# ExoALERT: 1 Year of AI-Enabled Space Traffic Management Services at GEO

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**ABSTRACT**

Space Traffic Management (STM) at Geosynchronous Earth Orbit (GEO) is possible with existing commercial services. Our system, ExoALERT, derived from empirical data and enabled by our worldwide persistent sensor network, has been developed and employed to provide STM services. ExoALERT leverages automated processing and human analyst expertise to provide these services. In this paper, we will describe the system, discuss the human-machine interactive workflow, and provide real-world examples to demonstrate its operations. We will also discuss the lessons learned from operating ExoALERT over the past year.

## 1. INTRODUCTION

Space activity has grown dramatically in the past decade. This is driven by several trends, including a lowering of the cost of access to space and the cost of space systems themselves. As a result of these trends, the operators of space systems today face an environment more challenging and congested, with a wider variety of space operations, leading to a need for Space Traffic Management (STM). The associated technical and organizational challenges to STM are manifold [1, 2]. There are an increasing number of governmental and commercial actors operating platforms in space, and these systems are an increasing part of critical infrastructure in many parts of the globe.

The traditional model of Space Situational Awareness (SSA) data collection which focuses on catalog maintenance and conjunction assessment will not be sufficient for affirmative flight safety. Flight safety services which constitute traffic monitoring and control ultimately dictate dedicated monitoring frameworks and have little tolerance for data gaps. Data strategies which collect the minimum number of measurements required to provide conjunction warnings should not be the basis for a modern approach to STM.

Starting from algorithms based on the empirical observation of orbital behaviors both routine and anomalous, we developed ExoALERT (ExoAnalytic AI-assisted human-in-the-Loop Exploitation and Reporting Tool). ExoALERT is an automated alerting system, designed and developed using data collected on the entire GEO object population since 2012. ExoALERT was put into operational use beginning in 2017 with the ExoAnalytic Global Telescope Network (EGTN) capture of the Telkom-1 anomaly [3]. The operation of this alerting system, which starts from persistent observation data, and includes automated correlation and object characterization, will be discussed in the following sections. ExoALERT includes single object alerts, both astrometric and photometric in nature, as well as multi-object alerts such as conjunctions.

## 2. ALERTING SYSTEM

### 2.1 Components

The basic ingredients required for an alerting system for STM are sensor measurements correlated to space objects, a system for categorizing observed behaviors, and a human-machine interface to present them in a fashion that is relevant for an analyst. With over 350 telescopes operating worldwide, ExoAnalytic Solutions provides persistent measurement and tracking for space objects above 8,000 kilometers altitude with minimal solar exclusion gaps using the EGTN. This persistent observation capability, operational since 2012, provides a basis for commercial services that can enable true STM. GEO is a domain suitable for the development and testing of STM services because it can be addressed comprehensively today.

The relevant figures of merit of the EGTN for the discussion of STM and SSA are timeliness, persistence, and measurement accuracy. The global distribution of observing sites provides 100% coverage of GEO, MEO, and HEO orbits, with a very high availability figure (>98%). The persistence, with a mean solar exclusion gap of approximately 6 hours, together with the sub-arcsecond measurement accuracy obtained, allows for highly reliable near real-time automated object correlation (99% correct). Images collected by the EGTN telescopes are processed in situ at observatories and the extracted observations are received with a latency of 15-30 seconds.

The data accuracy provided by the EGTN into the automated process is a critical factor that allows ExoALERT to perform at a low false alarm rate with a low rate of missed detections. The data accuracy has been verified and validated by numerous customers over the past 10 years (0.2 – 0.5 arcsec, 1 sigma). Fig. 1 shows results from an ExoAnalytic data quality validation as well as two independent data quality validations. The left plot is a summary of the average data quality over 160 days in 2016-2017 across our network (0.51 arcsec). The center plot is a summary of our data quality (0.25 arcseconds) performed by Air Force Research Laboratory (AFRL) in 2014. The right plot is a summary of our data quality (0.22 arcseconds) performed by the National Space Defense Center (NSDC) in 2017.

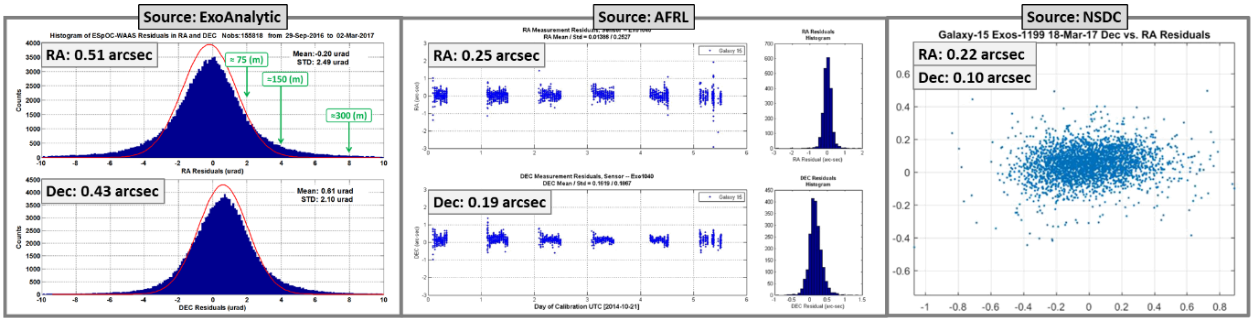


Fig. 1: Internal and independent validation of data quality.

ExoALERT consists of our suite of alerting algorithms and human-machine interactive workflow solution that operates 24/7 on EGTN data collected for thousands of space objects scanning persistently for anomalies. ExoALERT autonomously processes 30TB of raw data each day (for approximately 4,500 objects) into real-time alerts. The operation of this system and the human-machine integrated workflow will be described in detail in later sections.

### 2.2 Space Traffic Classification

The most common categories employed historically for space object classification have been by orbit regime, e.g. LEO / MEO / HEO / GEO. Over time, other more specific and specialized orbit descriptions, such as a Molniya orbit or a sun-synchronous orbit have come to be utilized [4]. Some orbit categories are typically temporary, such as GEO transfer orbits (GTO). While there is some arbitrariness in some of these designations (for example, the LEO – MEO boundary), the categories are generally accepted across the communities of practice that deal with space objects either as operators, users, or observers.

Categorization by orbit type is not sufficient for the detail required to develop the understanding of the population of space objects necessary for STM. For example, is a given object an active satellite under control of a launching or operating entity, or is it an inactive object? If the latter, is it a formerly controlled satellite, or a spent rocket stage, or a piece of debris created intentionally or unintentionally? For many objects, this information is known, while for many others, the true nature of the object is only inferred through observations of their behaviors.

Historically, the typical space object at GEO has been a government or commercially owned communications or weather satellite. When stationed in its assigned orbital location, the behavior of such an object is typically very routine, with station-keeping maneuvers usually occurring on a predictable schedule. Persistent and precise observations can detect these relatively small maneuvers, and patterns can often be teased out of the observed data.

Behaviors of a single object can be divided into those that are observable via the astrometric characteristics of an object and those that are observable via its photometric characteristics. Of course, the photometric and astrometric characteristics of an object are not truly independent: at the very least, the pose (orientation in 3-space) and motion of an object will affect the signature observed by a sensor, and in some cases, if this signature is faint, the ability of a sensor to localize the object will be degraded. In general, the astrometric and photometric behaviors are considered at least somewhat independently.

If all space objects remained continuously able to be considered in isolation, the exercise of object characterization would stop there. STM requires the understanding of collective object behaviors. For example, one of the main goals of any mature STM system, and of the not yet fully mature systems operating today, is to prevent unwanted interactions between space objects (ex. unsafe close approaches, collisions, radio frequency interference, etc.) that can be prevented. The identification, prevention, and mitigation of unwanted interactions between space objects is one of the primary responsibilities of any STM system.

While many potential interactions are unintentional, there are also an increasing number of events in orbit that are intentional close interactions between objects. For many years, some GEO satellite owners have operated multiple satellites in proximity within a single GEO longitude slot, using a variety of techniques to maintain safe operating distances. In some cases, the operational modes can be inferred from off-board sensor information [5]. More recently, rendezvous and proximity operations (RPO), where a space object makes an intentional controlled approach to another object, are increasingly common across orbit regimes, for a variety of purposes including satellite servicing, inspection, and active debris removal. The most recent examples of such operations at GEO, the servicing missions of MEV-1 and MEV-2, were supported by commercial services provided by ExoAnalytic [6].

### 2.3 ExoALERT Operations

ExoAnalytic currently provides space traffic management services using the ExoALERT system for government and commercial customers. For this service, we produce high fidelity ephemeris based on tracking data collected by the EGTN and considering any planned maneuvers. In addition, flight safety services are provided in the form of conjunction screening assessments, conducted over a moving analysis window, against other satellites and considering planned maneuvers. Additional measurements of the potential conjuncting objects are collected by an analyst as needed to reduce their orbit uncertainty and to be able to accurately estimate time and distance of close approaches. The overall system shown in Fig. 2 allows a single analyst to produce reports for events as they occur in near real-time, and to evaluate alerts about future predicted events.

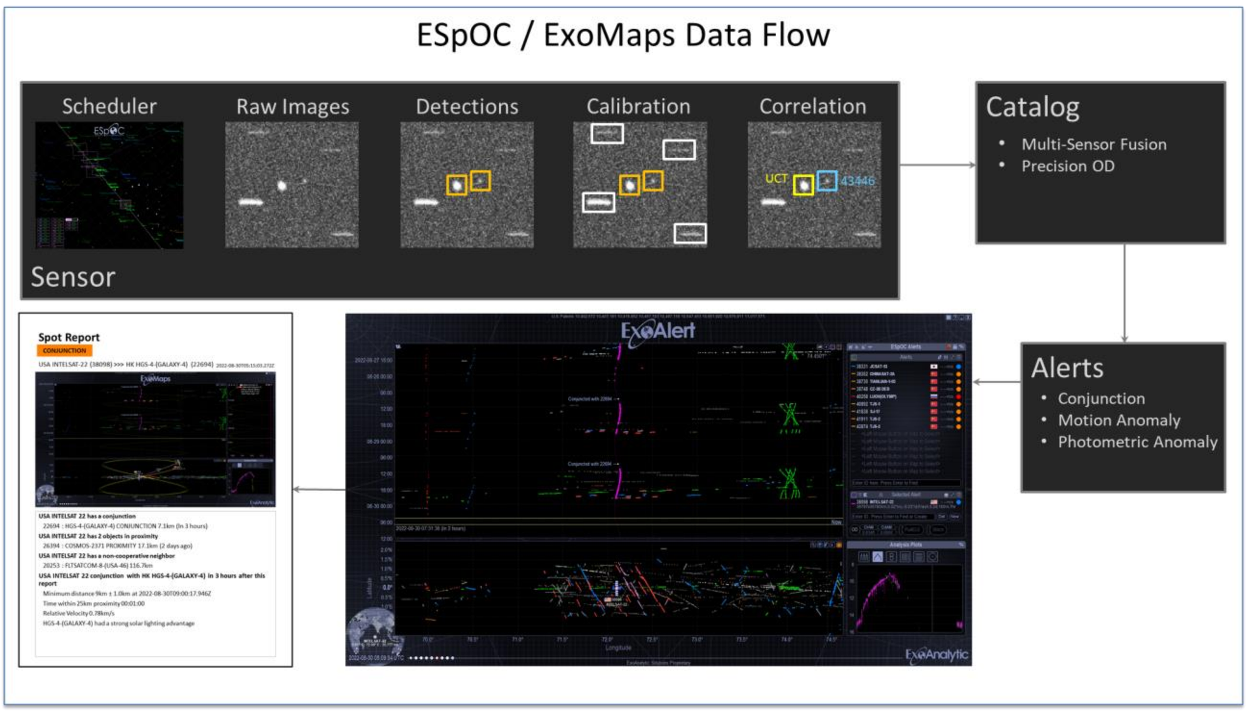


Fig. 2: High level summary of the data flow supporting the ExoALERT system.

The flow of image data through our detection process produces measurements which are then correlated and result in periodic updates to our space object catalog. Automated alerts are generated on a 15-minute cadence and presented to the analyst. The analyst can evaluate those alerts and rapidly either dismiss or publish them depending on the results of their evaluation. The automated generation of human-readable reports helps to minimize human errors that can be introduced in the process.

### 2.4 Human-Machine Integrated Workflow

During typical operations, observations are collected by the EGTN at a rate greater than 15,000 observations per 15-minute period for ~2,000 objects. As shown above in Fig. 2, the processing of image data to generate detections and the correlation process of turning detections into observations of known space objects are automated and occur without user intervention. The automated ExoALERT algorithm process that checks for alerting conditions operates on a 15-minute cadence. The current rate of alerts arriving for the user is ~10 per 15-minute period. The impact of automation is highlighted in Fig. 3. Alerting thresholds can be configured on a per object or per customer basis. Some examples of customized alerting schemes include altered conjunction notification windows for some space objects, and reduced alerting cadence for station-keeping operations for satellites for which we receive maneuver plans.

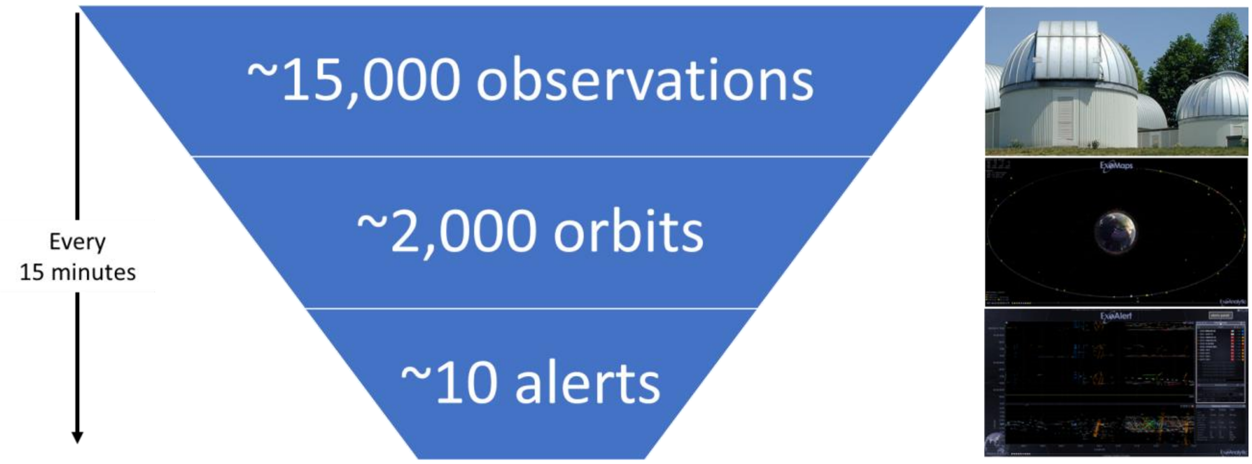


Fig. 3: ExoALERT Automation processes ~15,000 observations for ~2,000 objects into ~10 alerts every 15 minutes.

The operational procedures that have been developed are shown in the flow diagram in Fig. 4. As described in Fig. 3, the automated process turns observations into correlated object states, and these object states drive the ExoALERT algorithm suite. As alerts arrive, they are either adjudicated by an automated process ("AI / ML Adjudication") or presented to the analyst ("Analyst Adjudication"). Alerts that are adjudicated by the automated process immediately update our catalog states and ontology.

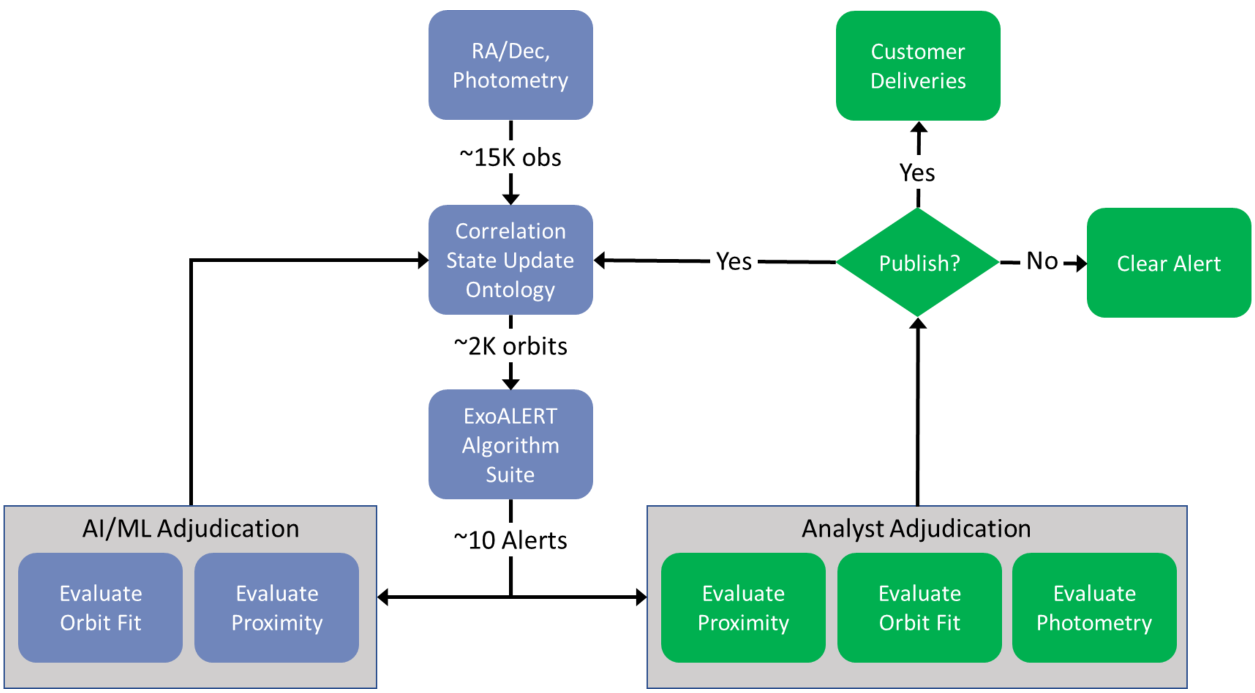


Fig. 4: Overview of the ExoALERT human-machine integrated workflow. Blue processes or decisions are entirely automated, while green processes or decisions are analyst-driven. The complete process runs every 15 minutes

Alerts presented to the analyst from specifically flagged objects or urgent alerts are presented with a higher contrast to draw analyst attention immediately. When an alert is selected by the analyst, a summary of the alert type and space object(s) involved is shown in a pop-up window. The alert can be quickly resolved with a single rapid action by the analyst. Alternatively, the analyst can select the alert and is then presented with the relevant observation, orbit, and historical data for the object(s) involved. After performing any required tasks (orbit determination, evaluation of orbit residuals, photometric anomaly identification, etc.), the analyst publishes the alert, which updates our catalog states and ontology. If the alert is related to an object which is specific to a customer, the analyst generates a human-readable report which is then delivered to the customer via some specified means (e-mail, file server, etc.). ExoALERT is designed such that an analyst can adjudicate an alert in ~1 minute, enabling near-real-time customer alerting.

## 3. EXAMPLE STM USE CASE

In this section we will follow the thread of a single alert through the human-machine integrated workflow described by Fig. 4 above. The screenshots below were produced in ExoMaps (ExoAnalytic Master Analytics Processing System). ExoMaps the primary tool used by the analyst to interact with the automated alerting system and the supporting data and analysis tools. The primary ExoMaps view of the observation data is in the main waterfall window, which has Time on the y-axis and Longitude on the x-axis. Beginning at the ExoMaps screen, the analyst is presented with alerts in the alerts panel to the right which displays the current alerts of interest as shown in Fig. 5.


Fig. 5: ExoMaps screenshot showing the alerts panel with a highlighted alert.

In the next few figures, we show the analyst workflow for selecting and evaluating the alert. In Fig. 6, the analyst selects the highlighted alert. When this action is taken, the main view of the ExoMaps observation window is shifted to the time and longitude where the alert is taking place.

Fig. 7 shows that in the main view the observations of the alerted object are now selected and highlighted in magenta, as well as a short summary of the alert(s) that have been triggered for that object. The summary is presented to the analyst when the alerted object is hovered over in the Selected Alert window.

With another single keystroke the analyst can access more details about the selected alert, as shown in Fig. 8. The analyst reviews the alert details and decides if it requires further action or dismissal. If the alert is not relevant, it can be quickly dismissed.

What are the criteria for dismissal or further evaluation? Some examples of alerts that may be dismissed without further action by the analyst might be future conjunctions more than 24 hours away; conjunctions between nearby RSOs with the same owner/operator that normally operate in close proximity; or duplicate alerts on an ongoing astrometric or photometric anomaly. In the example shown in this use case, this is a non-cooperative conjunction, and we will assume that if the close approach distance is less than 10 kilometers, it will be reportable to some external customer.


Fig. 6: Analyst selects a specific alert.

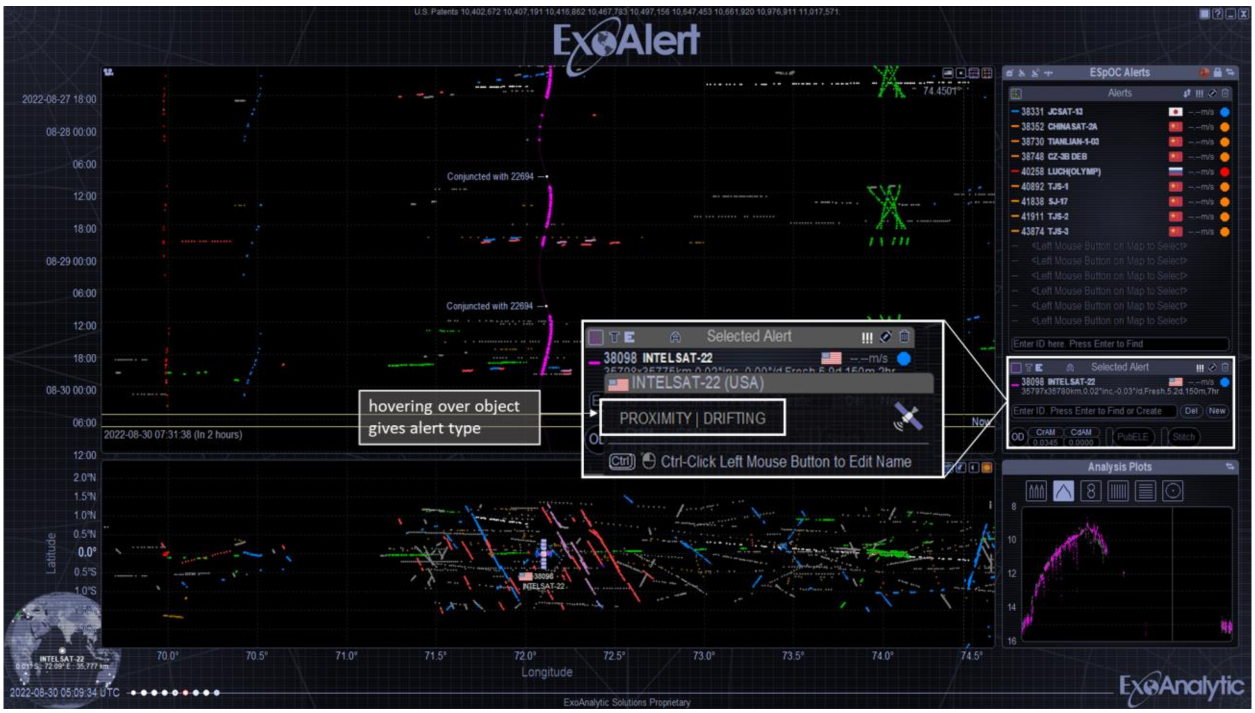


Fig. 7: The analyst can mouse over the alert to see a summary of the specific alert type(s).

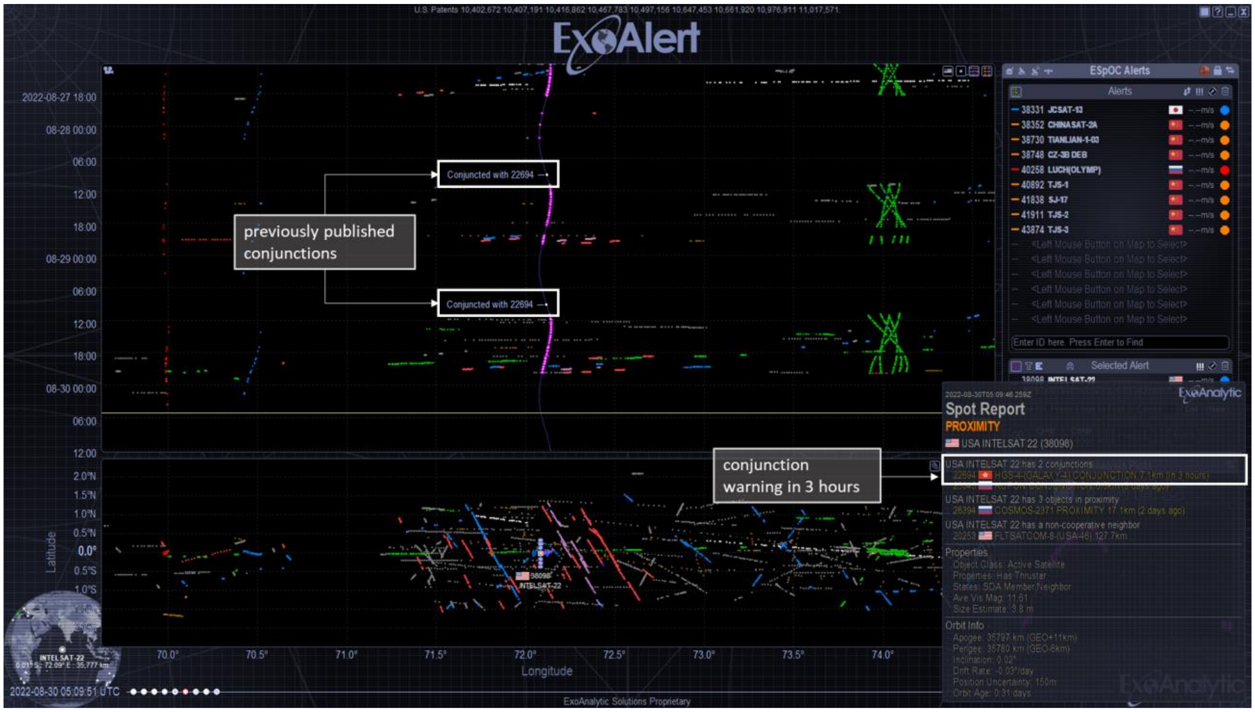


Fig. 8: Additional alert details. Also note previously published (curated) conjunctions.

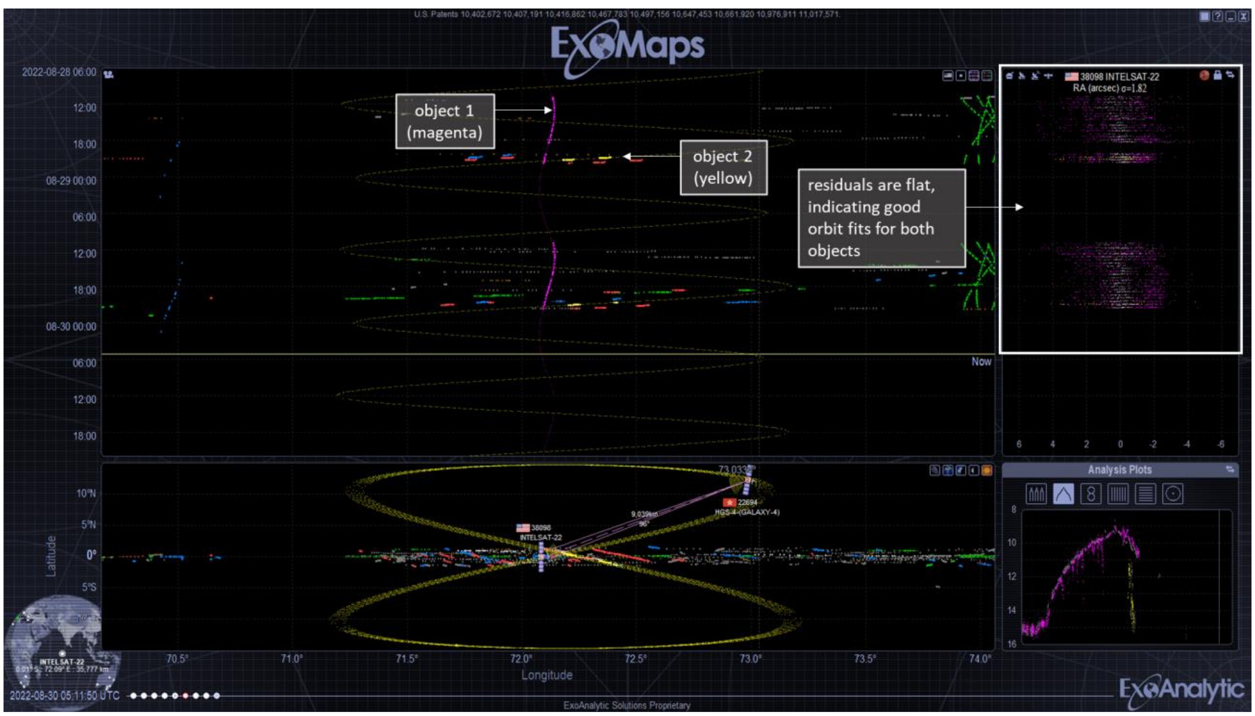


Fig. 9: Orbit details of the two objects involved in this conjunction.

In this use case, the alert is not dismissed since it is a relatively close approach a few hours into the future, as shown in the alert details in the lower right of Fig. 8. The analyst can perform several analysis tasks: orbit fit evaluation, proximity evaluation, and photometry evaluation. These actions are shown in the diagram in Fig. 4 in the box titled "Analyst Adjudication." Here, the analyst chooses to load the catalog orbits of the two objects, INTELSAT-22 and HGS-4, in order to get more understanding of the alert. Fig. 9 shows that in the analysis pane on the right-hand side, the orbit residuals are flat and relatively low magnitude, so the catalog orbits match the most recent observations of the objects involved. This is an indication that further orbit evaluation actions are not required by the analyst.

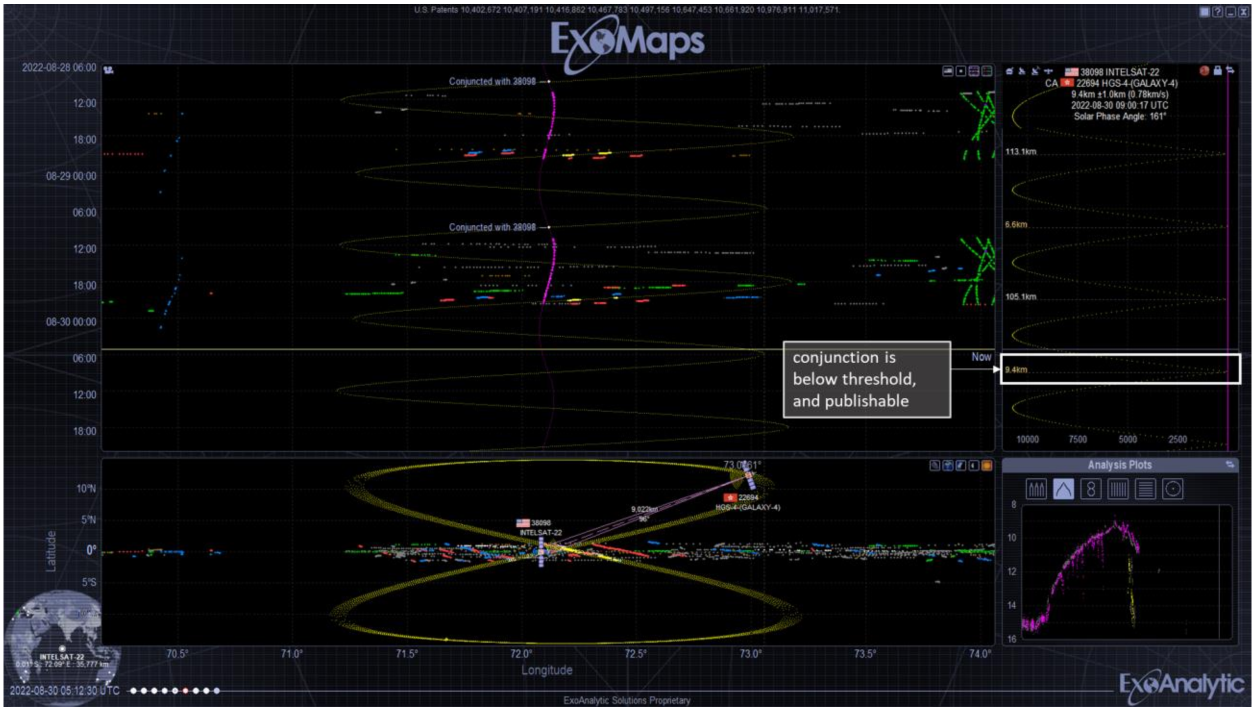


Fig. 10: Analysis of close approach distances between the two objects.

After gaining the insight that both objects have good orbit fits, the analyst decides to examine the close approach distances of the two objects during the period of interest. In Fig. 10, the analyst uses the right-hand pane to display close approach information, which is calculated from the orbits of each object. The analyst then notes that upcoming conjunction is below the selected 10-kilometer threshold, so for our example use case this alert would be reportable.

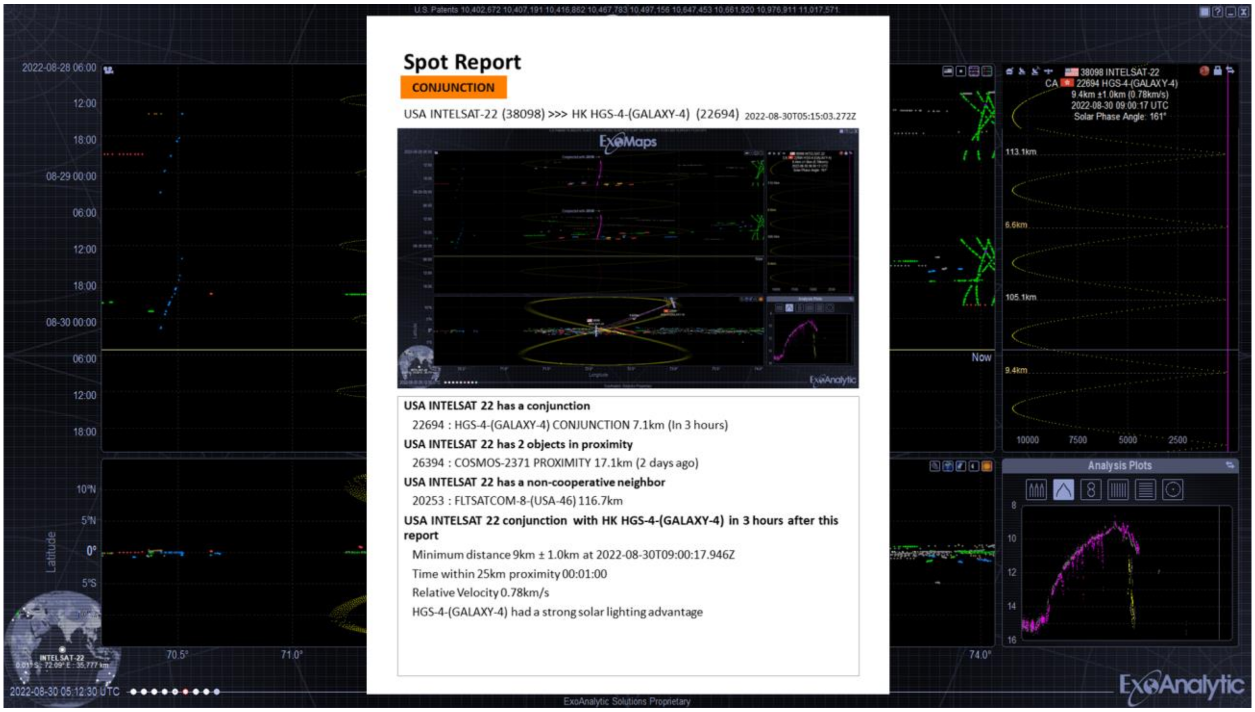


Fig. 11: Spot report of the alert generated by the analyst.

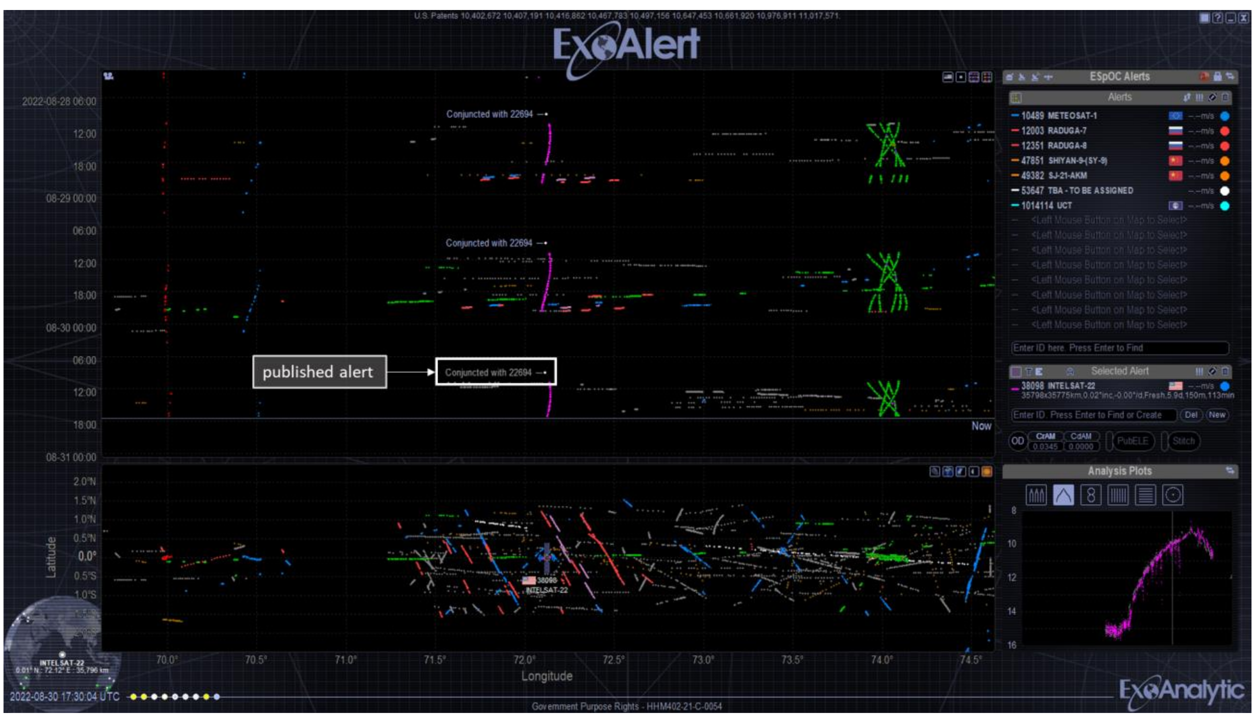


Fig. 12: Final state with curated alert published and incorporated into the historical alert database.

Having made the decision that the alert in this use case meets the reportability requirement, the next action that the analyst will take is to generate a human-readable Spot Report. This is accomplished in a single click (the small MS PowerPoint icon in the upper right) which generates the report shown in Fig. 11. The astrometric details of the alert are presented in summary form in this report. Since the report is generated as a standard MS PowerPoint slide, the analyst can add or remove annotations and details as needed to meet specific customer requirements.

Lastly, in Fig. 12, we show a screenshot from several hours later. The published alert has been incorporated into the historical database of events, and the annotation of that conjunction (as well as the other recent conjunctions between the two objects) can be seen in the ExoMaps main window. The machine-readable version of the alert that is stored in the historical database contains the same information as the human-readable Spot Report, but to more degrees of precision and with additional information such as the estimated orbit states of any objects mentioned in the report.

## 4. CONCLUSIONS

The ExoALERT system has been in development since 2017 and operating with consistent analyst feedback since 2021. The overall system design philosophy is to have automation enable human analyst expertise, and for the human analyst to be engaged and empowered. The automated alerts are used to cue a human analyst, and the system is designed so that the most common analyst tasks related to alert evaluation and publishing are as easy as possible to accomplish. The analyst can focus on developing relevant insights about behavior of space objects, instead of wrestling with a challenging user interface.

Feedback from analysts using the human-machine integrated workflow has enabled us to improve our algorithms and reduce the overall number of alerts presented to the user while maintaining a very low rate of missed events of interest. As a snapshot of this improvement, comparing a 4-day period in October 2021 with a 4-day period in August 2022, after significant improvements, the number of alerts presented per hour to the analyst was reduced from 60 to 40 with no loss of performance in terms of missed events.

Future ExoALERT development efforts will include improvements to the overall infrastructure supporting our commercial SSA and STM products and services, as well as improvements to the front-end analyst interface. As the cadence of commercially provided STM services increases, the cadre of analysts using the ExoALERT system will increase, which will provide additional insights to guide improvements.

## 5. REFERENCES

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