Satellite Monitoring, Change Detection, and Characterization Using Non-Resolved Electro-Optical Data From a Small Aperture Telescope

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ABSTRACT

The Air Force Research Laboratory has been pursuing development of the exploitation of passive reflectance signatures collected from electro-optical sensors to obtain information on man-made satellites. Recent data collection campaigns have acquired filter photometric signatures in the visible regime from satellites in a variety of orbits and under a variety of operating conditions. The orbits include semi-synchronous, geosynchronous (geo), geosynchronous transfer, and supersynchronous. The operating conditions include active, inactive, stable, and unstable. These satellites pose unique challenges because many times they are too distant or too small or both to image using conventional means. Therefore, they are ideal candidates to use to develop techniques that exploit non-resolved photometric intensity measurements to determine status, detect changes, identify, and characterize.

The data were collected using a Raven-type sensor system. The telescope has a 16-inch aperture and the optical path includes a filter wheel and a charged-coupled device (CCD). In this paper, we present the data collected from these recent campaigns, the exploitation techniques used, and the results of the analyses. The results will compare signatures from satellites in different orbit regimes under different operating conditions and illustrate the robustness of the techniques.

1. INTRODUCTION

Over the past decade, we have shown the following can be determined about geo satellites at the 90 – 96% confidence level[1]:

- Classification of geosynchronous satellites (geos) by their bus type;
- Identification of individual geos in a cluster (resolution of cross-tagging);
- Anomaly detection and change of operating conditions; and
- Solar panel orientation. (Refs. 1 – 13).

Additionally, we have now collected color photometric signatures of most GEO satellites from mid-Atlantic to mid-Pacific. Most of the observations presented in this paper were collected using the Albuquerque Color Raven telescope that is part of the extended HANDS program. The telescope has a 16-inch aperture and the optical path includes a filter wheel and a CCD.

[1] This is with only 3 to 5 sets of observations in a 24 hour period.

Using these data, we previously have determined there are classes of photometric signatures that correspond to satellite types. The details of the phenomenology are still under study, but initial indications are that these repeatable details and seasonal variations in the signatures might be exploited to determine satellite configuration information and health and status. With data alone, we've been able to ascertain certain differences between individual satellites and solar panel offsets. Simple satellite models with reflectance functions of common materials, we have been able to reproduce some of the visible signatures. (Ref. 13)

This paper highlights the current status of this work via six different examples:

1. Comparison of signatures from a satellite under two operating conditions: active vs. inactive;
2. Comparison of signatures from a satellite with no change;
3. Signatures of unstable objects: a satellite and a rocket body;
4. Signatures of Global Positioning System (GPS) and Molniya satellites;
5. Comparison of satellite signatures taken in different seasons (solar latitudinal effect); and
6. Recent suspected cross-tag situation in the 101^o cluster.

2. CHANGE DETECTION

Due to the dynamic nature of the space environment, satellites can undergo several types of changes. These can include changes in operating conditions where the satellite stops operating normally and can be caused by many different events. A satellite under these conditions many times can become dynamically unstable and start to tumble. However, due to various factors (environmental, aging of system performance, etc.), even satellites operating nominally can undergo changes. The orientation of the solar panels is one example. Often, these changes, both benign and catastrophic, will be reflected in the photometric signatures.

A common situation occurs when a satellite is at the end of its operating lifetime. For a satellite in geo orbit, the satellite is commonly boosted to supersynchronous orbit and then turned off, changing its status from active to inactive. Figure 1 shows the visible photometric signature and color index of Gstar 4 under both active and inactive conditions. These data were taken using the astronomical filters B and R. The full set (UBV) were originally described by Johnson and Morgan, and then later extended by Johnson into the near infrared (RI). (Refs. 14, 15) The B-R color index is defined as:

$B - R = C - 2.5\log\frac{f_B}{f_R}$; where C is a zero-point constant chosen such that B-R = 0 for an A0 type star; and f_B and f_R are the fluxes measured through the B and R filters respectively. The equatorial phase angle plotted on the ordinate axis is defined as the longitudinal component of the angle between the satellite and the anti-solar point. At zero degrees the side of the satellite that is fully illuminated is visible from the observer ("full moon" phase). For positive phase angles, the western side of the satellite is illuminated and for negative phase angles, the eastern side of the satellite is illuminated.

In Figure 1, the 2002 data shows a slowly varying brightness and color change with phase angle indicative of operational geo satellites. The large variation in the 2007 data clearly shows that the satellite is no longer maintaining an orientation with the sun that would indicate that it is operating.[2] It should be pointed out that in this case where the brightness is changing rapidly with respect to the duty cycle of the data collection through the filter set, the B-R values shown in Figure 1 are questionable.

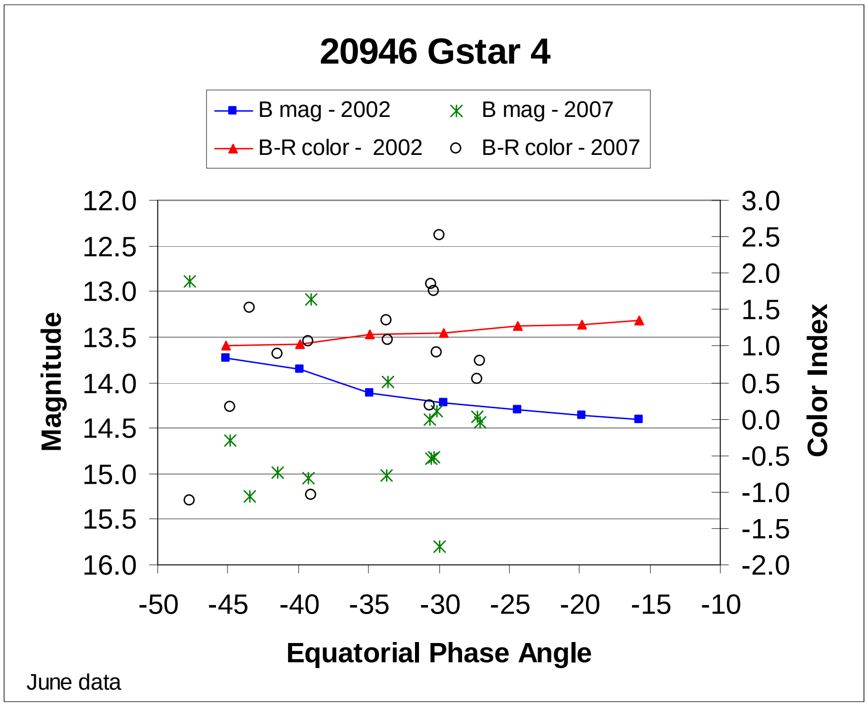

Figure 1. Signatures of Gstar 4 while active in 2002 and inactive in 2007.

It is instructive to examine the case where no operational change has occurred. We can present such as example using the satellite, Brazilsat B3. It is also important to note that not always do we need a full signature (over several decades of phase angle) in order to detect a change or not detect a change. Both of these points are illustrated in Figure 2. It can be seen that the 2007 data, sparsely sampled in phase angle during one night's data collection, compare well with the catalog data from 2006. Over the span of one year, this satellite's signature has not changed dramatically. The quantification of what kind of phase angle sampling is necessary in order to detect changes, minimize false alarms and false positives is currently under investigation. Our results to date indicate the optimal sampling may be dependent on signature/object class, but a standard phase angle sampling may exist that will yield detection of most changes. Figure 3 shows one such data collection concept.

[2] In this instance, we also know this from its supersynchronous orbital element set.

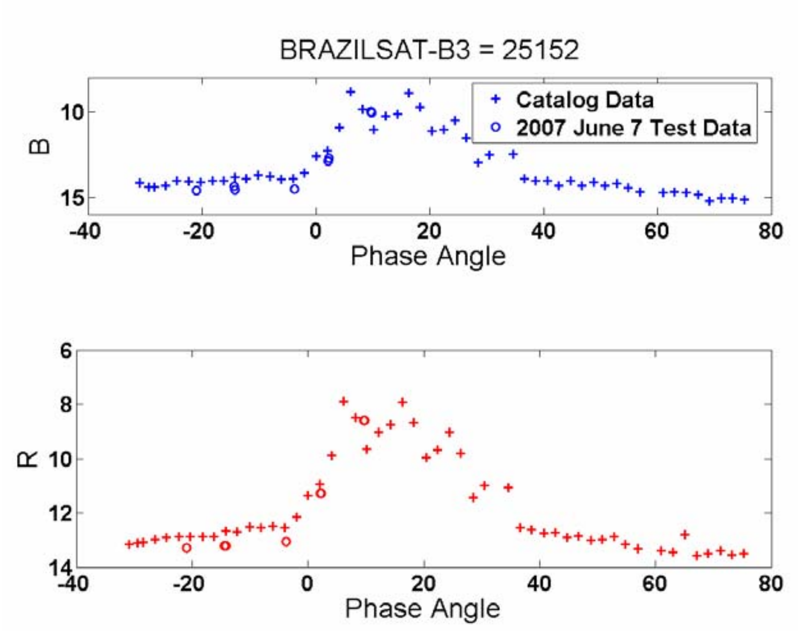

Figure 2. Signatures of Brazilsat in both B and R filters. The catalog data was taken in June 2006. Sparsely sampled data was taken in June 2007.

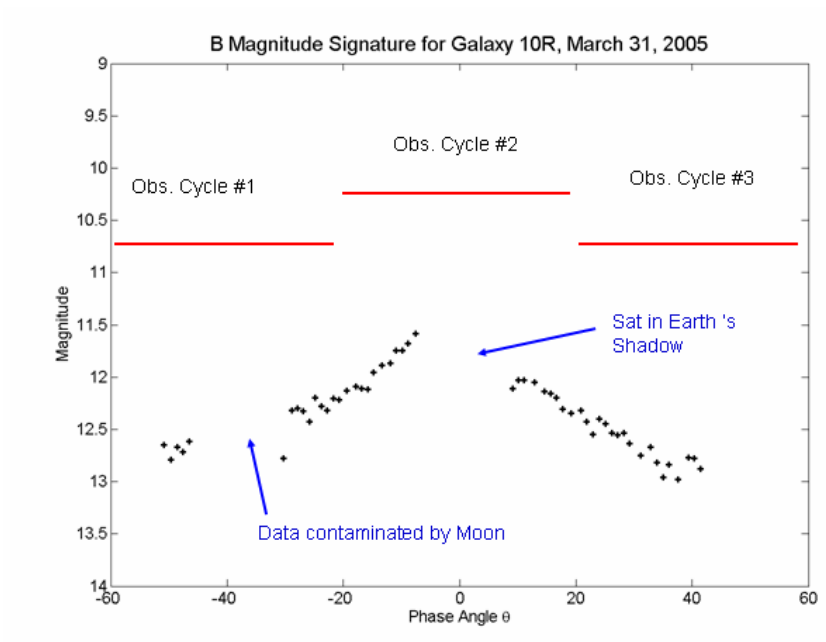

Figure 3. Photometric signature of Galaxy 10R and an example of how data might be collected in order to determine a change in signature but without dedicating an entire night of observing.

Finally, it is instructive to examine photometric signatures of unstable objects. We present two examples of these. The first is an inactive, unstable satellite, Raduga 18. Its signature is shown in Figure 4 taken with no filter. It is slowly tumbling with a period derived from this signature of about 30 minutes. There is a risk of labeling an unstable object in a slow tumble as stable if the data are taken only for a short duration.

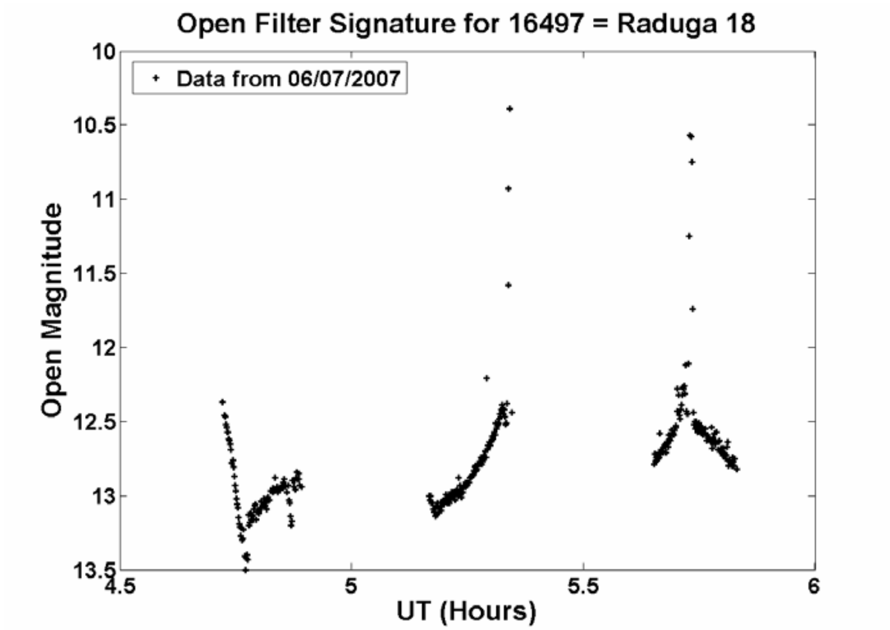

Figure 4. The photometric signature of an unstable satellite, Raduga 18 that is slowly varying.

The second example of the signature of an unstable object is from a rocket body (21129) in geo transfer orbit. Its photometric signature (no filter) and the resulting periodic analysis are shown in Figure 5. The period obtained from this signature is 0.77 minutes. The data in both Figures 4 and 5 were taken at a rate of every six seconds. The gaps in data seen in the Figure 4 are due to taking data on other objects and then returning to this satellite. Both these examples illustrate the need to acquire data for different durations at different times in order to detect changes that exist at different temporal frequencies.

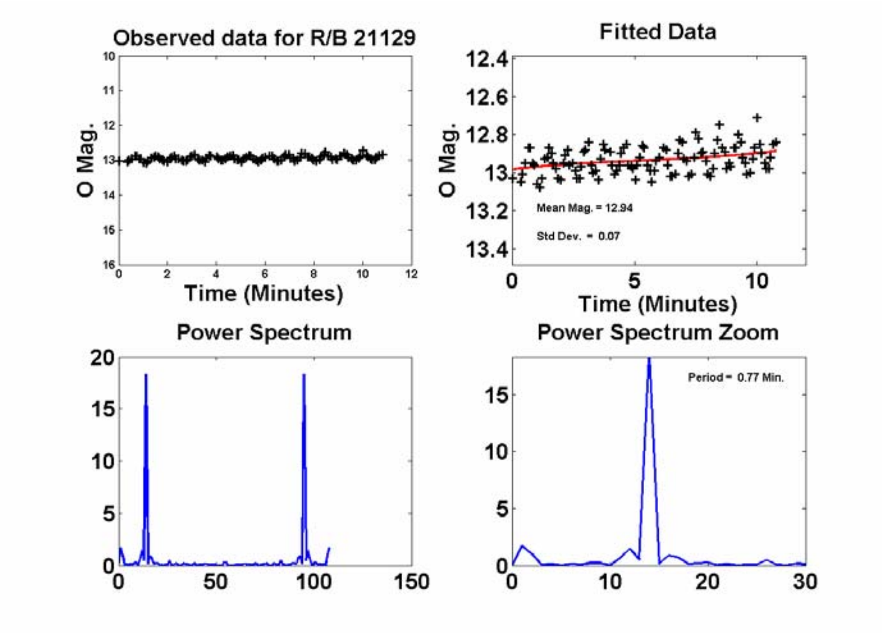

Figure 5. The photometric signature of a rocket body in geo transfer orbit that is rapidly varying with the power spectrum analysis.

Visual inspection of the graphical display of the data easily shows change vs. no change. However, quantification of how different or how much the same the data are is necessary to develop change detections metrics that can be applied over decades of data and over hundreds of satellites. Many statistic methods are available and a few have been tested by the authors. We would like to present results using a metric based on an approach that fits the data to an n order polynomial and then computes the standard deviation of the distances of the data points (both catalog and test) from the fitted polynomials. Recall that the standard deviation is defined as $\sigma = \sqrt{\frac{1}{N-1}\sum_i (x_i - x_{mean})^2}$. So we define R as the ratio of the standard deviations of the test data to the catalog data: $R = \frac{\sigma_{test}}{\sigma_{cat}}$, where the σ's are the standard deviations of each data set from the n order fitted polynomial to the catalog data. So smaller the value of R, the better the fit and the more likely the test data and catalog data come from the same source (i.e., satellite with no change).

The R value that this technique yields for the data presented in Figure 1 of Gstar 4 is 10.2, whereas the R value for the data of Brazilsat B3 is 4.0. We present the R values for some other comparisons in Section 5. We are still assessing whether using this method is the best quantification of change detection and if so, what R values denote a change and the probability of that being in error.

3. EXTENSION TO OTHER ORBIT REGIMES

The passive visible photometric signatures from space objects depend on several parameters that affect the number of incident photons at each wavelength received on a sensor due to the satellite itself: materials, configuration, orientation with respect to the sensor, and range. There are other parameters that affect the detected radiation: atmosphere, optical transmission, and sensor characteristics. By using the astronomical stellar magnitude system and calibration techniques, these latter factors are removed. In this multi-variate problem, then, one approach is to try to hold constant as many parameters you can in order to study the effect of the variation of the others. Using active geo satellites as test objects enables one to hold range and orientation more or less constant and understand the variations in signatures as a function of materials and configuration. Additionally, the illumination angle changes slowly for them and so data collection requirements are minimal. They are also ideal in their tracking simplicity. Our past research efforts have been focused thus.

Recently, we have extended our interests to other orbit regimes and would like to present examples here of that effort. This has necessitated two changes to our typical reporting structure. One is that the magnitudes need to be corrected for changes in range. We have range-normalized the magnitudes to 36,000 km. Another is that the total phase angle needs to be used since the latitudinal changes can occur during a pass depending on the pass geometry.

We present examples of signatures from satellites in two different orbital regimes. The first orbital regime is semi-synchronous. Figure 6 shows the magnitudes and colors of two GPS satellites as a function of the total phase angle. For these initial data collections, the phase angle coverage only overlaps for less than 20 degrees and for larger phase angles. It can be seen that for much of those phase angles, the magnitudes are almost identical, although the signatures are of different slopes. However, at all phase angles sampled, the color indices of these satellites are highly different, so that by using the color index, they could be distinguished from one another easily and thus our conclusion based on this data set is that these are probably satellites with different configurations.

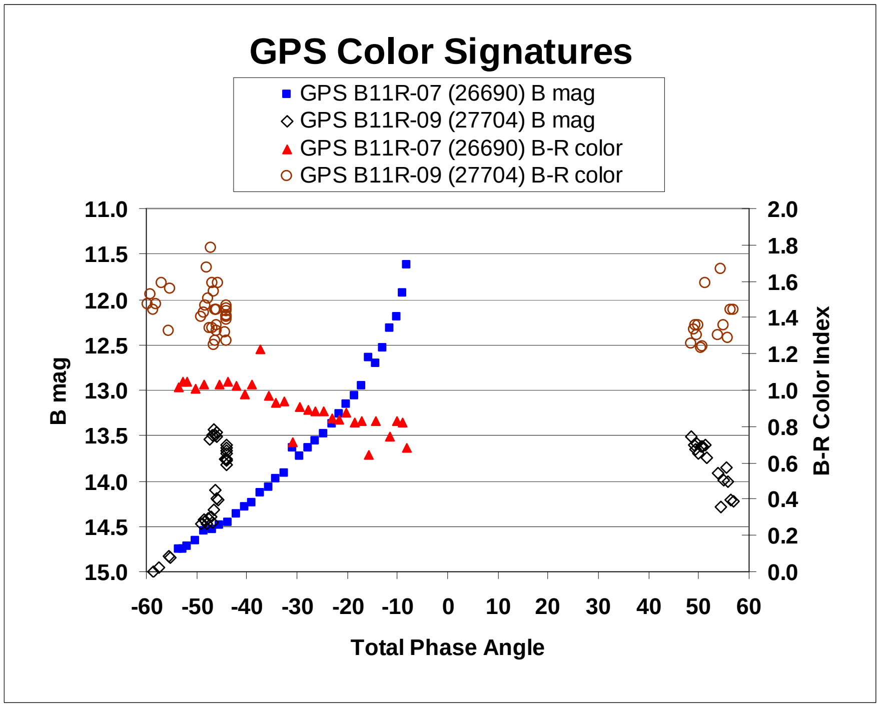

Figure 6. Color signatures of GPS satellites, GPS B11R-07 and GPS B11R-09.

The second orbital regime we collected data on was the highly elliptical orbits. In Figure 7 are the results of our observations of Molniya 1-92 and Molniya 3-51. As can be seen, their signatures in both magnitude and color are virtually the same and so we would conclude that they are similar, if not, identical satellite configurations. Information found on the world wide web by the authors seems to support these conclusions regarding the GPS and Molniya satellites.

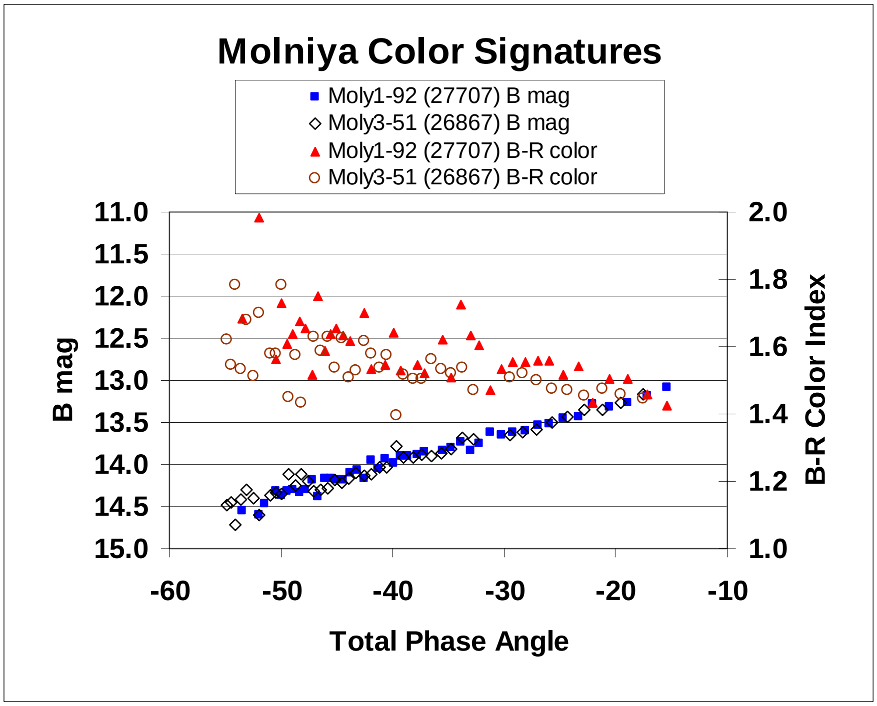

Figure 7. Color signatures of satellites in highly elliptical orbits, Molniya 1-92 and Molniya 3-51.

4. SEASONAL VARIATIONS

In Section 1, we examined magnitudes and colors as a function of the equatorial phase angle for geo satellites. We could do this because over the course of a night the solar illumination angle changes slowly and only in this equatorial plane (except for inclined geos). The effects of the latitudinal variations of solar illumination angle are interesting to consider. During the equinoctial times of the year, a first order effect is that the satellites in geo go in and out of Earth's shadow. Another first order effect is that the direct reflection of the sun into the observer's line of sight. The exact dates this occurs depends on the observer's latitude. The exact times this occurs depends on the orbital parameters of the satellite and its configuration.

We have previously shown how these data can be used to determine solar panel orientation. (Ref. 13) Here we show the extremes of signatures that can be observed to make the point that whatever method is used to monitor and discriminate satellites needs to take this variability in signature character into account. Figure 8 contains two signatures of DTV 1R at different seasons. This satellite has a Hughes 601 bus and exhibits a canonical behavior where it monotonically increases in brightness for both positive and negative phase angles toward small phase angles. The brightening in the June signature appears muted because the scale was set to be able to include the brightening in the March signature. It can be seen that the color in June gets dramatically redder during this low phase angle brightening. At larger phase angles, the color is fairly constant but with smaller fluctuations. In the March data, the brightness varies by almost four orders of magnitude and the eclipse of this satellite occurs between -4.6^{o} and +5.3^{o}, almost centered on zero phase angle. However, the peak in brightness occurs at $+7.7^o$. There are much larger variations in color in the March signature. Some rather large color changes both redder (at -15^o for instance) and bluer (at $+7^o$ for instance). The latter occurring during the peak brightness. Note that this is an opposite color change from the June peak brightness when the color got redder. Other color variations in the March data are rather small (at -20^o for instance). We have tried to ensure that these changes represent true color changes in the satellite by closely examining the data, so at this time, we do not believe these changes are artifacts of any kind. Current research efforts are attempting to understand the mechanism behind these color changes.

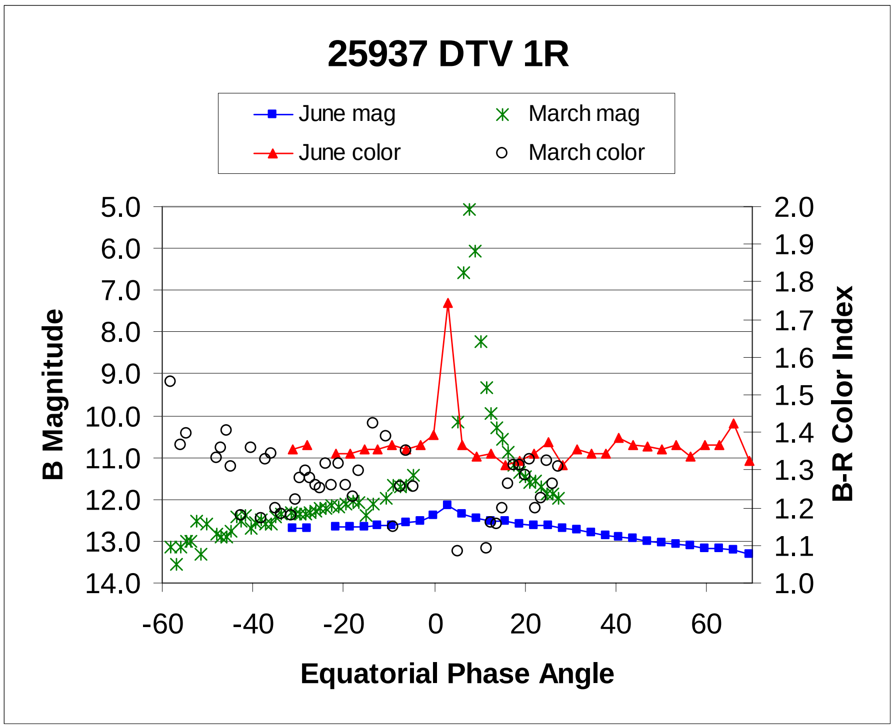

Figure 8. Color Signatures of a geo satellite (DTV 1R) during different seasons.

5. CLUSTER CROSS-TAGS

A problem can occur in tracking and tagging closely spaced geo satellites (commonly referred to as clusters). These are satellites that are station kept within 1^o in angular subtense of the sky as seen from a ground-based observer. One such cluster contains the satellites GE-4 and DTV 4S and is located at roughly 101^o longitude. We have a great deal of historical data on all the satellites in this cluster (since 1996), so we know their individual signatures well. Our recent data suggests that these two satellites have been cross-tagged. Figure 9 shows the photometric signature of the cataloged data for GE-4 taken in June 2006 and a subset of data taken in June 2007. Clearly these data do not match and yield an R = 31.3.

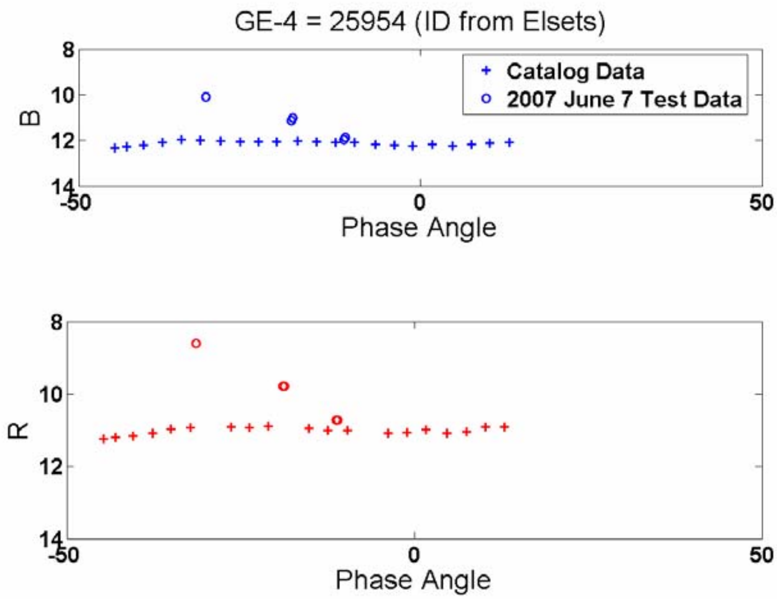

Figure 9. B and R cataloged signatures of geo satellite GE-4 taken in 2006 compared with B and R data taken in 2007 of a geo satellite labeled GE-4 from the element set.

However, if we compare this same 2007 data to a cataloged signature of DTV 4S taken in June 2006, Figure 10 shows that the 2007 data agrees much better. The R value in this case is 1.9.

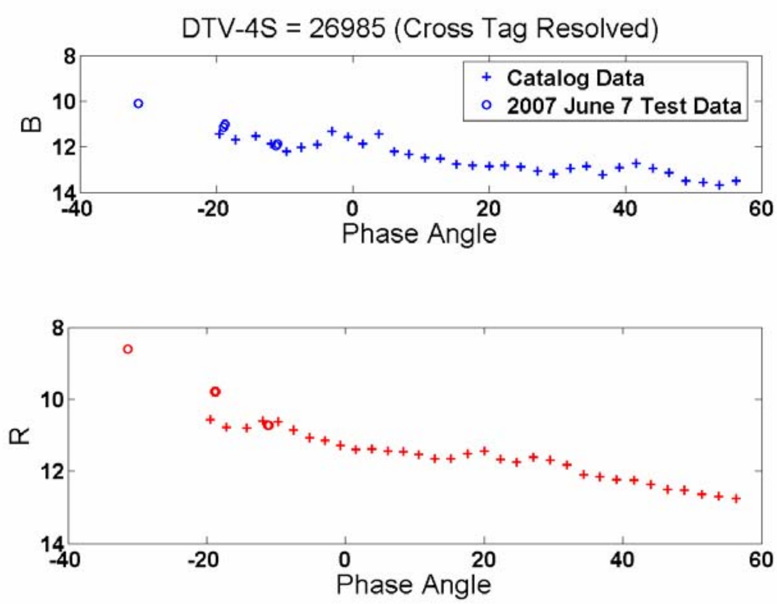

Figure 10. B and R cataloged signatures of geo satellite DTV 4S taken in 2006 compared with B and R data taken of what was labeled GE-4 in 2007 element set.

Alternatively, we can compare the results of the 2007 DTV 4S data to the cataloged GE-4 signatures taken in June 2006. Figure 11 shows that this too is a much better fit with an R value of 3.4.

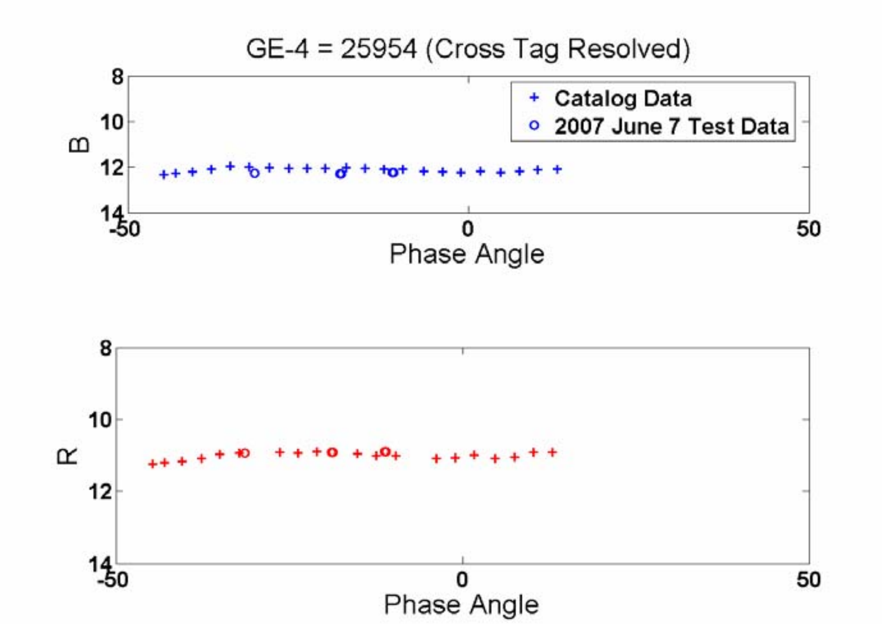

Figure 11. B and R cataloged signatures of geo satellite GE-4 taken in 2006 compared with B and R data taken of what was labeled DTV 4S in 2007 element set.

6. CONCLUSIONS

We have summarized the recent results of using color photometry signatures of satellites in six different areas:

- A comparison of signatures from a satellite under two operating conditions: active vs. inactive;
- A comparison of signatures from a satellite with no change;
- Signatures of unstable objects: a satellite and a rocket body;
- Signatures of satellites in non-geo orbital regimes: GPS and Molniya satellites;
- A comparison of satellite signatures taken in different seasons and a description of the solar latitudinal effect; and finally,
- Recent suspected cross-tag situation in the 101^{o} cluster and a hypothetical resolution of that cross-tag.

We have presented a statistical method (the R value) with which to quantify how similar cataloged data is to newly acquired test data and its application for detecting changes and cross-taggings. We have shown that satellites in other orbital regimes besides geosynchronous orbits have similar color signatures to geos and that the application of color photometric techniques can be applied to ascertain if satellites have similar or different configurations.

Future work will involve exploring 1) the mechanism behind the color changes noted in the color signature data, and 2) assess statistical approaches needed to assign a quantitative value to the probability of change or no change, and minimize false negatives and false positives. The approach presented here being one possibility.

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