Accurate Optical Observation of Space Objects in LEO regime

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ABSTRACT

Observation of space objects for estimating the orbital parameters of the observed objects are normally done from passive optical sensors (telescopes), radars and SLR sensors. SLR sensors required the observed object to have a retro-reflector system to allow detection, improved observation techniques have lead to observe non 'collaborative' objects. Radar sensors are normally used for observing objects in Low Earth Orbits (LEO) as their efficiency reduces largely with the distance between the sensor and observed object. On the contrary, passive optical sensors work well at large distances, but observation at short distances are impacted by limitations that shall be accounted to provide accurate observations in the LEO regime.

Those limitations are mainly derived from the Earth shadow, the meteorological and diurnal constraints but also the high relative velocity between the observed object and sensor, which increases the requirements on the sensor capabilities in terms of speed, sensitivity and UTC registry accuracy. Therefore the main aspects to be considered are related to field of view -, which shall be traded-off with the read-out time; the image triggering mechanism allowing an extremely accurate time tag of the observations; the impact of trailing loss and trail detection mechanism which lead on the optimal exposure times, and derived signal to noise ratio.

These aspects need to be addressed to design a suitable passive optical sensor for LEO object observation, and to define the proper observation strategies in terms of prioritization of target objects and the way they would be processed subsequently.

This paper describes these theoretical aspects and present the solution considered during the design and deployment of a new LEO sensor within the DEIMOS Sky Survey (DeSS) observatory. Some results from observation campaigns are provided, allowing evaluating the data rate and accuracy achievable with such a sensor.

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

1 INTRODUCTION

Satellite and Space Debris observations are mainly executed by:

- Radars: Normally used for observing objects in Low Earth Orbits (LEO) as their efficiency reduces largely with the distance between the sensor and observed object,
- Passive Optical Sensors (telescopes): They work well at large distances, but observation of objects at short altitudes are impacted by limitations due to relative velocity and observation geometry (illumination and weather conditions), and
- Active Optical Sensors (SLR): SLR sensors required the observed object to have a retro-reflector system to allow detection, improved observation techniques allows to observe non 'collaborative' objects.

Mail limitations for the observation of objects in LEO with optical sensors have to be addressed in order to produce efficient and significant contribution to the SST field in LEO. Overcoming these limitations brings benefits to several actors and can be addressed nowadays. Regarding the required technology, the optical sensor improvements in regards to camera efficiency and readout capabilities, the time tag accuracies, mount responses, etc. may allow addressing these observations, which were not possible some years ago.

For the astrodynamics scientific community and industry, it is normally difficult accessing Radar Data (as it has normally dual use), only limited research or service provision development can be accomplished. Research on LEO regime SST services (Re-entry, Fragmentation, Conjunction analysis) and main activities like cataloguing, orbit computation have been up to now based mainly on simulated measurements for these actors. SLR observations do allow LEO object observation and do not have such dual use, but they have been limited up to the recent days to collaborative objects.

For final users, and in GEO regimes, there are already satellite operators demanding and using efficient and operational services based on traditional SST observations. Receiving optical observations allow feeding the flight dynamic systems to improve the orbital determination, calibrating ranging stations and manoeuvres through independent means. In LEO regime, considering the large population of objects, the increasing number of operators and future large constellations, and the more frequent conjunction and re-entry events, similar services could be envisaged if they demonstrated to be as efficient as in GEO regime.

Finally, for the telescope operators, accurate observations of objects in LEO provides additional motivation to improve observation methods and strategies. Optical sensor operators moved from the observation of distant and very slowly moving objects (like Near Earth Objects, NEOs) towards objects in GEO and MEO, requiring new techniques that need updates for the observation in LEO.

Taking all these considerations in mind, DEIMOS works on setting up LEO optical observation capabilities within the DEIMOS Sky Survey (DeSS) observatory, which is also devoted to the more traditional MEO/GEO and NEO observation. 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].

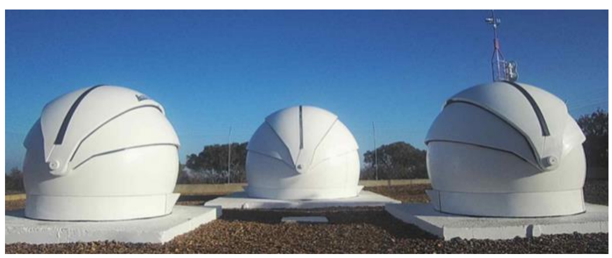

Fig. 1. DeSS observatory at Niefla Mountain from left to right: Tracker1's dome, Centu1's surveillance dome, and the dome of the experimental LEO sensor

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 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.

Four 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 and Tracker 2**, 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. An upgraded version with a larger optical tube will be installed by end of 2018.

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 and the whole process is adapted to all kind of objects (from low LEO to upper NEO).

2 GEO TRACKING EXPERIENCE

Since the beginning of DeSS operations in February 2016, GEO surveillance and tracking have been the main activities within the observatory. In parallel, system improvements have been implemented for the execution of observations with the experimental LEO sensor Antsy as a much more demanding test bed system.

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 observations 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 (part of the EU SST) activities and bilateral projects with other sensor operators.

The following Fig. 2 shows some calibration results 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 (if needed).

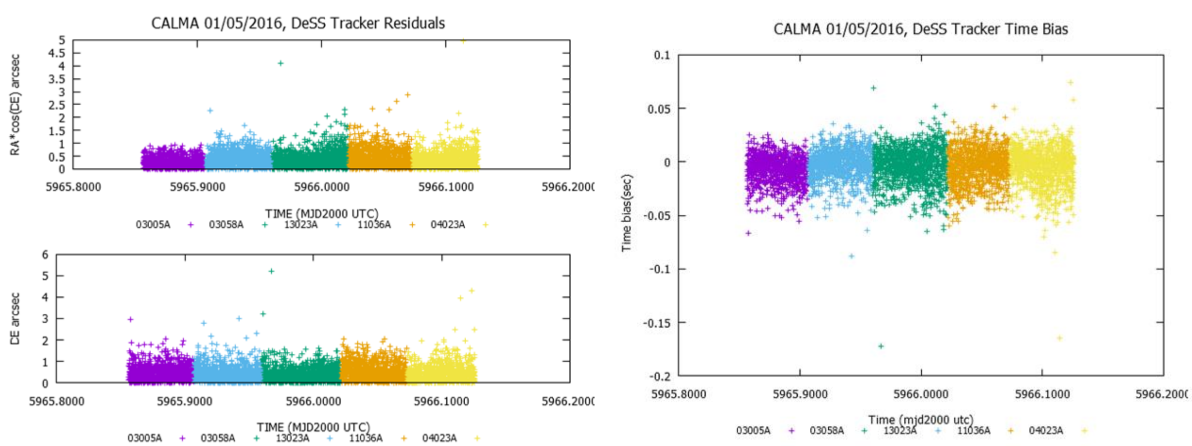

Fig. 2. Five consecutive Navstar satellites observed by Tracker1 under calibration activities, left: Ra-Dec residuals, right: time bias distribution.

A high measurement ratio (3 seconds in between single plots) is provided. Most of the measurements show an accuracy below 0.5-1 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 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. These time tag accuracy can be associated, for example, with the error introduced by the shutter opening times when using a mechanical shutter (see next Fig. 3 related to observations from Centu1 sensor). This undesirable effect, typical on full frame CCD architectures which require mechanical shutters. can be avoided, looking for other solutions when observing on the LEO regimes, requiring time accuracies better than one millisecond

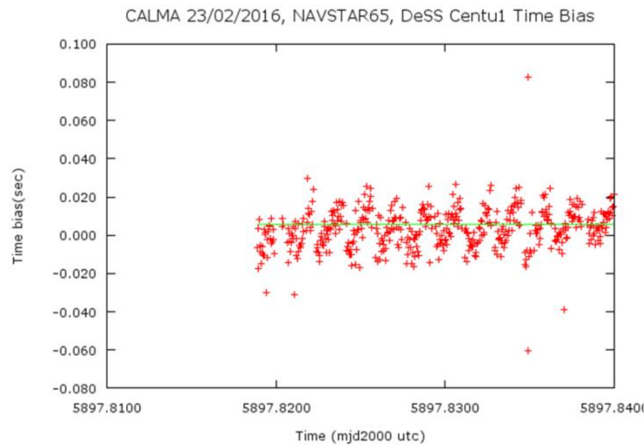

Fig. 3. About 20 ms mechanical shutter uncertainty due to the opening and closing times, shown as an along track broken line depending on the target position on the FoV (measurements obtained with DeSS Centu1)

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 here below.

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 relevant factors defining the measurements quality. Therefore, a precise timing control integrated inside the software and hardware system must be available.

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.

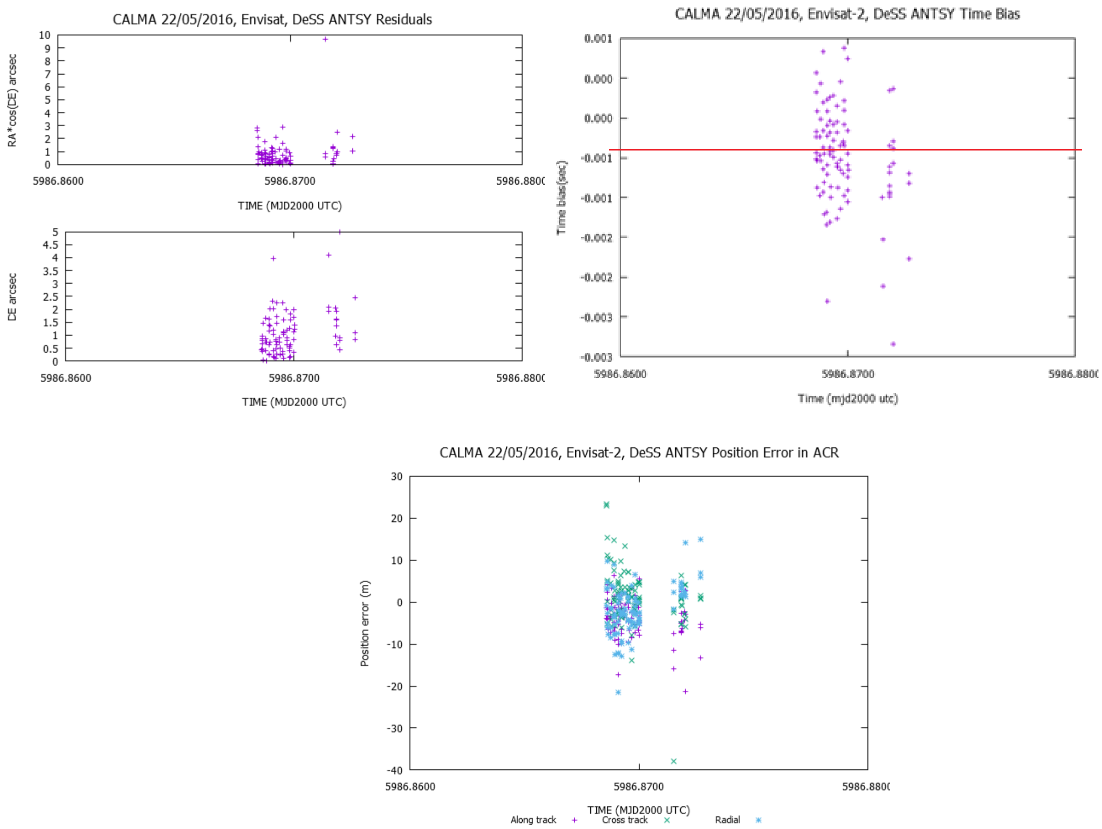

Fig. 4. Top left: Ra-Dec residuals of an Envisat pass compared to an accurate orbit, top right: the time bias dispersion and bottom the deducted position error

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 should be avoided.

Fig. 4 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 Fig. 2 and 4, 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.

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] and [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 onwards, the SNR slowly decreases.

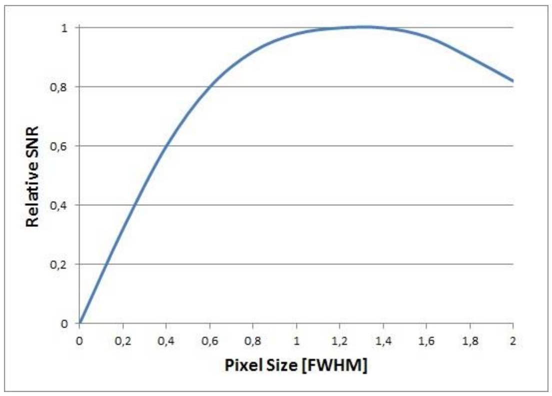

Fig. 5. SNR evolution according pixel distribution

The critical sampling is the best astrometric scale on where the Full Width Half Maximum (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 FWHM is not equal all the nights.

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 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:

3.1.1 CCD read noise dominance on the shortest exposure times

The following Fig. 6 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.

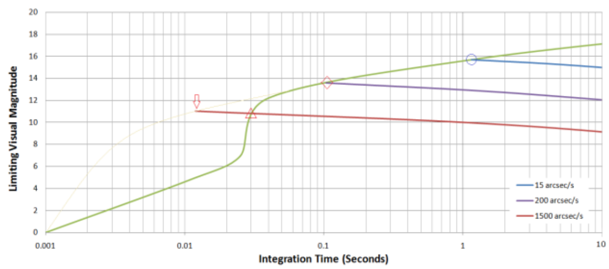

Fig. 6. Evolution of the reached visual magnitude as a function of the CCD exposure time for Antsy sensor.

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 seconds, this minimum time is selected to avoid the noise dominance in spite of the longer trail achieved.

3.1.2 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 be considered. On the contrary, the detection could end completely useless.

According the previous Fig. 6 and considering 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

Elevation and angular speeds

The angular speed for a LEO, assuming a circular orbit that crosses 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: close to the horizon, the same object apparently moves at around 200 arcseconds/second. Next Fig. 7 shows the evolution speed for this case.

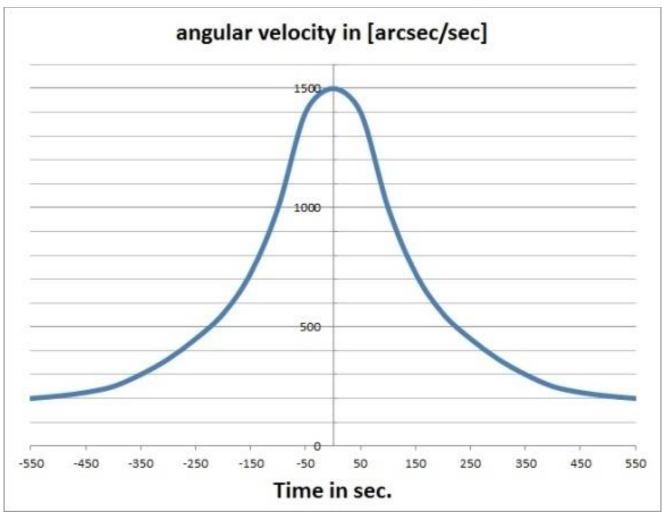

Fig. 7. Angular speed and elevation for a LEO circular orbit of 1000 kms altitude crossing the zenith.

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

Following Fig. 8 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.

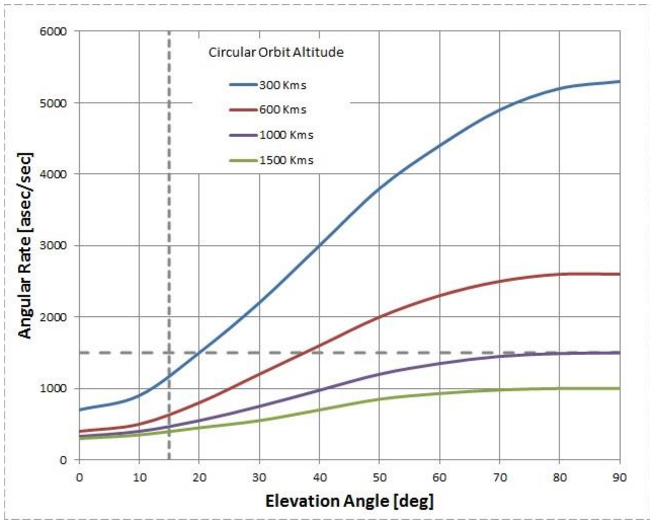

Fig. 8. Angular speed and elevation for 4 different orbital circular altitudes at 300, 600, 1000 and 1500 kms. Doted lines define the Antsy observing limits.

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 Fig. 8 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. Fig. 4 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.

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.

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 CAMPAINGS

LEO general observation campaign

During August 2016,: 11th, 12th, 13th, 14th and 22th Antsy was executing 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 object became 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 relatively small aperture of the experimental Antsy sensor preventing to include enough number of stars for image solving.

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 plots in Fig. 9 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 Fig. 4).

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

Night	Observed objects	Number of tracks	Average 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

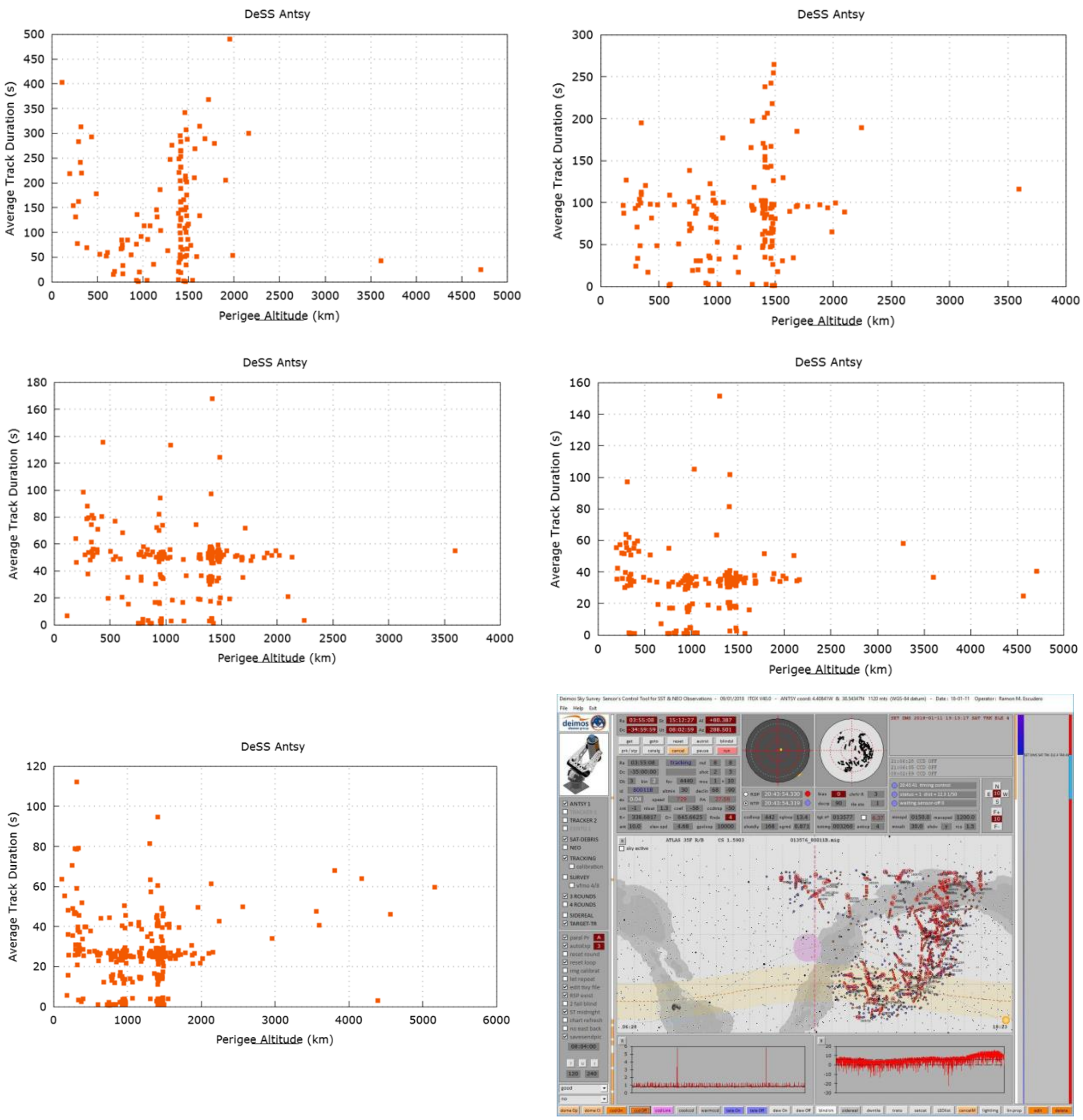

Fig. 9. Tracks duration according perigee altitude of the 5 nights, 11th,12th,13th,14th and 22th August, 2016 and RA/DE distribution of observations during one night.

Tiangong-1 observation during Re-entry phase (January 2018)

Tiangong-1 station re-entry occurred on the 2nd April 2018. During previous months, it was observed by several sensors in order to estimate the orbit, its dynamics and the possible re-entry date. DeSS contributed to those observations with some optical data generated along the nights of 15th and 16th January. Observation during the weeks previous to the actual re-entry were not possible due to weather considerations and observation geometry limitations.

In January, there were possible passes of Tiangong-1 over DeSS almost every night (Fig. 10), the ANTSY sensor was available along 4 nights, generating observations from two successful passes. The altitude of the station at that time was about 280 km. The size of the station and the low altitude make the object to appear very bright, creating saturation problems in the images, which limited the generation of more observations and had to be accounted when processing the images.

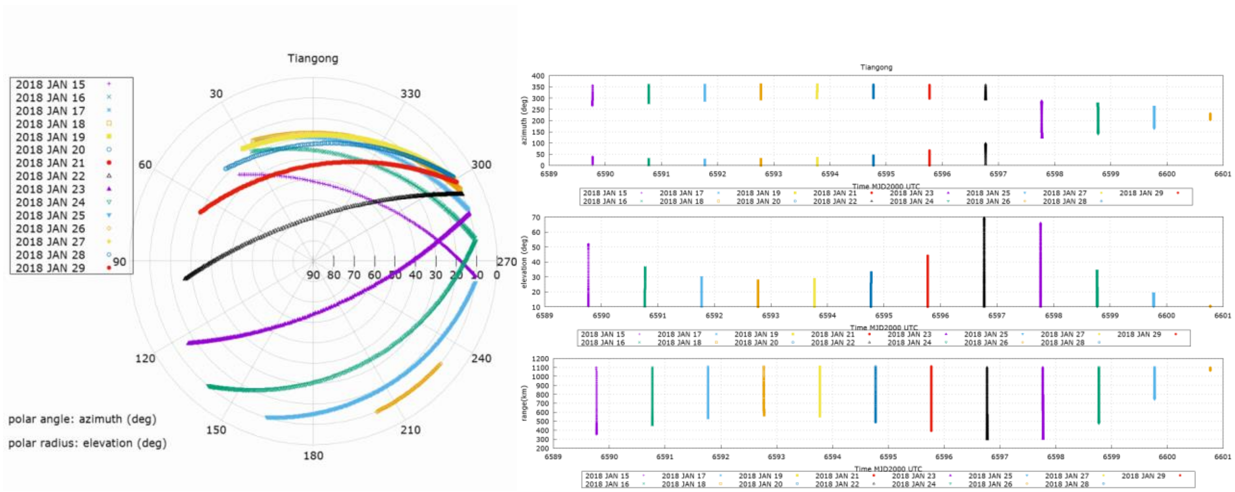

Fig. 10. Observations opportunity of Tiangong-1 from DeSS in January 2018.

The comparison of the generated observation against TLE produced differences of about 1.5 km, corresponding to about 300 arcseconds in along-track (Fig. 11), which can be associated to the lack of accuracy of TLE information. Computing an orbit with those observations, measurement residuals are limited to about 2 arcseconds (Fig. 12).

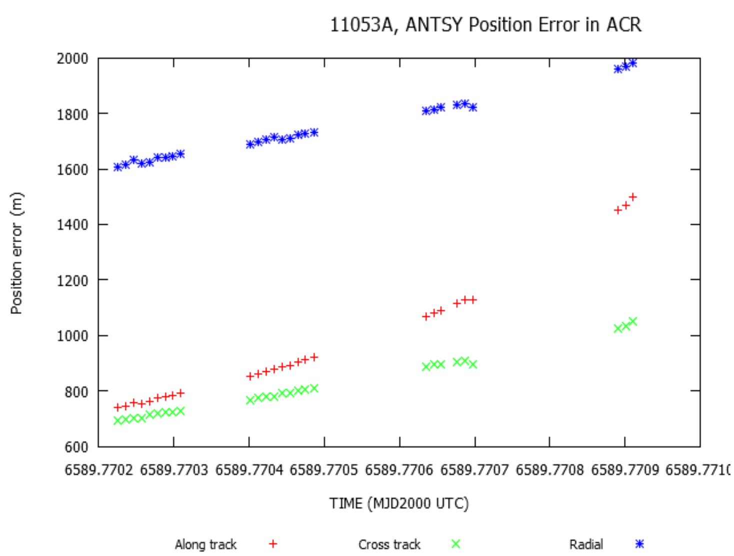

Fig. 11. Deviation in Along-track, Cross-track and Radial (ACR) direction of observations with respect to TLE data.

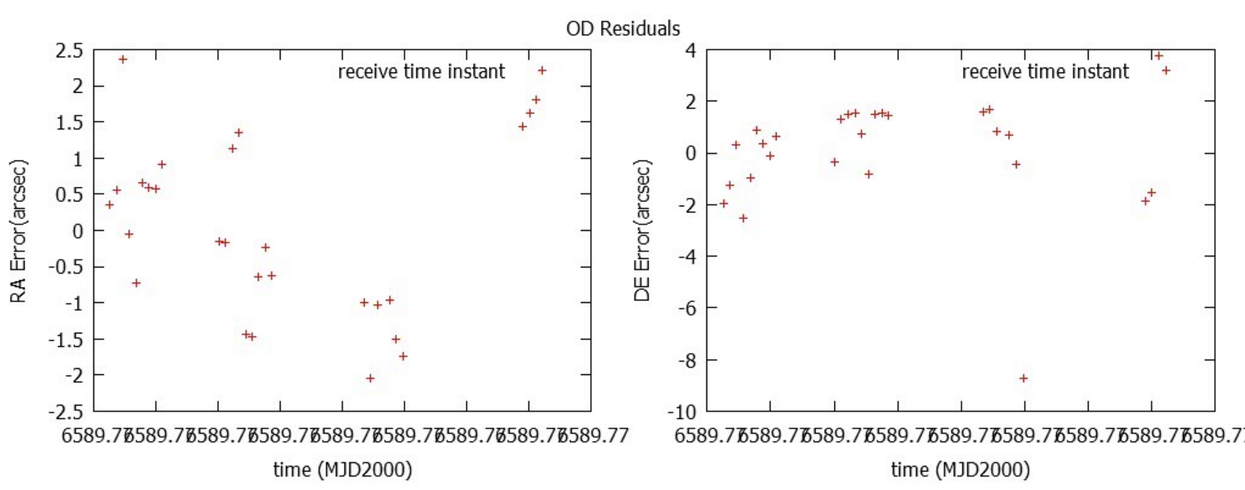

Fig. 12. Residuals in Right Ascension and Declination when estimating an orbit from the Tiangong-1 observations.

5 CONCLUSIONS

In the basis of the analyzed options for LEO objects observation with optical sensors, it is considered that very compact, reliable, autonomous, simple, not expensive solutions can be envisaged. Modular option for these kinds of sensors is also desirable allowing easy and quick replacement in case of failure expansion of the operational capabilities to different sites.

In order to get such solutions, it is worth highlighting the following aspects:

1) **Hardware requirements:**
    a. **Mount,** requiring compact design, fast slew, azimutal or equatorial (avoiding german equatorial designs due to the meridian flip, rolling wires, defocusing after long slews and sensor usually requiring bigger domes, since OTA does not evolve from the center). The mount shall allow free access to low elevations, all azimuth regions and close to polar regions; with fast slews and ramps and close loop for synchronization after several hundreds or even thousands of slews per night . Closed loop is normally required with high resolution encoders + solving plates, together with stable focus (there is no time for frequent re-focusing routines)

    b. **Opticals,** it is needed to have the widest FoV as possible even for tracking purposes (anticipation + pointing + imaging small time delay random inaccuracies on the fastest targets > 2000 arcssec/sec). FoV of 1.5 x 1.5 degreess is considered as a minimum. Relative low resolution can be a feasible approach (4-6 arcsec/pixel), with fast focal relation providing speed and FoV < f2.

    c. **Camera,** with fastest read-out as possible, which may require not very large number of pixels (slower read-out + slower file saving time + slower processing of the images procedure). It is considered mandatory to avoid mechanical shutters (problems with full frame architectures) avoiding the problems of variable shutter delay, shutter life time (no longer than 6 months for tens of thousands of images per night), opening and closing shutter times (20-40ms, as per Fig.3, the larger the FoV is, the larger the time tag uncertainties). The best option considered up to now is the EMCCD (back illuminated transfer frames), other solutions present some drawbacks, as interlined cameras (with lower sensitivity) or CMOS (with too small pixels and less sensitivities compared to back CCD)
    d. **Domes,** solution based on Full all-sky aperture (clamshell) are preferred as LEO apparently move fast and there are continuous slews across the sky (contrary to the case of observations of objects in GEO regime). Additionally, exposure times are very short for being affected by wind gust.

2) Software requirements:

a. **Observing strategies** that can be associated to performance aspects considering the need of operating in sevice mode, as many nights as possible, supported by all-sky camera and weather monitoring. It is also interesting to identify the prioritization scheme more suitable for the target objects. The observation strategies shall address the minimum number of images or trail length for confirmation of the object detection. It is needed to avoid also false detections.
b. **Control SW**, it is required a tight control minimizing spare times during loops, a time tag accuracy under millisecond accuracy, with no random time errors. It is needed to integrate the pointing towards the object in the basis of a TLE propagator or OEM ephemeris interpolation.
c. **Processing SW**, the image processing pipeline is a complex sw element which requires data processing in near real time, with no human in the loop. It is normally developed according to the observation strategy, and it shall be flexible to accommodate detectability thresholds to the sky conditions.

Considering all those aspects, it is possible to have LEO optical observations with accuracies below 2 arcseconds on single measurements corresponding to uncertainties of around 10 meters at 800 kms altitude (suitable with Antsy experimental low-cost setup). Even re-entering objects at much lower altitudes are possible to be observed generating accurate measurements, as demonstrated during the Tiangong-1 station reported in this paper.

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