# Accurate Optical Observations of Space Objects in GEO and applicability to closer LEO regimes

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## ABSTRACT

Observations of space objects in high altitude regimes (MEO and GEO) are normally done by means of passive optical sensors (telescopes). Accuracy of the astrometric data down to 1 arcsecond is achievable with appropriate sensor hardware, observation strategies and suitable image data processing pipelines. Considering the diurnal, meteorological and Earth shadow constraints but also the higher relative angular velocities when observing objects at closer orbits, passive optical means traditionally becomes less suitable for LEO regimes, however the practical experience and the challenge trying to maintain this accuracy and performance tracking at lower orbits with modified optical sensors, taking into account better time registry and carefully evaluating some parameters as trailing losses and optimal exposure times among others, provides interesting results and opportunities for optimized LEO optical sensors as well.

A review of the impact of the main aspects is provided in this paper by testing and comparing the observing results obtained with the sensors installed at DEIMOS Sky Survey (DeSS) observatory, first on GEO, but last on LEO following a similar approach. Finally, a review of some techniques to improve the data accuracy and results from observations are presented on where astrometric observation residuals down to 2 arcseconds allow to single-detection errors down to 10 meters for sun-synchronous orbits and tracking campaigns providing observation of more than 330 objects per night with arcs lasting up to 30 seconds, and about 200 objects with arcs on the order of 100 seconds. Observed objects show perigee altitudes from 500 kms with a large number of objects observed in the Sun-synchronous regime and the dense 1400 kms altitude band.

Key words: LEO tracking; Angular speed; Trailing losses; Optical sensor.

## 1 INTRODUCTION

### 1.1 DEIMOS Sky Survey Concept

DeSS is a new optical observatory placed in Niefla mountains (Ciudad Real, Spain) , inside a Natural Park with very dark skies, aimed to detect and track close to Earth space objects, both, Natural: Near Earth Objects and Artificial: Space debris and satellites, operating three different optimized sensors for covering both observing fields: Surveillance and tracking and all four orbital regimes: NEO, GEO, MEO and LEO. More information on DeSS can be found at [1]

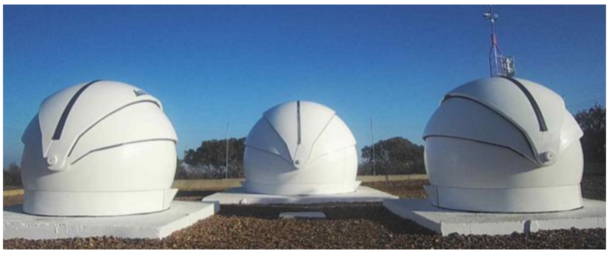

*Figure 1. DeSS observatory at Niefla Mountain from left to right: Tracker1's dome, Centu1's surveillance dome, and the dome of the experimental LEO sensor*

The main features of this new observatory are:

- **Designed and optimized for close to Earth objects.** Clamshell domes for a full access to the sky, robust HW and SW for thousands of cycles per night, fast slews, accurate timing, high CCD frame ratio and processing of the images in real time.
- **Remote and automatic operation.** Operation is controlled and supervised from 40 kms apart by means of a 200 Mbs radio-link. No computers are placed at the observatory. This is a quite challenging matter, since computers for control and processing of the images are all placed at the control centre and commanding sensors for slewing, CCD triggering and image downloading are remote without random

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latencies and time accuracies better than 1 millisecond of UTC.

- **Simple and cost effective concept.** Almost no civil works at the observatory, mostly COTS hardware and the developed SW is conceived according own observing strategies which are fully related with the processing of images procedures.

## 1.2 DEIMOS Sky Survey Facilities

### 1.2.1 DeSS Observatory

Three optical sensors are placed at the observatory

- **NEO and GEO-MEO Surveillance: Centu1** A surveillance sensor of 45cms aperture, opened to f2.8 with a FoV of 1.5 x 1.5 degrees. It is able to scan most of the GEO ring per night and carry out NEO surveillance of selected areas of around 500 square degrees per night.
- **NEO and GEO-MEO tracking: Tracker1** With a higher scale pixel resolution, a 40 cms aperture f10 providing smaller FoV of 20 x 20 arcminutes and faster read-out.
- **LEO tracking: Antsy** This is an experimental LEO tracking sensor with an aperture of 28cms at f2.2. It has an extremely fast mount slew capabilities of 10 degrees per second, and a very fast read-out and sensitive EMCCD camera. It provides an accurate time tagging better than 1 millisecond, needed for the accurate observation of fast moving objects.

### 1.2.2 DeSS Control Centre

The remote control and supervision centre is placed 40 kms apart, at Elecnor Deimos premises in Puertollano (Ciudad Real)

The sensors are automatically controlled and the generated images are downloaded and processed in almost real time. Both Sensor Control Software and the Moving Object Detecting Pipeline have been developed by DEIMOS Space.

# 2 GEO TRACKING EXPERIENCE

Since the beginning of DeSS operations in February 2016, GEO surveillance and tracking have been the main performed activities, in parallel experience has been applied together with implemented improvements to the experimental LEO sensor Antsy as a much more demanding test bed system. Also current GEO tracking capabilities are evolving with an improved Tracker2 version.

This constant evolution on the software and hardware can be performed and checked by frequent periodical observations and comparison with objects with very precise orbits as the GPS or GNSS satellites, thanks to CALMA (**CALibration Measurement Ancillary Tool**), a software tool developed by DEIMOS Space that compares actual measurements with theoretical measurements computed from known precise orbits. The tool has also been used for evaluation of performances of several third party sensors, in the frame of European Space Agency (ESA) and S3T Spanish SST activities and bilateral projects with other operators.

The following Figure 2 shows some calibration activities over 5 consecutive Navstar satellites observed by Tracker1, on where the number of measurements, residuals on Right Ascension-Declination as well as random-bias time errors can be evaluated and corrected.

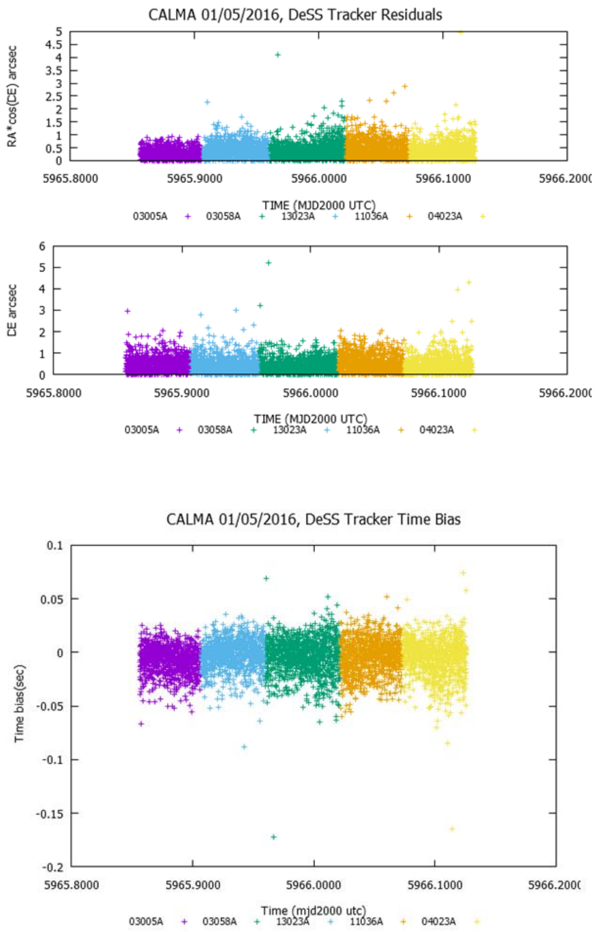


*Figure 2. Five consecutive Navstar satellites observed by Tracker1 under calibration activities, top Ra-Dec residuals, bottom, time bias distribution.*

A high measurement ratio (3 seconds in between single plots) is provided. Most of the measurements show an accuracy below 1 arcsecond with very few outliers, mostly produced by the automatic processing of the images when the detection 'centroiding' over the target is wrongly determined if some star-target involvement occurs, more often inside crowded fields close to the Milky Way.

No time bias is shown, and the apparently random time uncertainty gap of around 0.050 seconds is the result of the lack of more astrometric resolution, demonstrating that time errors of +/- 0.020 seconds would be almost not noticeable with good astrometric accuracies of less than 1 arcsecond on GEO observations.

## 3 LEO TRACKING: MORE DEMANDING REQUIREMENTS AND STRATEGIES

The LEO optical sensor shall consider very particular requirements if we compare it with sensors devoted to GEO observations for providing LEO measurements with high accuracy under such more demanding conditions (due to the larger relative velocity of the observed object). Some of those relevant requirements applied to the DeSS LEO experimental Antsy sensor are described hereafter.

### 3.1 Time control

The time tag accuracy when observing NEO and close asteroids is not critical when the round-off errors are even of 1 second. On such cases the uncertainty error of the astrometric measurement introduced with the centroiding determination (identification of the centre of the light source in the CCD image with subpixel resolution), the poor SNR and the seeing quality is usually bigger than the error due to the time tag identification. Even under close NEO approaches to Lunar distances, errors about 1 second produce residuals under the common residuals introduced by the astrometric uncertainty of the object position.

On the contrary, for Earth orbiting objects, being much closer targets, the timing errors are critical and they are one of the most determinant factors of the quality of the measurements. Therefore, a precise timing control integrated inside the software and hardware system must be developed. It is not possible to trust on the PC time accuracy, even connected by NTP to internet time providers, because errors over several milliseconds are common and completely useless.

In general, two kind of timing tag errors are observed: Random and Systematic deviations. Random errors represent the real source of lack of accuracy, since systematic errors can be measured and subtracted from the time registry, in fact, all sensors have some amount of systematic time error that can be neutralized usually after calibrating campaigns. Systematic errors are sensitive even to new control of the sensor software updates and of course hardware new components, therefore periodic calibrating campaigns are required to analyse and measure the modified time bias and to apply to further observations of the system if modifications are implemented.

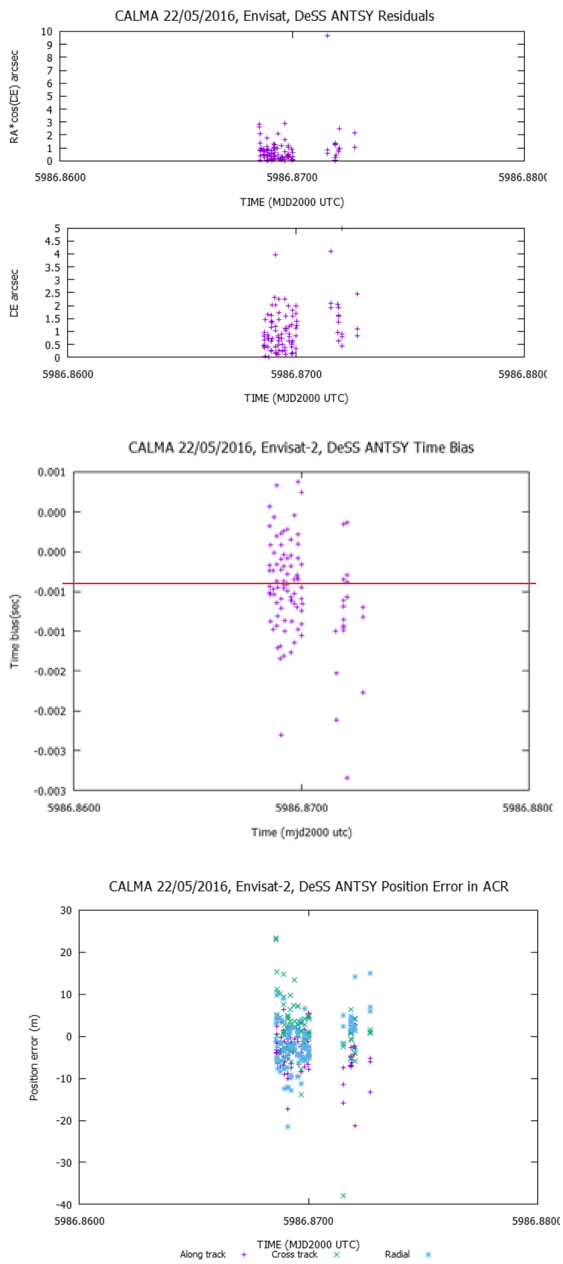


*Figure 3. Top:Ra-Dec residuals of an Envisat pass compared to an accurate orbit, middle the time bias dispersion and bottom the deducted position error*

As starting point and as already discussed, in section 2, the random error over the UTC time should be smaller than +/-0.020 seconds if the aim is to produce accurate space debris measurements on upper-MEO and GEO regimes below 1 arcsecond resolution. However for LEO observations, many of them with roughly around 100 times faster angular speeds than GEO, time errors of +/-0.020 seconds would be responsible for 30 arcseconds residuals on the object along-track path. Consequently errors above 1 millisecond of UTC should be avoided.

Figure 3 shows the residuals of the measurements obtained by Antsy over an Envisat pass, after the sensor was previously calibrated with high accurate LEO geodetic satellites orbits: Larets, Stella and Lageos.

Residuals are mostly under 2 arcseconds but if we compare both time bias charts of Figure 2 and 3, and due to the high angular speed, time scale resolution and the bias is clearly detectable even down to 1 millisecond.

The time accuracy of Antsy shown on the bias chart and the other requirements hereafter discussed and applied to Antsy help to determine the angular position by +/-10 meters at around 800 kms altitude orbits.

### 3.2 Exposure times and trailing losses

Given the extremely fast angular relative velocities of the LEO targets, the exposure times and the arcsecond/pixel resolution of the sensor are directly related to the produced object trail length measured in pixels. It is known that the signal to noise ratio of the detection decreases with the trail length. This is due to the fact that the incident light is not being accumulated always over the same pixels, but spreading it the overall length, and the sky background and noise is being also accumulated with the exposure time over the already exposed pixels with the trail. In principle the SNR decreases linearly with the trail length and this effect is defined as trailing loss.

Therefore, the exposure times must be as short as possible, and there is no advantage exposing longer with the purpose of finding fainter LEO objects under sidereal tracking, unless very precise tracking is performed over the motion and constantly updated over the variable speed and angle of the target. However, there are some detecting techniques based on direct trail detection algorithms where performances are better for longer streaks in spite of missing SNR, and CCD exposure times are then longer, which is not unexpected because this is the characteristic that provides the discrimination capability. [2],[3],[4].

For a given angular speed, trailing is related to the exposure time, but also the scale/pixel resolution of the sensor. To maximize the SNR on the image against the sky background, the size of the detected source should match approximately the pixel size of the camera, usually this is not the case and the signal is spreading over several adjacent pixels.

Trying to define the shortest and longest suitable exposure times for Antsy considering their highest SNR and best detectability by the Moving Object Pipeline in spite of missing some astrometric resolution, and to avoid trailing losses and the inconveniences of long trails, is interesting to consider that for faint sources, the highest SNR is achieved when the object signal matches approximately the pixel size of the CCD, in fact this value is a little bit higher and optimal at around 1.2 pixels, as is it shown in Fig. 4. From this point the SNR slowly decreases.

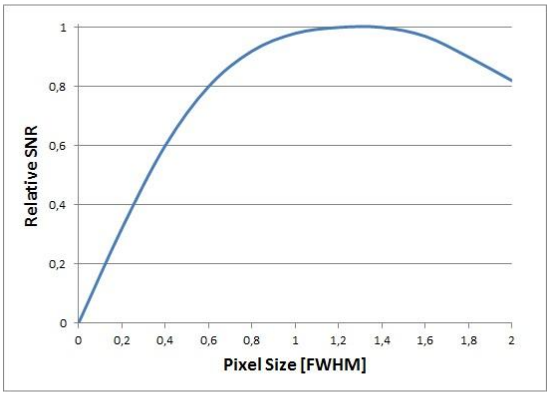


*Figure 4. SNR evolution according pixel distribution*

The critical sampling is the best astrometric scale on where the FWHM of the source spans around 1.8 pixels, and preserves just enough information that the original PSF can be restored and on where the SNR still remains quite high for an easier detection [5].

From this critical sampling, a larger number of pixels involved in the point source decrease the SNR in the same way as the trail length in number of pixels produces trailing losses. It is not possible to reach always this critical sampling due to the LEO targets are moving continuously at different speed rates. For the fastest objects, it is not even possible to include its entire signal inside 1.8 pixels even under the shortest exposure times. Additionally, the Full Width Half Maximum (FWHM) is not all the nights of the same amount.

### 3.3 Slowest and Fastest LEO angular speed detecting capabilities

It is possible to define the slowest detectable object as the one moving slow enough to produce all its signal inside one pixel under a given exposure time, scale pixel resolution and FWHM sky conditions, ideally when the signal is accumulated inside 1.2 pixels, this happens on Antsy when the LEO target is still moving quite slow, at around 200 arcseconds/second. The fastest detectable speed is defined as the shortest trail length considering to minimize the trailing losses and the inconveniences arisen when trying to accurately auto-detect and auto-measure them when dealing with long chained trails of faint and rotating objects with undefined trail ends. This is around 6-7 pixels for Antsy.

Given the aim of automatize the LEO tracking observations and the processing of the images, an angular speed gap of detectability shall be set according also the sensor features, particularly, FoV, scale pixel resolution and CCD image re-acquisition delay.

A minimum detectable speed would always be found, when the object is bright enough and that at least the detections on consecutive frames are separated by more than 2 pixels. Therefore it is only a matter of increasing the exposure time and the time gap between images, however as soon as the object moves faster, closer to the zenith or the object shows lower orbital altitude and thus higher angular velocity, the signal to noise decreases by the trailing losses and the target risks to go partially or fully out of the FoV. Therefore exposure times must be shortened for them, stumbling with two other main problems, which are described in the following sections:

### 3.3.1 CCD read noise dominance on the shortest exposure times

The following Figure 5 illustrates the evolution of the visual magnitude (equivalent to SNR or sensor sensitivity) as a function of the integration time, derived for Antsy system. This curve allows calculating the optimal exposure times. [6]. The not linear behaviour on the left side of the curve (with the exposure times shorter than 0.030 seconds) is due to the read noise dominance. From this point onwards, the visual magnitude increases as a function of the exposure times for the not moving objects. This performance is very depending on the optical configuration and EMCCD camera features of the described sensor. Additionally, the increasing magnitude with the exposure time seems a stripe line on the chart because it is only estimated up to 10 seconds. Longer exposure times are never chosen for satellite observations.

Red and purple lines are representing the evolution of the reached magnitudes from their optimum exposure times for the respective fastest and slowest Antsy detectable LEO targets (1500 and 200 arcseconds/second apparent motion) and how magnitudes decrease with longer integration times due to trailing losses.

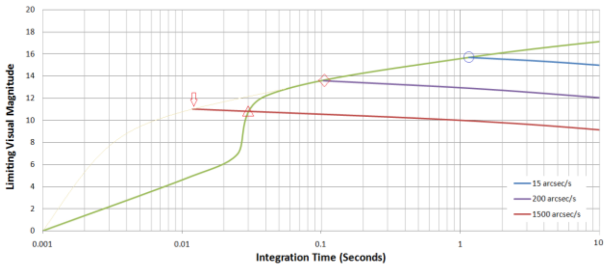


*Figure 5. Evolution of the reached visual magnitude as a function of the CCD exposure time for Antsy sensor.*

Concerning the speed evolution of the LEO tracked targets related to their elevation and the orbital altitude, Antsy works continually re-calculating the optimum exposure time for providing always the same trail length on each new image, independently of the variable angular speed of the object according the following formula:

$$Exp.Time = \frac{Resolution \times Binning \times Trail\ Length}{Angular\ Speed}$$

Properly setting this value assures the best SNR on the CCD images, the easiest detectability by the processing pipeline and a steady astrometric accuracy.

For calculated exposure times shorter than 0.030 second, this minimum time is selected to avoid the noise dominance in spite of the longer trail achieved.

### 3.3.2 Lack of background stars for solving

For the fastest detectable targets very short integration time does not allow to register too many stars on the background for a reliable plate solving, particularly far from the Milky Way regions and close to the galactic poles. This is a determinant matter to consider, on the contrary the detection could end completely useless.

According the previous Figure 5 and taking into account the small aperture and relatively small FoV of Antsy, 0.03 seconds, the shortest practical exposure time for the fastest targets allows to reach around the 10.7 magnitude on the detected LEO objects but also on the surrounding stars. Next Table 1 summarizes the average number of stars on the sky per square degree and per Antsy FoV. Brighter than 10.7 magnitude, not many stars can always be registered for a reliable plate solving, the average number of stars is 12.3 for $10^{th}$ magnitude, risking to fail when solving on the emptiest star fields close to the galactic poles.

*Table 1: Average number of stars by magnitude and square degree and for Antsy FoV*

| magnitude | stars per degree2 | stars per FoV |
|---|---|---|
| 6.0 | 0.117 | 0.178 |
| 7.0 | 0.347 | 0.527 |
| 8.0 | 1.00 | 1.52 |
| 9.0 | 2.82 | 4.29 |
| 10.0 | 8.13 | **12.36** |
| 11.0 | 21.88 | 33.26 |
| 12.0 | 57.54 | 87.46 |

### 3.4 Elevation and angular speeds

The angular speed for a LEO, assuming a circular orbit that crosses by the observer's zenith at 1000 kms altitude reaches a maximum speed of around 1500 arcseconds/second, just on the limit of the maximum detectable speed for Antsy, at lower elevations this speed decreases and close to the horizon for the same object apparently moves at around 200 arcseconds/second. Next Figure 6 shows the evolution speed for this case.

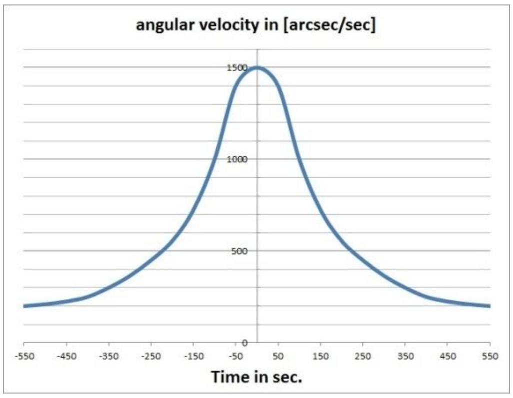


*Figure 6. Angular speed and elevation for a LEO circular orbit of 1000 kms altitude crossing the zenith.*

Trying to correlate different speed rates as a function of the elevation until zenith is possible to define de minimum and maximum elevation opportunities according the Antsy angular speed limiting gaps.

Following Figure 7 illustrates the angular speed rates as a function of the elevation of 4 different orbital altitudes, of 300 km , 600 km, 1000 km and 1500 km.

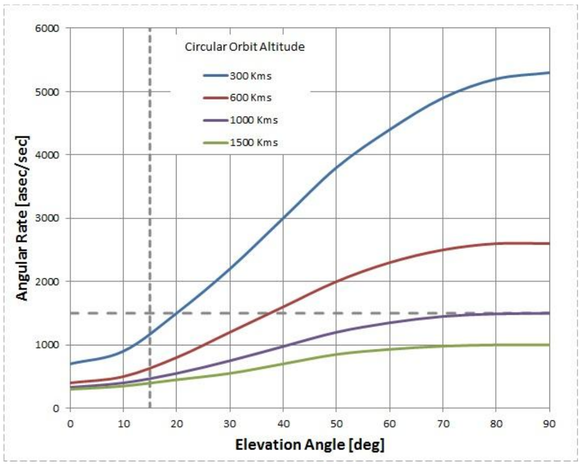


*Figure 7. Angular speed and elevation for 4 different orbital circular altitudes at 300, 600, 1000 and 1500 kms. Doted lines define the Antsy observing limits.*

The sky conditions are not often very good and transparent at very low elevations, due to mist, fog and particularly the increased brightness of the sky background by the twilight on Eastern and Western directions. These facts make the observation conditions rather adverse at very low elevations [7]. In addition to that the large phase angles also impose another constraint, due to the small light reflected by the observed object in those conditions. Therefore in practice and being realistic, the observable limit turns out to above 15º elevation. Doted vertical line of the Figure 7 is representing the borders of this minimum practical observable elevation and the doted horizontal line the practical maximum detectable speed for Antsy (1500 arcsecond/second). Theoretically only the 300 km altitude orbit always represents an almost impossible target, which already moves at 1500 arcsecond/second at 20 degrees elevation, but in practice it is not possible to efficiently observe lower orbital altitudes of less than 600 kms. For those fastest reachable targets two opportunities allow providing astrometric measurements, when the object is rising and setting between 15 and 40 degrees above both opposite horizons. Figure 3 shows two areas with observations and the lack of measurements when Envisat was crossing close to the zenith at its highest apparent angular rate above 2500 arcseconds /second.

### 3.5 LEO tracking scheduling and observing windows

LEO observations must take into account all the general observing optical constraints, (common to GEO observation cases) as the weather, the Earth shadow, for LEO objects with larger impact, the low elevation, the geographical latitude and longitude of the site, but particularly the much shorter observing windows restricted to a few minutes, this makes the scheduling very tight, requiring some dynamic tool for selecting new target opportunities on live, just when the previous has been finished, if the aim is not only to observe one or few previously selected targets at a given time.

### 3.5.1 Automatic target prioritization

Within the Antsy control sensor software a dedicated module is in charge of prioritizing targets to be observed according to some criteria and Antsy own capabilities in order to optimize its maximum performance concerning the number of measurements and objects. Therefore, after filtering the target candidates by the mentioned observable minimum elevation and sun illumination condition and the apparently velocity, (inside the defined angular speed gap according to the sensor capabilities), this prioritization shall sort those affordable targets by some criteria (which can be considered at the same time also), among them:

- Highest elevation
- Closest to Earth Shadow
- West of East preference
- Last track angular distance
- Closest to polar region
- By predicted passes on good conditions
- By Radar cross section catalogue

Highest elevation or closest to Earth shadow prioritization benefit of the best and brightest observing conditions, West or East sorting is interesting according to phase angles and twilight glow disturbance. The angular distance from previous target reduces the not observing times shortening the slewing times from one target to the following, closest to Polar region prioritizes many passes with high inclination orbits. Predicted passes allow best correlation opportunities and finally, mixing radar cross section information prevents to select objects presumably too faint and under the reachable magnitudes of the system.

Tracked targets might be automatically cancelling when reaching too low elevations, shadow conditions, or when a minimum number of observations for that object is reached.

## 4 EXAMPLARY LEO OPTICAL TRACKING CAMPAING

### 4.1 Campaign description

During August 2016: 11th, 12th, 13th, 14th and 22th Antsy was devoted to a full five nights of LEO tracking observations test under the highest elevation prioritization scheduling strategy described above.

The campaign was extended between nautical twilights. August nights not far from the summer solstice still provide a quite high observable ratio of LEO targets free from the Earth shadow condition from the latitudes of DeSS (at +38º North). At mid night, almost no LEO targets or only few of them were observable, however the sensor remained computing opportunities until a new one came observable.

At the beginning of the campaign the main objective was taking long arcs for best orbit determination purposes. Therefore once selected the target was tracked until it was observable down to the minimum elevation and within the detectable angular velocity limit. This strategy was reducing the number of observed objects particularly at the beginning and at the end of the night, when many observable LEO objects were crossing at the same time over the site. Therefore, and in order to increase the number of observed objects the following nights, the length of the arcs per target were progressively shortened and consequently less number of measurements of each target were obtained. Thus increased number of different observed objects is encountered.

It is important to mention that no manual procedure was taken when targeting the objects (telescope control) processing the images, and detections and astrometric results were fully obtained with no human in the loop and in almost real time process. It also be noted that a number of detecting omissions or not properly solved plates could occur, due to the relative small aperture of the experimental Antsy sensor preventing to include enough number of stars for image solving.

### 4.2 Campaign results

Next Table 2 summarizes the number of observed objects, number of tracks and observations per night (typical duration of about 6 hours). As described above, the number of observed objects and total tracks increase at the expense of the track lengths from one night to the following due to the changing configured strategy.

Following Figure(s) 8 provide information (night wise) on average tracks duration as a function of object perigee altitude. Two peaks in the figures correspond to the higher density of LEO orbits at 800 and 1400 kms altitude. The results confirm de suitability of the observations in LEO regime with optical sensors for contributing to the knowledge of those regimes (accounting for the confirmation of the accurate observations at those altitudes as demonstrated is section above, see Figure 3) .

*Table 2. Antsy five nights campaign results of LEO tracking under highest elevation priority strategy*

| Night | observed objects | Number of tracks | Averge track length (sec) | Number of observations |
|---|---|---|---|---|
| 11/08/2016 | 111 | 113 | 100.5 | 7350 |
| 12/08/2016 | 165 | 172 | 81 | 7311 |
| 13/08/2016 | 236 | 236 | 77 | 5463 |
| 14/08/2016 | 217 | 217 | 101 | 4188 |
| 22/08/2016 | 337 | 352 | 26.8 | 7149 |

## 5 CONCLUSIONS

Modified GEO optical sensors and observing strategies, taking into account better time registry, and carefully evaluating other parameters as trailing losses and optimum exposure times, rigorously tested and fine-tuned under recurrent calibrations brings to a interesting results and opportunities for accurate LEO optical tracking SST services as well. Below two arcseconds accuracy on single measurements corresponding to uncertainties of around 10 meters at 800 kms are possible with Antsy experimental low cost setup, however some critical aspects shall be taken into account:

- The design of the LEO sensor, its observing strategy and the automatic mode of processing of the images in real time are fully related each other and might be developed together.

- The angular speed and the apparent brightness of the objects are the driving parameters concerning the 'detectability' capabilities further than the reachable orbital altitude ranges and corresponding sizes of the objects.

- The principle of trailing losses guides the full sensor concept related to resolution, FoV and exposure times definition and the way on how the processing of the images for auto-detection has been designed and implemented.

- The elevation degree and the related angular speed brings the opportunity for detecting and measure the fastest targets.

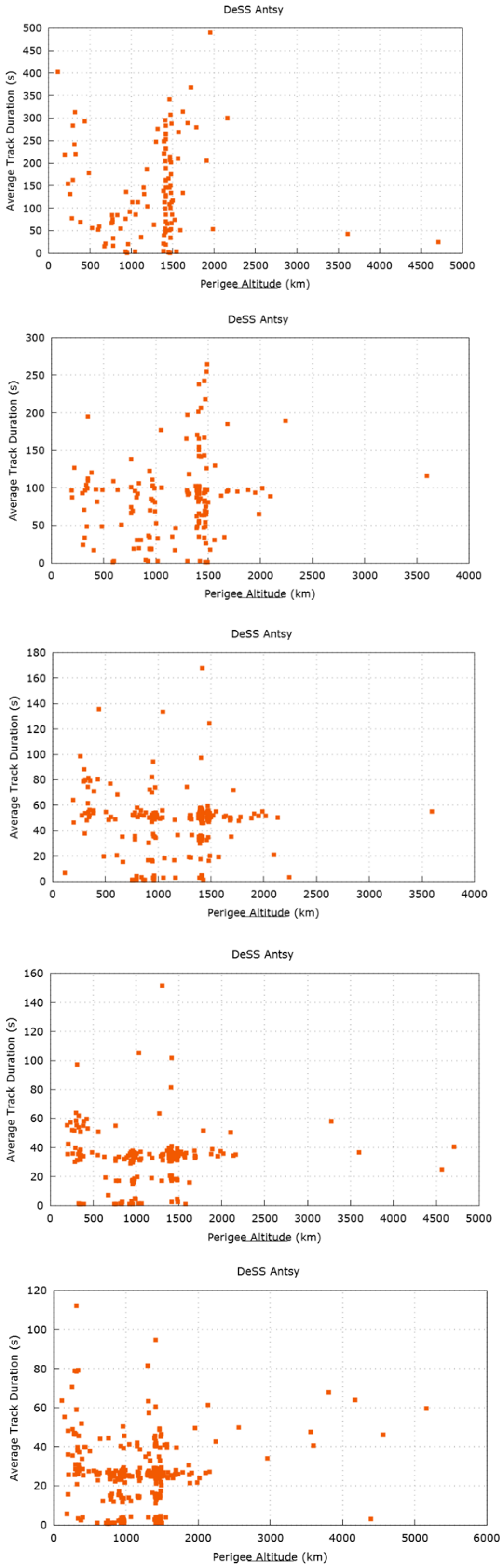


*Figure 8. Tracks duration according perigee altitude of the 5 nights, $11^{th}$,$12^{th}$,$13^{th}$,$14^{th}$ and $22^{th}$ August.*

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