Analysis of Photometric Signatures of DTV-10 Collected 8 Years Apart

C1C Adam W. Masters[1], Major Kody A. Wilson [1], Francis K. Chun [1], David M. Strong [2], Casey P. Schuetz-Christy [3]

[1] *USAFA, DFP, 2354 Fairchild Drive, Suite 2A31, USAF Academy, Colorado 80840*

[2] *Strong EO Imaging, Inc., Colorado Springs, Colorado 80908*

[3] *Millennium Engineering & Integration Co., Colorado Springs, Colorado 80919*

ABSTRACT

This paper will describe the process we used to photometrically reduce data from the Falcon Telescope Network (FTN) in 2021-20222 and compare it to data gathered from the Geosynchronous Observations with Latitude/Longitude Diversity Simultaneously (GOLDS) campaign in 2013. The data collected is of DirecTV 10 and the goal is to make a first-order analysis of the differences and similarities between DirecTV 10 from 8 years apart to include unique characteristics that are present at the same phase angle for both data collections. I will present, in detail, the methods and procedures involved in the photometric process and how this reduced data was applied.

1. INTRODUCTION

Space Domain Awareness (SDA) involves the monitoring and tracking of satellites in space and is a vital national security interest. The United States has a vested interest in space operations due to our nation's dependence on satellites for command, control, and communication. The ability to characterize and identify space objects using methods such as optical observations is necessary in order to achieve SDA. This necessity arose over the years as the space domain became increasingly more congested and dynamic. In the past few years, the number of space objects the military tracks increased from 22,000 to 30,000 objects [1]. The reduction of barriers restricting launch has caused an increase in space objects as more countries, companies, and academic institutions now have access to space. In addition, rising concern due to peer adversaries such as Russia and China's increased counter-satellite research and operations brought SDA from a luxury to a necessity. The ability to correctly identify and characterize geosynchronous objects will allow the United States to know what activities adversaries are conducting as well as the ability to find and track new debris that may pose a problem to space operations.

In order to achieve SDA through non-resolved ground-based observations, efforts such as the Air Force Research Laboratory's 2013 GOLDS campaign employed photometric light curves to determine unique satellite characteristics [2, 3]. Photometric light curves are most often defined as an object's apparent magnitude versus time but may also be defined versus a spatial measurement such as longitudinal phase angle. Using longitudinal phase angle is particularly useful because unique characteristics of a satellite appear most evident before, during, and after a satellite glint. For the past three years, The Center for Space Situational Awareness Research (CSSAR) has used the FTN to observe and correlate optical measurements of geosynchronous satellites [4]. Specifically, in the Fall of 2021 to Spring of 2022, a significant number of measurements of DirecTV 10 were captured with the goal of comparing them to the DirecTV 10 data collected by the GOLDS campaign in 2013 to find any first-order similarities and/or differences that could show the effects that must be considered if using an old basis to compare new observations. While the 2013 GOLDS data was already reduced, the newly collected data from 2021-2022 consisted of raw image observations from multiple nights across geographically diverse locations. Due to instrumentation differences between different telescope sites as well as nightly and geographical differences in atmospheric conditions the shape of the photometric light curve was focused on rather than the absolute numerical values for this analysis.

DISTRIBUTION STATEMENT A: Approved for public release: distribution unlimited. PA#: USAFA-DF-2022-704

2. Telescopes Used for GOLDS 2013 and USAFA 2021-2022 Observation Campaigns

In 2013 the GOLDS campaign five telescopes were used to collect nearly 150,000 images of 20 satellites. For the analysis in this paper we will only be looking at the 7500 processed blue and red filter images of DirecTV 10 collected across six nights by United States Air Force Academy (USAFA) owned telescopes [5]. Two telescopes were used: the Air Force Academy (AFA) campus telescope located at USAFA, Colorado, and the AFA mobile telescope located at Plentywood, Montana which was later moved on-campus at USAFA, Colorado. The AFA campus telescope is a DFM Engineering f/8.2, 0.4-meter Ritchey-Chrétien telescope. The AFA mobile telescope is a f/8.1, 0.5-meter RC Optical Systems telescope. The geographic location of these telescopes can be seen in Fig. 1.

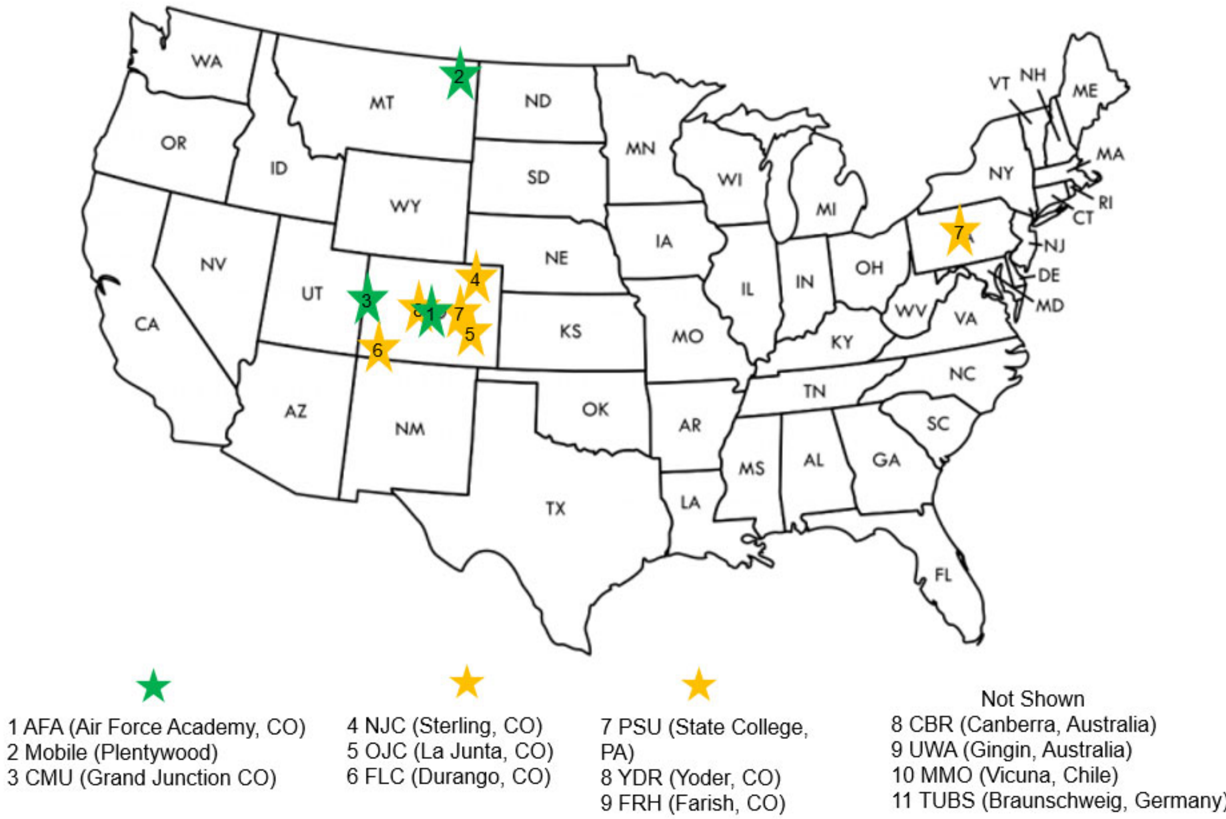

Fig 1. Location of Air Force Telescopes used in 2013 and 2021-2022 campaigns. Green star represent telescopes used in this analysis. Yellow stars represent Falcon Telescopes not used in this analysis. The far right column lists sites that are not in the United States.

In 2021 the USAFA FTN was used to collect and process 2600 blue and red filter images of DirecTV 10 across five nights by USAFA undergraduate cadets and faculty. Two telescopes were used: the AFA located at USAFA, Colorado, and the Colorado Mesa University telescope (CMU) located at Grand Junction, Colorado, shown in Fig. 1. The AFA telescope was used for both the 2013 and the 2021-2022 observation campaigns[6]. The FTN telescope locations use identical hardware consisting of a 20-inch, f/8 Richtey-Chretien telescope as well as an Andor Ulta F47 1024x1024 CCD camera with nine filters: B, V, R, g’, r’, i’, z’, 100 lines/mm diffraction grating, and exoplanet filter. Although nine filters were available, in this project only the blue and red filters are shown to compare to the 2013 GOLDS campaign which only used blue and red filters. Although there are eleven sites in the FTN only two sites are shown in this paper. The FTN telescopes were most commonly operated in automatic mode during the campaign and the exposure times would be determined beforehand. It was common that the satellite glint would saturate the detector, limiting the number of full glints observed. The FTN locations can be remotely controlled by an operator or automatically controlled through a website created for the Cadet Space Operations

Center (CSOC). This website takes inputs such as the filter, requested object, location, start time, end time, and exposure time.

Fig 2. AFA, AFA-Mobile, FTN Telescopes

The output of nightly observations was saved in the form of 1024x1024 .FITS images. These images consisted of one or more satellites along with background noise and star streaks. An example of a raw image is shown in Fig. 3 left. Photometric calibration was achieved by observing calibration stars (CalStars) of well-known magnitudes. These CalStars were chosen from a catalogue of Landolt and Oja CalStars with varying magnitudes and somewhat evenly spaced through the sky. Most observations were conducted by autonomous scripts.

3. DATA REDUCTION

The raw images of the FTN must be reduced to analyze the data it contains. An example of a raw image for DirectTV 10 is shown in Fig. 3 left. Due to the close proximity of DirecTV 12 and DirecTV 15 they are often seen in images of DirecTV 10 for our telescopes. Additionally a common sight are star trails which can sometimes cross paths with DirecTV 10. When this occurs that image is removed from the analysis. A standard raw image is then background subtracted, turned into a binary image, as shown in Fig. 3 center, to assist in identifying the centroid of the target satellite. Then, aperture photometry techniques are applied to the raw image. This consisted of creating a signal aperture around the centroid of the object that included both the source and the background as well as an equal area background annulus around the signal aperture that included just the background noise as shown in Fig. 3 right.

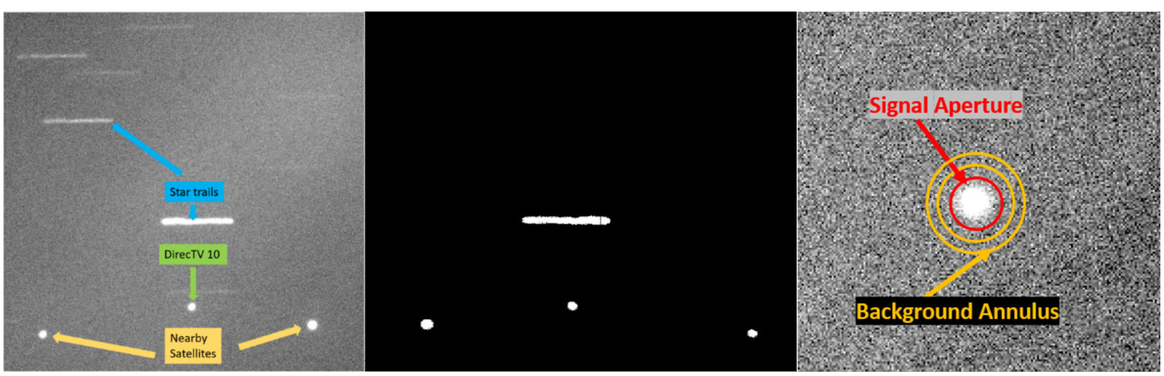

Fig. 3. Left example image from the FTN. Center example of a processed binary image. Right signal aperture and background annulus, chosen to be of equal area.

By summing the counts per pixel in each area and knowing the exposure time, the flux of the source is found using Eqn. 1. Subsequently, the instrument magnitude of the object is found by Eqn. 2. After the user selects the centroid of the target, in-house generated software calculates the instrument magnitude for each image [7]. Unfortunately, the centroid is not likely be in the same location on each image due to minor drift between images as well as reacquisition of the target when multiple targets are being observed in a single night by the telescope. This fact, compounded by each night potentially having thousands of collections, made it difficult to process data in a timely manner. To resolve this issue, another script was created to take user input for the first centroid and update each subsequent centroid after. In the case of a major change in the object's location, the program would request user input again.

$$F_{source} = \frac{(Source + Background) - Background}{Exposure\ Time} \quad (1)$$

$$m_{inst} = -2.5\log(F_{source}) \quad (2)$$

After the instrument magnitude is found, the next step in creating a photometric light curve is developing an axis to compare it to. There are two options when choosing this: temporal or spatial. The most common light curves are the object's brightness versus time, but this does not give any insight into the object's phase which is important for satellites during glint. Longitudinal phase angle (LPA) is the projection of the solar phase angle onto the equatorial plane and is shown in this paper calculated with the same method as Payne [8]. LPA has the distinct advantage in that the coordinate system does not rely on where the observer is located but rather it is only based on the satellite itself.

4. RESULTS

Six nights of observations were used from the 2013 GOLDS campaign. These light curves are shown in Fig. 4. For nights where it is clear that the full glint was observed a vertical line is shown representing the LPA where peak brightness occurs. As can be seen glints only occur around a single LPA location near 0 degrees.

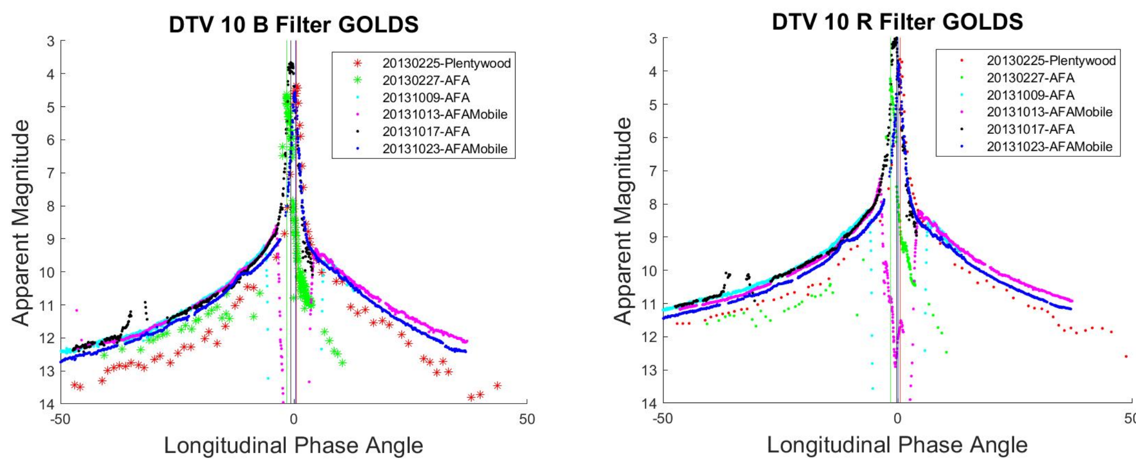

Fig. 4. DirecTV 10 GOLDS Data from 2013. Blue and red filter light curves collected from the USAFA campus telescope and mobile telescope in 2013 as part of the GOLDS campaign. Vertical lines represent the location of peak brightness when the entire glint period was observed.

Five nights of observations were used from the 2021-2022 FTN campaign. These light curves are shown in Fig. 5. For nights where it is clear that the full glint was observed a vertical line is shown representing the LPA where peak brightness occurs. A set of two distinct peaks appear the first corresponding to observations made in October and the second corresponding to observations made in February.

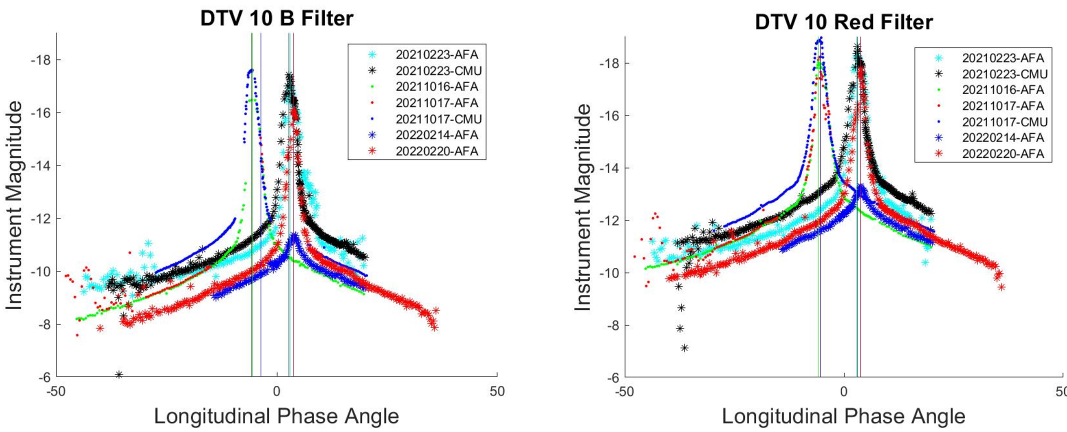

Fig. 5. DirecTV 10 FTN Data From 2021-2022. Blue and red filter light curves collected from the Falcon-Telescope Network in 2021 and 2022. Vertical lines represent the location of peak brightness when the entire glint period was observed.

These graphs present three interesting qualities—the first being that the location of the peak glint occurs at different LPAs. This change is attributed to increased sun tracking with the solar panel orientation as the satellite ages. Due to the 10-degree difference between where the peak glint occurs it isn't recommended as unique identifier for DirecTV 10. The next feature is that some days had a sudden drop of brightness when a glint was expected. This is attributed to the Earth's shadow reducing the expected brightness and is considered a factor associated with what night the data was collected for this particular satellite as opposed to giving us information about the satellite. The third feature is the increase in the spread of the glints between different seasons.

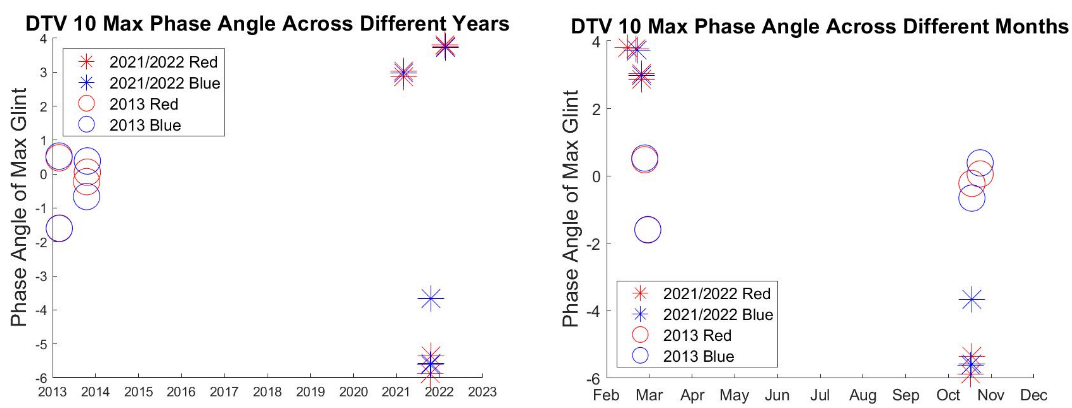

Fig. 6. Peak Intensity Longitudinal Phase Angle Changes Over Time. Longitudinal Phase Angle when peak brightness occurred for data shown in Fig. 4 and Fig. 5. Broken down by date as well as time of year.

Fig. 6 shows the longitudinal phase angle when peak brightness occurred for DirecTV 10 as can be seen in 2013 the glint happened near 0 degrees of longitudinal phase angle where as in 2021-2022 the glint happened much further from 0 degrees of longitudinal phase angle. One potential explanation could be this was due to the time of year as opposed to a change in the satellite. However when looking at when the glint occurs throughout the year we see that in both spring and fall in 2013 the glint occurs closer to 0 degrees of longitudinal phase angle when compared to the 2021-2022 observations made during the same time of year.

5. CONCLUSIONS

The ability to quickly identify and characterize satellites based on their photometric light curves is a core component of SDA. In order to accomplish this, a catalogue of photometric light curves and their associated unique characteristics must be created. This research is the start of that process by analyzing data of DirecTV 10 from 8 years apart and identifying possible unique characteristics. While there were many differences between these two periods of collections that would not be useful for building a catalogue, there were features that could be used to identify a change in satellite operations such as the spread in LPA where glint occurs. More data and research is needed to corroborate these findings, and more research is needed to continue to build a catalogue of known light curves.

6. Acknowledgements

We want to acknowledge the support of the Air Force Office of Scientific Research. Additionally, this paper is the result of multiple physics senior capstone projects and independent studies at the United States Air Force Academy. DISTRIBUTION STATEMENT A: Approved for public release: distribution unlimited. PA#: USAFA-DF-2022-704. DISCLAIMER: The views expressed in this article are those of the authors and do not necessarily reflect the official policy or position of the United States Air Force Academy, the United States Air Force, the United States Space Force, the Department of Defense, or the U.S. Government.

7. REFERENCES

(1) Tadjdeh, Y., U.S. Strengthening Space Domain Awareness. National Defense, 2021.
(2) DeMeulenaere, A., Harmon, E., and Chun, F., "Simultaneous Glint Spectral Signatures of Geosynchronous Satellites From Multiple Telescopes". In Proceedings of Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS), Conference 2018, 2018.
(3) Seitzer, P., Barker, E., Cowardin, H., Lederer, L., and Buckalew, B., "Bistatic Optical Observations of Geo Objects" 1, 2. 2014.
(4) Albrecht E., Jensen, A., Jensen, E., Wilson, K., Plummer, M., Key, J., O'Keefe, D., Harley, J. Chun, F., Strong, D., and Schuetz-Christy, C., "Near-Simultaneous Observations of a Geosynchronous Satellite Using Multiple Telescopes and Multiple Remote Sensing Signatures" Journal of the Astronautically Sciences 25 Oct 2021 Issue 4
(5) Gregory, S., Murray-Krezan, J., Fulcoly, D., GOLDS Project Technical Report I – Calibration and Technical Discussion of the Photometry. April, 2013
(6) Chun, F., et al. "A New Global Array of Optical Telescopes: The Falcon Telescope Network." Publications of the Astronomical Society of the Pacific, Sept. 2018, p. 20.
(7) Albrecht E., Jensen, E., Wilson, K., Key, J., Harley, J., Chun, F., Strong, D., Schuetz-Christy, C., "Calibration of the Falcon Telescope Network for Geosynchronous Satellite Photometric and Spectral Signatures" Advanced Maui Optical and Space Surveillance Technologies, 14 Sept 2021
(8) Payne, T., Gregory A., Dentamaro A., Ernst, M., Hollon J., Kruchten, A., Chaudhary, A., and Dao, P. "Development and Evaluation of New Methods for Estimating Albedo-Areas for Three-axis Stabilized Geosynchronous Satellites." The Journal of the Astronautically Sciences, 66(2):170–191, 2019.