LCLEOSEN-B: Design and Development of a Low-Cost Low Earth Orbit Optical Surveillance Sensor System, a Phase B study

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ABSTRACT

LCLEOSEN-B aims to develop and demonstrate an innovative optical space surveillance system with the capability of achieving full-sky coverage and near-real time image processing. A full-sky coverage system has the key advantage of allowing users to observe objects without prior knowledge of their orbits. Use cases include the tracking of a) new and lost objects, b) fragmentation events and c) objects with non-Keplerian motion. This project builds upon Phase A of a UKSA project called Low-Cost LEO Optical Surveillance Sensor (LCLEOSEN) and continues the development as a Phase B study. During this Phase B study the existing processes are being refactored to be more efficient and incorporate more advanced functionality. The Phase B prototype consists of two telescopes deployed at the Deimos Sky Survey observatory in Puertollano, Spain. The optical telescope system has been built using carefully selected commercial off-the-shelf (COTS) equipment in order to keep the cost low, while retaining an effectiveness to capture fast moving low-earth orbiting (LEO) satellites. Significant advances in image processing will demonstrate cross-correlation of object tracks across multiple fields of view, which requires the coordination of observations from multiple telescopes. The correlation of an identified tracklet to an existing catalogue of objects is also fully automated.

1. INTRODUCTION

In recent years, the increasing commercial use of space has led to a significant rise in the number of objects present in Low Earth Orbit (LEO). Traditionally, ground-based optical sensors have mainly been used for the observation of Medium Earth Orbit (MEO) or Geostationary Orbit (GEO) objects that move sufficiently slowly in the sky, while radar sensors are more commonly used in LEO surveillance and tracking. However, the observation of LEO using optical systems has significant advantages. Optical observations of LEO offer a more cost-effective alternative to radar systems and are particularly effective at detecting objects that are not radar reflective. By lowering the expenses associated with each sensor and enhancing their capabilities, it becomes feasible to establish a network of interconnected sensors for efficient data collection and surveillance of space.

As the altitude of LEO satellites is low (less than 2000 km), their velocity is very high (typically 7-10 km/s), and they quickly escape from a single Field of View (FoV) unless that FoV is very wide. There are two general approaches to address this issue: track objects across the sky or image the full sky. The former involves complex challenges as the telescope requires frequent and rapid slewing maneuvers to keep up with the object, posing mechanical difficulties. Moreover, this approach limits the coverage of the sky that can be monitored simultaneously. Therefore, LCLEOSEN focuses on the latter solution of imaging the entire sky, adopting a comprehensive wide-FoV surveillance strategy.

The LCLEOSEN design consists of an array of high sensitivity telescopes, providing near full sky coverage. Each telescope consists of a wide field of view lens, a CMOS sensor, and an image processing unit, capable of processing images in near-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 Fig. 1.

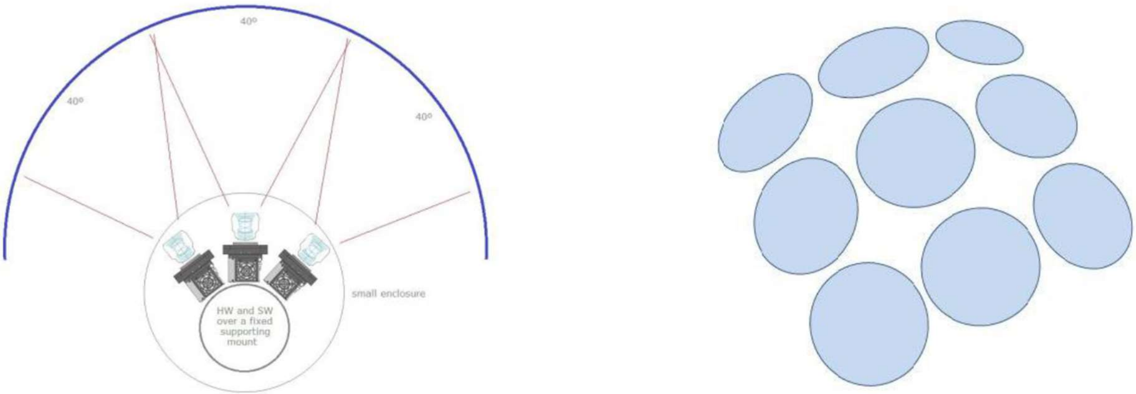


Fig. 1. Schematic layout of LCLEOSEN system.

The full system design is being developed through series of prototypes with increasing complexity. LCLEOSEN-B will build on work done in a Phase A for UKSA under the 'Advancing research into space surveillance and tracking' grant, which demonstrated the core functionality and capabilities of a single-element telescope based on Commercial Off-The-Shelf (COTS) hardware components [1][2]. The Phase A prototype also included the development of a bespoke image processing pipeline to perform image processing and tracklet generation of target objects. The major development in Phase B will be to develop a second prototype sensor to demonstrate the full system capabilities, including the cross-correlation of object tracks between adjacent FoVs and the correlation to existing catalogues to identify known objects and track potential false negatives (objects the sensor should see but doesn't), potential false positives (objects the sensor sees but shouldn't) or potential errors in, or additions to, the catalog. A demonstration of the prototype system and its capabilities will be conducted through an observation campaign, which is expected to have a duration of at least a few months, with the possibility of extending it based on weather conditions.

The Phase B prototype is intended to be a scaled-down version of the full system, consisting of a two-element telescope array integrated with a monitoring and control service, a data processing service and a local or remote storage. The prototype is intended to provide a simple and low-cost demonstration of the system's multiple FoV capability, so the presence of few components in the system model is an advantage, reducing its complexity. The prototypes effectiveness will contribute to a better understanding of the capabilities achievable with a multiple FoV architecture. As the full system will achieve near full-sky coverage, the resulting image quality will also depend on the sky conditions because its wide FoV will include areas that might affect the observations (like the Milky Way or the moonglow).

This paper builds on previous work done in the Phase A study [1][2] and will briefly summarize the conclusions of this study before presenting the full LCLEOSEN design and a description of both Phase A and Phase B prototypes. The results section comprises with initial testing aimed at evaluating the developed image processing algorithm in Phase A and comparing the solving time with the computational power made available to execute the pipeline.

2. USE CASES AND SITE SELECTION

The LCLEOSEN Phase A study included an exploration of use cases for the system and a site selection process.

The site selection process was based on the sequential application of filtering criteria that considered the technical performance and practical issues associated with different geographic locations. This process assigned scores to parameters such as altitude, latitude, seeing conditions, weather, light pollution, geographic location, logistics and potential optical interference for each site to perform a full trade-off of potential advantages and disadvantages.

The use cases for the system considered both the generic benefit of deploying additional optical tracking systems and the additional use cases facilitated by the ultra-wide FoV of the LCLEOSEN system, including the discovery previously unknown objects. The general case was focused on ephemeris enhancement and is based on the need to conduct regular updates to estimates when monitoring the position of objects. This includes improved accuracy of the positional estimates and faster detection of changes to an object's orbit when maintaining custody. However, the ultra-wide FoV also provides the capability to sense and track objects without prior knowledge of their positions. This is relevant for tracking of new and lost objects including companion and ejected objects, identification of fragmentation events, and maintaining custody of non-Keplerian objects. The ultra-wide FoV also facilitates the special case of tracking object re-entry and offers more opportunities for coincident observations and cross-cuing of other sensors for complimentary information.

This design aims to provide a significant LEO SDA capability in optical space surveillance, and improve access to relevant space domain awareness data for its user. For a full discussion of the use cases please see previous work, [1, 2].

3. FULL SYSTEM DESIGN

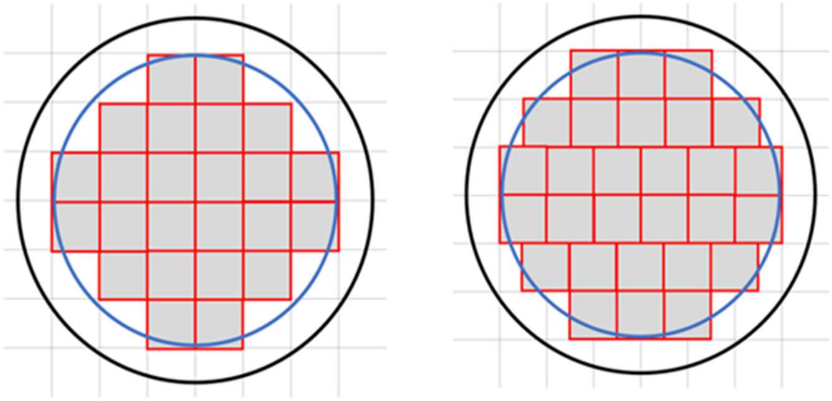
The full system design considered arrays of between 24 and 41 optical telescopes distributed with the intention of observing close to full sky coverage. It would capture an approximate FoV near to 150 x 150 degrees as seen in Fig. 2. The blue circle denotes the 150 x 150-degree coverage, whereas the black circle represents the furthest possible observation angle of around 180 x 180 degree. However, the observations from the 15 degree region above the horizon are the poorest as it is highly impacted by Earth's atmosphere and other external factors. Each of the telescopes is composed of the following elements: a wide FoV lens, a sensor, a control/image processing unit.

Two designs for the full configuration of the LCLEOSEN system are considered:

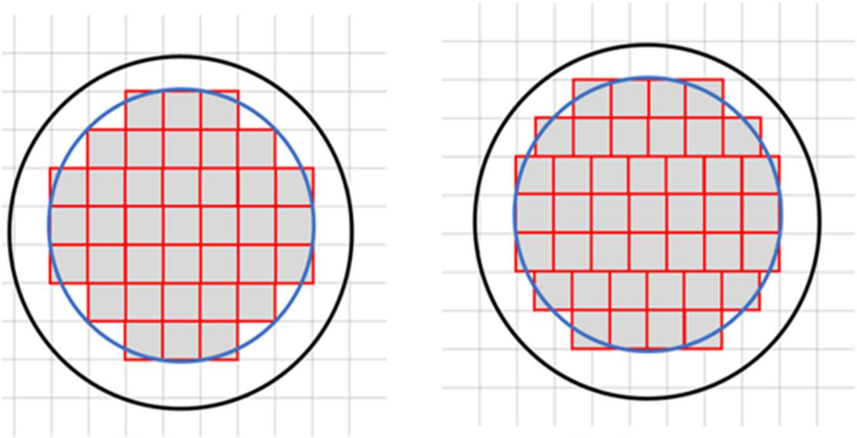
- a 24 or 28 telescope cluster utilizing 85 mm lenses to cover the furthest feasible extent of the sky.
- a 37 or 41 telescope cluster with 105 mm lens.

The 24-telescope array will cover approximately 15,000 square degrees, while the 28-telescope array will cover approximately 17,500 square degrees with more coverage close to the horizon and less blind spots. The estimated dimensions of the 24-telescope system are approximately 100 x 100 x 100 cm. The addition of four extra telescopes to form a 28-telescope array results in a significant increase in cost without providing substantial performance improvements compared to 24 as the extra coverage would be capturing close to the horizon, where the observational performance is the poorest. Hence, making the 24-telescope system the more cost-effective choice.

The 37 or 41 telescope cluster with 105 mm lens offers improved accuracy and enables the detection of fainter and/or smaller objects. However, it comes with the drawback of increased overall system cost. The 37-telescope array provides coverage of approximately 14,800 square degrees of the sky, while the 41-telescope array covers approximately 16,400 square degrees. Adding 4 telescopes to the design with 105 mm lenses results in a 10.8% increase in covered area, whereas the design employing 85 mm lenses achieves a 16.7% increase. The telescope arrangement for the 24, 28, 37 and 41 telescope options can be seen in Fig. 2.



24-telescopes 28-telescopes



37-telescopes 41-telescopes

Fig. 2. The four telescope arrangements considered to gain the most optimal full-sky coverage. Each red square represents a telescope/camera. Note: the black circle denotes the horizon, and the blue denotes the approximately 150° FoV.

The COTS approach enables each telescope to be equipped with an affordable lens with a fixed focal length. The selection of the sensor aims to minimize unused space, having minimal gaps between the edge and optimal FoV. The array of telescopes would be connected to the control server that would be able to control the sensors and all their functionalities remotely. The captures from the optical system would then be fed into an image processing unit. This is a crucial component in the overall approach, which needs to operate in near-real time to prevent delay in information and data storage problems. To achieve this near-real time objective, consideration will be given to the most effective software design and optimal hardware components to avoid any additional delays in information transfer, while still producing a cost-effective solution.

4. PHASE A PROTOTYPE

The prototype consisted of 3 components; the hardware, the control software and the image processing software. The prototype design included 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 fixed f-number, pixel size and sensor size, allowing detection of smaller and fainter objects.

The system design of the single-element prototype in Phase A employed a simpler architecture than the full system design detailed in Section 3. The processor units (one for the image processing and one for the hardware control) were two independent PCs for the prototype while in the full design the processing power will potentially all be included in a single server. The mount was simpler since it was not necessary to accommodate the multiple telescopes of the array. Due to the restrictions in budget and build time, the prototype was co-located with Deimos Sky Survey, 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. Fig. 3 shows Deimos Sky Survey domes, and the prototype located inside the dome with the 85mm lens fitted.

Fig. 3. Deimos Sky Survey dome (left) and the control system setup with 85mm lens (right).

Conclusions from the Phase A observing campaign [1][2] were used to guide the design of the Phase B prototype. Part of the Phase-A study was to determine the most optimal lens for the full system. In the comparison between 50mm, 85mm and 105mm lens, the focal length and f-number was fixed, hence the varying factors that the lenses were compared between was the aperture and the degrees of FoV. Based on these specifications, it was evaluated that the 50mm lens had too narrow FoV and low aperture, which would result in the need to add more telescopes and longer exposure time so that enough light is captured. Hence, the test campaign was conducted to evaluate the performance of the 85mm and 105mm lens. The conclusion of the campaign was that the optimal lens as a cost-effective solution was the 85mm with f-number of 1.4, the aperture of 6.07 cm and the FoV of 25 degrees.

Other key considerations included:

- 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 and makes the system faster.
- There is a non-linear relationship between the processing power and the time to solve images, so with more powerful processor significantly better results were produced by processing close to near-real time.
- There is also a non-linear relationship between the number of single detections (loners) per image and the solving time. Thus, reducing the number of false loners can produce a significant impact on the detection solving time. This can be done by refining the filters used in the pre-processing stage or reducing the exposure time to minimize the noise signal.
- The optimal parameters for the search area around the predicted trajectory can be found through analysis of large amounts of data. Phase A test campaign conducted their analysis on 1904 images for each night as the correlation of false positives/false negatives was done manually leading to a heavy manual labor burden. This, however, is only 15% of the total number of images captured each night. 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. As discussed in Section 6, processing will continue on the data acquired from the Phase A test campaign and this will inform optimization of the image processing pipeline during Phase B.

5. PHASE B PROTOTYPE

The Phase A prototype focused on demonstrating the functionality of an individual sensor, while Phase B will further demonstrate effective surveillance operations by correlating objects across adjacent FoVs. The successful demonstration of this capability in Phase B will lay the foundation for implementing the full system, enabling monitoring of the entire sky through overlapping FoVs. The Phase B prototype will not implement the full system design; however, it will incorporate 2 cameras (shown in Fig. 4) that would allow further advancements made towards the final system in both hardware and software aspects.

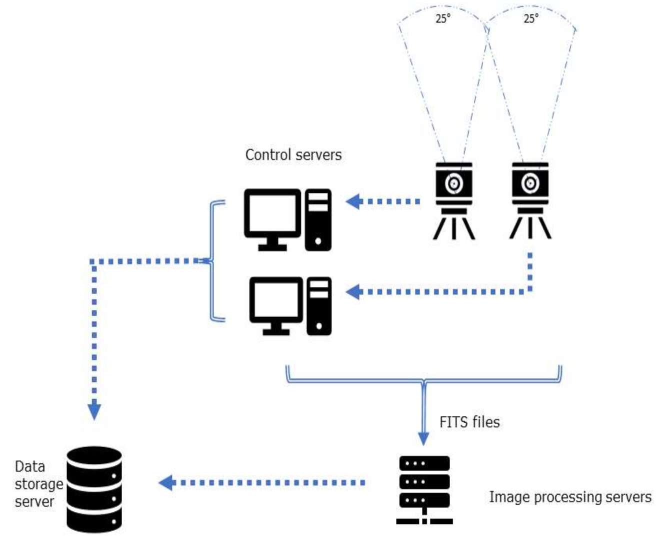


Fig. 4. Diagram of the Phase B prototype arrangement.

Alongside the deployment of the updated hardware prototype, the main technical objectives that will guide the software design and development for this prototype are:

- Improve the image processing performance to meet the near-real time objective,
- Implement parallel processing to enable processing of data from each sensor in parallel,
- Implement automatic correlation of the extracted catalogue with an external list of confirmed objects.

The overview of a simplified data flow during the image software execution can be seen in Fig. 5. Note that, the data flow considers single detections from a single FoV (loners), detections through sequential images of the same FoV (movers) and objects that have been correlated across two FoV (jumpers) to distinguish between the different types of detections resulting after each phase of processing.

The image processing software plays a crucial role in enhancing and analyzing the obtained images of the sky. It consists of several stages, each contributing to the overall improvement of image quality and the identification of objects within the images. The key components for the image processing software can be subdivided into five main stages:

- Image Calibration
- Image Processing
- Tracklet Generation
- Correlation of tracks across multiple FoV
- Object Correlation to existing catalogues

The first three stages of the software, as listed above, have been initially developed in previous work, but need refinement to improve performance. The first stage is image calibration, where various image artefacts are removed. This involves correcting lens distortion, vignetting, sensor noise, biases, and other imperfections that can affect the accuracy of the image. By applying precise corrections, the software ensures that the images are as clear and accurate as possible.

Following image calibration (used to remove image artefacts), the software moves on to image processing, which involves the identification of loners. Loners refer to individual points that appear in a single image capture. By detecting these loners, the software can distinguish them from the background noise or other image elements. This step is crucial for identifying potential observable objects or anomalies within the images. The two main software packages used in this stage are SExtractor [3] and SCAMP [4]. A detail description of the process and analysis can be found in Phase A papers [1, 2]. The next stage is tracklet generation, where the loners detected in sequential images are correlated to identify movers. Movers are objects that appear to move through multiple captures of the same FoV in an expected manner. By establishing correlations between the loners, the software can track the movement of these objects accurately. In addition to tracklet generation, the software also performs correlation across multiple FoVs. This stage builds further on the tracklet generation process but involves different criteria and techniques to capture the correlation. By extending the correlation across multiple FoVs, to identify jumpers, the software can provide a more comprehensive understanding of each object's movements and behavior. With the final step, the software employs object correlation, which involves comparing the identified movers and jumpers with existing catalogues. This step helps to identify known objects and track potential false negatives (objects the sensor should see but doesn't), potential false positives (objects the sensor sees but shouldn't) or potential errors in or additions to the catalog. By correlating the movers with catalogued data, the software can ensure accurate and reliable object tracking, minimizing errors and providing valuable insights from the images.

To reach near-real time processing with a multi-camera array system, parallel processing is an important consideration for achieving this goal. To implement this in the software, it is essential to consider having only Central Processing Unit (CPU) power or also adding Graphics Processing Unit (GPU) processors to the server system. The CPU is mostly known as the computer's brain as it is well suited to process a wide variety of workloads, especially those for which latency or per-core performance are important. GPUs have the advantage that they are made up of many smaller and more specialized cores than a CPU. These cores can deliver high performance when a processing task can be subdivided into smaller tasks and performed across many cores. Therefore, as the data software receives images as input, adding a GPU processor to the system would speed up processing and increase the capability to handle large amounts of incoming data.

6. RESULTS

Phase B prototype development has begun with initial tests to evaluate the existing image processing software and the efficiency of the image processing algorithms. These tests have been conducted to determine the appropriate processing power required to achieve the system's near real time objective. During testing, the pipeline was evaluated on a subset of the data collected in Phase A [1, 2]. One hundred image sets were chosen from a single observation night for this purpose, with each set consisting of four captures taken of the same field of view. The total number of processed images in each run was 400 FITS files, which represent around 0.3 hours of observations. The same sample subset was used in all test runs to maintain a consistent test set for comparing the computational timing of the algorithm. Regarding hardware, the processing server purchased during Phase A was also utilized in Phase B. This server features an 8-core Intel i9 processor with a clock speed of 3.6 GHz and 1 TB of SSD storage. It was employed for developing and analyzing proof-of-concept for the image processing pipeline of a single camera system. The developed algorithm is implemented on a virtual machine (VM) with a Linux operating system, hosted on the aforementioned server. The VM configuration allows adjustments to the number of CPUs, enabling evaluation of the relationship between processing power and overall computation timing.

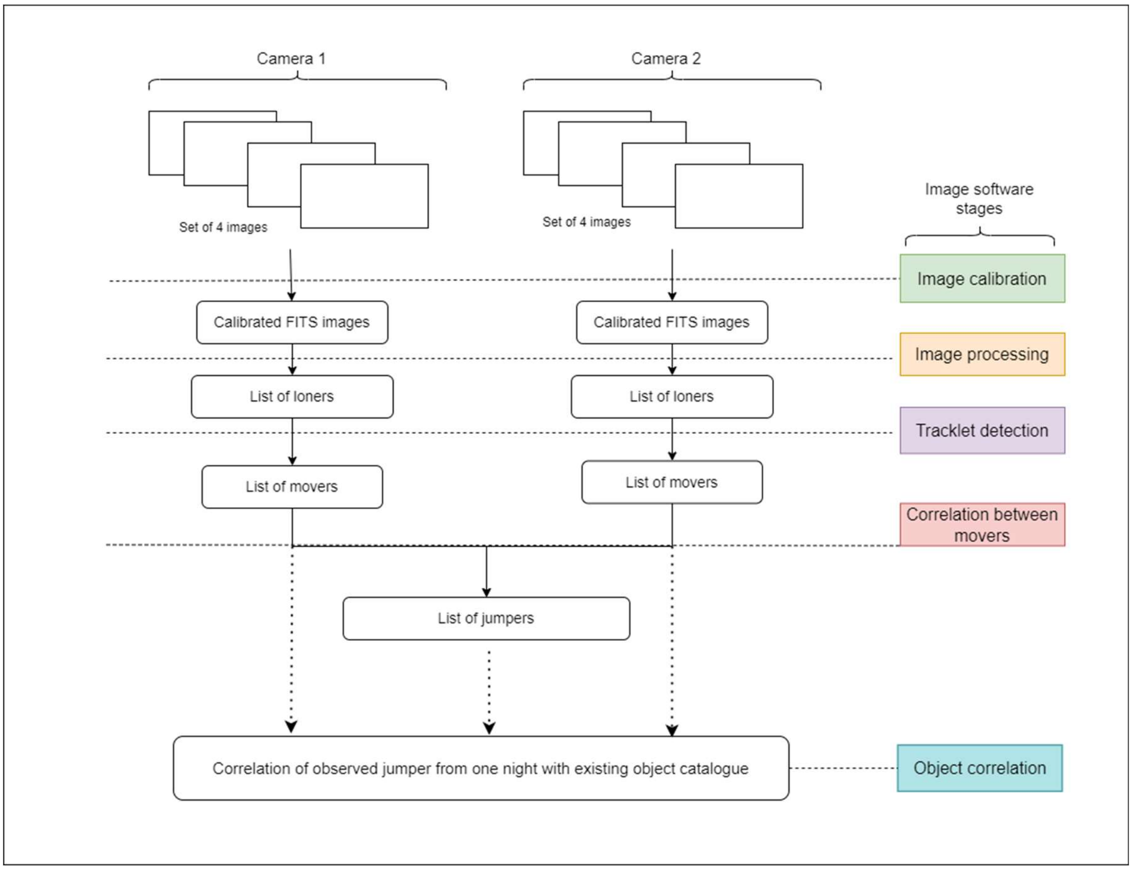


Fig. 5. Data flow through the image processing software.

As illustrated in Fig. 6, configuring the VM to run on multiple CPUs has a significant impact on image solving time. For each data point, a single processing pipeline was initialized to solve 100 sets. The longest processing time for these sets occurred when utilizing only a single CPU. However, incorporating a second CPU for image processing resulted in a 0.8-hour improvement in solving time, which made the significant impact on this aspect. However, as more processing power was allocated, successive improvements to the overall efficiency of the image processing pipeline were less significant.

Considering this in the context of the near-real-time processing objective, for a set of observation images totaling 0.3 hours from a single source, the completion time could range from a worst-case scenario of 1.84 hours to a best-case scenario of 0.54 hours, assuming each processing pipeline operates within its dedicated VM (no parallel processing). It would require between 76.6 and 22 hours to complete the processing for an entire night's worth of observational data (spanning a 12.5-hour time interval), considering a limiting factor of 6 processors. Therefore, an essential aspect of Phase B involves enhancing the algorithm and assessing the optimal solution in terms of the processing servers and hardware required to handle such a significant volume of data.

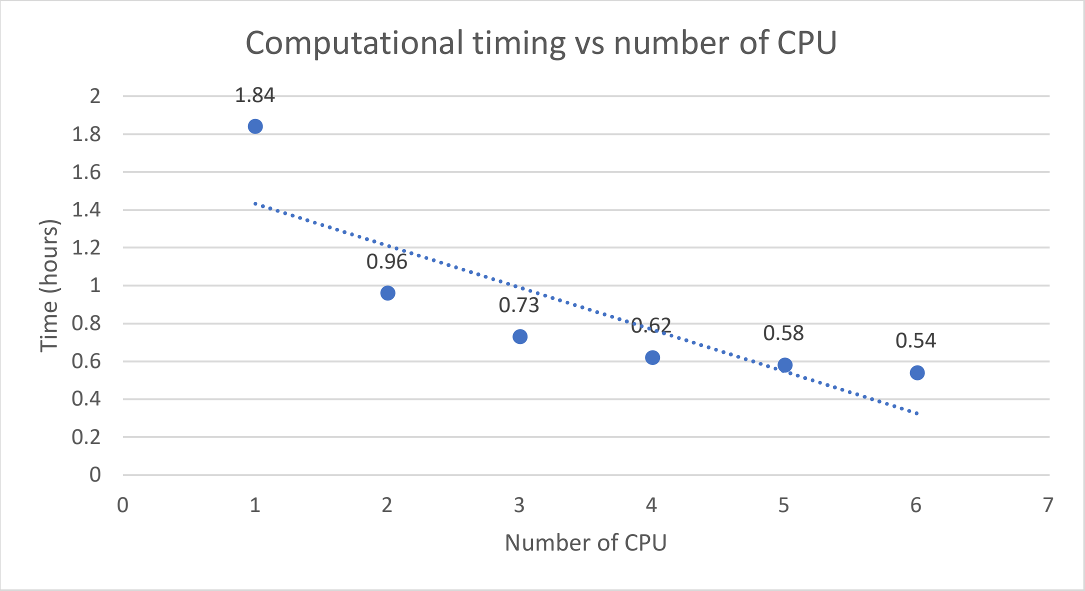


Fig. 6.Visualizing the trend between processing time and number of available CPU

The results running of multiple processing pipelines in parallel are presented in Table 1. These results were obtained by initializing two separate pipelines of the image processing software at the same time with a few seconds delay. Overall, the solving time becomes longer in comparison to the results shown in Fig. 6. When utilizing only 2 processors, the time increased from 0.96 hours to 1.425 hours, reflecting an approximately 50% increase. However, when employing multiple processors with the same number of parallel processes, the increase in solving time is less significant, as the servers are subjected to less intense computational load. Particularly, with the utilization of 6 processors, the solving time only increased by 18%. Therefore, while increasing the processing power beyond 2 CPUs only showed incremental increases in efficiency for a single process, the results were more pronounced when looking at multiple processes in parallel.

Table 1. Results from initializing the processing pipeline in parallel.

Number of CPU	2	4	6
Number of processes (running in parallel)	2	2	2
Number of sets (per process)	100	100	100
Average total time (hours for each process)	1.425	0.77	0.64
Average time of sets (s)	51	28	23

The results presented in this section are part of an initial testing phase for the Phase B project, which highlight the importance of considering multi-core architectures for efficient processing. Subsequent stages will extend to assessing the performance of GPU-based architectures and more work will be undertaken to enhance the image processing pipeline and, consequently, improve overall efficiency. Following this, processing will continue on the data acquired from the Phase A test campaign, with the objective to optimize the tracklet generation stage within the image processing pipeline. This aspect has already been extensively investigated and presented in [2]. However, due to time constraints, only 15% of the total dataset was subjected to manual checks and processing. This data will be supplemented with data from an extensive Phase B observing campaign, which will provide the opportunity to demonstrate object correlation across multiple fields of view. Phase B prototype development will also involve automation and integration of correlation process between the extracted catalog of the movers and jumpers from the observations and an external catalog of expected LEO objects. This integration aims to minimize the need for manual checks during subsequent stages of the system development, at which point it becomes crucial to understand the accuracy and limitations of the image processing pipeline.

7. CONCLUSION

The LCLEOSEN design consists of an array of high sensitivity telescopes arranged to achieve near full-sky coverage. The full system design is evolving through a sequence of prototypes, which have now progressed to a Phase B design. This design consists of a two-element telescope array that is intended to be a scaled-down version of the full system and provide a demonstration of the next stage of system capabilities.

At this stage of development, design the data processing software is driven by the need to process a high volume of images in near real time. To achieve this objective, the full system is required to implement parallel processing in the image processing pipeline including parallel processing for each sensor in the array. As a first step in the Phase B development, a simple evaluation of the image processing pipeline efficiency has been performed and the improvements offered by running parallel processes across multiple CPUs have been considered, which highlight the processing efficiency enhancements offered by multi-core architectures.

Further demonstration of the prototype system and its capabilities will be conducted through an extensive observation campaign, which aims to provide a simple and low-cost demonstration of the system's multiple FoV capability and contribute to a better understanding of the capabilities achievable with the design of the full LCLEOSEN system.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

[1] E. Kerr, B. Del Campo Lopez, N. Maric, J. Nomen Torres, G. Falco, N. Sanchez Ortiz, C. Dorn, S. Eves. *Design and Prototyping of a Low-Cost Leo Optical Surveillance Sensor.* 8th European Conference on Space Debris, 2021.

[2] B. Del Campo Lopez, E. Kerr, J. Nomen Torres, C. Dorn, S. Eves. *Development and Testing of a Novel Low-Cost LEO Optical Surveillance Sensor.* The Advanced Maui Optical and Space Surveillance Technologies (AMOS) Conference, 2021.

[3] E. Bertin, S. Arnouts. SExtractor: Software for source extraction. Astronomy and Astrophysics Supplement Series, 117(2):393–404, 1996.

[4] E. Bertin. Automatic Astrometric and Photometric Calibration with SCAMP. ASP Conference Series, Vol. 351, C. Gabriel, C. Arviset, D. Ponz, and E. Solano, eds., p. 112, 2006.