FireOPAL: Analysis of One Million High Time Resolution Optical Light Curves

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ABSTRACT

There is significant interest in the SSA community in using optical light curves of satellites and debris to infer properties such as tumbling, size, pose, composition, etc. The large number of free parameters make the interpretation of the observations particularly challenging. Comparing data taken at different times from different sensors also introduces an extra level of complexity. Here we describe an analysis of a very large, unique dataset of light curves from FireOPAL, a distributed network of sensors built with the same hardware and employing identical image processing systems. These fixed mount sensors measure both the integrated brightness during an exposure and a higher time resolution light curve as an object moves through the field of view. Each unit in the network has recorded data over hundreds of nights, with thousands of light curves generated each night. The images are synchronised across the network, providing simultaneous observations of the same objects from different places on Earth. In addition, the use of Bayer filters in the sensors enables simultaneous measurements of RGB colour of the same objects at the same time. We describe our analysis of these data, including light curves of objects of known shape and the pattern of life of objects established over long periods of time.

1. INTRODUCTION

FireOPAL (Fireball OPtical ALert) is a network of optical SSA observatories that traces its engineering heritage to the successful Desert Fireball Network, the world's largest planetary science observational facility. The observatories are standalone, weather-hardened systems housing a COTS camera, with a high resolution lens, a GPS receiver, and a multi-core CPU on an embedded PC. The camera is a full frame 36MP cooled CMOS sensor. When coupled to a 105mm lens, the field of view is approximately 20° x 12.5° with 10 arcseconds/pixel. The observatories are solar powered with battery storage, and are capable of 3G/4G, wireless, satellite modem, or Ethernet connectivity. They are designed to function as a coherent network, to monitor a large number of artificial satellites simultaneously, and provide wide area surveillance and precision tracking in near real time. FireOPAL observatories take 5 second exposures on a fixed mount, with observations synchronized and time-stamped to millisecond precision across the entire network. Synchronised observations over a large distributed geographic network enables range estimation through triangulation as well as comparison of apparent brightness from different points on Earth. Thirty TB of hard drive space allows all imagery and other data products to be stored onboard. The entire package is designed to be low cost, and easy to deploy. The observatories are capable of operating completely autonomously for 24 months in a harsh environment without maintenance. All the image processing is done onboard within seconds after each image is taken and results are reported back to a central server in near real time. More details on the system and pipeline processing can be found in [1] and [2].

Here we describe an analysis of optical light curves from our prototype network of eleven sensors in South and Western Australia. With over one million light curves observed in the past few months, we demonstrate the quality of the data and illustrate some examples of how the data can be used to infer important properties of different satellites. Because the units are all clones of one another and processed and calibrated with the same pipeline, data from different sensors can be combined with reduced concern for systematic effects between sensors.

2. PHOTOMETRIC PROCESSING AND CALIBRATION

Each unit processes images in near real time, providing measurements of streaks found on individual images (LEO/MEO), as well as measurements of point sources from groups of images (GEO). After identifying a satellite candidate, a small thumbnail/cutout is extracted around each candidate. The photometric calibration is performed in-frame on these cutouts.

The current observatories use detectors with Bayer (RGGB) filters. This means that in principle, a three colour image is recorded for every object with all three colours recorded at the same time. The processing, for now, only considers the green channel pixels. A full frame equivalent green image is calculated by interpolating over the red and blue channel pixels. Future improvements will include the implementation of a procedure for extracting and calibrating red and blue images for observed satellites.

The fluxes of objects consistent with stars are calculated on each cutout using aperture photometric techniques. Aperture corrections are estimated and applied to recover the total flux from trailed stars; on a 5 second image a star near the GEO belt has a length of about 7-8 pixels with current optical setup. Stars that do not suffer from crowding are matched to stars in the Tycho-2 catalogue [3] that have a reported B and V band magnitude; Tycho-2 magnitudes are in the Vega system. An instrumental magnitude is calculated for the observed stars and corrected for attenuation by the atmosphere. The median difference between the instrumental magnitude and Tycho-2 V band magnitude among matched stars defines the magnitude zero point for the image. On a clear night, we find a typical root-mean-squared scatter in the magnitude zero point of about 0.1 mag. The scatter appears random; there is no evidence that the inclusion of a (B-V) colour term or other terms reduce this scatter. This suggests that the Bayer green channel is an approximate match to the Tycho-2 V band system. The relatively large uncertainty of 10% is due to the combination of the challenge in accurately measuring the flux from trailed stars on a de-Bayered image, as well as the different spectral response between the Bayer green channel and the Tycho-2 V band system. We are pursuing efforts to understand and minimize the source of this uncertainty; we are limited at the moment to uncertainty in the absolute photometric calibration of 10%.

If the photometric calibration fails, usually due to an insufficient number of matched reference stars, a default value for the magnitude zero point is used and the object is reported as potentially having unusable photometry. We have monitored the network over enough nights to build reference maps of the magnitude zero points on clear/photometric nights for each sensor. The 'photometric' zero point is reported along with the measured magnitude zero point and enables an assessment of the photometric quality of the data. In addition, the point source sensitivity for each cutout, taking into account the measured noise in the background sky, is reported. On a clear night, the limiting magnitude for a 5-second image taken near sea level in the Australian desert, with a 105mm lens, is typically around $m_V = 14$ mag (5-sigma). For a group of 60 images combined for GEO processing, the sensitivity is typically around $m_V = 16$ mag.

The LEO/MEO image processing produces two sets of photometric data for each object. One is the 'integrated' magnitude where the total flux across the entire streak is recorded. Another data product is a much higher time resolution measurement of brightness *along* the streak. These are extracted from processed images by placing a 'slit' along the streak and estimating the flux (similar to processing spectra). For GEO data, the magnitude is a time-averaged, flux-weighted estimate of the object's position and brightness; this averaging occurs over the ~10 minutes of images combined together. The magnitude zero point is determined on the image taken in the middle of the sequence of combined images, but the flux is measure on the stacked image.

Figure 1 shows the distribution of apparent ('integrated') magnitudes of LEO/MEO and GEO objects as observed by the FireOPAL network over March 2018 – August 2018. Only objects with magnitude zero points within 0.1mag of the 'photometric' zero point are shown (i.e. no clouds). Almost one million photometric measurements have been recorded; almost half of the measurements were taken over 1 June 2018 – 15 August 2018.

3. LEO/MEO OBJECTS

Since the prototype network first started being deployed in March 2018, we have observed thousands of objects in the space-track catalogue. For almost 500 objects, we have recorded more than 100 clear-night observations. Figure 2-4 show the results of the integrated magnitude observations for one object that was observed more than 3,000 times since March 2018. ATLAS 2AS CENTAUR R/B (SSN #26072) is a on a highly eccentric orbit and has been observed by all sensors in the network over a range of distances and solar phase angles.

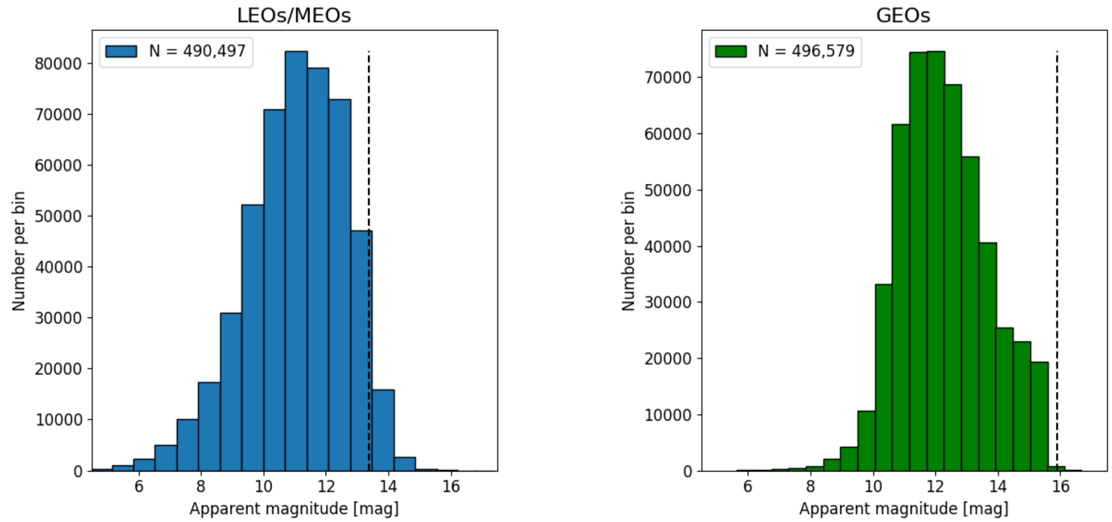

Fig 1: Distribution of apparent magnitudes of LEO/MEOs (*left panel*) and GEOs (*right panel*) as observed by FireOPAL since March 2018. Only objects observed on photometric/clear nights are shown. The vertical dashed line shows the average limiting magnitude (5-sigma) over this period for the two different kinds of processing. For LEO/MEOs, the apparent magnitudes shown here are the integrated brightness along the detected streaks.

In order to compare observations taken under different conditions, we use a very simple model where apparent brightness depends on three parameters: slant range from the sensor to the object, the solar phase angle, and the optical reflectivity (cross section * albedo). Figure 2 shows the change in apparent magnitude with slant range. A simple linear fit is shown on the plot as a solid red line. The slope of that line was used to calculate a 'range-normalised' magnitude, i.e. the expected brightness the object if it were at the same distance for every observation. The range-normalised magnitude is shown in Figure 3 as a function of solar phase angle. As expected, the object is brighter when observed at a lower phase angle. The solid red line again is a simple linear fit to the data and is further used to calculate a range and phase normalised magnitude. Variations in the range and phase normalised magnitude are likely due to changes in optical reflectivity.

The changes in range and phase normalized magnitude over several months are shown in Figure 4. The different coloured points represent observations by different FireOPAL sensors. Variations of the order of 2 magnitudes are seen over a range of time scales. Figure 5 shows the same data zoomed in over a narrow date range. The top panel shows data over a 20-minute time span when the object was observed by three sensors at the same time, then seen later by two other sensors. The figure shows very good agreement among observations taken at the same time – this confirms the accuracy of the photometric calibration. A strong periodic variation in magnitude is also apparent. The dashed vertical lines are all separated by 105 seconds and are well matched to the successive peaks in magnitude across the panel. The bottom panel shows observations of the same object but taken more than two months later. The periodicity is still seen, but the period has decreased over that time to 92 seconds per cycle. This suggests that the spin rate is increasing, but more detailed modelling is needed.

The other kind of photometric data available for LEO/MEO objects is shown in Figures 5 and 6. The left hand side of the figures show the cutout of an image centered on a streak; North is up, East is left. The green box shows the end points and orientation of the streak as determined by the near real time processing. The right hand side show the flux of the streak as a function of position along the streak; the streak coordinates increase with increasing RA. These 'light curves' show variation in flux on very short time scales. In Figure 5, the object moved about 232 pixels in 5 seconds, or 0.02 sec per pixel. A periodic variation of about 50 pixels is evident in the light curve.

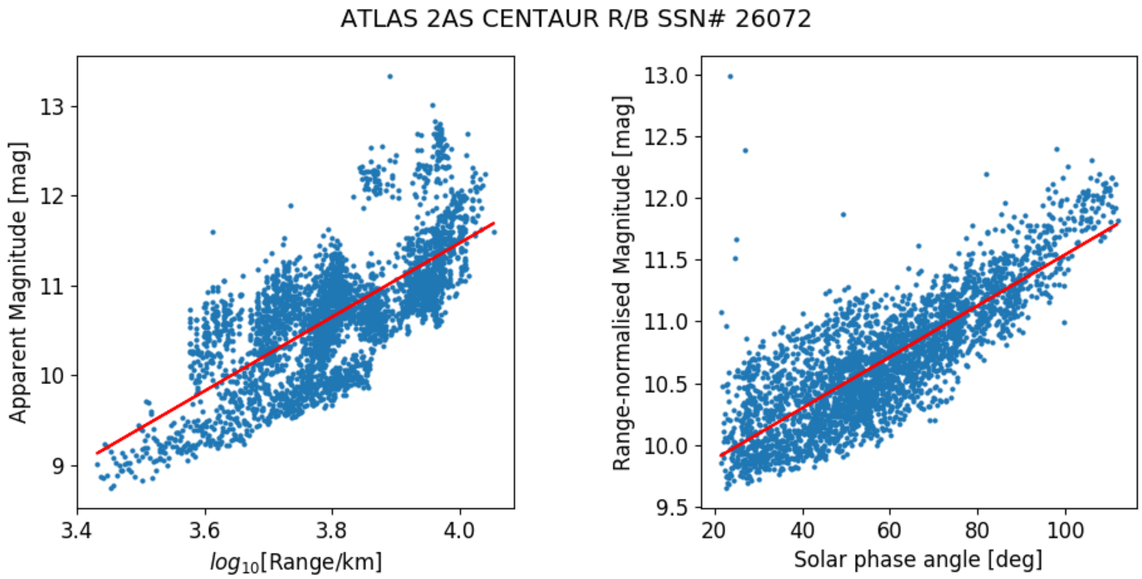

Fig 2: Apparent brightness of streaks associated with ATLAS 2SA CENTAUR R/B (SSN# 26072). Each panel shows more than 3,000 photometric observations of this object; for clarity error bars of about 0.1mag have been omitted. The left panel shows apparent magnitude as a function of slant range, where the range comes from predictions from space-track TLEs. The right panel shows the magnitude (normalized to the same slant range) as a function of solar phase angle. In both panels, the straight red line is a simple least-squares fit to the data and is used to normalize the magnitudes (see text).

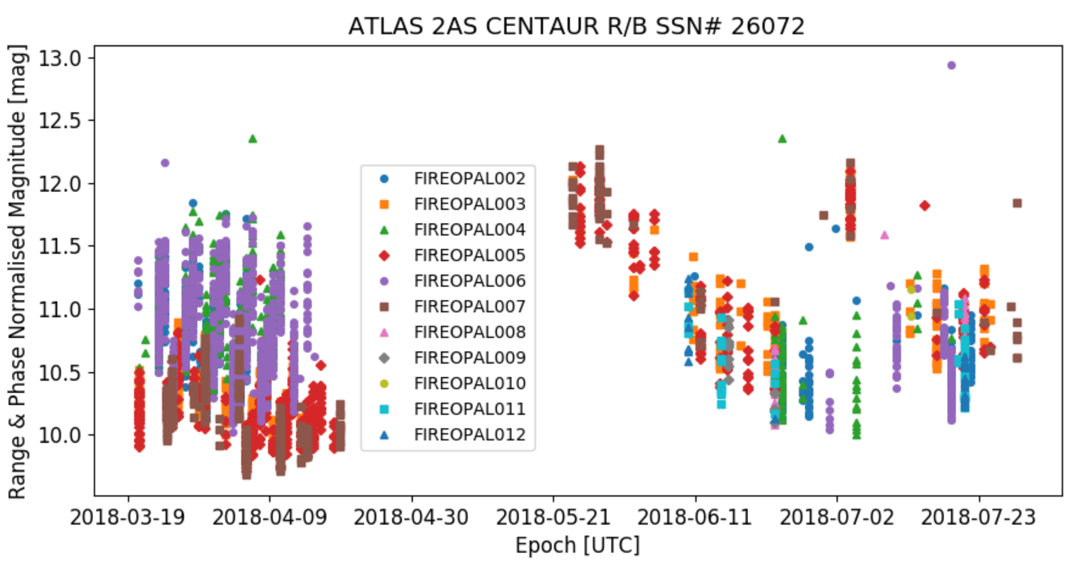

Fig 3: Long-term light curve for SSN#26072. The magnitudes, normalized by range and solar phase, are shown as a function of epoch of observation. The normalization aids the comparison of magnitudes observed by different sensors at different places at different times. The data in the panel are colour coded according to sensor. This LEO was seen by every sensor in the prototype network.

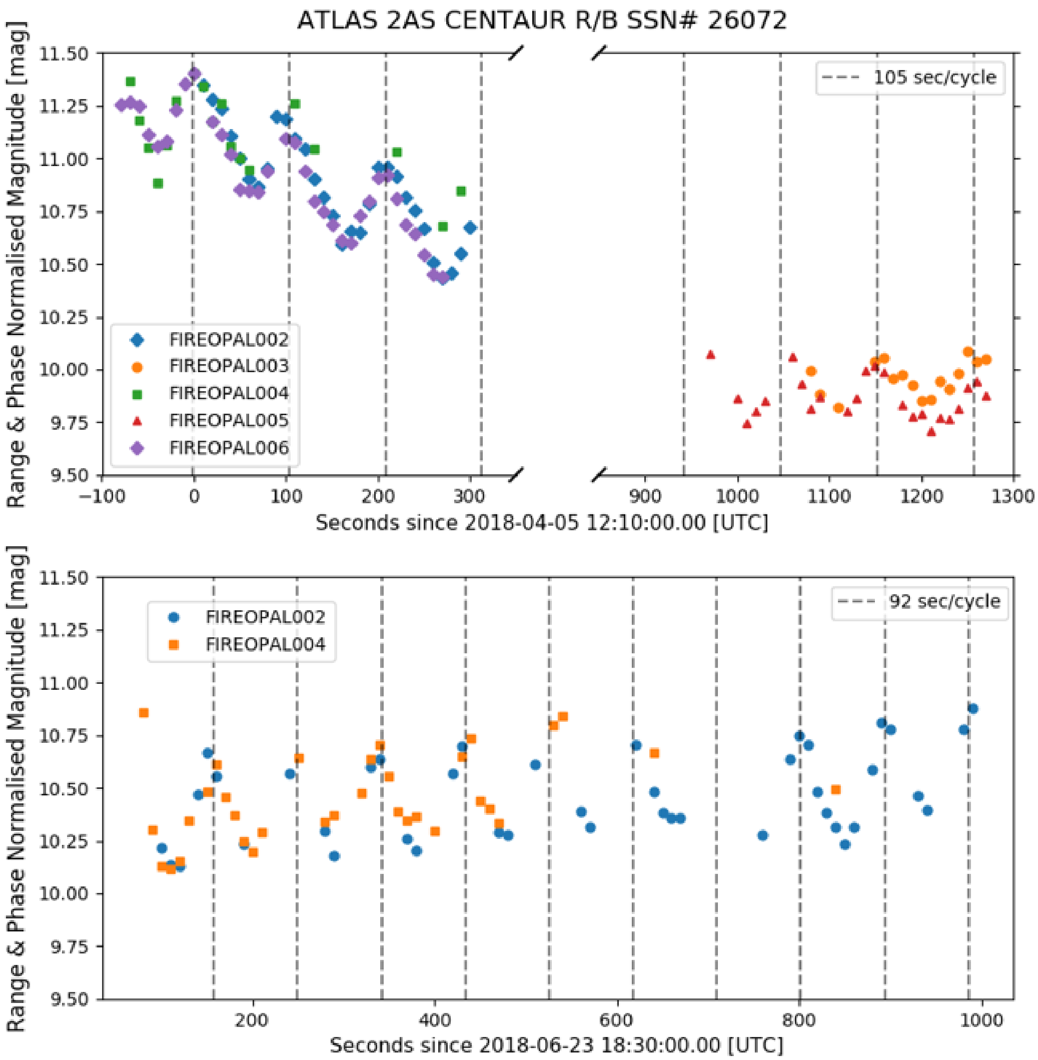

Fig 4: Same as Figure 3 but zoomed in over narrow date ranges. The top panel shows a strong variation in magnitude during this single pass and viewed by five different sensors. Note the excellent agreement in magnitude among the different sensors (all independently calibrated). The observations are consistent with an object whose optical cross section varies periodically with 105 seconds per cycle. The bottom panel shows the same object observed more than two months later. These observations are consistent with an object whose optical cross section varies more quickly with a 92 cycles per second. These data demonstrate the consistency and quality of FireOPAL photometry and how it can be used to infer three-dimensional information about satellites.

Figure 6 shows as series of three consecutive observations of the same object from the same sensor (each separated by 10 seconds). The observations are associated with the active NASA Earth observation satellite SMAP (SSN #40376). It moves at an apparent speed of 0.007 sec per pixel – enabling the detection of photometric changes over a very short time scale. According to NASA[1], this satellite has a complicated shape including a 6-meter deployable mesh reflector that spins at 1.2 revs per 5 seconds. The light curves show strong and irregular variations. With sufficient modelling, the combination these light curves together could be used to estimate the three-dimensional rotation or shape of the object.

[1] https://smap.jpl.nasa.gov/resources/39/smap-orbital-motion/

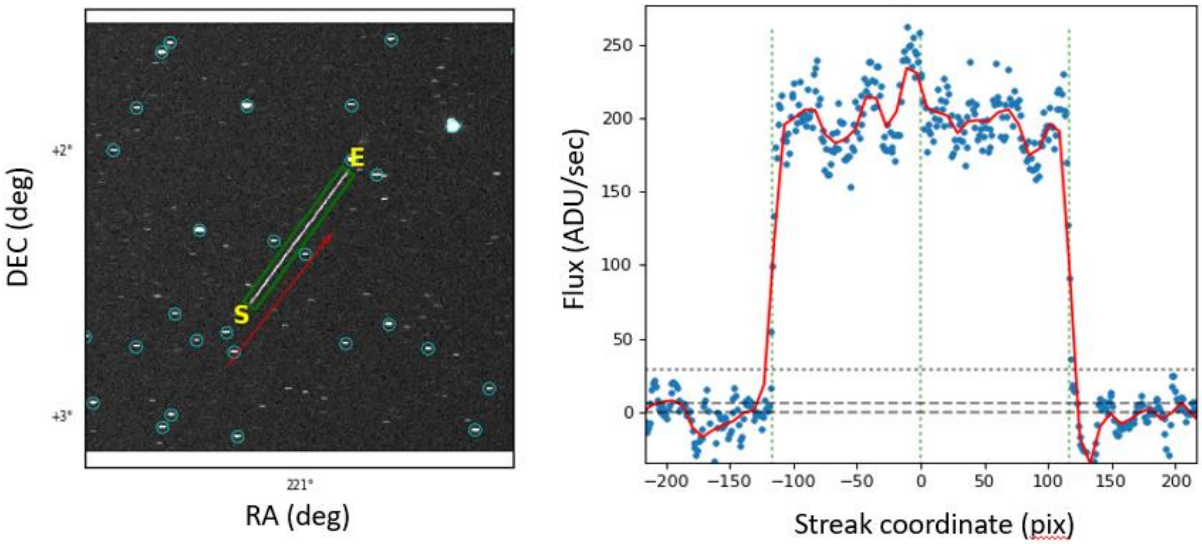

Fig 5: Sample diagnostic thumbnail from LEO/MEO processing. The left panel is a cutout of a raw image centred on the detected streak and subtends 1.5° on a side; North is up and East is to the left. The green box shows the estimated location of the streak; the yellow 'S' and 'E' indicated which streak end point is the temporal Start and End, respectively. The cyan circles show the predicted location of Tycho-2 reference stars using the in-frame astrometric calibration. The red arrow shows the predicted position and motion of BREEZE-M DEB (TANK) (SSN# 39477) using the most recent TLE from space-track. The integrated visual magnitude of this streak is 9.9mag. The blue dots in the right panel shows the extracted light curve for this streak. A periodic variation in the light curve with a period of about 50 pixels (~1 Hz) is evident, highlighted by the smoothed data shown by the red line. With a streak length of 232 pixel over 5 seconds, each pixel is separated by ~0.02sec.

4. LIGHT CURVES FOR GEO OBJECTS

The rate at which GEO observations are recorded is lower than for LEO/MEO; measurements are reported every 10 minutes instead of 10 seconds. However, the wide field of view of the sensors mean that a lot of GEOs can be seen in a single stacked image. As discussed in [2], we estimate that we currently detect more than 90% of slow-moving objects in GEO. Our protoype network has recorded more than 1,000 measurements each for more than 100 GEO objects. Some sensors are located more than 2,000 km away from each other and monitor the same part of the GEO belt.

Figure 7 shows an example of a collection of light curves for CHINASAT 9A (SSN #42763). We have observed this object more than 10,000 times from both South Australia and Western Australia group of sensors; only a small handful of data are shown in the figure. In order to compare the data from different sensors, the x-axis is the time since solar midnight at each sensor. It is a proxy for solar phase angle and enables the comparison of brightness taken around the same phase angle but from different geographic locations. The apparent magnitudes are grouped and colour coded by night, the sensors are coded by symbol. For clarity, the magnitudes from consecutive nights are offset from each other by -2.5 mag. The familiar phenomena of glints, or objects going into shadow, are obvious. There are other lower amplitude features, including large differences in apparent magnitude taken at the same time since solar midnight. These data can be used to model the satellite and to establish a pattern of life over long time periods.

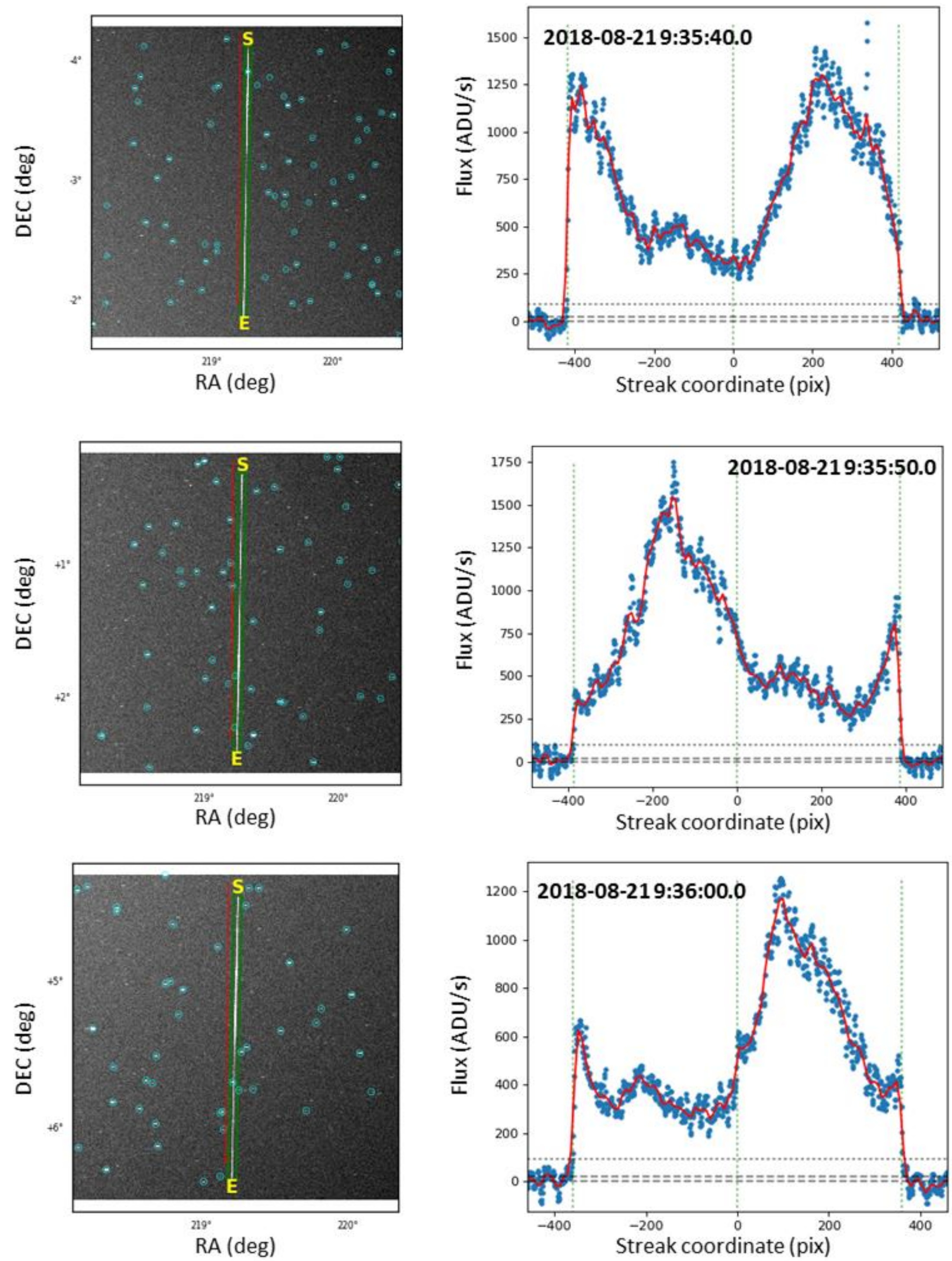

Fig 6: Similar to Fig 5, but for a streak associate with SMAP (SSN#40376). Three consecutive observations from the same sensor are shown; note the time stamps in the light curve panels. The light curves for this bright, fast moving LEO are sampled at about 0.007 sec /pix. FireOPAL light curves like these, sampled at a high rate and exhibiting large amplitude and irregular variations from multiple geographically distributed sensors at the same time, can be used to infer shape information about the satellite.

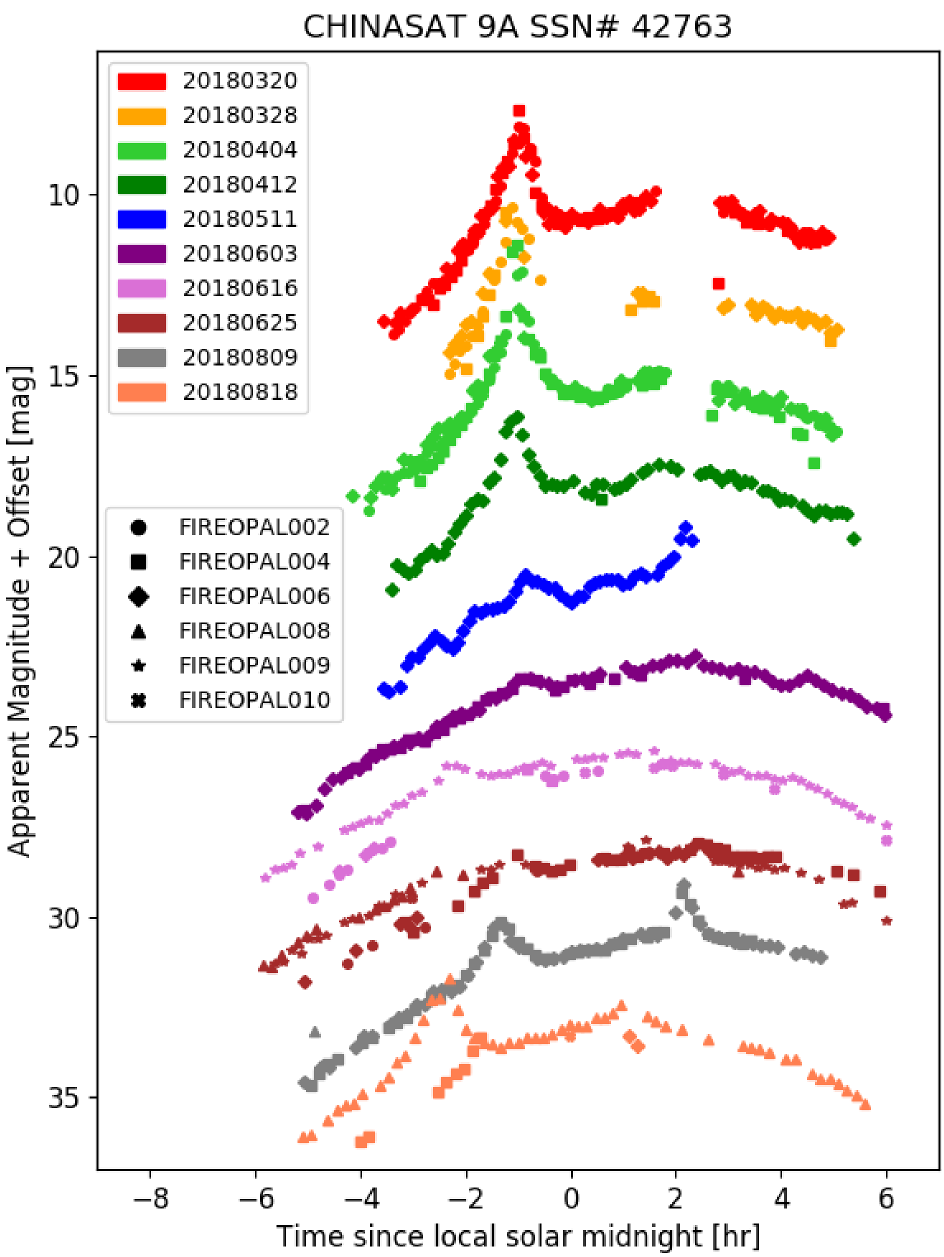

Fig 7: Apparent magnitude measurements associated with the GEO comms satellite CHINASAT 9A (SSN#4273). FireOPAL has observed this object almost 10,000 times in the past five months; only a small sample is shown here. To facilitate the comparison of observations taken at different times with different sensors, the x-axis is the time since solar midnight at each sensor. The coloured curves are groups of observations taken on the same night; the observing sensor is indicated by different symbols. For clarity, the apparent magnitudes from consecutive dates are offset from each other by 2.5 mag. FireOPAL sensors 2,4, & 6 are more than 2,000km away from sensors 8,9, & 10. In addition to the familiar glinting and shadowing, there are several light curve features that change amplitude and phase that could be used to further characterize the object.

5. SUMMARY

We have presented an overview of the current capabilities and performance of the FireOPAL observatories with an emphasis on the utility of photometric light curves. Observations from the FireOPAL network can establish the pattern of life and identify changes in apparent brightness of objects on time scales as short as ten milliseconds or as long as years. Thousands of light curves, with a photometric accuracy of 10%, are recorded each night from each sensor. Improvements to the image processing will reduce the photometric uncertainty and will generate simultaneous three colour light curves for every streak or point source.

The FireOPAL system is designed to be a cost effective optical SSA solution that tracks objects in LEO, MEO, and GEO. Our observatories can be mass produced, are simple to deploy and maintain, and can operate autonomously in remote environments for extended periods. Although the imaging systems in an observatory are comparatively low cost and low resolution (compared to larger telescope solutions), multiple, synchronized, triangulated observations deliver highly accurate orbits – comparable to results from exquisite (single look) optical sensors. The additional benefit is that a distributed network is disruption tolerant, unaffected by weather, images a large fraction of the sky, and extends the optimal terminator observation period. A FireOPAL optical fence, covering the entire GEO belt, with triangulation and redundancy, can be built from a network of a handful suitably placed observatories. Several fences, distributed at different latitudes, can be built for a fraction of the cost of a single one-metre class telescope. It is our goal to build a global system that can follow objects multiple times per day, is capable of catalogue maintenance for a large fraction of all satellites and is able to detect anomalous events in space as they occur.

6. REFERENCES

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3. Høg, E., Fabricius, C., Makarov, V.V. et al. The Tycho-2 catalogue of the 2.5 million brightest stars. Astronomy & Astrophysics, 355, L27-L30, 2000.