DESIGN AND PROTOTYPING OF A LOW-COST LEO OPTICAL SURVEILLANCE SENSOR

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ABSTRACT

Optical tracking of LEO objects has been extensively studied and exercised. In this paper, we describe a novel approach surveillance method using an array of collocated fixed Field of View telescopes. In this project a Low-Cost Low-Earth Orbit Optical Surveillance Sensor has been developed to target a similar market as conventional radar systems through the reduction of the cost per sensor while maintaining a similar performance. This cost reduction of the full system will be achieved by employing an array of low-cost optical telescopes as a multi-eye system, with an ultra-wide Field of View capable of imaging the full sky. Having full sky coverage allows each telescope in the system to point in a fixed direction, decreasing the complexity of the subsystems involved.

1 INTRODUCTION

LCLEOSEN (Low-Cost Low Earth Orbit optical surveillance SENsor) is a new low-cost optical sensor proposed for Low Earth Orbit (LEO) surveillance tasks with capacity to process data in near real time. Currently, the use of radar systems for this purpose is widely considered the standard due to the all-weather, day/night usage and detection of objects down to few centimetres. However, radar systems are expensive to build and operate. LCLEOSEN is intended to target a similar market via the combined use of many individual low-cost optical systems (with modern high-sensitivity detectors) in order to increase the Field of View (FoV) and effectiveness of the overall system, while maintaining an overall reduced cost for the system. Another important advantage of the proposed design is the absence of security constraints for this data type, which is an important concern when dealing with some military-owned radar systems.

In order to compete with radar systems, LCLEOSEN consists of an array of telescopes providing near full sky coverage. Each telescope consists of a wide field of view lens, a CMOS sensor, and an image processing unit. The image processing unit will be capable of processing images in real time, to prevent backlog of images. The telescopes are arranged in a grid pattern, with a slight overlap in FoV to prevent coverage gaps, see Figure 1.

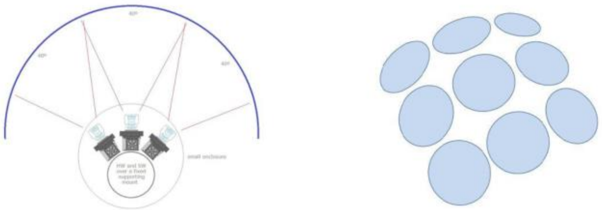

Figure 1. Example schematic layout of LCLEOSEN system

Each telescope has a low-cost Commercial Off-The-Shelf (COTS) lens of fixed focal length. The sensor has been selected with the aim of minimising the unused area, such that the sensor is at least a little bigger than the image projected by the lens onto the sensor. Another important design driver is sensor resolution, which has to be able to capture the motion of detected objects. The last main element is the image processing unit. It is important that processing is done in near real time to avoid data storage issues, meaning at least one processing unit for each telescope will be required in order to achieve parallel processing capability.

Since the final system will image the whole sky, it can be pointed in a fixed direction. The telescope will be on a fixed mount without sidereal compensation. Sidereal compensation is not required as the system has exposure times of less than a second, so the apparent motion of background stars is negligible. The system has a clam-shell type dome to protect it from the external environment. This cover is an automated system, which is able to be operated remotely if manual input is required for testing and maintenance.

The system also has two main software components: hardware control software and image processing and track detection software.

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The core of the software development of this project was focused on the image processing and track detection. The purpose was to develop an automated and optimized software solution which is able to detect and measure the different necessary object parameters (at least equatorial angular coordinates, magnitude and measurement times) from the captured images in near real time, while rejecting spurious artifacts.

The system is able to capture images in which it is possible to tell LEO objects apart from the star background or even hot pixels and noise. The extraction of candidates (movers) after single detections (loners) is different dependent on if they appear on images as trails or points. The reason for having two modes of extraction is due to the difference in apparent angular speed with the elevation angle and the difference of possible altitudes in the range of LEO region, which is the region of space up to 2000km altitude. The highest angular speed is observed when the object is closest to the zenith and decreases as the elevation decreases, so objects at higher elevations are captured as longer trails. The difference in altitude also has an influence on the orbital velocity, which means that a longer trail is captured in images for objects with higher orbital velocities (those in lower altitudes), for a given fixed exposure time. Objects that move slower leave a shorter trail, leading to point detections in the most extreme cases. It is important that trails are not too long (12 pixels max), to avoid a decrease in SNR, overlapping with the star background and for the sake of the image cleanliness. Moreover, objects with faster velocities escape the FoV so the number of captures of those is lower.

In the case of point detection, it is necessary to get a minimum of three loners aligned to be able to state that an object has been detected while in the case of trails, it is only necessary to detect a minimum of two of them which are aligned. With the number of detections used increased by one in both cases, we can ensure with more accuracy that there are not false detections (false positives). However, while the accuracy of the detection and measurement is improved when the number is higher, we could be missing real detections (false negatives) because more stringent conditions are applied to confirm that the detection is a real object. The core of the development consists of a system which compares data extracted from the different correlative images and detects objects efficiently.

The main software output is a list with the astrometric details of all detected objects which includes:

- The measurement time with microsecond accuracy
- The equatorial angular coordinates of right ascension (RA) and declination (Dec) of the object's centroid
- The estimated magnitude of the object

This data can be used to generate orbital parameter estimates for inclusion in, or comparison with, existing catalogues.

2 USE CASES

This section considers the use cases for the application of an ultra-wide field of view telescope system, to track objects and space debris in Low Earth Orbit (LEO). The key advantage of the system is the tracking of objects without prior knowledge of their arrival over the horizon. The analysis is based on the working assumption that a 40cm spherical object at 650km altitude can be observed. This can be interpreted as slightly larger than a 3U CubeSat.

Figure 2 illustrates the potential use cases graphically. These use cases were derived by considering the potential users, their needs and the system features.

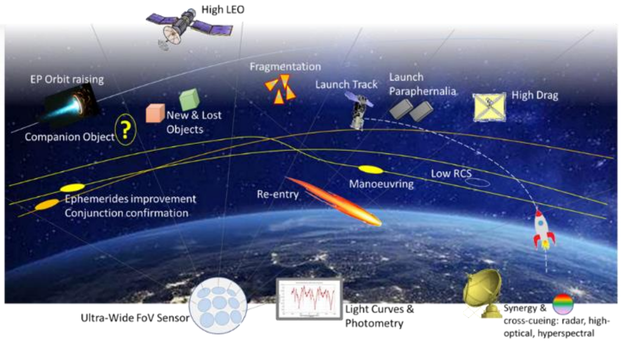

Figure 2. Summary of LCLEOSEN Use Cases

The main use cases can be summarised as:

- Gathering higher accuracy ephemeris, especially on multiple targets simultaneously
- Discovering new objects, including those created by fragmentation events
- Cross-cuing of narrow FoV and other sensors (e.g., hyper spectral) for improved knowledge
- Custody of non-Keplerian objects (high drag or long-low thrust e.g., electric propulsion orbit raising)
- Re-entering objects being a special case that the ultra-wide FoV sensor manages effectively
- Companion and ejected object detection
- Low Radar Cross Section (RCS) targets
- Photometric assessment

While a wide range of possible users could make use of data from an optical sensor, the following are considered illustrative of potential use cases:

- **Governmental Organisations** – responsible for state owned assets, requiring capability to assess risks to those assets.
- **Space Agencies** – typically responsible for the licencing of spacecraft, which has recently seen a huge increase in small spacecraft in LEO.

- **LEO operators & users** – All spacecraft operators have a strong interest in the resident space object population that could potentially interact with their asset. Their customers (who use the data) will also have a vested interest in the quality and resilience of those data feeds.
- **Insurance sector** – Welcome additional information that provides materially useful information on risk. This tends to be longer term risk factors.
- **Satellite manufacturers (1)** - In order to design a satellite with an adequate propulsion capability to respond to conjunction warnings, manufacturers require data on the debris population in order to assess the number of likely avoidance manoeuvres that the satellite would be required to perform over its lifetime.
- **Satellite manufacturers (2)** - An improved understanding of the changing optical properties of satellites over the course of their lifetimes (as a result of exposure to the space environment, see figures below) would assist with the design of thermal control measures, (blanketing, etc).

3 SITE SELECTION

The site selection process is based on the sequential application of filtering criteria that considers the technical performance and practical issues of each site, through 3 tiers.

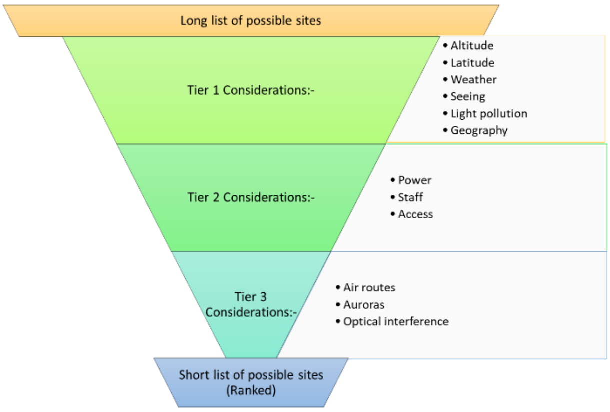

Figure 3. Sequential application of tier considerations to down-select sites

For an optical facility designed to perform surveillance of space, the key (“Tier 1”) technical considerations include:

- **Altitude**; principally a factor in ensuring cloud-free access to the sky, but also a contributor to the technical performance of the system
- **Latitude**; since this will determine the lighting conditions at the site and the duration of twilight conditions at different times of the year
- **Seeing conditions**; sites located on islands e.g. the Canaries and Hawaii, tend to benefit from a stable, uninterrupted air flow over the site
- **Weather conditions**; the amount of water vapour in the climate is a factor in terms of seeing – dry sites offer better performance
- **Light pollution**; sites away from conurbations will offer improved conditions
- **Geographic location relative to other facilities**; access to a pool of expertise in instrument management is expected to improve availability

Logistical (“Tier 2”) considerations include:

- **Access to power,** communications, and other utilities such as water; having good communications avoids the need to locate the system adjacent to data processing facilities or end user/customer sites
- **Staff availability**; very remote sites may be hard to maintain
- **Ease of site access** for hardware installation; the first step in the construction of many observatories (such as the European Extremely Large Telescope, is building a road up the selected mountain).

A desire to avoid major air routes, and other potential sources of airborne optical interference (such as auroras), are “Tier 3” considerations, since they can largely be addressed by additional processing.

In order to assess the various candidate locations, scores can be assigned to each, based on the different criteria listed. It is proposed to assign each site a score for each of the above criteria on a scale of 1-5, (with 5 being the best). These scores are assigned using as much technical data on weather, (cloud-free nights), altitude, etc. as possible. The scoring for altitude and latitude is based on ranges, which can be tailored to the user needs. Seeing conditions are scored using the Antoniadi scale. Weather conditions are scored using the site mean cloud cover. The Bortle scale is used to assess light pollution. The geographic location and logistics are scored using a range to closest facilities, these can also be tailored to used needs (for example, by implementing the range to closest company facility). Finally, optical inference is scored using a simple ‘extremely common’ to ‘extremely infrequent’ scale.

In each case the scores assigned to each of the sites will be weighted according to the Tier in which they reside. The weighting scheme proposed is to assign a weighting multiplier of 3 to the Tier 1 factors, 2 to the Tier 2 factors, and 1 to the Tier 3 factors.

Having multiplied the scores for each site by the appropriate weighting factors, a total score for each of the sites will be achieved and can be used to reduce a Long List of candidate sites to a Short List.

4 SYSTEM REQUIREMENTS

The system requirements were defined based on the user needs and available technology. These requirements were derived for the full system and as such they cannot all be applied to the prototype system.

Some of the key system requirements are:

- Low-cost
- Full sky coverage (at least 150° Field of View)
- High enough resolution to capture LEO objects
- Short enough exposure time to capture LEO objects in Field of View
- Near real-time image processing
- Software should auto-filter images for movers
- Creates catalogue of movers detected
- Remote operations
- Autonomous operations, with minimal human intervention required
- Reliable and Robust

Each of these requirements has been mapped to a test in the verification and validation plan to ensure all are met by the system.

5 PROTOTYPE IMPLEMENTATION

The prototype consists of 3 components; the hardware, the control software and the image processing software.

The prototype design includes a single telescope of the same design specification as one of the arrayed telescopes from the final design. Two lenses, 85 mm and 105 mm, were tested in the prototype to assess performance, in order to make a decision about which is the best option for the final design. The 85 mm lens provides a wider FoV than the 105 mm lens for a given a fixed f-number. However, angular resolution is better with the 105 mm lens, given a f-number, pixel size and sensor size, allowing detection of smaller and fainter objects. The system design of the prototype is simpler than the final design:

- The processor units (for image processing and hardware control) are two independent PCs for the prototype while in the final design will all be included in a single server.
- The mount is simpler than in the final design, since it is not necessary to accommodate the multiple telescopes of the array.
- Due to the restrictions in budget and build time for the prototype, the prototype was co-located with Deimos Sky Survey, in order to take advantage of existing facilities there. The telescope was placed in an existing clam-shell type dome, to negate the need to build a new dome. Figure 4 shows the Deimos Sky Survey domes, and Figure 5 shows the prototype located inside the dome with the 85mm lens fitted.

Figure 4. Deimos Sky Survey clamshell domes

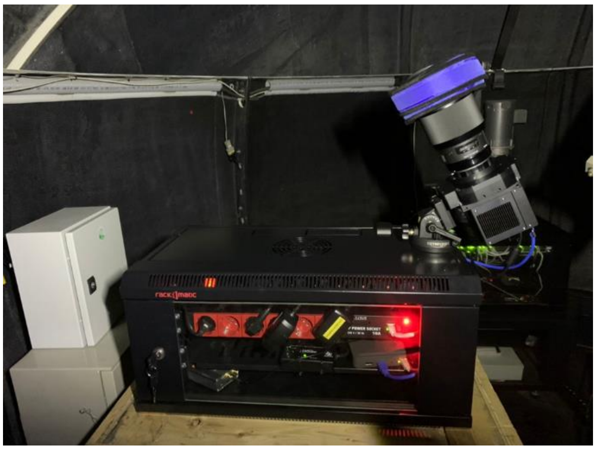

Figure 5. LCLEOSEN Prototype Sensor located in DeSS dome

The final FoV of the 85 mm lens is 25.4°, while for the 105 mm lens it is 20.8°. The system has been set to point to 0° azimuth and 61.5° elevation. The black box in Figure 5 contains all the required subsystems: the chrono-stamper (including the GPS antenna), the controller and necessary components to exchange information between the system and the processing and control computer.

The processing computer is located at Deimos UK, and can be accessed remotely, it has an 8-core Intel i9 processor with 3.6 GHz clock speed and 1 TB of SSD storage. The control computer was initially located in DeSS Control Room at Puertollano and remotely operated but after having issues with a delay in the time between images it was relocated to allow hard-wired connection, this relocation happened part way through the test campaign.

The prototype hardware was implemented in the dome in early January, however, due to poor weather conditions the first images were not taken until late January. Figure 6 shows the first image taken by the prototype fitted with the 85mm lens on January 24th 2021.

Figure 6. First image taken with the LCLEOSEN prototype, fitted with the 85mm lens, on 24 Jan 2021

There are no commercial software solutions available for control of the sensors and processing of the images, nor standard SST observing strategies either, since they depend on many specific factors, such as the need to integrate and operate different parts of selected hardware and have them work together under particular observing strategies. Therefore, existing Deimos software has been adapted to the specific control needs of this sensor.

The Control SW provides the information to the image processing SW, regarding the mode of how the images were obtained and how they might be further reduced in order to extract and measure the moving objects contained. This information is transmitted through the FITS image key headers; therefore, the FITS image metadata works as an interface between hardware control software and image processing software.

The software in charge of processing the data coming from the sensors is divided into two parts:

- Image processing
- Track detection

The function of the first part is identifying what elements appear in the images while the aim of the latter is combining the information coming from several images in order to identify an object track.

When raw FITS images are obtained by the sensor, they are calibrated. Calibration consists of performing corrections of bad pixels, irregularities of the instrument, biases, image noise and other effects that can appear on the image. This calibration process is performed before the images are entered as inputs to the image processing software.

The image processing starts by writing necessary keywords and values to the FITS image header. Once this step is carried out, the software will follow this sequence using external libraries: SExtractor-SCAMP-SExtractor. These two software libraries are obtained from the Astromatic website (www.astromatic.net/software) have been integrated in the developed solution.

The first SExtractor use is intended to generate a catalogue of sources from the input FITS file in image cartesian coordinates. This is used as an input to SCAMP along with an approximate World Coordinate System (WCS) solution of the FITS image which is contained in the previously written header. SCAMP turns these inputs into the accurate WCS solution of the image. Finally, this WCS solution is written to the FITS header and SExtractor is used again. The new SExtractor input is then the solved FITS image, which provides high-accuracy angular coordinates to the output catalogue as well as the information obtained in the first step.

This process is repeated for all the images in the set, and the sources extracted from those images are sent as an input to the track detection module. The software works with sets of 4 images. Before starting the detection process, the coherence of the images is checked to be sure the images show similar number of stars and background, indicating if they had similar observing conditions. The next step consists of extracting the loners for every image in the set. This is achieved by comparing one image of the set with the rest separately, then comparing those resulting lists to filter objects which may be repeated in other two images of the set.

The elements in the loners lists of each image in the set are combined in order to find any movers contained in the set. With the aim of improving the performance, some filters have been applied to those loners to discard those element combinations that cannot be a real mover. Finally, once the list of mover candidates is ready the software performs a linear regression for each of them and accepts them if the R-value is above a threshold defined by the user.

The output of the software is a folder per each set of images, which contains files with solved FITS images, sources lists and loners lists per each image, and a list containing the detected objects (movers). The folders are arranged by the observation dates.

6 CAMPAIGN RESULTS

A total of 9 full nights of observations were taken during the LCLEOSEN test campaign. Of these 5 nights were taken with 85mm lens, and 4 nights were with the 105mm lens. The dates are detailed in Table 1. It should be noted that there was a slight change in the setup affected on 17 February. Prior to the 17th the images were transmitted via internet connection for storage offsite, causing a delay between images, while the images were uploaded. On the 17th a hard-wired connection was implemented to increase the speed of transfer, decreasing the time between images and hence increasing the total number of images taken per night. Since this change was made after the lens was changed it was decided to replace the 85mm lens and complete one additional night with it, in order to compare the difference in the results since the difference in the timestep affects the performance of the detection software.

Table 1. Test Campaign Summary

Date	Time	Lens Used	Number of Images Obtained
12-13 February 2021	18.30-06.00	85mm	6808
13-14 February 2021	18.30-06.00	85mm	7464
14-15 February 2021	18.30-06.00	85mm	6904
15-16 February 2021	18.30-06.00	85mm	7144
16-17 February 2021	18.45-06.15	105mm	7384
17-18 February 2021	18.45-06.15	105mm	13544
18-19 February 2021	18.45-06.15	105mm	13620
22-23 February 2021	18.45-06.15	105mm	13112
23-24 February 2021	18.45-06.15	85mm	14052

Not all images taken by the prototype have been processed, a representative sample for each lens was selected to perform more detailed analysis for comparison of the performance of prototype equipped with each lens. The features of each of these samples is given in Table 2.

Table 2. Test Campaign Data Sample Selections

Data Set	1	2	3	4
Date	14 Feb	23 Feb	17 Feb	18 Feb
Lens	85mm	85mm	105mm	105mm
Observation Start Time	6.30pm	7.00pm	6.45pm	6.45pm
Observation End Time	9.30pm	8.30pm	8.30pm	8.30pm
Total Time	3 hours	1.75 hours	1.75 hours	1.75 hours
Number of Images Selected	1904	1904	1956	1904
Image FoV	25.4°	25.4°	20.8°	20.8°
Pixel Scale	44.8 arcsec/pixel	44.8 arcsec/pixel	36.6 arcsec/pixel	36.6 arcsec/pixel
Exposure Time	0.1s	0.1s	0.2s	0.1s
Image Time Step	6-9s	3s	3s	3s

During the test campaign some changes were made to the method, with the goal of improving the overall performance of the system. The first change was the 2x binning of the images which decreases the number of pixels in the image and increases the pixel scale value, essentially grouping together sets of 4 pixels into 1. This angular resolution reduction has a positive impact on the system performance and has the advantage of increasing the SNR (Signal to Noise Ratio) because the light coming from moving objects is accumulated in a lower number of pixels. Another change, was a reduction in the image size, going from 32 MB to 8 MB which decreases the computational and save-to-disk times. The most important change was a reduction of the exposure time from the initial planned 0.5-1s to the current 0.1s. The aim of this change was again increasing the SNR to improve the detectability of moving objects. In addition, this reduction makes the system faster.

There was also an undesired difference with respect to the original plan, which was the increase in the time step between the capture of images caused by the image storage issue; originally images were stored offsite via internet connection introducing a delay between images. The main inconvenience caused by this is the increase in the length of the arc defined by the object trajectory. This posed two problems, which are; that the curvature of trajectory is not negligible anymore and that the fastest objects' motion is not completely captured in the image frame. Considering these problems, the software was modified accordingly to account for the new characteristics and now it works by trying to find the next point of the curved arc. In the end, the solution to the increased timestep was found by relocating the hardware to allow hardwired connection for image storage, so the new software feature was not absolutely necessary. However, it does help to find candidates more accurately and can be useful if the system suffers a temporary slowdown in the image capture pace.

During the test campaign it was found there is a relationship between the processing power and the time to solve images, this relationship is not linear, the more powerful processor tested produced significantly better results. Therefore, the final design should consider carefully the processing power required to benefit from this relationship. Furthermore, it was found that there is also a non-linear relationship between the number of loners per image and the solving time; see Figure 7. Thus, reducing the number of loners slightly can produce a significant impact on the detection solving time. The number of loners can be reduced by refining the filters used in the processing method.

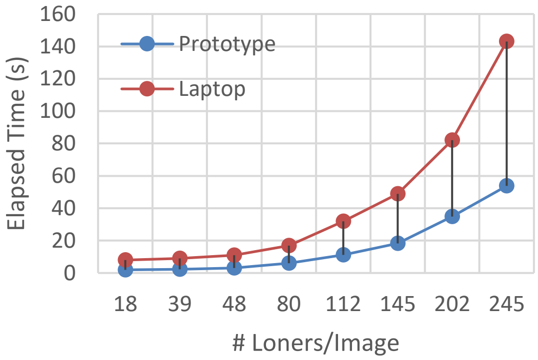

Figure 7. Detection Time vs. geometric average of number of loners in images 1 & 2 of a set

During the testing of the 4 data sets, the limiting magnitude for each setup was found to be 9 in the case of the 85mm lens and 10 in the case of the 105mm lens. Above these magnitudes no real objects were detected, and increasing numbers of false detections were found. It should be noted that these limiting magnitudes may not be the true limiting magnitudes for the final design, as these results were derived from a limited data set, taken with non-optimal conditions (particularly the delay between images as previously discussed).

Regarding false detections, another issue was discovered. As the taken images cover a very wide FoV, there is a non-negligible distortion in the edges of the images. When SExtractor provides the catalogue of the objects appearing in the images, it takes into account this distortion to a certain extent but there is still an error which can be considerable (up to approximately 400arcsec) at the edges of the image. As such the position error between the same object in different images can cause the misinterpretation of a star as a loner, consequently leading to a false detection. It is therefore recommended, for the final design, to have a small overlap in images, which could allow minimisation of these distortion effects.

It should be noted that there were some sets which were not processed. This is because the first images of the night were taken when there was too much ambient light (just after sunset) and the number of stars was too low so the software wasn't able to solve them.

The average time per set was dependent on the prototype setup (exposure time, timestep etc.) and the filters applied to reduce the loners list. More work could be done to ensure the software will always run in real-time. However, if necessary, the final design could include multiple processing cores per telescope to allow staggering of image processing across cores to maintain real-time processing. Note the average time to solve per set was higher for the 105mm lens than the 85mm lens, this was due to the higher number of objects captured, which has an impact in the length of generated loners' lists (the main factor for computational time). Reducing the exposure time, reduces the loners list (due to a reduction in noise) and hence reduces the computational time. This is demonstrated in the results for the 105mm lens where the two data sets have different exposure times, which results in significantly different processing times; see Table 3, results for data set 3 and 4.

There is one other aspect that can be changed to improve the performance. The optimal detection parameters can be found through an exhaustive study of large amounts of data. The software tries to predict the third and fourth loners for two given loners so it tries to search in a specific area. The size of this search area depends on the uncertainty to find the next loner which is even greater when having to predict a curved trajectory instead of a straight line. Through a thorough analysis of multiple detections, it would be possible to define these boundaries more accurately, so that it is not necessary to search in a larger, more conservative area to ensure there are not missed detections. This way the number of candidates assessed by the software could be reduced drastically. It is also notable that for smaller FoV images with the 105mm lens and shorter time steps, such search radius can be reduced further, with respect to the 85mm case previously analysed, because the curvature of the trajectory is not as large for each set of images.

Table 3. Campaign Results Summary

Data Set	1	2	3	4
Lens	85mm	85mm	105mm	105mm
Total Processing Time	2.42h	3.10h	6.77h	4.19h
Successful Sets	450 (94.54%)	474 (99.58%)	489 (100%)	448 (94.12%)
Unsuccessful Sets	26 (5.46%)	2 (0.42%)	0 (0%)	28 (5.88%)
Average Time Per Set	18s	24s	50s	32s
Total Number of Detections	87	298	247	271
Real Objects (True Positives)	82	-	214	-
False Detections (False Positives)	5	-	33	-

Given the results in Table 3, it is recommended that the 85mm lens is used in the final design. It provides good detectability, while keeping the system cost low. However, the software solution developed can be used for both systems, as such it is not unreasonable to suggest that it could be possible to offer both solutions, depending on needs in terms of limiting magnitude and cost. It is also possible that other, more powerful lenses, could be considered if a higher budget is available. Since the software solution can be tuned to suit the lens, it is possible that the final system could be tailored specifically to user needs. However, as a baseline, the 85mm lens is selected for the final design in the scope of this project.

7 VERIFICATION AND VALIDATION OF PROTOTYPE

The purpose of the Validation and Verification Plan (VVP) was to assure that the system meets requirements and specifications set out, and that it fulfilled its intended purpose and objectives.

The Verification and Validation (V&V) process consisted of a review and analysis of the campaign results. The main objectives of the V&V activities were:

- To verify the performance of the prototype telescope and the related image processing software.
- To verify and validate the software before it will be used in an operational environment.
- To guarantee the product satisfies the conditions and needs of the customer, detailed in the proposal, during the test campaign.

In the V&V process outlined in the VVP four methods exist (inspection, review, test and analysis), which are somewhat hierarchical as each one verifies requirements of a product with increasing accuracy.

Inspections are carried by visually inspecting hardware. In case of software inspection, tests are executed to visually check that the product displays what is requested.

During a Review test the entire product is manipulated to verify that the results are as planned or expected.

For a Test, a predefined series of inputs or data are used to ensure that the product will produce a very specific expected output as identified by the requirements.

The Analysis approach allows the tester to understand the typical performance of the product based on the test results of a set of cases.

Software tests and analysis were run remotely, and all physical inspection and review tests were done onsite at the premises in Puertollano.

All tests that could be run for the prototype in each category passed. In a few cases tests could not be conducted because they only apply to the final system. For example, it is not possible to test correlation between multiple telescopes, as the prototype has only one telescope.

There were, however, several tests which were executed even though they were designed for the final system. In these cases, the obtained results for the prototype can be extrapolated and applied to the final system. For example, by testing the prototype telescope Field of View, it is possible to confirm the final system design total FoV.

Further analysis testing could be done in conjunction with and expanded observations campaign to expand the scope of the VVP and provide more detailed analysis on the performance of the system.

8 FINAL DESIGN

Following the conclusion of the test campaign, the final design has been defined. Given the analysis of the results of the test campaign it has been decided that the 85mm lens will be selected for the final design.

In order to get the best performance from the system in terms of sky coverage a 28-eye configuration has been selected, as seen in Figure 8.

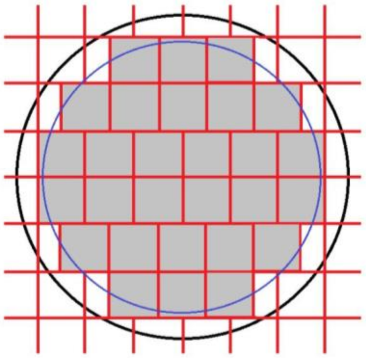

Figure 8. 28-Eye Sky Coverage Map. Note: the black circle denotes the horizon, and the blue denotes the approximate 150° FoV. Further the 85mm lens is here assumed to have a 25° FoV to produce slight overlap of images to allow minimisation distortion effects and prevent coverage gaps.

9 CONCLUSIONS

The LCLEOSEN system has been defined and the prototype has been implemented and tested. Based on the results of the test campaign the 85mm lens, 28-eye configuration was selected and the final system cost defined. The 85mm lens provides a good balance between system cost and functionality. As a possible extension of this project, a prototype of the full system could be implemented, to test and verify the final requirements that apply only to the full design.

While we recommend the 85mm lens, 28-eye configuration based on the results of the limited testing campaign completed within the scope of this project, there are some further developments that could be made to improve the final design, for example the software solution could be expanded to include automatic correlation. If this improvement was made, it would be interesting to test the two lenses again, to verify that the performance is as expected.

Other possible improvements include:

- More expansive testing could be done to refine the optimal search area, decreasing the uncertainty when finding subsequent loners. By optimising the search area, the length of the loners list could be minimised, hence increasing system processing time, while ensure no real objects are missed.
- More expansive testing could be used to test for missed objects. This could be implemented in combination with the automatic correlation.
- More extensive testing could be used to find the true limiting magnitude, and true size of objects seen across the LEO regime. We could do this by comparing automatically correlated objects to those expected to be seen.

Given the results of the test campaign, it is recommended that the 85mm lens is used in the final design within the scope of this project. However, the software solution developed can be tailored for use with either lens tested, as such it is not unreasonable to suggest that it could be possible to offer both solutions, depending on user needs in terms of limiting magnitude and cost. It is also possible that other, more powerful lenses. In fact, it is possible that the final system could be tailored specifically to user needs.

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