# Satellite Fingerprints

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**CONFERENCE PAPER**

## 1. ABSTRACT SUMMARY

Techniques for improved characterization of Satellites located at GEO have been an area of research for several years. Many of these approaches show great promise and have been validated using models and simulations. In this paper, a trade study of various characterization techniques for GEO satellites is performed to select one that will be implemented using data obtained from the Space Surveillance Network (SSN). The paper will identify the techniques used to gather data and will detail progress in establishing a fingerprint database. The effectiveness of the SSN data to perform satellite characterization will be explored and recommended changes in sensor tasking and collection will be identified. The paper will discuss the impact of changes in satellite characteristics over the life of an on-orbit asset to the fingerprint database. The selected characterization technique will be evaluated with recommendations for approaches to extend the technique to address more objects in the catalog. The benefits of such a fingerprint database will be discussed, to include re-acquiring objects after a maneuver.

## 2. INTRODUCTION

The Space Surveillance Network (SSN) observations are used to maintain the space catalog. The methods used to identify the observed object rely heavily on the object's position with respect to the object's expected position. This may cause misidentification, resulting in cross tagging objects. Occasionally, objects may not be located because of maneuvers and they are placed on the lost list. These issues are more severe in the geosynchronous orbital (GEO) regime because of the inability for ground based sensors to produced resolved images. Techniques for improved characterizations of satellites at GEO have been an area of research for several years due to issues with the current method of satellite identification.

Research in this area has resulted in several diverse approaches being proposed. Many of these approaches show great promise and have been validated using models and simulations. In this paper a trade study of various characterization techniques for GEO satellites is conducted to select the characterization approach that will be implemented using data from the SSN. The effectiveness of the SSN data to perform satellite characterization is explored. The selected technique is evaluated with recommendations for approaches to extend the technique to address more objects in the catalog.

## 3. CHARACTERIZATION TRADE STUDY

Multiple approaches to characterize GEO objects have been presented at various conferences. The objective of our trade study is to identify a single GEO object characterization technique that will establish a starting point for our research. Capabilities of the techniques not selected will be considered when exploring how to extend the selected characterization technique.

Multiple criteria were identified to make this selection. We considered our team's ability to implement the selected characterization approach. This included examining our team's understanding of the approach based on the information provided in the available material. The synergies with our data sources is important since our intention is to implement the selected characterization approach and have it ingest data obtained from the SSN. The input data needs of the algorithm were examined against the available GEO object data readily obtainable from the SSN. Algorithms heavily dependent upon data not collected by the SSN received a lower score for this criteria. Our team's access to referenced data stores was the next criteria. Some of the papers refer to data stores of previously collected data. Scores in this area ranged from information available in the public domain (high score) to information available to a restricted set on a closed network (low). Our team's knowledge of referenced model was the next criteria. This was a measure of how much information our team was able to obtain that would assist our team in learning the characterization approach.

A search of available satellite characterization approaches was conducted. Fig 1 identifies the characterization approaches evaluated in our trade study and provides selection consideration information. Each technique was examined for further consideration in our research based on our trade study's evaluation criteria. For a comprehensive list of the evaluated techniques please refer to the paper referenced.

**Characterization Approaches Considered**

| Paper | Selection Notes |
|---|---|
| Propagation of Bayesian belief for near-real time statistical assessment of geosynchronous satellites status based on non-resolved photometry data [1] | Needs Inversion Model, Predictive Model and statistical assessment – works on metric observations |
| IR Spectrophotometric Observations of Geosynchronous Satellites [2] | Identifies thermal emission variations based on solar phase angle |
| Surface Material Characterization from Non-resolved Multi-band Optical Observations [3] | Un-mixing analysis to arrive at reflective contribution of satellite sub-components |
| Understanding Satellite Characterization Knowledge Gained from Radiometric Data [4] | Model based estimation approach – single satellite demonstration |
| * Fingerprinting of Non-resolved Three-axis Stabilized Space Objects Using a Two-Facet Analytical Model [5] | Identifies features at four levels – detailed explanation of algorithm provided |
| Algorithms for Automated Characterization of Three-Axis Stabilized GEOs using Non-Resolved Optical Observations [6] | Empirical seasonal model simulated canonical satellite data – tools to automate analysis underway |
| Satellite Characterization with uvbyCaHß Photometry [7] | Requires standard set of Strömgren uvbyCaHß filters and rigorous data processing |
| Satellite Imaging and Characterization with Optical Interferometry [8] | Requires large apertures, telescopes with adaptive optics and coherent integration techniques |

*** Selected Characterization Approach highlighted in green**

Fig. 1 Techniques Considered

The approach described in *Propagation of Bayesian belief for near-real time statistical assessment of geosynchronous satellites status based on non-resolved photometry data* [1] focuses on identifying anomalies in optical observations and then attributing these anomalous observations to changes in status or an error in object correlation (cross-tag). To achieve this goal, a model to predict the expected brightness is used. The predicted result is compared against the actual observation. This approach works well with the routine metric mission of the Space Surveillance Network sensors. The prediction model can be obtained using any analytical model chosen by our team. The Bayesian belief network is updated after each observation to adapt as conditions change on orbit. In this method, the focus is on geosynchronous satellites, however the method appears to be expandable to other orbital regimes. The characteristics evaluated are limited to the metric observations. It would be difficult to match an Un-Correlated Track (UCT) to the database with the expectation of object identification. This method does appear to perform well with differentiating between the members of a cluster of geosynchronous objects.

The approach described in *IR Spectrophotometric Observations of Geosynchronous Satellites* [2] investigated the application of spectrophotometric techniques to determine observable signatures that will allow for the identification of resident space objects. The work focused on geosynchronous satellites, and appears to be readily adaptable to other orbital regimes. The research was based on observations from the Advanced Electro-Optical System (AEOS) 3.6 meter telescope, utilizing the Broadband Array Spectrograph System (BASS) 3-13 micron sensor. The specific data collected may not be readily available over the SSN. The satellite thermal emission detected was evaluated in terms of a simplistic model of geosynchronous satellites that estimates a color temperature for the satellite based upon Plank function fits to the thermal spectra. Our team's ability to duplicate this model based on the available information would be difficult. The maturity of the model is based on a small number of objects and from observations collected over five collection periods. Additional research is needed to improve the fidelity of the geosynchronous satellite thermal model.

The approach described in *Surface Material Characterization from Non-resolved Multiband Optical Observations* [3] explores the theory required for an un-mixing analysis to examine characteristics of the satellite's individual sub-components. Two methods are presented. Both require a set of multi-band measurements of a satellite's brightness in reflected sunlight, the satellite's wire-frame model, and the satellite's attitude specifying the orientation of all the body's component at the times of each measurement. Additionally, a library of bi-directional reflection distribution functions (BRDFs) for a set of candidate materials covering the satellite's surfaces will be needed. The paper concluded the first method can suffer from limitations of the BRDF database of candidate materials that it requires, making it inappropriate for unknown of aging satellites. The second method did not use the BRDF database. However, it required data with significant geometric observation diversity to converge with reasonable accuracy. This geometric diversity will not be possible with the SSN data available to our team.

The approach described in *Understanding Satellite Characterization Knowledge Gained from Radiometric Data* [4] outlines an approach for determining satellite characterization knowledge in the form of estimated parameter uncertainties, from radiometric observation type, quantity, quality and in combination. It uses a complex forward modeling capability with an Unscented Kalman Filter (UKF) to map observation uncertainties into a wide variety of satellite characterization parameters. The approach predicts the amount and type of data required to obtain the desired satellite characterization knowledge. The paper indicates this would be useful in future sensor development efforts our team would use this capability for sensor tasking. The approach described uses a satellite model, forward model for the satellite dynamics, and an observation model for the radiometric data. The observations leverage five simultaneous light curve bands that was difficult for our team to obtain from the SSN. The maturity of the model would need further refinement because the information provided in the paper was limited to one satellite pass. This model would benefit from simultaneous data collections from multiple geographically separated sites. For this study, our team has no control over sensor tasking to achieve this site diversity. Our team was not prepared to mature this model further. This approach should be considered when extending the selected approach.

The approach described in *Fingerprint of Non-resolved Three-axis Stabilized Space Objects Using a Two-Facet Analytical Model* [5] uses visible spectrum data to establish multiple characteristics used to fingerprint 3-axis stabilized geosynchronous satellites. The approach can be implemented using two, single point brightness data points of panchromatic, multi-spectral, or hyperspectral data. The availability of extended duration signature data is not essential, but this data should be considered when attempting to extend this algorithm. This approach uses the most prevalent data available from the SSN and can extend to multi-spectral or hyper-spectral data when available. The approach uses a reduced parameter, two-facet model that results in analytical expressions that allows the number of unknowns to equal the number of equations. The approach makes it feasible to make the calculations repeatedly on a daily basis in order to quantify the bias in the solution.

The approach described in *Algorithms for Automated Characterization of Three-Axis Stabilized GEOs using Non-Resolved Optical Observations* [6] explores an approach to account for seasonal effects in the optical observation. The approach uses an empirical model to provide a varying correction factor that is used to arrive at an observation adjusted to a standard day. The paper provided a description of the model, however our team would require some additional details to implement the model. The approach used the GEO-Sat Color Photometry Catalog (GCPC) that contained observations of 115 GEO satellites over several years, and focused on 3-axis stabilized objects. Because our team could not gain access to this catalog and the focus of the paper was to correct for season effects on the observations rather than identifying characterizing features this approach was not considered as our starting point. The concepts presented in this paper may be considered when extending our selected approach.

The approach described in *Satellite Characterization with uvbyCaHβ Photometry* [7] provides a technique to characterize satellites using simultaneously collected photometry in multiple filters. The approach calibrates the collections using the extended Stromgren standard stars. Our team's inability to modify the stars used for calibration may impact the quality of results that could be obtained in our research. The approach requires the usage of multiple filters that our team will not be able to enforce. This approach describes a specific collection technique to remove atmospheric extinction effects. Our team will not be able to modify the collection technique used by the SSN.

The approach described in *Satellite Imaging and Characterization with Optical Interferometry* [8] provides concepts to image geostationary satellites with optical interferometers. This method requires large apertures, exceptionally good sites for the telescope, and makes use of a large number of telescopes (10). This approach would be viable for multiple orbital regimes and object types. Although the approach may be feasible, our team will not have access to the number of observing locations described for geosynchronous objects. The concepts in this paper motivated our team to evaluate the impact of multiple geographically diverse observing locations as a means of extending the selected algorithm.

Scores were assigned from 1 to 10 in each criteria area for each characterization approach being considered. The scores were scaled based on weighting factors assigned to each criteria. A single score was assigned to each characterization approach and fig 2 depicts the weighted score trade study results in a graphical format. *Fingerprint of Non-resolved Three-axis Stabilized Space Objects Using a Two-Facet Analytical Model* [5] received the highest scores and has been selected for our research.

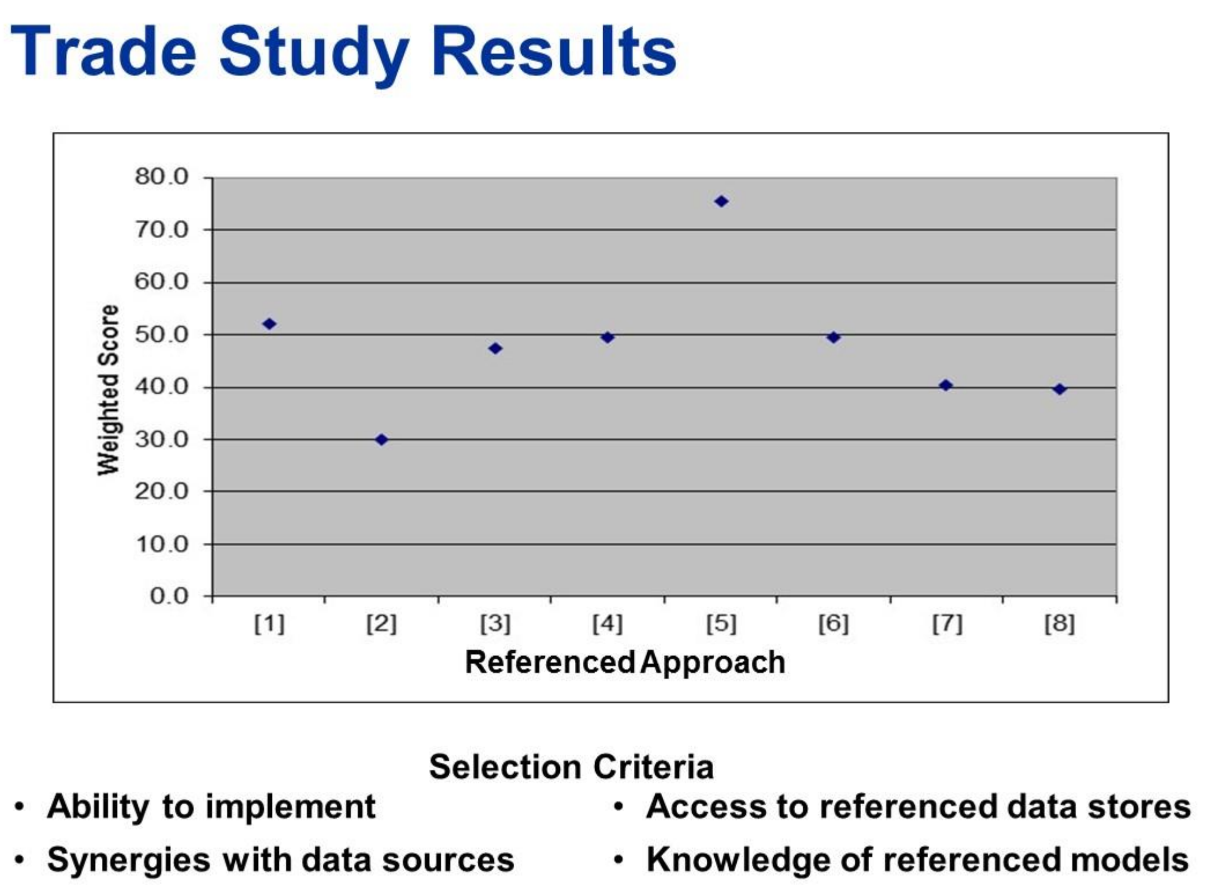


Fig. 2 Trade Study Conclusion

The selected approach produces multiple levels of information. Each level builds upon the previous and provides greater detail. This is referred to as an "Lx Fingerprint". L0 identifies the sentinel features such as the location, width and contrast of the specular peak. L1 captures the macro character of the Resident Space Object (RSO) by accounting for the effect of the subsolar angle and the phase angle on the single point brightness by synthesizing the historical archive of RSO photometry observations data into a single representation. The L2 calculations solve for the invariant information (albedo-area product) to understand the material content of the solar panel and body. The

L3 computes the fractional contribution of the solar panel and body to the visual brightness. Fig 3 depicts a brief summary of the characteristics obtained by each level. Details describing the necessary computations to arrive at the Lx Fingerprint from Visible Spectrum observations can be found in the referenced paper [5].

| Feature | Information |
|---|---|
| L0 | RSO specular glint offset, contrast, width or FWHM, etc |
| L1 | A polar representation of RSO signature as a function of phase angle and ordinal date |
| L2 | Material spectra of the solar panel and body |
| L3 | Separation of RSO signature into contributions by the solar panel and the body |

Fig. 3 Lx Fingerprint Characteristics Summary

## 4. EXPERIMENT

The selected characterization approach required optical observations of 3-axis stabilized geosynchronous satellites to establish a collection of fingerprints. The approach described in *Clients of Space Situational Awareness (SSA) Net-Ready Data* [9] was followed to become an authorized user of the Net-Centric Sensors and Data Sources (N-CSDS) Ground-based Electro Optical Deep Space Surveillance (GEODSS) Sidecar. Metric Observation Data and Space Object Identification Data were collected for the analysis. Data collection from Diego Garcia (DGC) began in early June 2015, Maui (MAU) data collection started in Apr 2015 and Socorro (SOC) data started Aug 2015. Our processes to collect and organize the data have been highly manual and the volume of data greatly exceeded our ability. As a result we decided to focus on a small set of specific objects to evaluate. The process of selecting a reasonable subset of geosynchronous objects was based on evaluating our research objectives. Fig 4 identifies the key questions our experiment would like to address.

| Experimental Questions |
|---|
| Does the SSN provide the necessary data for characterization? |
| Can the algorithm discern between similar spacecraft of similar age on orbit? |
| Will the approach characterize highly inclined deep space objects? |
| Will changes in inclination impact characterization results? |
| What improvements in the characterization can be achieved when multiple locations can observe the same object? |
| What can be done to extend the approach beyond 3-axis stabilized satellites? |
| Will the approach continue to identify an object that was previously characterized but suddenly experiences a failure becoming unstable? |
| How will a breakup event impact characterization results? |

Fig. 4 Experiment questions addressed

Our primary objective was to determine if the SSN provides the necessary data for satellite characterization. It was our intention to perform this evaluation with the maximum amount of data against a 3-axis stabilized vehicle with the minimum inclination. We selected CHINASAT 2A (38352) because the vehicle has zero inclination and it is visible to Diego Garcia giving our team the maximum length of historical observations. We initially realized element set information was required to compute the necessary angles depicted in fig 5. We obtained element set information from SpaceTrack.org.

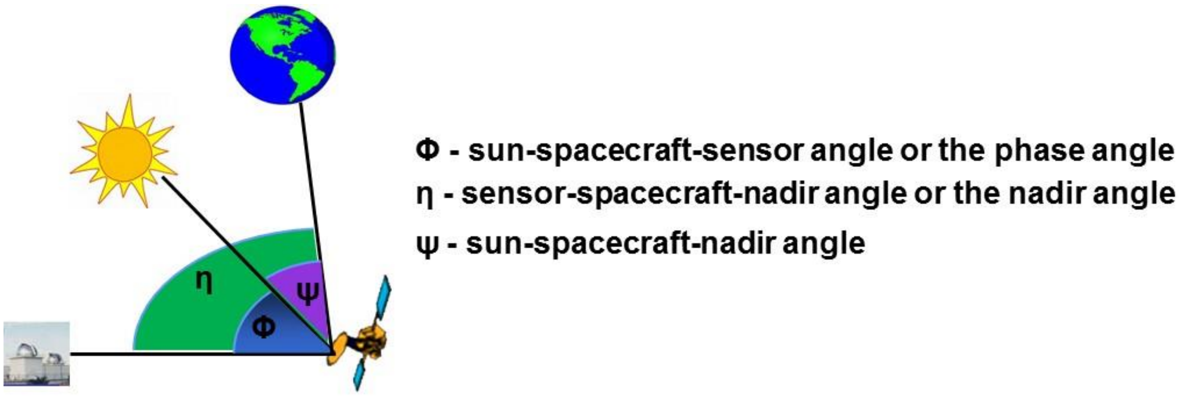


Fig. 5 Angles computed from Element set data

The differences in some of these angles are very small. Element set information inherently introduces positional uncertainty. This uncertainty is compounded with the lack of knowing which element set was used by the telescope to make the observation and if the satellite was located in the expected observing point. These uncertainties did not prevent our ability to continue with the available data, however increased the likelihood that similar objects would yield overlapping fingerprints.

The algorithm conducts a material spectral analysis to complete the L2 portion. This requires use of multicolor photometry data. The data our team was able to obtain from the selected SSN sensors only report metric observation in the visible range. As a result our analysis was reduced to a single outcome set. This reduced the potential utility of the fingerprint database being produced.

Given the uncertainties identified in the positional information and the lack of multicolor photometry data, our next objective was to examine if the algorithm could discern between spacecraft of similar size, type, and age on orbit. Our team used data from the internet located at http://www.n2yo.com/ to identify similar space craft observable from our selected SSN sites. In order to examine this objective two pairs of satellites with similar characteristics were selected. The first pair CHINASAT 10 and CHINASAT 6A were selected because the vehicles have the same mass (5000 kg), the same radar cross section (50.1187 $m^2$), the same vehicle bus (DFH-4), and are performing the same mission (Communication). These vehicles were launched within 6 months of each other. Given the similarities of these two vehicles and acknowledging potential uncertainties in the positional data, the prevailing opinion of our team is that it would be extremely difficult to discern any meaningful differences between these objects using only our selected approach. Thus, a second pair (CHINASAT 1A and CHINASAT 11) was selected for evaluation because the delta between the identified attributes is greater. This second pair was launched 2 years apart with Radar Cross Sections of 15.8489 $m^2$ and 11.7985 $m^2$ respectively and both vehicles use the same bus (DFH-4).

After establishing a baseline with these well behaved satellites, our efforts would shift to a highly inclined vehicle. Our objective is to determine the effects of inclination on the characterization approach. Our focus will be in the algorithms ability to separate the solar panel and body characteristics. The vehicle selected was BEIDOU I1-S that operates in orbital slot 106.8° E with inclination of 54.9°.

A related objective is to evaluate the relationship between changes in the vehicles inclination and how that might impact the vehicles fingerprint signature. This evaluation is to address changes in the North/South station keeping strategies satellite operators employ as the vehicle ages to conserve fuel. To fully explore this characteristic will require data collection over much longer time scales or will require the need for simulation and modeling of such events.

Given the overlapping coverage between Socorro and Maui our team is interested in identifying any improvements in the characterization that can be achieved when multiple locations can observe the same object. Our expectation is that the increase in available data will improve the fidelity of the obtained fingerprint. Coordination between sites to collect at the same time would provide observation of the object by two geographically diverse perspectives with the observed object illuminated with the same lighting conditions. During the course of the experiment, our team will have no control over the sensor tasking or collection times. To improve the likelihood of overlapping collections, multiple objects have been selected for data collection and analysis to include: GALAXY 14, AMC 21, and TELSTAR 4.

Fingerprints are used as a means of positive identification of people. This fingerprint remains as the person ages or changes physical appearance. That should also be the goal of satellite fingerprint strategies. Once a satellite has been fingerprinted and the information stored in a database, if the object is later observed, it can be positively identified from the previously established information.

Our team wanted to explore the algorithms ability to continue to identify an object that was previously characterized but suddenly experiences a failure becoming unstable. Thus far during our collection, no known failures have been identified. To attempt to address this question we have analyzed the GALAXY-15 failure of 2010 depicted in Fig 6.

The GALAXY-15 vehicle was an ideal candidate for our fingerprint analysis. It is a 3-axis stabilized geosynchronous vehicle. In early August 2010, it began to drift out of its orbital slot with a potential loss of attitude control. This loss of stability would result in the solar panels no longer being oriented towards the sun and the body no longer being nadir pointing. The algorithm depends on the vehicle maintaining the proper orientation to conduct the material spectra analysis of the solar panel and body (L2) and to perform the separation of solar panel and body contributions (L3). The metric observation data obtained once stability was lost would include reflections from surfaces not previously expected. This will reduce correlation between the established fingerprint and the current observations.

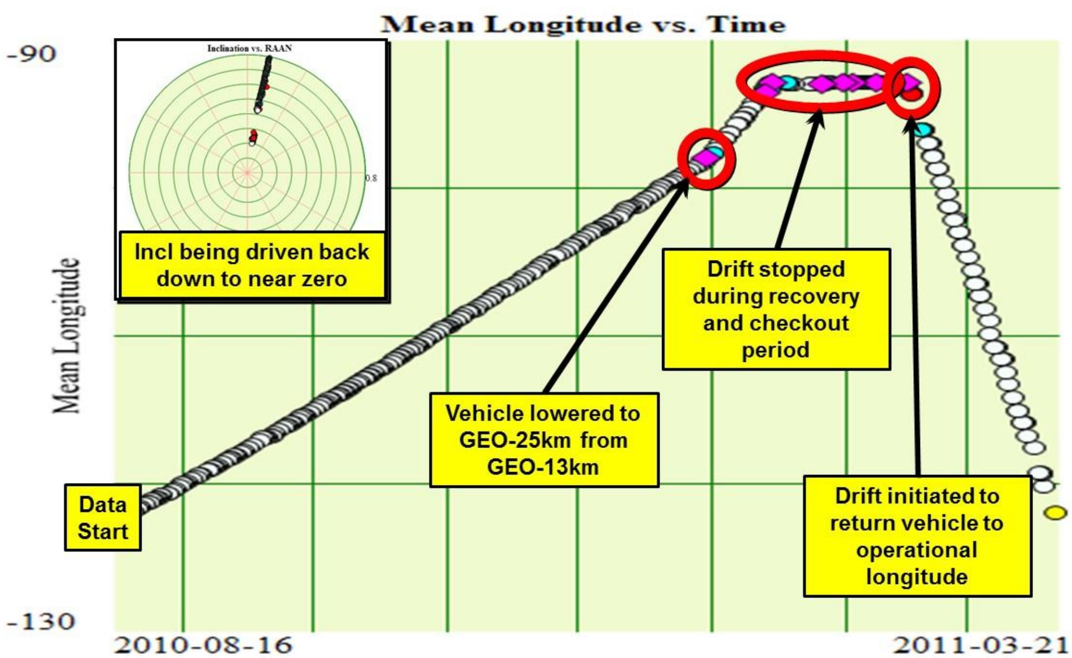


Fig. 6 GALAXY-15 Failure of 2010

Future considerations should examine approaches to improve the satellite model to account for rotation should the vehicle become unstable. Understanding the vehicles rotation rate and axis of rotation would be the first step in addressing the L2/L3 limitations identified.

Most Resident Space Objects (RSOs) are not 3-axis stabilized geosynchronous spacecraft with solar panels and a body. Extending the approach to other object types or orbital regimes would be very beneficial. Our analysis focused on a Rocket Body with orbital characteristics similar to geosynchronous objects (SL-12 R/B 33111).

Techniques of determining an objects rotation axis and spin rate were evaluated in an attempt to extending the fingerprinting approach beyond 3-axis stabilized vehicles. The approaches described in *Cylindrical RSO Signatures, Spin Axis Orientation and Rotation Period Determination* [10] and in *Optical Characterization of Deep-Space Object Rotation States* [11] were used for Rocket Body analysis. The determination of spin rate and rotation axis will be needed to identify the objects orientation at the time of the observation. Additionally, a wire frame model of the object being observed along with a model of the objects reflection would support fingerprint. Our team set the solar panel portion of the L2/L3 fingerprint to zero for analysis of a rocket body. An analysis of this method will be considered for extending the approach beyond 3-axis stabilized vehicles and for vehicles that have become unstable.

Our team would like to evaluate the characterization technique during a breakup event. Our team has not observed a breakup event during our collection period and it is unlikely that one will occur. A simulation of the event may be necessary for this analysis. Our expectation is the breakup event will alter the fingerprint significantly and cause identification of the object using historical data difficult.

## 5. DISCUSSION

The selected Space Surveillance Network sensors did not provide our team data that utilized color filters. This impacted the algorithms ability to establish the material composition of the object. Our team's L2/L3 analysis was limited to a single output set. Support to material analysis could be enhanced by obtaining multicolor photometry from the SSN sites or by accepting data from existing sites which can provide the request data.

Our analysis of the fingerprints of RSOs observable from multiple locations was limited by our inability to coordinate the data collections. Observing the object from multiple sites simultaneously has the potential of yielding a greater fidelity fingerprint for 3-axis stabilized objects. The additional information could be used to determine orientation and spin characteristics when attempting to extend the algorithm to other object types. Our recommendation is that sensor tasking methods should include approaches for coordinated collections between sites. This would provide the opportunity for further research and allow the results to be exploited operationally.

## 6. CONCLUSION

We are in the early stages of our research. Our current efforts are focused on a small subset of objects to refine our processes. Our goal is to produce a historical database for all objects observed from the GEODSS sites. In order to create a historical database, automation of our processes to gather the available data, organize the information for analysis, and characterize objects will be necessary. Future plans would include ingesting additional data from other sources and expanding our database to other orbital regimes.

Once the database is established, it is our desire to compare UCTs against the database to answer the question, "Can a UCT be identified as a known object if it was previously characterized?" In order to provide a precise answer to these questions, additional research and improvements are required in the quality of data, type of data available, and algorithmic updates to account for all orbital types.

## 7. ACKNOWLEDGMENTS

This research has made use of the valuable resources of the AMOS technical paper repository, and data collected by the GEODSS system. This research would not have been possible without access to the technical papers presented at the AMOS conferences and the GEODSS data to validate the results.

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