Comparison of Phenomenology for Satellite Characterization

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1. ABSTRACT SUMMARY

Techniques for improved characterization of Satellites 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, multiple phenomenologies that support satellite characterization will be discussed to include: optical, radar, signals, and Infra-Red. The paper will identify satellite characteristics that could be gleaned from the various data types. Algorithms that support extracting the information will be referenced. Unique collection conditions that enable a phenomenology to yield desired data will be discussed. This paper will discuss the impact of changes to satellite characterization data types over the life of an on-orbit asset. 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) was comprised of 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 has caused misidentification, resulting in cross tagging objects. Occasionally, objects may not be located 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 and the space environment. Techniques for characterizations of satellites have been an area of research for several years due to limitations 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 specific information needs will be identified along with identified research techniques. The specific phenomenology necessary to obtain the desired information and potential sensors used in the research will be identified.

3. SATELLITE CHARACTERIZATION

In order to characterize satellites, we must first understand the specific pieces of information we need to obtain. Fig 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.



Fig. 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.

4. Orientation 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.

Analysis of time-series data, as shown in Fig 2, 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

Fig. 2 Orientation Characteristics

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

5. Material Composition

Many of the sensors used to maintain the 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

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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. Fig 3 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 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 require coordination of multiple observing locations.





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.

6. Thermal Composition

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 the 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, the observer is seeing the solar panels edge-on. With larger and smaller angles, the observer is presented with more of the solar panels' area. Given the solar panels large size, it would be the dominate feature. When observing satellites at ~90 degrees phase angle, we are seeing mostly the flux from (hot) transmitters and the cooler spacecraft bus behind the transmitters. The emissivity-area changes with the larger and smaller phase angles due to the solar panels converting sunlight into electricity, which is stored in on-board batteries.



- ~90 phase angles forms minimum
- Solar Panel dominates unresolved collection
- Solar Panel orientation to sun results in V shaped graphs

Derived Temp Vs Phase Angle



- Planck function fits used to derive temperate
- Techniques to de-mix component contributions area of future research



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.

7. Propulsion

The approach described in *Satellite Maneuver and Predictive Analysis (SatMAP)* [6] investigated techniques to extract useful information from GEO satellites' maneuver behavior. A time history of position and previously detected maneuvers was established to identify pattern of life behaviors. This formed the basis to predict expected

future position and identify maneuver points and type. Changes from the established behavior were examined to reveal useful information.

The creation of a database containing the time history of several vehicles revealed similarities in the data based on the propulsion type. SatMAP categorized the GEO population into two propulsion types: conventional thrust and electronic propulsion. Conventional thrust systems produce maneuvers of short duration with a significant delta velocity. The electronic propulsion systems had maneuvers of much longer duration with a delta velocity that gradually grew over time. The pattern of life information revealed the electronic propulsion strategy was directly correlated to available power. This resulted in season variations of the station keeping tolerances and shown in figure 5.

The figure also provides a pattern of life analysis used to estimate the available fuel aboard the satellite. East/West station keeping has been maintained throughout the life of the vehicle. A minor longitude adjustment was observed, but the East /. West station keeping continued. The vehicle initially performed North / South station keeping maneuvers (Inclination was controlled). Changes in the inclination strategy have been observed. This is a potential indicator that the vehicle may be low on propellant.

• Satellite Maneuver Analysis and Prediction (SatMAP) tool extracts useful pattern of life information from GEO satellites' maneuvering behavior

	Lon Min	Lon Max	Inc Min	Inc Max	RAAN Min	RAAN Max	Last Update
Jan	-100.8754	-100.8272	0.0401	0.0862	71.8284	92.0164	2011/01/31
Feb	-100.8714	-100.8268	0.0107	0.0901	70.3976	119.0013	2011/02/28
Mar	-100.8698	-100.8379	0.0379	0.0917	76.2511	112.0878	2011/03/18
Apr	-100.8806	-100.8416	0.0433	0.1157	71.1697	108.6256	2010/04/30
May	-100.9095	-100.8231	0.0241	0.1110	52.4845	89.5989	2010/05/27
Jun	-100.8827	-100.8215	0.0302	0.0960	65.7531	84.5546	2010/06/28
Jul	-100.8753	-100.8213	0.0044	0.0807	40.1156	90.2596	2010/07/31
Aug	-100.8738	-100.8399	0.0161	0.0780	68.5645	352.4971	2010/08/31
Sep	-100.8838	-100.8356	0.0318	0.1062	69.9786	116.0764	2010/09/30
Oct	-100.8746	-100.8366	0.0342	0.1027	60.7023	121.2602	2010/10/27
Nov	-100.8791	-100.8223	0.0470	0.1218	60.5853	85.6710	2010/11/30
Dec	-100.8803	-100.8358	0.0409	0.1447	66.5977	91.6755	2010/12/31

Later The Analysis

- Electronic Propulsion strategy
 based on available power
- Seasonal variations driven by eclipse conditions

Available Fuel Indicator



Chinasat 22

- E/W Station-keeping controlled
- Inclination went uncontrolled
- Inclination strategy change may indicate vehicle low on propellant

Fig. 5 Propulsion System Analysis

8. Mission Status

Pattern of Life information from SatMAP has been used to identify mission anomalies and recovery. 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.



Fig. 6 GALAXY-15 Failure of 2010

9. Results Summary

A search of available satellite characterization approaches was conducted. Fig 7 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 phenomenology 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 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	

Fig. 7 Characterization Attributes

10. 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.

11. REFERENCES

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