Satellite Characterization Data Collection and Analysis

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CONFERENCE PAPER

1. ABSTRACT SUMMARY

Techniques for improved characterization of satellites have been an area of research for several years. Our team evaluated Optical characterization techniques in 2015 and expanded to radar, signals and infra-red phenomenology in 2016. In this paper our efforts to collect optical, radar, and signal data for satellite characterization and Pattern of Life understanding will be covered. Algorithmic approaches to fuse data from multiple phenomenologies will be identified to include rapidly re-acquiring objects after a maneuver, estimation of available fuel, and power profile considerations. Tip and Cue points between collectors necessary to implement the multi-phenomenology data fusion algorithms will be identified. The benefits of such information will be discussed, to include re-acquiring objects after a maneuver.

2. INTRODUCTION

The ability to determine the current position and velocity and to predict the future position of satellites (metric data) has been a need ever since the first objects were launched into orbit. This initial Space Surveillance Network (SSN) comprised a network of phased array radar sensors, many of which had a primary mission other than tracking satellites. When satellites began to utilize geosynchronous orbits (GEO), optical telescopes were added to the SSN in order to augment the phased array space tracking capabilities. The methods used to identify the observed object rely heavily on the object's actual position with respect to the object's expected position. Errors in the expected position have caused misidentification, resulting in cross-tagging objects. Occasionally, objects may not be located at all because of maneuvers resulting in their placement on the lost list. These issues are more severe in the GEO regime due to the inability of ground based sensors to produced resolved images. Existing identification techniques could be improved by extracting additional data from the sensors and leveraging additional existing sensors.

In recent years, the term "space surveillance" has been subsumed by the broader term "space situational awareness," which adds additional types of information to metric data with the goal of characterizing objects in space as well as the space environment itself. Techniques for characterization of satellites have been an area of research for several years due to limitations inherent to 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 specific information needs will be identified along with identified research techniques. The specific phenomenology necessary to obtain the desired information and potential sensors our research team intends to leverage to obtain the data are identified.

3. SATELLITE CHARACTERIZATION

In order to characterize satellites, we must first understand the specific pieces of information we need to obtain. Figure 1 identifies the satellite attributes explored in this paper. These attributes were selected because they provide a broad set of information that could be used to uniquely identify the object and provide insight into expected changes over time. After identifying the satellite attributes, a search of existing approaches was conducted to determine viable methods to obtain the desired attributes. Several promising techniques were identified, and a summary of the approach is provided. For a comprehensive explanation of the identified techniques, please refer to the referenced paper.

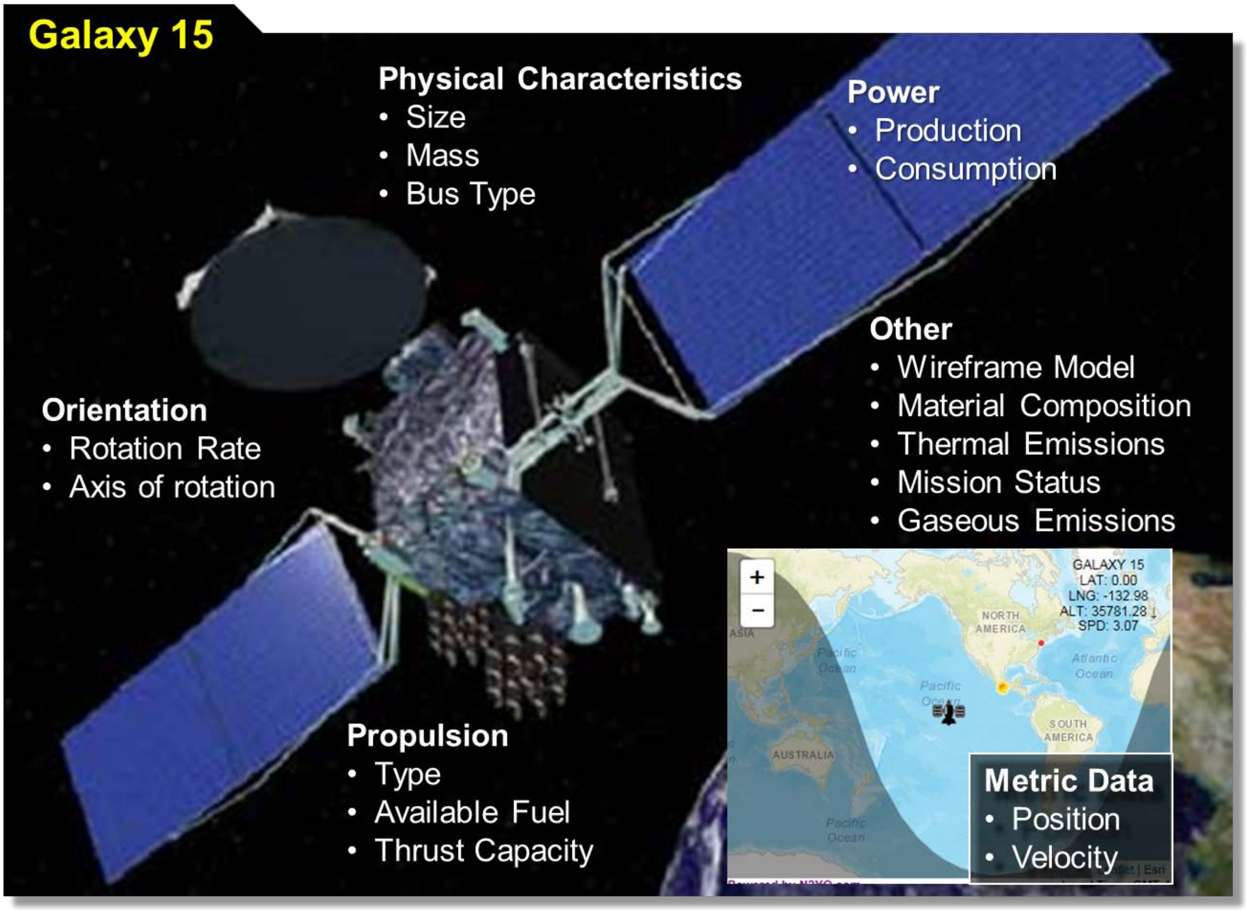


Figure 1: Characterization Attributes

The Orientation characteristic identifies the rotation rate and axis of rotation for a given object. Once a baseline is established that identifies normal behavior, variations from normal can be used to evaluate operational status. Physical Characteristics include the size, mass and bus type. The size and mass information would be used when evaluating collision and break-up scenarios. The Bus Type supports the creation of wireframe models used in material and thermal analysis. The Propulsion Characteristics identifies the type, available fuel, and thrust capacity of an object. This information can be used to identify the search area for an object that has become lost. The Power Characteristics include the production and consumption rates of the object. Understanding the balance between a satellite's ability to produce power and consume power would be used to determine degree of mission capability (i.e. duty cycling mission to conserve power). Other characteristics of interest include a wireframe diagram, material composition, thermal emissions, mission status, and gaseous emissions. These characteristics can be used to positively identify an object and support analysis to determine the mission status. These characteristics are in addition to the currently collected metric data that provides the position and velocity components of the object.

A search of available satellite characterization approaches was conducted. Figure 2 identifies the satellite attributes necessary for full characterization. For a comprehensive list of the evaluated techniques please refer to the paper referenced.

The Metric characteristics include the position and velocity of a given object. Each phenomenology capable of observing the object has knowledge of the observer location and the direction of the object being observed. With sufficient observations each of the phenomenologies is capable of providing metric characteristics. The physical attributes of size and mass are supported using RADAR data. Resolved images also support physical characteristics to include identification of bus type. Rotation rate and axis of rotation are readily determined from resolved images. Algorithms have been presented to obtain orientation characteristics from time series observations and can be adapted to any observing phenomenology. Propulsion characteristics are obtained using pattern of life data obtained from various sensor types. Power production and consumption information is an area of future research. A wireframe diagram of the object requires a resolved image. Material composition can be obtained from multi-band radiometric and/or spectrometric measurements. Thermal information requires data collected in the thermal part of the spectra. Additional research is required to un-mix the thermal information to obtain specific components of thermal data. Mission Status represents a pattern of life analysis of all of the available characteristics.

Attribute	Optical	Radar	IR	Signals
Metric-Position	Yes	Yes	Yes	Yes
Metric-Velocity	Yes	Yes	Yes	Yes
Physical - Size		Yes		
Physical - Mass		Support		
Physical - Bus	Yes	Support		
Orientation – rotation rate	Yes	Yes	Yes	
Orientation – axis of rotation	Yes	Yes	Yes	
Propulsion – Type	PoL	PoL	PoL	
Propulsion – Available Fuel	Support			
Propulsion – Delta Velocity	PoL	PoL	PoL	
Power – Production			Support	
Power - Consumption			Support	Support
Wireframe Diagram	Yes	Yes		
Material Composition	Yes			
Thermal Emissions			Yes	
Mission Status	Support	Support	Support	Yes
Gaseous Emissions			Yes	

Figure 2: Characterization Attributes

4. Optical Information

Ground-based and space-based optical and radar sensors routinely acquire resolved images of satellites, yielding a great deal of knowledge about orbiting spacecraft orientation. However, the satellite population that cannot be resolved, because they are too far away or too small, require alternative analysis methods. Techniques of determining an object's rotation axis and spin rate are described in *Cylindrical RSO Signatures, Spin Axis Orientation and Rotation Period Determination* [1] and in *Optical Characterization of Deep-Space Object Rotation States* [2]. These techniques rely on measurements of the object's brightness as a function of time (temporal photometry). The satellite's rotational motion can be detected and characterized by analyzing the periodic brightness variations. Temporal brightness patterns can also be exploited to characterize stabilized GEO satellites. The research has focused on how temporal photometry can be used to characterize non-resolvable object rotation states for GEO satellites. These techniques may also be adaptable for non-resolved objects in other orbital regimes.

One potential source of temporal photometry data for the GEO regime is the Ground-based Electro-Optical Deep Space Surveillance (GEODSS) sensor network. Figure 3 below identifies the general coverage areas of existing GEODSS sites which collect optical data during local nighttime. By leveraging the Net-Centric Sensors and Data Sources (N-CSDS) GEODSS Sidecar concept, these observations are published in near-real-time (NRT) via the Net-Centric Enterprise Services (NCES) interface, which provides request/response queries via web services. In this way, the web service hosting for the exposed data has been effectively decoupled from the host system operational string. For more information, refer to *Clients of Space Situational Awareness (SSA) Net-Ready Data* [8]. The N-CSDS GEODSS Sidecar provides Metric Observation data, Space Object Identification data, and Site-Generated Element Sets.

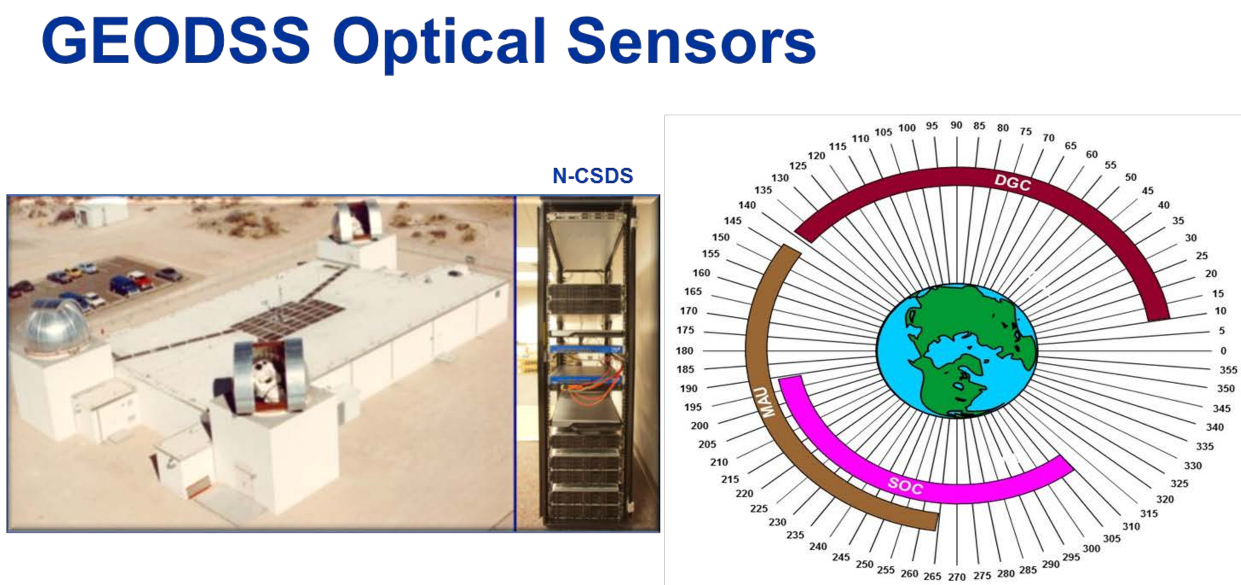
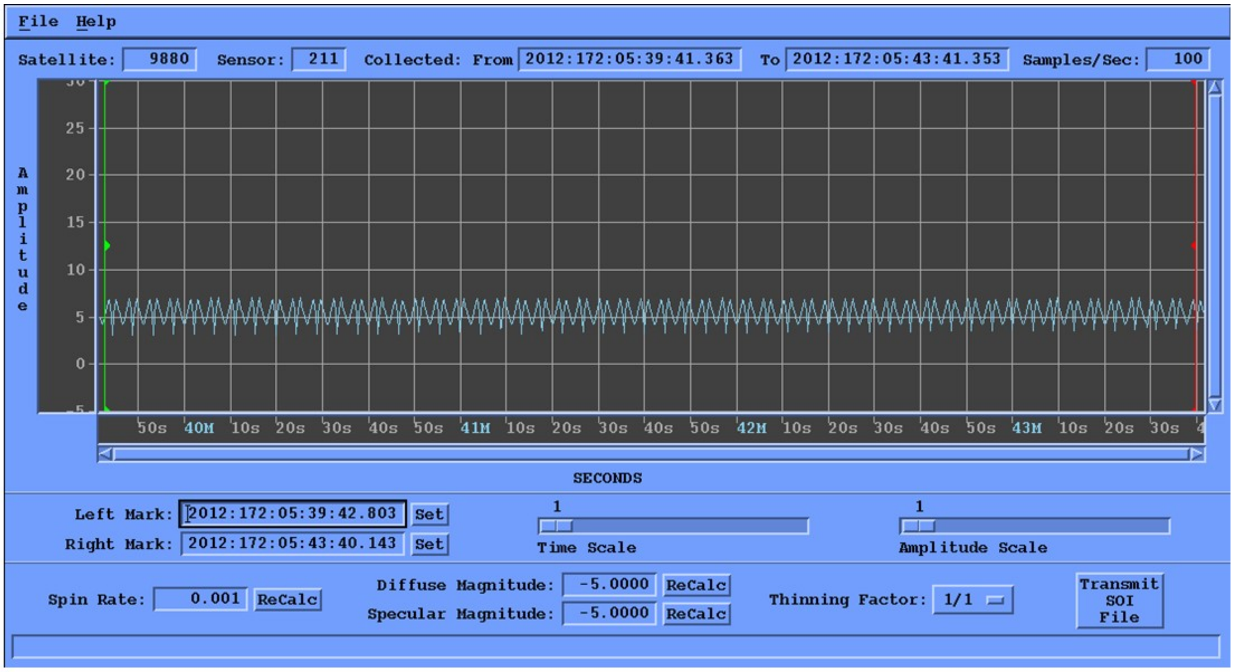


Figure 3: Optical Sensors

Analysis of time-series data that can be obtained from the GEODSS Satellite Object Identification data, as shown in Figure 4, can yield remarkably accurate estimates of the frequency of a satellite's brightness modulations. These "apparent" or synodic frequencies can vary in time, differing from the actual rotation rate of the object by an amount that depends on the relative angular motion between the satellite, illuminator, and observer for reflected light measurements (or between the satellite and observer for thermal emission measurements). When detected with sufficient accuracy, such synodic frequency variations can be exploited to characterize an object's rotation state, using an analysis that does not require any *a priori* knowledge of the object's shape. For instance, this *shape-independent* analysis method can be used to derive spin axis orientations and sidereal rotation rates for spinning objects. Remotely determining such rotation parameters can be useful in many circumstances, such as when performing anomaly resolution for satellites that have lost stabilization. Unfortunately, synodic variations cannot be detected by ground-based observers for many objects due to low rates of relative angular motion. This is especially true for non-specular objects in deep-space and geosynchronous orbits. In these cases, deriving spin axis orientations can be accomplished using a *shape-dependent* method that employs a model of the shape and reflectance characteristics of the object.



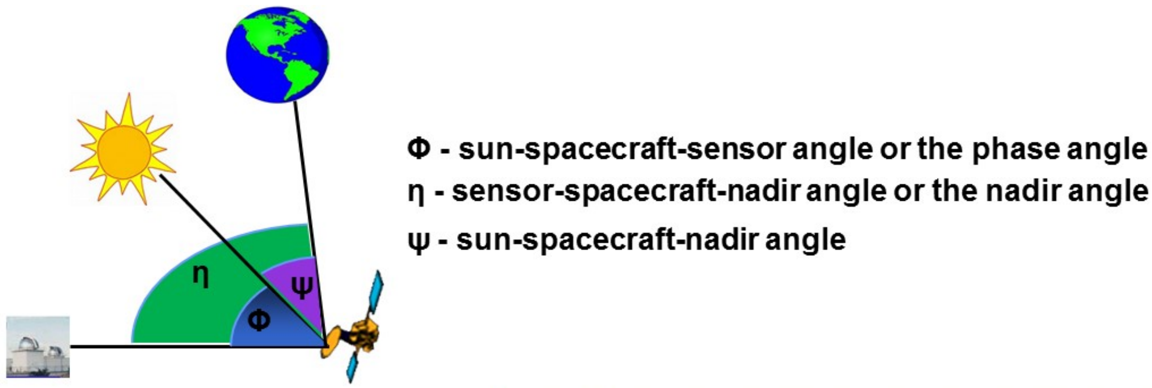
- Time series data used to determine spin rate and axis of rotation

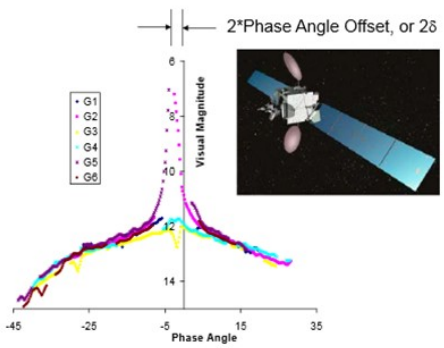
Figure 4: Orientation Characteristics

The determination of spin rate and rotation axis is foundational information needed to identify the object's orientation at the time of observations when evaluating material and thermal composition.

Many of the sensors used to maintain the space object catalog typically acquire observations at a single wavelength; this kind of analysis provides little or no information on the types of materials covering the satellite's various surfaces. Techniques for a satellite's detailed surface material characterization generally requires multi-band radiometric and/or spectrometric measurements. Many widely-available instruments provide such multi-band information (e.g., spectrographs and multi-channel photometers). However, these sensors typically measure the brightness of sunlight reflected from the entire satellite, with no spatial resolution at all. Because such whole-body measurements represent a summation of contributions from many reflecting surfaces, an "un-mixing" analysis must be employed to characterize the reflectance of the satellite's individual sub-components.

The approaches described in *Surface Material Characterization from Non-resolved Multiband Optical Observations* [3] and *Fingerprinting of Non-resolved Three-axis Stabilized Space Objects Using a Two-Facet Analytical Model* [4] explores the theories required for an un-mixing analysis to examine characteristics of the satellite's individual sub-components. Figure 5 illustrates the key attributes of the two methods. 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 components 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 papers concluded the first method can suffer from limitations of the BRDF database of candidate materials that it requires, making it inappropriate for unknown or 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 require coordination of multiple observing locations.





Feature	Information
L0	Identified the sentinel features such as the location, width and contrast of the specular peak
L1	Captures the macro character of the 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
L2	Calculations solve for the invariant information (albedo-area-product) to understand the material content of the solar panel and body
L3	Computes the fractional contribution of the solar panel and body to the visual brightness

Figure 5: Material Analysis

The determination of material composition at the component level provides needed information to positively identify the object. This can be used to reduce cross tagging of objects.

5. Signal Information

In order to collect signal information from an object of interest, an antenna is required. A typical antenna installation supports a specific operational system and is not available to be tasked for general passive collections. However, our research team in Valley Forge, PA obtained a decommissioned S-band Phased Array antenna that was still in operable condition. The antenna is currently being installed at our research site in Valley Forge for the purpose of conducting passive data collects of S-band signals from LEO and GEO regimes.

The Phased Array antenna provides a 60-degree field of view in the east-west direction as depicted in Figure 6. It consists of two 9’x8’ panels, each providing 3 beams with 8 dB/K of gain. Alternatively, each panel can provide 6 beams with 5 dB/K of gain by leveraging a Phased Array antenna technique known as “beam partitioning.” The electronically-steered array is capable of monitoring position and velocity of target objects, rapidly identifying when a maneuver has been performed by detecting gain fluctuations, geo-locating ground transmitters, and identifying electro-magnetic interference (EMI).

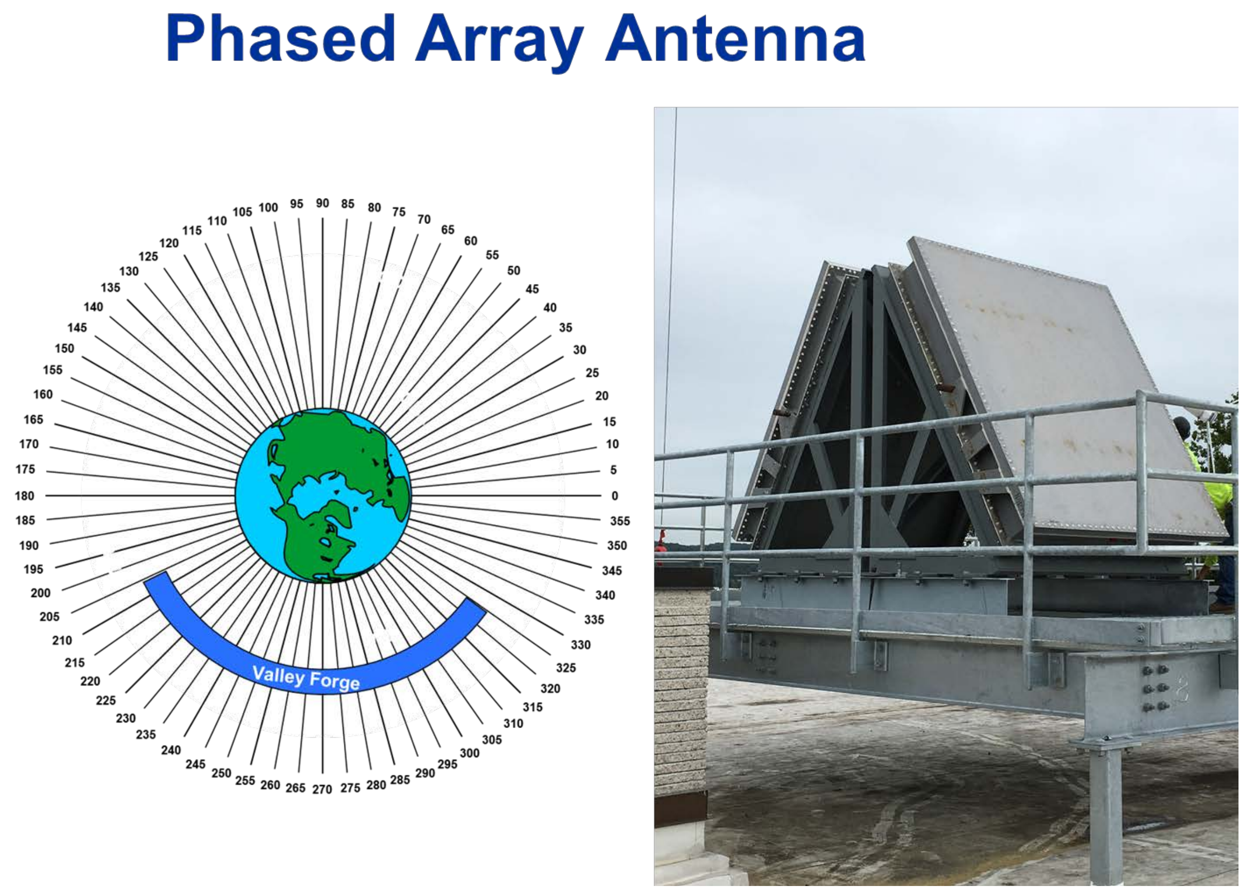


Figure 6: Phased Array Antenna

To understand data collection opportunities our team conducted a search of satellites' registered frequencies and compared them against the receive frequencies of our antenna. Figure 7 identifies a subset of potential collections. Many of these satellites overlap the collections that can be performed by the GEODSS system providing optical data.

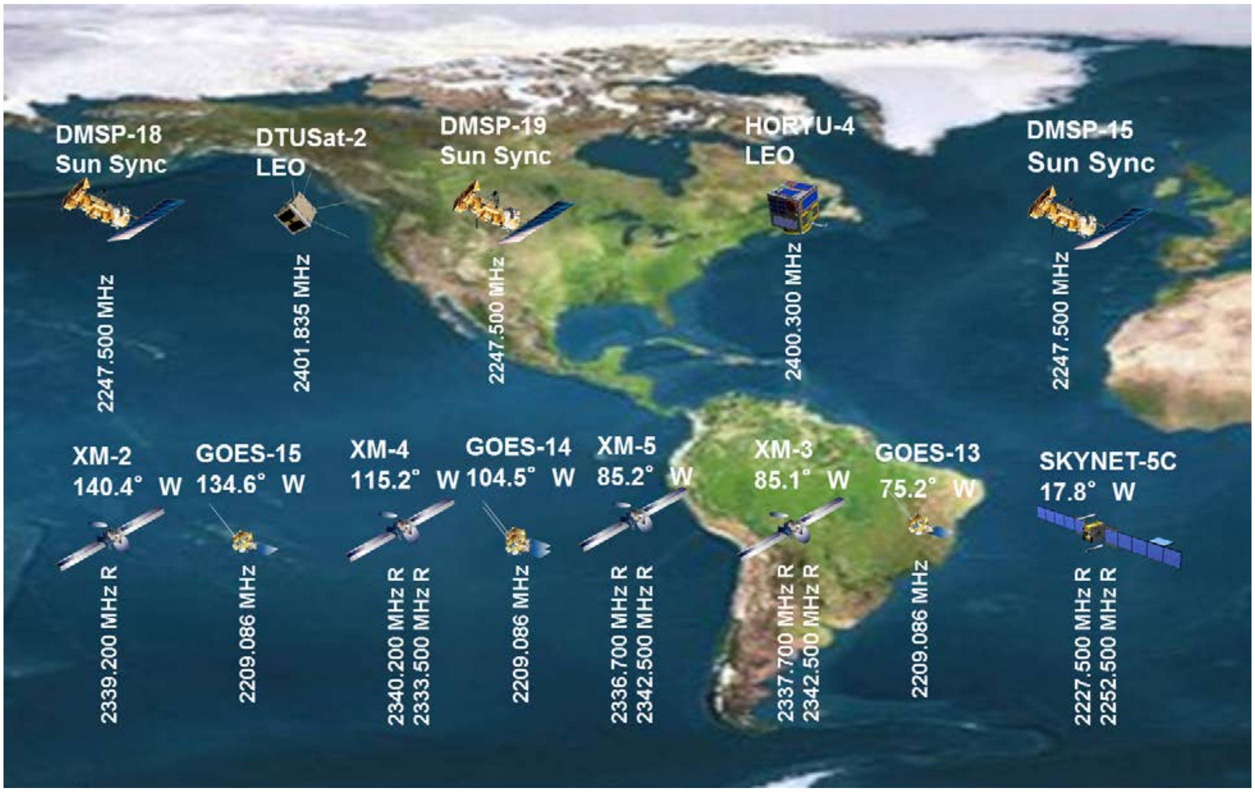


Figure 7: Phased Array Opportunities

The ability to concurrently collect information from multiple sensor types significantly improves the ability to understand unique features of the satellite being observed. By subscribing to the Site Generated Element Set information and Metric Observation data published from the GEODSS system, the phased array can direct observations to the azimuth and elevation corresponding to the GEODSS observations and listen for signal.

Subscribing to GEODSS Site Generated Element Set data provides track data generated when the site is unable to correlate an observation to the catalog information the site is holding. The location information contained in the Site Generated Element Set will be used to Tip and Cue a collection from the phased array. The object's downlink signals will be captured by the phased array and can be used to determine if the object is active and can assist in the correlation process resulting in a reduction of the number of satellites on the lost list.

Subscribing to GEODSS Metric Observation data provides an ability for near concurrent collections. Observations made concurrently from different phenomenology provides the ability to confirm and enhance conclusions drawn from a single observing type. The Metric Observation data identifies the observing telescope, the object being observed, and pointing information (azimuth/elevation). This information is published using the N-CSDS in near real time and can be used to point the phased array to collect signals on the object. By maintaining a database of historical signals collected by satellite ID, the phased array can quickly find the signals of interest for the identified object. Since the Metric Observation data contains a complete track of data the phased array can collect for many seconds. Using the visual magnitude information from the Metric Observations and the signal data from the phased array our system can verify the satellite ID is correct. This approach can be used to reduce the number of objects cross tagged in the catalog.

This same approach can be combined with Time Series collection data. By combining signal power level fluctuations we are able to confirm the spin rate and axis of rotation information obtained from the time series observations. The combination of these pieces of information supports characterization and will be a focus of further research.

6. Radar Data

Space Fence, a RADAR system that operates in S-Band, is currently being deployed to Kwajalein Atoll in the Pacific Ocean. To support this deployment, a test facility was constructed in Morristown, New Jersey depicted in Figure 8. Our team plans to explore using the Space Fence Test facility in Morrestown, NJ and the Phased Array located in Valley Forge, PA to produce bi-static and/or multi-static RADAR data. This is possible because the Phased Array and Space Fence both use the S-Band. Because the Space Fence test facility operates at a lower power than the operationally deployed system, our team plans to focus on Low Earth Objects with a large Radar Cross Section (RCS) such as the international space station. Obtaining these RADAR returns provides our team another phenomenology to confirm information derived from other data sources and improves our ability to characterize and fingerprint satellites.

Figure 8: Space Fence Testing Facility, Morrestown, NJ

7. Infrared Data

Our team is currently exploring sources of Infrared Data. At this point our team has not collected Infrared Data for Space Objects. The approach described in *IR Spectrophotometric Observations of Geosynchronous Satellites* [5] investigated the application of spectrophotometric techniques to determine observable signatures that will allow for the identification of resident space objects. 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 work focused on geosynchronous satellites producing spatially un-resolved data. The thermal part of the spectra (8-13 micron flux) was evaluated to estimate a color temperature for the satellite based upon Planck function fits to the thermal spectra. This technique relied on two free parameters: the flux level and the temperature of the target. The flux level depends upon the area, the emissivity of emitting surfaces, and the range to the target. The thermal signatures produced represented a mixture of emissions from the various parts of the satellite (e.g. solar panels, spacecraft body, antennas, and transmitters). Several satellites' data was collected at different phase angles. (Phase angle is defined as the angle between the ray from the satellite to the Sun, and the array from the satellite to the observer.) The plots of the thermal emissions as a function of phase angle, fig 4, showed a minimum flux with hotter temperatures at phase angles ~90 degrees, with thermal flux increasing with larger or smaller angles.

Given that the solar panels of a GEO satellite would be oriented towards the sun, the temperature relationship to the phase angle is reasonable. When observations at phase angles of ~90 degrees are examined, an observer is seeing the solar panels "edge-on," or perpendicular to the orientation of the collection elements. With larger and smaller angles, the observer is presented with more of the solar panels' area. Given the solar panels large size, it is frequently the dominant spacecraft feature. When observing satellites at ~90 degrees phase angle, observers are seeing mostly the flux from (hot) transmitters and the cooler spacecraft bus behind the transmitters. The emissivity-area changes with larger and smaller phase angles due to the solar panels converting sunlight into electricity, which is stored in on-board batteries.

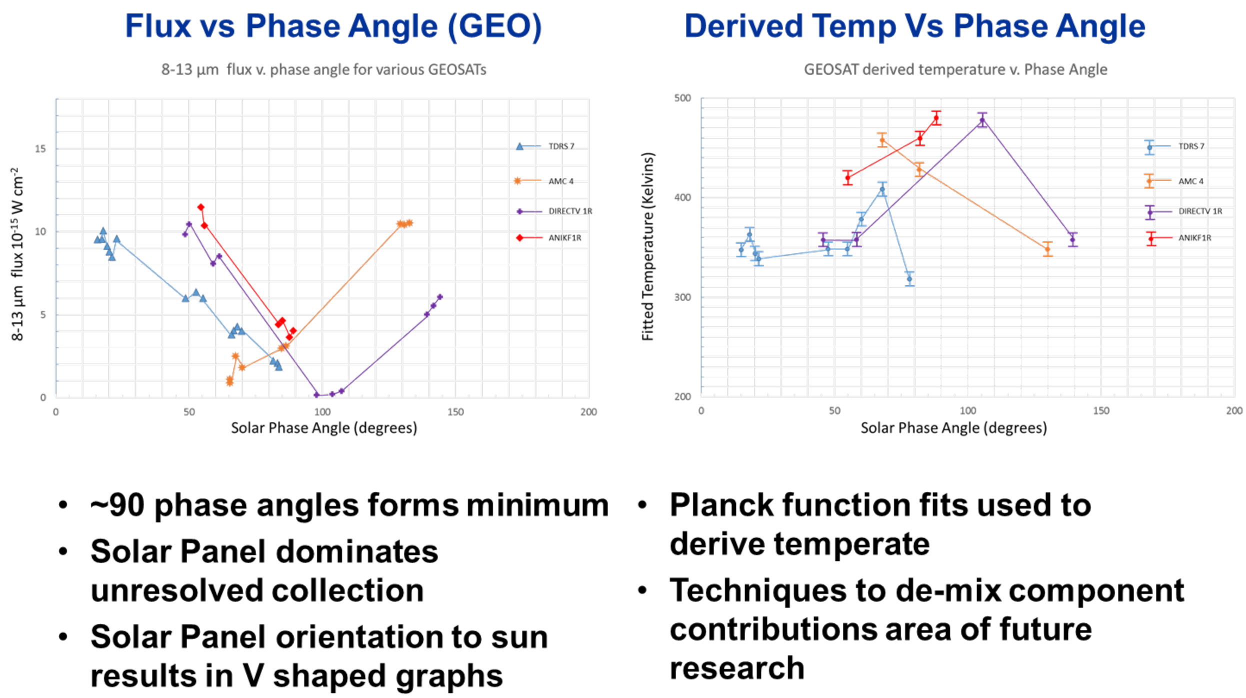


Figure 9: Thermal Properties

The maturity of this 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. Specifically, exploring approaches to separate the temperature for the various spacecraft components and exploring the thermal signatures of unresolved collections in other orbital regimes. Understanding changes in the thermal signature with respect to normal mission events would provide secondary confirmation of these events.

Understanding the Thermal Properties of a satellite and combining this information with orientation data obtained from time series metric observation data will unlock new information regarding the satellite's ability to produce power. The thermal properties V-shaped graphs are seen when the satellite is orienting solar panels to optimize power production. Orientation data obtained from time series metric observations can confirm the power production optimization. Changes in the thermal properties graph over time can be used to estimate changes in power production and confirmed using orientation data. The relationship between thermal properties and orientation data confirm the satellite's rotation rates and axis of rotation. This information is necessary in the un-mixing algorithms needed to determine material composition of satellite components.

8. Results Summary

One of the advantages of our characterization approach utilizing multiple disparate sensor systems is that the data provided by these sources can be collected independently and simultaneously, correlated using orbit track data, and combined for analysis at a later time. This approach becomes particularly important when considering that RADAR and signal data can be collected at any time, while optical and infrared data can only be collected from ground observation stations during local nighttime. By correlating these temporally disparate measurements using metric data, they are combined into the overall object characterization, which becomes more refined over time as the quantity of measurements grows to provide more overall data points.

However, access to near-real-time data sources such as GEODSS observation data via N-CSDS is important as well, since concurrent observations from multiple sources allow for greater refinement of object characterization particularly as it pertains to orientation and rotation. For this reason, greater overall value is placed on the timely collection of simultaneous observations in response to Tip and Cue triggers whenever possible.

Of greatest note at this juncture in our research is that the availability of sensors and sensor data outstrips the readiness of our mathematical algorithms and models to perform the correlative computations and arrive at normalized characterization fingerprints. Subsequently our goal is to begin collecting and storing these data as soon as feasible in order to establish a backlog of measurements which will inform the development of the models and algorithms. With a sufficient collection history, mature models will be able to identify pattern of life behaviors, and correlate measurements within the data backlog. Ultimately, one of the principal measures of our model maturity will be the ability to reliably predict future behavior of the identified objects once the backlog has been processed.

With sufficient maturity, the models and algorithms developed by this research will be capable of assisting in automated maintenance of the global community's satellite catalog, including correlation of lost objects to current observations and elimination of duplicate objects. Additionally, the correlation of satellite catalog entries to readings from multiple disparate sensor systems means that independent sensor sites will be able to correlate their own readings to objects of interest in the catalog and maintain their own metric data in the event connectivity to the larger enterprise and access to the satellite catalog is lost.

9. CONCLUSION

We are in the early stages of our research. We have established a set of desired satellite attributes. Our current effort is focused on identification of viable techniques to obtain the desired information. Our goal going forward is to identify specific sensors that could provide the data necessary to implement the identified techniques. We would then evaluate approaches to task the sensor and receive the information in a timely manner. Longer term we would establish a historical database for all objects to establish pattern of life baselines.

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.

10. REFERENCES

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