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Light Curve Generation for

Satellites in Geostationary Orbits

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This research were conducted at California Polytechnic State University San Luis Obispo throughout the Winter, Spring, and Fall quarters of 2013. The data presented in this paper was taken on the night of October 20, 2013 at the Cal Poly San Luis Obispo Astronomical Observatory and was reduced using IRAF software available on campus. This report describes the results of an observation of two bright XM geostationary satellites and the steps taken to get to those results. The average magnitude values of the XM-1 and XM-2 satellites were 13.753 ± 0.007 and 14.015 ± 0.007 respectively. The magnitude varied an average of 0.1 magnitudes around the average magnitude value.

Nomenclature

<i>3le</i>	=	three line element data
<i>CCD</i>	=	Charged Coupled Device
<i>FWHM</i>	=	Full Width at Half Max
<i>LEO</i>	=	Low Earth Orbit
<i>GEO</i>	=	Geostationary Earth Orbit
<i>IRAF</i>	=	Image Reduction and Analysis Facility
<i>tle</i>	=	two line element data

I. Introduction

Orbital debris is becoming a larger problem in space because there is no effective method for collecting debris, only regulations to control the number of uncontrolled objects. The first step to collecting debris would be to study it to determine its orbit, attitude, and tumble/spin rates to prepare for future missions that might possibly attempt to capture this debris or rendezvous with it¹. The research presented in this paper will be expanded to find the tumble rates of used rocket bodies in Geostationary Transfer Orbits (GTO) or in GEO graveyard orbits.

The data that has been collected and analyzed so far is of two bright geostationary satellites^{8,9}, XM-1 and XM-2 which are radio broadcast satellites that provide listeners with 100 different music channels^{10,11}. These two satellites are within a few arc minutes of each other in the night sky, and were therefore captured together in a series of images acquired using the Cal Poly 12" Meade telescope and SBIG CCD camera. More information about the components and software used for this research can be found in the appendix in Tables 1 and 2. This data was photometrically reduced using IRAF software to yield light curve plots that can be seen in the results section.

This report details the method and steps that were taken to yield the results of the project. It will also detail future work that is necessary to extend this process to the task of finding the tumble rate of rocket bodies.

II. Observation Run

Each observation run consisted of several parts: preparation, setup, data collection, and shut-down. The preparation involves choosing satellites and finding their coordinates, the set-up portion describes what must be done before the telescope is used, the data collection section describes the steps taken during observation to acquire images of the target(s), and the shut-down section describes what must be done to ensure the telescope and other

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equipment is protected in between observations and will remain in good operational condition. Each section also details any problems that may have occurred during that step so that the solution is documented for further use.

A. Observation Preparation

Space-track.org was used to generate lists of "3le" data to be used while observing. The two XM satellites were found on the space-track.org pre-made satellite list entitled "brightgeo". Geostationary satellites were chosen over LEO satellites because they move slower relative to the stars and are easier to capture with a telescope. Satellites were chosen for the first test objects because satellites still in operation would have more accurate tle data because they employ orbital maneuvers to remain in the same orbit, and therefore would be easier to find with a telescope even if the tle data was a few days old. Finally, bright satellites (as opposed to dim ones) made great first targets because they were easy to spot in the images!

Space-track.org can be used to query a satellite catalog for rocket bodies by searching for the "R/B" in the object name, and orbital elements can be specified such that the rocket body is in the desired orbit. Once a few desired objects have been chosen, space-track.org can be used to create a lists of specified satellites that can be accessed and updated just like the pre-made lists of satellites. Space-track was then used to generate a 3le text file with the selected list of satellites.

Finally, once a 3le list of objects has been saved as a text file, the file was slightly modified. The MATLAB script *remove.m* was used to remove the zeros (0) and the rocket body designation (R/B) from the name line of the 3le file such that only the object name was left. The script also gets the Norad object number from the second line of the 3le and adds it in parenthesis to the end of the name line of the 3le. The reason for this modification will be addressed later in the observation section. An example of the 3le text file with sample rocket bodies can be seen in Fig. 1.

0 TITAN 3C TRANSTAGE R/B	TITAN 3C TRANSTAGE (03692)
1 03692U 69013B 13266.39823828 -.00000320 00000-	1 03692U 69013B 13266.39823828 -.00000320 00000-
2 03692 009.0799 315.0839 0128538 084.6544 276.7507	2 03692 009.0799 315.0839 0128538 084.6544 276.7507
0 SL-12 R/B(2)	SL-12 (2) (26480)
1 26480U 00049D 13266.26597335 -.00000155 00000-	1 26480U 00049D 13266.26597335 -.00000155 00000-
2 26480 010.0800 049.1014 0012253 267.4673 092.4425	2 26480 010.0800 049.1014 0012253 267.4673 092.4425
0 BREEZE-M R/B	BREEZE-M (26738)
1 26738U 01014C 13265.84852773 -.00000213 00000-	1 26738U 01014C 13265.84852773 -.00000213 00000-
2 26738 009.8027 055.6091 0168104 110.7036 251.1823	2 26738 009.8027 055.6091 0168104 110.7036 251.1823
0 SL-12 R/B(2)	SL-12 (2) (27444)
1 27444U 02029D 13267.26939780 -.00000250 00000-	1 27444U 02029D 13267.26939780 -.00000250 00000-
2 27444 009.7139 049.2598 0008656 272.7463 087.2070	2 27444 009.7139 049.2598 0008656 272.7463 087.2070

Figure 1. Pre and Post images of a 3le text file when using "remove.m" in MATLAB. *The left image is the standard format of the Space-track 3le file from the website. In this image, four rocket bodies are listed and two have the same name. This is confusing! Therefore, in the right image, not only are the zeros and R/B no longer present, but the Norad ID numbers are present such that the two SL-12 rocket bodies can be distinguished.*

B. Telescope Set-Up Procedure

Before anything else can be done, light pollution must be minimized. This is very important because rocket body targets are very dim, and any light pollution can be detrimental to the observation. Because the Cal Poly campus is well lit at night to give a feeling of safety to its students, it is impossible to get rid of all light pollution, but there are some steps that can be taken to minimize it. Because the telescope resides in between two buildings, classrooms line either side to the North and South. When classrooms are not in use the lights can be turned off, however, if classrooms are being used then the blinds can be closed. There are also two outside lights that can be covered with very expensive light covers (cardboard boxes) placed over them by a very complicated mechanism (a two-yard stick) so that this little bit of extra light is minimized.

Placing boxes over the lights to observe drew campus police and custodians to the area while observations were taking place, and the boxes were found in a dumpster at the end of one particular night of observing. The next time, the boxes were nowhere to be found after observing! Even more recently than that, a message from the police was distributed through the observational astronomy professor to the students using the observatory that boxes were not to be placed over the lights anymore because covering lights was deemed a safety hazard. Luckily bright targets were being observed so far and not having the boxes out was not an issue. In the end, the boxes probably don't remove a significant amount of light pollution when compared to the remainder of lights on campus, and the boxes will probably not be used in the future.

Once the light pollution has been minimized (closing classroom blinds, NOT putting boxes on lights, etc.) the computer in the observatory needs to be turned on, and this set up information is taken from the set up procedures written by Dr. David Mitchell³. The power strip on the wall needs to be turned on to give power to the dome, and then the dome is opened through use of DDW Dome software installed on the observatory computer. If the targets for the night are high in the sky, then the windbreak on the dome is not connected (meaning the windbreak will block the view near the horizon) when the dome slit is opened. If the targets are close to the horizon, the windbreak on the dome must be open to allow for these low targets to be visible. If the windbreak is attached to the dome slit before it is opened, then the windbreak will recede upwards with the dome slit when opened, and block high elevation observations and is shown in Fig. 2.

Once the dome is opened, the telescope can then be uncovered. The telescope must be uncovered after the dome is opened to prevent excessive dust from falling on the telescope while the dome door is opening. The SkyX program is started on the observatory computer, then the telescope is turned on and quickly connected to The SkyX which is how the slewing and pointing of the telescope are controlled. Lens caps must be removed from the main section of the telescope and from the finder scope on the side of the main telescope body. The CCD camera power and focus controller power are turned on, and the camera software on the observatory computer is started, and the camera is connected. The program generates an error that the focuser cannot be connected, but this error is incorrect as the focuser actually does connect to the computer automatically when the camera connects. Once the camera is connected, temperature control is turned on and the temperature of the CCD is reduced to -5°C . Finally, in the camera software, the autosave option is turned on so that all images taken during the night are automatically saved with a specified prefix into a specified folder for later use.



Figure 2. Images of the Cal Poly Observatory. Left: Dome shut. Center: Dome open with windbreak up. Right: Dome open with windbreak down. The placement of the windbreak can allow for low altitude observations or high altitude observations.

Finally, it would be nice if the opening in the dome aligned with where the telescope is pointing, therefore in the Dome software window, the observer can check the button that says "slave to telescope" and the dome will update its position using data from The SkyX (assuming The SkyX knows where the telescope is). For a few days, the dome stopped working and could not tell that it was moving when commanded to move, and could not follow the telescope as a result. Therefore, it could not keep track of where it was, could not be slaved to the telescope, and had to be commanded manually. There are dome controls mounted on the wall near the dome home position that allow the observer to open or close the dome slit, as well as rotate the dome CW or CCW. If The SkyX does not know where the telescope is, the dome will still slave to where the SkyX thinks the telescope is. If the pointing of the telescope is so far off that the dome slit does not align with the telescope, the dome must be unslaved to the telescope and adjusted manually until the telescope is properly aligned and synced.

Once it gets dark, the telescope must be aligned and focused. Alignment consists of pointing at a bright star, and making sure it is in the center of an image when The SkyX thinks it is pointing at that star. The telescope constantly tracks at the rate the stars are moving, so whenever the telescope is disconnected/reconnected the tracking slightly misaligns the pointing. The telescope must be moved until the bright star is in the center of the field of view of the camera, and then The SkyX can be synced with that star so that the computer knows where the telescope is pointing. Focusing the telescope is best done with a star close to magnitude six in brightness and camera exposures of three

seconds. Images of the same star are taken over and over while the focus is adjusted until a maximum brightness is reached. An in focus star takes up less pixels on the CCD than an out of focus star, therefore all the light is concentrated in a smaller area yielding higher brightness values. However, due to fluxuations in the atmosphere, the graph of the star brightness over time can not always be trusted. A solution to this is to take several images before adjusting the focus again and to average the brightness at that value, or to examine the star in the image by eye and use the focus value that makes the star as small and round as possible.

C. Data Collection

Data collection is split into several different parts, collection of calibration data and science data. Calibration data is composed of bias images, dark images, and flat images. Science data is the term given to the images of the target(s) being observed for the night because those are the main images from which the scientific discovery comes from!

1. Calibration Data

Bias images are zero second exposures that are taken to eliminate noise added by the camera and are also known as "zeros". It is expected that if the camera collects photons for zero seconds, it would output that zero photons hit the detector, but in fact it displays that some positive bias number of photons hit the detector. For this reason, a bias image is subtracted from each dark, flat, and science image as the first step in data reduction.

Dark images are images that help eliminate thermal noise generated by the camera. Thermal noise is reduced by cooling the CCD to -5°C but this does not get rid of all the thermal noise. Darks are taken with an exposure time equivalent to the science data images, but the shutter remains closed. The thermal noise dark images eliminate is proportional to the length of the exposure. For excessively long exposure times, dark images can be scaled, but for this project that was not necessary. A dark image is then subtracted from each of the flat and science images as the second step in data reduction.

Flat field images are taken of the sky just after sunset or just before sunrise. The idea behind the flat field image is to evenly illuminate the CCD camera to see what the pixel response is for the camera. The camera response is likely not flat, meaning that for the same amount of photons, one pixel might output a higher brightness value than another pixel. Once the flat field image is obtained, then the relative scales of each pixel are known. If a science image is divided by the flat field image, then the variations in the camera response for the image will be removed, and the new brightness values will be standardized across the entire image. The camera response is not just different for different pixels however, but it is also different for different filters. If data is taken in more than one filter then more than one set of flat field images needs to be taken. The final step in data reduction is to divide all appropriate science images by a normalized flat field image of the same filter.

About eight to twelve pictures are taken for each type of calibration image, and each set is combined to create what are referred to as masterbias, masterdark, and masterflat files. Bias images are combined using an average, but darks and flats are combined using a median. The master files for this data set can be seen in Fig. 3.

2. Science Data

The science data is the group of pictures that were taken of the target of the observation run. In this paper, the two targets were XM radio satellites 1 and 2, which have Norad ID numbers of 26761 and 26724 respectively. They are within a few arc minutes of each other which is why they were able to be captured in the same images throughout the night. The 3le text files that were prepared for the observation can be uploaded directly into The SkyX program using Insert>Satellites and then choosing From File and browsing to locate the appropriate text file. This is also where the remove script comes in handy, because if 3le files are used, The SkyX will display the first line of each object on the star globe next to the object. This means the object name and its Norad number are displayed on the SkyX main window, where they can be clicked on and then slewed to with the telescope. The path of the satellite is also shown on the star globe so its movement relative to the stars can be predicted for a user defined number of minutes. If a tle text file is used, there are no name lines in the file, and The SkyX will display the first line of the tle which is not as convenient for the user.

Once the user has slewed to the location of the satellite with the telescope, it can still be a challenge to find the satellite. The tle's are not perfectly accurate, and as a result, the object will likely NOT be exactly where The SkyX says it is. From trial and error, I have found the satellite to pass through a given location a few minutes behind when it was supposed to pass through the field. Therefore, the radial error is not very large because the satellite follows the predicted path fairly well, however, the along-track error can be off by several minutes causing the satellite to appear "late." Once the target has been captured in the camera, it is easy to follow it manually with the telescope. Because geostationary satellites were being observed, several pictures can be taken before the targets left the field of

view of the CCD. The field of view is displayed as a purple box on the main window in The SkyX, so once the satellites are no longer in the image, the telescope can be slewed along the predicted path lines in the direction the satellites were moving, and are easily recaptured in another set of several images. The SkyX program itself is

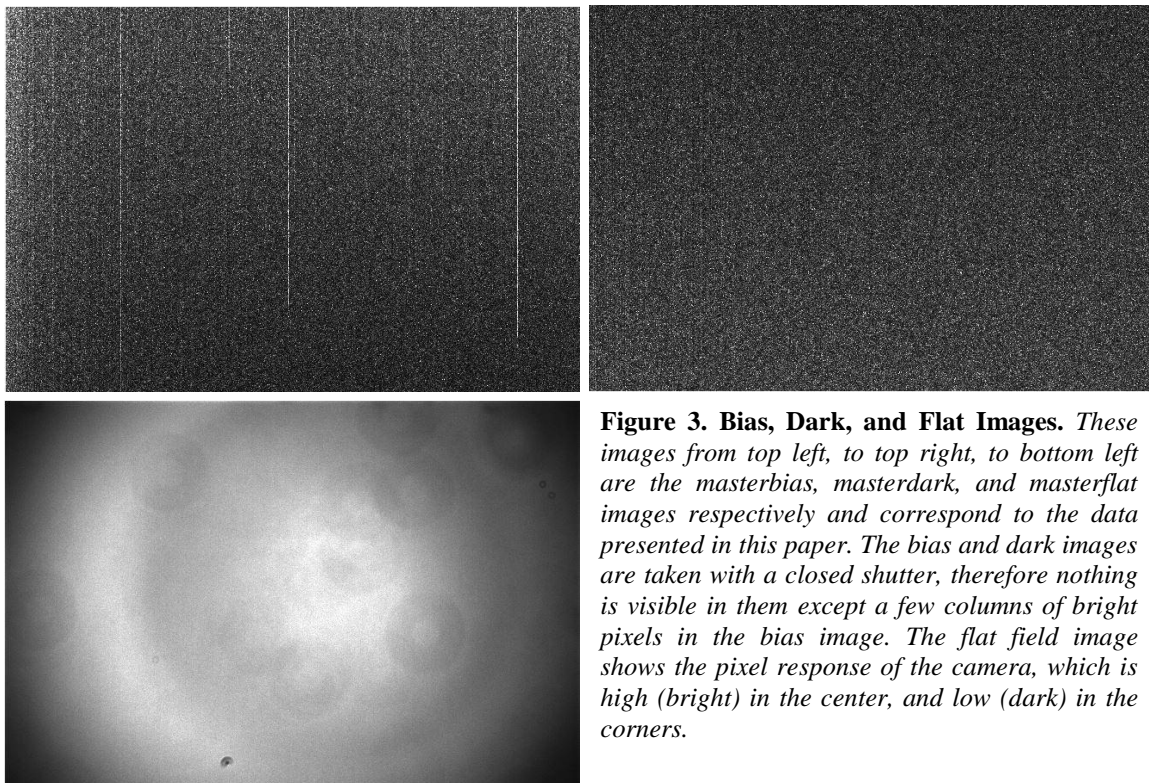


Figure 3. Bias, Dark, and Flat Images. *These images from top left, to top right, to bottom left are the masterbias, masterdark, and masterflat images respectively and correspond to the data presented in this paper. The bias and dark images are taken with a closed shutter, therefore nothing is visible in them except a few columns of bright pixels in the bias image. The flat field image shows the pixel response of the camera, which is high (bright) in the center, and low (dark) in the corners.*

capable of setting track rates equivalent to that of the satellite, however, the telescope mount being used is not capable of understanding track rate commands from the computer, therefore I am limited to manually slewing the telescope every few images. A raw science image can be seen in Fig. 4 as well as the same science image after data reduction has been performed.

A final note about taking science images: using the Cal Poly Observatory gives the user the option to remote observe from inside the neighboring science building. There is a computer inside that allows the observer to remote log in to the observatory computer and allows the user the ability to do almost everything that was possible in the dome. This serves two purposes: it enables the lights in the observatory dome (including the computer monitors) to be turned off to reduce light pollution, and it helps keep the observer warm because they don't have to spend the night outside in a room with a hole in the ceiling. Limitations to this method of observing include not being able to restart The SkyX if the program freezes and has to be restarted, also, the dome cannot be controlled from inside the science building. Normally The SkyX does not have to be restarted, and the dome is controlled by software and can track the telescope, but recently the dome has been having problems so if observing from inside, it must be checked up on every 20 to 30 minutes to ensure it is pointing in the same direction as the telescope. When done observing from the science building, the remote log in window is terminated, and the computer is logged off before going back to the dome.

D. Telescope Shut-Down Procedure

Once all data has been collected for the night (or whenever the weather stops cooperating) the telescope is parked in its home position, then be disconnected from The SkyX and switched off. Once covers for the main lens and for the finder scope are replaced on the telescope, the tarp is put over the top of the telescope to protect it from dust. The camera (and focuser) are disconnected from the camera software, and then each are powered off. The dome must be slewed to its home position using the manual controls on the wall because the DDW software has problems getting to the home position. Only once in the home position can the dome be closed! After making sure all data and images for the night have been saved, a file transfer window is opened⁷ and image data is transferred to a computer named "planet" which is the computer that can run IRAF software for data reduction. Finally, the

observatory computer is shut down and the main power switch on the wall for dome power is turned off. Once the observatory is locked up it is time to go home and go to sleep!



Figure 4. Science Images – pre and post reduction. *The image on the top is the raw science image that was taken with the CCD camera at the time of observation. The bottom image is the post reduction image. One noticeable improvement is the vertical lines of bright pixels that were seen in the bias image in Fig. 3 disappear after data reduction. The background sky in the post reduction image also looks much more uniform than in the pre-reduction image.*

III. Data Reduction and Photometry

There are two main steps to data reduction, calibration of images, and photometry. Data reduction⁴ is remotely performed on the "planet" computer by opening a terminal somewhere and using ssh to log into the user account on the host planet computer. The first few easy steps are listed in the first subsection, then the calibration process is discussed. Photometry⁶ is also performed on the planet computer and is discussed last in this section.

A. *.FIT to *.fits images

Once an IRAF login file has been made, the raw CCD files (*.FIT) need to be converted to the file type used by the IRAF software package (*.fits). This is very simply done using the *rfits* command found in the *dataio* package of IRAF. Using the command *epar rfits* allows the user to adjust the *rfits* parameters before calling *rfits* to do the file type conversion. The *rfits* parameters used are listed in Table 3. The image prefix is the prefix for the new *.fits files and does not have to match the prefix on the *.FIT files.

One unforeseen benefit to what seems like such a simple process is that it forces the user to make a copy of all the raw observation data before doing any data reduction. This way, if the data reduction process is messed up in some way, the *.fits images can be deleted, and the process can begin again using the raw *.FIT files.

B. Calibration

The ds9 program (which must be started outside of IRAF) is used to view images throughout this process. Then log into iraf and get to the right IRAF package following the directories: *noao*, *imred*, *ccdred*, *setinstrument*, and then typing "*cp*" for Cal Poly. Calibration of the science images then has several steps for each type of calibration image (bias, dark, and flat). The steps for bias calibration will be described in detail, and the steps for darks and flats follow the same structure and only the differences will be noted.

Step One is to view all the bias images in ds9 to ensure they all look normal and that nothing is obviously wrong with any of them. Any bad images should be deleted! Then, adjust the settings for the *zero* command (*epar zero*, or *epar dark* or *epar flat* as appropriate) using the values in the zero column of Table 4 (the other two columns are for darks and flats respectively). To combine the bias images, run the *zero* command (or *dark* or *flat* command as appropriate). Once IRAF has finished making the masterbias image, view the image in ds9 before continuing to ensure it looks ok. Next, edit the parameters of the *ccdproc* command (*epar ccdproc*) using the values in the zero column of Table 5 (or the dark or flat column as appropriate). Once this is complete, run the *ccdproc* command which will subtract the masterbias image from the dark, flat, and science images.

That entire paragraph of steps should be repeated two more times for the dark images and for the flat images. At the end of the dark stage, the *ccdproc* command will subtract the masterdark image from the flat and science images, and at the end of the flat stage it will divide the science images by the normalized masterflat image. If more than one different filter was used during observation, then more than one set of flats should have been taken, and the flat reduction process will need to be completed multiple times for each filter used. In this data set, only the Clear filter was used.

C. Photometry

The first step of the photometry process is to find the standard deviation of the sky background counts and the FWHM of the stars. In an ssh terminal connected to planet, ds9 needs to be open and IRAF needs to be in the *images*, *tv* package. Load a reduced science image into ds9 and ensure there are a few stars in the image. Use the command *imexamine* in IRAF and then click back to the image in the ds9. Move the mouse around the sky background and hit "m" a few times (no clicking required), and the standard deviation of the sky background will appear in the IRAF terminal window! Finding the FWHM is also just as easy, but move the mouse over a star and press "a" instead of "m." The average of the values under "Enclosed", "Moffat", and "Direct" will yield the FWHM of the star. To exit *imexamine* press "q".

Once those numbers are obtained, they are used to update the settings of five different parameter files located in the *noao*, *digiphot*, *apphot* package of IRAF. These parameter files are accessed by typing *epar datapars*, *epar centerpars*, *epar photpars*, *epar fitskypars*, and *epar phot* in succession. The first four need to be updated for photometry in general, the phot parameter file only needs to be updated if photometry is going to be done manually which was the case for the data set presented here. The settings used in each of these parameter files can be found in Tables 6-10 in the appendix.

The actual photometry can now be performed! Load the first image in ds9, then type *phot image001.fits* in the IRAF terminal with the image name that matches the image loaded in ds9. Then in the ds9 window, hold the mouse over each object you want to do photometry on, and press the space bar. When finished, hit q, load the next image into ds9, type *phot image002.fits* in the IRAF terminal, and hit the space bar over the targets in the same order. Continue this process until all images have been done. IRAF will create *.fits.mag.1 files for each image you perform photometry on.

The mag files are not the easiest to find things in because there is a lot of data dumped into each file, so the *txdump* command² was used to extract the desired information out of each file and dump it into a more useful format (text document). The *txdump* command is located in *noao*, *digiphot*, *ptools*, the parameters can be edited using the command *epar txdump*, and the settings⁵ used for this parameter file are listed in Table 11 which can be found in the

appendix. Once the parameters are correct, the command `textdump > data.txt` was used to create a text file that includes the parameters listed in the "fields" section of the parameter file. A data transfer window⁷ was used to copy this file from the planet computer to my personal computer, and the MATLAB script `plot_mag.m` (which can be found in the appendix) was used to read the data and make light curves.

IV. Results

The light curve for both XM satellites can be seen in Fig. 5. Clouds rolled in after about twenty minutes of data collection and the effect of the clouds can be clearly seen as the magnitude dims severely. If only the first twenty minutes of data collection is analyzed, the results can be seen in Fig. 6 and the average magnitude of each satellite is shown.

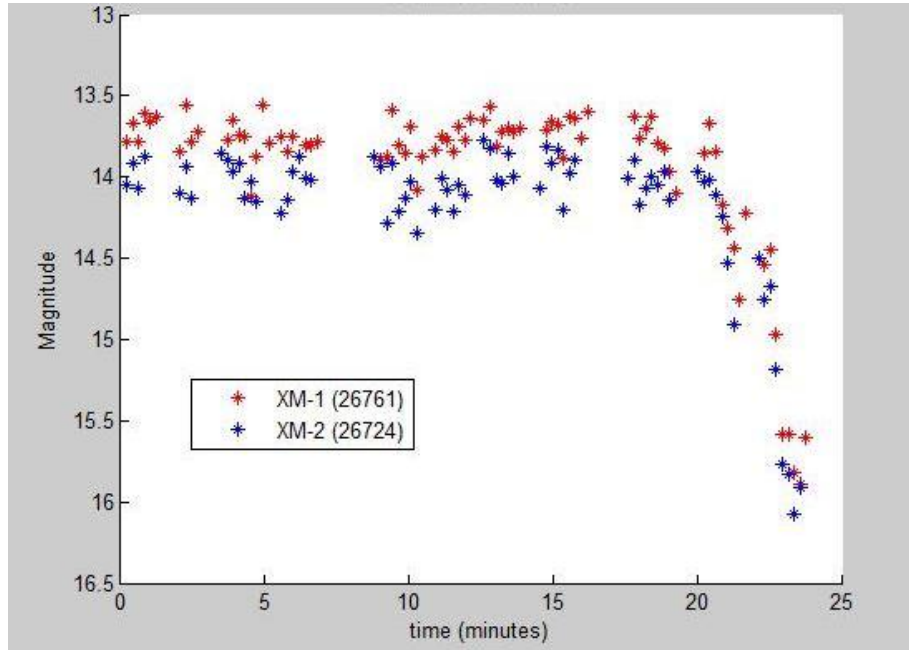


Figure 5. Satellite Light Curves. A light curve is a plot of the magnitude of an object over time. In this case, the objects are two satellites, and the only reason there is a curve in the plot is because clouds disrupted observations, and the brightness of the two satellites decreased as cloud thickness increased as expected. The beginning of the plot before the clouds arrived is relatively flat.

Looking at the first twenty minutes of data, the magnitude fluxuates around the average without any large variations in brightness. These minor fluxuations are of about 0.2 magnitudes and are likely due to atmospheric variations. This suggests that in the future I will need to include comparison stars when I perform photometry for the satellites. If the blue light curve is shifted brighter by the difference of the average magnitude, the result can be seen in Fig. 7. It becomes more obvious that many of the minor fluxuations are the same for both satellites, further suggesting that the atmosphere is the common source of this noise, and that a comparison star would help to eliminate some of the atmospheric variations in the final data.

Aside from the minor fluxuations due to the atmosphere, the absense of large fluxuations in brightness would suggest that the satellites are not tumbling, which seems reasonable given that these two satellites are likely in a fixed orientation relative to the Earth. In twenty minutes, I would not expect the sun-satellite-telescope angle to change very drastically, which also would predict the brightness to remain relatively constant over this short amount of time.

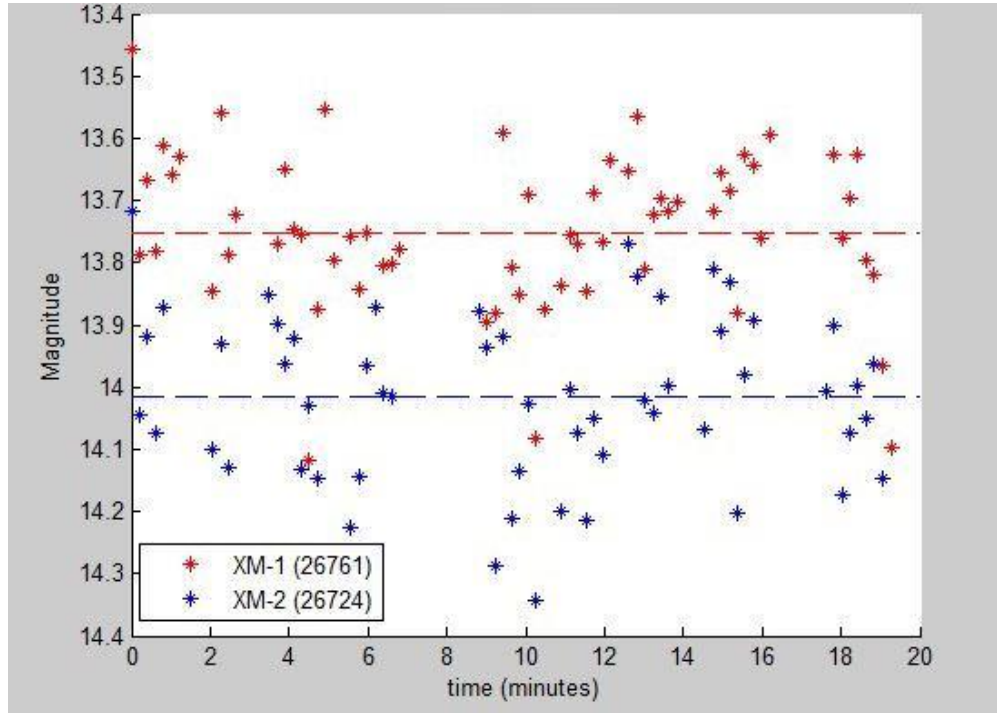


Figure 6. Satellite Light Curves without Clouds. *This image shows the first twenty minutes of data collected and is the same data as in Fig. 5. The average brightness for the shown points is shown as a dashed line in the corresponding color for each satellite.*

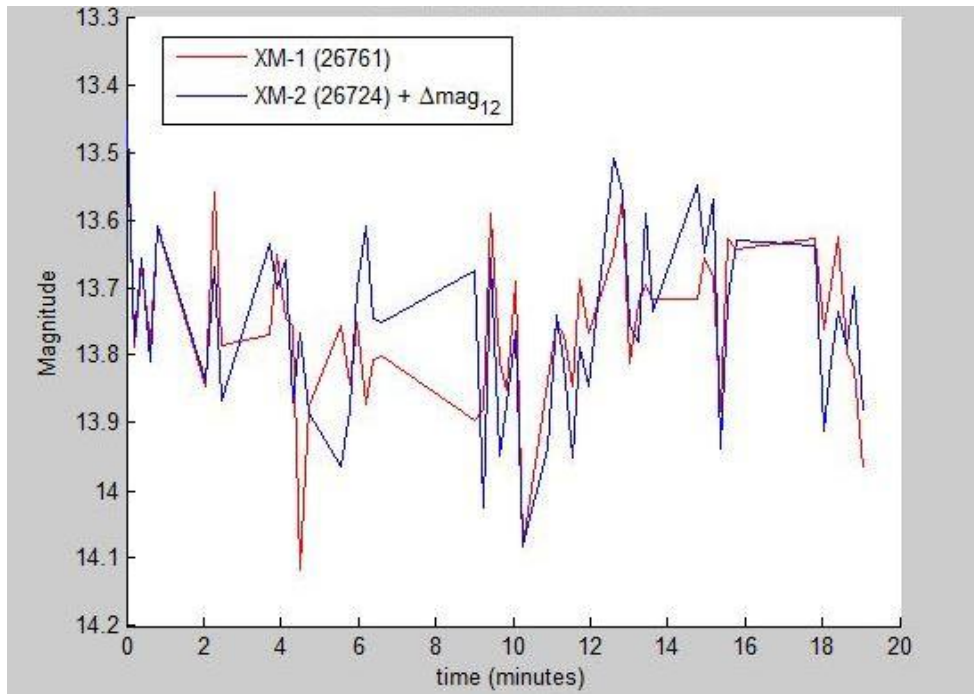


Figure 7. Overlapping Satellite Light Curves. *In this image, the light curves are plotted as lines instead of individual data points to better view trends. Also, the difference in average magnitude of the two satellites was added to the magnitude of the XM-2 satellite such that the light curves overlap. By examining the overlap similarities between the two curves, it is clear that some of the variations in brightness are due to the atmosphere because the variations are the same for both satellites.*

V. Future Work

It is already planned to extend this research to the observation of rocket bodies, not just bright satellites. The rocket bodies will likely be in near geo orbits while being observed because GEO orbit objects move slower relative to the stars and would be easier to target with the telescope. The rocket bodies will likely be dimmer than the bright geo satellites, which might pose a problem because the exposures need to be kept short so the satellites appear as circles in the images for photometry to work. If longer exposures are needed to capture the rocket bodies, some other photometry method might need to be worked with to allow the user to specify an elliptical shape around the object streak.

The next thing that needs to be worked on when expanding this research to rocket bodies is to look into how to eliminate the effects of the atmosphere on the light curve. This would be simple if the target was near a star of approximately the same magnitude throughout the night, but objects in orbit move relative to the stars, so having a comparison star would require having multiple comparison stars throughout the night. On the other hand, if a rocket body changes several magnitudes in brightness over the period of its tumble, then the small atmospheric variations of about 0.2 magnitudes will be negligible, and the overall period can be determined without using comparison stars.

Finding a more automated way of tracking the satellite would also be great if possible. Currently, images are being taken of the satellites as they pass by, then the telescope is moved over slightly, and more images are taken. There might not be a simple solution to this problem but it would be worth looking into.

A more automated way to do photometry would be just as nice (if not better) than an automated way to track the satellite with the telescope. There is currently some software other than IRAF made specifically for satellites that may help with the photometry process and this software will definitely be experimented with.

Finally, a way to find out if a target is visible before going to the observatory will be found. There have already MATLAB codes and programs in STK written to do just this process, but none have been looked into or used as of now.

VI. Conclusion

The Cal Poly Observatory is capable of observing bright satellites in geostationary orbits, and light curves can be found using IRAF software from those images. Much more work is needed for this research to be expanded to finding the tumble rates of rocket bodies in similar orbits, but it is a large step in the right direction after having taken many steps in dead-end directions.

The satellites observed and presented in this paper were likely not tumbling as their magnitudes stayed at about the same level during the twenty minutes of observation. Comparison of similarities between the two light curves leads to the conclusion that most of the fluxuations in the light curves were due to the atmospheric variations, and that comparison stars may be necessary in the future.

Appendix A: Detailed List of Components and Software Used while Observing

The components used to collect observation images are shown below in Table 1, and the software used for collection or reduction of data are shown below in Table 2.

Table 1. List of Components used for Observation.

Component	Brand	Model #	Serial #	Notes
Telescope	Meade 12"	LX200	A118931	
CCD Camera	SBIG Astronomical Instruments	ST-10XME	061100506	SBIG = Santa Barbara Instrument Group
Focuser	Temperature Compensating Focuser (TCF-S)			US Patent No. 6,327,081
Focal Reducer	Celestron Reducer/Corrector	94175		f/6.3
Dome	Digital Dome Works	4	8008	

Table 2. List Software used for Observation or Reduction.

Software	Version	Release Date	Notes
MATLAB	7.8.0.347	February 12, 2009	R2009a Student Version
IRAF	Revision 2.16	May 24, 2012	Image Reduction and Analysis Facility.
The SkyX	Pro		Licensed to "Cal Poly Physics" Serial No. D031-1B22618B
CCD Soft	5.00.210	2011	Copyright by Software Bisque
DDW	5.2	Revision Dec. 2, 2008	Copyright 1998 by Technical Innovations
SAOImage ds9	7.2	April 15, 2013	

Appendix B: Epar Settings

Table 3. Epar Rfits Settings

fits_fil	*.FIT
file_lis	
iraf_fil	<image prefix>
make_im	yes
long-he	no
short_h	yes
datatyp	
blank	0
scale	yes
oldiraf	no
offset	0

Table 4. Epar Zero, Epar Dark, and Epar Flat Settings

epar	zero	dark	flat
Input	*.fits	*.fits	*.fits
Output	masterbias	masterdark	masterflat
Combine	average	median	median
Reject	minmax	minmax	avsigclip
Ccdtype	zero	dark	flat
Process	no	yes	yes
Subsets	n/a	n/a	yes
Delete	no	no	no
Clobber	no	no	no
Scale	none	exposure	mode or median
Statsec			[700:1400,400:1100]
Nlow	0	0	1
Nhigh	1	1	1
Nkeep	1	1	1
Mclip	yes	yes	yes
Lsigma	3	3	3
Hsigma	3	3	3
Rdnoise	8.8	8.8	8.8
Gain	1.3	1.3	n/a

Table 5. Epar Ccdproc Settings

ccdproc	zero	dark	flat
Images	*.fits	*.fits	*.fits
Output			
Ccdtype			
Max_cac	0	0	0
Noproc	no	no	no
Fixpix	no	no	no
Oversca	no	no	no
Trim	no	no	no
Zerocor	yes	no	no
Darkcor	no	yes	no
Flatcar	no	no	yes
Illumco	no	no	no
Fringec	no	no	no
Readcor	no	no	no
Scancor	no	no	No
Readaxi	line	line	line
Fixfile			
Biassec			
trimsec			
Zero	masterbias		
Dark		masterdark	
Flat			masterflatClear
Illum			
Fringe			
Minrepl	1	1	1
Scantyp	shortscan	shortscan	shortscan
Nscan	1	1	1
Interac	no	no	no
Funcio	legendre	legendre	legendre
Order	1	1	1
Sample	*	*	*
Naverag	1	1	1
Niterat	1	1	1

Table 6. Epar Datapars Settings

Scale	1
Fwhmpsf	<FWHM>
Emissio	yes
Sigma	<std dev of sky>
Datamin	0
Datamax	60000
Noise	poisson
Ccdread	
Gain	EGAIN
Readnoi	8.8
Epadu	1.3
Exposur	EXPTIME
Airmass	
Filter	FILTER
Obstime	TIME-OBS
Itime	INDEF
Xairmass	INDEF
Ifilter	INDEF
Otime	INDEF

* found using the "a" key with imexamine

* found using the "m" key with imexamine

Table 7. Epar Centerpars Settings

Calgori	centroid
Cbox	10
Cthresh	0
Minsnra	1
Cmaxite	10
Maxshif	261
Clean	no
Rclean	1
Rclip	2
Kclean	3
Mkcente	yes

Table 8. Epar Photpars Settings

Weighti	constant
Apertur	7
Zmag	25
Mkapert	yes

Table 9. Epar Fitskypars Settings

Salgori	centroid
Annulus	20
Dannulu	5
Skyvalu	0
Smaxite	10
Sloclip	0
Shiclip	0
Snrejec	50
Sloreje	3
Shireje	3
Khist	3
Binsize	0.1
Smooth	no
Rgrow	0
Mksky	yes

Table 10. Epar Phot Settings

Image	
Skyfile	
Coords	
Output	default
Plotfil	
Datapar	
Centerp	
Fitskyp	
Photpar	
Interac	yes
Radplot	no
Icomman	
Gcomman	
Wcsin)_.wcsin
Wcsout)_.wcsout
Cache)_.cache
Verify)_.verify
Update)_.update
Verbose)_.verbose
Graphic)_.graphics
Display)_.display

Table 11. Epar Txdump Settings

Textfile	*.mag.1
Fields	IMAGE, ID, XCENTER, YCENTER, OTIME, MAG, MERR
Expr	yes
Headers	no
Paramet	yes

Appendix C: Matlab Code

remove.m

```
% Kimi Andersen
% Senior Project
% April 3, 2013
% Updated November 4, 2013

% remove the 0 and the R/B from the first line of a 3le
% this code also adds the satellite number to end of the first line

format compact
close all
clear
clc

file_x = fopen('Rockets_3le.txt','r');
file_z = fopen('rocket_body_names.txt','w+');
a = 1;
count = 0;
while a ~= -1
    count = count + 1;
    a=fgetl(file_x);
    if a == -1
        fprintf(file_z, '%s\r\n',hold_a); % print the last line of the file
        break
    end
    token = strtok(a, '');
    if str2num(token(1)) == 0;
        % redefine a without the zero and R/B
        a = strrep(a, '0 ', '');
        a = strrep(a, ' R/B', '');
    end
    if str2num(token(1)) == 1;
        % get the norad number to add to the rocket name
        num = [' (' ,token(3),token(4),token(5),token(6),token(7),') '];
    end
    if count > 1
        print_a = [hold_a,num]; % add norad number to rocket name

        if str2num(token(1)) == 1;
            fprintf(file_z, '%s\r\n',print_a); % print first line with norad #
        else
            fprintf(file_z, '%s\r\n',hold_a); % print lines 1 & 2 w/o norad #
        end
    end

    end
    hold_a = a; % save line data to print next loop

end

fclose(file_x);
fclose(file_z);
```

plot_mag.m

```
%% Kimi Andersen
% Senior Project
% November 3, 2013
% Updated November 5, 2013

format compact
close all
clear
clc

[image_n,id,xc,yc,otime,mag,merr] = ...
    textread('data2.txt','%s %f %f %f %s %f %f');

% time is a string (02:15:34.834)
% make it a number
timeobs = zeros(1,length(otime));
for i = 1:length(otime)
    time = char(otime(i));
    t = strtok(time,'');
    hour = str2num(t(1:2));
    minute = str2num(t(4:5));
    second = str2num(t(7:12));
    timeobs(i) = hour + minute/60 + second/3600;
end

% separate the two different objects by ID number
e1 = find(id == 1);
e2 = find(id == 2);
% get x axis time vector and start it at 0 minutes
timeobs1 = (timeobs(e1)-timeobs(e1(1)))*60; % minutes
timeobs2 = (timeobs(e2)-timeobs(e2(1)))*60; % minutes
% flip magnitudes so larger negative numbers (smaller #s) are dimmer
mag1 = -mag(e1);
mag2 = -mag(e2);
% plot of all data
figure
hold all
plot(timeobs1,mag1,'r*')
plot(timeobs2,mag2,'b*')
xlabel('time (minutes)')
ylabel('Magnitude')
title('Satellite Light Curve')
legend('XM-1 (26761)', 'XM-2 (26724)')
set(legend, 'Position', [0.206 0.3032 0.2393 0.1]);
set(gca, 'YTick', -16.5:.5:-13) % rename y axis points as positive numbers
set(gca, 'YTickLabel', {'16.5', '16', '15.5', '15', '14.5', '14', '13.5', '13'})

% remove the end bit of data that had clouds
f1 = find(timeobs1 <= 20);
f2 = find(timeobs2 <= 20);
% calculate the average brightness
avg1 = dot(mag1(f1), ones(length(f1),1))/length(f1);
avg2 = dot(mag2(f2), ones(length(f2),1))/length(f2);
vari1 = sum(abs(mag1(f1)-avg1))/length(mag1(f1));
vari2 = sum(abs(mag2(f2)-avg2))/length(mag2(f2));
```

```

% plot data before clouds arrived
figure
hold all
plot(timeobs1(f1),mag1(f1),'r*')
plot(timeobs2(f2),mag2(f2),'b*')
plot([0 20],[avg1 avg1],'r--')
plot([0 20],[avg2 avg2],'b--')
xlabel('time (minutes)')
ylabel('Magnitude')
title('Satellite Light Curve')
legend('XM-1 (26761)', 'XM-2 (26724)')
set(legend, 'Position', [0.1381 0.1318 0.2393 0.1]);
set(gca, 'YTick', -14.4:.1:-13.4) % rename y axis points as positive numbers
set(gca, 'YTickLabel', {'14.4', '14.3', '14.2', '14.1', '14', '13.9', '13.8', ...
    '13.7', '13.6', '13.5', '13.4'})

% find when both rockets were found in the same image
count = 1;
h = zeros(1,length(image_n));
for i = 1:length(image_n)-1
    if strcmp(image_n(i),image_n(i+1)) == 1
        h(count:count+1) = [i i+1];
        count = count + 2;
    end
end
j = h(h>0); % index values where both rockets are in the image
% make new id, time, and mag variables
id4 = id(j);
timeobs4 = timeobs(j);
mag4 = mag(j);
% separate the two different objects by ID number
e3 = find(id4 == 1);
e4 = find(id4 == 2);
% get x axis time vector and start it at 0 minutes
timeobs5 = (timeobs4(e3)-timeobs4(e4(1)))*60; % minutes
% flip magnitudes so larger negative numbers (smaller #s) are dimmer
mag1 = -mag4(e3);
mag2 = -mag4(e4);
% remove the end bit of data that had clouds
f6 = find(timeobs5 <= 20);
timeobs6 = timeobs5(f6);

figure
hold all
plot(timeobs6,mag1(f6),'r')
plot(timeobs6,mag2(f6)+(avg1-avg2),'b')
xlabel('time (minutes)')
ylabel('Magnitude')
title('Shifted Satellite Light Curves')
legend('XM-1 (26761)', 'XM-2 (26724) + \Deltamag_1_2')
set(legend, 'Position', [0.1666 0.7807 0.35 0.1167]);
set(gca, 'YTick', -14.2:.1:-13.3) % rename y axis points as positive numbers
set(gca, 'YTickLabel', {'14.2', '14.1', '14', '13.9', '13.8', ...
    '13.7', '13.6', '13.5', '13.4', '13.3'})

```

References

- ¹Cowardin, H., G. Ojakangas, M. Mulrooney, S. Lederer, and J. C. Liou. *Optical Signature Analysis of Tumbling Rocket Bodies via Laboratory Measurements*. Tech. Print.
- ²Massey, Phillip and Davis, Lindsey E. "A User's Guide to Stellar CCD Photometry with IRAF." Print April 15, 1992.
- ³Mitchell, David. "Instructions for CCD Observing at the Cal Poly Observatory." California Polytechnic State University San Luis Obispo, Print 2011.
- ⁴Mitchell, David. "Lab 4: Guide to Data Reduction in IRAF." California Polytechnic State University San Luis Obispo, Print 2011.
- ⁵Mitchell, David. "Txdump." California Polytechnic State University San Luis Obispo, Print 2011.
- ⁶Mitchell, David. "Photometry Guide for IRAF." California Polytechnic State University San Luis Obispo, Print 2011.
- ⁷Mitchell, David. "WINSCEP instructions." California Polytechnic State University San Luis Obispo, Print 2013.
- ⁸"Real Time Satellite Tracking." *XM-1 Satellite Details NORAD 26761*. ITPROSTAR, n.d. Web. 03 Nov. 2013. <<http://www.n2yo.com/satellite/?s=26761>>.
- ⁹"Real Time Satellite Tracking." *XM-2 Satellite Details NORAD 26724*. ITPROSTAR, n.d. Web. 03 Nov. 2013. <<http://www.n2yo.com/satellite/?s=26724>>.
- ¹⁰"XM-1." *National Space Science Data Center Master Catalog*. Ed. E. Bell. National Aeronautics and Space Administration, 16 Aug. 2013. Web. 3 Nov. 2013. <<http://nssdc.gsfc.nasa.gov/nmc/masterCatalog.do?sc=2001-018A>>.
- ¹¹"XM-2." *National Space Science Data Center Master Catalog*. Ed. E. Bell. National Aeronautics and Space Administration, 16 Aug. 2013. Web. 3 Nov. 2013. <<http://nssdc.gsfc.nasa.gov/nmc/masterCatalog.do?sc=2001-012A>>.