From NEO to LEO optical observations and back: Sensors features and observing strategies

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ABSTRACT

Since 1970s and during the 1980s, optical telescopes were aimed to a not traditional distant observational targets: Searching and tracking satellites (SST) and close asteroids (NEO). The Cold War and the Shoemaker-Levi 9 Jupiter impacts biased among other reasons towards these new concerns related to the space vicinity of the Earth.

At these early stages, most telescopes, which were initially designed for astrophysics, were not appropriate for these new tasks. The observing strategies, the detecting pipelines and the required immediacy of the data were limited and they needed to evolve together with optical correctors and the new digital detectors. Some experience came from SST to the NEO field, other took the inverse way.

However, once again, the sensors requirements and the observing strategies on both populations turned not exactly the same, mainly due to the huge difference on the angular speeds of those close to Earth objects, 100 times faster for a GEO satellite compared to a typical NEO (10 arcsec/min). Even within the SST domain, a LEO optical sensor shall detect and measure 100 times faster objects than those in GEO regime. Precise time tag down to millisecond of UTC, recurrent sensor calibrations, trailing, crowding and many other aspects also from the hardware side, become critical and they can be applicable for improving the quality of the NEO observations.

Mounts and optical designs, detector architectures, FoV, read-out, scale pixel resolutions and developed detection pipelines according to defined observing strategies require of very optimized solutions for every angular speed range, which, together with the limiting magnitude turn on the driving parameters of the sensors, instead of the nature or the orbital populations and sizes of the objects to be detected or tracked.

At DeSS (Deimos Sky Survey), four sensors are mainly devoted to SST activities from GEO to LEO and a large experience on NEO observations has also been gathered.

In this paper, a comparison of some of the required sensors features, constraints, differences, observing strategies from the NEO until LEO, from both, the software and hardware sides are discussed, after the practical nightly experience at DeSS.

1 INTRODUCTION

1.1 DeSS facilities and mode of operation

DeSS (Deimos Sky Survey) is a quite new system developed by Deimos-Space in Southern Spain [1],[2], designed and devoted to observe near-Earth space objects. Some of the current sensors and knowledge was transferred from the former site: La Sagra Sky Survey (LSSS), which with MPC code J75, has been so far the most prolific asteroid and NEO discoverer site from the European territories [3]. Since 2010, it started to participate in the SST domain with optical campaigns in the framework of the precursor services of the ESA SSA (CO-VI) together with Deimos.

Figure 1. The four domes of DeSS observatory at Niefla Mountain and DeSS Control Center 40 kms apart.

Nowadays the NEO surveillance and tracking requires quite big sensors apertures. Small telescopes with diameters below 1 meter are unlikely to make large contributions anymore [4]. On the contrary, sensors still efficiently work on the SST domain below that size.

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One of the former NEO 45cm aperture surveillance sensors: "Centu1" with tens of NEO and thousands of asteroid discoveries [5], is now located under the bigger dome of Fig. 1, and currently scans the GEO belt every clear night for the Spanish (S3T) EU-SST program together with “Tracker1”, inside the most distant dome of the former picture. The other two domes, are hosting “Tracker2” for tracking NEO, GEO and MEO and “Antsy”, devoted to LEO observations. They are routinely working for private operators and external companies, together with R&D activities within Deimos.

Nowadays, all 4 sensors together produce automatically more than 70.000 images during a clear winter night. The challenge moves then to the sensors hardware robustness, to the real time efficient processing of the images to extract measurements, and to the “service-like” immediate delivery of the products.

At this point, customers require from the SST optical sensors availabilities and robustness comparable to other commercial activities related to the measurements.

- Quantity (> x hour)
- Quality (< x arc seconds)
- Continuity and prompt delivery (close to real time)
- Cost (the least expensive as possible)

On this new era of mass production of optical SST data, it is difficult sometimes to share sensor observing time for a more scientific tasks, essential for research and knowledge evolution. However, working under this tight service mode of operation, nothing to do with traditional astronomical observing concepts, the hardware and software are pushed to their limits, failures must be promptly fixed and agile solutions and adaptations are constantly required and found, with lot of trial and error, looking for cost/efficiency and simplicity.

NEO and SST fields are both addressed towards a planetary concern. However SST traditionally became also associated to strategic alliances for defense and commercial activities. Until recently, the NEO has been mostly focused in scientific efforts. Future private enterprises on asteroids related to resource exploitation (asteroid mining and others) will perhaps turn the NEO field to a more profit-oriented one as well.

1.2 NEO and SST observing criteria

In general, the processing of the images could always include some false detections on aligned low SNR stars, CCD hot pixels, cosmic rays, bright spikes, optical ghost reflections, etc. Those situations often happen, and there is no clear boundaries on the faintest SNR detections to unambiguously assess that they belong to a false or real object. In consequence, the processing pipeline which automatically detects and measures, will inevitably produce few false detections (false positives) and some real omissions (false negatives) depending on the detecting aggressiveness threshold.

Collecting less false detections implicitly entails more real omissions or just the contrary, when trying to avoid missing any of the faintest objects, the risk to include false detections increases.

The observation of natural and artificial populations has had some different approach regarding the detectability aggressiveness criteria as well.

For the NEO community, it has been essential to not miss any of the objects that become close to the Earth, and discover them before they could impact or become lost after the close encounter. The main objective has been then to minimize the false negatives but at the same time to avoid alarming with false positives. Thus the processing of the images is still often based on higher aggressiveness and a last visual inspection for validation, previous sending the measurements to the Minor Planet Center NEO Confirmation Page [6], from where other observers will follow-up or will report unsuccessful attempts.

This visual inspection can be performed always the number of those validations is not growing over few hundreds per night, and still is utilized by experienced observers that feel more comfortable with their trained brain-eyes combination against algorithms for accepting or rejecting these faintest and uncertain candidates. New machine learning methodologies based on such amount of training examples will probably replace definitely the human dependency [7].

Besides surveillance tasks, some human support is also required during NEO tracking activities, as track and stack procedures, and for confirming or rejecting any cometary activity or particular features, or even reporting negative results of some NEOCP candidates that cannot be found, due to magnitude and/or ephemeris uncertainties or simply because they do not exist.

On the contrary, objects with orbits around the Earth can usually be re-observed more often, their risk of potential collisions has fewer consequences and much more number of images and detections, almost every few seconds, are produced along the night. Therefore, the objective has been then mainly focused on minimizing the false positives, taking a more conservative approach. Any visual validation attempt by humans is completely inconceivable and the processing of the images is treated fully automatically on operational systems. On that situation it is not so regrettable if some SST objects could remain sometimes undetected.

For very particular cases of characterization of SST targets, a visual inspection also might add qualitative information related to outgassing and fragmentations.

The aggressiveness principle, directly applies on the observing strategies on SST and NEO when a number of single detections or "loners" on successive images are combined to validate a "mover", still always treated as "candidate to be a real object" until it is independently re-observed and correlated.

SST usually proposes more loners combination, in order to avoid the false detections and additionally generate longer tracks, on the contrary, some NEO strategies only based on 3 loners combination are enough, they produce very few real omissions, what is essential, but they require of exhaustive visual confirmation and rejection. Images of NEO have much longer exposure times, and running 4 or even more rounds over the same sky areas is a time-consuming that greatly impacts on less coverage. Might be stressed that there is no standard common observing strategy nor general processing pipeline for NEO and SST. They are usually developed for every particular project, and for many of them, including DeSS, the main algorithm for image source extraction has been based or inspired on SExtractor [8].

The following Tab. 1 summarizes in a very schematic way some of the most common strategies based on the number of required point source loners for validate a mover candidate and on the number of detections based on trail morphology identification, comparing the advantages and drawbacks for each one and their possible applications.

Table 1: Common strategies based on number and shape of detections: Their advantages and inconveniences.

rnds	feature	advantages/disadvantages	project/app
1	point source	1 single "detection" puntual	?
1	streak	1 single streak . No direction info. chopper wheels ? . Short arc.	VFMOs? LEO surveillance
2/2	point source	Many combinations with many false detections if low SNR threshold	NEO night to night based strategies
2/2	streak	Enough for correlation to speed and angle.	LEO surveillance VFMOs
3/3	point source	Max surveillance speed Very few real omissions Many false detections require visual inspection	NEO surveillance **DeSS SST tracking with PA and Speed**
3/3	streak	Enough for correlation to speed and angle. 3-6 meas. Risk to miss the FoV	
2/3	streak	2-4 meas. few omissions, no false detections if not too short trails.	LEO
4/4	point source	Less surveillance speed Some more real omissions than 3/3. few false detect.	NEO surveillance **DeSS SST survey 4/4 + 4/4 correl.**
3/4	Point source	Advantages of 3 and 4 Very few real omissions Many false detections require visual inspection	NEO surveillance
4/5	point source	Slower speed Few real omissions Few false detections	NEO surveillance SST tracking
>5	point source	Slowest but very reliable Higher computing requirements	SST surveillance SST tracking

One real possibility is that a small very close NEO could be registered in the course of a SST surveillance session, and due to the small observing window and the large revisiting intervals, the object could be lost or become below the horizon before detected, identified as unknown and stablished an immediate follow up. In all those situations, it is then mandatory to have an almost real time processing capability, access for cross-checking on updated and complete catalogues of distant artificial satellites and space debris not included in the public TLEs, ephemeris generation, and a tracking sensor readily available. The not accessible SST classified objects and the unknown debris can puzzle the natural origin of the object further, until a longer observing arc is obtained. This it seems one of the interesting fields to improve and devote future efforts that fall in between of both communities [9]. In this regard, Spacewatch already coined in 1991 the FMO and VFMOs acronyms to refer to the extremely fast (between 10-60 degrees/day) and small (few meters across) NEOs that were registered as very faint trails below the detection software threshold on single CCD images and usually were detected too late only by visual inspection [10].

2 NEO AND SST: SOFWARE REMARKS

2.1 Angular speed and time registry impact

Mainly due to their distances from Earth, there is a big difference on angular velocities. Usual NEO speeds range from 1 to 30 arcsec/min when they are detected, and thus they apparently show around x100 times slower speeds compared to GEO objects.

The angular speed becomes the main driver when planning blind surveillance strategies, always the search is not restricted to a very specific orbital population as geostationary regimes. In general, every sensor is constrained to an angular speed range capability, in this way, not a distant NEO and a GEO might be detectable for a given sensor under the same observing strategy.

Speed rate also determines the exposure times, the revisiting intervals to the same FoV, the number of images required, and many other sensor parameters.

As far as the angular rate increases, the epoch registry turns more and more critical. In fact errors above 1 second of UTC are still common on the NEO community. The shutter triggering delay or the epoch registry based on internet NTP providers are responsible among others of those errors. In most of the cases, they are not impacting on the quality of the NEO astrometric measurements, however, under lunar distances, the time tag requires of tens of second precision, of few milliseconds for GEO and it becomes under millisecond on the fastest LEO regimes.

The following Tab. 2 correlates, as rough reference, the angular speeds of the different orbital regimes with a minimum reasonable UTC epoch accuracy for not impacting over 1 arcsec astrometric resolution.

Table 2: Minimum UTC time accuracy requirement according to the angular speed of different orbital objects that would not impact on the expected astrometric quality of 1 arcsec. (*) NEO for a typical discovery case.

Object	distance kms	speed "/min	UTC time accuracy expected 1 arcsec
MBA	200.000.000	0.5	2 minutes
NEO*	10.000.000	0-10-60	6 seconds*
GEO	36.000	900	0.060 seconds
High MEO	21.000	2200	0.027 seconds
LEO	1000	90.000	around half millisec
Low LEO	600	162.000	around 200 microsc

Two kind of timing errors are usually registered: Random and systematic deviations. Random errors represent the real source of lack of accuracy. Most of the sensors show some amount of systematic bias that can be known and neutralized after calibrating observations on very precise reference satellite orbits. The calibration is a mandatory procedure for SST sensors validation and also for periodically check-up during operations, and the performance of every sensor, not only related to the UTC accuracy, can be very precisely evaluated, corrected and improved if possible. Some attempts of calibration are carried out in the NEO community as well, by observing GPS satellites [11], given that the detection of distant satellites and very small NEO under lunar distances, nowadays increase with the new and more performing NEO sensors.

Precise time stamp demand both, software and hardware involvement and solutions. DeSS telescopes are remotely operated with the control of the sensors and the processing computers placed all at 40 kms apart. This brings additional complexity, dealing with latencies when the cameras are remotely triggered through a radio-link. For "Antsy" LEO sensor, timing test and calibrations are performed on a higher time scale resolution targets, as high precision LEO geodetic satellites.

2.2 Astrometric format constraints

Time registry accuracy brings further problems on part of the NEO community when fast detections are reported: The standard 80 characters MPC astrometric format is still extensively utilized in spite of the improved astrometric data exchange format proposal ADES [12]. It has room for some better precision than 0.1 second with six digits for the decimal part of the date and only for a tenth of the magnitudes. Moreover, it is still very common, that the topocentric coordinates and altitude of the sensor at the MPC database, time ago reported for many of them, is roughly referred to the full observatory facilities, and not to the particular sensor. Same for the altitude reference frame.

This MPC 80 characters format for astrometric data exchange of Small Solar System Bodies, including NEO, has some drawbacks, as mentioned, for the lack of room for reporting time precisions of milliseconds, or the photometry resolution, but includes the advantages of the single line per astrometric measurement, and a clear distribution of the columns.

At DeSS, in addition to the TDM (de-facto standard for SST), we use internally the so called HUN format for SST observations, what extends the MPC format trying to maintain each observation inside a single ASCII formatted line, containing all the relevant information with resolution enough and thus not requiring repeated common headers, being each independent measurement line as fully self-explanatory data.

Moreover, it provides more information in less extension of bytes than other commonly used formats for SST observations, and, in addition, all the data is clearly human-identifiable-readable providing some additional information as angular motion and speed over the plate, and a rough estimation of the confidence of the quality of the measurement itself, based on environmental conditions and features of the images, as limiting magnitude, FWHM, SNR, plate match residual, and from the RMS fitting quality of the tracklet detected. Further orbit determination processes may even differently weight or accept-reject those measurements according to their presumed quality depending on the observing conditions they were obtained, deduced from the own data of the measurement.

HUN observations are finally converted to TDM (or to a defined format depending on customer needs), taking into account that observations for SST, compared to NEO, must be previously corrected by aberration among others.

2.3 Trailing impact

The highest SNR is achieved when the object signal matches approximately the pixel size of the CCD (around 1.2 pixels) [13], and from there, the SNR of the detection linearly decreases with the trail length. This effect defined as *trailing loss*, is mainly due to the fact that the incident light is not being accumulated always over the same pixels, but spreading it along the overall length of the trail, and the sky background and noise are being also accumulated with the exposure time.

On traditional NEO surveillance, scale pixel resolution, exposure times and re-observations on the same FOV are accommodated trying to detect the NEOs under sidereal tracking from typical angular motions of the most distant main belt asteroids, around 0.2 arcsec/min. This minimum speed also determines the revisit period and the maximum speed range accepted by the processing pipeline. Most of the times, NEOs are detected as point sources or short trails. NEO last alert systems need to be adjusted to faster speed ranges, but still avoiding the long trails generation.

On the contrary, on SST, it is common to deal with trails and trail detecting algorithms, and the strategy for an efficient detection is even based sometimes precisely on the trail feature. Therefore, their morphology must be clearly generated and distinguished from the surrounding stars. For known objects or defined populations as GEO, the trails can be shifted to the stars for registering a higher SNR of the targets, given that the apparent motion of the objects is known.

However, in addition to the already mentioned trailing loss, other important inconveniences arise when the trails become too long, particularly on the target side. The following Fig. 2 shows some examples of SST trails found in the course of Centu1 surveillance nights. They seem not very appropriate for accurate automatic streak detection and even worse for mid-point trail or trail-ends measurements. In general streaks can produce the following undesirable effects, all them increased by the trail length:

- Not defined homogeneous streaks because of rotation of the observed object
- Trailing loss spreading on too many pixels
- Not defined trail ends, fading.
- Trail ends out of the FoV
- More involvements with stars
- Missing the trail on following FoV revisits
- Time-consuming due to longer exposures
- Turbulence shown on trails as oscillation
- False detections on bright stars spikes, blooming

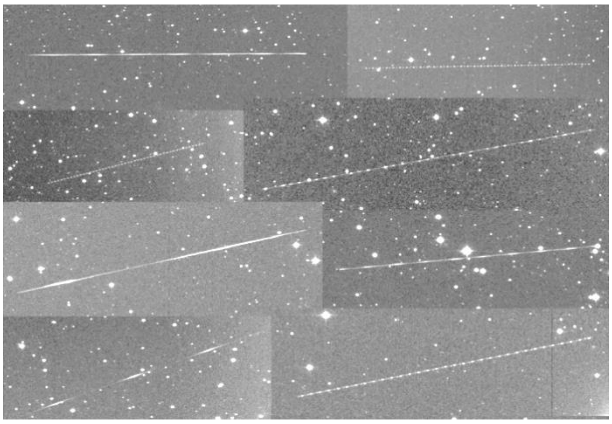

Figure 2. A variety of trails features imaged by DeSS Centu1 sensor.

A trade-off must then be taken for avoiding such long trails. As a first attempt, by shortening the exposure times and further, reducing the scale pixel resolution if still needed. This is not a problem when tracking over known objects, since the angular speed can be previously derived and the optimum exposure times can be then calculated. At DeSS the following formula (eq.1), is applied, according to an optimum trail length generation:

$$Exp.Time = \frac{Resolution \times (Trail\ Length\ - FWHM)}{Angular\ Speed} \quad (1)$$

Therefore, when tracking known SST objects, the CCD exposures are automatically adjusted for every new target and time. Thus, no matter for all the targets or stars, they always generate the same trail lengths on the images, independently of their angular motion. Additionally, this feature also helps on the further processing of the images where the trail length size in pixels is always expected the same.

However, given the high angular velocity of the closest LEO, the exposures often result too short according to the previous formula, risking not finding enough reference stars for plate solving or falling into the CCD noise dominance. In such cases, although missing some theoretical accuracy by binning the images, it indirectly benefits of the increase of the SNR of the target and the surrounding stars and additionally of the read-out speed allowing a higher frame rate.

For slower and brighter low-MEO on where SNR is high enough, sidereal tracking with very short trails on the target is preferred at DeSS. This will result on less star involvements and sharing a full common FoV for background comparison. On the opposite, for the fastest and faintest objects, the need of increasing SNR by accumulating light on the target, implies continuous tracking, but there is some more risk of introducing false detections compared with sidereal tracking. This is caused because of some hot pixels clusters, or faint sources combination over the sigma above the background, can mimic exactly the same motion than the tracked object. Moreover, the number of loners and their combination increases with the speed, given that consecutive images for comparison will only share a part or nothing of a common FoV background (Fig. 3). Some additional care, as image pre-processing and dithering acquisition techniques, adding more consecutive frames to the solution and even by applying star trails morphologic subtraction can help on those fastest and dimer detections.

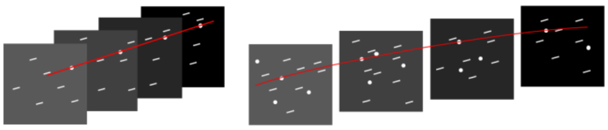

Figure 3. Draft simulating two fast tracked LEO. On the left, part of the same FoV is still shared.

At DeSS, it is possible to switch from sidereal to continuous tracking over the target and to adjust the trail length in pixels during the observation session. This procedure can be self-selected by the control software according to the target speed, frame rate and FoV. The streaks (on targets or on stars) are generated no longer than certain number of pixels, on the contrary the detectability ratio and accuracy begin to decrease due to the trail inconveniences already mentioned.

DeSS system usually establishes 12 pixels as maximum length, (this is certainly a not very long trail), and only 2 pixels as minimum for the brightest targets, if the estimated magnitude can be previously known.

The following Fig. 4 displays the astrometric accuracy variations compared with precise ephemeris of GNSS Navstar 60, (07047A), observed by Tracker2 at DeSS during 1 hour. After the first 30 minutes the tracking was switched from sidereal to target. On both intervals of 30 minutes, the exposure times were calculated to produce 4 pixels “trails” during the first 10 min, 12 pixels on following 10 min, and last interval with 24 pixels trails. Therefore during the first 30 minutes, streaks were associated to the target and during the last interval, they were on the stars. DeSS pipeline usually applies an RMS filter for rejecting consecutive measurements if they do not fit below a certain value. During this test, the filter was disabled accepting all measurements obtained.

Until around 12 pixels trails (no matter if tracking is sidereal or on target), astrometry accuracy with DeSS Tracker 2 is mostly below 0.5 arc seconds. Some of the outliers on the most left column belong to a more crowded field closer to the Milky Way at the beginning of the observations.

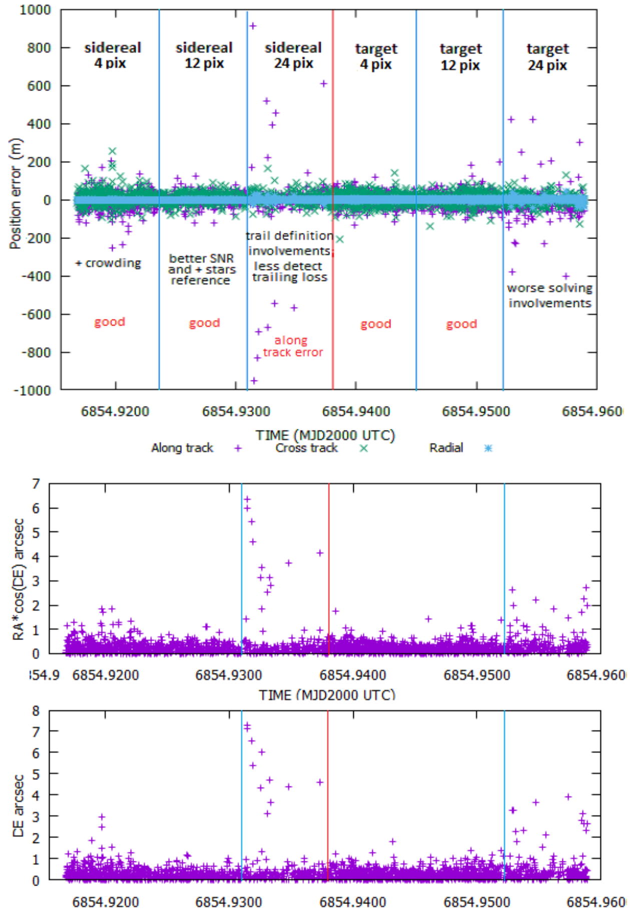

Figure 4: Positions errors and along-cross-radial astrometric residuals of 1.995 measurements of Navstar 60 obtained by DeSS Tracker2 sensor, between 22:00h- to 23:00h UT on 2018/10/07, combining 30 minutes sidereal and 30 minutes target tracking periods, both divided into 10 minutes gaps with different trail length generation of 4, 12 and 24 pixels.

As the trail becomes longer, if this was the case on the target side, astrometry even got better but on some trails, their definition between trail-ends were worse calculated. Additionally more involvements occurred and thus occasionally some measurements suddenly reach very high residuals on along track direction. Also the number of measurements decreases a bit due to the longer exposure times. We find a very similar behavior on the opposite, when the trailed stars became larger than 12 pixels. The dispersion, mostly on along track is remarkable, in spite of the expected better determination of the target centroid, given the higher SNR. This time the errors mostly came from a worse plate solving, together with more target-trails involvements. On Fig. 5, a typical case of involvement can be noticed. Although a high deblending contrast is applied, it cannot discriminate the object against the star trail.

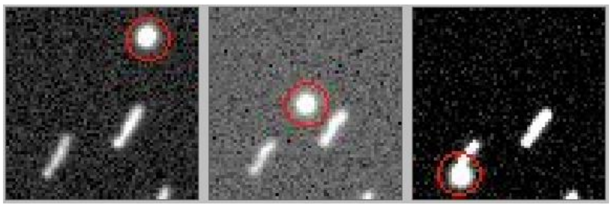

Figure 5: Navstar 60 falls involved with a star trail on the third detection, and the centroid is not properly determined.

Concerning involvements and deblending, another different approach is here taken when detecting point sources or trails: Trail detection requires of low deblending contrast to get the full trail and to avoid cutting its length in parts on their faintest brightness variations, this implicitly trends to produce more involvements around. On the contrary to the point sources extraction, which always rely on a high deblending contrast threshold to isolate them from any other close source.

The trail length accommodation can be applicable on tracked known objects and SST GEO surveillance, for others, as blind SST and NEO surveillance, the exposure times only can be roughly tuned to the expected population to be detected.

2.4 Crowding impact

Milky Way and crowded star fields have been traditionally a problem for detecting moving objects, and the detectability ratio and the accuracy of the measurements on that regions is much worse compared to the less dense areas closer to the galactic poles.

In general crowded fields are responsible of:

- Less detectability ratio due to full involvements start-target.
- Worse astrometric residuals when the partial involvements move the centroid to the star-target barycenter.
- Worse photometric quality when adding each individual flux on those involvements.
- Slower processing of the images when combining so many sources.

And those effects are more evident on strategies based on:

- Longer trails generation on stars or targets.
- Longer exposure times.

The following Fig. 6 shows the undesired effects of crowding when tracking 76039A LAGEOS1, a low MEO geodetic satellite, during a Tracker2 calibration session. It was deliberately left crossing the Milky Way, as the polar plot and the all-sky camera of DeSS show below in the same figure. The chart reveals how the measurements become of worse quality (up to 6 arc seconds), due to partial involvements, and even with many missing detections because of full involvements with stars, during the period that the object was crossing along the most dense regions of the Milky Way.

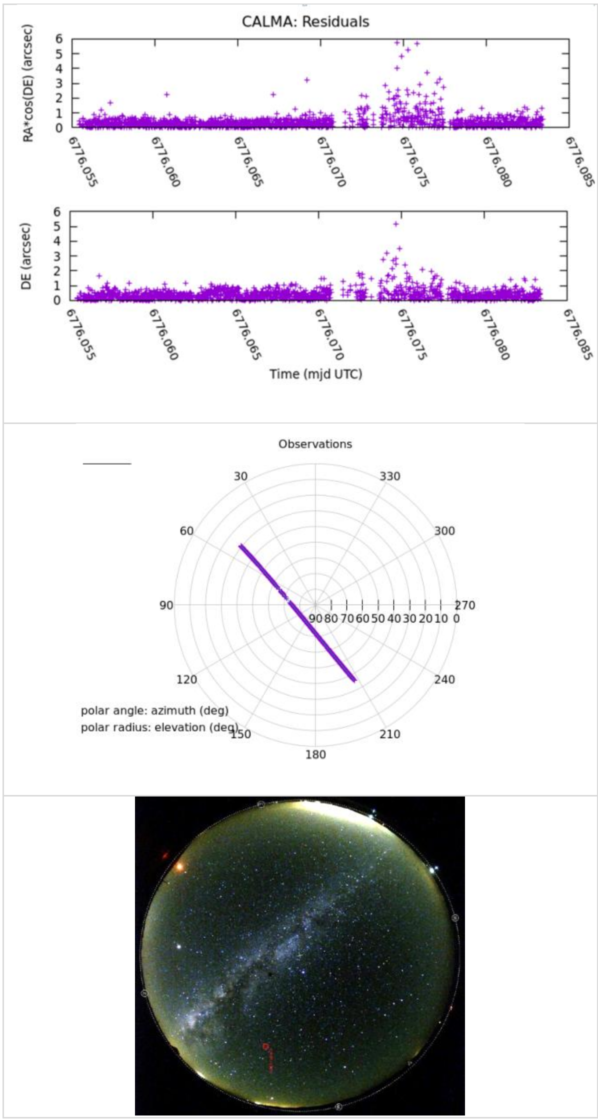

Figure 6: Upper plot, LAGEOS1 residuals compared to an accurate orbit, and the crowding inconveniences when crossing the Milky Way. Mid image shows the Azimuth Elevation during the track. Bottom image taken by DeSS All Sky.

NEO and SST observations both try to avoid the most crowded areas or applying background suppression techniques for mitigation of those effects. These regions are usually mapped by density colors on the graphical scheduler interfaces. Milky Way is worse for NEO and GEO due to the longer exposure times that reach fainter stars but surprisingly, it has the opposite effect on LEO tracking observations, when the extremely short integration times do not allow registering sometimes, far from the Milky Way, too many stars on the background for a reliable plate solving.

In general, it is never possible to detect 100% of the objects that cross inside a FoV up to the limiting magnitude of a given sensor. Crowded skies together with poor transparency and moon glow are the most important constraints for the low detectability ratio at DeSS, which can drop even to extremely low values when mixing all those situations.

2.5 Photometric particularities

Also some differences apply on photometric light curves according to their nature and orbital features. The integral flux or filtered light is compared by differential photometry against the stars background. The angular speed again determines some limitations on the fastest objects, which even could only allow the analysis of their trail light variations. On the contrary, NEO usually can be observed with much longer exposure times and thus integrate more light with almost no drift, they remain inside the same FoV for longer periods, this allows to maintain mostly the same reference stars for comparison and time enough for inserting photometric filters.

Some small elongated monolithic NEOs can tumble with very high speeds periods of even less than a minute, similar to some rotating SST objects, as rocked bodies, what could confuse, however most of NEO have smoother light curves [14], [15]. (Fig. 7).

The fast variation of the phase angle, the different reflecting materials, attitude changes and flares can introduce additional complexity when modelling SST satellite structures, but facilitate to derive nature and rotational periods (Fig. 8).

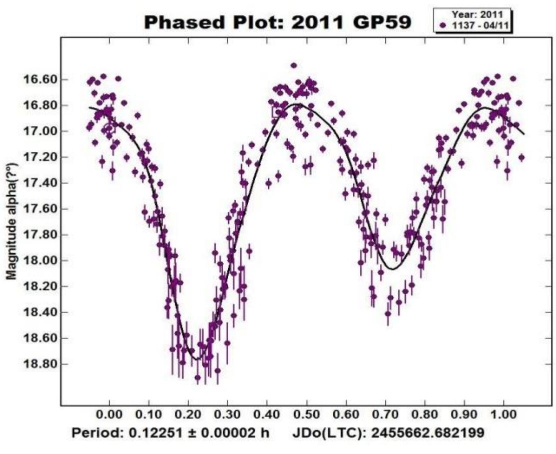

Figure 7:.Light curve of 2011 GP59 (Credit: Brian Skiff-Lowell Obs). A 50 meters elongated monolithic Aten NEO discovered by Centu1 on April 8th 2011 [16] when it was formerly placed at J75, LSSS. It showed almost 2 magnitudes variation along a period of 7.35 min.

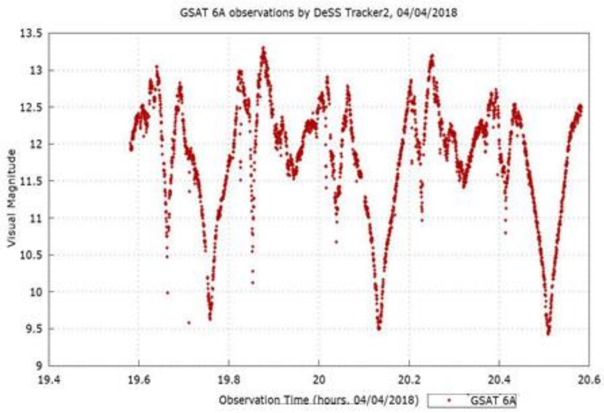

Figure 8: GSAT 6A a tumbling satellite observed by DeSS Tracker2 on April 4th 2018 with a main period of around 24 minutes and with more than 3 magnitudes variation.

However, the behavior of some SST light curves is sometimes undefined. The following Fig. 9 shows the magnitude variations obtained from the consecutive observation of three SST geostationary objects. Some objects show well defined light curves according to the photometric resolution of the sensor, but others (or even suddenly the same objects) reveal an apparently random reflective distribution along several magnitudes with the same setup that hardly can be explained by a lack of time resolution in front of extremely fast rotational periods, given that measurements are produced every 1.1 second, neither by worse photometric quality, given that they do not systematically belong to the faintest targets with lower SNR. This reflective behavior is very peculiar for some SST objects.

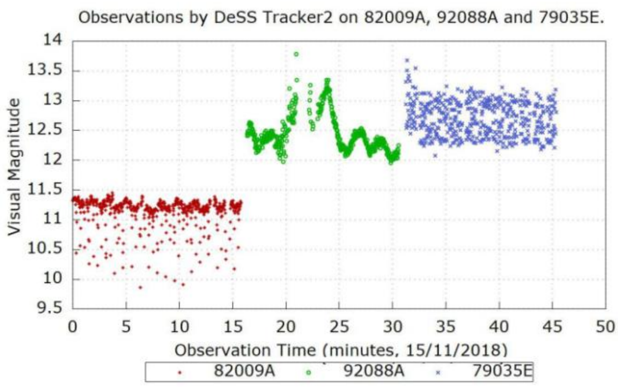

Figure 9: Consecutive 15 min observations by DeSS Tracker2 over 82009A, 92088A and 79035E. Some objects as 92088A show clear light curves, others as 79035E an apparently noisy dispersed cloud band, and 82009A mixing both behaviors.

3 NEO AND SST: HARDWARE REMARKS

3.1 Detector Architecture impact

Similarly as when comparing NEO and SST angular rates, a rough factor x100 of more images can be obtained for a given sensor and night when tasking SST activities, particularly on tracking. Exposure times on NEO usually range from 30 to 90 seconds, but from tens of milliseconds to a few seconds on SST. In this regard and for the detectors, mechanical shutters have been a big inconvenience at DeSS. They become responsible for time tag inaccuracies but also a source of recurrent mechanical fatigue failures. Shutters are usually guaranteed for one million images, this is more than enough for years of operation on most of the astrophysical projects and even for NEO, but such an amount of shots is reached already in less than 8 months of SST operations at DeSS. Consequently, when they break, it implies service impact, cost and unavailability for replacement, and some sensors later require additional effort for re-collimation and recalibration too.

The following Fig. 10 shows two common shutter breakages on different parts of the level arm after few months of DeSS SST operations.

Regarding the time inaccuracies due to the use of mechanical shutters, they commonly derive from:

- Shutter triggering delay, mostly related to time bias that can be roughly compensated.
- Shutter opening-closing time interval. This is responsible of around 20ms for opening and additional 20ms for closure on the 62mm shutters usually attached to 4x4 CCD chips. The full image is not being exposed during the same period and at the same time. This effect increases on 90mm shutters associated to bigger chip cameras.
- Shutter opening-closing unstable time cycle due to mechanical wear: loss of the shutter spring tension, clearance after the intensive use. They are responsible until around 10ms.

On Fig. 11 the shutter opening-closing loop effect is clearly spotted during calibrating activities on Centu1, showing a broken line of around +/-20ms gap on the time bias chart, according to the consecutive positions of the target relative to the center of the FoV. The effect is evidenced on along track direction, mostly on RA in that case, given that the GPS satellite was moving mostly toward the East at high declination. Detections on such images could be roughly corrected taking into account the distance of the target to the center of the FoV, and their measurements would still be under the limit of the UTC time uncertainty demanded for GEO observations according to the Tab. 2.

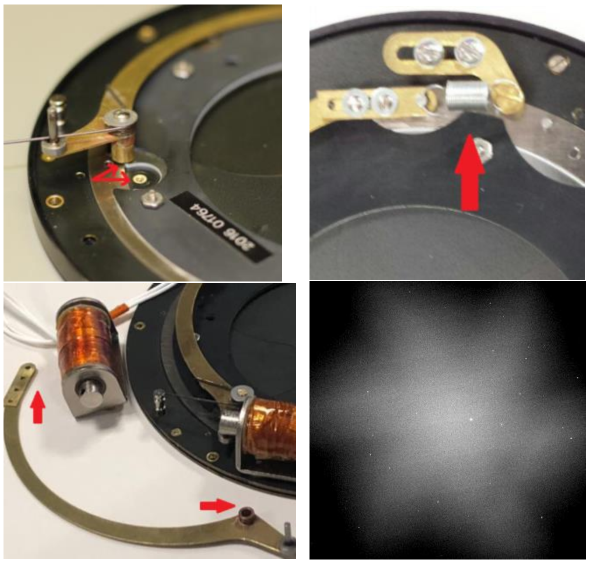

Figure 10: On the left, shutter breakages after mechanical wear. On Top right, variations of the spring tension also responsible of uncertainties of several milliseconds. Bottom Right, the imprint of shutter blades can be easily seen on very short exposures.

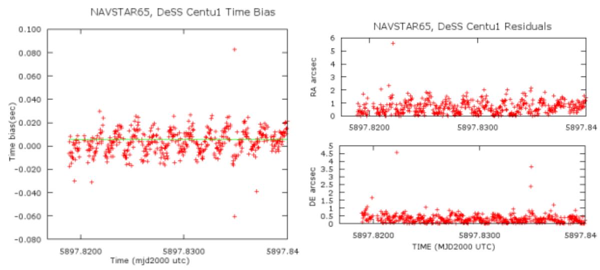

Figure 11: Navstar 65 observed during a Centu1 calibration session. Time bias is centered on zero but a broken line distribution mostly noticeable on along-track (here RA) of around +/-20ms is clearly shown due to the shutter impact, in relation to the satellite pass across the entire FoV and repeating the cycle on every following FoV. For LEO time errors of 20ms would be responsible of tens of arc seconds and even over an arc minute.

Some CCD architectures or CMOS detectors can suppress the problems derived from the short longevity and the lack of UTC accuracy due to mechanical shutters, but for SST surveillance, as for NEO, the sensors require of both, sensitivity and field of view. For getting them all, it is still very common to end up with back-illuminated CCD full frame chips which require of mechanical shutters. For tracking, and particularly on sensors working on LEO regimes, the use of mechanical shutters makes them completely useless due to the already discussed time registry uncertainties and the short life time of operation.

New CMOS technology brings interesting capabilities, with more sensibility and lower and better noise distribution [17], and alternatives to the use of mechanical shutters. However, many of those sensors use electronic rolling shutters on where the image is progressively read while it is active. The frames can also introduce temporal distortions resulting on wrong astrometric positions and errors on timing of around 20ms either from the first read line to the last. CMOS technology is evolving, also with electronic global shutters and probably will replace the Full Frame CCD architectures on many of the current SST surveillance sensors. For NEO surveillance, the required sensitivity and the smaller shutter impact in terms of time registry and of the durability still makes CCD the best option.

For tracking purposes on SST and NEO, and particularly for LEO, EMCCD cameras with Frame Transfer chips (which avoid the use of mechanical shutters) have very high sensitivity associated with the electro-multiplying gain and together with the very high frame rates, make them very suitable in spite of their medium chip sizes.

For LEO, the highest frame rate is mandatory and as the exposure times are very short, the fast EMCCD read-out leaves the exposure duty cycle jumping to nearly 100%, and surprisingly, the most limiting factor becomes to the time required for saving FITS files on disk.

3.2 Mounts and Domes requirements

The robustness of the mount for SST might be in accordance to the many slews along the night and to the angular velocity of the targets. Fortunately, for LEO tracking, mounts are relatively small permitting short inertial ramps and with high *go-to* speeds. They are almost continuously moving from one point to another on the sky, therefore equatorial fork mounts or azimuthal are preferred at DeSS, with respect to equatorial German ones, in order to avoid the continuous meridian flips, and thus being more prone to pointing inaccuracies, defocusing, rolling wires, slew time consuming and the requirement of bigger domes because the OTA is not emerging from the center of the dome. Fig. 12.

SST and particularly LEO sensors, due to Earth shadow constraints, need sky access to all azimuths above 8-10 degrees elevation. Clamshell domes are more appropriate on SST, not requiring dome rotations every few seconds. Sensor are more exposed to wind and Moon glow in those domes, but fortunately the short exposure times for SST are not so affected by the wind gusts. For NEO, mounts and domes needs are not so demanding in this regard, but observations are more critical and more sensitive to the local turbulence and environmental and sky conditions, given that exposures are longer with usually higher resolution.

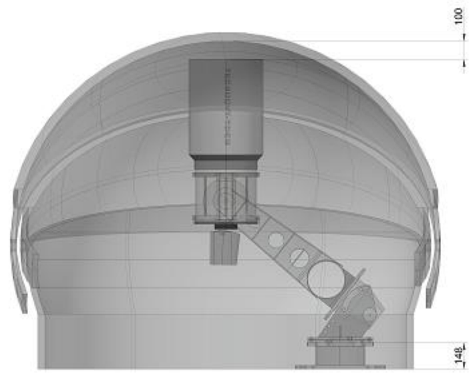

Figure 12: DeSS Antsy1 LEO sensor draft on its equatorial fork mount just fitting inside a small Clamshell dome.

4 CONCLUSIONS

The future NEO and SST sensors will require of very robust and automatic solutions, from both, the hardware and software sides. The cumulated experience, sometimes based on lot of trial and error on the already ongoing systems under this tight service mode of operation, could be of considerable help.

The processing of the images pipeline might be developed in agreement with defined detecting strategies, what also implies to the sensor control software integration for guiding the observations accordingly. The sensor might be capable of self-adapting on how images are obtained: sidereal/target, point sources/trails, exposure times and number of re-observations depending of the expected/known angular speed of the targets for a further more efficient and performing processing, automatically delivering measurements in close to real time.

NEO detection and NEO tracking still remain the most human dependent tasks for the last decisions until trained machine learning applications might take care in the next future.

The camera architecture, particularly on SST, might be planned and selected for the long and intensive use, considering the cost and unavailability consequences for the short live-cycle and their time registry inaccuracies due of some of their components or the read-out mode.

SST sensors performance can be very precisely measured**,** evaluated and improved by analyzing high precision GNSS and Geodetic satellite observations. These procedures also could be extensible to the NEO sensors for a regular calibration. This is an essential matter before providing thousands of biased or bad measurements, and for the continuous test, validation and evolution of the systems.

New optical astrometric formats might be discussed, including enough resolution space for mandatory data, additional data for an easier and more reliable processing, and observational variables at the moment of the observation, useful for weight the quality and degree of confidence of the measurements.

The more demanding SST requirements on hardware and software shall be incorporated in the NEO field, particularly for the management of the very small NEO close encounters, an interesting domain in between. For such cases, time accuracy, fast response, and access to a complete database of distant artificial satellites and debris, can help, among others, to decide to stablish the immediate follow up for the resulting detected unknown objects.

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