Optical-Infrared Colors of GEO Satellites

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ABSTRACT

We observed geosynchronous satellites simultaneously from two different telescopes and obtained optical-infrared colors. With the HANDS-IONS camera on the University of Hawaii 2.2-m telescope, we obtained K photometry of the satellites, while we used the Oceanit MStar 0.4-m telescope in Kihei, Maui, for the V measurements. We report V-K and light curves for several GEO satellites.

1. INTRODUCTION

Satellites in the geosynchronous Earth orbit (GEO) provide services we are dependent on such as communications and weather monitoring. As such it is important that we are able to monitor their positions and health in order to verify that they are functioning properly. There are times they are intentionally maneuvered to perform station-keeping while at other times a malfunction can occur such as a loss in communication and the satellite may unintentionally wander (for example, Galaxy 15 in 2010). Through all situations, satellite positions are observed and updated on a regular basis by the Space Surveillance Network (SSN) using both radar and optical systems. Occasionally objects get lost or closely spaced satellites get cross-tagged and characteristics besides the known position need to be used to correctly identify them. In this case the more characteristics that are known about specific satellites, bus types, or other features such as solar panels, the better chance there is to positively identify them. Our purpose is to find the brightness of GEO satellites in the infrared as it relates to their brightness in the optical with the expectation that this could contribute to the known characteristics of GEO satellites.

The magnitudes of the GEO satellites in optical filters as a function of phase angle is well understood compared to the brightness in short-wave infrared (SWIR). To formulate an educated guess with regard to the magnitudes of GEO satellites in the infrared we started by looking at the survey done by the European Space Agency. In this survey it is shown that the median brightness of correlated GEO satellites is 12.5 magnitudes in visual wavelengths [1]. To begin to answer how the magnitudes in the infrared might compare we consulted a plot showing the reflectivity of a silicon solar cell array from 0 to 3 microns. The reflectivity at the peak of the V band is close to 0.1 while the reflectivity in the K band is close to 0.2, nearly twice as reflective as in the V band [2]. Since many GEO satellites have large solar panels, which constitute the majority of their reflective area, we can guess that they will be brighter in the K band. We also spoke with Dr. Tamara E. Payne who, through her experience with infrared, suggested that it would make sense if GEO satellites were 2 – 2.5 magnitudes brighter in SWIR [3].

During the HANDS-IONS (High Accuracy Network Determination System - Intelligent Optical Networks for Space Situational Awareness) demonstration in November, 2012 we had the opportunity to simultaneously measure the brightness of GEO satellites in the astronomical V filter and in the SWIR K filter. In this paper we will cover the instrumentation used, information about the observations, and data reduction procedures. Finally, we will show resulting magnitudes and V – K color terms with errors.

2. INSTRUMENTATION

The observations of satellites in the infrared were done using the Oceanit HANDS-IONS camera mounted on the University of Hawaii 2.2-m telescope on Mauna Kea. The HANDS-IONS camera is designed to track and characterize GEO satellites during the day and night in the SWIR [4]. The sensor chip assembly is a 1280 x1024 HgCdTe MANTIS designed for SWIR and cooled via a helium refrigeration system to 80 K. The optical system is cooled to 100 K and consists of a classical refractive re-imaging design with a pupil image. A Lyot stop is placed at the pupil image to suppress the IR radiation from the telescope. Two cryogenic filter wheels hold the Mauna Kea J, H, K, and K-short filters and a blank used for dark calibration images.

The observations of each satellite in the visible band were conducted with the Oceanit-designed MStar telescope, a modified Cassegrain with a 0.4-m (16”) aperture and focal length of 1.8 m. The telescope is fitted with an Apogee Alta U47 back-illuminated CCD camera with midband coating optimized for the visible region. The CCD has 1024 by 1024 pixels. The telescope is located in a dome at low elevation (77 m) near the Oceanit office building in Kihei, Hawaii.

3. OBSERVATIONS

These simultaneous observations took place during the HANDS-IONS system demonstration from November 27 – 29th, 2012. The infrared system acquired data in J, H, and K filters from Mauna Kea while the optical system in Kihei, Maui acquired data in the standard astronomical V filter. For the purposes of this paper the V and K magnitudes are compared.

There were two nights during the demonstration when we had the opportunity to observe simultaneously. It was often cloudy during the nights in Kihei while on Mauna Kea conditions were not photometric much of the time. These conditions prevented the simultaneous acquisition of some of the satellites and introduced additional error into some measurements. So, though we have several datasets on several satellites, two of the best simultaneous observations were of the GEO satellites TDRS 5 and Galaxy 15 shown as artist’s renditions in Fig. 1.

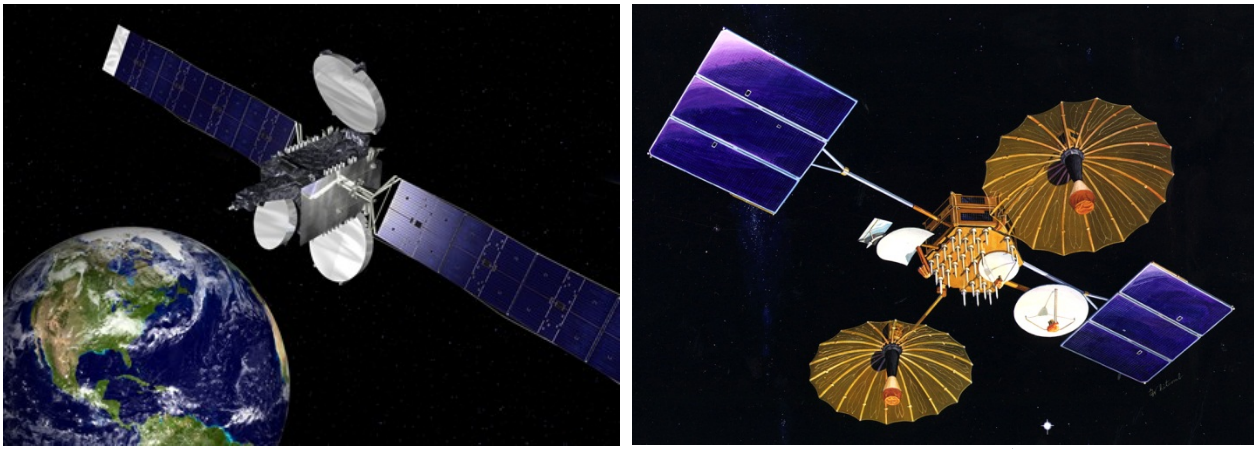

Fig. 1. Artist’s renditions of Galaxy 15 (left) from swfound.org (courtesy of Intelsat) and a 1st generation TDRS satellite to illustrate TDRS 5 (right) from NASA’s website.

For both the infrared and visible observations the satellites were tracked so the stars become streaks in each image. In the infrared, exposure times for the TDRS 5 and Galaxy 15 ranged from between 0.05 and 2.00 seconds depending on the satellite's brightness at the time of observation. For the visible observations, exposure times were 2, 3, or 4 seconds, depending on the apparent satellite brightness onscreen, in order to keep the in-frame satellite visible to the observer. A typical image is shown in Fig. 2.

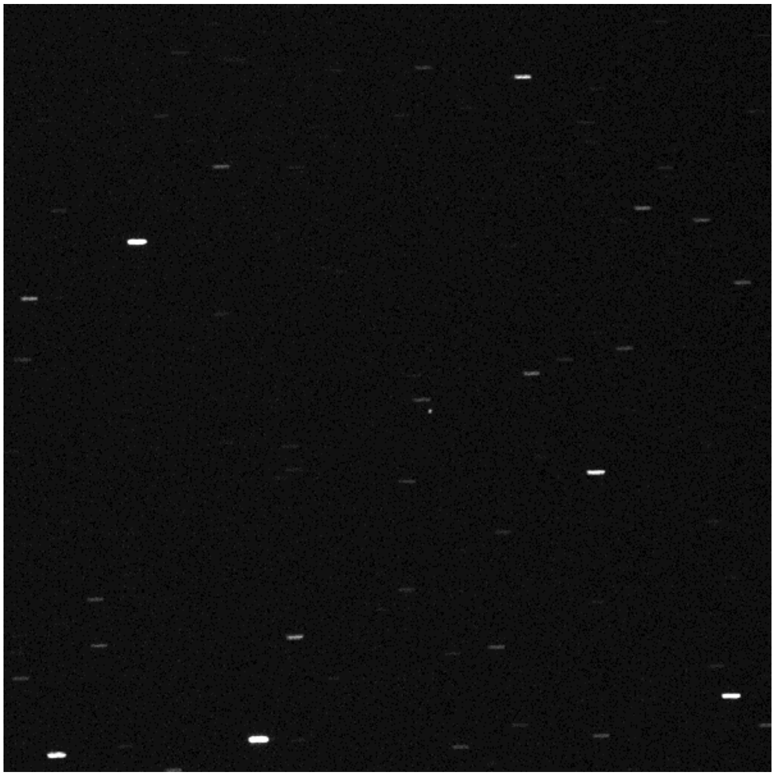

Fig. 2. A 2 second visible band exposure of Galaxy 15 on 28 Nov 2012

4. DATA REDUCTION

The infrared data is reduced in a partly automated fashion with parallelized standard astronomical image processing algorithms. The first part of the pipeline includes the application of dark and flat frames as well as bad pixel masks. Then, a synthetic background image is created for each raw image using several images close to the original raw image. To increase the SNR (Signal to Noise Ratio) images of satellites are acquired in sets and stacked. In the case of the TDRS 5 and Galaxy 15 observations, the stacks ranged from between 50 and 500 images. Once the stack is created the instrumental magnitudes of the satellite and stars are measured using Source Extractor. The apparent K-band magnitude of the satellite is found using in-frame differential photometry, see Fig. 3. The 2MASS (2 Micron All Sky Survey) point source catalog serves as the standards.

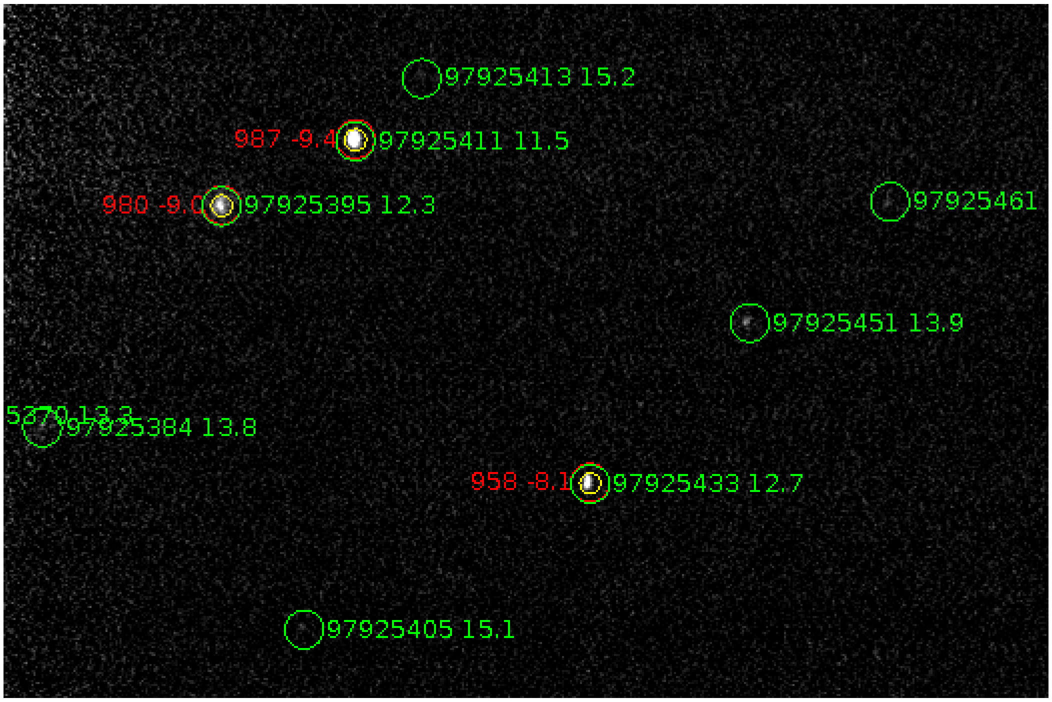

Fig. 3. The tool used to match stars for the IR data shows a match between the stars detected in the frame and the 2MASS catalog stars. This is a subframe of a stacked image from the 0.15-s TDRS 5 observations. The green circles denote the 2MASS K-band stars with their identifying numbers and catalog magnitudes while the red circles denote stars detected during the data reduction with their identifying indices and instrumental magnitudes. The smaller yellow circles illustrate the “match radius”.

The apparent visual magnitude of the satellite is determined with AstroGraph software. After each image is calibrated with an in-band flat frame and dark subtraction, AstroGraph subtracts the background by first dividing the image into a 12-by-12 array of tiles. The values of all the pixels in each tile are sorted, and the value at the 25% percentile in the sort range is selected to represent the background value of that tile. A bicubic spline is then used to interpolate background values between tile centers to complete the image. This manufactured background image is subtracted from the target image to remove ambient sky and cloud values. The star streaks in the images are detected in a threshold process, and centroids are calculated for the detections. The detections are matched to a star catalog that is a hybrid of Tycho-2 and USNO B 1.0, and the magnitudes of the matched catalog stars calibrate the flux levels on the CCD. The magnitude of the satellite is then obtained with this calibration.

The simultaneity of the V and K band measurements depends on the infrared stack length in time. In the case of the Galaxy 15 observation on November 28, the infrared stack length is about 75 seconds and consists of one measurement. To find the optical-infrared color, the visible observation closest to the infrared stack midpoint was used. This procedure was done for each measurement so if there were any variations in color on a shorter timescale they would be lost. This could be amended, however, since the infrared SNR at 842 is more than sufficient and the stack length could be shortened.

5. RESULTS AND DISCUSSION

The following two figures show the apparent magnitude of TDRS 5 as a function of time and of phase angle in both V and K magnitudes. The measurements in V are from two successive nights while those in K result from one night. The figures show that TDRS 5 is 2.6 to 3.8 magnitudes brighter in K, close to what we expect. The magnitude as a function of phase angle shows the familiar trend of the V magnitude becoming fainter as the phase angle gets larger. The K magnitude changes more than the V magnitude as the phase angle changes and this results in a smaller difference between the V and K magnitudes as the phase angle gets larger.

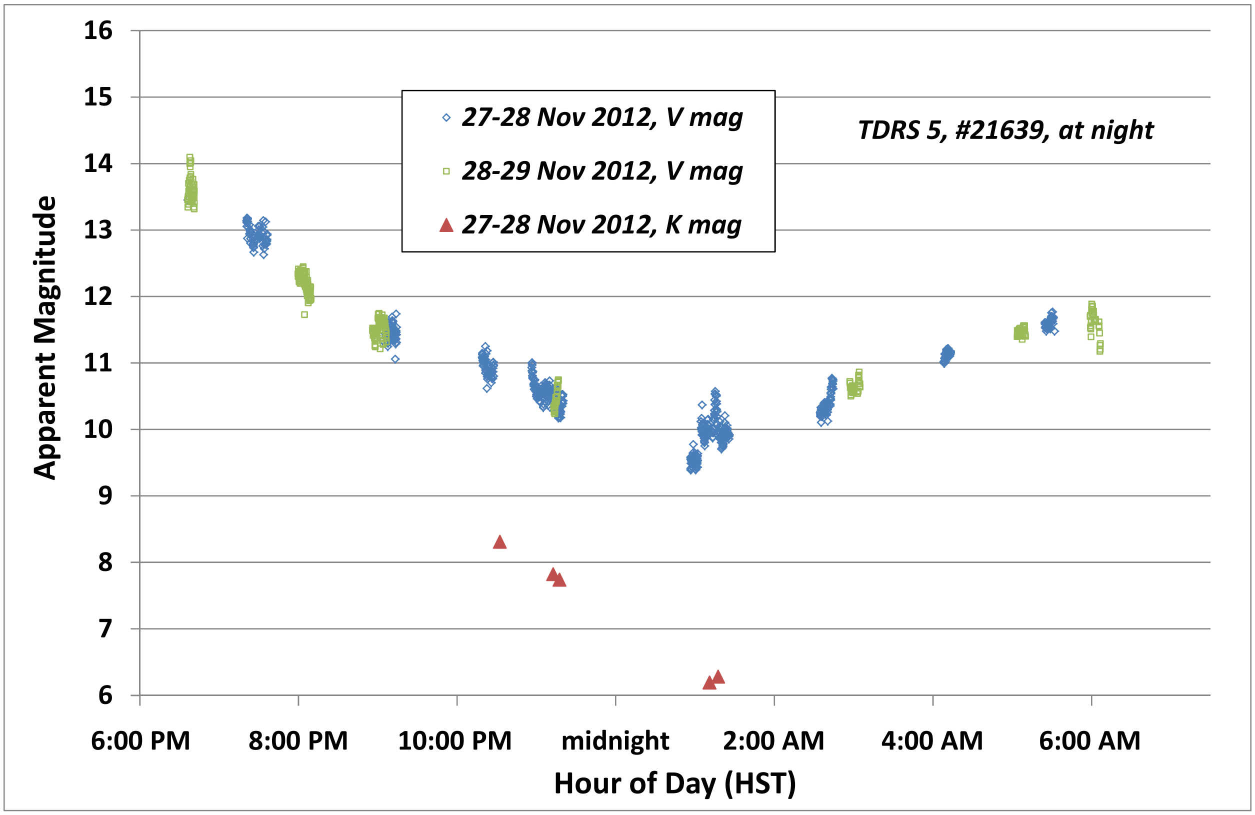

Fig. 4. The apparent magnitude of TDRS 5 in V and K as a function of local time

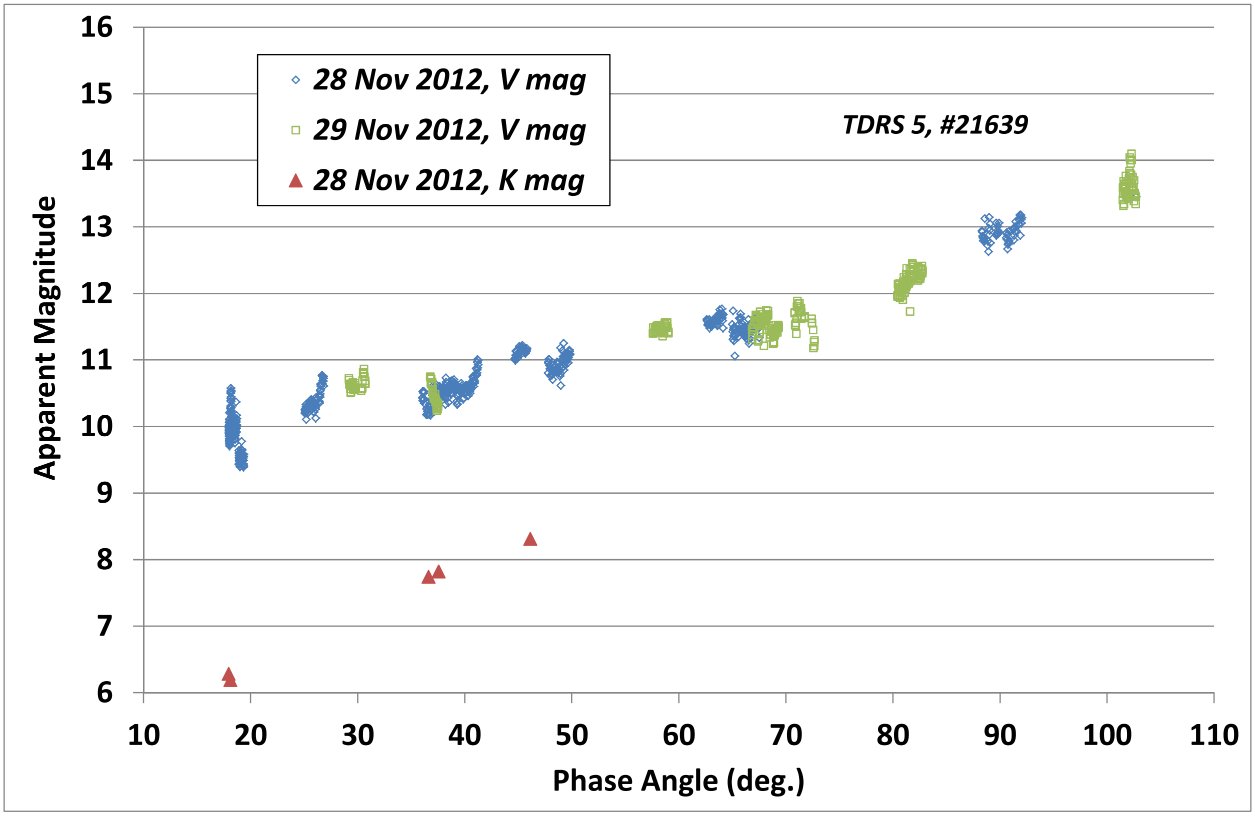

Fig. 5. The apparent magnitude of TDRS 5 in V and K as a function of phase angle

The apparent magnitude of Galaxy 15 in V and K are shown in Figures 6 and 7. The measurements shown in V and K are from both nights during the demonstration. The magnitudes become fainter as the phase angle get larger until it approaches 100° then at 110° phase angle the V magnitude appears to level off and become slightly brighter. At 40° phase angle there are two V magnitudes that differ by approximately 2 magnitudes. This is best seen in Figure 7. Each of these measurements were on either side of 0° phase angle (i.e. at -40° and +40°), once at just after 8 PM and the again just after midnight. Because of this, it is likely that the satellite is not in a symmetrical orientation on either side of 0° phase angle.

Like the K magnitude of TDRS 5 that of Galaxy 15 changes more than the V magnitude with a change in phase angle and results in a smaller V-K color at larger phase angles. The V-K color of Galaxy 15 ranges from 1.4 to 2.0 where 1.4 is at the larger phase angle.

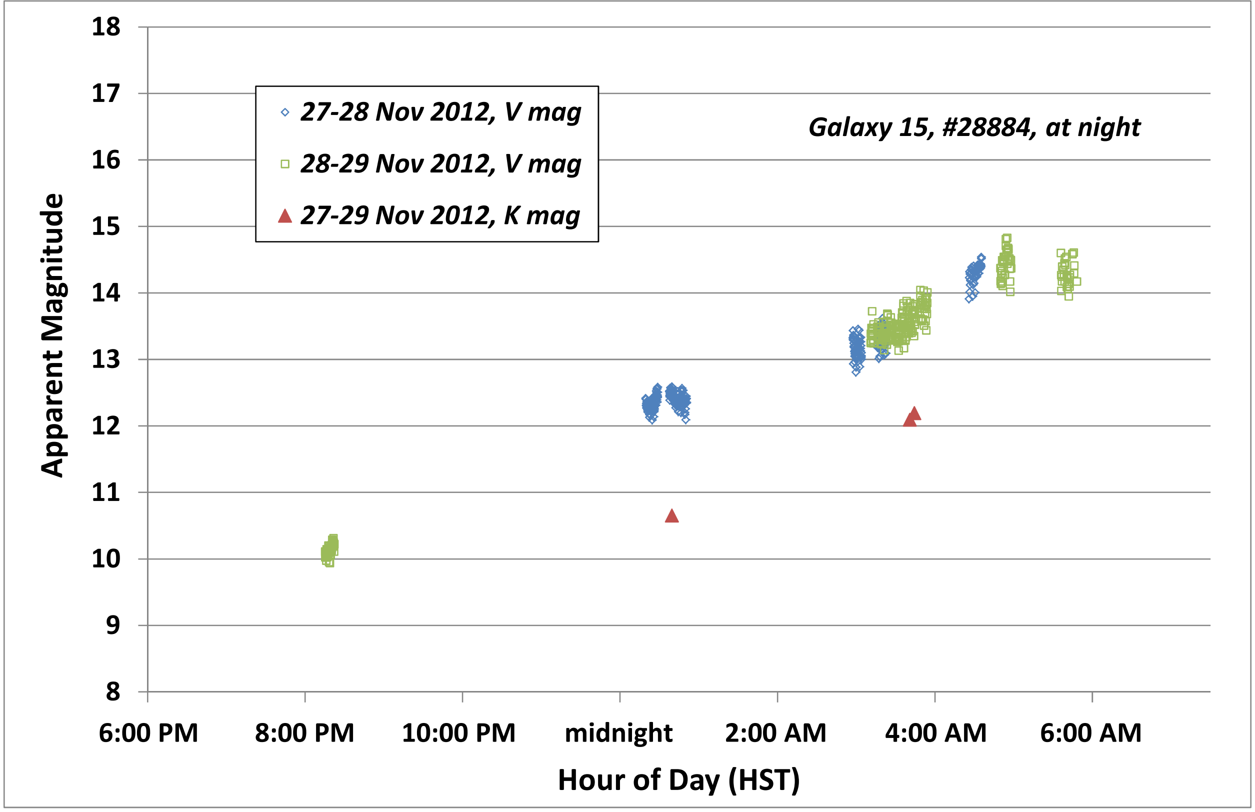

Fig. 6. The apparent magnitude of Galaxy 15 in V and K as a function of local time

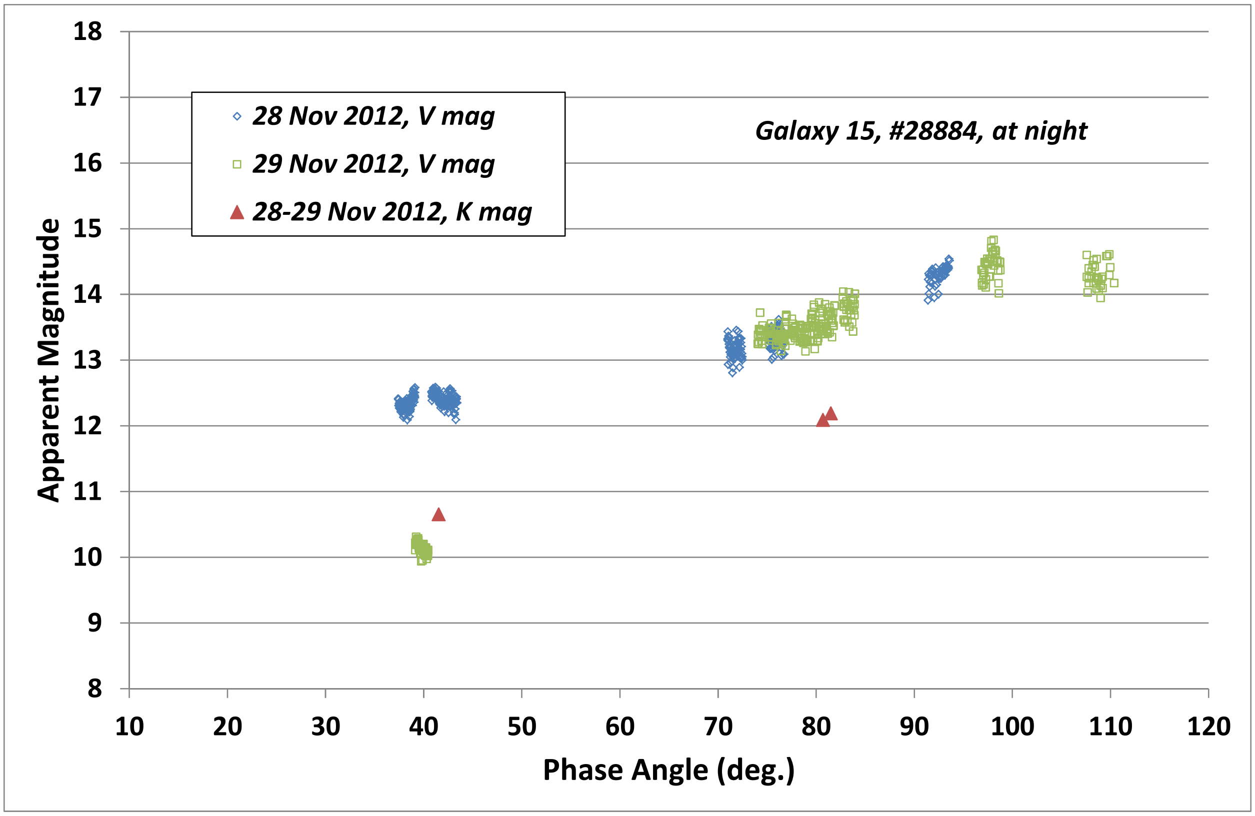

Fig. 7. The apparent magnitude of Galaxy 15 in V and K as a function of phase angle. The visual observations near 40° happened on two dates and on either side of 0° phase angle hinting that the satellite geometry may not be symmetrical on either side of 0° phase angle. The V magnitude observations at 40° on the 29th were not simultaneous with the K magnitude observations like those on the 28th. This is easier seen on Fig. 6.

The V and K magnitudes of TDRS 5 and Galaxy 15 are condensed in Table 1 along with their V – K colors and resulting errors. The error in the K magnitudes is the root sum of squares of the RMS error for the "AUTO" magnitude reported by Source Extractor and the standard deviation of the error in the zeropoint. This error is then divided by the square root of the number of stars matched and the result is the total error in the K magnitude.

The error in the calculated V magnitude of the satellite is assessed with the errors on the stellar magnitudes in each image. The stellar magnitude error is the difference between the calculated image magnitude and the catalog magnitude for each matched star in the image. The standard deviation of the stellar magnitude errors, divided by the square root of the total number of stars matched, is then combined with AstroGraph's reported error of the satellite's magnitude in a root sum of squares. The root sum of squares is the total error in the satellite's magnitude.

The error in the V – K color terms is a root sum of squares of the error in the K and V magnitudes.

Table 1. The apparent V and K magnitudes of TDRS 5 and Galaxy 15 along with their V-K color terms

Satellite	Phase Angle (deg.)	K	V	V - K
TDRS 5, #21639	37.6	7.82 +/- 0.03	10.46 +/-0.08	2.6 +/- 0.1
TDRS 5, #21639	36.6	7.74 +/- 0.05	10.21 +/- 0.07	2.5 +/- 0.1
TDRS 5, #21639	18.0	6.28 +/- 0.03	10.1 +/- 0.10	3.8 +/- 0.1
Galaxy 15, #28884	41.5	10.65 +/- 0.19	12.64 +/- 0.06	2.0 +/- 0.2
Galaxy 15, #28884	80.7	12.09 +/- 0.07	13.5 +/- 0.10	1.4 +/- 0.1

6. CONCLUSIONS

As expected, TDRS 5 and Galaxy 15 are brighter in the infrared than in the optical. The five V – K color terms show that these satellites are on average 2.5 magnitudes brighter in SWIR. TDRS 5 is 2.6 to 3.8 magnitudes brighter in K while Galaxy 15 is 1.4 to 2.0 magnitudes brighter in K at the phase angles reported in Table 1. Both satellites have larger V – K color terms at smaller phase angles. This shows an inverse relationship between the phase angle and the color terms; as the phase angle gets larger, the color terms gets smaller.

The V magnitudes all increase as the phase angle increases to around 100º. Then the magnitude levels off or even decreases as shown in Figure 7 around 110º. Magnitudes at the smallest phase angle shown for Galaxy 15 are measured on both sides of 0º at around 40º phase angle. However, Galaxy 15 does not have the same magnitude at 40º on either side of 0º. Instead, there is at least a 2 magnitude difference between the V magnitudes at 40º.

From these few V – K color terms it seems that that TDRS 5 could have a larger color term than Galaxy 15. Since both satellites are not measured at exactly the same phase angles this is not certain. Comparing the closest phase angles, TDRS 5 at 37.6º and Galaxy 15 at 41.5º, their color terms differ by 0.6 magnitudes.

If V – K color terms are significantly different when comparing satellites, they could prove to be a useful tool for satellite characterization. Additional data, mainly in the J, H, and K filters, would be useful in furthering the understanding of GEO satellite characteristics in the IR and consequently the ability to positively identify these satellites.

7. ACKNOWLEDGEMENTS

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