Space Object Characterization

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ABSTRACT

This paper reviews how space object characterization is performed for Space Domain Awareness. The phenomenology upon which space object characterization is based is reviewed first. Then we present the types of sensors and the observations that made of this phenomenology. Finally, we discuss how space object features are estimated using the sensor observations.

1.0 PHENOMENOLOGY

In the 17th century, Rene Descartes established the principles of the modern scientific method. Too numerous to mention are the philosophers over the preceding centuries and his contemporaries who contributed to the logic and processes of the scientific method. Figure 1-1 illustrates the scientific method and highlights how it is an ongoing process as more knowledge is obtained.

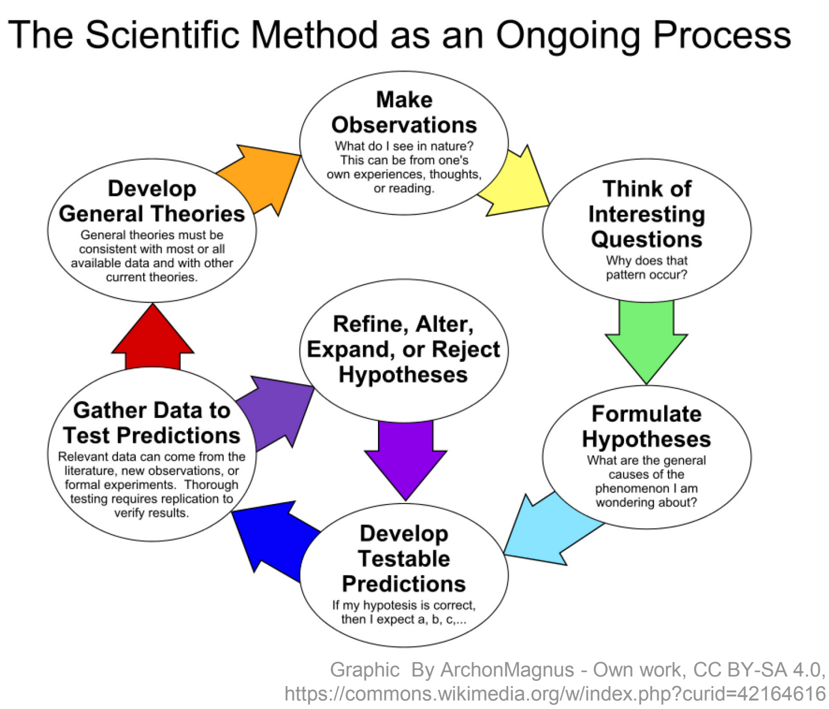

Figure 1-1: One Graphical Representation of the Scientific Method.

Remote sensing sciences are a branch of science for which following the scientific method is particularly challenging because by its very nature, no direct experimentation can be performed on the object under study. So techniques are required to establish protocols for remotely testing the objects under different conditions in order to understand their behaviour and predict it. Astronomy, as one of the oldest sciences, has established many of the methods by which most remote sensing techniques are based.

For the purposes of Space Domain Awareness, the objects being remotely sensed are man-made objects in Earth orbit. The light off of these objects is the mechanism by which they are sensed. The word light is a mundane term used for referring to the energy received via the electromagnetic (EM) spectrum. The EM spectrum ranges from radio waves with the longest wavelengths and the lowest frequencies through the infrared and visible regimes to the most extreme regime of gamma rays with the shortest wavelengths and highest frequencies. EM energy (light) travels at a constant speed, c, in vacuum, where $c = f \times \lambda$. Light that is emitted can be affected by matter in three different ways. It can be transmitted, reflected, or absorbed. Light interacts with other matter that is on the order of the same size as its wavelength. Figure 1-2 shows the range of the EM spectrum with some common everyday items that are the same approximate size as the wavelengths of the different EM regimes.

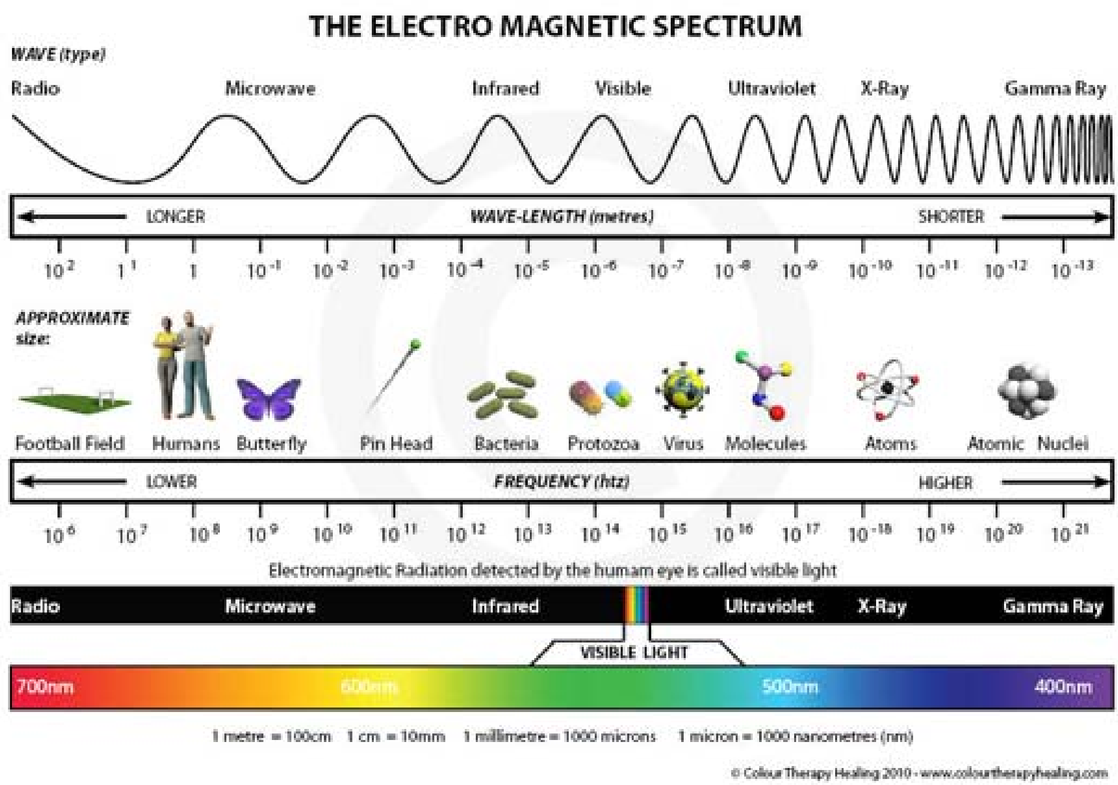

Figure 1-2: The Electromagnetic Spectrum.

The light from space objects in the different regimes of the EM spectrum is how the satellites are detected and tracked. To illustrate how this is done, the visible spectrum will be used. In Figure 1-3, the International Space Station (ISS) is shown. Note that the actual length of the ISS is approximately 100 meters (roughly the length of a soccer field). In the panel on the far left, a sensor collected an image of the ISS from which many distinguishing details of the ISS can be seen. But in Space Domain Awareness, these types of images are few. As you go from left to right in the figure, the images get smaller and fewer details can be seen until on the far right the ISS in only a dot with no distinguishing features discernible to the human eye. Mostly sensors collect data that appears like the image on the far right.

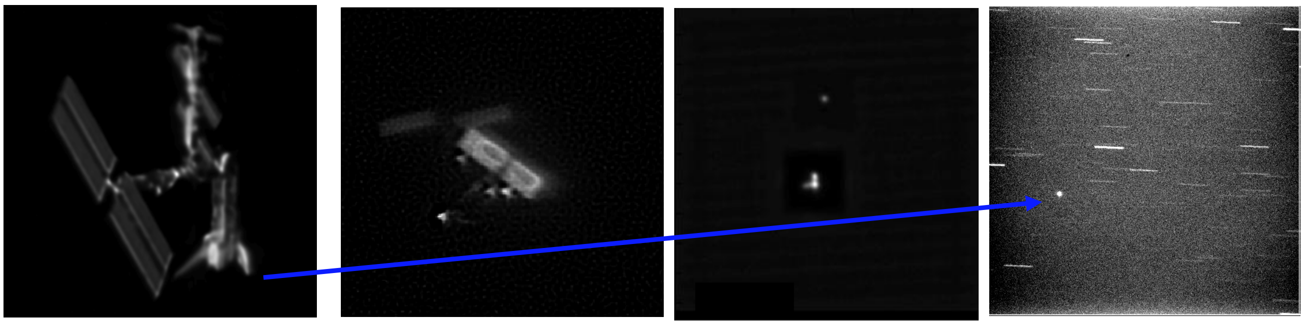

Figure 1-3: The Space Domain Awareness Challenge.

There are two factors that are responsible for this state of affairs. But first, let us review why an image can be taken at all. These images are taken using telescope systems. Telescopes magnify far-off objects viewed through them. As the telescope aperture size (the light collecting area) increases, so does its imaging capability, called resolving power, i.e. the ability to resolve details in the image. The first factor that causes most images to be only dots, is that the smaller the object, the smaller its angular size. The second factor is that as objects get farther away, their angular size gets smaller. An object 100 meters long at the distance of the geosynchronous orbit (40,000 km) has an angular extent of 1.4324 x 10-4 degrees or 0.52 arcseconds. An object smaller than 100 meters would obviously have an even smaller angular extent.

To get some sense of how small this is, the angular extent of the dot in far right panel of Figure 1-3 is about 5 arcseconds. So this dot is approximately 10 times larger than the extent of a 100 meter object in geosynchronous orbit. Using larger telescopes is not necessarily the answer either because the Earth's atmosphere dims and blurs light from space such that the smallest dot resolvable is about 0.5 – 1.0 arcseconds across. This same effect causes the stars to twinkle.

The phenomenology under study for Space Domain Awareness is contained in the EM energy from orbiting space objects. We can measure the position of the source of the energy, how much energy, the spectral content of the energy, and the polarization of the energy. We can also measure how these quantities change with time.

2.0 SENSORS AND OBSERVATIONS

Recall that light interacts with matter like a particle sometimes and at other times like a wave. The particles of light are called photons. When a photon impinges on a detector, it is called a photo-electron event because the photon causes a cascade of electrons in the detector. This event is recorded and read out of the detector resulting in a measurement of energy at a given time. Understanding the flow of this energy with time is how space object characterization is performed.

There are two main types of sensors used in Space Domain Awareness based on the type of EM energy they detect. For the purposes of Space Domain Awareness, the EM spectrum is divided into the radio frequencies and all other higher frequencies. The sensors that operate at radio frequencies are radar systems. Radar is an acronym for RAdio Detection And Ranging. Sensors operating in the shorter wavelengths are optical systems. They sense in the infrared and visible regimes.

2.1 Radar Systems

Radar systems emit a pulse of EM energy that travels outward. The signal is reflected back by the objects and received by the sensor. The antenna works as both a transmitter and a receiver. The receiver sends the signal to a detector where the returned energy is measured and recorded. Figure 2-1 shows what a radar dish antenna and a radomes look like.

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Figure 2-1: Radar Systems.

2.2 Optical Systems

These systems collect light from a space object in the ultraviolet, visible, and infrared parts of the EM spectrum. The larger the collecting area of the telescope, the fainter it can detect and the better it can resolve. The light telescopes detect can either be reflected or self-emitted EM energy. After the light is collected by the primary aperture, it is redirected through the system to a detector where the EM energy is measured and recorded. Figure 2-2 shows examples of various telescope systems. From left to right, they increase in primary aperture size. Telescopes of various sizes all have important roles to play in collecting data for Space Domain Awareness.

Figure 2-2: Optical Systems.

3.0 SPACE OBJECT FEATURE ESTIMATION

The goal of space object characterization is to transform the sensor observations into information about the space objects. The types of information that can be obtained from the measurements of the EM energy detected over time are shown in Figure 3-1.

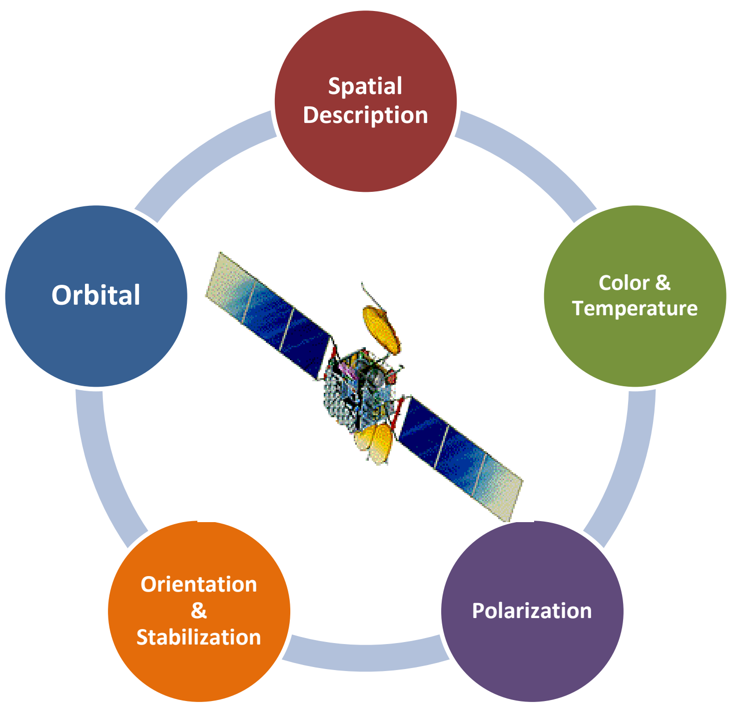

Figure 3-1: Available Information about Space Objects from Sensor Observations.

The exact process is different for each sensor type and varies among sensors of the same type depending on what kinds of detectors are used. For the purposes of this paper, the discussion is limited to optical sensors with imaging detectors where it is assumed that the space objects are too small, too far, or both to have measurements containing spatially resolved images.

In general, the processing involves extracting the energy off the detector. Figure 3-2 shows an image of the sky on the top left containing stars and space objects. The images are processed such that the space objects are identified, shown in the image on the top right. The energy collected on the detector is then typically converted to stellar magnitudes. A series of such images are processed resulting in light curves, which are brightness measurements with time. The graphs on the bottom left and right in Figure 3-2 show that for various space objects in the image, there are variations in the brightnesses. These variations are used to try to understand the properties of the individual space objects.

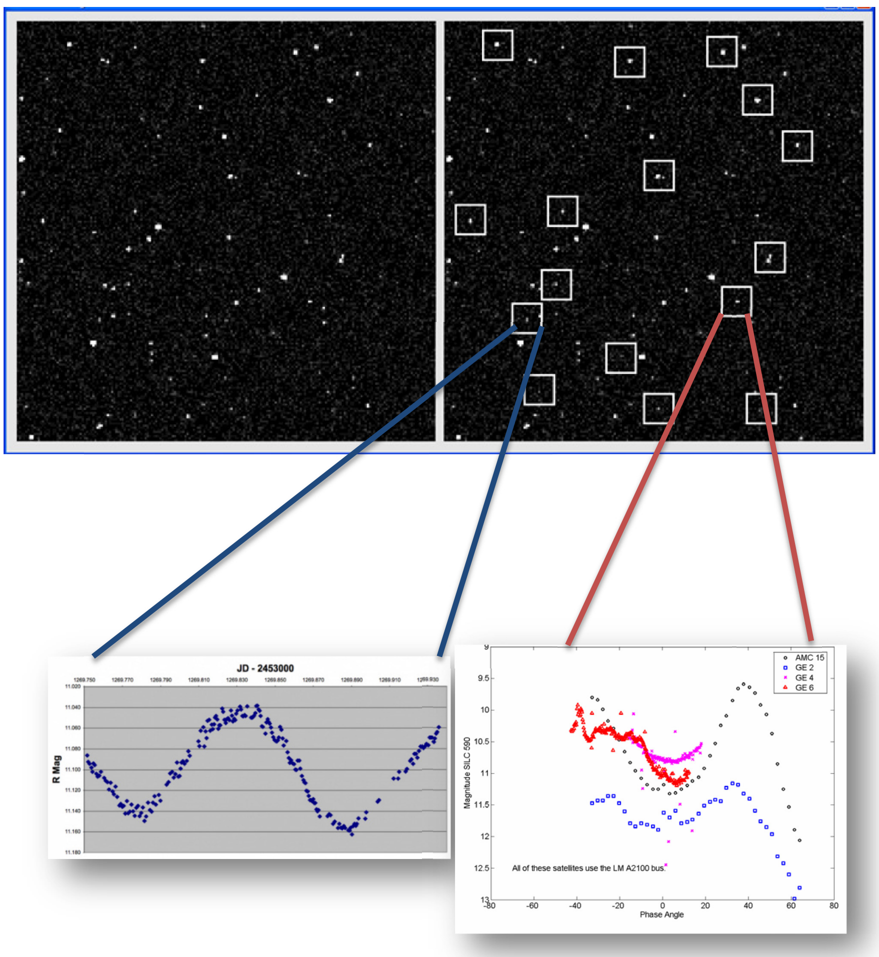

Figure 3-2: An Example of the Processing Optical Sensor Data.

3.1 Periodicity

Brightness variations with time can be used to determine if an object is spinning at a regular rate or is tumbling chaotically. The methods used in astronomical research on variable stars are applicable to studying the variability in the light curves of space objects. Figure 3-3 illustrates the basic process of determining a spin period based on Fourier analysis [1]. A Fourier transform of the brightness observations, shown in the top left panel, is performed and the results are used to form a phase diagram (shown in the top right panel). The Fourier transform yields a period of 10.6 cycles per day. However, because of the existence of harmonic periods, an autocorrelation calculation needs to be performed to verify that the period found was indeed the true period and not a harmonic. This is shown in the bottom left panel of Figure 3-3. The fundamental equation this method is based on is shown in the bottom right panel.

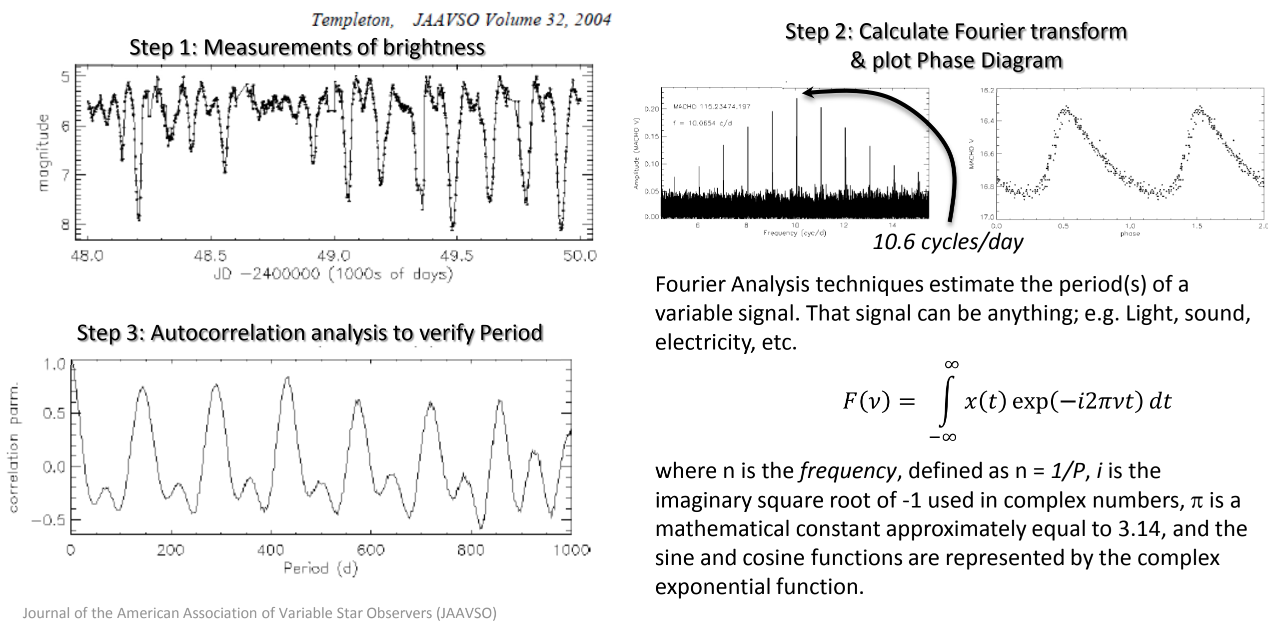

Figure 3-3: An Example of Fourier Processing of Brightness Data for Determining a Spin Period.

3.2 Albedo-Area

The reflected brightness of an object is proportional to 1) the surface reflectivity, i.e. its albedo, denoted *a*; and 2) the size of the reflecting surface, i.e. the area, denoted *A*. The brightness therefore can be used to calculate the albedo-Area product (*a* x *A*). If the value of one of these quantities can be estimated, e.g. the reflectivity, then the size of the object can be estimated. Caution needs to be used when interpreting the meaning on the albedo-Area product because a large object with low reflectivity can have the same albedo-Area product as a small object with high reflectivity. Regardless, the albedo-Area is a feature that can be useful for characterizing an object.

3.3 Three-Axis Stabilized Objects

In the 1990's, satellite manufacturers went from spin-stabilized satellites for deployment in geosynchronous orbit to three-axis stabilized satellites. Although the engineering of these satellites is more complex, the enhanced capabilities of these satellites have caused a proliferation of them in orbit. They are unique among space objects because they are composed of a body section that tracks the center of the Earth and solar panel arrays that track the Sun. The body section has antenna and other appendages that need to point to the Earth in order to perform their functions. Light curves such as were discussed in Section 3.2 yield no period detected for these objects, yet the exhibit changes in brightness. The changes in brightness are due to different illumination conditions experienced by the satellite observer. These conditions can be quantified using a phase angle similar to that of the moon. Over the course of a month, the moon exhibits phases from crescent to full and back again. Geosynchronous satellite also exhibit the same phase behavior but in their case, it cycle completed over the span of 24 hours. Figure 3-4 shows an artist rendering of a three-axis stabilized geosynchronous satellite and a graph illustrating the brightness variations observed in two three-axis stabilized satellites. The phase angle has been defined such that zero phase angle is coincident with the “full moon” phase of the satellite, i.e. the fully illuminated side of the satellite is in complete view of the observing sensor. The sign of the phase angle is such that the negative phase angles represent observations taken just after sunset and positive phase angles represent observations taken just before sunrise [2].

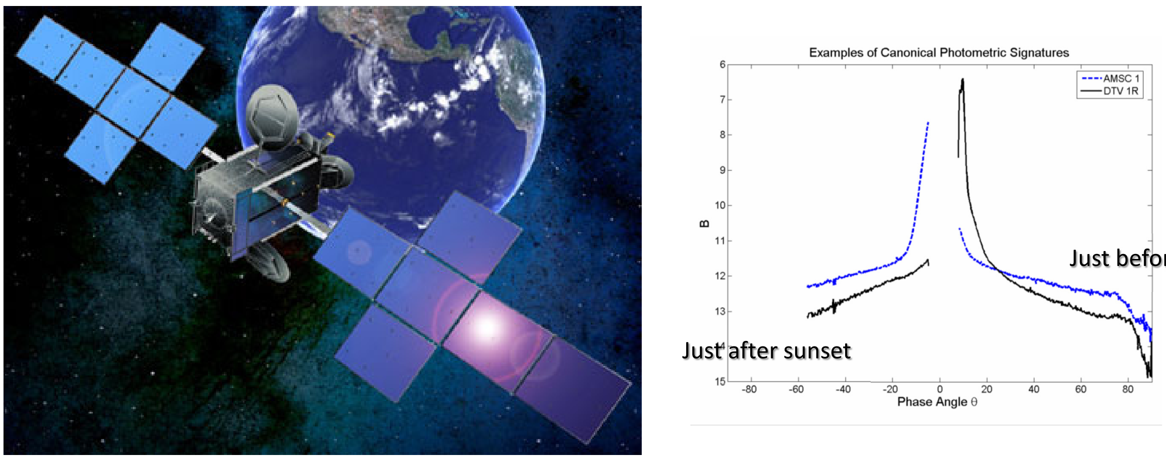

Figure 3-4: Three-Axis Stabilized Satellite Artist Rendering and Examples of Typical Brightness Variations Observed [2].

3.3.1 Solar Panel Pointing Offsets

These same sets of brightnesses collected over the course of the night under different phase angles can be used to determine the pointing angle of the solar panel with respect to the sun. The geometry of the observer, sun, and satellite is used to calculate the solar panel offset. Many satellite operators point their solar panels directly at the sun, others do not. A graphical illustration of this is shown in Figure 3-5. By the virtue of a prudent choice in defining the phase angle, the offset can be read off the graph [2].

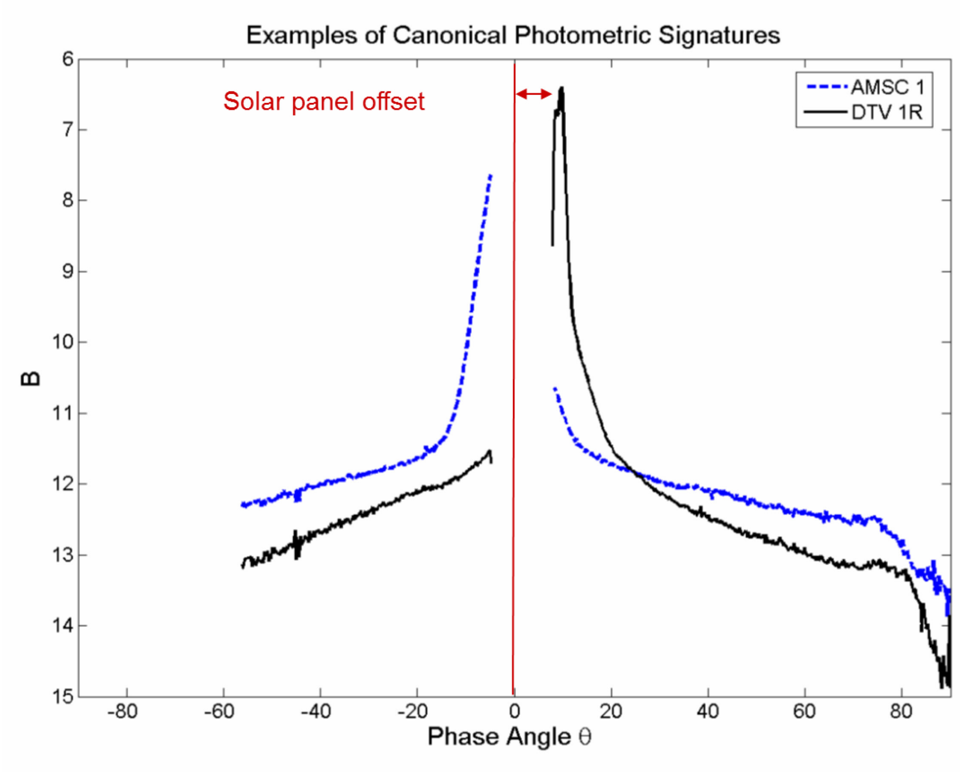

Figure 3-5: Illustration of the Solar Panel Offset Determined from the Brightness-Phase Angle Graph for Three-Axis Stabilized Satellites [2].

3.3.2 Empirical Features

The brightness variations with phase angle exhibited by three-axis stabilized satellites are related to the spatial configuration of the satellite (see Section 3.0 and Figure 3-1) and therefore can be an identifier of the object or object class. This is similar to how a human's signature can be used and so the term "signature" has been coined for these brightness variations with phase angle. The family of satellites with the Lockheed Martin A2100 bus can be used to illustrate how three-axis stabilized satellites can be characterized by their signatures. In Figure 3-6, an artist rendering of an A2100 satellite is shown on the left. On the right, Figure 3-6 shows four signatures of four different satellites all of the A2100 bus type. It can be seen through visual inspection that they all exhibit a significant dimming in brightness of 0.5 magnitudes or more near zero phase angle. They also all show a significant brightening of 0.5 magnitudes or more in the negative phase angles ranging from -40 to -20. Unfortunately, all the satellites could not be measured in the positive phase angle range of +20 to +40 where two of the satellites show a significant increase in brightness of 0.75 magnitudes or more [2]. However, one can still infer that satellites of this type exhibit similar features (brightenings and dimmings in specific phase angle ranges) in their signatures.

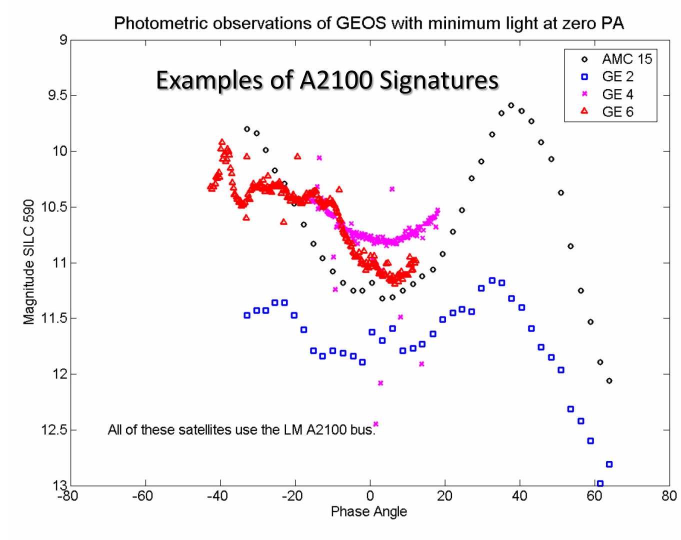

Figure 3-5: The Empirical Features in Signatures of Three-Axis Stabilized Satellites that Can be Used for Characterization [2].

4.0 SUMMARY

Space object characterization is an important part of Space Domain Awareness. By using remote sensing techniques to take observations and using math and science to create information from those observations, characterization of space object properties is performed. Characterization supports our ability to track objects and keep costly assets safe to perform their functions. Space object characterization also supports our study of debris objects and how the space environment affects them.

5.0 REFERENCES

[1] Templeton, Journal of the American Association of Variable Star Observers, Volume 32, 2004.

[2] Payne, T. E., Gregory, S. A., Hall, D.T., Wtterer, C.J., Luu, K., Vrba, F., "SSA Analysis of GEOS Photometric Signature Classifications and Solar Panel Offsets", AMOS Technical Conference, September 2006.