Autonomous Object Characterization with Large Datasets

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Timely and effective space object (SO) characterization is a challenge, and requires advanced data processing techniques. Detection and identification of signature changes due to potential SO changes (e.g., stability, material aging) is a critical capability that is growing in importance. Unfortunately, better knowledge of more objects requires an infeasible investment of current technologies, or a change in collection methodology. A combination of large datasets and simulation technologies can help. Space object stability, methods for space object correlation, and material characterization are a few of the techniques explored via a combination of simulations and large datasets. This paper describes an approach for automating characterization techniques for SOs using large photometric datasets from the ExoAnalytic Solutions small telescope network.

1. INTRODUCTION

There is no shortage of research on photometry-based space object characterization, including size, shape [1,2], orientation, motion, and material estimation [3,4]. Ascertaining these characteristics may enable an analyst to understand the higher level attributes of a space object, like capability, current activities and events, to ultimately infer spacecraft mission. This information is important for both monitoring the health and status [5] of vital assets as well as awareness (indications and warnings) of threats, both natural and man-made. While most research in photometry-based space object characterization provides high utility, it comes at a relatively high resource cost. Sensor collections either cause an impact to day-to-day tasking or the data must be obtained over a long period of time to obtain data sufficient for a solution. The real impact is realized at the analyst's desk, where a substantial amount of effort is required to transform raw photometry into a data product, minimizing the amount of time the analyst has to study the results of the products. Building a capability to autonomously run these algorithms, both persistently and on-demand will be required as more objects are launched, debris is generated, and in general access to space continues to be proliferated. Persistent characterization tasking for all space objects is likely not supported by sensor resources, thereby identifying a need for a robust algorithm management process. In support of an Air Force Research Laboratory (AFRL) Space Object Characterization initiative titled "Autonomous Characterization Algorithms for Change Detection and Correlation (ACDC)," ExoAnalytic Solutions seeks to identify a general object characterization and state change detection process, as seen in **Error! Reference source not found.**. Although there have been diverse prior efforts to build photometric characterization algorithms, there have been very few demonstrations of an end to end photometry-algorithm processing chain that is fully integrated with sensors for follow-up tasking; this is the relatively unique contribution of the ACDC capabilities.

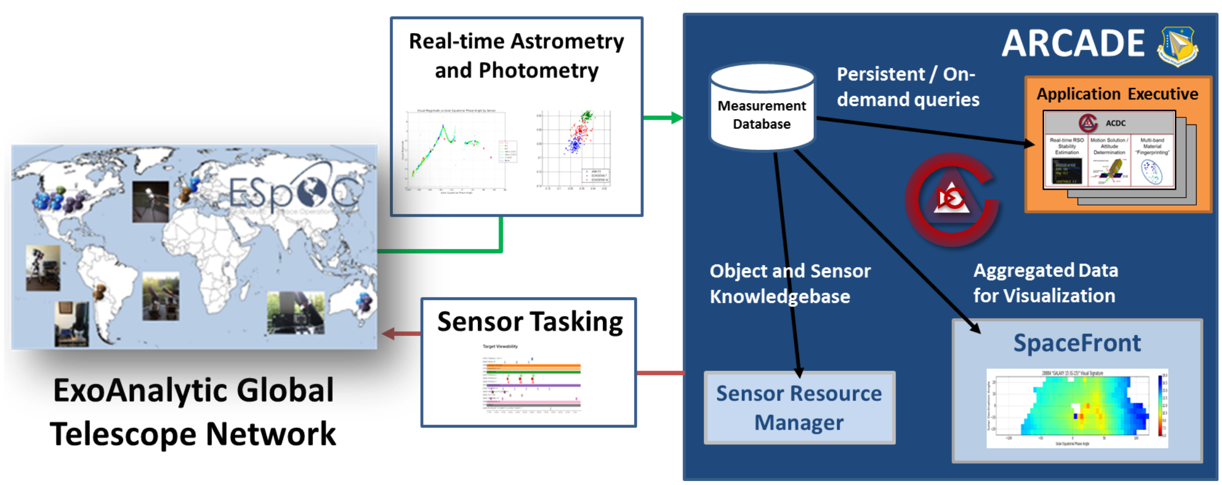


Fig. 1: Automated Characterization and Correlation Process

As shown in **Error! Reference source not found.**, a set of autonomous algorithms and application manager would reside inside the Advanced Research, Collaboration, and Application Development Environment (ARCADE) hosted by the AFRL. ARCADE was established in 2012 as a centralized test-bed for all research and development activities related to new Joint Space Operations Center (JSpOC) Mission System (JMS) applications: algorithm development, data source exposure, service orchestration, and software services. In addition to providing JMS with a modern test-bed environment, ARCADE is exploring new business processes for how the U.S. acquires and upgrades its operational information systems [6]. AFRL funded ExoAnalytic through the SBIR program to develop space object characterization and change detection algorithms with the intent to mature this technology through the ARCADE-to JMS-transition process. With a transition process in place for developing and maturing the technology, a sufficient data source is also needed to determine the robustness of algorithms also under development in the ARCADE. While supporting the ARCADE, the ExoAnalytic Global Telescope Network (EGTN) can provide data for algorithm maturation.

Observations collected by the ExoAnalytic Solutions Global Telescope Network (EGTN) are autonomously processed into astrometric and photometric data and stored in a measurement database. The goal is to develop an autonomous process for mining the astrometric and photometric data to characterize and detect state changes for Earth-orbiting space objects. In developing an automated process infrastructure, three algorithms were used to explore concepts in satellite characterization and satellite state change.

The first algorithm provides real-time stability estimation (RTSE), which would enable a user to be notified when an object's stability changes from a hypothesized mode. This algorithm can be run persistently on all objects observed without the need for unique tasking (i.e., serendipitous with astrometric collections).

Another set of algorithms estimate orientation and motion (not described in detail in this paper), and can be called on-demand. These algorithms would be called once an object's stability changed or signature is no longer consistent with historical statistics for that object. Then the object is prioritized and tasks are generated for the sensor network.

Finally, the Material Characterization Algorithm (MCA) enables the analyst to determine possible material makeup of a space object as well as support object correlation. This algorithm utilizes multiple optical bands, and was adapted specifically to utilize visible (color) bands, although the original algorithm estimates multiple object features by incorporating any number of infrared bands. This algorithm can be run both persistently and on-demand, as it can run in real-time.

Utilizing these algorithms in a general object characterization framework, space objects can be characterized in an efficient manner, providing both temporal and quality improvements to an overall user decision cycle. Note that many other algorithms, such as maneuver detection and estimation, could be incorporated into this architecture. The current focus is the signature-based algorithm suite described above.

Since the ExoAnalytic Telescope Network spans the earth in coverage of the GEO belt with no gaps, the ability to provide data on GEO objects is straight forward. The nightly operation for every sensor in the network is customizable and dynamically allocated. Sensors can be dedicated to broad tasks like GEO search, full-sky search and client-focused revisit. This mix of sensor operations provides a robust and highly adaptable opportunity to obtain ample data on all GEO events. With this architecture CONOPS, the ETGN can collect data on high interest and new launch GEO objects without any specific feedback loop. While the EGTN has coverage of other orbit regimes, the emphasis of this automated characterization and state change detection software architecture is primarily on objects near the geosynchronous orbit regime.

2. APPROACH

Fig. 2 shows within the context of a scenario or vignette, the logic and flow to obtain the knowledge needed to maintain sufficient awareness, enabling future tasking, intelligence, or courses of action (COAs). The importance of this graphic is to communicate the potential events that may trigger each of the algorithms being run by the Algorithm Manager, a software application that orchestrates algorithm flows based on available information. There are multiple event types that are envisioned to prompt one of the algorithms. Since RTSE is run persistently, it may be assumed to always be running on SO data as it comes into the database. Algorithms could be initiated 1) if RTSE detects a persistent change to the stability of an object, 2) an SO's signature is significantly deviated from its statistical history, to include regard for seasonal effects[3], 3) if a new SO is detected, or 4) a GEO New Launch is announced. If sufficient data is not available, the Algorithm Manager will generate tasking messages to acquire data necessary to perform characterization and change detection.

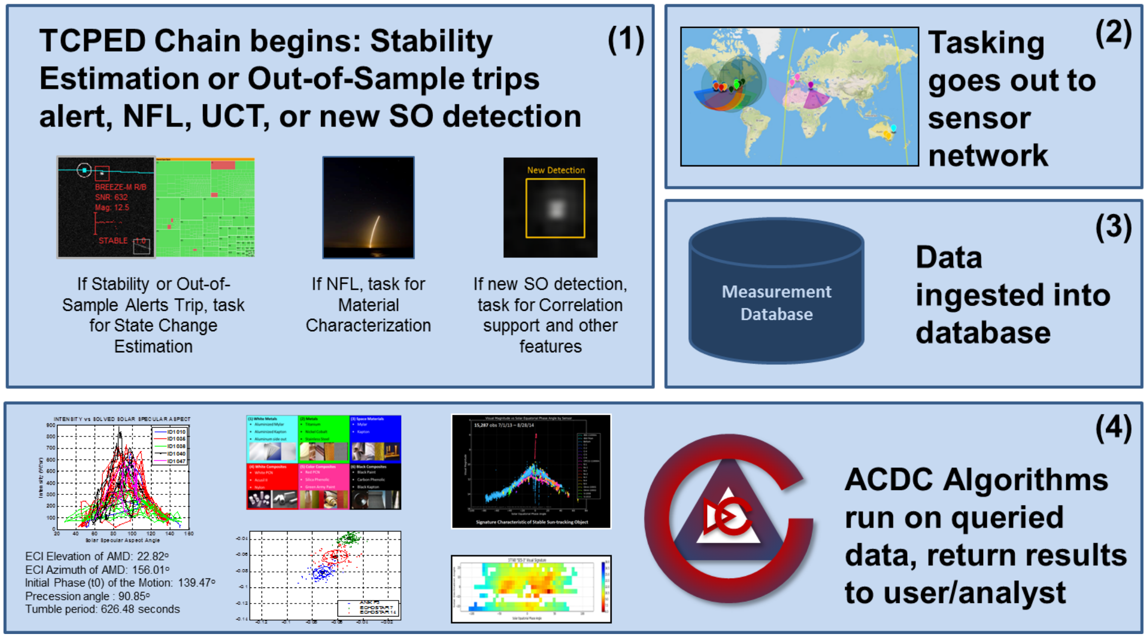


Fig. 2: Logic and Data Chain for Vignette Processing with ACDC Algorithms

Once the astrometric and photometric data is collected, it is stored in a database that is accessible by the Algorithm Manager. This data is also made available to the data-visualization application, SpaceFront, so an analyst can evaluate the photometric (or astrometric) data directly. The algorithm products will also be returned to the database and be available for visualization/reporting within the SpaceFront application.

Understanding of the phases of life of a spacecraft is crucial to interpreting the data from various algorithms. Each state change detected and characterized reflects a real event experienced at the spacecraft. The events that may cause observed state changes, and the algorithms and tools that provide those estimates for space objects, are shown in Table 1. Note, there are necessary capabilities to address the Event/States of interest that are not the focus of this paper, but are addressed by other applications within the ARCADE test-beds.

Table 1: Spacecraft Phases of Life - Attribute Mapping

Event/State	Orbit Regime	Attributes Determined	Algorithm/Tool
Launch	Launch	Addressed by other tools	Addressed by other tools
Spacecraft Separation	Launch/transfer	Stability, Size, Bus Pointing, Object Type	RTSE, Orientation/Motion, Material Characterization
TT&C Antenna Deployment	transfer	Stability, Size, Bus Pointing, Object Type	RTSE, Orientation/Motion, Material Characterization
Solar Panel Deployment	transfer/operational orbit	Stability, Deployment Confirmation	RTSE, Material Characterization
Payload Deployment	operational orbit	Stability, Deployment Confirmation	RTSE, Material Characterization
In-Orbit Test	operational orbit	Stability, Payload Pointing, Payload Type	RTSE, Orientation/Motion, Material Characterization
Operational Declaration	operational orbit	Stability, Payload Pointing, Payload Type	RTSE, Orientation/Motion, Material Characterization
Anomaly	operational orbit	Stability, Payload Pointing, Payload Type	RTSE, Orientation/Motion, Material Characterization
Station Change	operational orbit +/- specified distance	Stability, Payload Pointing, Payload Type	RTSE, Orientation/Motion, Material Characterization

On-Orbit Spare	operational orbit	Stability, Payload Pointing, Payload Type	RTSE, Orientation/Motion, Material Characterization
Deorbit	graveyard/disposal orbit/re-entry	Stability	RTSE

Each SO currently on orbit possesses specific traits and operates in a manner consistent with its mission. These operational characteristics reflect an operational mode or state, which can be inferred through estimation of the attributes named in Table 1. Determining the current state or mode of objects may require apriori information, either through traditional astrometric or radiometric observations or other data sources (e.g., open-source literature, direct communication with spacecraft operators). Once the states of the objects have been estimated, the focus for each object becomes state change detection. The next section details the first set of algorithms that have been considered for an automated characterization and state change detection architecture.

3. OBJECT STABILITY

Two methods for state change detection were briefly explored: real-time stability estimation and data-driven state change detection. A real-time capability that requires little or no apriori knowledge is important when new objects are detected. The data-driven state change detection approach has proven to be a strong source of insight, and could enable near-real time capability if designed properly. Monitoring behavior of space objects through the photometric response can enable higher level reasoning algorithms, to develop a threat indication or warning. State changes alone may not be sufficient to drive courses of action, but instead trigger other products to be generated that can be fused to provide an assessment. The capability to discover payloads and their orientation relative to the spacecraft bus, particularly at GEO, is significant. If this can be performed reliably, then this information can be combined with the material likelihood estimate to infer possible payload types (and CONOPS).

3.1. Real-Time Stability Estimation (RTSE)

The Real-Time Stability Estimation (RTSE) algorithm has been implemented to first order as a trigger to other algorithms. The algorithm operates as described below in text and Fig. 3:

1) An object is detected (unassociated detection)
2) With multiple observations, a track is established
3) After the track is established, the algorithm begins to establish enough data to estimate stability
4) If stability can be determined with some confidence, it is compared to the hypothesis
    a. If the object matches its stability hypothesis, the software reports the stability confidence and indicates this visually to the user in green
    b. If the object does not match its stability hypothesis, the software reports the stability confidence and indicates this visually to the user in red. This may be used to trigger other algorithms.

Yellow text indicates data does not yet exist to make a stability determination with sufficient confidence.

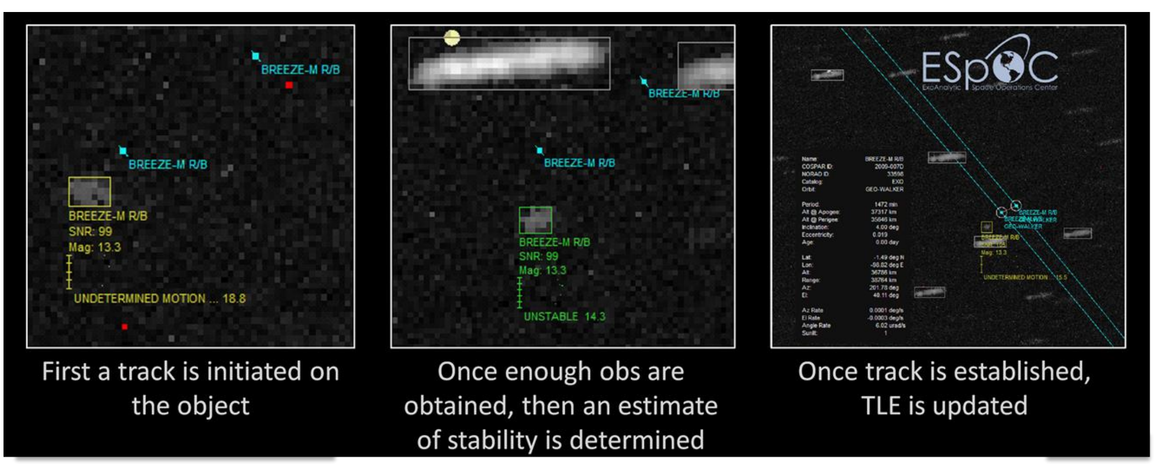


Fig. 3: Real-Time Stability Estimation Algorithm Process

Again, while objects may be reported as "anomalous" because they do not match their stability hypothesis, there may not be immediate need for concern. This is a trigger to other algorithms to perform more detailed characterization of the orientation and motion. Since a number of factors can influence the stability estimation algorithm (atmosphere, weather, platform instability, etc.), it is likely not an appropriate trigger for an indication or warning. Additionally, hypotheses can be customizable for objects or classes of objects. For geosynchronous SOs, a simple hypothesis can be set based on their semi-major axis and eccentricity (as shown in Fig. 4). Other orbits known to be an "operational orbit," such as the orbit of the GPS constellation could be hypothesized as an area where objects may exhibit "stable" signatures. This is a simple approach with relatively sparse data on individual objects, but a more sophisticated approach could incorporate historical data on a per-object basis.

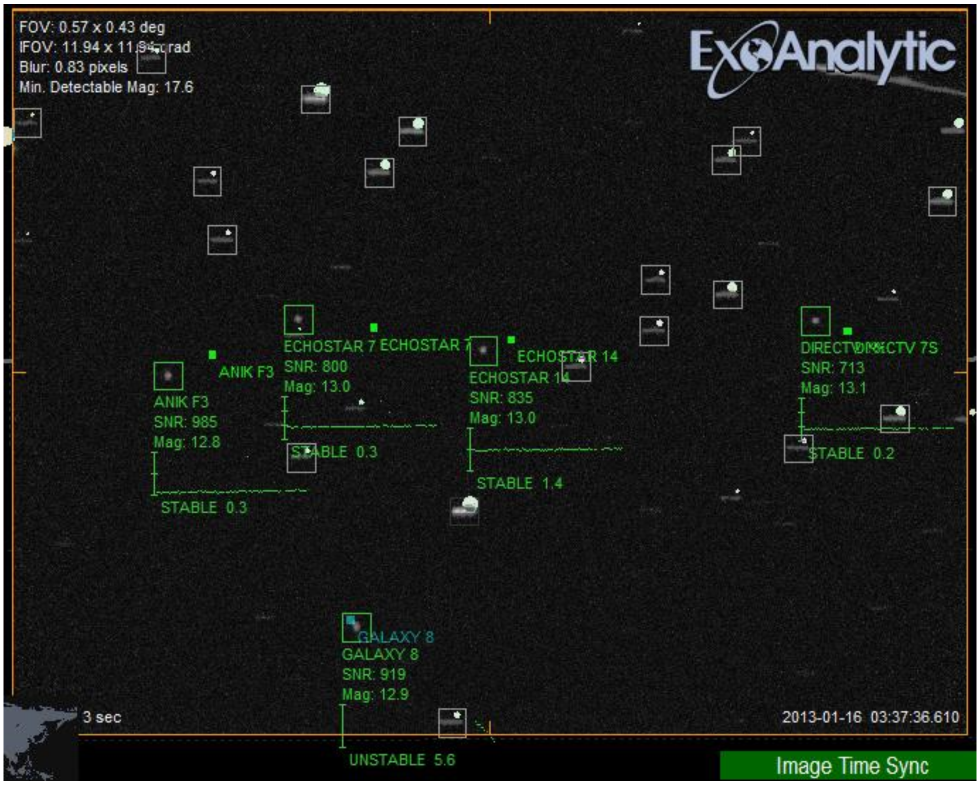


Fig. 4: GEO SOs Matching Orbit-Based Hypothesis

4. ORIENTATION

4.1. Orientation Change Dashboard

During this research effort, a dashboard view within the ExoAnalytic Solutions SpaceFront software was developed to maintain awareness of important assets by studying how closely their signatures compared to historical collections. A market map approach is useful to see the "state of the world" for a particular issue[8], as commonly used to analyze macroeconomic trends (and investment portfolios) in the stock market [7]. As shown in Fig. 6, this view bins the spacecraft by country or operator, then indicates the importance of investment by making the box size proportional to the launch epoch (newer objects are typically more capable, and represent a bigger investment than older spacecraft). This is a surrogate for the actual contribution that each spacecraft plays within its mission, and ultimately to its owners. The color of each box indicates how closely the signatures match the historical data. If the data is well outside the 10^{th} and 90^{th} percentile values for that given solar phase angle (solar equatorial *and* declination phase), then the box is red. If the photometric measurements lie within the 10^{th} and 90^{th} percentiles, and outside the inner quartiles (25^{th} and 75^{th}), then the box is yellow. Finally, if it lies between the 25^{th} and 75^{th} percentile values for that spacecraft for that solar phase angle, then the box is green.

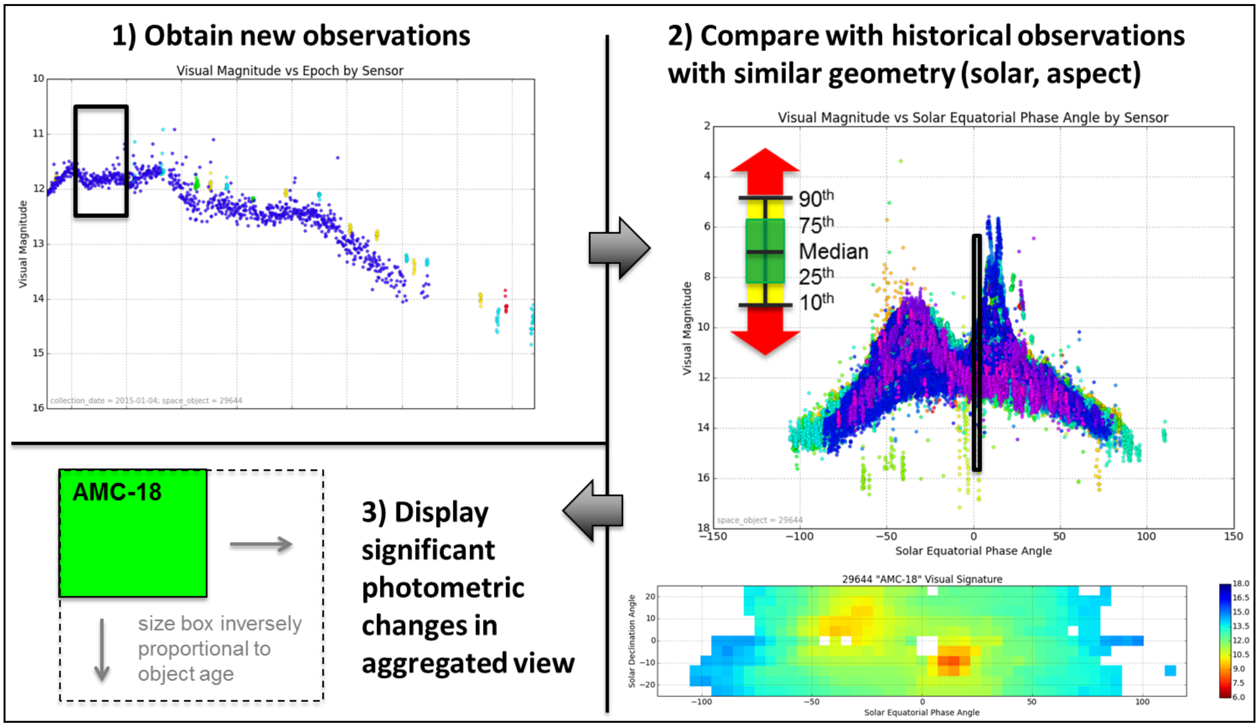


Fig. 5: Signature Change Detection Process

Each box is then shown in context with all other observed spacecraft in the market map view, as seen in Fig. 6.

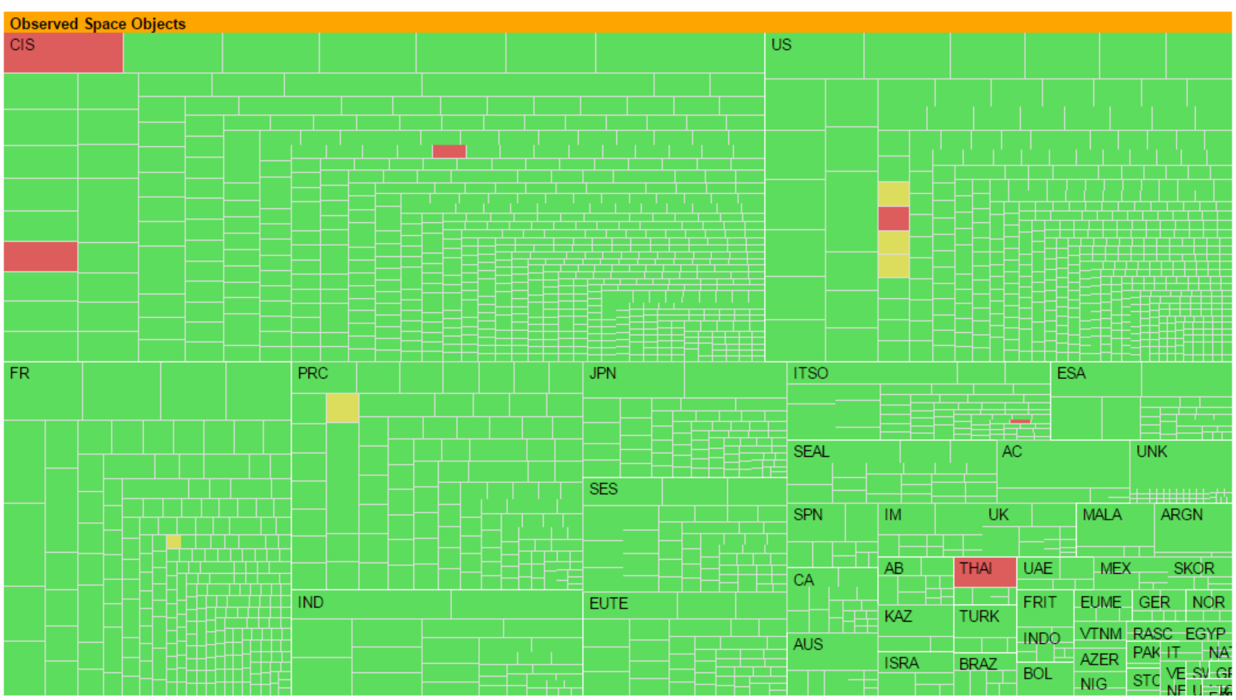


Fig. 6: Notional Anomaly Dashboard

The figure shown is a sample Photometric Change Detection Dashboard. It is reasonable (based on the last few months of use) that photometric anomalies will show up on very recent new launches. This is because there is relatively little data that comprises the foundational data for comparison. A hypothesis surrogate could be put in place to avoid false alarms, but very recent launches are, in all likelihood, worth drawing high interest during launch, initial orbit insertion, and transfer orbit. Now that the code is written to ingest the data, we can quickly visualize state change detection across an entire fleet of active payloads in a single view. This is extremely powerful, allowing a JMS decision maker to quickly understand the state of all objects at a glance, and to know where to focus attention. This view also provides the opportunity to understand if there are systemic issues across a particular set of objects, which may indicate a region of environmental disturbance or a coordinated adversarial action. Within the software architecture, the goal is to use a change detection tool to trigger additional algorithms to run in the event space objects exhibit out-of-sample photometric responses. This alone, similar to the RTSE algorithm, may not be enough to warrant an indication or warning message, but it will provide a mechanism for performing more rigorous analysis of the issue.

4.2. Spacecraft Fingerprint Plots

For GEO 3-axis stabilized spacecraft that have sun-tracking solar panels, the "fingerprint" plot generally should have a hot spot centered around (0,0), and gradually drop off as the solar phase angle moves away from zero[3]. Notice there is typically data missing near (0,0) – this is because when the solar equatorial and declination phase angles are near zero, the earth is shadowing the target. This could be overcome by observations made from a space-based asset, or using another waveband, such as MWIR or LWIR. Also note that to complete the "fingerprint" plot, observations need to be made at several points during the night (to cover solar equatorial phase), as well as over the course of a year (to cover solar declination phase). Even if there are several tiles of data missing from the fingerprint, it can still be useful to examine trends for both a single space object and a particular group of space objects. One such example is illustrated in Fig. 7, which is a snapshot on December 10, 2014. The important features of the fingerprints are the trends, particularly from the A2100 bus spacecraft. There is a signature peak near (0,0), as expected from the solar panels, but there is a secondary peak around (-35, 10) for all 4 spacecraft. This unique signature may be due to the comm payload or an additional glint from solar panels that are off-pointed from the sun[3], but without observing throughout the year, it would be difficult to fully realize this trend.

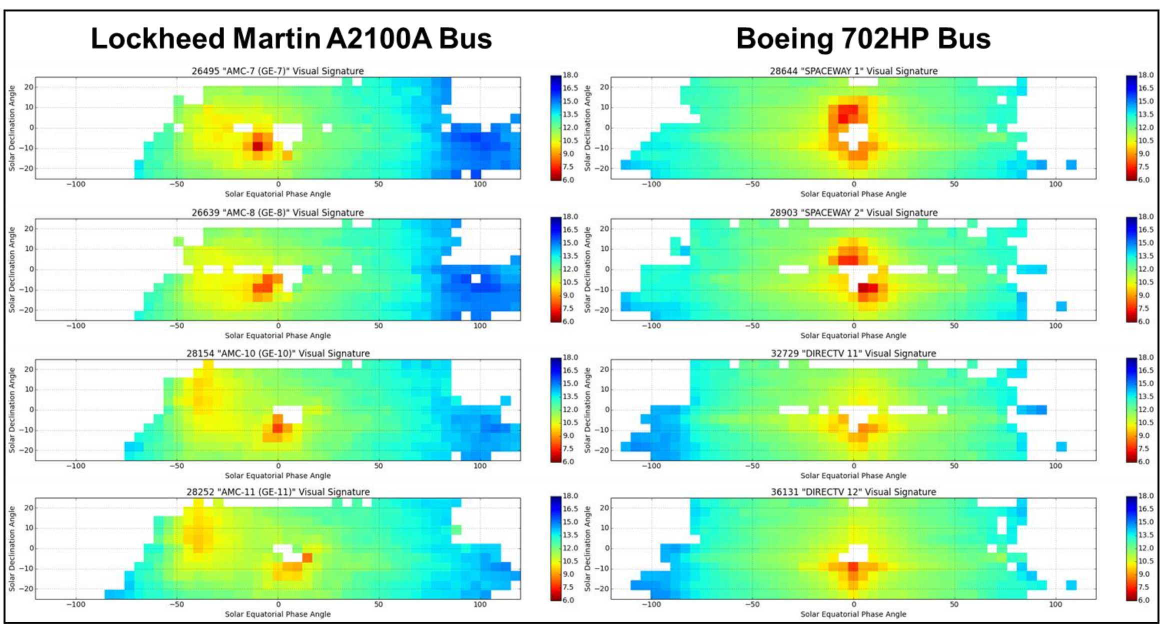


Fig. 7: GEO Spacecraft Product Line Comparisons (as of 12/10/2014)

The fingerprint plots are useful for several reasons, but fundamentally they provide the foundation for detecting state changes. With a fully-populated fingerprint plot, there is a historical basis on each space object that states can be compared to on a temporal basis. In the next subsection, a method for using the fingerprint data to estimate state change is described.

4.3. Orientation and Motion Estimation

With the introduction of the Phase Angle Bisector (PAB) plots and a multitude of data to analyze each one, there is an opportunity to learn information about each spacecraft, and infer similarities across spacecraft. The utility of identifying specific faces of the spacecraft and their pointing temporally is also valuable for state change detection. Fig. 8 is the Phase Angle Bisector plot for AMC-15, incorporating over 185,000 observations. For reference, pasted in the foreground of the plot is an artist rendering of the AMC-15 spacecraft, oriented with solar panels facing north/south as it is operationally. The comm reflector appears to be the source of the glint seen in the plot, but further analysis with facet models may help prove or disprove this hypothesis.

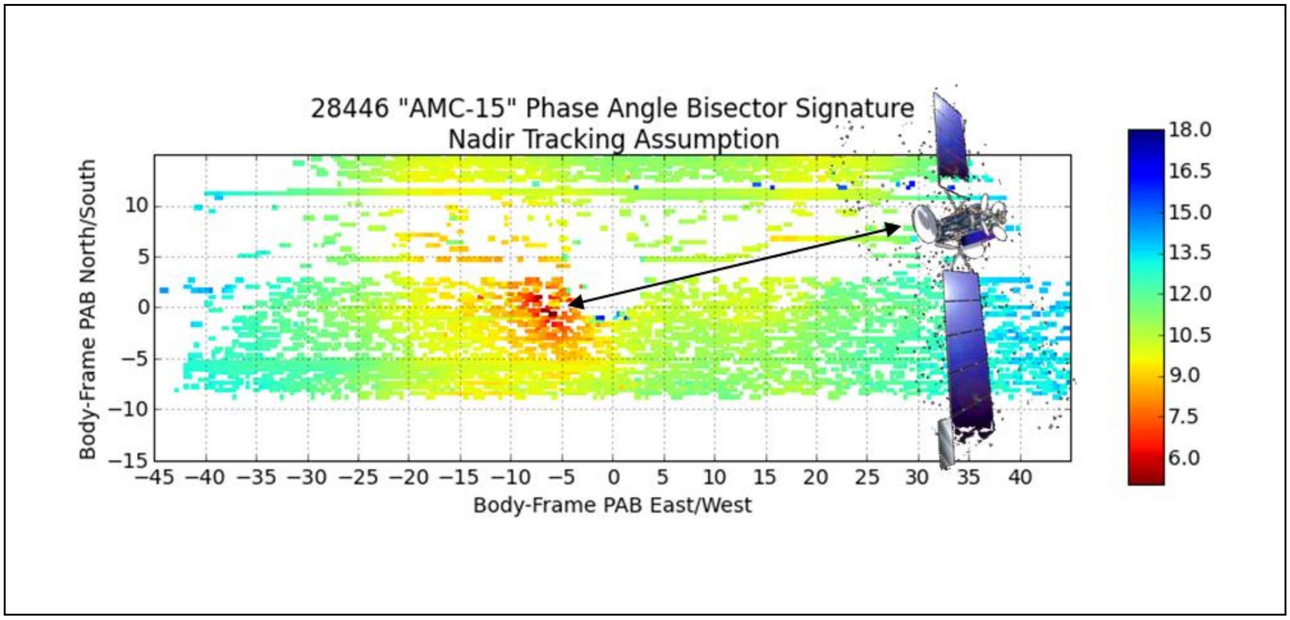


Fig. 8: AMC-15 Phase Angle Bisector and Image

With this example, the ability to attribute the source of non-solar panel glints will be studied with actual data from the EGTN during later efforts. For recently launched objects and other objects with sparse data sets, real data aided by facet-model signature matching approaches will be conducted to identify more advanced techniques with limited data.

5. MATERIAL CHARACTERIZATION

5.1. Correlation and Material Characterization of SOs

Under this effort, multi-band signatures were analyzed for material characterization and object correlation research. Although there have been a few studies previously, notably Ref.[4], the value of multi-color observations in spacecraft characterization is still relatively unknown due primarily to a lack of multi-color data. In these investigations, photometric observations were obtained with a color camera system on multiple spacecraft over multiple nights. These observations were correlated to GEO SOs from space-track's catalog. Once the position and velocity of the SOs were estimated, the same conditions were simulated for materials from the Optical Signatures Code (OSC) database. The estimated intensity ratios for each SO were analyzed. Taking each 3-band signature set, normalizing to unity, and plotting on a three axis plot can enable an analyst to see if there is significant separation among targets. Separately, the simulated signature ratios for all materials are shown in Fig. 10. In Fig. 10, each dot represents a material from the Optical Signatures Code (OSC) database. Individual dots are different materials, but all signatures are generated with the same conditions: shape, observer/solar geometry, and observation band (in this case, red, green and blue). The color coding in Fig. 9 represents the various classes of materials: white metals, metals, space materials, white composites, color composites, and black composites. These are summarized visually in Fig. 9, where the number in each box (top left) corresponds to the class number in legend of Fig. 10.

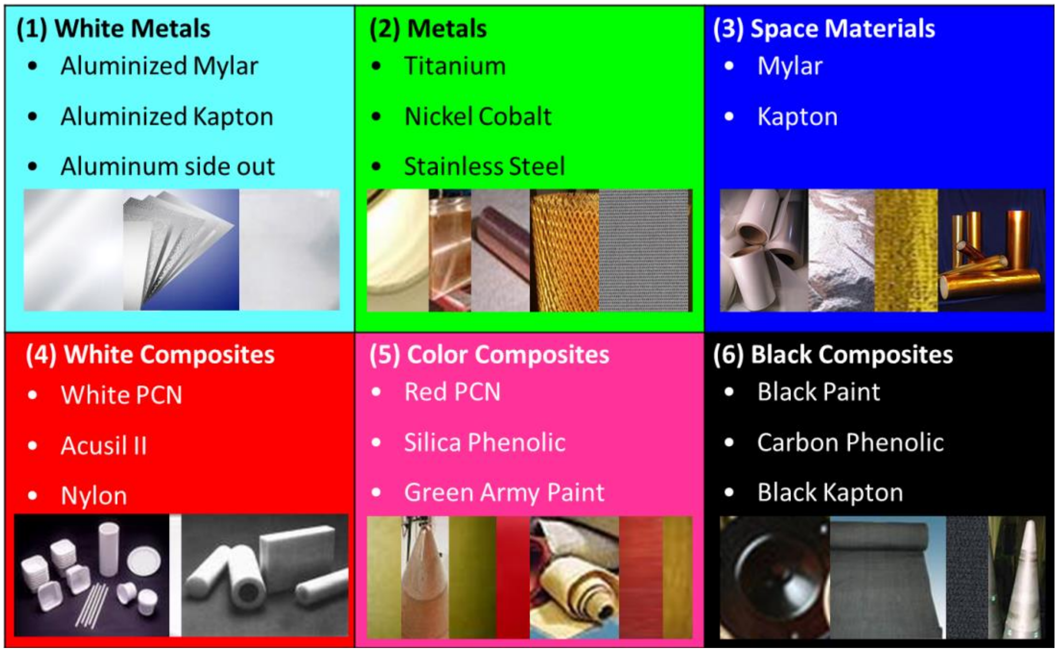


Fig. 9: Material Classes in OSC Database

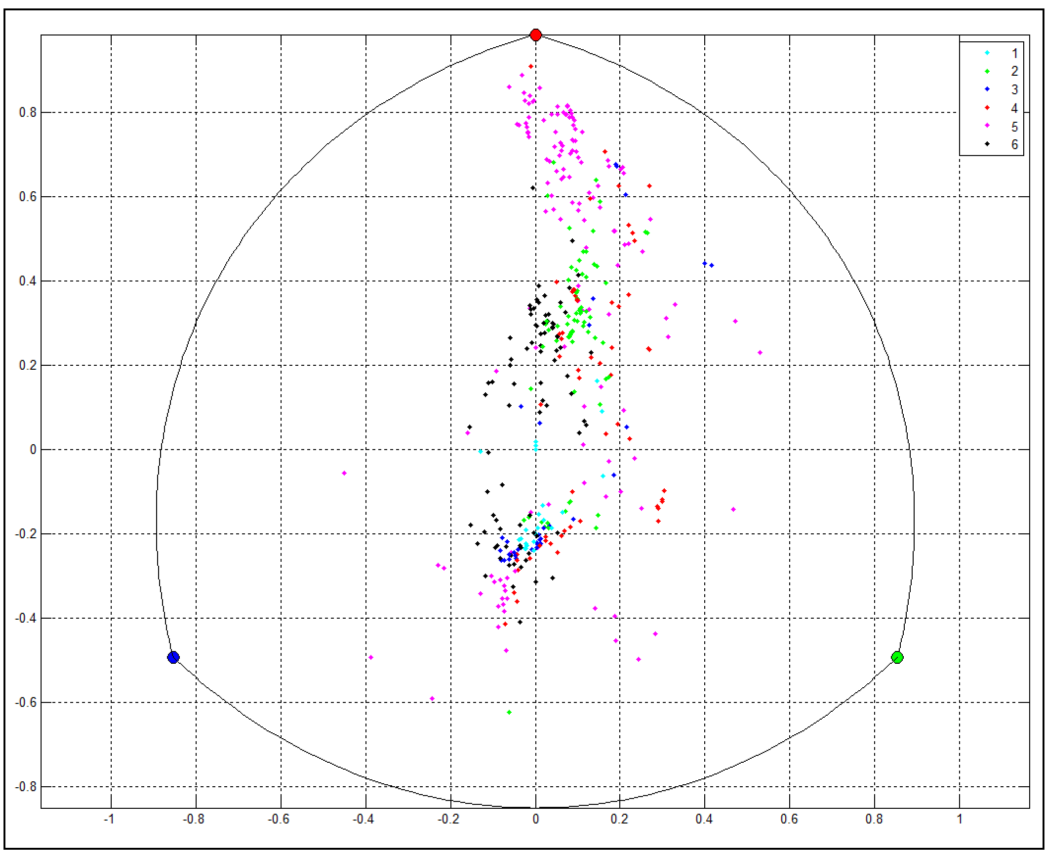


Fig. 10: Simulated RGB Signature Ratios of Materials from OSC Database

This plot shows the separation of material in the *visible* bands used here, but as can be seen from the plot in Fig. 10, there is some appreciable separation of materials. It is interesting to note that the metals (e.g., titanium and steel) tend to stay together in this plot (indicated in green and cyan), where there are a couple groupings for color composites. That is simply due to the fact that it depends on the color painted on the composite as to where it will land in RGB space.

Placing real observations over simulated materials provides an interesting context to the data. This is where an assertion of the material properties may or may not be made. As shown in Fig. 11, unresolved measurements of the GEO SOs overlap significantly in band ratio space with multiple materials (not surprising given the complexity of spacecraft composition), but it does allow the analyst to rule out several types of materials from likely for exterior components of spacecraft. Note that Fig. 11 has the top and right vertices switched from the simulated intensities in Fig. 10.

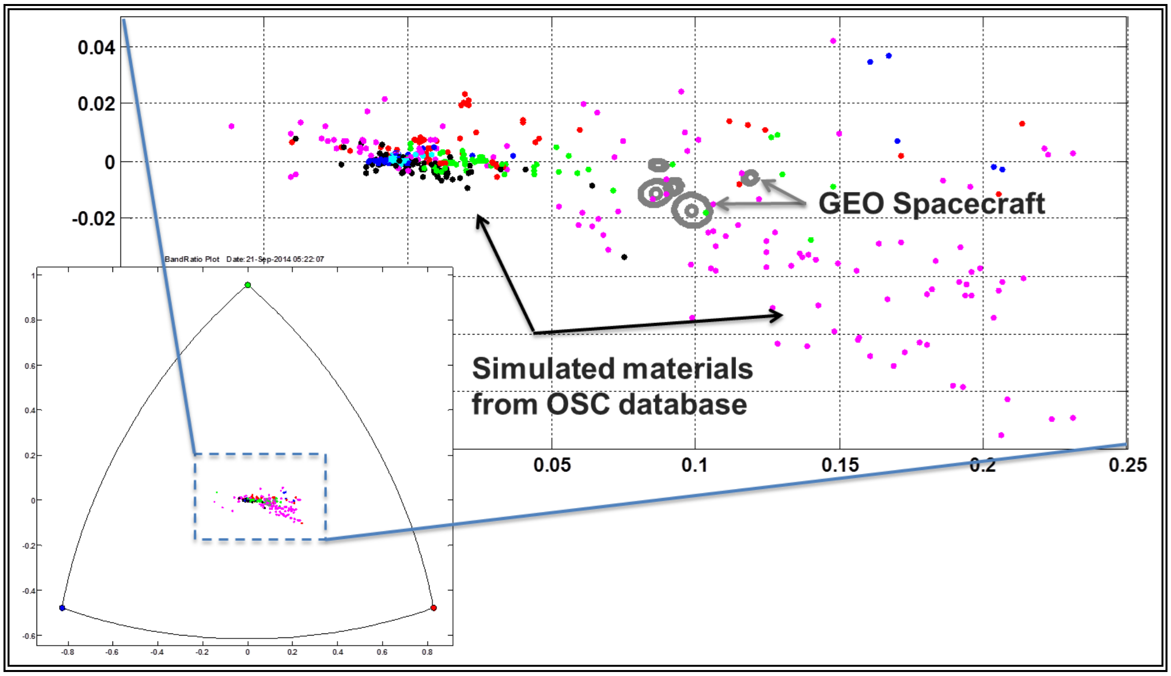


Fig. 11: Real and Simulated Signatures for Material Characterization

The next section shows actual RGB observations in a similar plot, but zoomed in. Additionally, the measurements are astrometrically correlated to individual objects, and the mean and covariance of the measurements are calculated and the 1-σ error ellipse is drawn with the mean indicated by the larger dots.

5.1.1. Analysis of "Neighborhood" Observations

Critical to understanding the results of the Material Characterization Algorithm (MCA) is to first understand the underlying data. Data was gathered on VIASAT-1, XM-4 and XM-1 (or neighborhood 1), ECHOSTAR 17, ANIK G1, ANIK F1-R, and ANIK F1 (neighborhood 2), and Fig. 12 shows band ratio data gathered on ANIK F3, ECHOSTAR 7, and ECHOSTAR 14 (neighborhood 3). This data is color coded by astrometric correlation to an object (not to a material class), and does not using any photometry to aid in correct correlation of the SOs. All of the neighborhood data shows similar results – there are trends that can be used to aid in object correlation. ANIK F3, ECHOSTAR 7, and ECHOSTAR 14 all have mean values that are sufficiently far away from the others to indicate they are separate objects. The measurements on Sept 22 indicate there was a cross-tag with the sensor correlator for ANIK F3. Visually, the cross-tag is conspicuous from the plot— but developing the automated techniques to utilize this information will take require additional research and development. Still, it is encouraging to observe objects that are near each other that can easily be distinguished from each other with a low-cost system and straightforward algorithm.

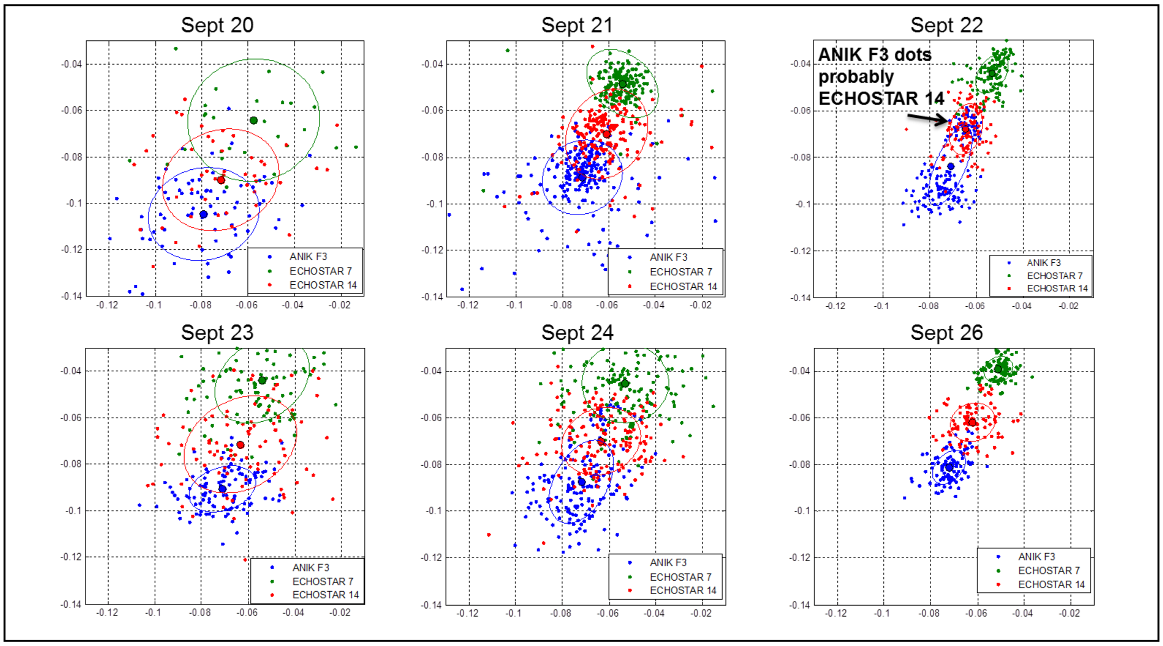


Fig. 12: Neighborhood 3 Band Ratio Plots

In future efforts, MCA can be run to determine the object material composition. Likelihood of material for every database entry will be output from MCA. The likelihood output, rather than a single material estimate, will be useful since most spacecraft are not comprised of a single material.

The band ratio information will be utilized within the automated change detection and correlation architecture in a similar way to the Signature Change Detection Dashboard will be used, with one key difference. Once large quantities of band ratio data exist for space objects, "anomalous" or out-of-sample band ratios can be used to trigger other algorithms to be run (such as a full material characterization algorithm).

5.2. Object Correlation Aid

This effort examined how the band ratio measurements (and other ACDC algorithms) could be used to aid correlation of space objects. Fig. 13 illustrates the methodology that could be used in object correlation, pointing out which techniques are capabilities of AFRL, ExoAnalytic, and specific to this SBIR effort (denoted by "ACDC"). Other techniques may exist, and could certainly be used as well in ARCADE and later within JMS as appropriate.

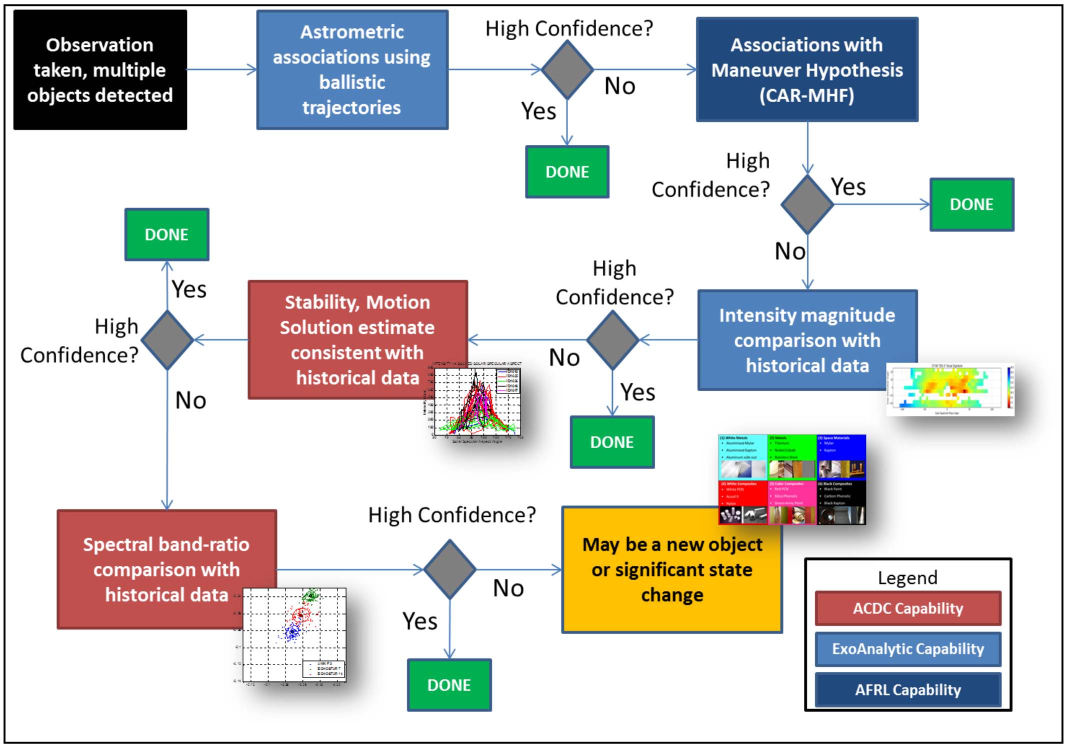


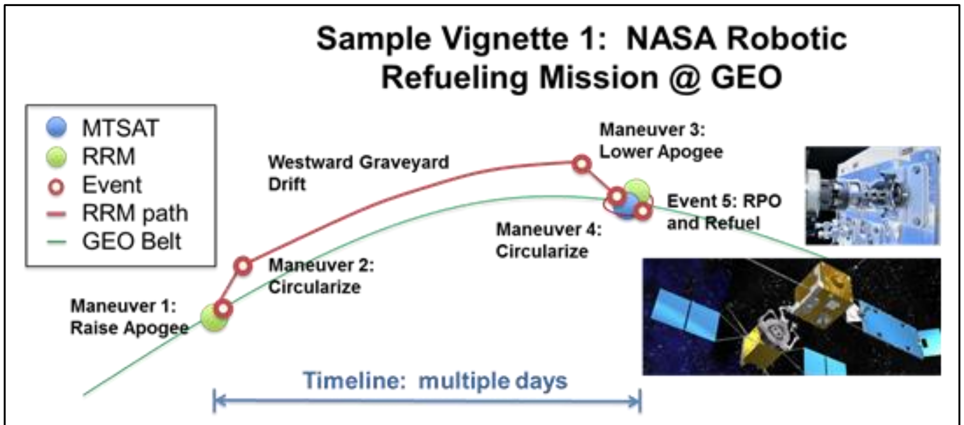
Fig. 13: ACDC Correlation Aid Methodology

The general goal of "feature-aided" object correlation is to correlate the SO with high confidence while minimizing the resources expended to provide the high confidence correlation. Since astrometric measurements are foundational for a track to be generated, these are used first. Implementing AFRL's CAR-MHF (Constrained Admissible Region Multi-Hypothesis Filter)[10] to account for maneuvers would be the next step in the chain before utilizing photometric observations. If the correlation is not returned with high confidence after these techniques, then compare all monochromatic brightness-magnitudes of the detections to the hypothesized SOs brightness magnitude history in the tasked "neighborhood." It is imperative to pull historical measurements that are coincident in solar-equatorial phase and solar-declination phase angles, which requires an extensive collection on the SOs of interest through at least a solstice and an equinox. If this technique does not return a high confidence correlation, then an orientation estimate compared to historical solutions for SOs in the neighborhood may be the next step. This may require more data than the final step, thus analyzing the band ratios on multi-band data may be faster if those sensors are available for collections. Comparison of band ratios to previous data would be the next technique in the chain. If this method does not bear a high confidence solution, then the object may be an entirely new object (or an object that had been previously lost from the catalog). If that is the case, then developing a brand new track on the object using Initial Orbit Determination techniques is required, and characterization the object's features (size, shape, orientation, motion, and material composition) is needed to maintain sufficient awareness.

6. SAMPLE SCENARIO

In any Space Situational Awareness scenario, the goal is to maintain awareness of space objects, and provide indicators and warning in regards to any capability that may pose a risk to those objects. During this research, sample vignettes were created to illustrate the use cases for algorithms developed under this SBIR effort. Each vignette contained a series of events, each of which has space objects with a defined state relevant to the algorithms. Based on the events and space objects, a list of observable features (specifically EO/IR-obtained features for this effort, but RF features could also be identified) were defined. Each algorithm in this framework is designed to determine attributes about a spacecraft based on the features that are observable. For example, if a spacecraft reorients, the photometric signature as viewed from a ground-based telescope will likely change. The change in intensity is an observable feature, which can be used to estimate the object's stability or attitude. The stability and attitude of the spacecraft are attributes about the spacecraft that an operator can use to guide their courses of action. The Real-Time Stability Estimation (RTSE) algorithm is designed to quickly estimate the stability of an object, which enables an analyst (or automated Algorithm Manager) to make decisions on future sensor tasking, call a spacecraft operator, or pursue another course of action. The change in photometric intensity alone is not actionable information, but a high confidence detection of change in operations would be. Through these vignettes, it can be understood when and why each of the algorithms would be useful to a JMS user.

The sample vignette described is a NASA refueling mission at GEO, where a NASA spacecraft attempts to rendezvous and dock with a spacecraft at GEO that has depleted nearly all propulsive fuel. NASA Goddard is actively pursuing the opportunity to take the technology demonstrated in LEO to servicing a GEO spacecraft [8]. The implications of a failed rendezvous could result in impacts to the refueled spacecraft (MTSAT), as well as other spacecraft in the GEO belt. A debris-causing collision could cause damage to neighboring spacecraft, and an incomplete mission may leave a communications spacecraft in a “zombie” state (similar to Galaxy 15 in 2010) that could disrupt operations to neighboring spacecraft. Fig. 14 shows the vignette details, where RRM is the NASA Robotic Refueling Mission spacecraft, and MTSAT (read: “empty sat”) is the spacecraft that is being refueled. There are a series of 5 distinct events, where the RRM moves from its initial GEO longitude to the MTSAT longitude, performs rendezvous and proximity operations (RPO), and ultimately docks with the spacecraft for refueling. In each event, there is a change in observed intensity from a visible or infrared sensor that is caused by the RRM reorienting. There would also likely be a change in spectral response as a function of waveband due to different materials reflecting light to the observer. This feature is referred to as “Δ color response” in Fig. 145.



Event	Description	Attitude/State	Observable / Feature	Attribute
1	RRM maneuvers from GEO Slot, raising apogee	Reorientation to align with velocity vector	Δ intensity, Δ color response	Δ stability during reor Attitudes 1,2 Mat’l fingerprint
2	Circularizes, drifts westward in graveyard	Reorientation to return to nadir pointing	Δ intensity, Δ color response	Δ stability during reor Attitudes 2,3 Mat’l fingerprint
3	Lowers apogee	Reor to align thruster with velocity vector	Δ intensity, Δ color response	Δ stability during reor Attitudes 3,4 Mat’l fingerprint
4	Circularizes at MTSAT	Reor to target pointing	Δ intensity, Δ color response	Δ stability during reor Attitude 4 Mat’l fingerprint
5	RPO with MTSAT	Target Pointing, RRM Docking with MTSAT	Potential CSO, Δ intensity wrt time, Δ color response	CSO detection*, Δ stability during reor RPO attitudes Mat’l fingerprint

Fig. 14: Sample Vignette Overview Chart

In Table 2, the list of attributes that can be determined in the vignette is mapped to the ACDC algorithm that can estimate the attributes. Note that during RPO and docking, there would be a Closely Spaced Object (CSO) event for the observing sensor. Future sensors would need to process focal planes for CSO detections and report them to be available in the ARCADE to enable change detection and warnings.

Table 2: Attribute to Algorithm Mapping for Sample NASA Vignette

Attribute in Sample Vignette	*Algorithm to obtain Attribute*	*Awareness Impact*
Change in Spacecraft Stability	Real-Time Stability Estimator	RRM reorientation cue, possible RRM/MTSAT anomaly
Attitude of Spacecraft	Attitude and Motion Estimation	Attitude consistent (or not) with mission, ability to assess RFI impacts
Material Fingerprint, Material Estimate	Material Characterization Algorithm	Deployment confirmation, correlation aide pre/post RPO (optical CSO)

Understanding the stability of either spacecraft in this example is useful in anticipating future events, and allocating sensor resources for those events. If both spacecraft become unstable during RPO, there is a chance for a debris-causing collision. This would be useful to know in advance, to schedule specific sensors to collect observations to detect a breakup. Understanding the attitude of each spacecraft is critical as well to ensure the safety of the NASA mission as well as anticipating any Radio Frequency Interference (RFI) events associated with anomalous off-nominal pointing. Additionally, determining the material composition of the spacecraft or a material fingerprint can support robust object correlation leading up to, during, and after the RPO events. Material estimates could indicate if pre-rendezvous deployments were successful or not. If there were to be debris generated by a collision, the material estimates of the breakup could be useful in predicting how the debris will propagate (e.g., High Area to Mass Ratio "HAMR" objects), and how detectible they may be going forward.

The described RPO vignette illustrates a specific approach to integrating various algorithmic and data products into a common indications and warning framework, where automation of traditionally manual processes is facilitated. As described in Sec. 1, the unique contribution of the work presented in this paper is that the processes and products are exercised in concert with a demonstrated and independently validated data source that is taskable and can be used for follow-up in a space object ID scenario. Aspects of these vignettes are still under investigation, as on-going work.

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