane (meaning apparent 2-dimensional motion only) on the vertical axis, indicating the difference in event timescales. While AMC-9 experienced an event that gradually created tracks of child objects (noted by the temporary ID names used in Fig. 12), Telkom-1 experienced a much more rapid event, with visible child object appearance occurring only over a period of about 5 minutes. Additionally, the 2-dimensional tracks from the AMC-9 event (on the right half of the figure) shows objects being emitted in roughly all four of the cardinal directions and several subsidiary directions, indicating an event without an obvious preference for child object travel angle. However, the Telkom-1 event shows a clear apparent preference for emission in a smaller subset of clustered directions on the focal plane; in fact, the arc subtended seems nearly hemispherical. While the analyses noted here are necessarily limited, at first impression the rich data are consistent with events that had similar effects but showed important differences. For instance, the data for AMC-9 are not obviously inconsistent with an event sequence that included a rapid spinning and gradual shedding process; while the data for Telkom-1 may well be consistent with a rupture event in a pressurized vessel onboard the vehicle.

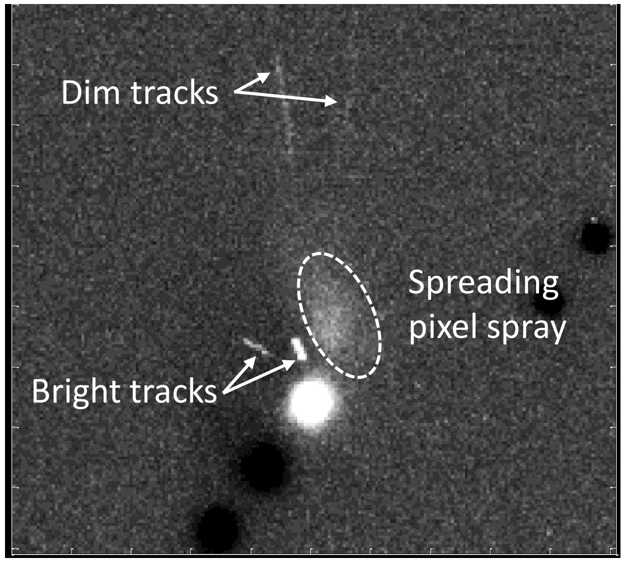


Fig. 17. Expanded view of Fig. 16 center image, showing tracks and pixel spray.

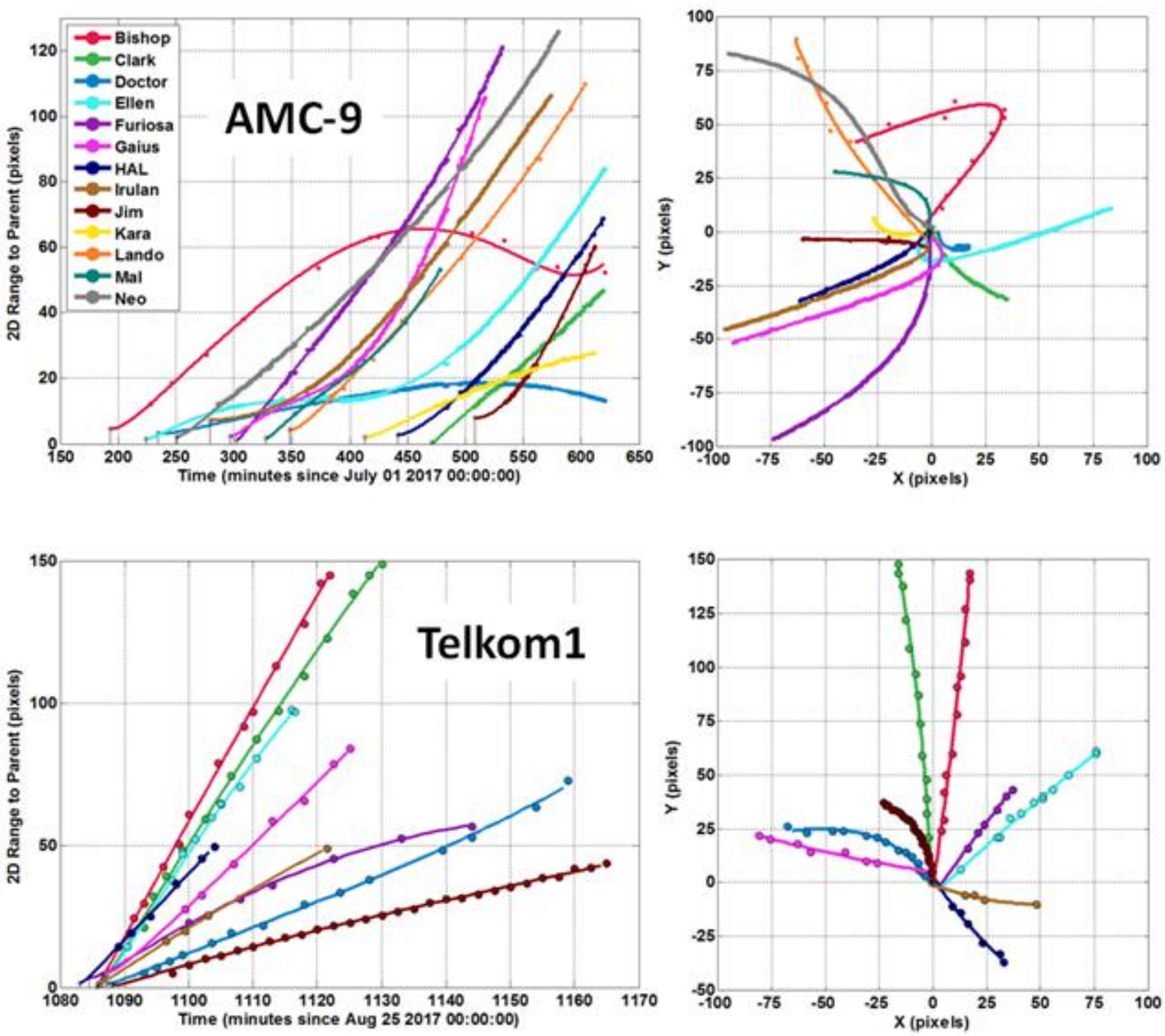


Fig. 18. Comparison of AMC-9 and Telkom-1 events.

One straightforward fact to derive from this is that other events like will likely continue to occur. When they do, the ability to detect, comprehend, and rapidly act to mitigate these events will be critical.

6. Policy Implications and Future Discussion

The suite of capabilities discussed in this paper could and should make a formidable contribution to international safety of flight, Space Traffic Management (STM) and threat warning and response support for the United States and our allies. The persistence, sensitivity, and coverage of these collection capabilities, coupled with robust processing and exploitation, would substantially increase the resilience of Space Battle Management and Command and Control (BMC2) decision-making. This diverse, distributed, and proliferated collection architecture is empowered by autonomous tasking and processing, timely reporting, and automated alerting of humans whenever a pattern of life shows unexpected photometric behavior. This suite of capabilities, together with continued advancement of coverage and limiting brightness for the network, can make tactically timely and confident responses to future events feasible.

The ability to tip and cue additional sensors (which already exists internal to the ground network which provided this data) can be extended to other sister networks, possibly including spaceborne elements. If this interoperability and collaborative approach were extended to augment the existing and planned Space Surveillance Network, and combined with increased research to understand space object behaviors, the state of national SSA would leapfrog into the decision superiority required to enable the Air Force Space Command and National Reconnaissance Office joint Space Warfighting Construct [5].

Accordingly, we propose an end-to-end satellite warning system as a viable short-term goal to be undertaken by the US national space enterprise. Fig. 19 shows the elements of this concept. The framework outlined here can serve as the optical arm of a multi-modal, multi-domain space traffic management and alerting system, beginning immediately. It is worth noting, in the face of two serious space traffic-related incidents such as the apparent breakup events seen here, that emplacing some kind of system with alacrity is much more effective than continuing to plan and rely on sparse, non-persistent data alone while further events may continue to occur on orbit. A full-scale, globally-coordinated and thoroughly-audited system would take years to implement. Existing hazards to safe operations at GEO will not remain in abeyance simply because the powers that would be are still weighing options.

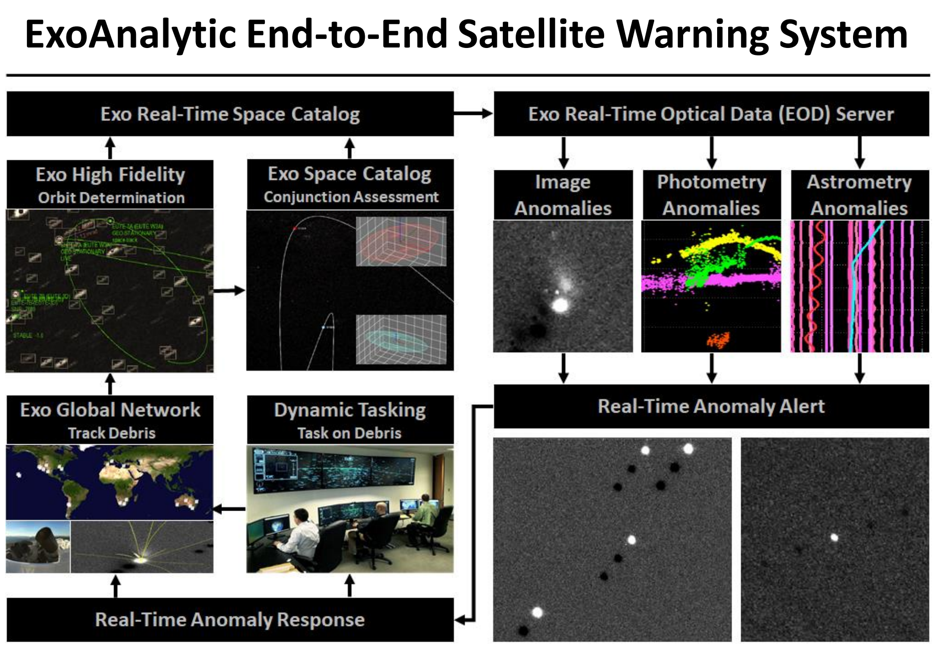


Fig. 19. Concept for end-to-end STM.

Reports recently prepared for Congress have given initial structure to the Space Traffic Management framework, suggesting giving responsibility to a civilian agency, with strategic thought on becoming a regulatory role. The

Federal Aviation Administration has to date been most closely associated with this role of lead civilian agency. The preferred framework would structure the "Civil-Based Space Traffic Safety Monitoring and Facilitation" such that it created a responsibility to facilitate voluntary information sharing among satellite owner-operators. This framework could use DoD and commercial systems to track objects, with the lead civilian agency providing warnings of potential collisions to satellite operators. Moving this responsibility for non-military satellites to a civilian agency in general, and to the FAA in particular, has garnered strong support from congressional and space agency circles. The benefits of this type of framework include its focus on paradigms other than national security, its ability to promote norms of behavior that can serve as international templates, and its ability to support national interests in space as well as commercial and civil needs. Additionally, it can be implemented comparatively quickly.

As such, there are a number of policy questions which should be attended to by stakeholders in the civil and commercial space regime. Among these questions are:

- How should detailed information extracted from rich photometric and astrometric datasets be used by the wide variety of stakeholders? Should broad international agreements be embraced, or can sharing be done by individual stakeholders and users in in ad-hoc fashion?
- What are the policy implications of this grade of knowledge being made available for purchase by insurance providers? Should governments consider offering incentives for good behavior in any form, if knowledge of behavior can be verified by third parties?
- If such neighborhood watch operations detect evidence of impending risky events, through what avenues should they report it, and to what bodies?
- How much should additional knowledge that multi-modal, multi-domain information will enable be restricted?
- To what extent should owner/operators of satellites be required or encouraged to share relevant telemetry and/or command history with government organizations that may be able to use these data to reconstruct on-orbit events? Should regulatory authorities pursue a system modeled on the automated recording and detailed investigation model successfully promulgated for air traffic events by the National Transportation Safety Board (NTSB)?
- If requirements for incident-reconstruction and risk evaluation purposes are instituted, should they be attended by requirements to operate regulated additional hardware systems, or be limited to data provision by means determined appropriate by the owner/operators?
- Are there viable model organizations or historical eras that can be used to suggest guidance as commerce continues to grow in high orbit?

The key discussions that the above questions may encourage are now within the realm of policy concerns, as the technical capability to handle them has arrived, and awaits only the right regulatory touch to provide the best service to all stakeholders, including the general global public who rely on any service that touches, is supported by, or passes through space.

With the capabilities we have outlined here and the data we have described, we look forward to participating in these discussions as we stand watch over the RSOs in the GEO neighborhood every night—all night.

7. REFERENCES

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