An Automated Indications and Warning System for Enhanced Space Domain Awareness

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ABSTRACT

Automated indications and warning (I&W) regarding abnormal events in space are needed help ensure the safety of all orbiting spacecraft. Such events may include maneuvers, attitude changes, breakups, conjunctions, and proximity operations. In this paper, we demonstrate an I&W capability using recent real-world events in which the Numerica Telescope Network (NTN) I&W analytics pipeline generated such automated alerts.

1. INTRODUCTION

The critical space domain awareness (SDA) mission involves the detection, tracking, identification and characterization of all Earth-orbiting objects and the prediction of events, threats, and activities in space. With the increase in new foreign launches, satellite constellations, and the number of agile or potentially separable satellites being placed in near-Earth space, it is critical that space operations analysts and satellite operators not only maintain custody of these satellites, but also quickly identify and interpret changes in their behavior. Thus, a key need for SDA is the capability to provide automated indications and warning (I&W) regarding abnormal events in space.

The increasing number of satellites in space, and the many small or maneuverable objects that are difficult to track, are leading to a more congested and contested space environment, which further complicates the problem of detecting and identifying abnormal events of interest that might require follow-up courses of action. To buck this trend, Numerica has taken an active role in recent years in providing alternative solutions that free-up government resources and improve our situational awareness of the evolving space environment. In particular, for the past decade, Numerica has been developing algorithms and software to support improved SDA which involves the detection, tracking, identification, and characterization of all resident space objects. More recently, to help address the need for real-time actionable I&Ws, Numerica has developed and combined a novel set of advanced algorithms, high performance software, and a globally-distributed network of small telescopes to demonstrate a responsive deep-space tracking and I&W alerting system.

As discussed in [1], data from the Numerica Telescope Network (NTN) is collected and processed in real-time via an integrated tasking, collection, processing, dissemination, and exploitation (TCPED) pipeline, in order to create and maintain an independent catalog of objects in multiple deep-space orbital regimes (e.g., GEO, GTO, MEO, and HEO). With support provided by Air Force Research Laboratory Information Directorate (AFRL/RI), Numerica has augmented this TCPED pipeline with additional analytics tools and architectural improvements in order to produce real-time I&W alerts regarding events of interest. These I&Ws currently include maneuver detection, no-show, conjunction, and photometric change detection alerts. In addition, a multi-source event correlation layer automatically determines certain types of relationships (e.g., co-occurrences) between events detected across multi-source data, which can aid in mitigating false alarms generated by a single data source. The alerts are disseminated in real-time to end users via the NTN application programming interface (API) and user interface (UI).

This NTN I&W alerts service is enabled by several software components, including the Multiple Frame Assignment Space Tracker (MFAST) [1, 2], Athena [5], and the Kollision Risk Assessment Tool in Orbital Element Spaces (KRATOS) [3] components of the NTN pipeline. In recent years, Numerica has enhanced MFAST to produce maneuver alerts when a change is detected in an object's orbital state that is inconsistent with natural orbital dynamics. These alerts contain an estimated time and delta-V associated with the maneuver. No-show alerts are produced when an object's orbital state should have been updated using a sensor observation, but was not. A no-show alert may indicate an abnormal maneuver or an anomalous event, and can be used to cue sensors to search for that object. Athena

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produces photometric change alerts, which can indicate a change in an object's stabilization state, attitude, or orbital state. Finally, KRATOS computes miss distances and produces probabilities of collision for potential conjunction events, and can also be used for detecting close proximity operations.

In this paper, we demonstrate automated I&W capabilities using recent real-world data in which the NTN I&W analytics suite generated examples of the aforementioned alerts. Examples of scenarios discussed include detection of abnormal maneuvers, changes in satellite stabilization mode, loss of control due to on-orbit anomalies, detection of photometric changes from stereo observations, and detection of correlations between multiple types of events. The layout of the paper is as follows. In Section 2, we provide an overview of the NTN and our I&W software components and technical approaches. In Section 3, we provide brief case studies on some recent real-world space events. Conclusions are made in Section 4.

2. TECHNICAL APPROACH

The NTN and its associated TCPED pipeline form the backbone data collection and processing infrastructure that enables our I&W alert generation components. In this section, we begin by describing the NTN and TCPED pipeline, then provide details about each type of alert generated by the pipeline. Alert types discussed include maneuver detection alerts, photometric change alerts, and conjunction alerts.

2.1 NTN Overview

The NTN currently spans 18 sites across 5 continents, as depicted in Fig. 1. Sites within the United States are located in California, Arizona, Colorado (two sites), New Mexico, Texas, and Hawaii. Sites outside the United States are located in Chile, Morocco, Spain, France, South Africa, Crete, Western Australia, South Australia (two sites), and New South Wales Australia (two sites). Together, this layout provides 100% coverage of all deep space orbital regimes, including geostationary orbit (GEO), with robustness to both regional and seasonal weather. For example, each GEO satellite will be visible from several geographically-diverse sites and by multiple co-located sensors.

The NTN consists of (i) small aperture, wide field-of-view sensors arrays, known as Argus sensors, that provide persistent coverage of a large swath of the night sky and (ii) medium aperture, fully-robotic and taskable telescopes that provide increased detectability and resolution with a smaller field of view. In particular, the Argus sensors' persistent coverage of GEO enables change detection to generate meaningful and consistent I&Ws, which can in turn provide tipping and cueing for larger-aperture telescopes. Further, the NTN contains two daytime systems (and counting) capable of detecting satellites in GEO during broad daylight [4]. The locations of these systems are shown in Fig. 1. Global daytime coverage by the NTN is anticipated by the end of 2021.

2.2 Indications and Warning (I&W) Analytics Pipeline Overview

The NTN I&W analytics pipeline is enabled via the integration of several components providing the following functions: (i) sensor tasking (NITRO); (ii) orbit determination and data association (MFAST); (iii) multi-source change detection (Athena); (iv) pattern-of-life learning (APOLLO); and (v) conjunction assessment (KRATOS). This integrated pipeline is enabled by real-time feeds from a robust set of data sources, including the NTN itself, as well as third-party data. Fig. 2 shows the high-level architecture of this I&W pipeline. Next, we describe these components.

NITRO (Numerica Intelligent Tasking and Resource Optimizer): NITRO enables maximum productivity from sensor networks based on mission objectives. It allows operators to view more objects at the right times with the right sensors by enabling cooperative tasking and effective task prioritization. NITRO guarantees rapid revisit rates on specified objects while still maintaining a high-quality satellite catalog. For more info on NITRO see [1].

Multiple Frame Assignment Space Tracker (MFAST): MFAST fuses astrometric data into high-quality orbits with realistic covariances through joint orbit initiation and determination. MFAST leads the market in deep-space (optical) UCT processing in terms of the number of high-quality orbits it is able to establish, and the software has helped the 18$^{\text{th}}$ Space Control Squadron (18 SPCS) personnel recover over 1000 objects on the Lost List. MFAST also performs maneuver detection, ballistic coefficient estimation (for drag and solar radiation pressure), and duplicate orbit resolution. MFAST-Maneuver-Detection (MFAST-MD) is a specific mode of MFAST that provides the maneuver detection service, and is discussed in further detail in Section 2.3. A general discussion of MFAST is given in [2].

Athena: Athena is a suite of multi-source, multi-INT change detection tools that constitute the NTN's change detection back-end. Athena exploits multi-source, multi-INT data in order to automatically detect, correlate, and recognize

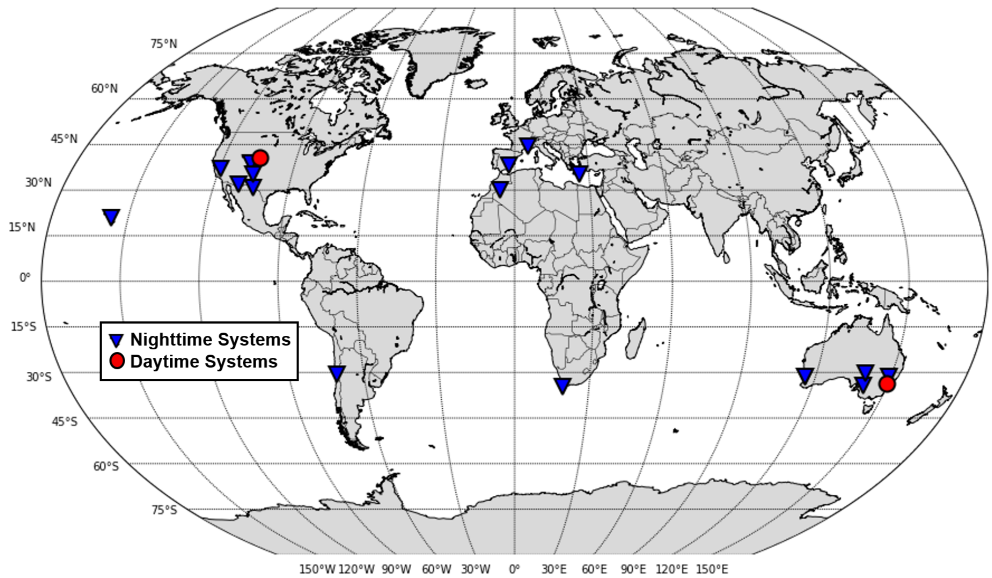

Fig. 1: Locations of Numerica Telescope Network Sensors

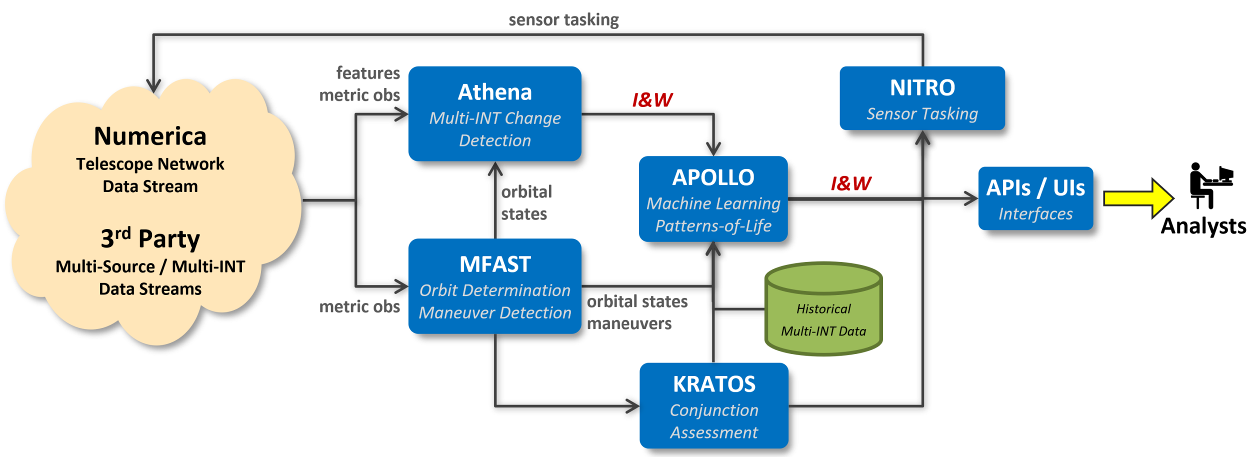

Fig. 2: The NTN I&W Analytics Pipeline

changes and abnormalities in multi-domain data to provide I&Ws regarding anomalies and potential threats to space assets. Some of Athena's key benefits to the warfighter include (i) cross-domain I&W analytics, (ii) improved probabilities of detecting changes, (iii) reduced false alarm rates, and (iv) timely change detection and threat notification and prediction. We discuss Athena in more detail in Section 2.4. For more info on Athena see [5].

Adaptive Pattern-of-Life Learning Operations (APOLLO): The APOLLO tool enables the learning of baseline patterns-of-life of deep space satellites in an adaptive manner, leading to the generation of I&W alerts, event predictions, and associated confidence measures. While Athena performs low-level change detection, APOLLO takes Athena outputs as inputs and attempts to determine if the events detected via Athena and MFAST-MD form a pattern, in order to ultimately detect mission-abnormal (i.e., out-of-family) behavior within appropriate contexts. Some specific use cases of interest to the space community which are addressed by APOLLO, are: (i) adaptively learning an object's pattern-of-life from multi-INT data, and detecting abnormalities (i.e., events inconsistent with an object's mission pattern-of-life), along with associated levels of confidence for the generated I&Ws; (ii) predicting events consistent with an object's behavior, along with associated levels of confidence; (iii) characterizing an unknown or newly-discovered object's behavior; and (v) performing forensic analysis on data corresponding to a detected abnormal event in a timely manner.

Kollision Risk Assessment Tool in Orbital Element Spaces (KRATOS): KRATOS [3] is the NTN's primary conjunction assessment tool, which provides I&W alerts regarding potential conjunctions or close proximity operations. More details about KRATOS are provided in Section 2.5.

We now describe in more detail the three of the most mature I&W functions within the NTN analytics pipeline: MFAST-MD, Athena, and KRATOS.

2.3 MFAST-Maneuver-Detection (MFAST-MD) Overview

MFAST is Numerica's main data fusion software product [2] that provides an autonomous multi-sensor, multi-target tracking system for space surveillance in support of uncorrelated track (UCT) resolution, breakup processing, attention- and lost-list processing, and catalog maintenance. MFAST fuses astrometric data into high-quality orbits with realistic covariances through joint orbit initiation and orbit determination. MFAST uses Numerica's special optimization-based formulation of the data association problem, namely the multi-frame assignment (MFA) formulation, that, when combined with efficient complexity reduction algorithms, is well-suited for large-scale tracking problems. MFAST includes customized algorithms for non-linear filtering, orbit determination, orbit and uncertainty propagation (including Numerica's implicit Runge-Kutta orbital and uncertainty propagator), and advanced physics-based complexity reduction (or hypothesis gating) techniques that are used to control runtime with little loss in accuracy. Such methods along with the portability of MFAST allow it to be run on most platforms and hardware setups, including laptops and both serial and parallel computing environments. MFAST excels in deep-space (optical) UCT processing in terms of the number of high-quality orbits that it is able to establish, and the software has helped personnel at space operations centers such as 18 SPCS/CSpOC to more quickly identify breakups, discover lost objects, and substantially reduce the size of the U. S. space catalog attention list. MFAST also provides some orbit post-processing components that perform maneuver detection, ballistic coefficient estimation (for drag and solar radiation pressure), and duplicate orbit resolution.

Recently, Numerica has exposed the maneuver detection mode of MFAST as a service (called MFAST-MD), which provides maneuver detection alerts within the NTN catalog maintenance pipeline. For objects that may be maneuvering, MFAST-MD estimates orbital states using an interacting multiple model (IMM) filter that includes several maneuver models. This IMM implementation is a specialization of the more general dynamic multiple model filter. The IMM uses r filter models with an initial set of r hypotheses representing the prior orbital state. Instead of these r hypotheses "fanning out" into r^k hypotheses after k filter steps, the IMM controls the computational complexity by mixing the r hypotheses at the end of a filter cycle into a new set of r hypotheses at the beginning of the cycle, based on prior model probabilities and an $r \times r$ transition matrix governing a first-order Markov process for model switching. For the maneuver and change detection application, we use $r = 2$ Gauss-Hermite (unscented Kalman) filters in conjunction with the aforementioned implicit Runge-Kutta orbital and uncertainty propagator (this is the default filter in MFAST) albeit with different levels of process noise. One model uses nominal process noise while the second uses elevated process noise in appropriate directions in an attempt to capture potential maneuvers or changes. As part of the output of the IMM, one obtains a time series of the probabilities that the nominal and elevated process noise models are active. If a high likelihood for the elevated process noise model is estimated during a filter update step, that event is interpreted as a possible maneuver. To characterize possible maneuvers that are flagged by MFAST-MD, we use the pre-maneuver and post-maneuver orbital state estimates produced by this service in a post-processing step in order to estimate a delta-V and time for the detected maneuver. These maneuver characteristics are recorded for each detected maneuver within the I&W alert message generated for the event.

2.4 Athena Overview

Athena is a multi-source, multi-INT adaptive change detection framework providing a suite of change detectors that use data-driven methods on various feature representations of photometric and orbital state data for joint normality modeling and change detection. Reference [5] provides some of the foundational details about the Athena framework. The current Athena system architecture, shown in Fig. 3, can be viewed as an unsupervised machine learning pipeline. One of the main goals of Athena is to correlate changes detected from multiple sources of data (and multiple types of data), in order to produce higher-level "aggregate" or "ensemble" I&W alerts that reduce false alarms and provide relevant context for understanding the detected events.

The Athena prototype is now operating live on the real-time data feed from the NTN, which collects astrometric and photometric observations on a nightly basis. Athena also provides a web-service application programming interface (API) layer, as well as a web-based visualization dashboard client that enables visual event recognition by an analyst. We now summarize the four layers of the Athena stack, as depicted in Fig. 3.

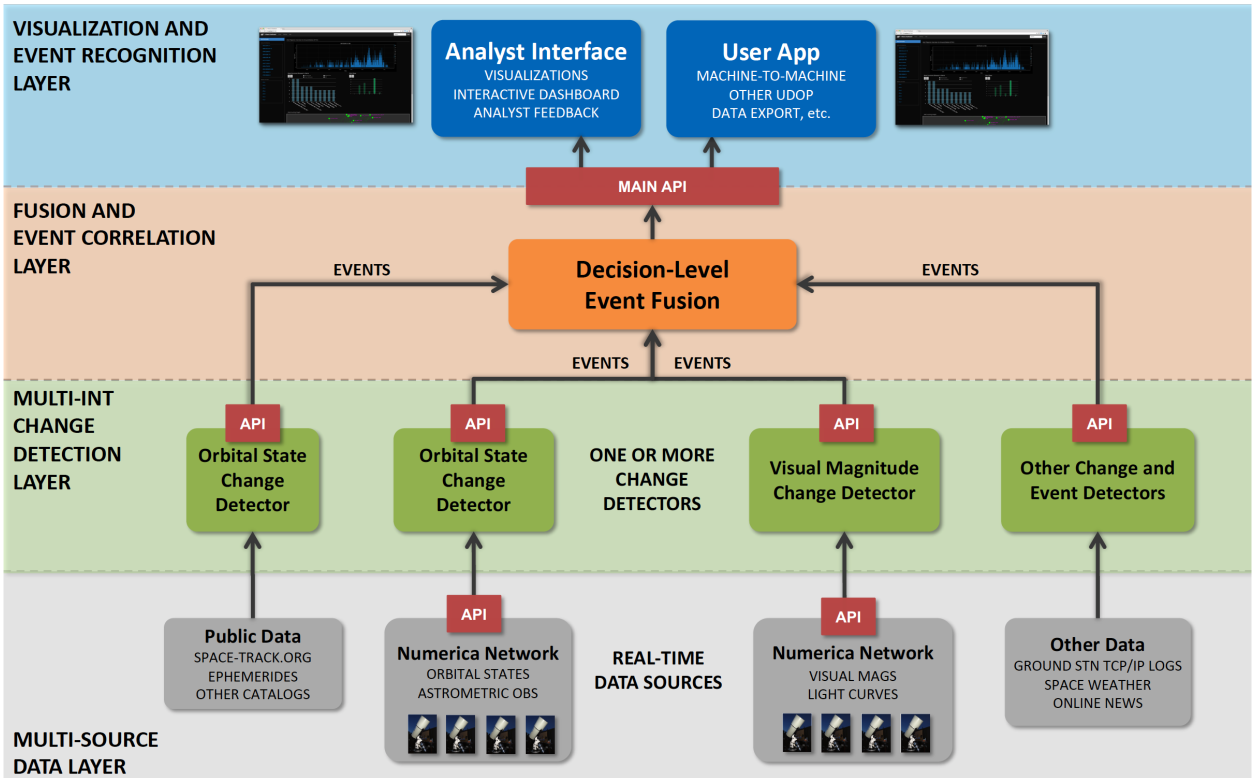

Fig. 3: Athena System Architecture

1. **Multi-Source Data Layer.** The Athena database currently includes a wide variety of data sources, including photometric and astrometric data, high-accuracy state estimates from the NTN, TLEs from Space-Track.org, and several open-source datasets containing satellite meta-data. The NTN provides high-accuracy and frequently-updated (i.e., in real-time) orbital states of deep space objects, as well as visual magnitudes, serving as a prime data source for demonstrating real-time anomalous event detection and recognition within Athena. In addition, Athena can also be run in a stand-alone mode on third-party data feeds, such as those enabled via the UDL.
2. **Multi-INT Change Detection Layer.** The change detection layer in the Athena framework ingests the raw data coming in from the various sources in the multi-source data layer, and connects the feeds with their respective change detectors. The current prototype includes two types of detectors: (i) orbital state change detectors that operate on orbital state data, such as state estimates from the NTN, TLEs from Space-Track.org, or other commercial and government space catalogs; and (ii) visual magnitude change detectors that operates on photometric signatures (i.e., light-curves), as well as sparse visual magnitude data collects. Both types of change detectors utilize unsupervised machine learning methods, and include various feature extraction methods.
3. **Fusion and Event Correlation Layer.** The next layer in the Athena stack performs decision-level fusion (as opposed to feature-level fusion) of the output streams produced by multiple change detectors in the detection layer. This entails detecting and reporting correlations between change alerts produced by multiple change detectors embedded within the change detection layer. In particular, this layer currently correlates the change detections output by the visual magnitude change detector with any changes detected by the orbital state change detectors and maneuvers detected by MFAST-MD. In addition, this layer correlates time-proximal changes detected by multiple sensors on the same space object(s), to enable a "stereo" change detection capability.
4. **Visualization and Event Recognition Layer.** Finally, Athena includes a visualization layer, which includes an API that exposes the underlying functions in Athena to external client applications, including applications running in a service oriented architecture (SOA). In addition to enabling machine-to-machine integrations, this API also enables web-based visualization dashboard applications. A screenshot of the NTN's I&W alerts user interface dashboard is shown in Fig. 4.

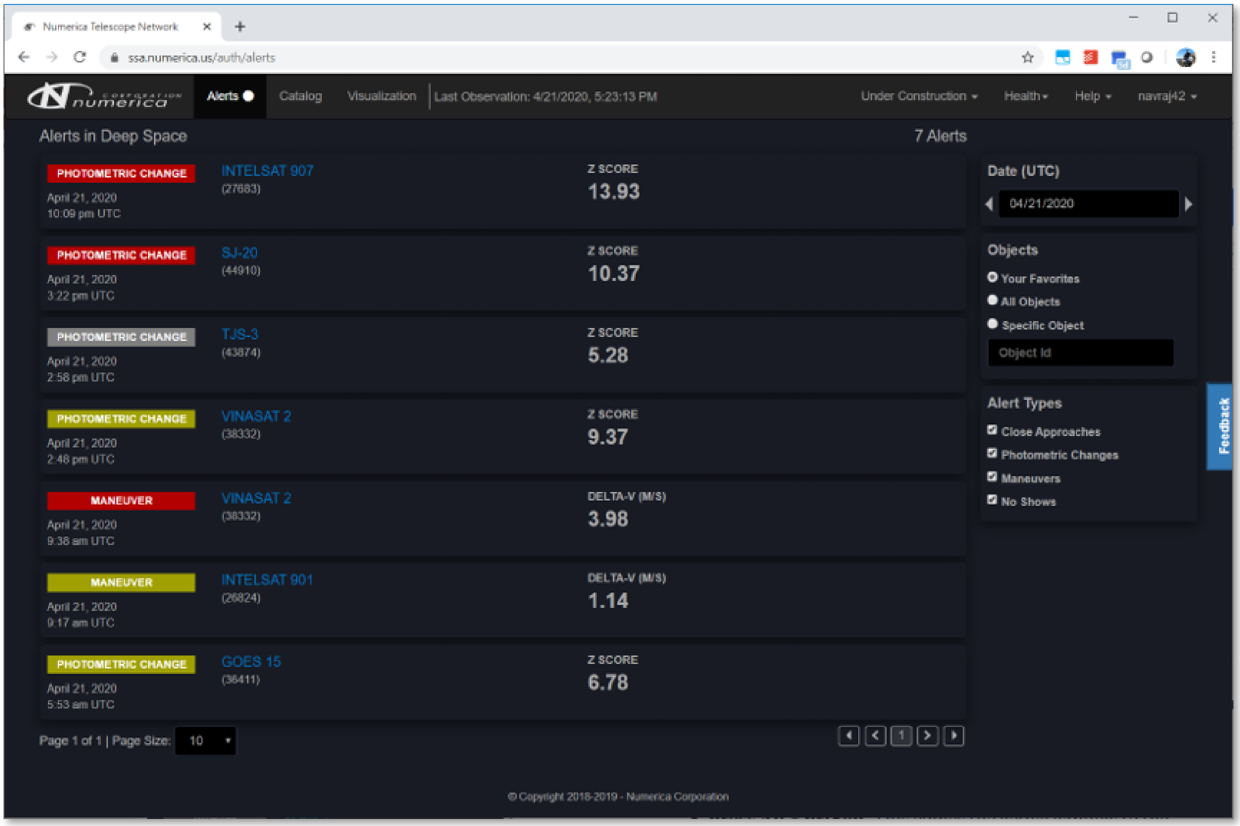

Fig. 4: NTN Alerts UI

We note that within the change detection layer, Athena can employ multiple change detectors for a given data type. For example, Athena currently employs two different change detectors that operate on visual magnitude data: (i) a photometric signature change detector based on Numerica's point-wise error constrained robust principal component analysis (termed *eRPCA*) method, which utilizes compressed sensing-based feature extraction from noisy data and a novel formulation of RPCA for anomaly detection [5]; and (ii) a statistically-robust visual magnitude outlier detector (SROD) that can operate on sparse visual magnitude collects.

More recently, Numerica has enhanced Athena's photometric change detector to enable generation of I&W alerts that involve stereo or near-stereo looks from multiple sensors. These enhancements have been validated using real non-resolved photometric data collected by the NTN. Deviations from normal behavior detected in and correlated across both astrometric and photometric data, from two or more simultaneous data collects from different sensors, are expected to lead to reduced false alarm rates and improved confidence levels. With respect to object characterization, simultaneous photometric data from geographically diverse locations can lead to a faster extraction of brightness features from different illuminated facets of the satellite body.

The key idea behind all change detectors included within the Athena stack is the exploitation of historical and real-time data collections intelligently in a hybrid data-driven and physics-based mathematically rigorous approach. In principle, the Athena architecture is flexible enough that an arbitrary number of such change detectors (e.g., multiple change detectors employing different algorithms that operate on a common data type, change detectors operating on different sources of a common data type, or change detectors operating on different data types) can be plugged into the multi-INT change detection layer, with the goal of the event correlation layer being to perform appropriate decision-level fusion of these multiple change detector alert streams.

Reference [5] provides a detailed description of the eRPCA approach for change detection that exploits photometric signature (i.e., light curves). For sparse visual magnitude collects, Athena employs the SROD method, which we discuss in more detail below.

2.4.1 Statistically-Robust Outlier Detector (SROD) for Visual Magnitude Change Detection

As mentioned above, for photometric change detection, Athena currently provides two different change detectors that utilize very different methodologies. The first change detector, described in [5], utilizes a Numerica-developed enhanced robust principal component analysis (eRPCA) method which utilizes compressed sensing-based feature extraction methods coupled with a novel formulation of RPCA for change detection. This detector is currently restricted to operate on full light-curve datasets only. The second change detector utilizes robust outlier detection techniques to build a historical baseline model of photometric behavior and detects changes from new data, in a manner that does not require full light-curves to be collected night after night. Thus, this statistically-robust outlier detector (SROD) component of Athena can operate on sparse visual magnitude collects.

The SROD algorithmic approach is illustrated visually in Fig. 5. The top-left subplot in Fig. 5 shows visual magnitudes observed over a span of ten days on GOES-13 (NORAD ID 29155), as a function of the signed longitudinal phase angle. The top-right subplot shows the result of building a robust *baseline model* of the photometric signature from such historical data. This baseline model is shown as red triangle markers in the top-right subplot of Fig. 5. Next, suppose we receive a set of new visual magnitude observations as shown in the bottom-right subplot, which overlays the new sequence (blue) over the baseline model (red). Visually, it is clear how the behavior of the light curve has changed. The bottom left subplot shows an 'anomaly score' (specifically a modified Z-score) for each observation within the newly-acquired light curve. The horizontal line marks the threshold γ (in this case, $\gamma = 4$), against which the modified Z-scores are compared. All new observations for which the corresponding modified Z-score is greater than γ, are declared as outliers.

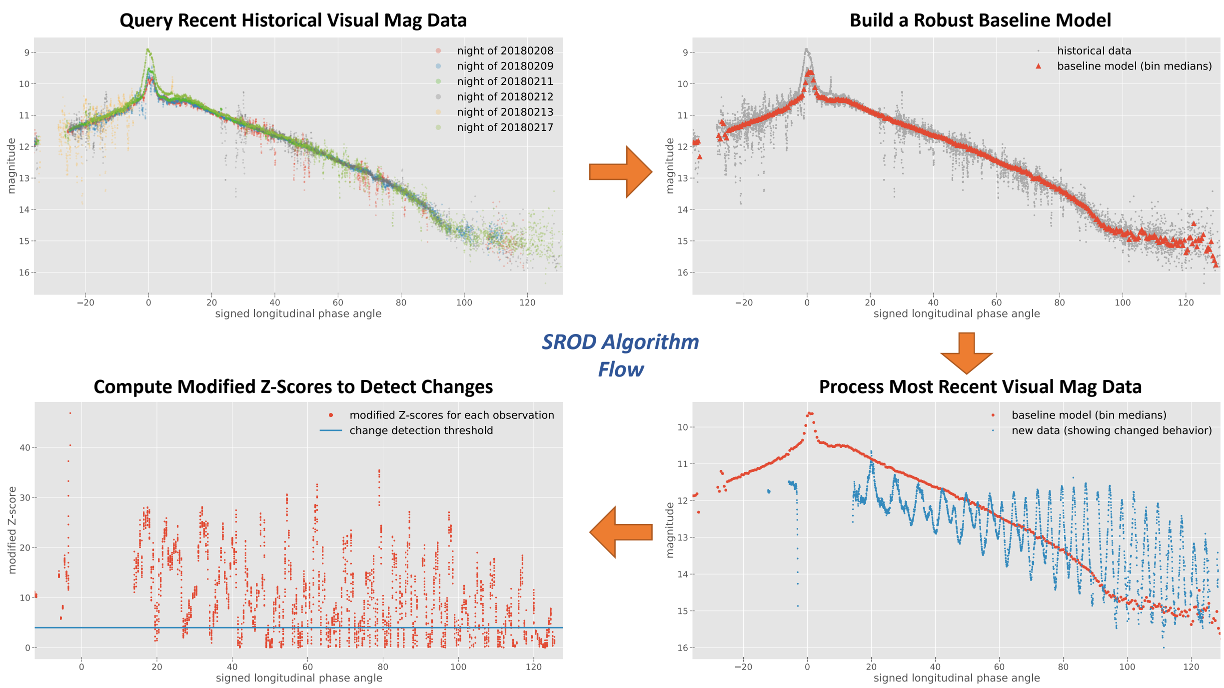

Fig. 5: Statically-Robust Outlier Detection (SROD) Method for Photometric Change Detection

2.5 KRATOS Overview

Finally, we provide a brief description of KRATOS [3], the NTN's main conjunction assessment (CA) and probability of collision (PC) tool that enables rapid CA screening further into the future while reducing misdetection and false alarm rates. Although applicable to all regimes of space, KRATOS is designed to treat objects in the challenging non-linear and non-Gaussian regimes, including situations where the velocity uncertainty is large or the encounter duration is long. Its implementation uses an adaptive framework that automatically selects the PC algorithm (e.g., Foster, Coppola, Gaussian sums) based on what assumptions are met, so that more computationally expensive techniques (i.e., Gaussian sums) are used only when needed. In short, KRATOS rivals the accuracy of Monte-Carlo methods but with little added computational cost relative to the traditional (Foster) method.

Within the NTN, KRATOS operates as follows. Beginning with a snapshot of a NTN-generated space catalog, preliminary CA filtering is performed in KRATOS to determine feasible conjunctions. Next, the KRATOS PC algorithm processes these conjunctions, and any conjunctions involving active satellites with high PCs are flagged and alert notification messages are produced. To substantiate the risk, the NTN can be dynamically tasked to collect new observations on the flagged satellites, and the overall revisit rates can be increased. Updated orbits are produced, and KRATOS publishes updates on the time-of-closest approach, miss distance, and PC. This cycle repeats itself thereby keeping interested parties "in the loop" on the evolving conjunctions, with regular updates and supporting bodies of evidence that can inform courses of action.

3. CASE STUDIES

We now provide some results obtained via the NTN I&W pipeline on recent real-world scenarios and events. Examples of events described in this section include maneuvers, attitude changes, stabilization mode changes, and loss of control events.

3.1 Detection of Normal and Abnormal Maneuvers

Common maneuvers for satellites in GEO include North-South and East-West station keeping maneuvers, and start-drift or stop-drift maneuvers used to change the satellite's longitude station within the GEO belt. Of these three types of maneuvers, North-South station keeping maneuvers are most commonly identified automatically using MFAST-MD, because their delta-V is sufficiently large that the satellite's trajectory does not match natural dynamics well. Satellites in GEO orbits tend to drift in inclination unless routine inclination change maneuvers are conducted. An example of such a North-South station keeping maneuver detected by MFAST-MD is shown in Fig. 6. The plot shows evolution of the inclination of object 39122, clearly indicating an inclination change maneuver conducted to bring the inclination closer to zero degrees. MFAST-MD also estimates the maneuver time (shown as a vertical line in Fig. 6) and a maneuver delta-V (estimated to be 4.2 m/s in the direction normal to the orbital plane for this maneuver).

The NTN pipeline routinely detects such station-keeping maneuvers. Although currently the I&W pipeline produces alert notifications for all such maneuvers detected, a nominal maneuver characterization is included in the alert message which allows end-users and analysts to potentially ignore events which are characterized as routine events.

Start- and stop-drift maneuvers in GEO often require a large delta-V in the in-track direction. Allowing maneuvers this large directly within nominal MFAST-MD processing could lead to unwanted cross-tagging; hence, start- and stop-drift maneuvers are treated during automated post-processing via subsequent MAST-MD runs with alternate maneuver models. In this post-processing step, maneuver details are estimated and maneuver alerts are automatically produced. Fig. 7 shows an example of maneuver alerts generated for object 40258, an object that performs frequent GEO slot change maneuvers. Fig. 7 shows the times for all maneuvers whose estimated delta-V is greater than 2 m/s. These maneuver estimates were automatically generated in MFAST-MD. The majority of detected maneuvers align with a start-drift or stop-drift maneuver, as indicated by the changes occurring in the object's longitude position within the GEO belt around the times of the detected maneuvers.

3.2 Detection of a Stabilization Mode Change

Photometric changes can be used to identify a number of different types of events, including breakup events, changes to satellites' stabilization states, and some types of maneuvers.

The first case we consider is the detection of a stabilization mode change, taking GOES-13 (29155) as a case to study. The reader was presented a first glimpse of a change detection result for this object in Fig. 5, where we used this test case to illustrate the SROD algorithm description. Fig. 8 shows the performance of SROD on visual magnitude data collected by the NTN on GOES-13 during the night of 3/21/18. The top subplot of Fig. 8 shows light curves before and after the mode change event. The bottom subplot shows modified Z-scores obtained for each track of observations seen on the night of 3/21/18.

Any track for which the modified Z-score is higher than a threshold (four in this case) is highlighted in the top subplot (as the circular markers with a black boundary). Fig. 8 shows that the algorithm successfully identifies visual magnitude measurements that stray from the baseline model. The SROD component generates alert messages for

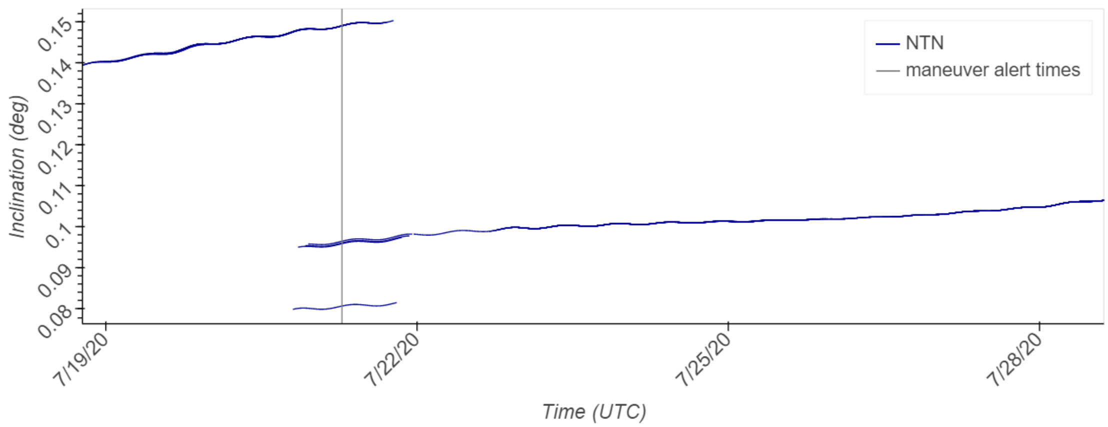

Fig. 6: EUTE 117 WEST (39122) Inclination vs. Time with an Automatically Generated Maneuver Alert

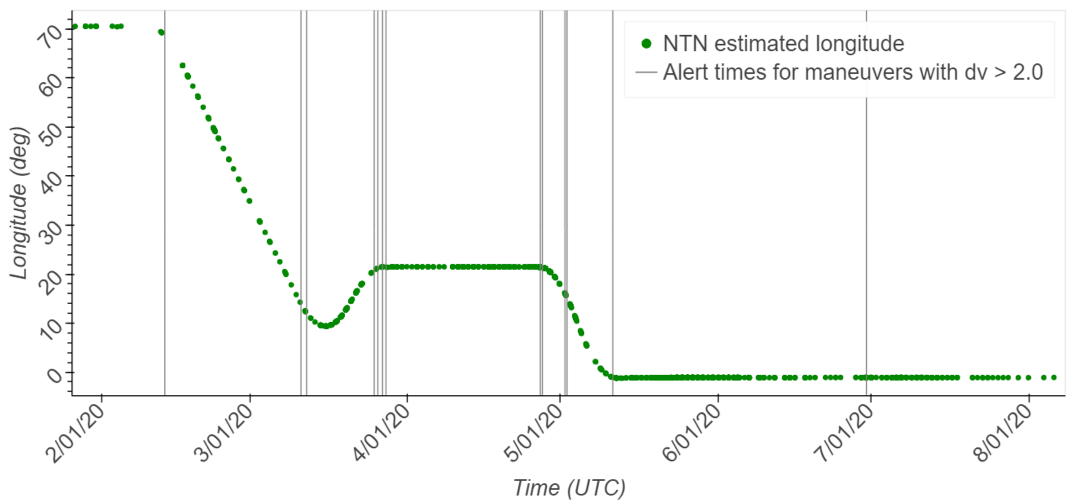

Fig. 7: Longitude vs. Time for Object 40258 Shown Along with Detected Maneuver Events

tracks whose visual magnitudes exhibit a modified Z-score value that is higher than 4, when compared to the local phase angle bin. These results indicate successful identification of a photometric change.

A Lomb-Scargle periodogram analysis for light curves obtained before and after the detected change, shown in Fig. 9, confirms the nature of the change in the spin mode for GOES-13. Numerica independently confirmed that this mode change into a spin state was an intentional action carried out by GOES-13 owners/operators during the process of retiring the satellite. Note that the periodogram analysis was not performed as part of the SROD change detection algorithm, illustrating the possibility of performing robust change detection without needing to fully characterize an object's behavior, which may not be possible to derive from sparse visual magnitude collections.

3.3 Detection of an On-Orbit Loss of Control

Another type of event that could potentially be detected via changes seen in photometry is a loss of control of a GEO due to an anomaly. For example on 4/8/2019, the propulsion system of INTELSAT 29E (NORAD ID 41308) suffered a fuel leak which caused the satellite to start drifting. The results of running Athena's photometric change detectors on observations surrounding this event are shown in Fig. 10. The figure shows a baseline set of observations seen prior to the event, as well as the post-event tracks of observations that triggered I&W alerts to be generated. As can be seen, significant change in the photometry is detected in the post-event data. The first change detections are generated at approximately 0608 UTC on 4/8/19. Each dot represents an individual observation, whereas the asterisks represent tracks (short sequences of observations) for which an alert was triggered. Fig. 11 confirms the change by showing a more complete light curve obtained on the object after the event, on 4/11/2019.

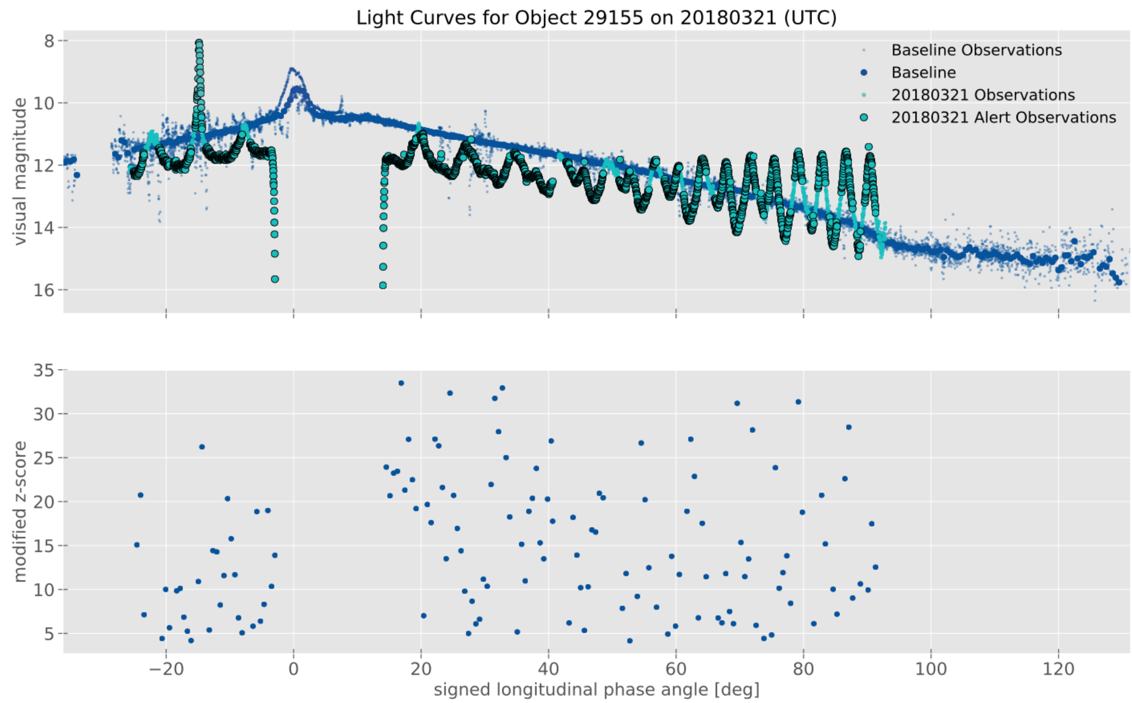

Fig. 8: SROD Photometric Change Detector Results on GOES-13 After Stabilization Mode Change

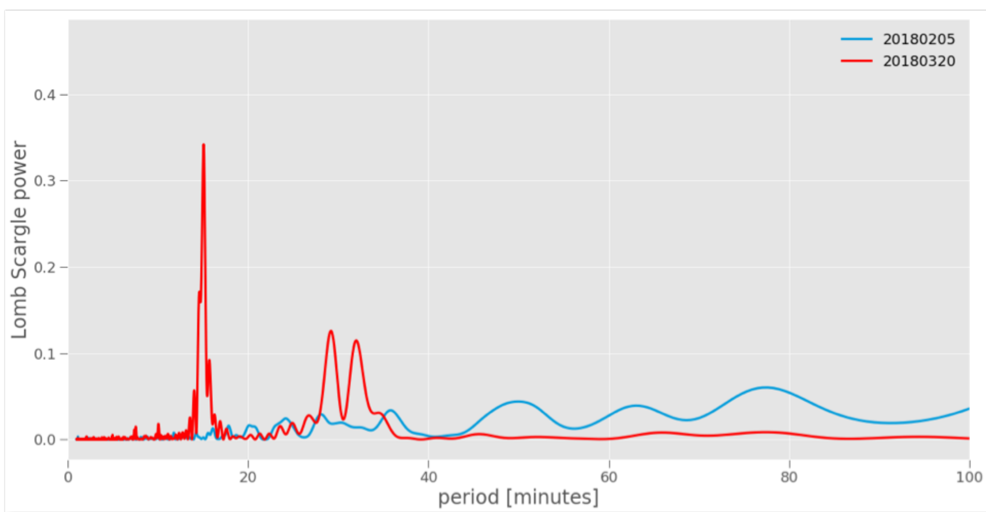

Fig. 9: Lomb-Scargle Periodograms for GOES-13 Light Curves Before and After Stabilization Mode Change

3.4 Detection of Stereo Photometric Changes

In addition to identifying outlying visual magnitudes collected from a specific sensor, the SROD alerting tool compares the geographic locations of sensors producing time-proximal change detections on an RSO. Change detection alerts produced with tracks from multiple locations are flagged as *stereo alerts*. To motivate the need for stereo photometry analysis, Fig. 12 shows three GOES-16 light curves collected on the night of 12/10/17 from three different NTN sites: Colorado, New Mexico, and Chile. GOES-16 conducted a relocation campaign in GEO during a time period spanning November 2017 to January 2018. All three sites indicate a change in the photometric signature (due to a known stop-drift maneuver), significantly reducing the possibility of a false alarm due to site-specific data integrity issues. In addition, the differences in certain light curve features seen from the three sites as a function of the signed longitudinal

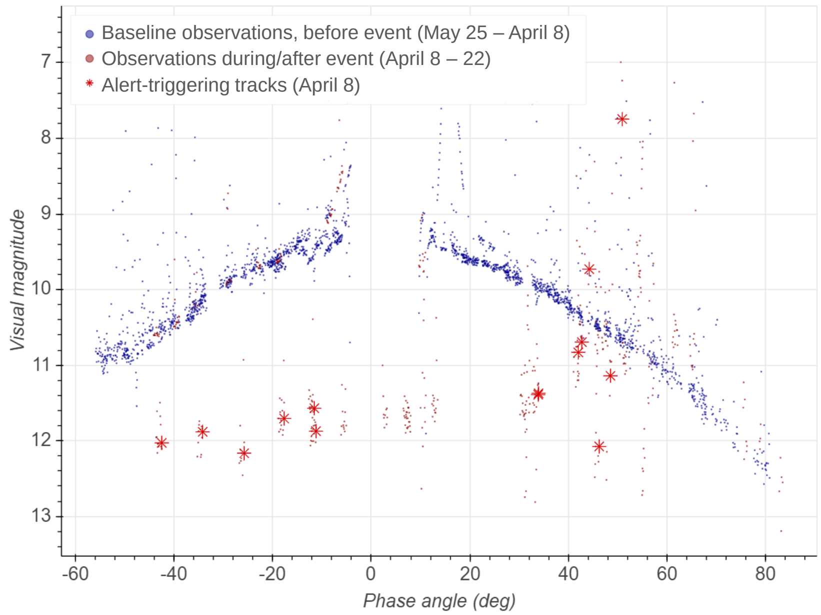

Fig. 10: Detection of INTELSAT-29E Fuel Leak and Subsequent Loss of Control

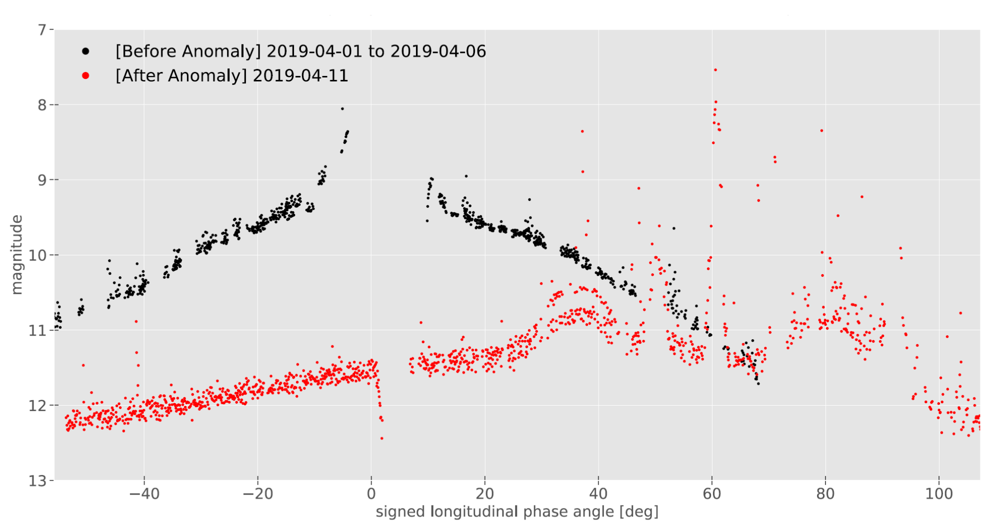

Fig. 11: INTELSAT-29E Light Curves Obtained via the NTN Before/After the Fuel Leak Event

phase angle are also evident. Thus, we obtain more information more quickly from the simultaneous looks compared to a single source light curve alone. With a single source, one would have to depend on either an attitude change or a change in the viewing angle due to seasonal variation in the solar declination angle, in order to capture a similar amount of information.

Fig. 13 presents photometric data tagged in a stereo photometric change alert for GOES-16 during the stop-drift maneuver. With information contained in an NTN alert message, we are able to differentiate between stereo and non-stereo alerts, provide context for the alert, and analyze the circumstances leading to the alert. This allows us to determine under what conditions the change detector performs well and correctly identifies photometric changes, as well as under what conditions it struggles such as when false alarms are generated or true photometric changes are not detected.

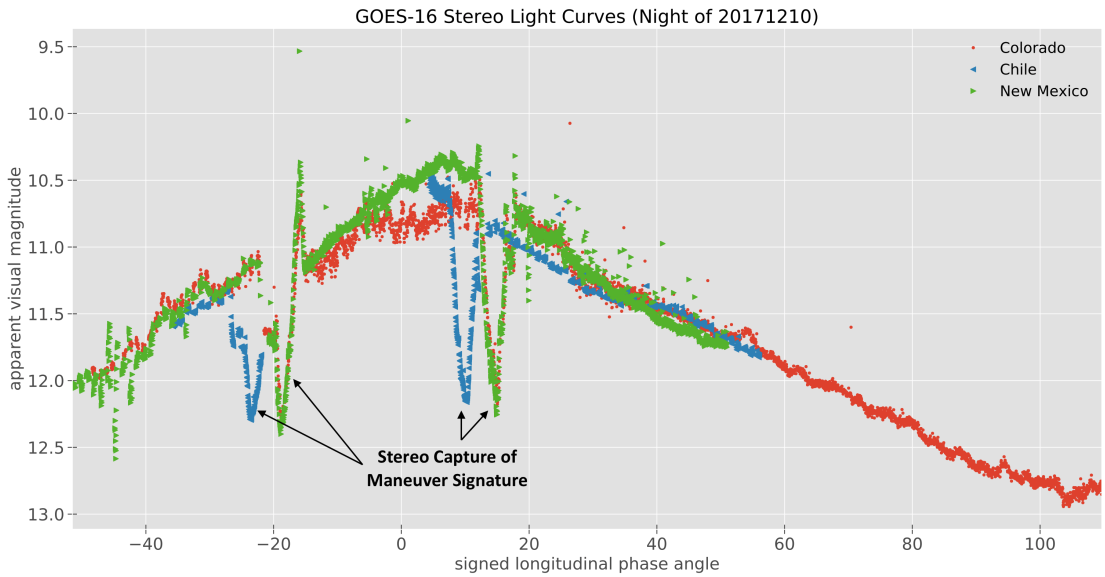

Fig. 12: GOES-16 Light Curves Collected by the Numerica Telescope Network During a Stop-Drift Maneuver

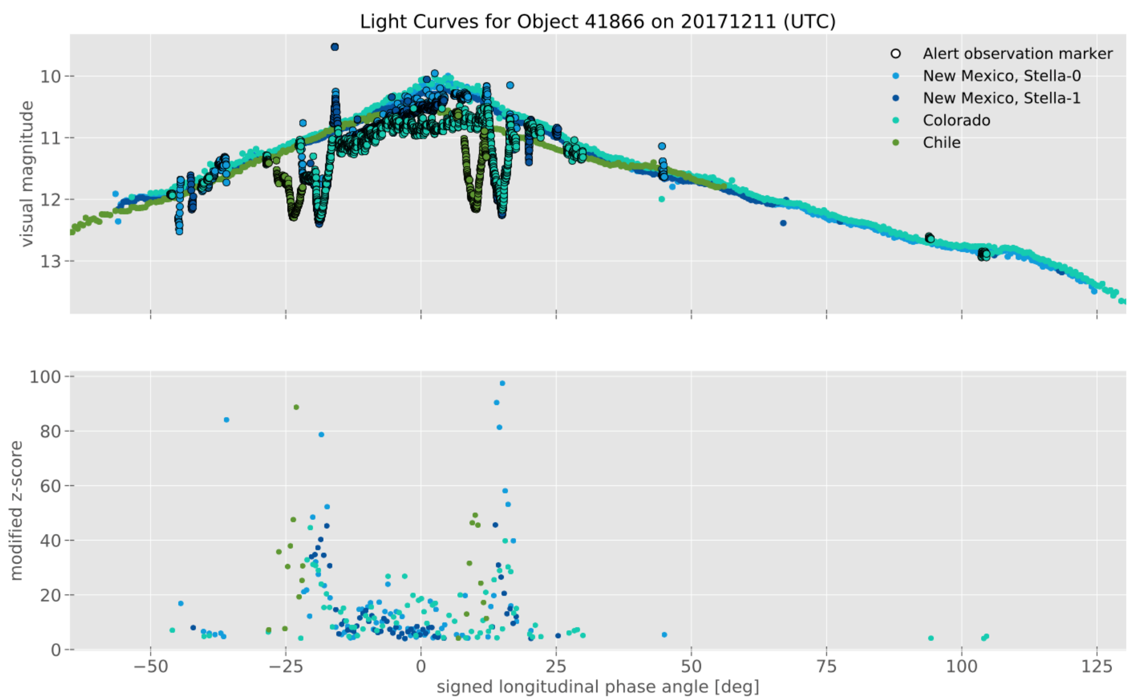

Fig. 13: SROD Results with Stereo Photometric Data on GOES-16 During the Stop-Drift Maneuver

3.5 Detection of Correlated Maneuver and Attitude Change

Often an abnormal maneuver conducted by a satellite may be accompanied by an attitude change just prior to the maneuver. Thus, correlating photometric and maneuver alerts can increase confidence that a maneuver really occurred, and can even provide an early signal that a satellite is about to maneuver. As an example, consider the GOES-16 relocation campaign described in the previous case study for stereo change detection. On 12/1/2017, the GOES-16 satellite initiated an eastward drift (via a start-drift maneuver) with respect to its original longitude of 89.3 degrees West. Fig. 14 shows the maneuver along with the satellite's longitude vs. time. The maneuver time shown in the

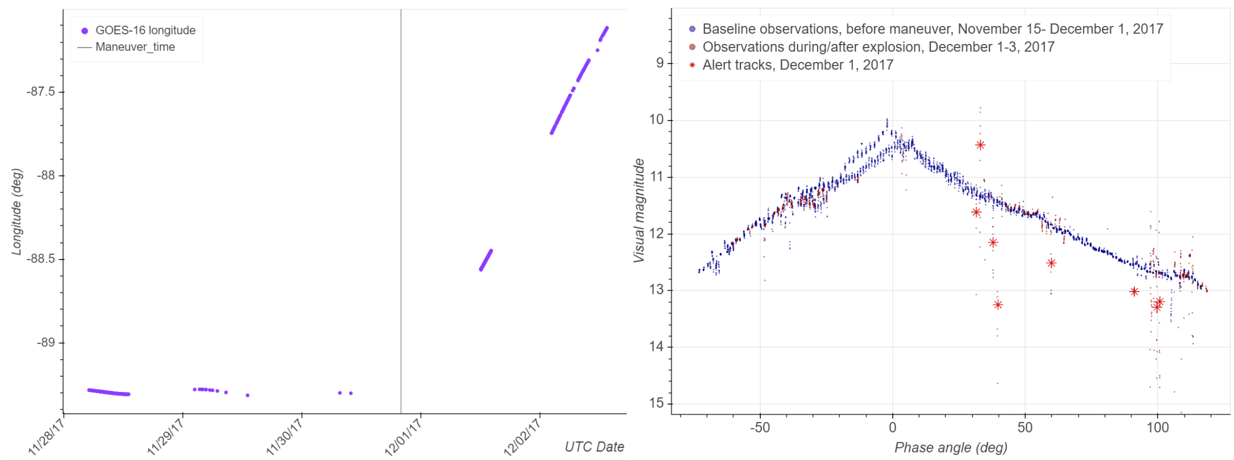

Fig. 14: Maneuver and Attitude Change Correlation Detection: (left) GOES-16 Longitude vs. Time Before/After Start Drift Maneuver, and (right) GOES-16 Light Curves Before/After Start Drift Maneuver

longitude plot (left subplot) corresponds to the estimated maneuver time in an alert generated in post-processing. If maneuver alerts had been live in the NTN pipeline at the time of this maneuver, this alert would have been generated via MFAST-MD as soon as the state estimate was produced. Just prior to this maneuver, significant photometric changes were also observed as GOES-16 changed its attitude to prepare for the maneuver. Athena's photometric change detection was run on observations surrounding this slot change maneuver. The photometric changes shown here occurred prior to the maneuver, and would have been generated immediately within the NTN pipeline if photometric alerts had been live at the time. Importantly, during such an event, the NTN pipeline (in particular, the decision-level fusion layer of Athena) also automatically correlates such low-level alerts in order to produce a higher-level aggregate/ensemble alert that combines the low-level maneuver detection and photometric change detection alerts. Such alert correlation typically reduces false alarms and provides additional context around the events being alerted on, in order to aid follow-up courses of action.

4. CONCLUSIONS

A key need for responsive SDA is the capability to provide automated I&Ws regarding abnormal events in space. In order to meet this need, Numerica has augmented its NTN TCPED pipeline with additional analytics tools and architectural improvements in order to produce real-time I&W alerts regarding events of interest. These I&Ws currently include maneuver detection, no-show, conjunction, and photometric change detection alerts. In addition, a multi-source event correlation layer automatically determines certain types of relationships (e.g., co-occurrences) between events detected across multi-source data, which can aid in mitigating false alarms generated by a single data source. In this paper, we provided an overview of the technical approaches employed within this I&W pipeline and demonstrated these I&W capabilities using recent real-world data. Examples of scenarios discussed included detection of abnormal maneuvers, changes in satellite stabilization mode, loss of control due to on-orbit anomalies, detection of photometric changes from stereo observations, and detection of correlations between multiple types of events.

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DISTRIBUTION

Cleared for Public Release (Case No. 88ABW-2020-2776, 10 September 2020).

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