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RECENT EVENTS AND HIGHLIGHTS IN SPACE SITUATIONAL AWARENESS: EXPLOITATION OF GLOBAL, PERSISTENT, REAL-TIME OPTICAL OBSERVATIONS OF DEEP SPACE

Brien R. Flewelling

ExoAnalytic Solutions Inc., bflewelling@exoanalytic.com

Ben Lane

ExoAnalytic Solutions Inc., blane@exoanalytic.com

Douglas L. Hendrix,

ExoAnalytic Solutions Inc., hendrix@exoanalytic.com

William Therien

ExoAnalytic Solutions Inc., btherien@exoanalytic.com

Mark W. Jefferies Jr.

ExoAnalytic Solutions Inc., mjeffries@exoanalytic.com

ABSTRACT

The rate at which space traffic density is increasing is accelerating. We expect this trend to continue as various contributors to the commercial space market plan constellations that are orders of magnitude larger than has been flown to date. Commercial companies, such as ExoAnalytic Solutions, have deployed ground-based sensors to maintain track custody of these objects. Further, advances in the commercial sector have allowed improvements in the ability to detect and track small pieces of debris near Geosynchronous Earth Orbit (GEO) that have gone unnoticed in previous years. Using the ExoAnalytic Global Telescope Network (EGTN), observations are collected at the rate of over 10 million unique observations per month. The EGTN allows global, persistent, and real-time detection, tracking and characterization of a significant subset of the deep space object population, collecting data in impressive detail on real events that would have gone under-reported and unanalyzed in the past.

This paper discusses recent events near GEO as collected by the EGTN, including the AMC-9 debris-producing anomaly events in June and July, as well as the Telkom-1 debris-producing anomaly. While these are certainly not the first events of their kind [1], our observations illustrate an enhanced level of detail on anomalies and break-ups at GEO that have potential to critically impact other operators, showing the need for timely, persistent, global SSA in near real-time. Data of this type is invaluable in its ability to advise owner operators on debris producing events and support detailed forensic analysis of anomalies when observed. We discuss these recent events in the context of the future needs for innovations which enable a modern approach to space traffic management. Finally, we summarize here new capabilities currently in development to further refine the EGTN's ability to detect, track, and characterize events in deep space in near real-time including advanced methods for inter- and intra-sensor image integration.

INTRODUCTION

2017 and 2018 have been very interesting years in Geosynchronous Earth Orbit. It has truly been amazing to watch. From more than 230 telescopes at 25 geographically dispersed observatory locations, more than 280,000,000 images producing more than 200,000,000 correlated observations were collected by our industry leading space observation network, the EGTN. The average resident space object (RSO) is observed about once every 5-10 seconds when tasked during a night. Every space object has a story which is told by the reflected solar photons which may be collected by observers across the globe. Included in our independent catalog of more than 2000 deep space objects are stories of very precisely flown active space objects, active space traffic with novice operators or degrading performance of on-board systems, and various passive objects which may be entire derelict spacecraft, fragments of spacecraft, expended rocket bodies, and other objects. Exhibit 1 illustrates the geographic distribution of observatories and sensors contained in the EGTN.

Exhibit 1. Geographic distribution of 25 observatories containing 230+ telescopes comprising the EGTN

Exhibit 2 illustrates the vast amount of simultaneous evolutions of space object states observed by the EGTN in 2017. Some of these state evolutions resulted in close range relative motions, conjunctions, changes in state, population of new members of space traffic in the geosynchronous orbit region, and departures of members of the geosynchronous region to graveyard altitudes.

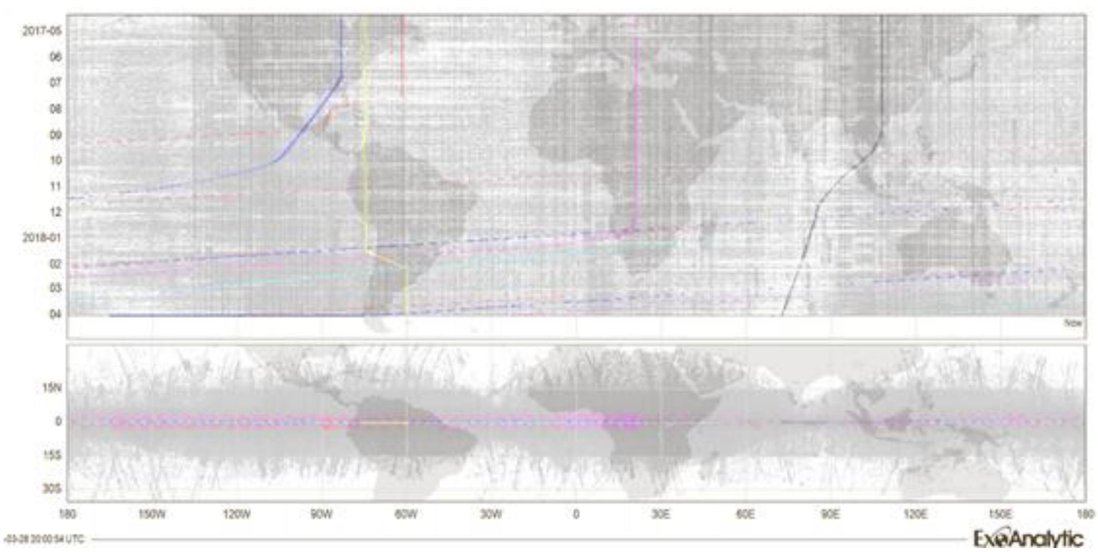

Exhibit 2. Millions of correlated space object detections shown in time=longitude and latitude-longitude plots with anomalous space objects highlighted in multiple colors

The rest of this paper will introduce the current levels of performance achieved by the EGTN and the implications this has on the broader understanding of deep space traffic events its data can support. We will then discuss three significant debris producing events, two associated with the AMC-9 spacecraft (NORAD ID 27820) and one associated with the Telkom-1 spacecraft (NORAD ID 25880) which represented non-zero probabilities of subsequent debris on active space traffic collisions which would have went un-warned given the current paradigms in space traffic monitoring and management. Finally, we also discuss advanced forensic analyses afforded by on-demand frame stacking as a follow-up analysis given the initial detection of astrometric and photometric anomalies. Persistent datasets represent an important tool in supporting the development of advanced methods for tracking objects presenting complex behaviors and enhancing the important visual context inherent to collections taken by a coordinated network of sensors.

EGTN PERFORMANCE OVERVIEW

Today, the EGTN enables an impressive level and quality of service in detection, tracking, identification, and characterization of space objects with altitudes greater than 10,000 km. Of importance is the routine sensitivity and accuracy with which our observations are collected. Typically, we evaluate our astrometric accuracy by observing active space objects which publish their position and velocity states as a function of time. When observing well controlled and understood space traffic, our observation accuracies routinely achieve better than 0.25 arcseconds. To get an idea on how this can translate to more challenging objects to track, we show in exhibit 3 the combined photometric sensitivity and astrometric accuracy achieved on the MSG 1 DEB (Cooler Cover) object which has a high area to mass ratio when compared to intact satellites in deep space.

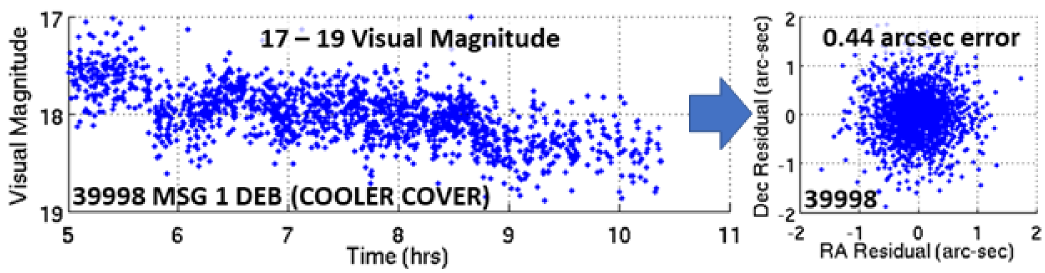

Exhibit 3. Better than 0.5 arcsec accuracy on M_v 17-19 High Area to Mass Ratio Object

This is an example of the available performance in EGTN data responding to direct tasking from our customers. Achieving this level of sensitivity and accuracy on demand is useful in enabling rapid follow-up observations of difficult objects, but we routinely employ our coordinated detection capabilities to enable even more sensitive and informative optical data. In the last year, we have explored methods for combining information contained within multiple frames collected across multiple sensors. After properly accounting for the stars observed in the image background, determining the shifts a resident space object will take in between frames given its motion, and correcting for differences between each sensors pixel geometry, it is possible to significantly enhance the detection sensitivity and resolution achieved by only a single sensor. When combining observations across multiple sensors at the same observation site, we are routinely achieving detection sensitivities as dim as $M_v = 21$. It is this capability which enables the achieved context enhancement used to support detailed analyses of the debris generating events which occurred in the summer of 2017. Exhibit 4 illustrates the theoretically achievable increase in performance afforded by inter and intra-sensor frame stacking as well as our achieved results against a star background with known magnitude stars.

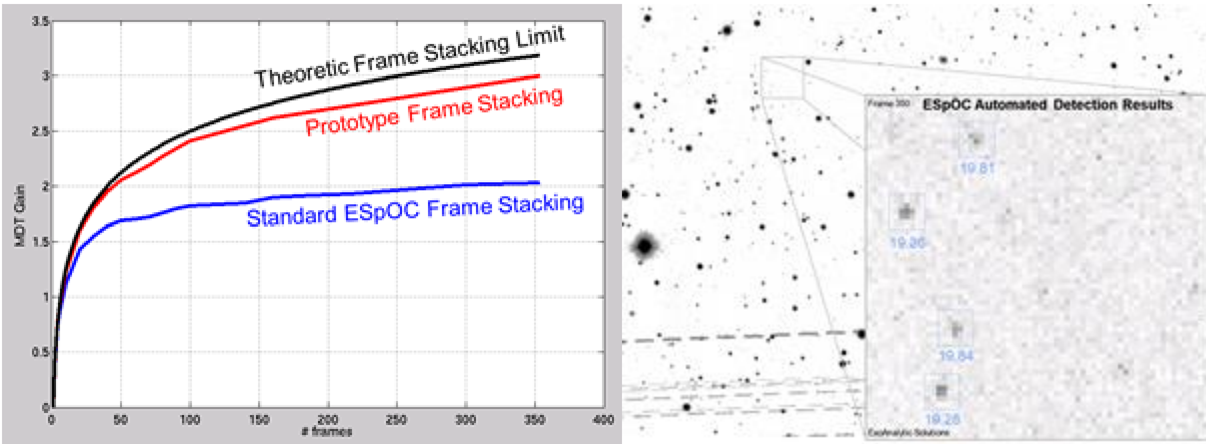

Exhibit 4. Theoretically achievable and empirical results of ExoAnalytic non-coherent image addition

As an example of the significant enhancement in context in a local region of deep space which is achieved by this type of data exploitation, Exhibit 5 illustrates the immediate increase in detail when comparing the best image taken by a single EGTN sensor of a debris generating event and the results of combining N images from M sensors during the same event:

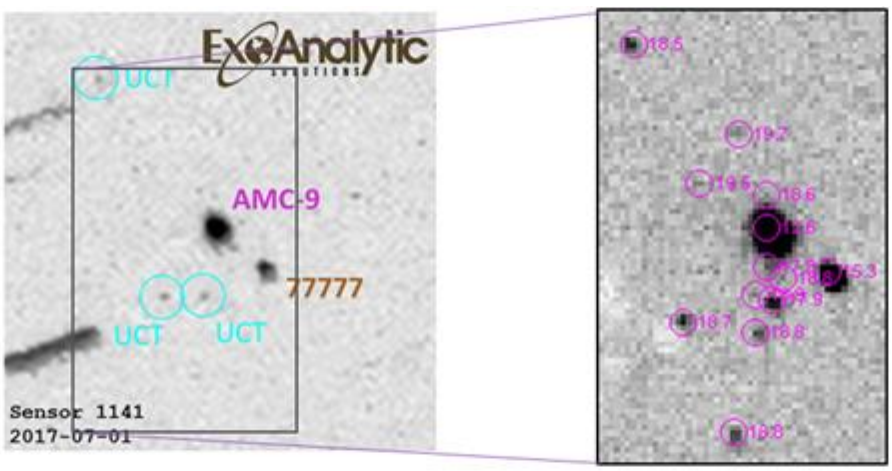

Exhibit 5: Context Enhancement afforded by coordinated sensing and non-coherent image addition

The next sections will explore in detail multiple significant debris generating events including the timeline of events, single and multi-sensor observations, and subsequent characterization of the nature of each anomaly. We further describe techniques used to autonomously identify these occurrences as significant events collected within our database of more than 325,000,000 observations growing at the rate of 500,000 observations per day. Finally, we discuss the implications of the increasing trend of active space traffic exhibiting more frequent and long duration non-ballistic behavior and conclude with a discussion of the key challenges these trends will impose on future space traffic managers.

ANALYSIS OF AMC-9 DEBRIS GENERATING EVENTS

The AMC-9 communications spacecraft was launched in June of 2003 and served customers near 83 degrees west longitude for 14 years. Built upon the Spacebus-3000B, this space system had an intended design life of 15 years. On June 17th, 2017, multiple independent observes reported indications of changes in the behavior and stability of the spacecraft [2,5]. This included optical observations and radio frequency observations. Exhibit 6 shows an example image taken during the time in question as well as a plot of the variation in apparent visual magnitude for a period centered at that image time and spanning N days.

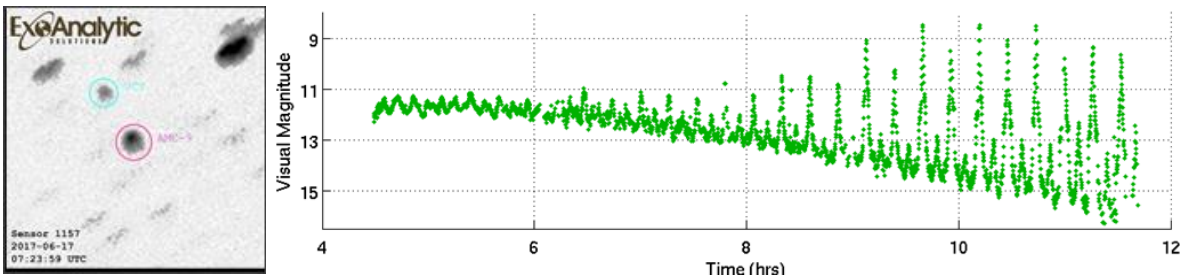

Exhibit 6: Variation of AMC-9 appearance to optical sensors during the June 17th anomaly onset

Upon analyzing the astrometric data throughout this event, it is easy to see that coincident with these observed variations in apparent magnitude is an immediate change in astrometric behavior. The long duration behavior of AMC-9 is highlighted in exhibit 2 in yellow. A drift of 0.2 degrees per day was observed to begin and persisted for nearly 3 months. Over this time, the AMC-9 spacecraft traveled more than 15,000 km along the GEO arc. Exhibit 7 shows this in more detail.

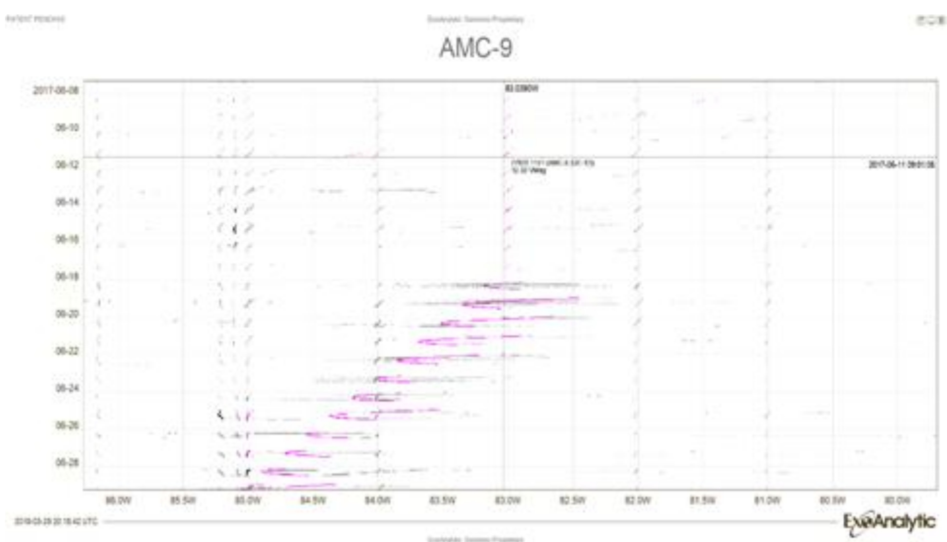

Exhibit 7: Classical post anomaly indicators of unstable drifting spacecraft observed

It is understood that over this time, every effort was taken to recover the spacecraft and prevent any long-term degradation of the geosynchronous orbit environment. In fact, our observations also indicate that some recovery of spacecraft stability was indeed successful. This is shown in Exhibit 8 which illustrates the deceleration in rotational period of the spacecraft from 16 minutes to 68 minutes over a two-week period. As the spacecraft rotates more slowly, it is theoretically easier to establish more reliable communication, and this enables additional and more complex commands to be used to exercise various options for system recovery.

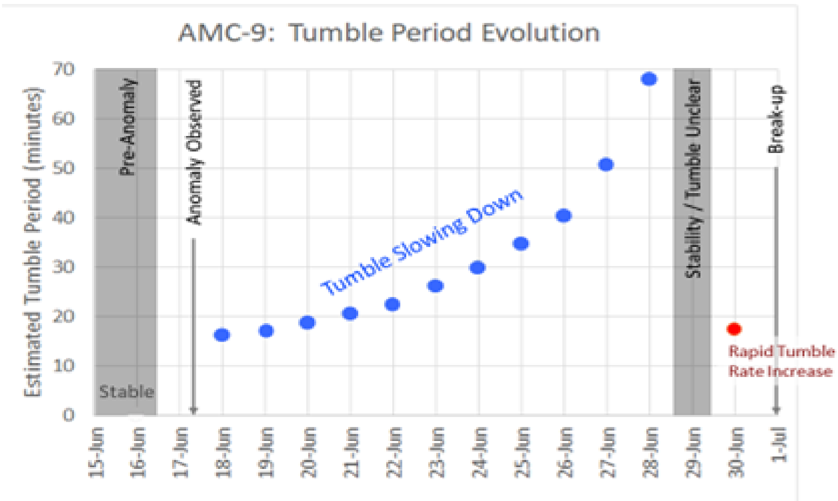

Exhibit 8: Indications of preliminary system recovery observed in apparent rotational period increase

Unfortunately, on July 1st, a sudden reversal of this trend was observed followed by new significant variations in both astrometric and photometric behavior including a slight increase in drift rate. This again was present in our observation data and was indicated by a change in apparent drift rate and in the photometric signature. More significant was the sudden presence of additional uncorrelated tracks which upon inspection of the neighboring pixels of each detection appear to be associated with additional objects. Exhibit 9 shows these changes for comparison to the changes observed for the June 17th event.

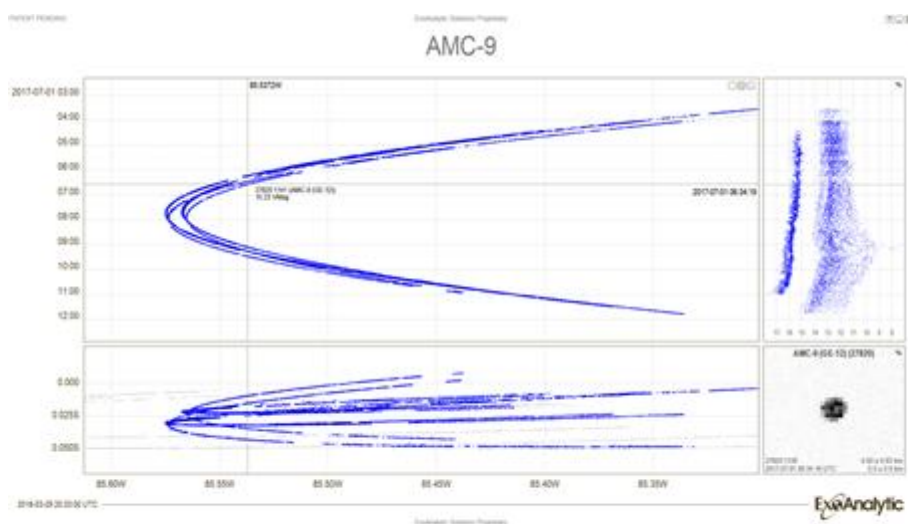

Exhibit 9: Additional astrometric and photometric change indicators observed for July 1st

Upon inspection of the full-frame imagery taken by the participating sensors during this time, additional detectable and trackable pieces of debris are easily seen generated from the spacecraft. While any individual image provides a limited indication of this behavior, truly detailed visual understanding of this context can be made apparent by using non-coherent image addition to combine the frames over time and across multiple sensors. An example image produced by a single-frame from a single sensor during this event is shown on the left in Exhibit 10. On the right, is an example of a post-processing product achieved by combining multiple frames from multiple sensors.

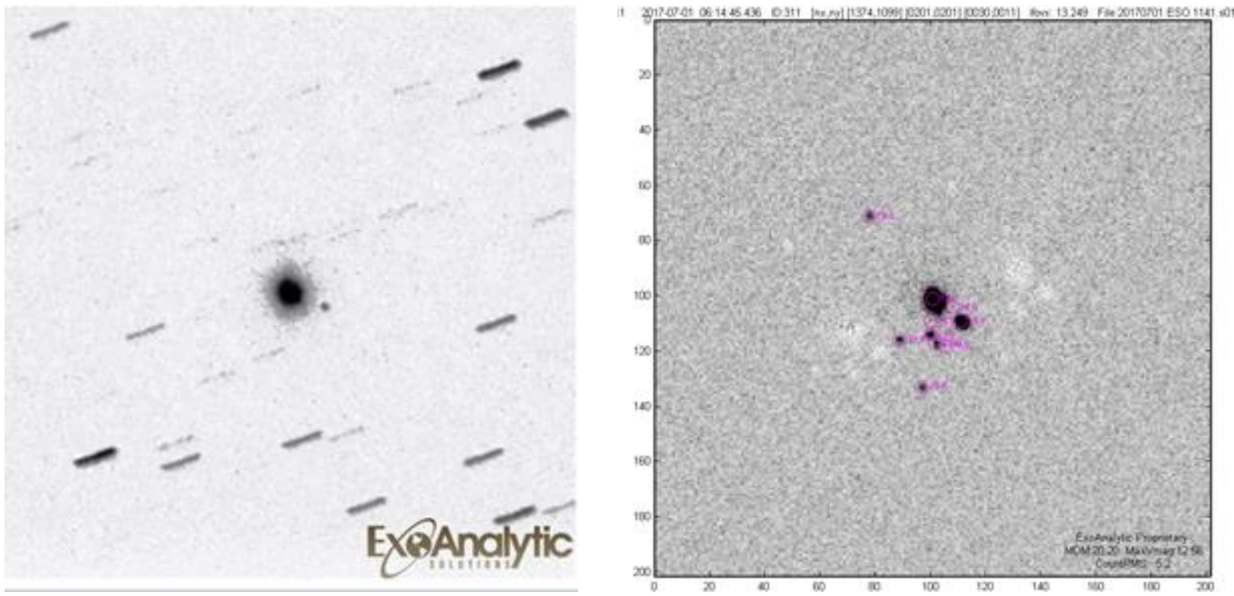

Exhibit 10: Context enhancement using post-processing shows debris produced by AMC-9 spacecraft.

Exhibit 11 illustrates the apparent angular distance between all observed debris fragments generated by AMC-9 as a function of time. It is readily observed they are generated over a relatively long duration of approximately 5 hours. By observing this event persistently, significant data can be made available to support post anomaly forensics, data that is not otherwise available by catalog maintenance focused sensor-tasking schedules.

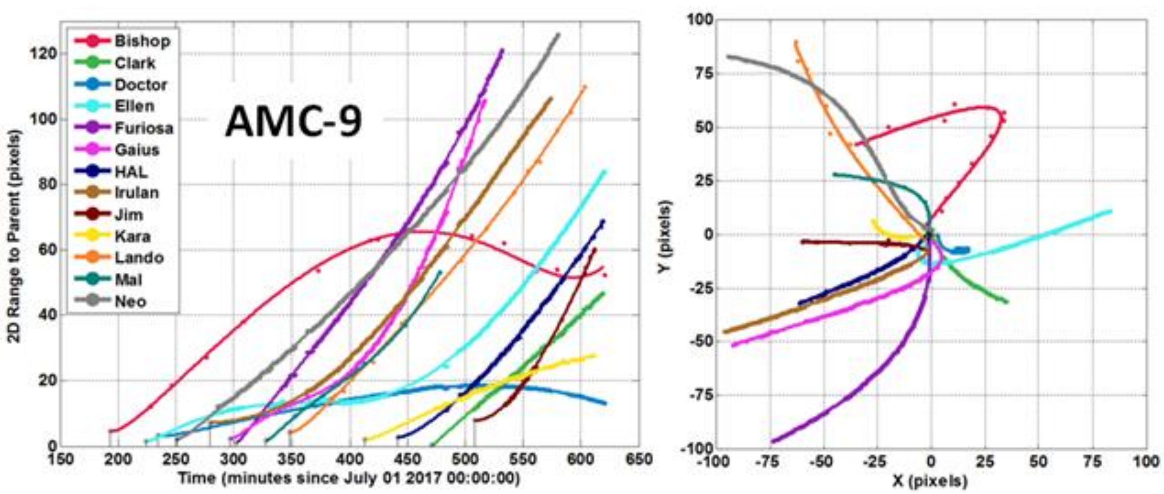

Exhibit 11: Observed AMC-9 fragment geometry as a function of time

While it is unfortunate that the experienced post-anomaly attitude instability resulted in the generation of multiple debris fragments at altitudes near GEO, the story of AMC-9 does have an impressive, and positive ending. On or about 20 September, SES was able to successfully command the spacecraft and execute a burn to raise it to graveyard altitude. This was most certainly done with significant care and technical skill. It is no small feat to recover from and anomaly and still ensure your spacecraft is successfully disposed of. Exhibit 12 illustrates the indications we observed of this successful ending to the story of AMC-9. Simultaneously the erratic photometric behavior of AMC-9 subsides and the consistent drift rate of the object begins to vary as the object gradually achieves a drift rate consistent with other objects observed at graveyard altitudes around 20 November. The interested reader is referred to [3,4] for additional analysis of this event.

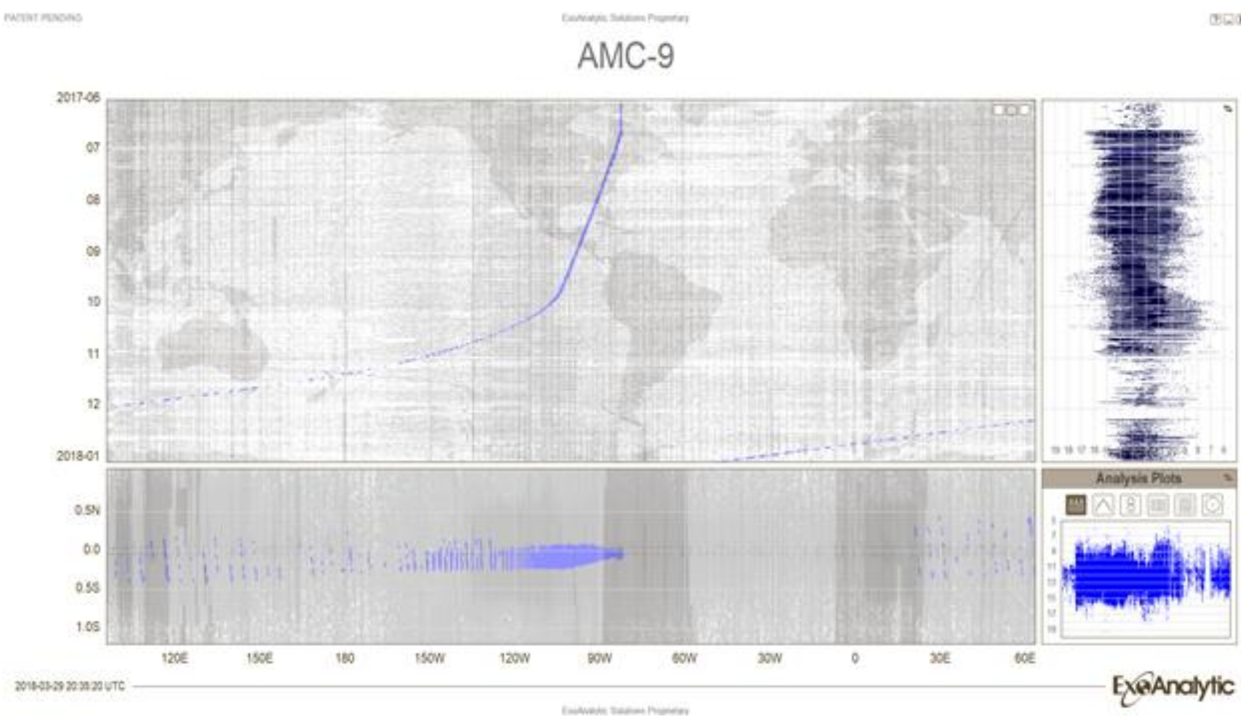

Exhibit 12: Astrometry and Photometry observed for AMC-9 anomaly, recovery, and disposal

Using the view shown in exhibit 12, it is easy to interpret the observed history of this event as it evolved over several months. Additionally, astrometry and photometry can be viewed on variable resolution time scales enabling an operator to understand the rates at which various spacecraft motions occur. Having all this detail in one place within one tool provides a state of the art interactive dashboard capability for extracting the maximum amount of relevant information in real-time and during follow-up forensic analysis. Having this tool driven by hundreds of observers across the globe brings provides vast opportunity to understand thousands of these evolution histories to the fingertips of future space traffic managers.

ANALYSIS OF TELKOM-1 DEBRIS GENERATING EVENT

In August of 2017, another debris generating event was observed. In contrast to the AMC-9 event, which evolved over a relatively long duration, this event was more sudden. Indications of its occurrence were generated automatically based on algorithms developed since the AMC-9 event and trained to look for the features discussed in the previous section. The first indicators are again observable as a coincident change in both astrometric and photometric behavior. Exhibit 13 shows these indicators as viewed in our analysis software. For reference the trajectory observed in Exhibit 13 is a subset of the data shown as a white track in Exhibit 2.

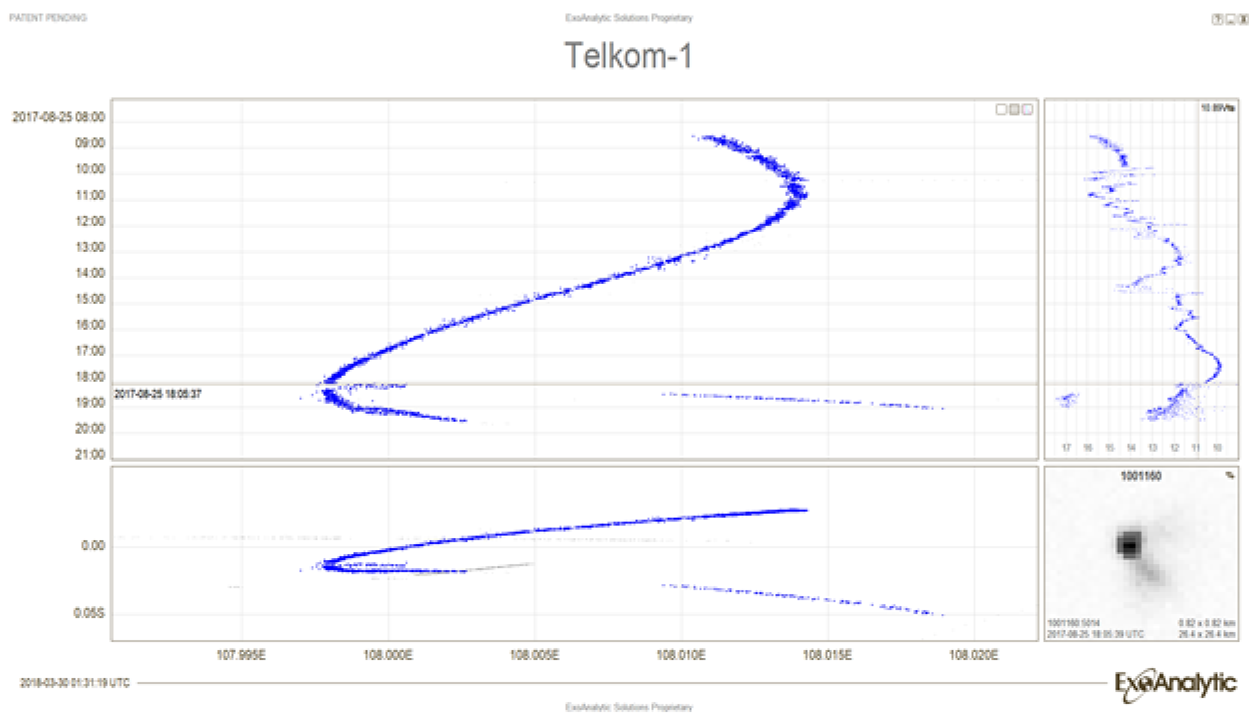

Exhibit 13: Astrometric and Photometric indicators of system behavior and stability changes

In this case it was again observed that a sudden change in the typical photometric signature of the spacecraft is coincident with a sudden change in the drift rate over the course of the night and the presence of multiple short duration uncorrelated tracks. In this case, elevated concern was warranted due to multiple neighboring spacecraft being sufficiently close to Telkom-1 had less than 1 hour to react to any newly generated debris. For these reasons, the need for rapid indications and warnings for this event was high.

Upon inspection of the associated imagery, some subtle variation in the appearance of the detected spacecraft seems to be present, but this may or may not be explainable by other variations in system parameters including focus, seeing conditions, or other source of variation. Exhibit 14 shows and example of one of these single images.

Exhibit 14: Single image taken during the Telkom-1 anomaly provides limited context

It isn't until we apply our image combining post-processing that we can learn from the significant context enhancement it affords. Exhibit 15 illustrates a combined imagery product which can be used to enhance the signal to noise ration and the resolution during the event. Looking at events forensically in this way represents a significant advancement in the use of commercial-off-the-shelf technology to infer valuable forensic insight from spacecraft anomalies.

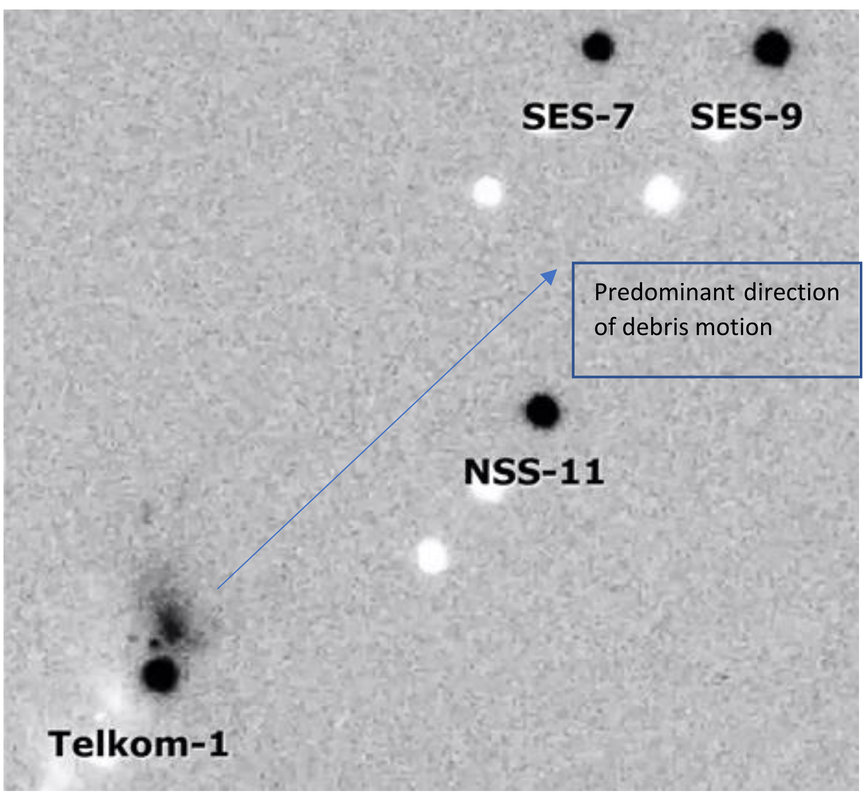

Exhibit 15: Significant increase in visual context afforded by combining imagery. White dots are signal artifacts caused by inter-frame subtraction

In this case, the nature of this anomaly represented a rapidly evolving apparent threat to neighboring satellites' flight safety. Exhibit 16 shows the range and angular dispersion of the observable debris fragments over time. It is easily seen that multiple debris pieces we expelled in the general direction of neighboring satellites which are visible within the full frames like those shown in exhibit 15.

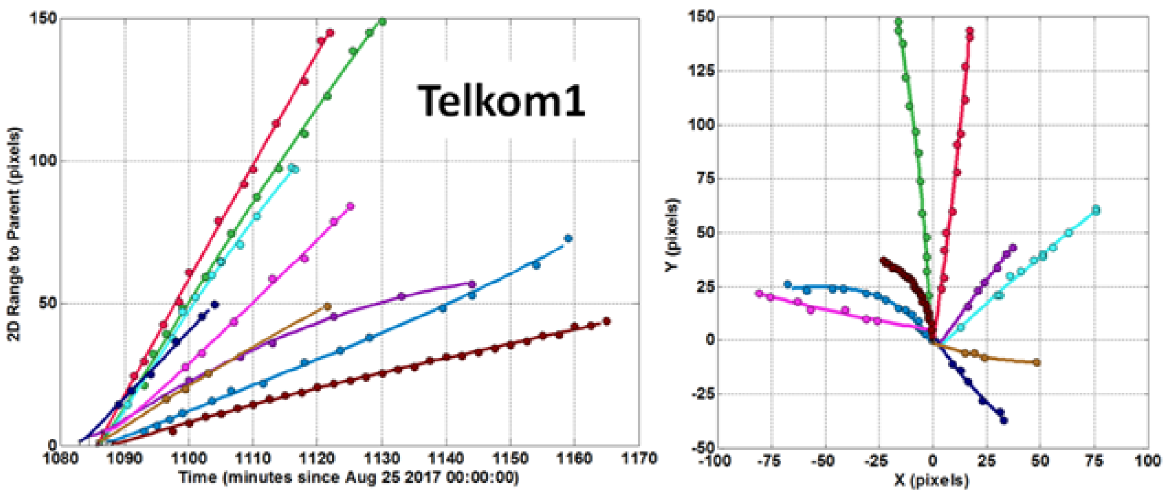

Exhibit 16: Explosive anomaly producing rapidly dispersing debris

It is fortunate that additional anomalies or debris on spacecraft impacts did not occur (as far as the authors are aware). Anomalies like those presented here are historically rare, and we are certainly hopeful that they stay rare in the future. As deep space traffic continues its trend of becoming more congested, it is our hope that observation and monitoring services can help keep these types of events rare, and when unfortunate events unfold in deep space, can support the most detailed forensic analyses possible. For additional discussion regarding the potential cause and comparative nature of these two debris generating events the reader is referred to [3,4]

CONCLUSION

Civil Space Traffic Management will focus on the continuous support of flight safety for all members of space traffic. To this end, global, persistent, real-time SSA is a useful tool. As space traffic density increases, and members of the active space traffic population continue to exhibit complex behavior, persistent data sets afford the richest opportunity for STM. This can be to enable effective tracking and characterization of objects exhibiting frequent and long-duration non-ballistic behavior, or to support post incident analyses and anomaly resolution. The EGTN represents a mature commercial capability as a service available to support various STM functions.

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2 Space Intel Report. Peter B. de Selding. July 02, 2017. SES re-establishes communications with AMC-9; pieces of satellite appear to have broken off. Online at: https://www.spaceintelreport.com/ses-re-establishes-communications-amc-9-pieces-satellite-appear-broken-off/

3 Cunio, P. M., Bantel, M., Flewelling, B. R., Therien, W., Jeffries, Jr., M. W., Montoya, M., Butler, R., and Hendrix, D., Photometric and Other Analyses of Energetic Events Related to 2017 GEO RSO Anomalies. AMOS 2017.

4 Cunio, P. M., Flewelling, B., Bantal, M., Therien, W., & Hendrix, D. (2018). Advanced Debris Analysis Techniques Enabled by Rich Persistent Datasets.

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