CMOS CAMERAS IN SST SENSORS: OPTIMIZING OPTICAL SYSTEMS FOR LEO SATELLITE TRACKING

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ABSTRACT

To achieve good quality SST observations of LEO objects, there are many factors that should be taken into consideration. There are simple ones such as FOV, size of the camera's chip, pixel size and its effect on astrometric solutions. Additionally, there are more complex considerations such as the rolling shutter effect and the corrections to minimize its negative impact on the observations. Additionally, size of the mirror and the pixel scale affect SST measurements and data quality, as well as collimation of the optics and the tracking accuracy of the mounts.

Studying and properly fitting these parameters can bring significant improvement in data accuracy and the ability to observe and correlate fast moving objects on LEO and VLEO orbits.

1 INTRODUCTION

Up until a few years ago, there was little discussion about space safety. However, starting from 2018, the number of artificial satellites has been growing rapidly. In the last two years, there have been ~2500 new satellites each year – a staggering number of 7 new satellites in orbit each day.

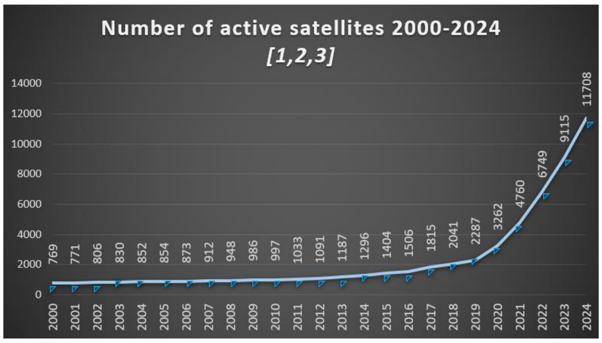

Figure 1: The growing number of active satellites with time [1,2,3]

But these are only the active satellites – the number of catalogued objects is greater and close to 40000 as of 2023, with more than 50% in LEO.

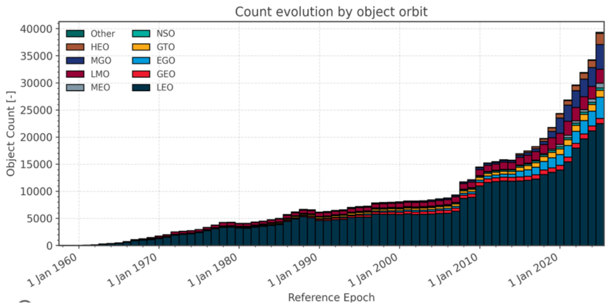

Figure 2: Evolution of the populations of objects in different orbit regimes [4].

Additionally, there is also significant amount of space debris outside of the catalogued objects. There are:

- 40500 space debris objects greater than 10 cm.
- 1100000 space debris objects from greater than 1 cm to 10 cm.
- 130 million space debris objects from greater than 1 mm to 1 cm [4].

To provide safe Operations in such a crowded LEO orbit, constant monitoring of objects is needed.

Visual observations are one of the easiest and financially efficient ways of observing satellites. But to make it effective, proper configuration of the equipment is necessary so that it can work with fully automatic astrometric software.

The aim of this study is to analyze the most important hardware parameters and the impact of camera electronic shutter characteristics on the accuracy of astrometric solutions during LEO observations.

2 REQUIREMENTS

The main requirement for LEO observations is to achieve a minimum of 8 arcsec accuracy in defining the satellite position within the TDM output file. This kind of accuracy corresponds to 100-150 meters of accuracy depending on orbit height (300-400km orbit height, 380 meters for a 1000km height orbit).

The second requirement is to deliver final data (TDMs) to the customer within a time shorter than 90 minutes which usually corresponds to one orbit of a LEO object.

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Editors: S. Lemmens, T. Flohrer & F. Schmitz, (http://conference.sdo.esoc.esa.int, April 2025)

3 SENSOR HARDWARE

At Sybilla Technologies (ST) we are using multiple types of sensors depending on needs and expected results. Below are a few examples of standard configurations within the ST portfolio:

- **PAN6** – Orion class tracking sensor (RASA 11’’ – Rowe Ackermann Schmidt Astrograph, QHY268M camera, Planewave L350 mount).
- **PAN12** – Hercules class tracking sensor (Planewave Delta Rho 350, QHY 4040 camera, Planewave L350 mount).
- **CONST-003** – URSA MINOR class sensor for survey observations (RASA 8’’ – Rowe Ackermann Schmidt Astrograph, QHY163M camera).

Figure 3: Orion class sensor.

Figure 4: CONST class sensor prototype.

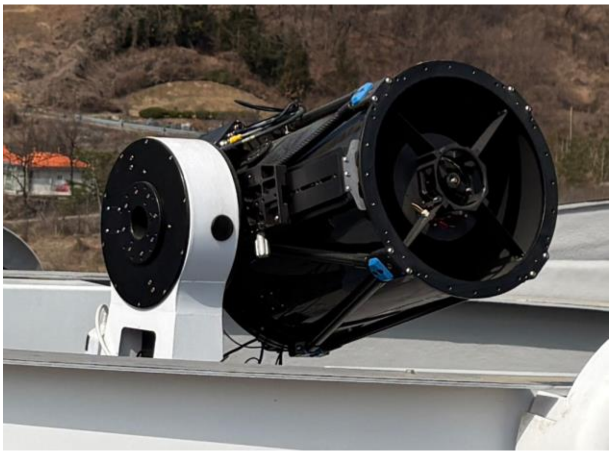

Figure 5: Hercules class sensor.

Figure 6: Orion class sensor with QHY268 camera

Multiple factors are important for the above configurations to meet the 8 arcsec accuracy requirement.

For static (CONST) sensors:

- Known line period value of the electronic rolling shutter of the camera – to include corrections and limit time-bias almost to zero.
- Pixel scale.
- Large field of view (FOV), with very good optics collimation within the whole FOV.

For tracking (ORION, HERCULES) sensors:

- Known line period value or calculated time-bias for the frame center.
- Pixel scale.
- High mount tracking accuracy.

4 OBSERVATIONS

- Pixel scale

Frames registered by cameras in all of the sensors mentioned in Section 4 are processed by Astrometry24.NET software immediately after collection (this is a real-time, automatic process). Based on multiple measurements different accuracy levels can be achieved for different objects.

Objects	Astrometric solutions pixel / subpixel accuracy
Stars, DSO (tracking with star speed)	0,1 - 0,2 of pixel
GEO objects observations	0,2 - 0,3 of pixel
MEO objects observations	0,3 - 0,5 of pixel
LEO objects observations	1-3 pixels

	CONST [1,96"/pix]	ORION [1,25"/pix]	HERCULES [1,77"/pix]
Astrometric accuracy [arcsec]	0,2 - 0,39	0,13 - 0,25	0,18 - 0,35
	0,39 - 0,98	0,25 - 0,63	0,35 - 0,89
	0,59 - 0,98	0,38 - 0,63	0,53 - 0,89
	0,98 - 5,88	0,63 - 3,75	0,89 - 5,31

- Field of view (FOV)

The FOV is mostly important for static (CONST) sensors where the object is moving through the whole frame. Generally, there is no issue for objects like stars, GEO and MEO satellites which are moving with minor (or zero) angular speed. However, the FOV is very important for LEO observations – when an object is on low orbit and moving with high angular speed, the streak created on registered frame can be long. To build a valuable TDM, there is a need to have at least three streaks on frames in a row. Taking the above under consideration clearly shows that for CONST sensors a larger chip and correspondingly larger FOV are essential – a small field of view can significantly limit the ability to observe small LEO objects. The minimal reasonable FOV is around 2.5 x 2 deg.

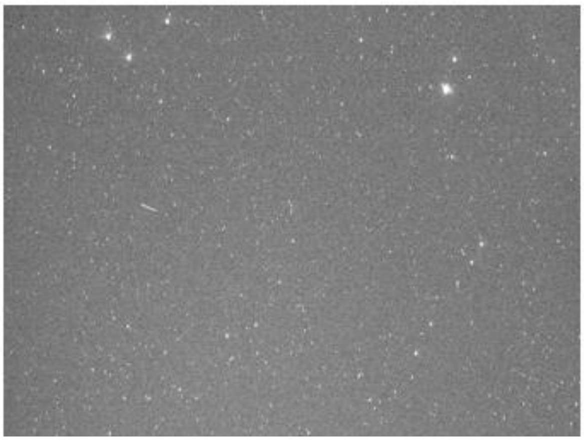

Figure 7: MEO satellite on high 7000km orbit – 1s exposure time.

Figure 8: LEO satellite on high 400km orbit – 1s exposure time.

- Proper optics alignment

Collimation of optics is a similar topic to FOV – it is more important for static sensors than for tracking sensors. In survey mode, we use the whole area of the chip, while in tracking mode typically only the center is used for the targets. Any distortions on the chip edges can lead to growing correlation errors or even no correlations. In Fig. 9, there is an example of improperly aligned optics and camera plane, leading to a situation where one corner has properly focused stars and the other has significantly defocused stars. This will result in growing astrometry solution errors.

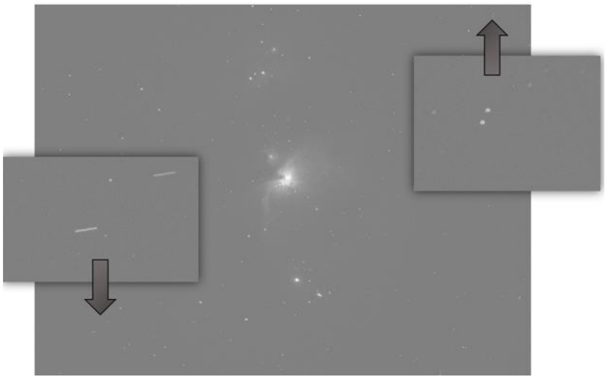

Figure 9: Camera matrix tils offect on frame – defocused stars on part of the frame.

- **Line period of rolling camera shutter**

Most modern CMOS cameras have an electronic rolling shutter. That means that the frame is created from the upper left corner to the lower right corner line by line. If we have objects which are moving through the frame then they can be distorted. Distortion increases together with the value of the line period. If the object stays in the same area of the frame – then the rolling shutter effect can be corrected via time bias. But if we have a static sensor (CONST) and the object is moving through the whole frame, then the correction for each frame should be different. If the line period value is known, then the proper adjustment can be implemented to each frame – depending on the position of the object. In Fig. 10, there is an example of a LEO satellite with CPF ephemerides which can be used for calibration purposes. In Fig. 11 and Fig. 12, there are examples of the use of Astrometry24.NET tools to solve the frame and match the registered satellite with ephemerides. The use of line period correction makes correlation accuracy 10x more precise.

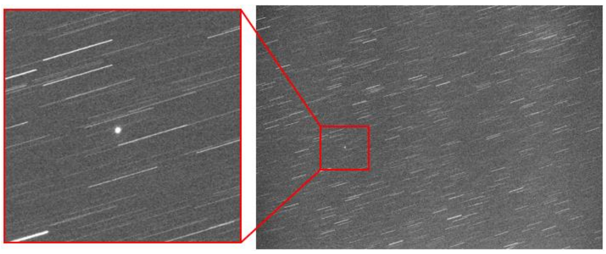

Figure 10: Frame with LEO satellite NORAD 41240 (JASON-3).

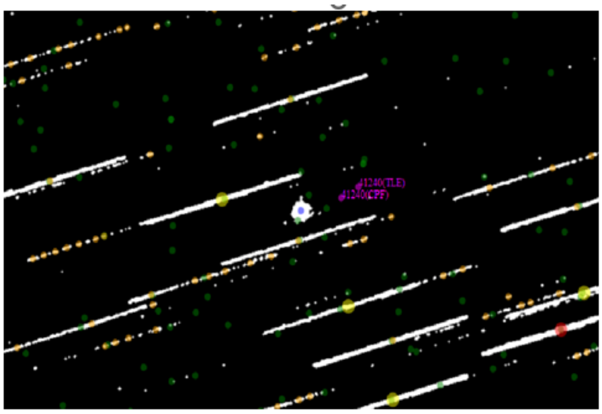

Figure 11: LEO satellite NORAD 41240 (JASON-3) correlation without line period correction (CPF correlation distance = 125 arcsec) [5].

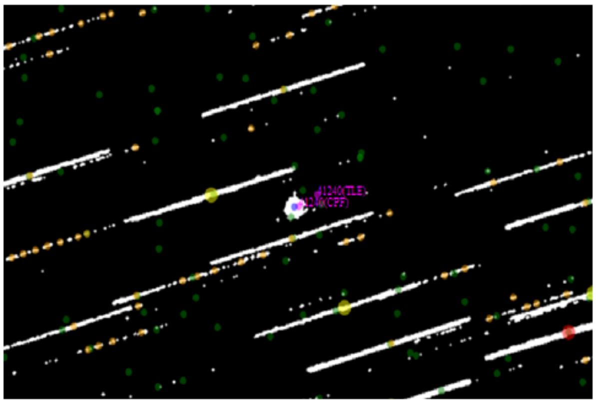

Figure 12: LEO satellite NORAD 41240 (JASON-3) correlation with line period correction (CPF correlation distance = 9 arcsec) [5].

5 CONCLUSIONS

Multiple factors can significantly impact the accuracy of observations – from sensor configuration, to optics alignment, and ending with rolling shutter effect correction. If all of these aspects are properly addressed, then achieving a minimum of 8 arcsec accuracy in defining the LEO satellite position within the TDM output file is very easy. Achieving better accuracy of 1-2 arcsec for LEO is also possible – working with higher gain on CMOS cameras and shorter exposure times should be the key to success in this matter.

6 REFERENCES

[1] https://www.statista.com/statistics/897719/number-of-active-satellites-by-year/

[2] https://orbit.ing-now.com/

[3] https://nanoavionics.com/blog/how-many-satellites-are-in-space/

[4] https://sdup.esoc.esa.int/discosweb/statistics/

[5] The presentation shows the results of the project no. POIR.01.01.01-00-0831/19-00 "LightStream - preparation and implementation for production of innovative software for efficient, accurate astrometry and photometry of point and streak sources for astronomical CCD, CMOS cameras" - project co-financed by the European Union from the European Regional Development Fund under the Intelligent Development Operational Program. The project is carried out as part of the competition of the Polish National Center for Research and Development: “Fast Path”.