Determination of Satellite Characteristics through Visible Light Intensity Analysis

C1C Shane Bruski, C1C Samuel R. Harms and C1C Michael P. Jones
Department of Astronautics, United States Air Force Academy, Colorado, 80841

Lt Col Neil Thomas and Dr. Scott R. Dahlke
Department of Astronautics, United States Air Force Academy, Colorado, 80841

While many governments attempt to obtain information about satellites passing overhead using expensive equipment such as radar or large telescopes, many characteristics of a satellite, its orbit, and possible mission type can be inferred through analysis of its light intensity variations as it passes overhead. Using off-the-shelf equipment, a satellite can be tracked and recorded with a camera during visible sightings. Images are normalized based on range, the amount of atmosphere the light travels through, and the percentage of satellite illumination. A plot of the intensity versus time is created from these images. Based on patterns displayed by the light intensity graph, a satellite's cross-sectional ratio, its orientation to the earth, and its movement in the orbit can be determined. This inexpensive and easily duplicated process is done with only light intensity analysis. The satellite itself need not actually be resolved in the images.

Nomenclature

B_I = Intrinsic brightness of satellite
B_O = observed brightness of satellite
F_ρ = Coefficient of range's effect on satellite observed brightness
F_{atm} = Coefficient of atmosphere's effect on satellite observed brightness
F_{ill} = Coefficient of percentage of satellite illuminated by the Sun's effect on satellite observed brightness
ρ_m = minimum range from satellite to observer for a given pass
ρ_o = actual range from satellite to observer at a certain instant
N_{atm} = Number of atmospheres light must pass through from satellite to observer at a given moment
el = elevation of satellite at a given moment
α = extinction constant

I. Introduction

The following paper describes the developed mathematical process to determine satellites characteristics based off their light intensity curves. First a technical analysis will outline the tracking and recording system we use to gather data. Then the development of the mathematical data reduction model will be explained to provide insight about how the recorded data is corrected to describe the intrinsic brightness of a satellite that directly correlates to the characteristics of the satellite. Additional sections on the models application to data results, real world application, and potential improvements to the model will also be addressed.

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II. Technical Analysis

This system uses entirely commercial off-the-shelf equipment. The main component of this system is a camera attached to a telescope tracking mount driven by a computer. The computer controls both mount tracking and image acquisition. The camera was purchased from The Imaging Source, which also provided IC Capture.AS 2.2. IC Capture interfaces with the camera to provide a live preview window and the ability to record images in a variety of formats. The software utilized is either freeware or provided with the equipment. SatTracker, one type of freeware, interfaces with multiple brands of telescope mounts and tracks satellites based on TLE text files. TLEs for most satellites can be obtained from NORAD or websites such as heavens-above.com. For this project, we recorded the data as uncompressed avi video files. Many different software packages are available that accomplish the same objectives, but two more freeware programs, Virtualdub and Iris, were used in initial data reduction. Virtualdub is a tool used to break up the avi video recordings into image sequences. Iris is then used to analyze the satellite's brightness value in each frame, providing an output data file of the apparent intensity.

The current system has successfully recorded satellites as dim as magnitude 5.6. Based on saturation estimates from the camera, it is estimated that good data can be gathered on satellites as dim as magnitude 6.2. Dimmer satellites will of course require longer exposures in order to gain usable intensity data, decreasing the number of samples acquired through the duration of the pass. Some passes have recorded up to a 160 degree sweep of the sky with up to 900 frames of usable intensity data.

III. Model Development

A mathematical model to translate the observed brightness into intrinsic brightness was created to infer shape and dimensional information from the recorded data. The intrinsic brightness is how illuminated an object is if it were at a set distance and fully illuminated with nothing obscuring the path between the observer and object. An ideal satellite would be spherical in shape and have a perfectly reflective surface which would produce a constant intrinsic brightness. The raw data provides us with uncorrected absolute brightness values which inherit the effects of the atmosphere, range of the satellite, and the angle between the sun, satellite, and ground observer, causing a higher or lower percentage of the satellite to be illuminated.

To create the model, a few assumptions must first be made. The first assumption is that the satellite is assumed to have a constant albedo. Second the model does not take into account possible cloud layers that could skew the data. The skewing of data due to cloud layers is reduced by reviewing sky coverage predictions during observational planning. Data is not used for analysis if cloud cover is noticed by the observer. The four main factors that our model takes into account to determine the intrinsic brightness of a satellite are considered the most significant and sufficient to gain an understanding of the satellites characteristics. The following is how our model corrects for these factors. The final equation that takes into account all the attenuating factors affecting the raw data is the following:

$$B_I = \frac{B_O}{F_\rho F_{atm} F_{ill}} \tag{1}$$

A. Range Factor

The simplest factor that affects the raw data is the range of the satellite, F_ρ. The range of the satellite to the observer can be determined from its orbit, provided the TLEs for each satellite observed are known. It is know that light radiates in a spherical manner and a portion of the spherical area is captured by the camera's sensor. The result is the factor that is dependent on range is calculated using the square of the range of the satellite; this is due to the fact that the area of a sphere is the square of its radius. Additionally, the factor is the result of the ratio between the minimum range the satellite will reach during a pass and its range at any instantaneous time during a pass. This ratio is used to standardize the range effects across observations. The range factor equation has the following form:

$$F_p = \left(\frac{\rho_m}{\rho_o}\right)^2 \tag{2}$$

B. Atmosphere Factor

The next factor that is taken into account is the attenuation of the raw data due to the thickness of the atmosphere. This dimming is dependent on the distance that the light travels through the atmosphere. This dimming is not constant due to the differing thickness of layers of the atmosphere. Where at an elevation of 90° light has to travel through only one atmosphere, at elevations approaching 0°, light has to pass through nearly 40 atmospheres. The atmosphere is considered the thinness at the zenith and increasing with thickness as the angle of observation increases towards the horizon. The elevation angle between the horizon and the object observed has been correlated to the number of atmospheres by astronomers that developed the following equation [1]:

$$N_{atm} = \frac{1}{\cos(90° - el) + .025 e^{-11\cos(90° - el)}} \tag{3}$$

The amount of attenuation of that the light will experience due to the atmosphere will be dependent on the number of atmospheres the light passes through and the opaqueness of the atmosphere on the wavelength of light. The resulting change in brightness, ΔB, based on an infinitesimally small increase in atmosphere length, Δx, can be determined by simply multiplying the change in atmosphere length by the intrinsic brightness of the object and some coefficient α, which increases as the number of atmospheres increases. This is represented in Equation 4.

$$\Delta B = -\alpha B_I \Delta x \tag{4}$$

Integrating over the total number of atmospheres in the path to determine the final brightness at the observer, B_O yields the below integral.

$$\int_{B_I}^{B_O} \frac{dB}{B} = -\alpha \int_0^{N_{atm}} dx \tag{5}$$

And thus

$$\ln B_O - \ln B_I = -\alpha N_{atm} \tag{6}$$

Rearranging the previous equation results in the final equation describing the diming factor of the atmosphere

$$F_{atm} = \frac{B_O}{B_I} = e^{-\alpha N_{atm}} \tag{7}$$

The value of the extinction constant α is taken as 0.137 for observations made at approximately 2 km above sea level [1].

C. Illumination Factor

The last factor affecting the intrinsic brightness of the satellite is the percentage of satellite illumination at each moment of the observation. This is determined by the angle between the Sun, satellite, and observer. When the angle between the sun, satellite, and observer equals 180 degrees, the satellite does not appear to be illuminated. This occurs when the sun is directly behind the satellite as perceived by the observer on the Earth. When the angle is less than 180 the satellite is illuminated, becoming fully illuminated at zero degrees. At angle the observer is directly in between the sun and the satellite. The percentage of illumination of the satellite can thus be determined by the following equation:

$$Illumination\,\% = \left[\frac{180° - (Angle_{Sun-satellite-observer})}{180°}\right] 100\% \tag{8}$$

The resulting percentage of illumination is used to extrapolate what the approximate illumination of the satellite is. This percentage is thus applied to the raw data by multiplying the percentage value by the other extinction factors. There is some error created by this process which could be due to an irregularly shaped satellite appendage causing shading of the satellites body surface. Error could also stem from the satellite being covered with highly reflective paint or metal, etc., which would reflect more light back to the observer, creating a larger signature than the actual dimensions of the satellite would imply. The assumption is reasonable for symmetric bodies like rocket boosters/stages, or cube like satellites. The final form of the illumination attenuation factor is the following:

$$F_{ill} = Illumination\ \% \tag{9}$$

Again the final equation below shows how the intrinsic brightness is calculated by dividing the absolute brightness, or raw data value, by the multiplied sum of all the attenuating factors.

$$B_I = \frac{B_O}{F_\rho F_{atm} F_{ill}}$$

IV. Model Application

The mathematical model used to translate the observed brightness into intrinsic brightness was created to infer shape and dimensional information from the recorded data. The raw data provides us with uncorrected absolute brightness values which inherit the effects of the atmosphere, range of the satellite, and the angle between the sun, satellite, and ground observer, causing a higher or lower percentage of the satellite to be illuminated. Our model corrects for these factors. Figure 1 shows each of these extinction factors during an observation of an SL-3 R/B on 22 October 2011. ‘Fro’ is the range factor, ‘Fatm’ is the atmosphere factor, ‘Fill’ is the illumination factor, and ‘Ftot’ is a combination of all of the extinction factors. For example, when at frame 200 this satellite will only appear about 20% as bright as it does at its maximum during frame 375 if its actual intrinsic brightness is unchanging.

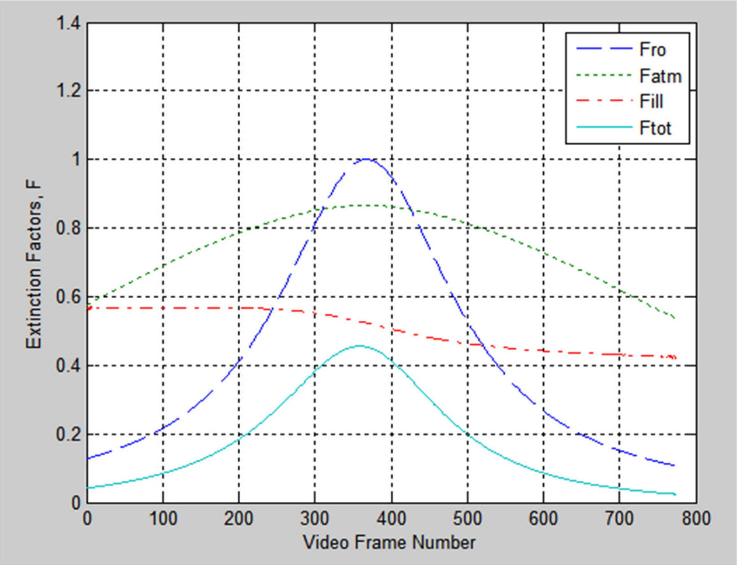

Figure 1: Combined graph of extinction factors. *This based on the correction model as applied to SL-3 R/B on 22 Oct 2011.*

A featureless reference satellite is a spherical object at a constant distance that is fully illuminated. As discussed above, this ideal case has a constant normalized intrinsic brightness of unity since a constant surface area faces the observer during the entire pass. But if the observed satellite is not ideal then the range of observed intensities will yield information about the object’s shape. After multiple observations of the same satellite this model would provide us with the estimated absolute area ratio for the satellite. Once this data is compiled for multiple satellites with known dimensions, a correlation of the ratio data for actual size of the satellites compared to the brightness values would be known. Thus the dimensions of an unfamiliar satellite can be determined based on ratios of intrinsic brightness.

After applying the model we have the intrinsic brightness of the satellite as it passes overhead. Intrinsic brightness is required so that values from different parts of the pass can be compared directly. Figures 2 and 3 compare the apparent and intrinsic brightness of SL-3 R/B, NORAD ID 12586. Figure 2 shows the brightness before the model was applied and Figure 3 shows after it was applied. Without applying the corrections it would be very hard to draw any conclusions from Figure 2 since it is dominated by the aforementioned attenuation factors. In Figure 3, however, it is obvious that the satellite appeared unusually bright initially and exhibits an even dimming in intrinsic brightness with a minimum shortly after its highest elevation.

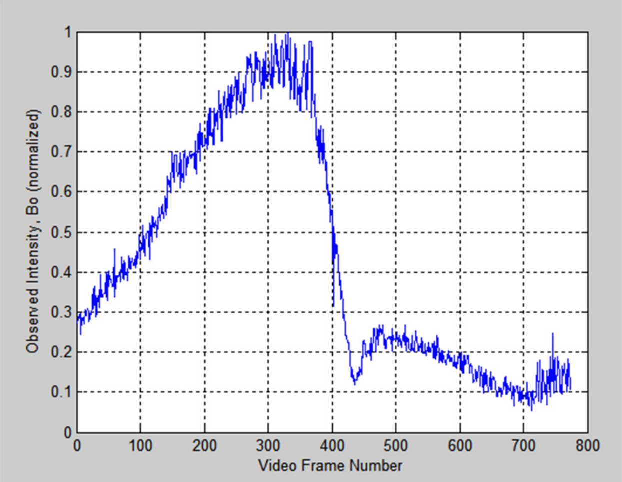

Figure 2: **Raw apparent brightness without model applied for SL-3 R/B on 22 Oct 2011.**

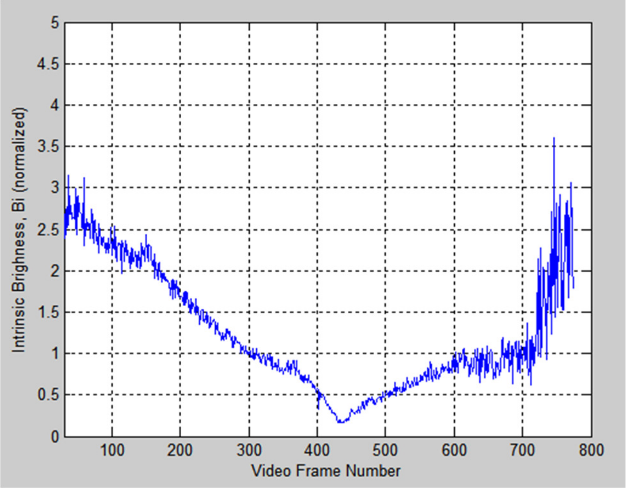

Figure 3: Corrected intrinsic brightness with model applied for SL-3 R/B on 22 Oct 2011.

The data analysis tools we developed can provide a great deal of other information regarding the satellites that we tracked. Most of the graphs of their intrinsic brightness displayed similar patterns; some maintained a constant brightness, others decreased in brightness as they flew overhead, some increased in brightness as they passed over, and some displayed sinusoidal oscillations.

NORAD ID 04814 displayed a constant brightness through the duration of its pass also on 22 Oct 2011. Based on the TLE data, we plotted the expected change in brightness of the object based on range, percent illumination, and the amount of atmospheres the light would travel between the spacecraft and the ground camera. This was done by merely summing each extinction factor at each frame number of the pass. The graph of this estimation was overlaid by the actual viewed brightness and is shown below in Figure 4. Our approximation proved incredibly accurate, and because of that we can discover the intrinsic brightness of the spacecraft did not change during the duration of its pass. The graph of ID 04818's intrinsic brightness for the duration of the pass is shown in Figure 5.

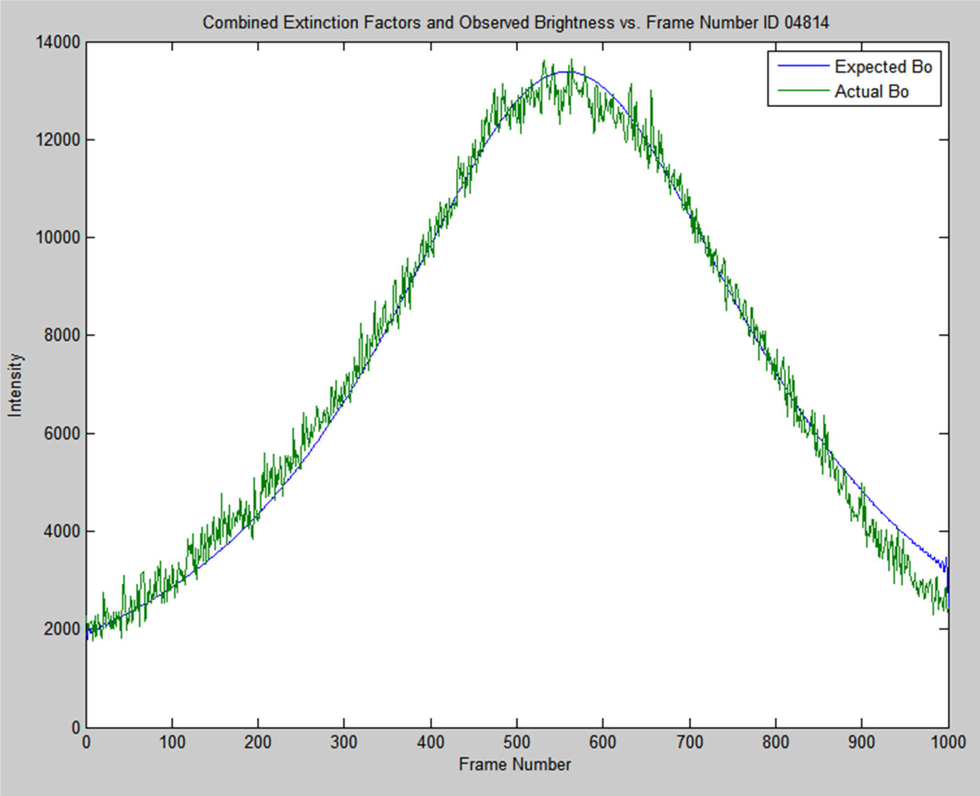

Figure 4: Raw apparent and expected brightness for ID 04814 on 22 Oct 2011

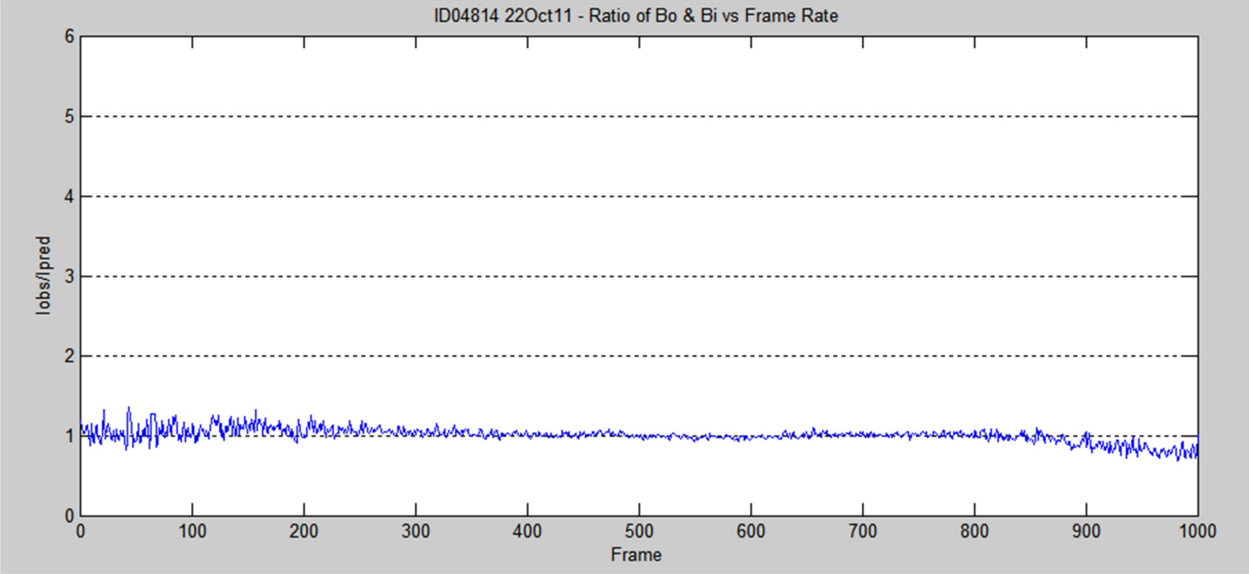

Figure 5: Intrinsic Brightness during pass for ID 04814 on 22 Oct 2011.
Notice the nearly steady brightness intensity for the duration of the pass.

Recall that the model was created to estimate the brightness resulting from a spherical or cube-like shape. According to the RAE Table of Earth Satellites from 1970 [2], NORAD ID 04814 is a Cosmos Rocket body, cylindrical in shape, with dimensions of 3.8 meters long by 2.6 meter in diameter. Since it is roughly spherical in shape, almost as wide as it is long, the data we found closely approximates what the data shows in Figure 5. Because the estimated real brightness from the extinction factors matched almost identically the actual brightness data observed on 22 October 2011, it can be inferred that at the angle the spacecraft was viewed from the ground, its perceived surface area remained the same. This is either due to the spacecraft itself being homogenous in shape or because the spacecraft's orientation to the observer remaining constant throughout the pass.

Some spacecraft also exhibited an intrinsic brightness through the duration of a pass that fluctuated in a sinusoidal manner. NORAD ID 28096, an Atlas 2AS Centaur Upper Stage booster, was observed on 17 November 2011. Its normalized intrinsic brightness is shown below in Figure 6.

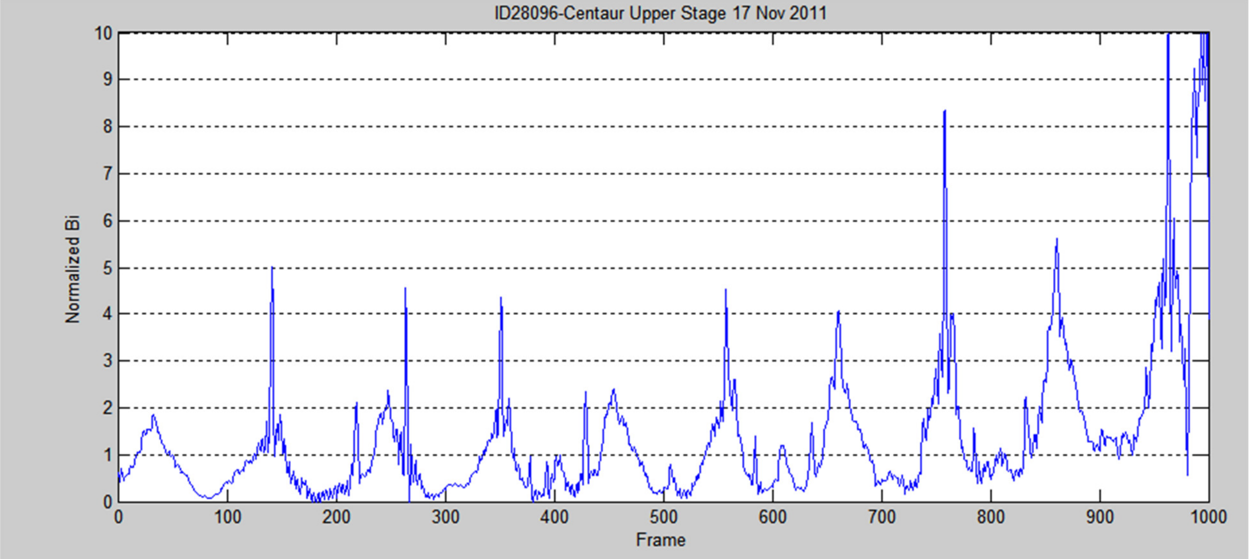

Figure 6: Intrinsic Brightness during pass for ID 28096 on 22 Oct 2011. *Notice sinusoidal nature of brightness intensity.*

It is quite obvious to note the cyclical nature of the intrinsic brightness of this spacecraft. This is due to alternatively larger and smaller surface areas reflecting sun back to the observer. The only way a satellite would reflect brightness in this manner is if it were tumbling in orbit. Further the individual periods of brightness cycles are constant throughout the pass, indicating that the spacecraft has reached some sort of steady state in its rate of tumble, suggesting that the spacecraft is no longer operational. In the case of a rocket body, this should be known anyway. If, however, a previously operational satellite displayed these sorts of tendencies, ground observers could determine the spacecraft is at least at this point in time no longer operational. This could be extremely beneficial for ground controllers in trying to determine causes for possible losses in communication with spacecraft.

The brightness spikes that occur near frame numbers 150, 260, 560, and 770 also are interesting to note. These flashes could indicate moments where some part of the spacecraft body reflected direct sunlight toward the ground observer, similar to using a magnifying glass or watch face to direct sunlight onto a single point.

While in most cases the model provides a close approximation to the actual size of a satellite, it does not always occur. Depending on the orientation of a satellite, it could appear to have a constant intrinsic brightness when in reality it is rectangular or spherical in shape, much longer than it is wide. For a constant brightness to be observed, a cylinder would only have to be oriented as shown below in Figure 8.

Figure 7: Top View, Front View, and Side View of cylindrical object that from ground could be perceived as spherical in shape

Shapes and basic mission profiles can be inferred for many of the above brightness patterns. Satellites that had a constant brightness are most likely stabilized, with an equal surface area on each side. These are most likely spherical or box-like in shape. Satellites which displayed increasing or decreasing brightness, like SL3-R/B, are again most likely stabilized in their orbit, but have body profiles that cause this change in intrinsic brightness. For example, a satellite with a long, rectangular body pointed at the Earth would appear largest near the horizon, but appear to be smallest when directly overhead. Satellites like this are more than likely used to collect data on the Earth, such as weather data collection, communication antennas, or even some spy satellites. Likewise, satellites which have increasing intrinsic brightness when flying towards the observer and decreasing intrinsic brightness when flying away from the observer have a shape that looks smallest when near the horizon and largest when overhead. This could be the result of a stabilized rocket body in orbit or other school-bus shaped objects oriented horizontally. Finally, satellites which show sinusoidal oscillations in their observed intrinsic brightness are tumbling objects, either old and inoperative satellites or rocket bodies discarded after launching some payload. The largest danger is in collisions with other operative satellites. Since they are uncontrolled, other satellites would have to maneuver to avoid them in cases of impending collisions.

The first three patterns all infer a stabilized and operative satellite, with the exceptions of rocket bodies. Particularly interesting are satellites that decrease in brightness as they fly over, a potential indicator of surveillance satellites. Many rocket payloads launched by countries such as Iran and China are closely held secrets, but if this analysis was used to observe a satellite launched from one of these countries as it flew over the United States, easily and quickly obtained information could be provided to decision makers as to the potential mission profile of the satellite.

V. Conclusion

Real World Application

The system developed in this paper can prove useful for any agency interested in developing cheaper methods of acquiring and maintaining LEO situational awareness. This has recently become an increasingly sought after asset. Alternative methods to light intensity analysis include resolving the satellite directly, or space-based surveillance. The first of these methods requires a much larger, more expensive telescope and highly accurate pointing and tracking software. Even with the best telescopes, atmospheric distortion will preclude direct resolution of many small satellites. In-situ spaced-based surveillance would be even more demanding of resources. The system developed in this research can also provide information on the size, shape, and orbit of most LEO satellites. While this information may not be as exact as that provided by a more complex analysis tool, there is a clear benefit to possessing a mobile, easy to use system that provides consistent usable data at a fraction of the cost.

Potential Improvements

One of the first improvements that could be made to the system is to create software that combines all the functionality of the current freeware and provided programs. A MATLAB program has already been developed to interface with the camera mount and track satellites from their TLEs. Another MATLAB program has been developed to interface with the camera and provide image acquisition. This program will be able to use azimuth and elevation data from the tracking program to provide positional data for each frame that can be used in the future for orbital analysis.

Our current system is mobile, but not weatherproofed to allow for temporary long-duration deployment. There would be no reason to try to observe a satellite during inclement weather due to the lack of visibility, but due to the tedious setup and alignment procedures required for proper operation, weatherproofing would mitigate operational maintenance and save time for the user to focus on data analysis.

Additionally, the current system is setup with the user near the system and fully controlling the data recording process. Improvements are in the works to remotely control the system off-station via the internet and remote desktop control software. The system is also being developed to automate data recording to minimize user time spent during the recording process and maximize time available for the data analysis process. By maximizing user time for the data analysis process, a higher degree of situational awareness can be obtained.

While our current model provides data that seems to be fairly meaningful, there is always room for improvement. Currently, brightness is just normalized to a value of one for each satellite. This is because based on predicted brightness; camera shutter length is increased or decreased to ensure quality data is collected. By taking into account that the shutter length varies on a logarithmic scale and that satellites with longer shutter lengths are typically much dimmer than those with shorter shutter lengths, the intrinsic brightness of each object could be compared on the same scale to other observed objects. After collecting data from known spacecraft such as the ISS, weather satellites, and other objects of which the dimensions are known, a database could be created which relates brightness to actual satellite size. While a precise size cannot be determined due to uncertainty in regards to the reflectivity of each object due factors such as paint color, this model would at least be able to indicate differences in the relative size of two objects compared to each other, as well as say if an object is school bus sized or merely couch-sized.

Further, a more refined sketch of a satellite could also be determined through use of a polar plot. At each time step of a pass, the range, azimuth, elevation, and brightness of the object being tracked are known. By plotting the intrinsic brightness of the object with the azimuth for each time step a silhouette might be created. The rendering can further be refined by plotting multiple observations of the object from different relative positions, such as viewing the object from Montana and Arizona simultaneously, etc. Unfortunately, this analysis does not work for tumbling satellites.

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[1] Luciuk, Mike. "Atmospheric Extinction and Refraction." *Amateur Astronomers, Inc.* 23 Mar. 2004. Web. Dec. 2011. <http://www.asterism.org/tutorials/tut28-1.htm>.

[2] "The RAE Tables of Artificial Satellites 1957-1992 and the Extended Tables 1993-2011." *SATLIST*. 2 Nov. 2011. Web. 07 Mar. 2012. <http://www.satlist.nl/>.