

SSA PRODUCTS FROM WIDE FIELD OF VIEW OPTICAL SENSORS

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INTRODUCTION

The Space Age is only half a century old. During that time, the population of man-made objects in Earth orbit has grown year by year. Already the number of objects whose orbits are maintained exceeds 14000. Early on, the number of objects was sufficiently small that each one could be tracked individually, whether by radar or by optical systems. For example, the 250-foot diameter Jodrell Bank radio telescope was the first radar system to track a space object (Sputnik-1 rocket body); kinetheodelites were used for optical tracking.

Fig. 1 shows how the number of objects in higher Earth orbits has increased. The population at any time is composed of the accumulation of new and past launches and the debris created by a number of fragmentation events. Unlike the lower Earth orbits there is no attrition process for objects in high Earth circular orbits.

The problem with tracking objects is that the sensor time needed (and thus the number of sensors) is directly proportional to the number of objects.

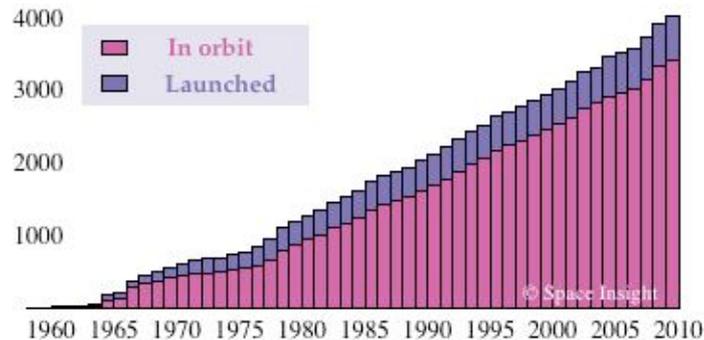


Fig. 1. Population growth for high Earth orbit objects

If each object requires three 5-minute tracks per 10-hour night then the number of tracking sensors needed can be determined and is shown in Fig. 2 for both the GEO and the combined GEO and MEO populations.

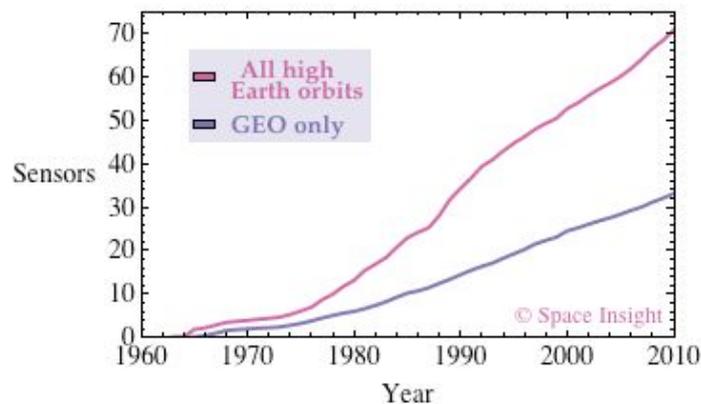


Fig. 2. Tracking sensor requirement

The surveillance problem is illustrated well in Figs. 1 and 2: the number of objects in higher Earth orbit is growing almost linearly with time and thus so is the required number of tracking sensors. With the consistent rate of launches to higher Earth orbits and with no natural attrition process it is clear that the acquisition of surveillance observations using tracking is unlikely to be sustainable in the longer term.

Wide field of view surveying sensors are being deployed increasingly to overcome the requirement for unrealistically large numbers of tracking sensors. Large fields of view sensors have both advantages and disadvantages, the benefit of observing large numbers of objects simultaneously being offset by the complexity of attributing the object observations to the correct catalogue entry.

Given the large volume of observations from a network of surveillance sensors, dealing with information quality issues (such as correlation accuracy) is critical to ensure the SSA database purity. In generating SSA knowledge, exploiting non-metric data is extremely important to add value to the pool of SSA products, as well as helping with the maintenance of information quality.

In this paper we discuss the use of surveying sensors in the provision of enhanced-value data to an SSA system with particular reference to the maintenance and verification of SSA on GEO clusters, cluster member discrimination, and optimal sensor scheduling.

SURVEILLANCE BY SURVEYING

There are specific instances where tracking will remain the strategy of choice: for example, high-precision satellite laser ranging, enhanced-accuracy monitoring of conjunction candidates, and satellite imaging (by radar or high-resolution optical systems). However, surveying has many advantages for the general day-to-day surveillance of the space population upon which the bulk of SSA products are based.

From the surveying sensor's point of view, the observing workload is invariant with the numerical size of the space population. This decoupling of sensor requirements from the growth of the space population is a key advantage and is a good foundation for a sustainable surveillance strategy. Surveying is also efficient: no sensor time is spent hunting for either new or no-show (manoeuvred or lost) objects.

From an operational perspective, targeted scheduling is not necessary, relaxing the urgency of the observe–schedule–observe diurnal activity cycle and removing the need for centralised target scheduling. For militarily-sensitive targets, the defence user does not need to indicate (by scheduling requests) an interest in any object: data collection can be anonymous.

From an analyst's perspective, new and unknown objects are discovered *en passant*. Higher throughput improves the coverage of orbits; for example, the GEO belt sector visible from a site can be scanned many times during a night to sample periodically the GEO population orbits. Periodic sampling over a long duration provides usable-quality orbits even from low-resolution sensors.

Although many general surveillance questions are known prior to observing and can be answered by analysis of a night's observations, *post hoc* enquiries which were not envisaged when observations were collected can often be answered by data mining the sensor's archives.

SURVEILLANCE AND SSA

One of the key issues in generating SSA products is the purity of the observations database. Impurities (such as misidentified objects) corrupt all down-stream SSA products. Tracking specific objects is likely to produce high-integrity observations because the tracking process itself acts as a filter which discriminates against other objects. However, surveying with wide fields of view captures many objects simultaneously (there may easily be 10 or more objects in the field of view) and so there is more scope for misidentification.

Correct correlation of observations with a catalogue of objects is one of the key requirements for database purity. Correlation may be carried out at a sensor or at a data processing centre. For example, if a (tracking or surveying) sensor is required to work in a way which is target specific then observing must involve on-site real-time correlation.

Correlation is not difficult if the surface density (on the celestial sphere) of objects is low and/or if there is significant diversity in the motion of objects. For example, in the higher Earth orbits, the low spatial density of objects in MEO assists in correct correlation.

The higher spatial density and low motion diversity of objects in GEO makes correlation a more difficult task. Of specific difficulty is the correlation of objects in GEO clusters. By definition, cluster objects are close together and have very small differential motions. It is not uncommon for radars to see some members of a cluster at very similar range and range-rate values; optical sensors often see the spot-like images of cluster members merge to become one object.

In addition to confusion between cluster members there is also the potential for confusing a cluster member with an object which is in a drift orbit and which is passing through a cluster.

For example, in 1997, a member of the Astra cluster at 19° East (COSPAR id 1996-021A) was cross-identified with a drifting object, resulting in the cluster member's orbit being miscalculated (1996-021A's calculated orbital position was many tens of degrees away from its true location). The longitude history of 1996-021A is shown in Fig. 3 in which it is clear that at least three instances of this type of problem occurred in the 1997 to 1999 period.

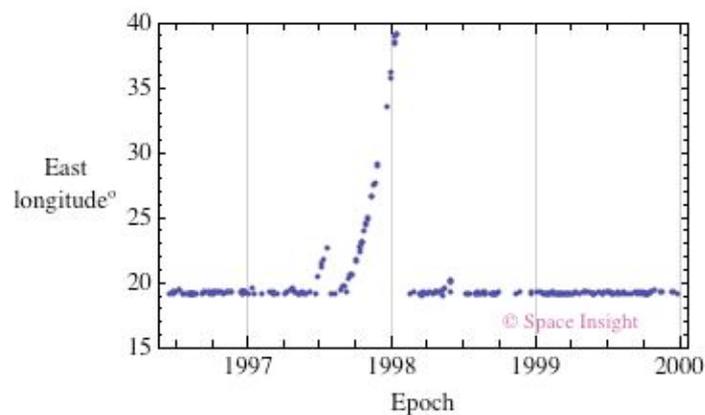


Fig. 3. GEO longitude history of Astra member 1996-021A calculated from TLEs

WIDE FIELD SENSOR SSA PRODUCTS

Like their tracking counterparts, wide field optical sensors are used to collect position information (normally triplets of {right ascension, declination, time}).

The collection of photometry data is usually thought of as being a task for a tracking sensor. Photometry may be collected unfiltered (“white light”), in broad-band filter channels (10 to 100 nm wide), or by spectroscopy. Certainly, to acquire good signal-to-noise narrow-band data needs a large aperture which usually prescribes a narrow field of view.

From an SSA product perspective, surveying sensors with wide fields of view may offer advantages in both the integrity of correlated position–object data and in the collection of broad-band or unfiltered photometric data, provided that the images taken are processed to exploit the information offered by the wide field of view.

One exploitation method for positional data is double correlation in which correlation can be carried out with a knowledge of both i) the set of observations (on all objects in an area) and ii) the set of predicted sightings. Double correlation enables the correlation process to be driven by the best fit, taking into simultaneous account all options and (as the process proceeds) ignoring objects for which a correlation has been established. Double correlation is not possible with narrow field of view sensors because the sensor data stream does not sample objects in an area simultaneously. Indeed, a narrow field of view sensor might not be aware of close-by objects and the potential for misidentification they create.

In the case of photometry, wide field sensors allow simultaneous acquisition on all objects within the field of view which guarantees that the atmospheric conditions are highly similar for all the objects, so making inter-object comparisons more reliable.

CLUSTER SURVEILLANCE

As noted above one source of difficulty encountered during observation of the higher Earth orbits is the presence of clusters of co-operated geostationary satellites. With the aim of exploring whether the wide-field advantages discussed above can be used to maximise the number of observations that can be positively attributed to each cluster member, one of Space Insight's sensors was used to observe GEO clusters.

The Starbrook sensor used for this study has a 15 cm aperture, f/2.8 optics, and a 10 megapixel CCD with ~20 s image cycle time. The dome, mount, detector, ancillary systems, and environment sensors are computer controlled and observing is fully robotic. Data reduction is carried out automatically in near real time so object positions and initial orbits are available within a few minutes. The sky coverage rate for this Starbrook sensor configuration in its normal operating mode is ~400 sq° hr⁻¹ which enables, for example, Starbrook to scan the GEO belt sector visible from its site every 90 minutes.



Fig. 4. A Starbrook sensor

Currently, the primary source of space object orbits and identifications is the data released by the US Strategic Command via Space-Track[1]. The nature of the data is such that its accuracy and currency are not sufficient for unambiguous discrimination of clustered objects. In many cases the attempt to correlate the observed tracks of two different objects results in both sets of observations matching most closely to the same object in the Space-Track catalogue, and conversely the published orbital elements of a cluster member may not correlate closely to any observations.

An example of the problems with correlating cluster members is shown in Fig. 5 in which the tracks of two observed cluster members (marked in grey) are compared with the orbital element predicted positions for the closest two cluster members (shown coloured). It is not clear to which object either set of observations should be attributed. It can be seen that one of the sets of observations fits reasonably well in length and direction with one of the predicted orbits but is closest in angular distance to the other orbit. The other set of observations is closest in right ascension to one orbit track but closest in declination to the other and it is not particularly similar in direction of motion to either orbit prediction. From these observations alone, therefore, it is not possible to correlate unambiguously either set of observations to either of the orbital elements.

For this study, the Starbrook sensor undertook continuous observations of regions of the GEO belt containing clusters to determine whether photometric analysis of the observations can assist in the discrimination of cluster members both from each other and from other objects in the sensor's field of view.

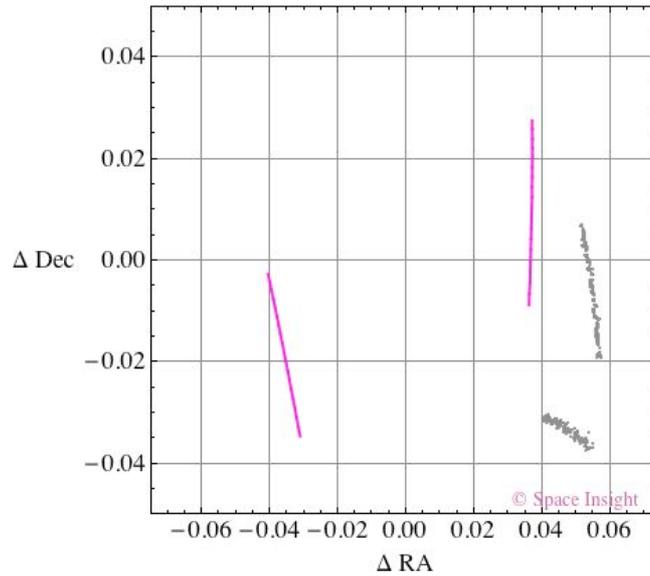


Fig. 5. Cluster member predicted (coloured) and observed positions (grey)

Since the geometry of the arrangement of the sun-satellite-sensor changes continuously it is anticipated that any object's brightness will vary throughout the night and that each night's signature will vary throughout the year. The signature consists of a mixture of specular and diffuse reflections from the various elements of the satellite, the contribution from each element changing with time of day and season. The variation of the nightly signature with season was also sampled to determine whether there are elements of the signature that are present throughout the year that can be used to assist cluster discrimination.

The observational strategy for this study involved pointing the sensor at a fixed GEO longitude and latitude, and taking a continuous sequence of images. The space object positions on the $\{x,y\}$ plane of the Starbrook sensor, through the course of one night's observations of a field containing a GEO cluster, are plotted in Fig. 6. In this figure the GEO belt runs through the centre ($y \sim 600$). The observed positions of some of the objects can be seen grouped along this ($y \sim 600$) centre line: these objects are low-inclination controlled payloads. Other, uncontrolled objects cross the field of view with varying rapidity depending on the nature of the object's orbit; these other objects include super-GEO drifting non-operational payloads and rocket bodies in GTO orbits.

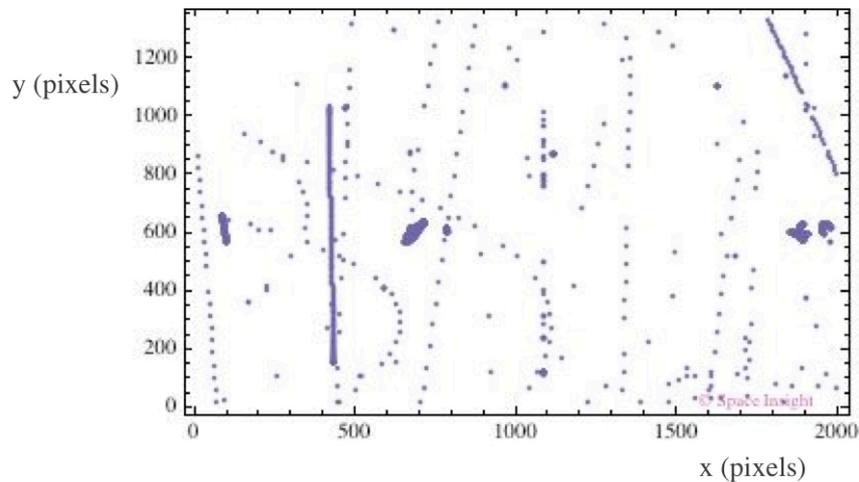


Fig. 6. Object $\{x,y\}$ positions during one night's observations

The optical signatures of the objects in, or crossing, the field of view during the night were automatically generated by passing the initial $\{x,y\}$ position of each object to an analysis programme which then followed the object as it moved from frame to frame. Fig. 7 shows the photometric signatures extracted for all slow moving objects within the Starbrook field of view. The observations were taken in early February 2011. In Fig. 7, and subsequent photometry plots, the uncalibrated brightness (B) of the object is plotted against the time of day in hours, corrected for the Equation of Time (shown for clarity with hours after midnight given as time + 24 hours).

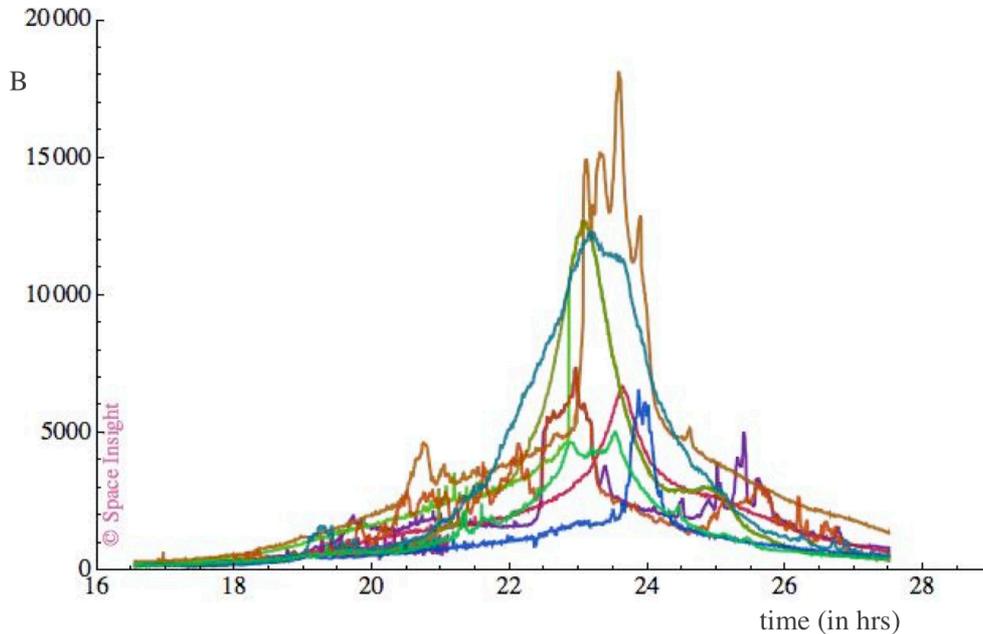


Fig. 7. Photometry on objects shown in Fig. 6

All of the signatures in Fig. 7 show considerable structure on many different timescales and amplitudes. It is beyond the scope of this paper to attempt to characterise all these features. However, an examination of some of the signatures indicates a number of points of interest.

Figs. 8a and 8b show the signatures of two companion objects. For most objects the slope of the brightening and fading phases are similar. However for the object in Fig. 8a the brightening and fading slopes are significantly different. When the signatures of both objects in Fig. 8a and Fig. 8b are plotted together (Fig. 8c) it becomes apparent why this is the case. For the latter part of the night the two profiles are exactly the same – a situation which should be viewed as highly unlikely. Referring back to the original images from which the photometry was derived it becomes clear that, close to the moment of maximum brightness, the images of the two objects have coincided and the automatic extraction tool has followed the same object in both cases.

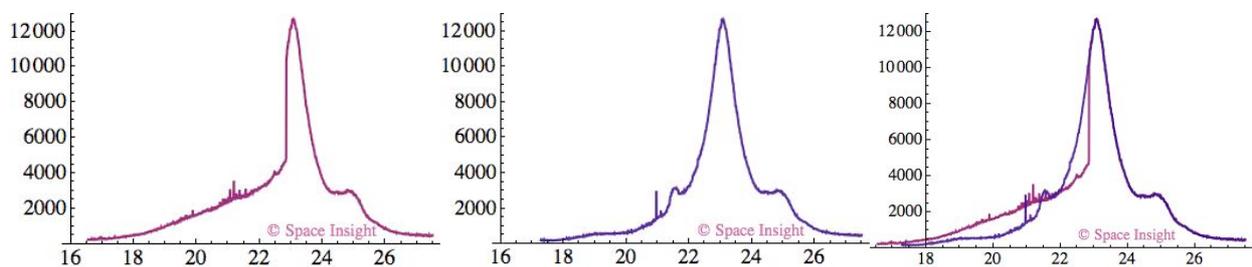


Fig. 8 a. b. c. Signatures of clustered satellites with crossed identification

The cause of the erroneous object-following can be easily seen in the sequence of images shown in Fig. 9. Due to their brightness the two target objects are each spread over a large number of pixels. As the two objects come close their images coalesce, so that it is easy for an automatic object-following algorithm to become confused. Where a human

finds it easy to use the motion history to maintain continuity of identification, simple algorithms cannot always correctly follow an object through such a coalescence. Through the use of analyses of this kind, automatic procedures can be improved to be able to follow close companions more successfully.

The analysis of the photometry signatures in this case allowed the recognition of the misidentification of one of the two objects. Once the cause of the problem had been identified the attribution of the observations could be corrected and the analysis could be rerun from a later starting point after the satellites had separated. Although this workaround results in some observations being rejected during coalescence, the unique identification of the two satellites is possible for a much larger part of the night. Only approximately one hour of observations has been lost and the risk of any possible contamination of the catalogue through misidentification has been removed.

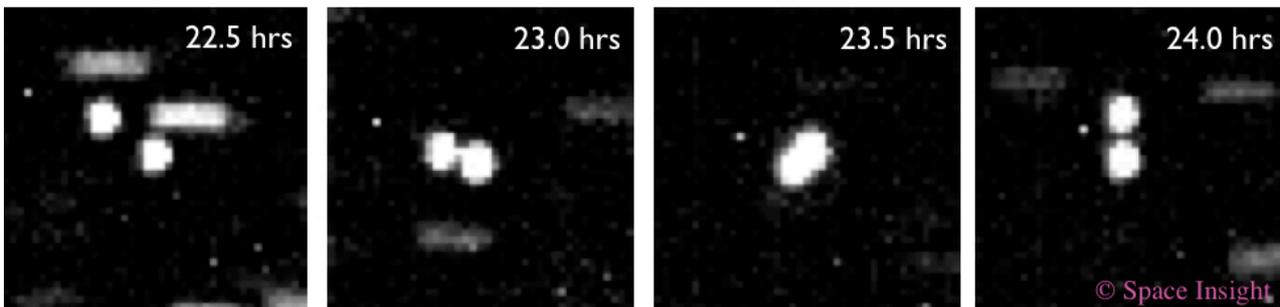


Fig. 9. A sequence of Starbrook images showing cross identifications of two clustered objects

The photometry of groups of objects seen in a single field of view also includes drifting objects which pass through the longitude slots occupied by clusters. In general these objects can be distinguished from active GEO satellites by their motion which will show both an East-West drift and significant inclination. However the rate of drift is highly dependent on the success with which the satellite was graveyarded at the end of its operational life. When an object has been poorly graveyarded, or has failed before being moved into a graveyard orbit, a short track of observations of a drifting object can be hard to separate from that of an active payload.

Cross-tagging with such an object is likely to be the cause of the deviations of the Astra cluster member shown in Fig. 3. The use of mass photometry of all objects in the wide field of view of sensors like Starbrook can be invaluable in differentiating drifting objects to avoid the confusion that they can cause. An example of an uncontrolled object from the set shown in Fig. 7 is shown in Fig. 10. Sampling the brightness of such an object at the rate of the Starbrook sensor results in a distinctive quasi-periodic shape of profile.

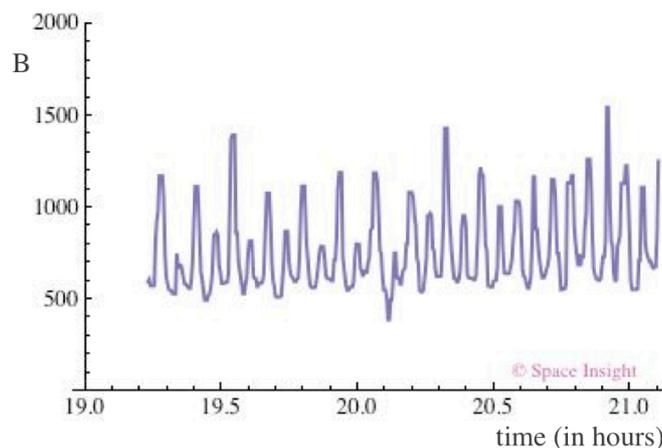


Fig. 10. Photometry of a tumbling object

An analysis of the light curves taken during other periods of the year shows that signatures still include a significant amount of structure although they do not have the large range of brightness seen during the specular season. Fig. 11 shows a typical signature from a cluster member taken during July. Signatures taken at differing times of year vary greatly and are difficult to relate to each other because of the large differences in Sun angle.

However signatures gathered at any time of year show enough variation of cluster member from each other and from the population of nearby objects that are useful in maintaining the cluster member identification over short periods. The use of relatively inexpensive, wide field of view sensors makes the regular provision of mass photometry on appropriately chosen locations of the GEO belt practicable.

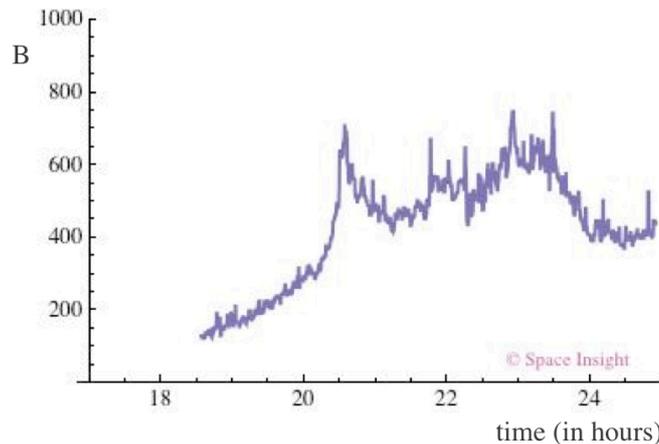


Fig. 11. Photometric signatures from July

ENHANCED-VALUE SSA PRODUCTS

In the maintenance of database purity, enhanced-value SSA products are of significant importance. The value enhancement may come from both the fusion of positional and photometric information and the symbiosis of observing strategy and expectation analysis of object (or object group) behaviour.

For wide field of view optical sensors, value enhancement from double correlation has been discussed. Photometric observations can be co-analysed with positional measurements to provide a better estimate of the integrity of object identification. Other by-products include confirmation of satellite attitude and attitude stability. For GEO clusters, photometric analysis can also confirm tentative night-to-night correlation as well as helping to identify non-cluster objects which happen to be drifting through the cluster region.

Although surveying sensors do not need a time-object schedule, it can be valuable to interrupt the routine of surveying with specific requests. An understanding of the photometric behaviour can be used to schedule optimally cluster-specific observations so that they take place when objects show identity-related behaviour.

ACKNOWLEDGMENTS

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REFERENCES

- [1] <https://www.space-track.org>.