Chimera: a high-speed three-color photometer for satellite characterization

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Abstract

High-speed optical photometers have been used for decades to characterize man-made satellites and space debris in Earth orbit. In the 1970s and 1980s, these instruments were typically based on photomultiplier tubes (PMT) and provided single-color, or in some cases simultaneous multicolor, photometric data with high time resolution. The original GEODSS PMT photometers were designed to collect photometry on deep space satellites at rates up to 1 kHz. CCDs have since displaced the use of PMTs in photometers in the astronomical community and the GEODSS system. CCDs offer higher quantum efficiency and two-dimensional imaging arrays, but at a lower speed than PMTs. The latest developments and introductions of commercially available Electron-Multiplying CCD (EMCCD) imagers is driving a renaissance in this field with several new instruments in development.

Chimera is a high-speed photometer with simultaneous three-color photometry in the Sloan *r'* (562-695 nm), *i'* (695-844), and *z'* (826-920 nm) bands. The optical design provides well-corrected fields of view of 9.7 arcmin in the z' band and 6.0 arcmin in r' and i' bands on the Steward Observatory 61" Kuiper telescope at Mt. Lemmon. The wide field of view facilitates acquisition and tracking of rapidly moving satellites and allows for a variety of photometric calibration methods. The optical design uses a wide-field collimator, two dichroic beam splitters, and three re-imagers. Chimera utilizes three Princeton Instruments Pro-EM HS cameras, which provide data at rates up to 228 Hz in full frame mode. Rates over 1000 Hz are possible by defining photometric regions of interest (ROIs). A highly-modified version of Michael Mommert's photometric pipeline (PP), originally developed for near-Earth asteroid photometry, is used for data processing. A real time graphical user interface is under development to allow real-time data quality assessment and period determination during data collections.

In space surveillance, the optical signature characteristics of rapidly rotating satellites necessitate the use of high-speed multicolor photometers. Satellite photometric analysis takes advantage of reflections off flat surfaces of the satellite. The duration of these flashes are as short as a few ms. The high frame rate of Chimera will allow detailed study of the temporal profile of these reflections, which will allow assessment of the quality and characteristics of the reflective surfaces. The simultaneity of the multicolor measurements ensures that data unambiguously refer to the same surface in the same orientation.

In this paper, we document the optical and opto-mechanical design of Chimera and assess the first light performance of the instrument and its cameras and characterize the operational modes of our new instrument. While the unique electron multiplication feature of EMCCDs provides high frame rates with low noise, other noise sources, which are generally negligible with traditional CCDs, must be considered including dark noise and clock induced charge (CIC). We also present the first-light results of Chimera on a sampling of SSA targets, including multicolor observations of a SL-12 rocket body we previously surveyed in the SWIR and satellites with distinctive specular signatures to demonstrate the capabilities of the instrument.

Keywords: Photometry, High-speed, multi-color, electron multiplying CCD, space surveillance

1. INTRODUCTION

Since the beginning of the space age, tracking and characterizing satellites in Earth orbit has been the activity of many including the US government with the US Space Surveillance Network. Over the decades various methods and technologies, each with its own advantages and disadvantages, were developed to accurately assess and characterize satellites from ground-based observatories. Direct imaging of satellites is challenging and has been demonstrated for satellites in low Earth orbit(<2000km) with the use of adaptive optics and radar imaging. However at higher altitudes, like geosynchronous orbit (approx. 36000km), the significantly further distance makes optical imaging infeasible and limits radar imaging to rotating objects. Photometry must be used to characterize the unresolved images of satellites at high altitudes.

As part of the GEODSS system operations, photometry of satellites was first documented by Souvari[1]. Broadband photometry is easily collected at low time resolution (<100Hz) however this data is limited in value to assessing the overall rotational motion and stability of objects. Conducting low time resolution photometry in multiple color-bands simultaneously produces more information about the object than simple broadband photometry. Differences in the relative brightness of each color can indicate different surfaces of the satellite. The Air Force Research Lab (AFRL) and others have experimented with low bandwidth multi-color techniques[2][3][4]. These studies classified satellites by color and did simple frequency analysis to determine rotational periods.

Ground-based satellite characterization can be improved with increased temporal resolution photometry. Russian scientists have shown interest in high-speed multi-color photometry with early efforts using photomultiplier tubes installed on 1-2m class telescopes. Studies conducted at the Odessa Observatory (1977), and later at Uzhgorod, investigated techniques for determining the shape and orientation of a satellite from photometry. Researchers at the Kosmoten Station (near the Special Astrophysical Observatory), claimed to be able to determine the shapes and general characteristics of US intelligence satellites through the analysis of light curves[5]. Researchers at the AFRL and USAF Academy have recently been investigating similar reconstruction techniques (cf. Hall[6] and Fulcoly[7]).

High-speed photometry can be used to characterize a satellites shape by differentiating reflections from different surfaces on the structure of the satellite. One crucial element, and the easiest to detect, is the specular or near specular reflection off a flat surface like a solar panel, radiator, or antenna. These reflections offer the observer the opportunity to isolate a signature of a specific spacecraft feature from an otherwise convolved signature. Due the to constant motion of the satellite and narrow angle of reflection, these specularities are only visible to an observer for a short period of time («1s). Thus to capture and differentiate these reflections photometry must be conducted with a time resolution much greater than 1Hz. Historically the ability to conduct high-speed photometry has been limited by imaging technology. Until recently, most high-speed photometry instruments utilized photomultipliers as detectors. In the late 20th century, CCDs became the predominant detector for astronomical observing due to their much higher efficiency, low read noise, and convenient grid of pixels. Though traditional CCDs slow read rates restricted their use in high-speed photometry. In the 21st century new Electron Multiplying CCDs (EMCCD) have triggered a renaissance in high-speed photometry with several new astronomical instruments utilizing the detector technology.

Chimera is a three-color high-speed EMCCD-based photometer for space surveillance and astronomy. Chimera has three Princeton EMCCD cameras which simultaneously observe the *r'*, *i'*, and *z'* color bands. Designed specifically with space surveillance in mind, Chimera is able to record photometry with time resolution of hundreds of frames per second. This speed combined with the simultaneous multicolor is able to differentiate reflections and characterize the motion and structure of satellites. Moreover, utilization of color-indices, instead of absolute photometry, greatly simplifies calibration and allows the technique to be used under a broad range of operational conditions.

Although an unusual instrument, Chimera is not alone. High-speed photometry has made a resurgence in the astronomy community with the creation of several new instruments over the last two decades. Most notable of which is the ULTRACAM developed by the University of Sheffield and used on both the 4.2 m William Herschel Telescope and the 8.2 m VLT[8]. ULTRACAM was developed prior to the widespread availability of commercial EMCCD cameras and relied on E2V frame transfer CCD's. ULTRACAM supports a maximum frame rate of up to 500 Hz. ULTRACAM was a pioneering instrument and opened a new realm of very-high-speed science. Dhillon has recently created a new instrument, HiPERCAM, a successor to ULTRACAM[9]. Other instruments are also utilizing the unique capabilities of EMCCD's for their detectors. TOFCAM was the first to use an EMCCD for astronomical photometry[10]. More recently Xinglong Observatory has created a three-channel photometer with one channel utilizing an EMCCD with the same architecture as the Princeton camera's in Chimera[11]. Caltech has a two-channel high-speed photometer, also called CHIMERA, which utilizes two EMCCD cameras[12].

2. INSTRUMENT DESIGN

The Chimera photometer was designed around the use of three Princeton Instruments ProEM HS cameras. Each camera is designated to a single Sloan photometric band; *r'*, *i'*, and *z'*. The basic structure is a rectangular enclosure which serves as the chassis and optics housing. The three cameras attach to the outer walls of the enclosure. Light from the telescope enters through an opening on one end and is collimated by a large 4-element, air-spaced collimator lens. The *r'* and *i'* light are each separated from the main beam by a dichroic beamsplitter and redirected to a camera. The remaining beam goes straight through to the *z'* camera. Each camera is equipped with a bandpass filter and a 4-element, air-spaced re-imaging lens. The Princeton cameras are self-contained units with only the detector exposed to capture the incoming light.

The optical design is optimized for used on the Steward Observatory 1.58m Kuiper Telescope located on Mt. Bigelow. It is possible to use Chimera on other telescopes by exchanging the collimator lens. Plans for adaptation include support for use on the 6.5m MMT. On the 1.58m Kuiper telescope Chimera has a well-corrected field of view of 6.0 arcmin in the *r'* and *i'* channels and 9.7 arcmin in the *z'* channel. This corresponds to a plate scale of 0.7 arcsec/pixel for the *r'* and *i'* channels and 0.6 arcsec/pixel for the *z'* channel. The wide field of view allows multiple reference stars to be visible in a single image. This is vital for non-sidereally tracked object like satellites when the presence of a reference star in the field cannot easily be predicted or planned.

Within the constriants of the cutoff wavelengths of the two beamsplitters, the Sloan filters can be exchanged for specialized measurments. The Chimera team intends to use this capability to perform very narrow (10s of nm) band measurements of ion thruster plumes in two channels while guiding using the third broadband channel. Such dual-band measurements of ion thruster plumes can be used to characterize thruster type and performance characteristics.

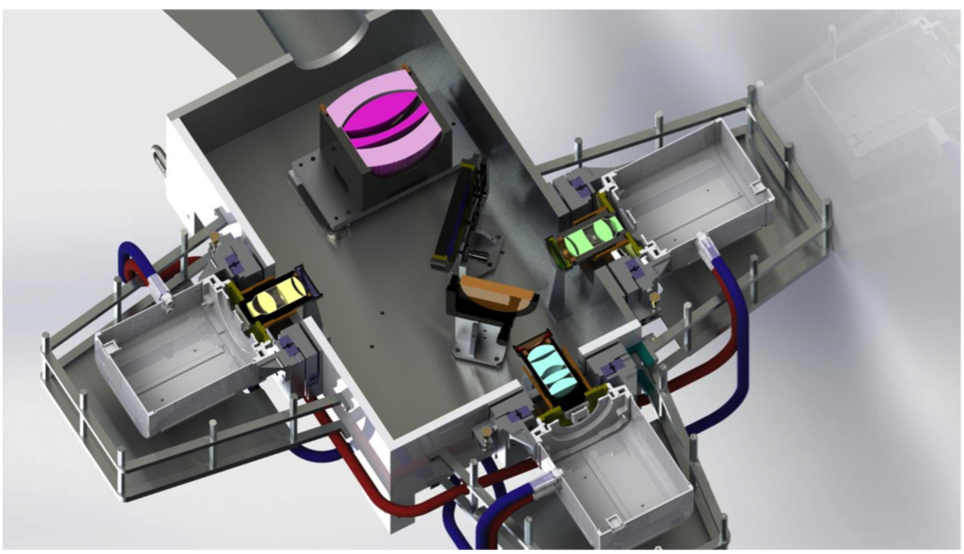

Figure 1: A horizontal cross section of Chimers showing the optics and three cameras

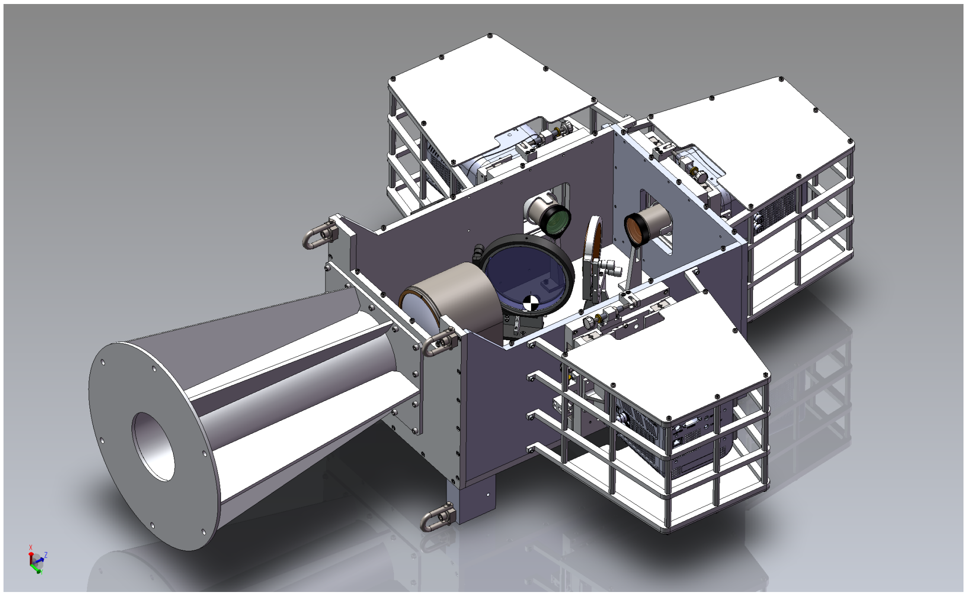

Figure 2: Chimera's structure consists of a rectangular enclosure which houses the four optical assemblies. The three cameras mount to the sides of this enclosure. The round snout attaches to the backplate of the telescope.

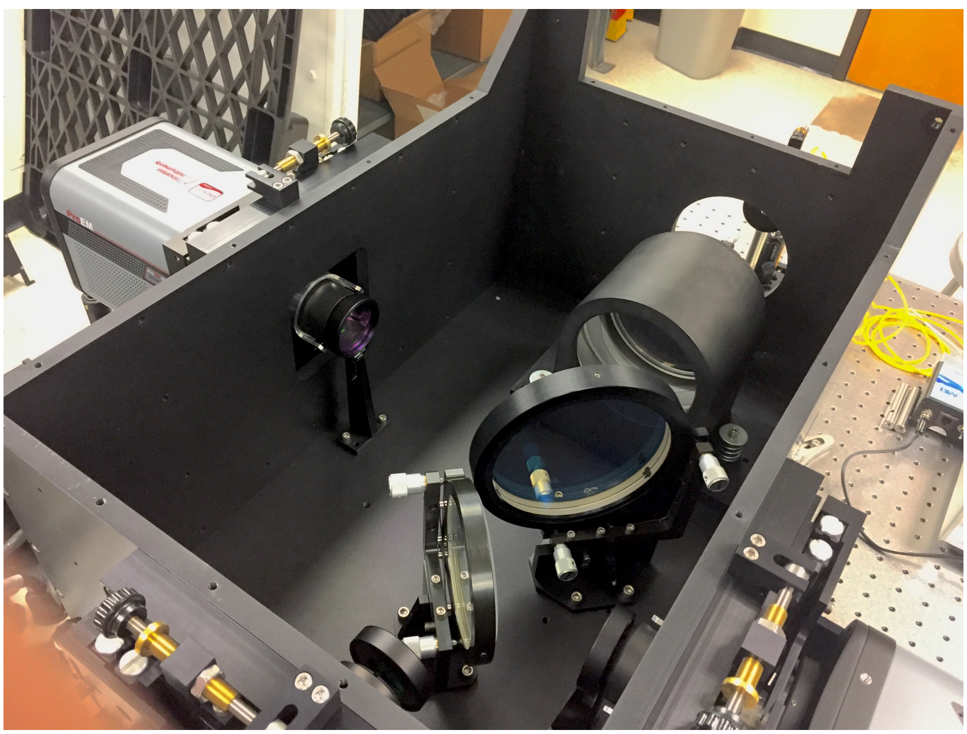

Figure 3: The Chimera optics inside the enclosure. Chimera uses a wide-field collimator and two dichroic beamsplitters. Each camera is equipped with a bandpass filter and re-imaging lens.

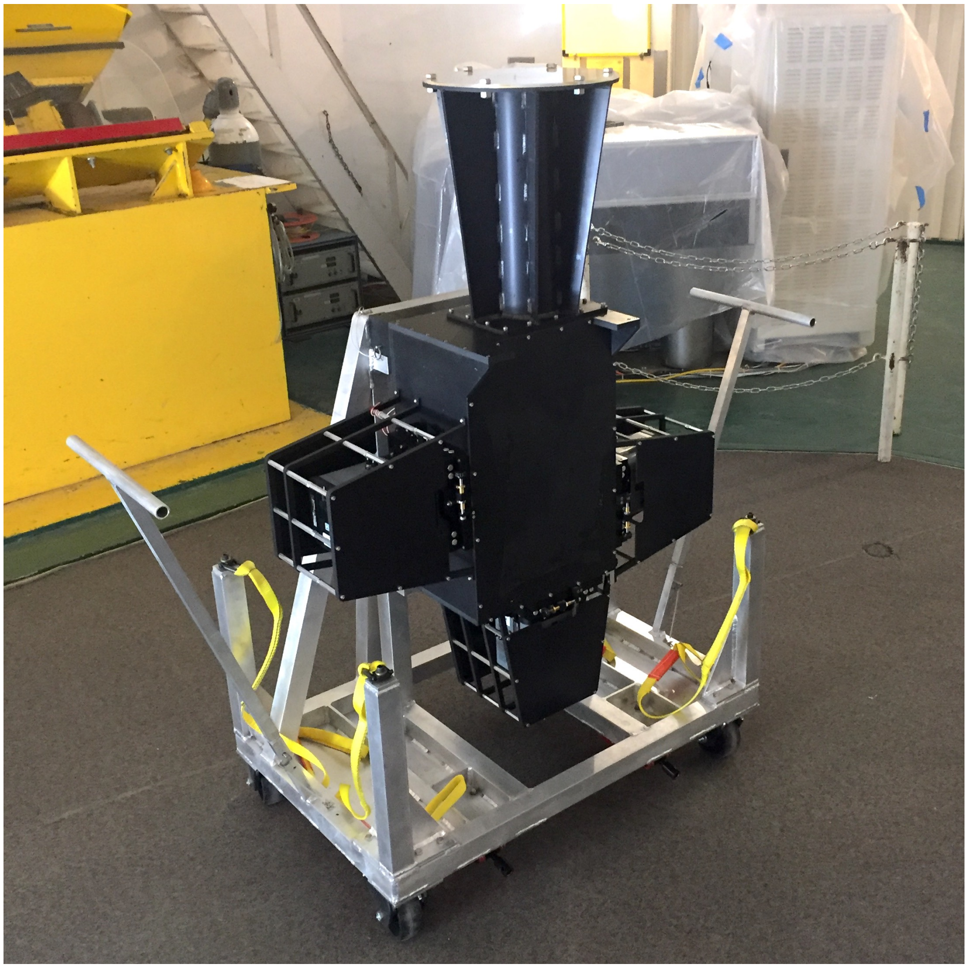

Figure 4: The complete Chimera instrument loaded on the transport cart

2.1 EMCCD DETECTORS

Chimera's high-speed capabilities are possible because of the unique design of EMCCDs. Chimera uses three Princeton Instruments ProEM HS cameras; two 512x512 cameras for the r' and i' channels and one 1024x1024 camera for the z' channel. The 512x512 cameras have $16\mu m$ pixels and the 1024x1024 camera has $13\mu m$ pixels.

The EMCCD detector is unique in that it enables much faster readout than a traditional CCD, but maintains a low noise level. The difference between a traditional CCD and an EMCCD is the addition of a gain register. A traditional CCD incrementally shifts the electrons from cell to cell across the array until they are output into a readout register from which the signal is amplified and measured by an analog-to-digital converter (ADC). In an EMCCD, an additional shift register is added between the array output and the analog amplifier. The cells of this shift register are pre-charged with high-voltage such that passing in a signal triggers an electron-multiplication effect via a similar process to impact ionization. This electron-multiplication results in massive gain to the signal with minimal noise. A signal of only a few electrons can easily be multiplied into thousands. The major advantage is that this signal multiplication is done on-chip before readout noise is present. Thus the read noise is not multiplied and remains at the same level as a traditional CCD. Combined with the advantages of traditional CCDs, including frame transfer and high clock-rate, EMMCDs are able to run at very high-speeds with low noise.

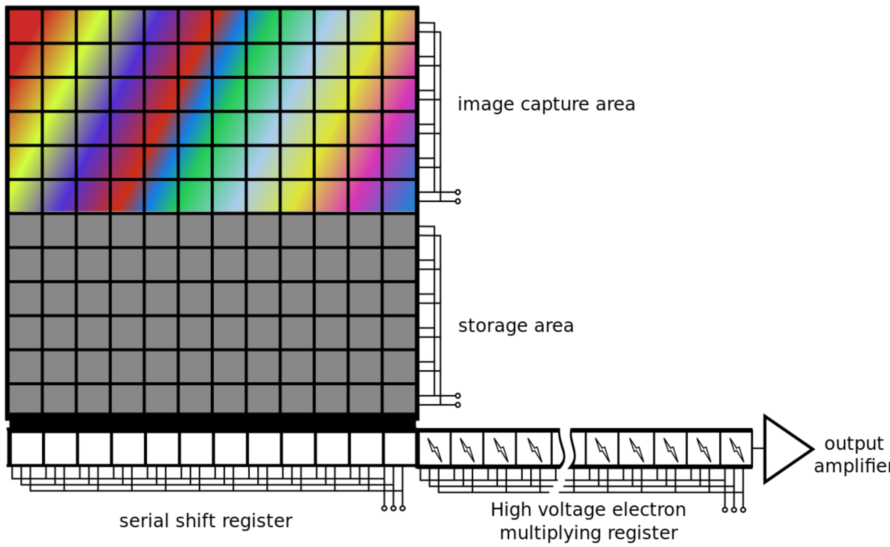

Figure 5: The EMCCD uses a high-voltage shift register to multiply the signal coming off the CCD [1]

The Princeton EMCCD cameras can be operated in two modes: a high-gain mode where the gain registers are activated or a low noise mode where the gain registers are not activated and the camera acts as a traditional CCD. Characterizing the performance of the EMCCDs in the high-gain mode is complicated. EMCCDs suffer from noise sources that are not typically considered with traditional CCDs. Noise sources include a non-linear quantum efficiency due to variable gain and clock-induced charges which are extraneous electrons produced during a clock event[10]. When running the cameras at near-maximum gain levels we have also observed unusual non-uniformity in the images likely due to effects of the high readout rate.

We are working to fully characterize the performance and behavior of the EMCCDs in both operating modes. We intend to detail the performance impact of the various settings of EM-gain, analog-gain, and readout settings. The details of this characterization will be included in a future publication. Based on our work users of Chimera will be able to customize the operating configuration to optimize performance and match required bandwidth, field-of-view, and calibration requirements.

The published frame rates for the Princeton camera's in high-gain mode are shown in table 1. When reading out the full frame of the detector at the maximum read rate the smaller cameras will run up to 228 fps and the larger camera 89 fps. Binning the pixels will increase the frame-rate by effectively reducing the number of pixels that must be read by the ADC.

The fastest frame-rates are achieved by selecting a region of interest (ROI) which crops the output image by only reading the pixels necessary and discarding the rest. Multiple ROI's can be selected for each sensor and the final frame rate is dependent primarily on the total number of pixels being read, though is also impacted by the location of the ROI on the detector. With small ROI's frame-rates of 1000 fps or more are possible.

In practice the limiting factor for frame-rate is the photon count from the target object. Even at the highest gain settings the usable frame-rate is determined by the necessary integration time to achieve a sufficient signal-to-noise ratio (SNR).

[1] https://commons.wikimedia.org/wiki/File:EMCCD2_color_en.svg

Table 1: The possible frame-rates for the Princeton cameras for various detector settings.

Band	Resolution	FOV (arcmin)	Full Frame Binning (fps)			ROI Binning 32x32 (fps)		
			1x1	2x2	4x4	1x1	2x2	4x4
r'	512x512	6.0	61	120	228	711	1099	1506
i'	512x512	6.0	61	120	228	711	1099	1506
z'	1024x1024	9.7	25	48	89	481	675	847

The Princeton cameras cool the detectors with a thermoelectric cooler. This device can cool the detectors to -70°C. Additionally, the cameras have ports for attaching an external liquid cooling system. In our experience, the thermoelectric cooler is sufficient for nearly all observations. Only when running the cameras at the near-maximum speeds and gain settings is the temperature unstable. In this regime, the temperature slowly rises approximately one degree every few minutes. Thus we expect the liquid cooling system to only be necessary for very long duration observations at the highest speed and gain settings.

2.2 SOFTWARE AND DATA PIPELINE

The Princeton cameras and capture-software produce SPE files, a proprietary format only utilized by Princeton's software. These files consist of a binary header, binary data for each frame, timestamp metadata, and a XML footer. For the Chimera photometer, custom software was developed to ingest these files and analyze the data. The underlying data analysis methods are adopted from Michael Mommert's automated photometric pipeline[13].

A graphical user interface (GUI) shows observers a live photometric(instrumental or differential) measurement of the target and an accompanying lightcurve. Additional period analysis can be performed live for relevant targets. The observer provides the bias, flat, and dark images for basic image reduction. Selected science files have the master bias and master dark subtracted and the master flat divided to reduce noise. After selecting the target and comparison stars, the software automatically tracks the centroid of the target and comparison stars across the frame to account for any errors in telescope tracking. Pertinent data from the GUI can then be exported for later use. The Chimera pipeline has been tested on various targets including variable stars, artificial satellites, and fast-rotating asteroids.

The rotational period determination within the GUI utilizes a Lomb-Scargle Periodogram from Astropy, which has the capability to compute the period by means of Fast-Fourier or Lomb-Scargle analysis depending upon the uniformity of measurement intervals present in the processed lightcurve data. Additionally, the observer may specify a target frequency range to exclude inherent noise. The results of the analysis are displayed and a best fit sinusoidal curve is plotted over the lightcurve, providing a visual check. Period analysis has been conducted on several objects captured by Chimera as well as by UKIRT WFCAM, to include SL-12 rocket bodies.

Future software developments include retrieving telemetry from the telescope to write in the file footer, incorporating all three Princeton cameras in the GUI for real-time analysis, improving the aperture photometry process, and generating efficient live plot. Drivers are currently in development to allow remote and robotic operation of Chimera in preparations for the Steward Observatory 1.58m Kuiper telescope upgrades to robotic operations.

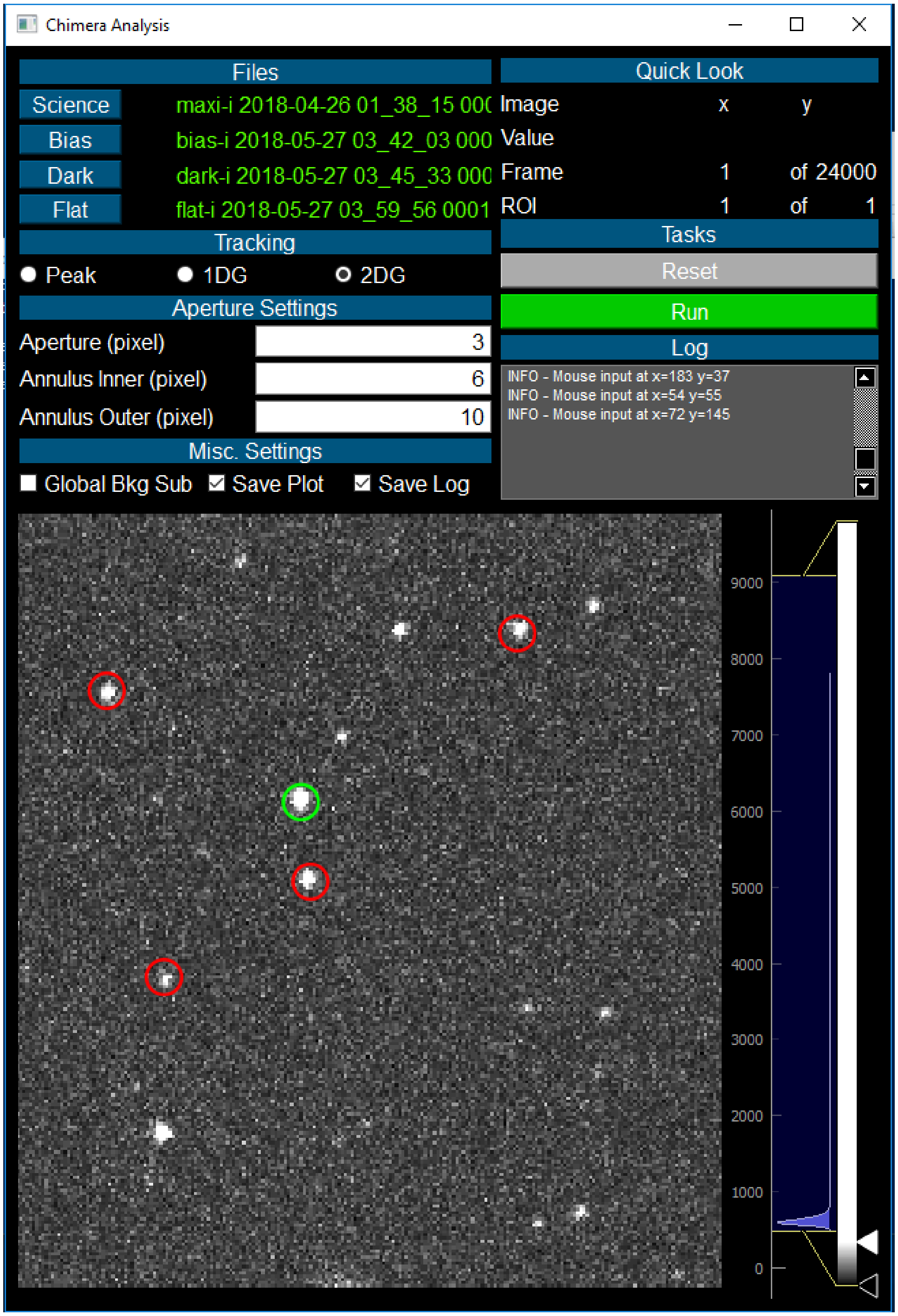

Figure 6: The Chimera Analysis software displaying live photometric data analysis.

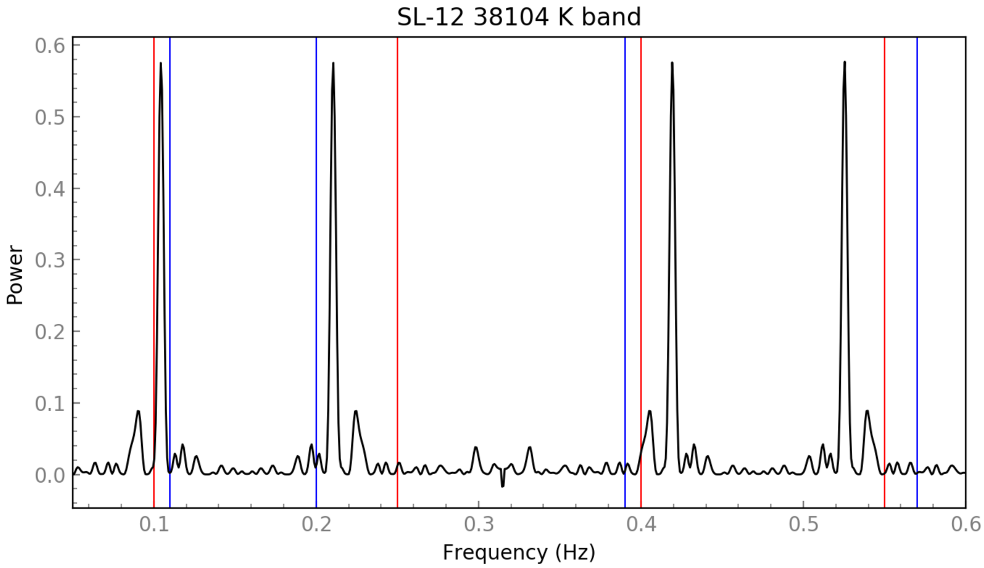

Figure 7: The period analysis within the Chimera Analysis software plotted with published frequency measurements for SL-12 38104. The red and blue vertical lines represent the published observations taken May 2013 and December 2013 respectively [3], while the black curve is representative of post-analysis UKIRT WFCAM data taken January 2017

3. OPERATIONS

3.1 FIRST LIGHT

The complete Chimera instrument achieved first light on April 3rd 2018. Chimera was installed on the 1.58m Kuiper telescope on Mt. Bigelow[14]. During this observation run data was taken on numerous reference stars for characterization as well as time-dependent photometry on a number of objects including satellites and rocket bodies.

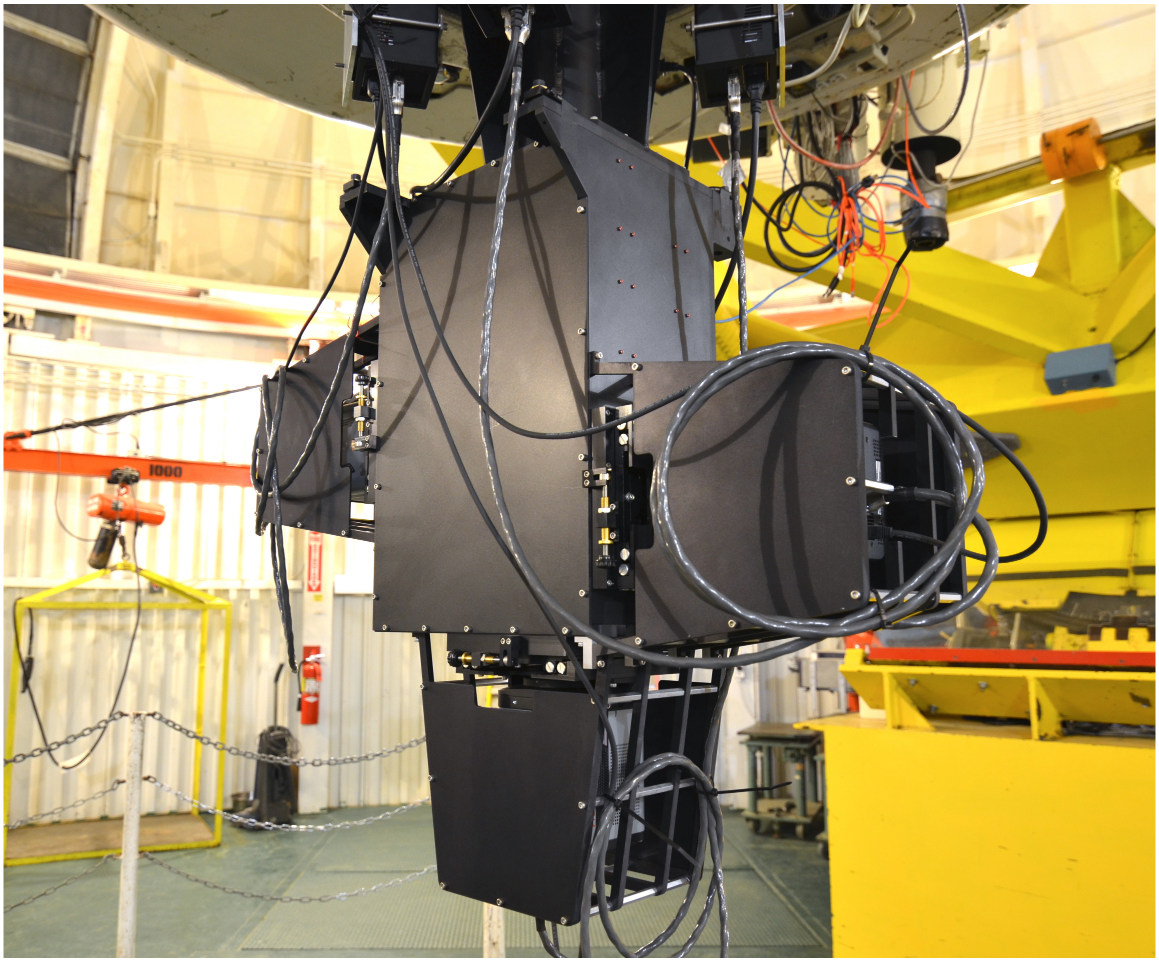

Figure 8: Chimera installed on the 1.58m Kuiper telescope at Mt. Bigelow in southern Arizona

3.2 OPERATING MODES

Depending on the observational target there are several different modes that Chimera can be operated in.

3.2.1 SIMPLE PHOTOMETRY

Even though Chimera was designed with the intention of doing high-speed photometry on SSA targets, the instrument itself is still fundamentally a imaging photometer. With the Princeton camera's EMCCD's operated in the low-noise traditional CCD mode classic imagery and photometry can be done on astronomy targets with long or short integration times. Chimera provides the additional benefit of producing photometry in the *r'*, *i'*, and *z'* bands simultaneously thus significantly reducing the needed observing time compared to a single channel photometer. The wide field of view also allows for many possible reference stars to be visible in the field with the target. The maximum frame-rate in this operating mode is about 1 fps.

3.2.2 HIGH-SPEED FULL-FRAME PHOTOMETRY

With the Princeton camera's EMCDDs operating with EM-gain activated, Chimera can conduct high-speed photometry. The camera's can operate in the full-frame mode up to approximately 60 fps without binning or 200 fps with binning. Operating in full-frame mode requires little setup beyond adjusting the integration time and gain settings. The full-frame also takes advantage of the wide field of view which allows multiple reference stars to be used for photometric and astrometric calibration. This is especially important for non-sidereally tracked objects such as satellites. While the telescope is tracking the satellite background stars will appear to pass through the image. The wide field of view all but guarantees that multiple background stars will be in any given frame.

3.2.3 VERY-HIGH-SPEED PHOTOMETRY

To reach maximum speeds the camera's must be operated with one or more ROI's selected. This significantly reduces the number of pixels which need to be read thus allowing faster readout of the image. Typically an ROI will be selected for the target and additional ROIs selected for the reference stars. Minimizing the number of pixels selected will maximize frame rate. ROIs should be sized to include the target and a border of 2-3 sky pixels around it thus resulting in a ROI of 25-36 total pixels. This operational mode can only be applied to sidereally tracked objects.

3.2.4 VERY-HIGH-SPEED PHOTOMETRY WITH NON-SIDEREAL TRACKING

For non-sidereally tracked objects, getting the highest frame-rates with ROIs requires sacrificing one of the color channel cameras for tracking. Typically this channel will be *z'* since it has the largest field-of-view. In this mode, the *r'* and *i'* cameras will be run with an ROI for the target and the *z'* camera running full-frame. This allows for the *z'* camera to capture reference stars as they pass through the image while the *r'* and *i'* cameras capture very-high-speed photometry.

4. RESULTS

Figure 9 shows the brightness of the now defunct communcations satellite Echostar 2. This satellite is in geostationary orbit at an altitude of approximately 35,765km. Photometric data was recorded in all three color channels with an integration time of 200ms. The data shown in figure 9 has been calibrated to a reference star. The lightcurves show a long period with semi-regularity. The shape of the curve and spikes and dips in brightness are indicative of the physical structure of the satellite.

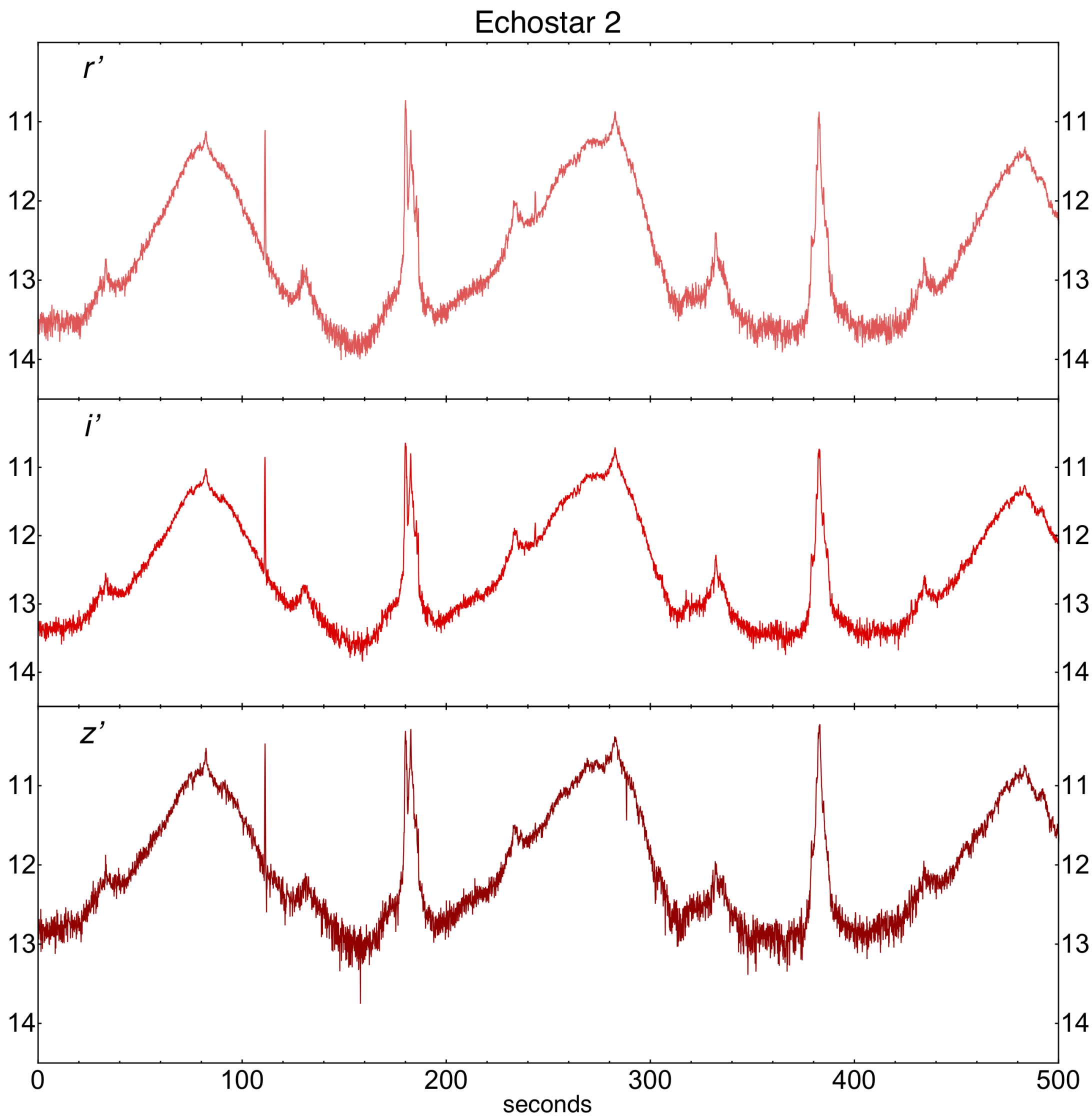

Figure 9: The *r'*, *i'* and *z'* band lightcurves of satellite Echostar 2 show semi-regular variability with large spikes and dips in brightness which may be indicative of structure.

Figure 10 shows the brightness of an SL-12 rocket body, NORAD ID 18718. This object is near geostationary orbit with an altitude of approximately 35,400km. Photometric data was recorded in the *r'* channel with an integration time of 50ms. The data shown in figure 10 is instrumental photometry and has not been calibrated to any reference star. The lightcurve shows a regular variability indicating a rotational period of about 10 sec.

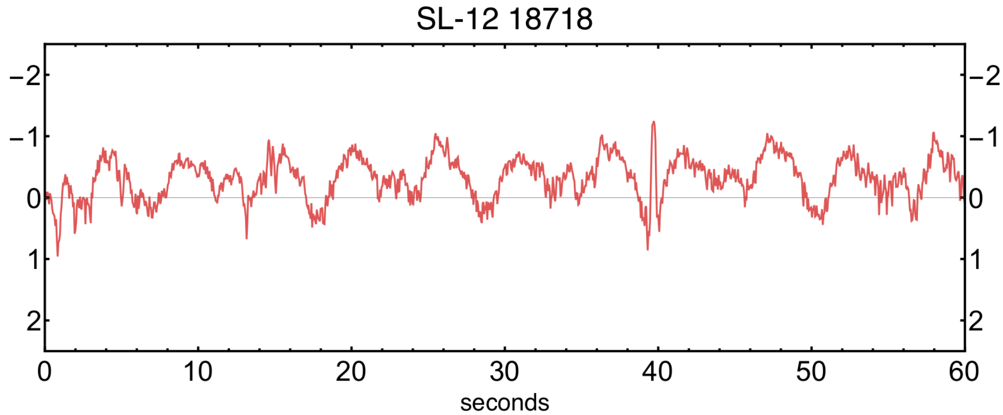

Figure 10: The *r'* band lightcurve of SL-12 rocket body NORAD ID 18718 shows a regular variability with a period of about 10 seconds indicating a rotational period.

Additionally, photometric data was recorded of black hole candidate MAXI J1820+070. This is a transient object which was first reported as an X-ray transient on March 11, 2018[15]. Numerous observatories have been collecting data on this new transient object. The high-speed abilities of Chimera allow us to make a unique contribution to the observations of MAXI J1820+070, and other transients. High-speed photometric data will be able to temporally resolve outbursts and variability in a way that has not been done before.

5. CONCLUSION

The Chimera high-speed photometer is now operational at the Steward Observatory 1.58m Kuiper telescope. Chimera is able to record photometric data at high-speed in three Sloan color bands, *r', i'*, and *z'*, simultaneously. Since first light we have been taking data on a variety of targets including satellites, rocket bodies, and astronomical objects. Lightcurves of satellites and rocket bodies show well resolved variations in brightness that are indicative of rotational motion and physical structure.

Work on Chimera continues, primarily in software and data analysis. The custom software package allows observers to view the photometric data and initial analysis in real time. Real-time feedback enables the observer to make impromptu decisions during observing runs. This is valuable for SSA targets with short observation windows and are often variable and unpredictable.

We plan to make regular observations with Chimera. Targets include satellites, rocket bodies, space debris, asteroids, NEOs, transients, and other astronomical targets. The unique capabilities of Chimera, including its high-speed and simultaneous three-color operation, will enable numerous observations and science opportunities that were not previously available.

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