SSA Analysis of GEOS Photometric Signature Classifications and Solar Panel Offsets

Tamara E. Payne
Boeing LTS

Stephen A. Gregory
Boeing LTS

Kim Luu
Air Force Research Laboratory

1. EXECUTIVE SUMMARY

We analyze the photometric signatures of 36 GEOS located over CONUS or US Pacific territory by introducing a photometry-based classification system. Approximately 80% of these satellites appear to belong to one of two different classifications and can be qualitatively explained by the actual satellite shape. For those satellite signatures with an identifiable peak in brightness, we also examined the satellites' solar panel pointing offsets. The distribution of offsets ranges from -10^o to $+10^o$ and is slightly concentrated near a value of 0^o with a slight positive bias.

The utility of this kind of study lies mostly in two areas. The first is that development of the classification system will lead to better Space Object Identification (SOI) techniques. The second will lead to better Space Situational Awareness (SSA) techniques as observations of change detections in the solar panel offsets give insight into operations, health status, and/or anomalies of satellites.

2. INTRODUCTION

In mid-2006, we are half way though a two-year informal program of data collections and analysis of GEOS located over the US and its possessions. The purpose of this research is to characterize the photometric signatures of satellites in order to determine the feasibility of using of this type of data. This interim report serves to 1) establish our techniques, 2) present our current status, 3) inform our sponsors of where we are and what we have planned, and 4) help cultivate an understanding of the relevance of this work.

The data for this analysis comes from either of two kinds of observing programs. In one kind, a single satellite is monitored throughout the night in order to examine as much of the phase angle (PA) dependence of the photometric signature as possible. In the other kind, specifically designed for this analysis, continuous observations through various filters were conducted for approximately one hour on either side of the predicted zero phase angle for each satellite. In this manner more than one satellite can be observed on each night, and the part of the signature near zero PA is well established, but the large PA portions are not observed. From the resulting light curves, our analysis shows that a large number of satellite signatures can be assigned naturally to a few distinct classifications. In this technical report, we define a new photometry-based classification system, determine the numbers of satellites having each classification; and, for the subset of satellites that show a solar panel signature, determine the degree by which the solar panels are offset from the Sun. Both the classification system and solar panel offset determination contribute to a set of overall diagnostics that enable us to characterize satellites meaningfully as well as to assess certain change detections that may indicate satellite health status or anomalous conditions. The classifications are important because they are tightly correlated with basic bus structure. In addition, the solar panel offsets offer a glimpse into the operations of a satellite. We will justify and elaborate on these points in this report.

Fig. 1. illustrates two of our concepts simultaneously. We use the term "signature" for the behavior of a satellite's brightness vs. either PA or UT. The brightness is measured in magnitude units in which smaller numbers indicate brighter measurements, with a 1 magnitude change or difference representing a flux ratio of $100^{(1/5)}$. So the rise in the signatures seen in Fig. 1. indicates a brightening near 0 PA. Both AMSC 1 and DTV1R have the kind of signature that we define as "Canonical". Although the use of this term for a classification generally implies that it is the most common, we emphasize its use as the archetype, or the most easily understood class, and we will determine the relative frequency of the type later.

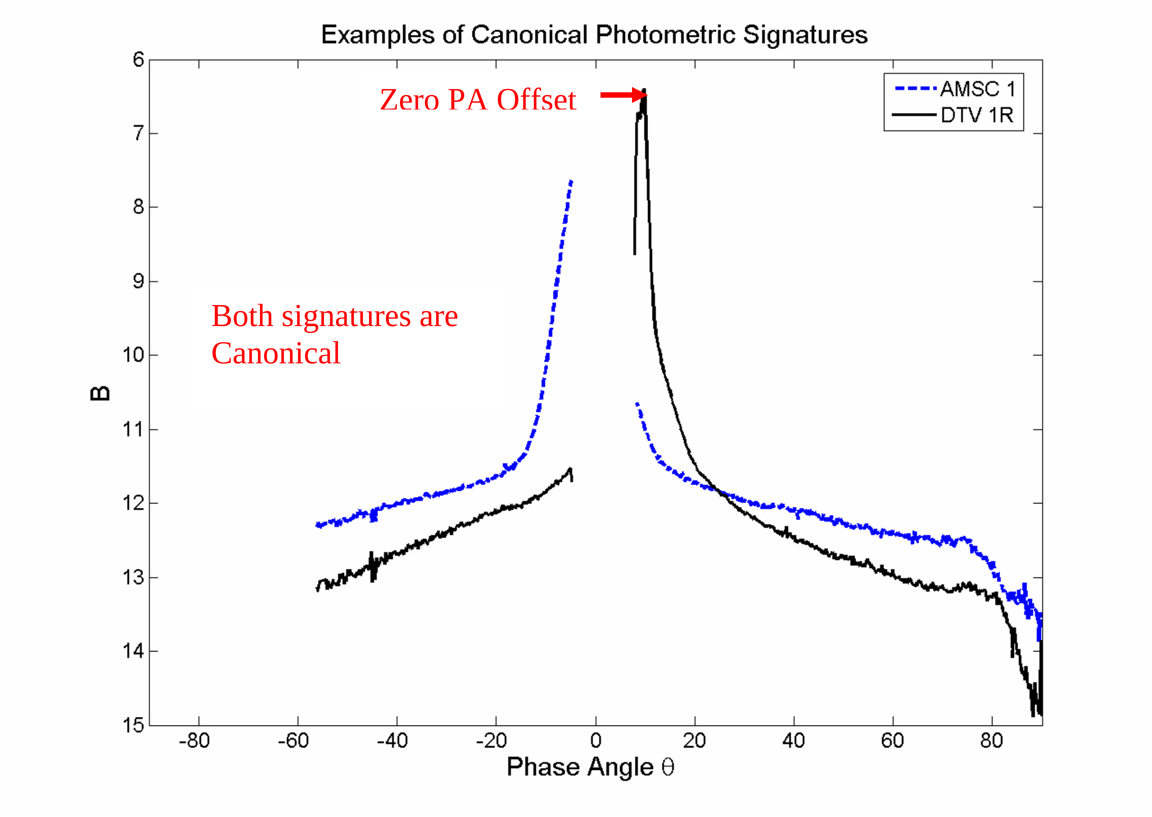

Fig. 1. B magnitude signatures of the GEOS AMSC 1 and DIRECTV 1R from October of 2004, observed with the US Naval Observatory, Flagstaff Station (NOFS) 40" telescope. The gaps in the data near Zero Phase Angle are from passage of the satellites through the Earth's shadow.

3. CLASSIFICATIONS

In order to correlate signatures with models and/or with satellite bus structure, we illustrate an artist's conception of AMSC 1 in Fig. 2. In the Canonical type, the simplest of all photometric signatures, the articulation of the solar panels as they pivot about the major axis of the satellite (to our knowledge always aligned with the Earth's polar axis) leads to the broad "wings" of the signature. The panels are seen edge-on at PAs of $\pm 90^{\circ}$ and face-on at zero PA, leading to the general brightening at the center and a smooth falloff on either side. This signature pattern is interpreted as mostly arising from the diffuse reflection of sunlight from the solar panels. There is often an additional brightness peak near zero PA that varies through the seasons as the sunlight is specularly reflected near the Equinoxes (thereby producing glints) but contributes a much smaller "spike" nearer the Solstices. Contributions from the antennae and the central bus structure add complexity to the signatures and may allow the observer to distinguish among different types of satellites.

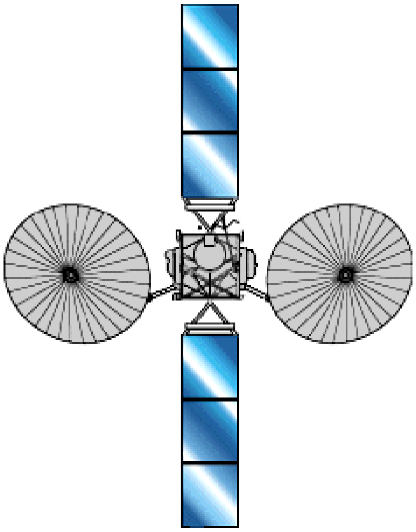

Fig. 2. Example of satellite with canonical signature, AMSC 1. Artist's conception from the Boeing Company web site.

We have modeled satellites with canonical signatures and have used these models to simulate photometric signatures that match the observations to a high degree. However, some other classes of signatures have not been successfully modeled. Yet they are commonly seen, and we need to understand them better. One particular signature is of the A2100 bus type, manufactured by Lockheed Martin. Fig. 3. illustrates this type of signature as seen in the GEOS AMC 15, GE 2, GE 4, and GE 6.

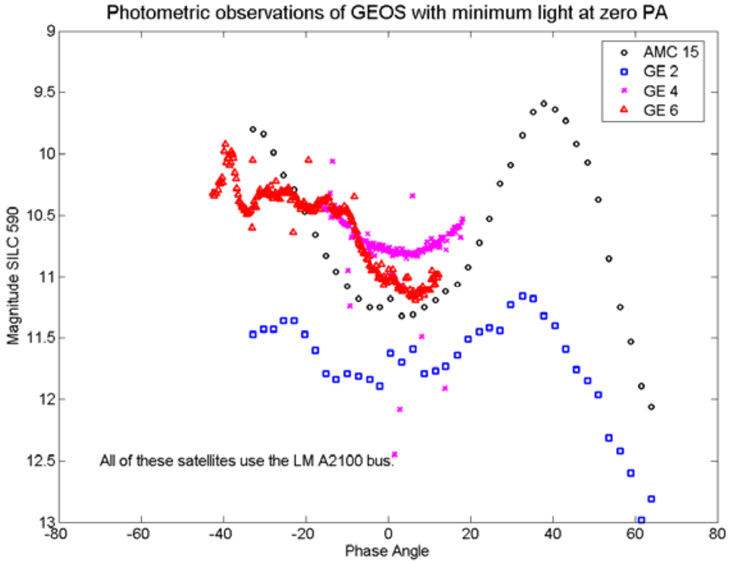

Fig. 3 – Examples of the A2100 class of signature.

An artist's conception of AMC 16, which is also an A2100 satellite with this type of signature, is shown in Fig. 4.

Fig. 4. Example of satellite with A2100 signature, AMC 16. Artist's conception from the Lockheed-Martin web site.

Although we have not developed a full model and simulation of the A2100 satellites, we believe that the central dip in brightness comes from the parabolic reflectors seen in the figure. One might ask why the influences of these antennae are stronger than those of AMSC 1 as seen in Fig. 2. In the latter case, the antennae are built of a mesh structure which unfolds in orbit. If the A2100 antennae are surfaced in a solid (or nearly so) manner, then the effects they produce on photometric signatures would be quite different. We believe that a physical interpretation of the central dip in brightness is better thought of as the redistribution of light to larger values of PA than the removal of light near zero PA.

4. DEFINITION OF THE PHOTOMETRIC SIGNATURE CLASSES

We now list the photometry-based classifications and their definitions:

Canonical Class – In these signatures, there is a zero PA peak with the brightness decreasing on either side of zero PA in a symmetric and smoothly monotonic manner.

A2100 Class – In these signatures, there is a local minimum in brightness at zero PA. One either side, the brightness increases in a smoothly varying manner to about $\pm 40^{o}$ PA. At still greater phase angles, the brightness again decreases smoothly. Most of these signatures show general but imperfect symmetry.

Telstar Class – In these signatures, there is an underlying Canonical signature. However, there are secondary minor brightness peaks (seen most strongly via observations in the blue part of the spectrum) at about $\pm 40^{o}$ PA.

BSS702C Class – In these signatures, there is an underlying Canonical signature. However, there are secondary major brightness peaks at about $\pm 60^{o}$ PA. The secondary peaks are not only brighter but also broader than in the Telstar Class. In this type, the secondary peaks are known to come from solar panel concentrators.

Peculiar Class – In these signatures, there is either a lack of symmetry about zero PA or the brightnesses do not vary smoothly or both.

5. SOLAR PANEL OFFSETS

We now turn to the topic of solar panel offsets, which are detected when the brightness peak (for appropriate signatures) or the center of symmetry (for other types of appropriate signatures) lie at PAs that are different from the value zero. Naively, one would expect all solar panels to point directly at the Sun since, in principle, they follow the Sun as it moves in a circle around the satellite (as seen from the satellites reference frame). However, we have identified three situations in which the panels might have detectable offsets in their pointing: 1) Satellites are generally designed with expected lifetimes of eight or more years. In order for the satellites to have sufficient electrical generation capacity at the end of the designed lifetime, they are built with excess capacity at the beginning to allow for degradation of the electronics and panel materials. The operators are likely to point the solar panels with an offset at launch so that the “young” satellite does not produce too much electricity. 2) With no friction at GEO orbits, very small forces or torques can affect the stability of the satellites. By offsetting one or both (most satellites have two) panels, biases in gyroscope or other torques can be nulled out by re-directing the small radiation pressure forces on the panels. 3) The panels are generally pointed at the Sun by use of two light sensors on each panel. Balancing the voltages of the two sensors should be accomplished when the Sun is centered. However, if the sensors degrade unevenly, then balancing the voltages can lead to un-intended pointing offsets.

6. RESULTS

In Table 1, we present our findings for 36 satellites for which we have sufficient data. Although it would be desirable to perform this analysis with homogeneous data (i.e. observed with common filters), we have completed this work with whatever data we have. Clearly, additional observations through a variety of filters would be helpful. Columns 1 and 2 list the satellite ID number and name. Column 3 provides the solar panel offset (in degrees); “Na” is listed for those whose offset cannot be measured. Column 4 gives the signature classification as defined above with obvious refinements. (For example, a nearly canonical signature would have a type of “Canon-“.) Columns 5-7 list the properties of smoothness, central peak, and symmetry, respectively by use of “n” and “y” to indicate “no” or “yes”; minus signs indicate those cases in which the property is somewhat modified. We note that the strength of the central peak has a strong seasonal dependence, so those with “weak” classification might have strong classification at other times of the year.

Table 1
Results for Classifications and Solar Panel Offsets

Sat #	Name	Offset (degrees)	Signature Class	Smooth?	Strong Central Peak?	Symmetric?
28252	AMC-11	0	A2100	Yes	Weak	No
28446	AMC-15	2	A2100	Yes	Weak	No
28472	AMC-16	2	A2100	Yes	Weak	No
27820	AMC-9 (GE-12)	-5	Canonical	Yes-	Weak	Yes-
23553	AMSC 1	-1	Canonical	Yes	Yes	Yes
26624	ANIK F1	5	BSS702C	Yes-	Yes	Yes-
28378	ANIK F2	-2	Canonical-	Yes-	Yes/ weak dip	Yes

23199	Brasilsat B1	NA	A2100	Yes-	No	No
25937	DirecTV 1-R	7	Canonical	Yes	Yes	Yes
23598	DirecTV 3 (DBS)	9	Canonical	Yes-	Yes	Yes-
26985	DirecTV 4S	-6	Peculiar	No	Yes-	No
28659	DTV-8	7	Canonical	Yes	Yes	Yes
25331	Echostar 4	8	A2100?	No	No	No
27378	Echostar 7	-8	A2100?	Yes	No	?
27854	Echostar 9 (Telstar 13)	6	Canonical	Yes	Yes	Yes
26056	Galaxy 10R	-5	Canonical	Yes	Yes	Yes
26038	Galaxy 11	NA	Peculiar	No	No	No
23016	Galaxy 1R	NA	Peculiar	No	No	No
27445	Galaxy 3C	3	Canonical	Yes	Yes	Yes
23741	Galaxy 3R	3	Peculiar	No	Weak	No
23877	Galaxy 9	-9	Peculiar	No	Yes	No
28884	Galaxy 15	NA	A2100	No	No	Yes-
25954	GE-4	5	A2100	Yes	No	Yes
26580	GE-6	NA	A2100	No	No	No
26639	GE-8	NA	A2100	No	No	No
24713	GE-2	1	A2100	Yes-	No	No
26871	GOES 12	4	Canonical	Yes	Yes	Yes
27954	Horizons 1 (Galaxy 13)	3	Canonical-	Yes-	Yes	Yes-
23846	MSAT-M1	3	Canonical-	Yes-	Yes-	No
24714	Nahuel 1A	-4	Canonical	Yes	Yes	Yes
25740	Nimiq 1	10	Canonical	Yes	Yes	Yes
25558	Sat Mex 5	0	Canonical	Yes	Yes	Yes
25626	Telstar 6	8	Telstar	Yes-	Yes	Yes
25922	Telstar 7	-7	Telstar	Yes-	Yes	Yes
26761	XM-1	-1	Canonical-	Yes-	Yes-	No
26724	XM-2	-1	Canonical-	Yes-	Yes-	No

Table 2 summarizes the relative frequency of the different types. The Canonical class, while not the majority, is the most common.

Table 2
Frequency of Classes

Type	Number	Percentage
Canonical	17	47.2%
A2100	11	30.6%
Peculiar	5	13.9%
Telstar	2	5.6%
BSS702C	1	2.8%

7. DISTRIBUTION OF SOLAR PANEL OFFSETS

Fig. 5. shows a histogram of the distribution of solar panel offsets. They are found to range from -10^o to $+10^o$ with a concentration near 0 PA. (We have observed a -18^o offset – Telstar 7 during its November, 2004 electrical problem. The offset was quickly changed after the problem was resolved.)

There is a slight asymmetry with somewhat more satellites having offsets in the positive direction (panel aligns with Sun later in time than the instant of 0 PA).

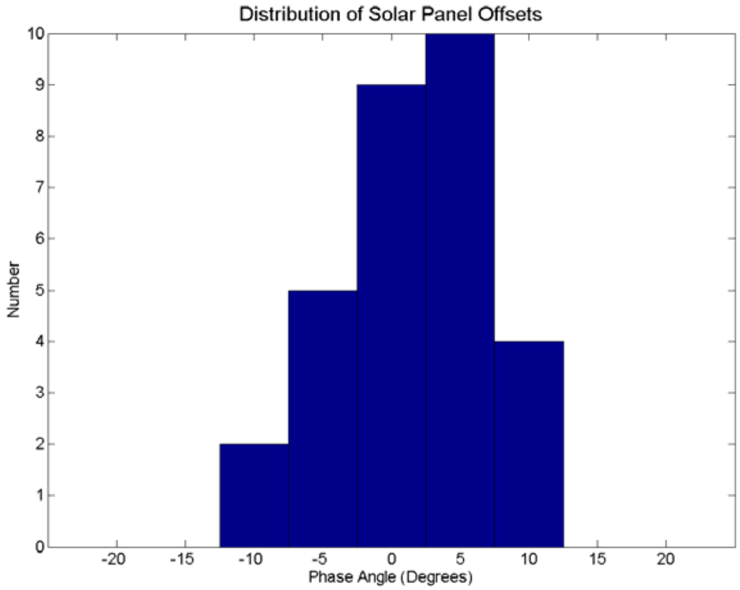

Fig. 5. – Distribution of Solar Panel Offsets

8. DISCUSSION

Why is the military utility of these analyses? The answers lie at the heart of SSA. We give two examples. First, the observational difference between Canonical and A2100 classes is very clear – the difference between a maximum brightness and a minimum brightness at 0 PA. DoD sensors can quickly discriminate between the two since a set of 3 brightness measures with one near 0 PA would immediately decide whether the satellite is most likely one or the other of the two classes. Since these two classes together account for 78% of our sample, this kind of quick classification assessment can be of great importance. If we are eventually able to extend this kind of classification worldwide, then new foreign launches might very quickly be classified.

The second application lies not so much with the distribution of solar panel offsets but with the details. As satellites age, their operators are likely to change the offset. This has already been detected by us between December 2004 and November 2005 for Telstar 7. We thus have made change detections for periods during electrical failure, after resolution of the failure, and after a second offset was applied to the solar panels.

It must be emphasized that this is a work in progress. In addition, our analysis has been based on observations taken through inhomogeneous filters (not all filters were available at all sensors) and sometimes limited to the central 20^o of the PA range. We will revisit the analysis when we have observed all the GEOS over CONUS and US Pacific assets, some satellites multiple times during different seasons and with different filters. With an increase in sample size, we may find more classes than we have currently encountered. This is especially true if we are eventually able to extend this analysis to Asia and Europe where different design philosophies and satellites from different manufacturers will be found.

Finally, the observations necessary to carry out this analysis can be done with inexpensive off-the-shelf telescopes and sensors. These systems lend themselves to automation, and multiple systems at multiple sites could be deployed for global coverage, duplicative coverage to alleviate weather concerns, or on space-based platforms.