



AFRL-AFOSR-VA-TR-2022-0136

Obtaining and classification of nearby objects and atmospheric parameters
using an ommissa sensor arrays in subantartic skies

Roberto Solis
ACADEMIA POLITECNICA AERONAUTICA
GRAN AV. JOSE MIGUEL CARRERA, 11087 PARADERO 36 1/2
SANTIAGO, SANTIAGO,
CHL

04/24/2022
Final Technical Report

DISTRIBUTION A: Distribution approved for public release.

Air Force Research Laboratory
Air Force Office of Scientific Research
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

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1. REPORT DATE 20220424	2. REPORT TYPE Final	3. DATES COVERED	
		START DATE 20181201	END DATE 20210531
4. TITLE AND SUBTITLE Obtaining and classification of nearby objects and atmospheric parameters using an omnissa sensor arrays in subantartic skies			
5a. CONTRACT NUMBER	5b. GRANT NUMBER FA9550-19-1-0028	5c. PROGRAM ELEMENT NUMBER	
5d. PROJECT NUMBER	5e. TASK NUMBER	5f. WORK UNIT NUMBER	
6. AUTHOR(S) Roberto Solis			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) ACADEMIA POLITECNICA AERONAUTICA GRAN AV. JOSE MIGUEL CARRERA, 11087 PARADERO 36 1/2 SANTIAGO, SANTIAGO CHL			8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Office of Scientific Research 875 N. Randolph St. Room 3112 Arlington, VA 22203		10. SPONSOR/MONITOR'S ACRONYM(S) AFRL/AFOSR IOS	11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-AFOSR-VA-TR-2022-0136
12. DISTRIBUTION/AVAILABILITY STATEMENT A Distribution Unlimited: PB Public Release			
13. SUPPLEMENTARY NOTES			
14. ABSTRACT This project is complete and all deliverables sent. APA will be working with the FACH as well as USSPACECOM counterparts to develop new SSA research interests utilizing the all sky camera			
15. SUBJECT TERMS			
16. SECURITY CLASSIFICATION OF:		17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U	SAR 2
19a. NAME OF RESPONSIBLE PERSON DANIEL MONTES			19b. PHONE NUMBER (Include area code) 000-0000

Detection and Classification of Various Astronomical Events Near the Earth, Using an OmniSSA Sensor Arrays in Subantartic Skies.

Dr. Roberto Solís V. * (PI)

May 31, 2021

Final Performance Report

Grant Number: FA9550-19-1-0028.

Period of Performance: 1 Dec. 2020 – 31 May 2021.



* *Center of Investigation and Development of Aerospace Sciences, Chilean Air Force.*
roberto.solis@usach.cl; tcarrascod@gmail.com

Summary

Nowadays, the Space Situational Awareness (SSA), is particularly important due to astronomical phenomenon that could have serious consequences to the human, generating the need of knowledge applied in the area. This knowledge is uniquely hampered by a dearth of information available in the southern hemisphere. In recent years, various research projects based on the All Sky concept, which is based in optical system, and that shown to be a potential way in the detection and classification of astronomical events close to the earth, for instance, meteorites or space debris. The equipment is built using an optical sensors arrangements, followed with an image processing technique. The synthetic survey telescopes (All-Sky Cameras) are considered to be a collection of ultra-wide field-of-view images that simultaneously image the visible sky with overlapping fields of view, where the images are fused to synthetically improve both resolution and detection capability. Both super-resolution and image stacking techniques will be combined to allow collections of these sensors to synthetically improve their detection capabilities (signal-to-noise ratio - SNR), angular resolution, and brightness resolution using post-measurement computing processing resources.

An initiative that was developed in conjunction with the University of Georgia Tech and the University of Chile, during the years 2016 and 2017, with the name: All-Sky Image Fusion for a Synoptic Survey Telescope, allowed the Center of Research and Development in Aerospace Sciences (CIDCA) obtain experience in this area. This new proposal intends to continue this research line in Magallanes region. The Magallanes region is, at present, a strategic point in Science and technology in the south American continent, and is located nearby to Antarctic zone.

The main goal in this project will be investigate algorithms and sizing relationships that enable the use of synthetic survey telescopes with performance acceptable for NEO (near Earth objects) detection & tracking, transient astronomical event detection & characterization, and space domain awareness activities in the Magallanes region.

The basic purpose of learning and generating experience in the field of Situational Spatial Awareness was fulfilled by successfully implementing the OmniSSA system in the southernmost city of the southern hemisphere, and by achieving super-resolution techniques applied to the captures obtained from these skies. The foregoing allowed to establish the bases for future research that the Institution and the scientific community should carry out in this scientific area and in this geographical region.

1.-Introduccion

Due to particular location and climatic conditions, the Magallanes region has been a place that has generated scientific interest and at the same time, a new challenge in the continuity of the All-Sky research line for use this system in harsh condition, and contributing in the development of the Space Situational Awareness area with difficult access. At present, in the extreme south of the continent, the information of SSA is not available. CIDCA search to use the array of sensors developed by Georgia Tech to collect information from near-Earth objects in this region, evaluating algorithms and sizing relationships that enable the use of arrays cameras with performance acceptable for NEO detection & tracking, transient astronomical event detection & characterization, and space domain awareness activities. Initially the work will be based on the investigations of Coder [1,2] and Grøtte [3]; in particular, the latter provides the guidelines for the construction and operation of the Omnidirectional Space Situational Awareness (OmniSSA) camera array, which is expected to be used.

Parallel to the technological improvements that have been developed in All-Sky commercial sensors, scientists have worked on new techniques of super resolution, based on the use of multiple images of low resolution [4-7]. There are several techniques to increase the resolution of images and also reduce noise, such as reconstruction techniques [8] and frequency domain [9], respectively.

It is clear the interest that exists for the transitory events that occur in the sky [10], as well as the importance in detecting objects that are close to the earth, due to damage they can produce [11] and the quantity that exists of these objects [12]. Camera arrays allow obtaining relevant and necessary information regarding as was described above.

This would contribute not only to the international scientific community working in this area but also to national institutions such as the General Directorate of Civil Aeronautics (DGAC).

The principal question:

Is possible use arrangement of camera to continuous monitoring of sub-Antarctic skies?

2.-Methods, Assumptions and Procedures

The sensors will be triggered simultaneously for several consecutive frames, each with 30 second integration times. Here, only a single set of four simultaneously captured images are investigated using super resolution and frame stacking methods.

2.1 Calibration and inertial image registration

Due to the nature of wide field of view lenses, light passing through the lens onto the sensor is distorted, displacing the centroids of detections in the resulting image, ultimately producing erroneous vectors. The Brown distortion model [13], given in Equation (1), relates distorted coordinates $(\bullet)_d$ to undistorted coordinates $(\bullet)_u$, using five distortion parameters, K_1, K_2, K_3, P_1 , and P_2 , where K_1, K_2 , and K_3 quantify the radial distortion and P_1, P_2 quantify the tangential distortion.

$$\begin{bmatrix} x_d \\ y_d \end{bmatrix} = \begin{bmatrix} x_u \\ y_u \end{bmatrix} = \begin{bmatrix} x_u r^2 & x_u r^4 & x_u r^6 & 2x_u y_u & r^2 + 2x_u^2 \\ y_u r^2 & y_u r^4 & y_u r^6 & r^2 + 2y_u^2 & 2x_u y_u \end{bmatrix} \begin{bmatrix} K_1 \\ K_2 \\ K_3 \\ P_1 \\ P_2 \end{bmatrix} \quad (1)$$

$$r^2 = x_u^2 + y_u^2 \quad (2)$$

Since Equation (1) is not invertible in x_u and y_u , the Newton-Raphson method is used to infer the undistorted coordinates. Letting $f(x_u, y_u)$ be the right hand side of Equation (1), define a new function $g(x_u, y_u) = f(x_u, y_u)[x_d, y_d]^T$. The sequence given in Equation (3) quickly converges, yielding the best-fit undistorted coordinates, where J is the Jacobian matrix of g .

$$\begin{bmatrix} x_u \\ y_u \end{bmatrix}_n = \begin{bmatrix} x_u \\ y_u \end{bmatrix}_{n-1} - J^{-1}g \quad (3)$$

To calibrate the lenses and the cameras, a checkerboard pattern will be projected onto a large screen and various images were taken with the camera in different orientations to map the distortion field in the entire image. Since the size of the squares is known, the intrinsic and extrinsic properties along with the distortion coefficients of the lens will be determined using the Image Processing Toolbox in MATLAB.

Tools from Astrometry.net [14] are used on the undistorted frames to positively identify stars within the field of view using blind astrometric calibration routines. While blind astrometric calibration routines such as those found in Astrometry.net do not need undistorted images in general, the distortion in the Rokinon lenses used by OmniSSA is sufficient to cause problems in this process if unaided. After this process the individual images are registered against the inertial frame.

2.2 SNR improvement using image stacking techniques

One of the ways to improve the signal-to-noise ratio of a signal in an image is by using image stacking techniques. This method involves taking multiple exposures of the same field of

view and use additive stacking techniques for noise reduction. Typically, this is done by taking short exposures of a target using a single camera. Since OmniSSA’s main goal is to detect and track space objects, the platform uses four cameras to simultaneously image the moving objects. The position and orientation of four cameras and lenses differ. Hence, image registration techniques are required to first align the images together before stacking the images. After the images are aligned and the background is subtracted, a frequency domain approach by Vandewalle [15] is used to register the images. Once, the images are aligned, simple additive stacking is used to generate the stacked image.

Table 1 shows the scaling between mosaic and synthetic apertures. Theoretically, the SNR of the signal after image stacking is expected to increase by the square root of the number of images, ~ 1.73 , on average. SNR is computed using Equation 4, where $E(S_i)$ is the expected value of the signal and σ is the standard deviation of the noise.

$$SNR_i = \frac{E(S_i)}{\sigma} \quad (4)$$

Table 1: Comparison of Selected Synoptic Survey Systems

	Mosaic	Synthetic
Required Signal-to-Noise Ratio (m)	$SNR_{i,req}$	$SNR_{i,req} / \sqrt{n}$
Effective iFoV (rad)	$iFoV_i / n$	$iFoV_i / \sqrt{n}$
Effective shot noise (counts)	$\sigma_{r,i}$	$\sigma_{r,i} / \sqrt{n}$
Effective brightness resolution (bits)	d_i	$d_i + \log_2(2n)$

Several sources, such as errors in calibration, background subtraction and image registration, can cause the ratio of the SNR before and after stacking the images to differ from theoretical value. Advanced background subtraction techniques and image registration in the angle space will significantly improve the SNR increase after stacking.

2.3 *Resolution improvement using Super Resolution methods*

To increase the resolution of the image, Projection on Convex Sets (POCS) based Super-Resolution image reconstruction technique will be used [16]. The image is scaled by 2. Note that the raw and reconstructed image show the same region of interest. However, for the same region, the reconstructed image is twice as large in pixels as the raw image. Therefore, the instantaneous field of view (iFoV), which represents the field of view a single pixel can see.

2.4 *OmniSSA Sensor Arrays.*

Omnidirectional Space Situational Awareness (OmniSSA) sensor arrays have been designed, built, and tested by Georgia Tech over several years [3]. The 3rd iteration (Mk. 3) is discussed in detail, along with representative data, in Appendix A. For this research it is proposed to acquire a 4th-iteration (Mk. 4). This unit will consist of a) a triad of three wide-field, high performance CMOS monochrome imagers with overlapping fields of view mounted to Kowa lenses. b) a high-performance commercial SDR receiver and antennas for UHF, VHF, and L-Band passive omnidirectional reception, c) an on-board Ubuntu PC that synchronizes

electro-optical image capture and stores data and d) associated firewall, gigabit ethernet switch, power conditioning & distribution, and thermal management systems to maintain system integrity, functionality, and operational temperatures. Based on Georgia Tech's experience in the construction, deployment, and operation of OmniSSA Mk. 3, for this proposal is expected to acquire the OmniSSA Mk. 4 (Appendix B).

A component diagram on the OmniSSA Mk4 is shown in Figure 2.1.

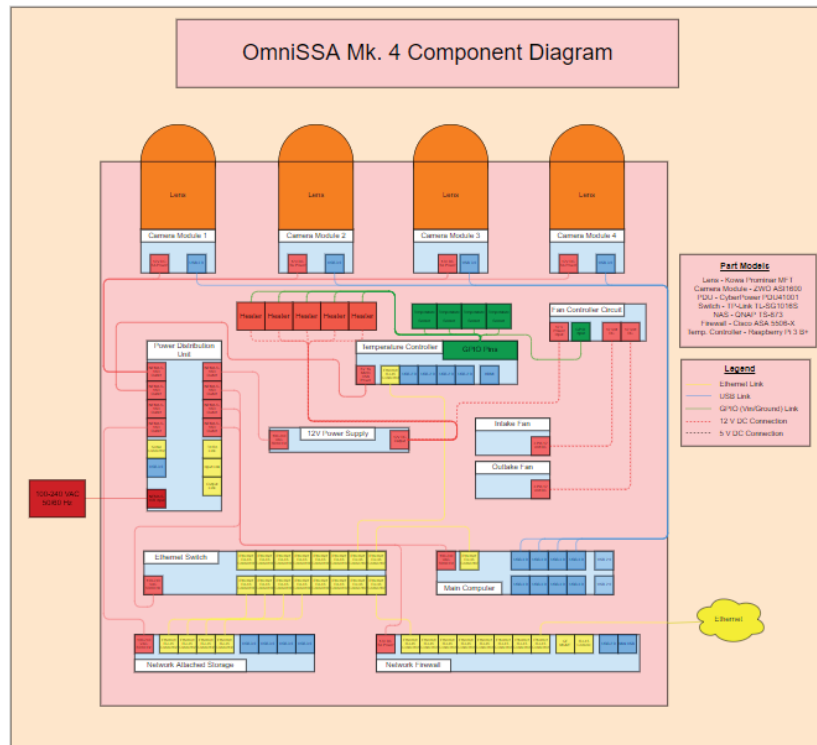


Figure 2.1: Component diagram of the OmniSSA Mk4.

The equipment used by Georgia-tech, will enable a plurality of ultra-wide field-of-view cameras to intelligently fuse collected observations and serve as effective synoptic survey systems over the entire night sky with very high global revisit times (several times each minute), obtaining important information regarding SSA in the southern hemisphere.

2.5 Hypothesis

The use of the OmniSSA system in a subantarctic region will confirm efficacy in supplementary synoptic survey efforts for transient astronomy, NEO searches, and SSA.

2.6 Main Objective

Evaluate the feasibility of detect and classify near-Earth objects in the city of Punta Arenas, using an OmniSSA sensor arrays, concept based on combined Bayesian Super-Resolution and synthetic image stacking image fusion of lower resolution all-sky images.

2.7 Specific Objectives

- Extend recent analytical results in super-resolution and image stacking to ultra-wide field-of-view sensor arrays in Magallanes region.
- Develop a tracking algorithm that can be validated with the trajectory of the Chilean satellite Fasat Charlie.

2.8 Tasks to be carried out according to the Objectives

It will be acquired Omnidirectional Space Situational Awareness (OmniSSA) system designed and used by Georgia Tech in the project: All-Sky Image Fusion for a Synoptic Survey Telescope.

The sensor arrays will be installed in Punta Arenas Chilean Air Force Base corresponding to the IV Air Brigade, place where a trans-Andean climate predominates, characterized by the regularity of the present rainfall, with an average of no more than 300 millimeters per year; due to the presence of the sea and glaciers in the area, temperature averages ranging from 5°C to -1°C are presented, but with maximums that can reach 20°C and minimums that can reach -13°C. The relative humidity varies between 60% and 89%; the wind can reach an annual average speed of 23 km/hr, with maximums of up to 120 km/hr and the atmospheric pressure varies between 995.8 hPa and 1010 hPa [17].

Depending on the atmospheric conditions of the Magallanes region, the optimum performance characteristics of the equipment will be evaluated, taking into consideration the internal temperature conditions, hermetic nature, possible energy independence, among others.

The functional requirements to obtain images of super resolution, the development of the design of algorithms of image processing, and the validation of these using computational tools of numerical analysis, will be worked by Students Officer of the Aeronautical Polytechnic Academy.

CIDCA will develop and introduce a computer system, which main purpose is allowing and controlling the obtained images and the storage of these, with a monitor, generating reports of the information by using various sensors. People will have access to this information through Internet, the main characteristics of the system are: daily access to the sequence of the obtained images, video summary of the photos sequence (Time Lapse), identification and classification of the detected elements and the possibility of modifying the configuration of the sensors remotely.

2.9 Modes of operation

The system must have two modes of operation:

a *Capture Mode*

In the period that includes an hour before sunset until an hour after dawn. The system will capture images, and save them in a Q-NAP mass storage system.

b *Analysis Mode*

The analysis of the images is composed of two main stages: initially, a series of processes are applied to improve the visibility of the objects and in the second stage different methods are evaluated to detect the spatial objects automatically.

In both stages a package of images with relevant information is created, which is sent via 4G Internet service to the CIDCA facilities in the Metropolitan Region. This procedure must be optimized due to the large size of the images.

In the initial stage, the four images that capture the array of OmniSSA cameras are simultaneously merged, generating a single image with less noise. Based on the above, it is necessary to align the four images using as reference the brightest stars that appear in the captured field of view.

The new image is limited to the range of vision that is common for the four individual images. This theoretically fused image would reduce the noise by a factor of \sqrt{n} , where n is the number of images used in the fusion. This procedure will be developed in Python programming language, using *Canny* borders along with a segment detector.

The operation of the cameras is automatic and the only line maintenance task required is the manual cleaning of the protective covers of the optical sensors, prior to entering the system into its capture mode.

CIDCA must have an operator who will download the data sent daily, review the status of the system and manage its maintenance.

2.10 Data Submission

Due to the amount of LEO events detectable in the Magallanes region, the weight of the images and the greater probability of sighting objects near the earth, it is estimated that the weight of the image packet with relevant information is 5 GB.

You must specify that the connection needs have different requirements depending on the time, however, you must have a network of lower permanent performance to maintain control and status of the system 24 hours a day.

Finally, there must be permanent communication between the CIDCA and the GOE (Space Operations Group) to coordinate the ephemeris of Fasat Charlie satellite the following night, in order to ensure that the system is working at the time of satellite traffic and by on the other hand, check the files the next day to verify the positive observation of the system.

The development of the Project will proceed according to a series of phases, which are detailed below:

2.11 Development Phases

Different tasks have been planned and performed according to four phases of development and implementation. In all phases, two researchers and a CIDCA technician have been involved.

Each of these phases is detailed below:

a. First phase

- Evaluate implementation areas.

- Manage acquisition of design and manufacturing documents.
- Establish operating protocols.
- Execute acquisition processes.

b. Second stage

- Assemble electronic systems in the laboratory.
- Generate preliminary tests of first iteration software.
- Design of structures and survival systems.
- Perform complete system assembly.
- Evaluate possible communication channels.

c. Third phase

- Design calibration processes.
- Design system tests.
- Implement tests in the central area of the country.
- Iterate design.

d. Fourth phase

- Implement system in Punta Arenas.
- Set calibrations and tests.
- Operate the system remotely.
- Image Analysis.
- Publish results.

3.-Project Development - Results

As a result, it is intended to obtain a database of high-resolution images of the southern night sky of the Magallanes region, which will be characterized by anomalies related to the capture of satellites that travel through their field of vision. Additionally, a record and analysis of astronomical phenomena that are captured by the optronic sensors will be carried out, in order to deliver more information to the research project, regarding the events that normally occur in the South Pole, gaining experience in the field of Space Situational Awareness (SSA) and having a solid basis for future research in the area.

With respect to the first phase of development, indicated in 2.11; Once the implementation zones were evaluated, it was determined that the astronomical phenomena monitoring and control system be installed in dependencies of the IV Air Brigade, specifically in Hill Mirador, the highest point of the city of Punta Arenas and without light pollution that affect the optical sensors and therefore the images obtained.

Figure 3.1 shows the location of Hill Mirador with respect to the City of Punta Arenas, the final location determined to install the sensors, this being the northwestern area adjacent to the generator set hangar, due to availability of electric power and low interference with other teams deployed on site and the amount of light pollution in radiance.

The final location of the system was determined according to the light pollution in Punta Arenas. This information coincides with that provided by the site www.lightpollutionmap.info. A portal normally used by astronomers and fans of night photography. This tool delivers the light pollution map, being able to easily establish dark locations where the sky is not affected by this pollution, which allows better observation of stars and photographs of the night sky.



(a)



(b)

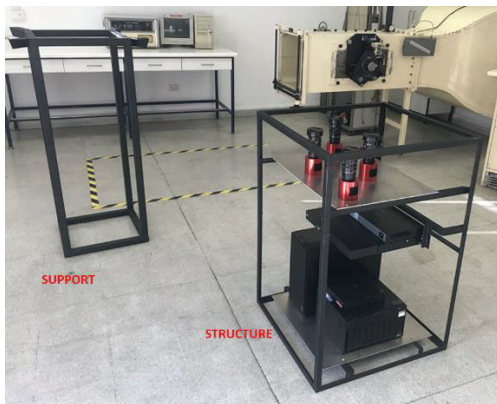


(c)

Figure 3.1: (a) Location of Hill Mirador with respect to the City of Punta Arenas and (b) Dependencies of the IV Air Brigade in Hill Mirador and location of sensors adjacent to the generator set hangar (red square), and (c) light pollution in the place of installation of the equipment.

The development of the All Sky system was carried out from the March until August; period that began with the acquisition of the elements that make up the system and ended with the complete integration of the system. The acquisition of the components that constitute the array of sensors took almost six months after the funds were delivered; ending this process at the beginning of August 2019, due to the natural delay in the import of essential components such as cameras, lenses and data storage equipment, from the United States and China.

In Figure 3.2, a series of images of the construction of the structure and connection of the different components that constitute the array of sensors is shown.



(a)



(b)



(c)



(d)



(e)



(f)



(g)



(h)

Figure 3.2: (a) General view of the structure of the sensor array and the support on which this structure will be installed, (b) General view of the cameras and their regulation system,

(c) General view of the array of sensors (cameras, PC, storage system, etc.), (d) Detailed view of the designed thermal support system, (e) and (f) Top view of camera arrangement and finally (g) and (h) assembly and painting team end.

The structure and support were built in steel; The tops of the structure and the thermal stabilization support system were built in 2024 aeronautical aluminum.

The aluminum used was treated with different components and paints (anticorrosive and first) to favor protection against the climatic conditions of the City of Punta Arenas. The entire system has been internally insulated with sealants and aeronautical waterproofing, in order to avoid the ingress of moisture to the electrical components and thereby the deterioration and malfunction of these. Externally, the equipment was painted orange (paint used in Antarctica and snow areas), so that it can be easily seen.

As for the third phase of development, the preliminary test and calibration process, it was developed until November 2019, a period in which different procedures for the calibration of the system and its subsequent functional verification were carried out.

The above implies verifying your ability to:

- Waterproof conditions of humidity and cold.
- Generate the correct image analysis processes.
- Apply superposition appropriately.
- Send data packets correctly.
- Establish the correct communication channel for remote operation.

In August 2019, an invitation letter was received from Dr. Marcus Holzinger to visit the Colorado Center for Astrodynamics Research (CCAR) at the University of Colorado Boulder. With the purpose of supporting the development of this research.

The visit took place between November 11 and 15, 2019, sharing the results and experience to adapt the sensor design for the subantarctic region. This allowed us to strengthen relations and answer a series of technical questions regarding the original design of the OmniSSA system.

A photograph of this visit at the CCAR premises is presented in Figure 3.3.



Figure 3.3: Visit to the Colorado Center for Astrodynamics Research (CCAR)

No-Cost Extension of the project was formally requested, for a period of six months (until May 31, 2020), due to the delay in the initiation of the Project, for the aforementioned reasons. This extension was authorized and confirmed by the respective GRANT on October 23, 2019. GRANT document FA9550-19-1-0028 P00001 is attached in Appendix C.

Regarding the fourth phase of development of the Project, in December 2019 the installation of the equipment is completed in Hill Mirador, the images are obtained and the remote link verification is carried out from the Chabunco Air Base in Punta Arenas and from the Polytechnic Academy Aeronautics in Santiago.

Images of the OmniSSA system installed and operating in its final position at Hill Mirador are presented in Figure 3.4.

In Figure 3.5, examples of captures achieved during the month of December 2019 are presented. The images obtained in Hill Mirador show a large number of stars and also present cloudiness. It should be noted that the climatic conditions present in the place throughout the year, complicate the obtaining of quality images, in terms of monitoring and detecting in a good way objects that transit in the sky.



(a)

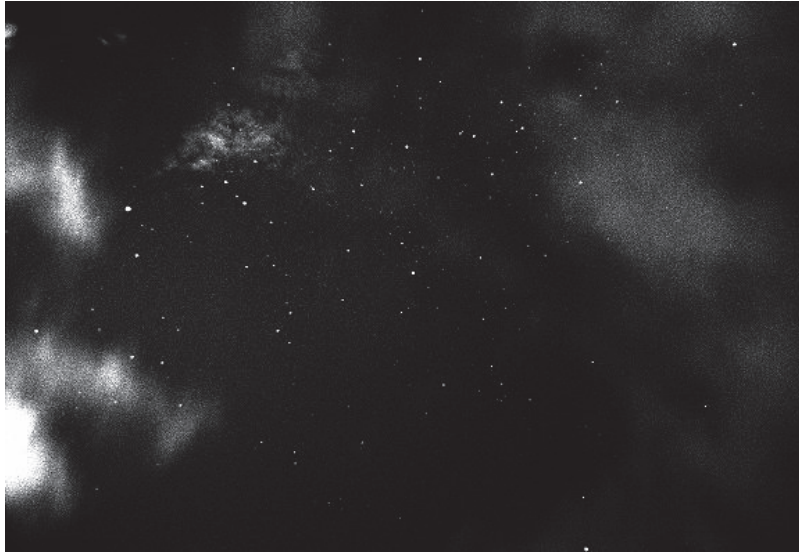


(b)

Figure 3.4: Location of the OmniSSA equipment in Hill Mirador, Punta Arenas.



(a)



(b)

Figure 3.5: Examples of images obtained at Hill Mirador, Punta Arenas.

Since the installation of the system in Hill Mirador, it worked according to plan and managed to resist in a good way the adverse weather conditions present in the place that even occur in the summer months, managing to verify that the design and construction of the system operates adequately.

On March 26, 2020, AFOSR offers the possibility of extending the project due to the global COVID-19 pandemic. Extension that was requested, because due to the state of emergency established in the country, it was not possible to travel for several months to the city of Punta Arenas to carry out maintenance on the equipment.

The aforementioned request was accepted and granted on May 30, 2020, for a period of 12 months. GRANT document FA9550-19-1-0028 P00002 is attached in Appendix D.

Various revisions are continuously made to the system components, an improvement was made to the camera cover, managing to automate and control this function remotely. In addition, a series of captures are constantly made to verify calibrations and improve the quality of the images. Figure 3.6 shows an image of the modification made to the camera cover.



Figure 3.6: On-deck automation of the cameras

The captures obtained have been calibrated and worked with different software, to finally be analyzed with a super resolution algorithm and digital filters.

In Figure 3.7 a diagram of the operation of the system is presented, from the simultaneous capture of images to the final result of an image in super resolution condition. In the first stage, the team with its four cameras obtains simultaneous images of the night sky, then its calibration is carried out together with the superposition of images, in order to rescue the greatest amount of data from the captures. In the third stage, the image obtained from the overlay of captures is processed in the super-resolution algorithm and is also digitally filtered, to finally obtain a single super-resolution image of the night sky in the fourth stage of the process.

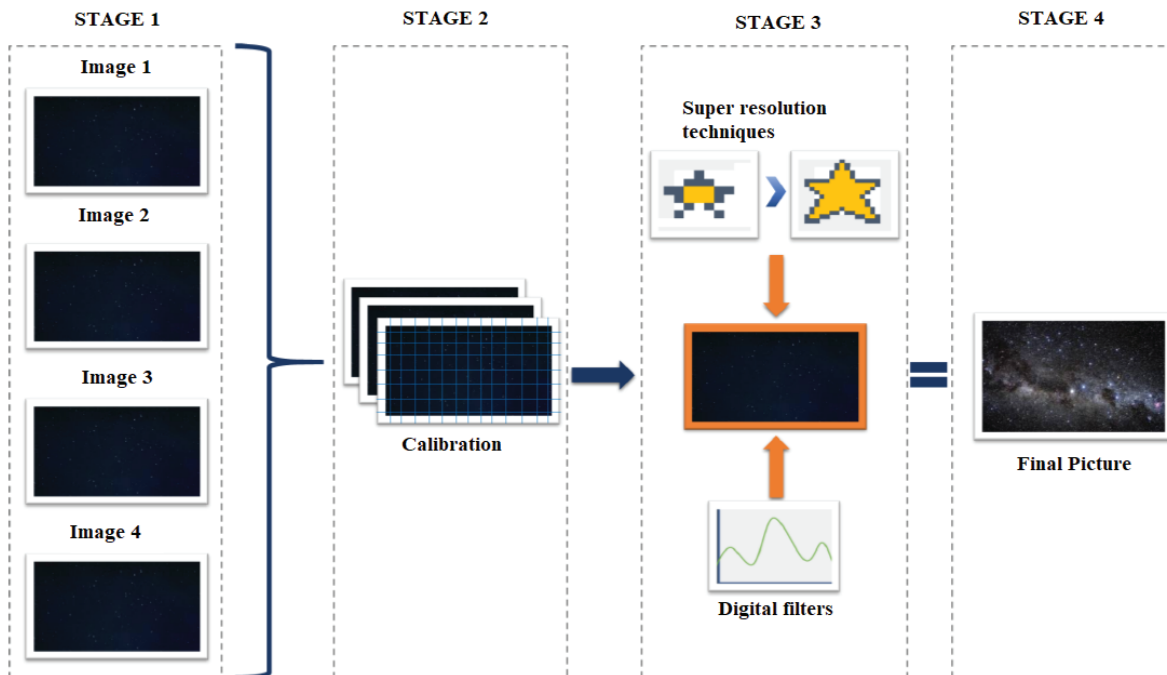


Figure 3.7: Conceptual diagram of the development stages, from the captures obtained to the final result of a single super-resolution image.

The proposed design corresponds to a super resolution model based on the restoration and reconstruction of atmospheric images; the model considers that atmospheric images present a large number of elements that are considered as noise, but in practice they correspond to transient elements that should not be eliminated. The model is in charge of rescuing pixels from the shots taken, presenting an improvement in the quality and resolution of the processed image from processes focused on improving the capabilities of the sensor that captures the images. The sequence is formed to reconstruct pixels and not remove any element from the digital image. The solution proposes a logical sequence of stages that are defined below.

1st Stage

The need to have four images captured simultaneously by four different sensors was raised. This solution is born due to the electromagnetic properties of light in space, which when

interacting with the atmosphere generates a disturbance of the oscillation of the electromagnetic wave, which causes the captured images not to represent all the elements that the scene contains. This disturbance corresponds to a wave disturbance already established for astronomical models, which can be suppressed by other sensors that capture these frequencies when they are in another position.

The proposed solution allows to capture a greater number of pixels of the element that transits through the atmosphere, also considering that the rotation of the earth is 30 km per second. The elements that pass through will be captured in millisecond segments (flashes of light per pixel), each image will come with a pixel variant, allowing greater detection by applying the super resolution algorithm to the system, to reconstruct the image segment.

Another reason why four images are used is due to the vision area that it reaches at an altitude of 500 km, which corresponds to the maximum height of the atmosphere, and which was requested in the operational requirements. For the element at a higher height to be detected, it has to complete the area of vision extension of the pixel by 80%. It should be noted that, by using four images from four different sensors, the resulting composite image to which the algorithm is applied allows the capture area to be reduced to a quarter. This area can be further improved by applying an optical lens over the sensor, although it decreases its angle of view.

2nd Stage

By having four images of a common scenario, it is necessary to obtain the validated section to apply the super resolution. This section corresponds to the matrix of pixels that the four images captured at the same time. An example of the section corresponding to this segment is shown in Figure 3.8.

This process is known as image registration. There are numerous techniques to carry out the proposed process, to present a better result and use fewer command lines. To do this, each valid segment in the four images must be cut, then superimposed to generate a composite image with a greater amount of data per pixel. This is due to the electromagnetic properties of light when interacting with the atmosphere, which was pointed out earlier.

3rd Stage

The third stage required evaluating functional techniques of super resolution based on image reconstruction and restoration that improve atmospheric images, in addition to presenting filters that reduce noise and blur generated in the captured scene in order to deliver a better final result. For this, different techniques and filters were evaluated.

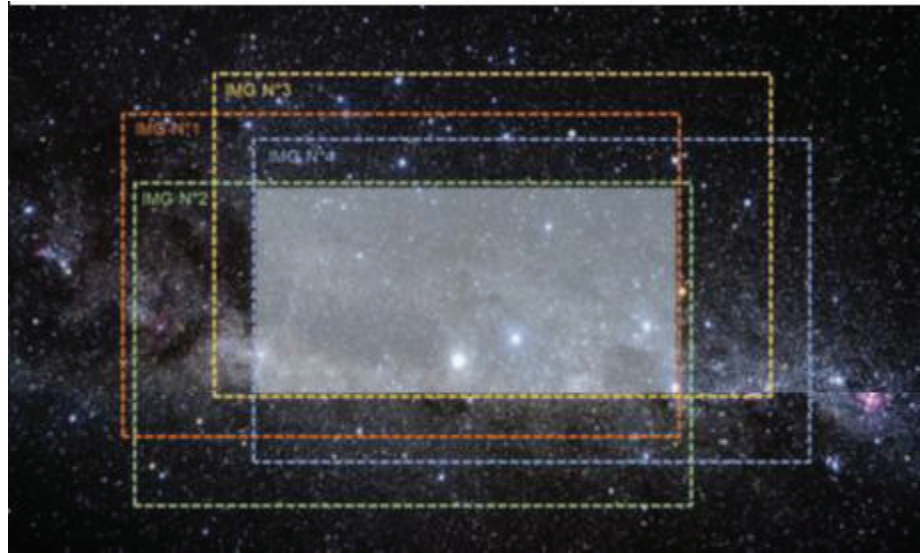


Figure 3.8: Composition of the valid segment to apply super resolution.

a.- Super resolution technique

To select the super resolution technique to be used, it was first necessary to select the techniques that correspond to image restoration and reconstruction processes. Interpolation was the technique that met these requirements, because it does not modify the image data, does not perform transformations to the data matrix and its function is to subsample the image signal, being the most suitable to apply in astronomical images.

To select the type of linear interpolation, you must first know that not all interpolation methods are recognized as super resolution techniques; only models that use polynomials as carriers are valid. In this case, only the Bilinear, Bicubic and Lanczos3 interpolation correspond to this process. A selection evaluation was carried out which focused on measuring the initial resolution, the final resolution, the average matrix, the processing time, the structural similarity index and the signal-to-noise portion. This process was carried out using a low resolution image of the night sky, applying interpolation and comparing it with the initial image to define and support the selected decision.

The first results of the final resolution of the image did not show any variation, while the response times ranged from a non-significant second time to be considered. However, the difference is indicated in the structural similarity index where this value, being closer to one, corresponds to the fact that there is a greater structural similarity between the images evaluated. As the process is based on image restoration and reconstruction, this value has to be the closest to one, while the signal-noise portion, the lowest. Noise can be corrected using filters, on the other hand, the structural similarity index is more complex to correct, since it changes the data matrix of the image. The use of bicubic interpolation was defined as a super resolution technique because it presented the best results for astronomical images.

b.- Focus filter

The bicubic interpolation when applied generates a blur of the image, which must be corrected to continue increasing the visual capabilities of the image. A comparison was made between three non-pixel destructive motion correction filters; these were the Wiener filter, the Lucy-Richardson algorithm, and a regularized Gaussian filter.

As in the previous case, a low-resolution image captured by the system was selected, a movement of 2 mm to the right and 3 mm to the left per pixel was added to the image, which corresponds to an approximate of what generated in astronomical images by the rotation of the earth. Subsequently, the response was evaluated by applying the selected filters.

In this process, the structural similarity index, the signal noise portion, the mean square error and the processing time were evaluated. As a first result, the Gaussian filter presented a high structural similarity and was the one that took the least time, because the Gaussian filter uses an auxiliary matrix with established parameters that are applied in a fixed way to the image without determining automatic correction parameters. This filter presented the optimal conditions, but it was defined to use the Wiener filter because it presented a small improvement compared to the Gaussian filter and the lowest mean square error index. The Lucy-Richardson algorithm did not achieve the expected structural similarity indices, as it works best with high light brightness images, not astronomical images, so it was completely ruled out.

c.- Increase the contrast of the elements in the image

For this process, it was defined to use a technique based on adding a percentage of the negative of the image to enhance the elements found in the image. To do this, the inverse image of the image band is constructed: as the image scale is represented in grayscale, the black color corresponds to 0 and the white color to 255. The negative generates that the elements of the image are reflected of black color and by adding a percentage of the negative image, it allows to enhance the brightness of the elements in the image, making them more recognizable and managing to detect elements that were invisible within the image. The whole process is based on astrophotogrammetry techniques.

d.- Histogram equalizer

This technique was chosen because it allows the histogram of an image to be distributed homogeneously by increasing its brightness and separating the small variations between pixels of the image, thus the image is better visualized and an increase in its quality is appreciated. The technique is used in astrophotography.

4th Stage

By presenting the final result of the algorithm, a high resolution image is delivered that is born from low resolution images, which corresponds to the foundation of super resolution.

The capture of the images, as well as their calibration, is done through algorithms developed in Python language. One of the tools used for overlaying the images was the DeepSkyStacker 4.2.5 software. Later, the images were worked with the aforementioned super-resolution techniques and filters, in order to obtain a final image of better quality.

Prior to capturing images with the four cameras, the calibration process must be carried out, this in order to correct each of the images that will later be considered under study. Although the Kowa lens manufacturer's indications indicate that it has a low distortion, the field of view of cameras having a wide field of view has a geometric distortion in the captured images. To carry out this calibration, radial and tangential distortion was taken into account.

In radial distortion, aberrations produced by construction defects in the lens are considered. These defects usually cause that the further the point of impact of the incident light beam is from the center of the image, the greater the deviation to which it will be subjected. In this way, the accumulated error of the image pixels is directly proportional to the distance they are from the center of the image, and that the distortion of two points located at the same distance from the center will be similar. To represent this problem, a model of circles is used. Meanwhile, tangential distortion is the distortion that occurs due to the lack of parallelism between the camera lens and the camera sensor and generates trapezoidal images. Equations that depend on distortion coefficients are used to correct both types of distortions, which were obtained for each of the four cameras used.

On the other hand, intrinsic and extrinsic parameters of the chamber must be considered. Among these are, for example, the focal length and optical centers, with which what is known as a camera matrix was obtained. This matrix of parameters was obtained for each of the cameras used.

The above described allows to calibrate the images obtained in each of the equipment's cameras. Twenty images of a chessboard were used for each camera, captured at different angles. In Figure 3.9, an example of what has been described is shown, where the edges of the chessboard used for calibration are recognized, which are later used by the algorithm to obtain the parameters mentioned above.

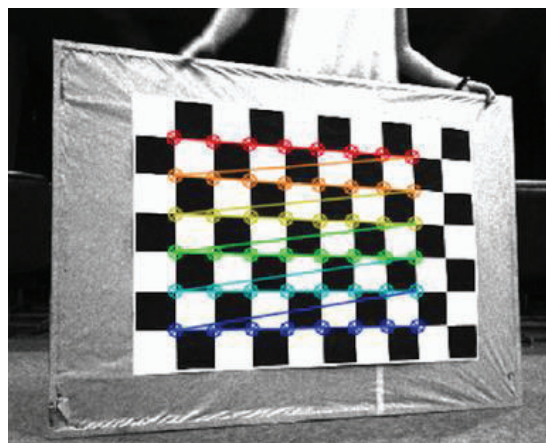
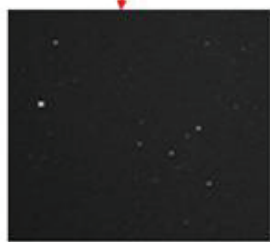
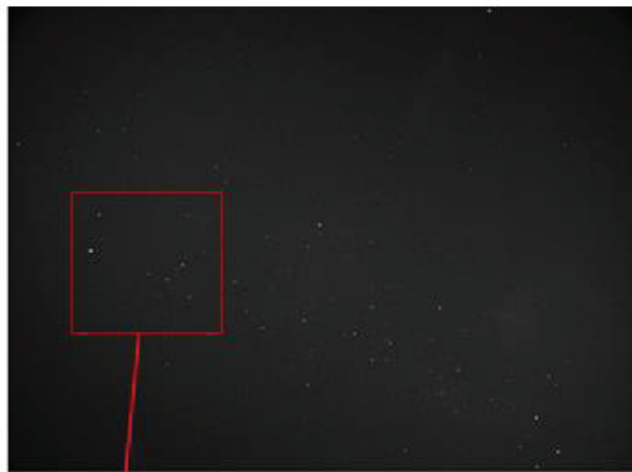
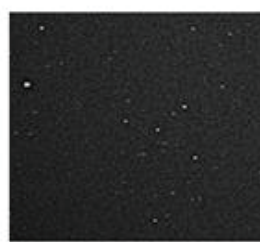


Figure 3.9. Recognition of the edges of the chessboard grids used for image calibration.

On the other hand, Figure 3.10 shows an example of the development carried out from captures compiled and worked in super resolution and a segment of the final image once filtered, where it is possible to verify the largest amount of data collected from the initial images and with this the greatest detail obtained from the night sky.

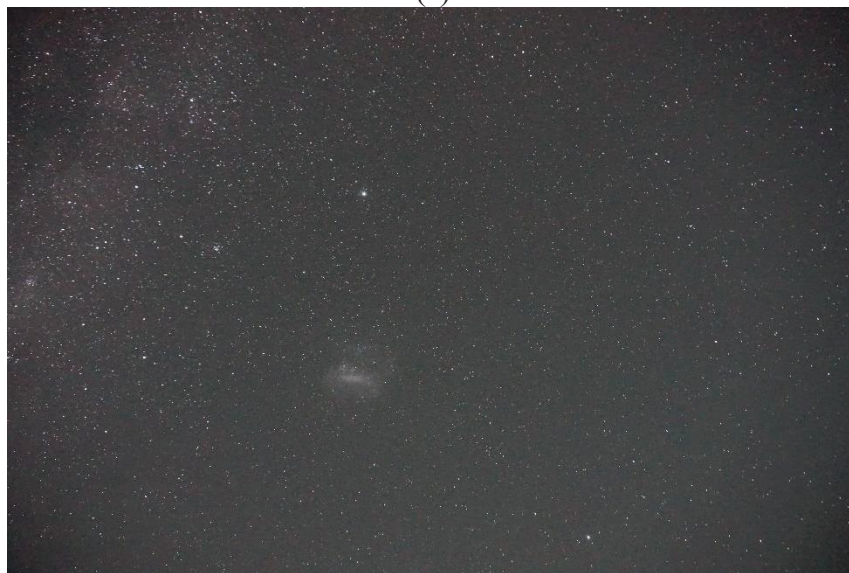


original segment



segment in super resolution

(a)



(b)



(c)

Figure 3.10: (a) Original image segment and the same one treated in super resolution, (b) Super resolution image, and (c) Transient object detection.

With the treatment of the images it has been possible to establish the detection of objects near the earth, where once the captures made have been compiled and processed, it is possible to clearly visualize the passage of different nearby objects. It is clear that viewing objects is not easy, especially under adverse weather conditions such as those found in the extreme south of Chile, where rain, constant cloud cover and also the presence of snow make it very difficult to acquire photographs of the sky and being a constant challenge to maintain the survival of the equipment in these conditions.

Figure 3.11 shows an example of the detection of a series of transiting objects after having carried out the superposition of captures. Images were captured in approximately two hours (between 20:00 and 22:00) during October 2020. This Figure also shows a close-up of one of these transitory objects, where it is possible to appreciate the sequence of positions that the object had.

The capture schedule was defined after establishing that between these hours there is the greatest probability of object sighting, since it is still possible to have a sufficient amount of sunlight to be reflected by transient objects, which then enter the zone of gloom, where the amount of light that they can reflect is practically null and therefore its detection becomes extremely complex.

Regarding the detection of the Chilean Fasat Charlie satellite, as indicated above, it was supported by the Space Operations Group (GOE) of the Chilean Air Force. They continuously provided information on the dates and times of the satellite passes over Punta Arenas.

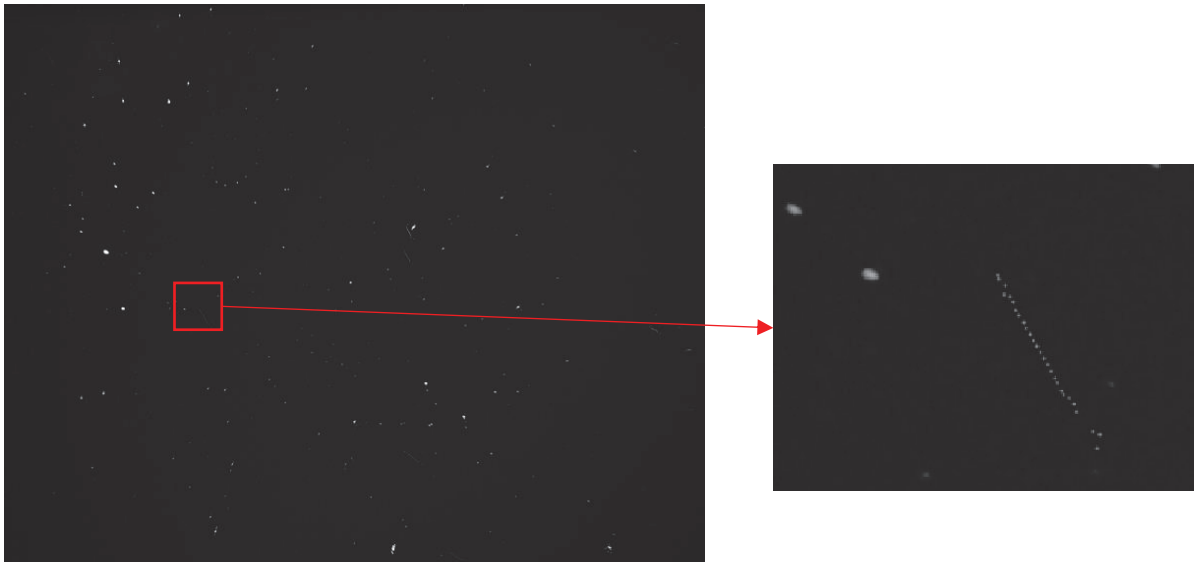


Figure 3.11: Example of detection and tracking of transient objects

In an average of ten consecutive days, the national satellite spends five days between 3:30 and 4:00 and another five days between 14:30 and 15:30; with a run time of no more than three minutes each.

At the aforementioned PM times and due to the characteristics of the All-Sky system cameras, it is impossible for the system to detect the satellite. Regarding the AM times indicated, the satellite is in a twilight zone with minimal probabilities of being detected, since the amount of sunlight capable of reflecting the satellite and that the cameras can receive is practically nil.

Due to the position and geographical characteristics of Punta Arenas, the amount of sunlight that occurs at night in the town, increases the probability of being able to detect the national satellite. But this probability is likewise greatly affected since the high cloudiness and rain present throughout the year, added to the snow during the winter months, make it difficult to coincide the satellite passes with good weather conditions for the taking of images and thus device detection.

It was possible to establish and confirm the transits of the Fasat Charlie through the use of the STK 12 software (SYSTEMS TOOL KIT). With this program, a series of scenarios could be generated, which allow selecting both the national satellite, as well as others with similar characteristics, positioning sensors and their coverage ranges.

Figure 3.12 shows one of the scenarios created to monitor the national satellite, considering the characteristics and range of the cameras of the All-Sky system.

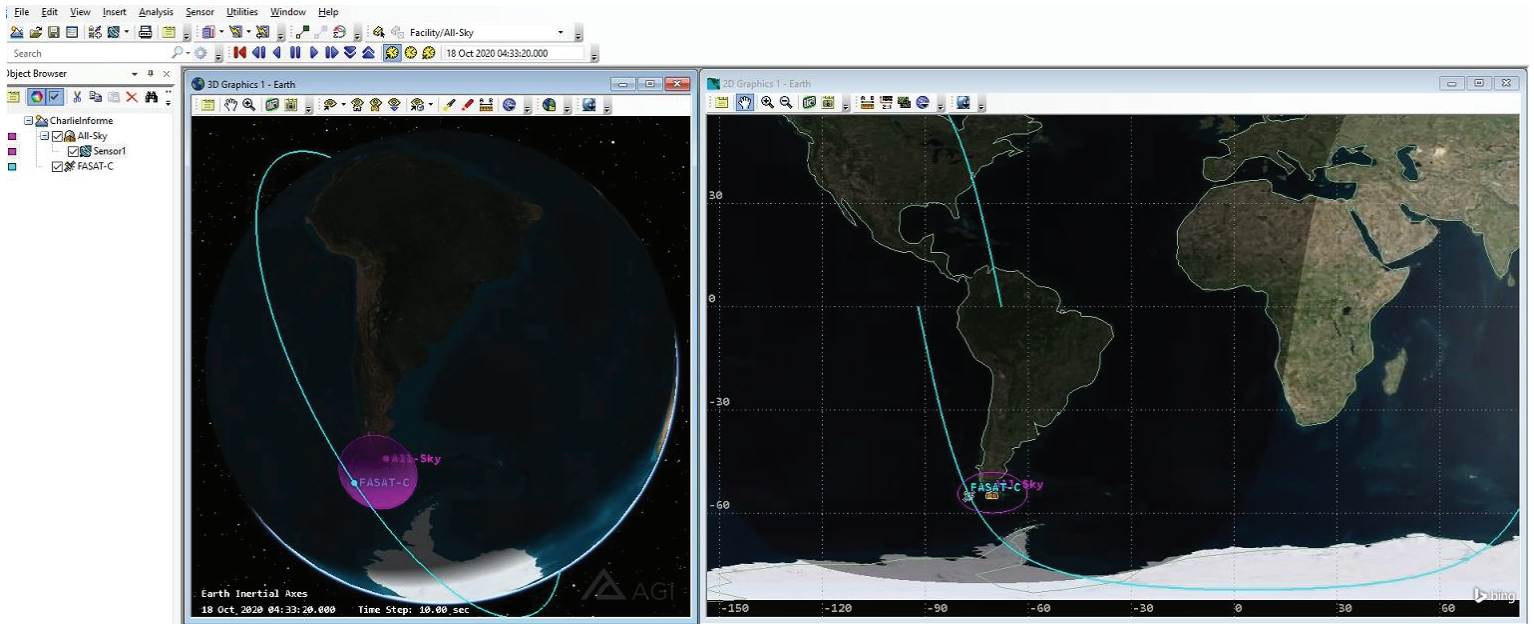


Figure 3.12: Scenario that allows monitoring the national satellite.

Figure 3.12 allows visualizing in 2 and 3D the position of the All-Sky system in Punta Arenas, as well as the trajectory that the satellite is developing around the Earth. It is also possible to see the coverage of the cameras of the system, and its coincidence with the satellite pass.

It is also possible to appreciate in the simulation that the coincidence of the satellite passage with the coverage area of the cameras occurs within the twilight zone, thus confirming the calculations made regarding the low probability of detection of the satellite. This is due to the passing hours and the little light available to be reflected by the satellite, preventing it from being detected by the built system. Despite the above, it was determined that due to the geographical condition and the orientation of the angle of the earth's axis, the best date to detect Fasat Charlie is the month of December.

Finally, it should be mentioned that part of the results of this research will be published in a scientific article titled: *Super resolution algorithm for images captured by "All-Sky System"* in the International Journal of Innovative Science and Research Technology.

4.-Conclusions

From the development of the Project, it is concluded:

- According to an analysis of light pollution to the City of Punta Arenas, it was determined to install the array of cameras in installations of the IV Air Brigade, specifically in Hill Mirador, the highest area of the city.
- A series of modifications were made to the original design of the OmniSSA 4 equipment, depending on whether the equipment can function optimally under the adverse weather conditions that exist in the City of Punta Arenas (rain and cold throughout the year)
- It was possible to obtain captures of the night sky in the Magallanes region, having the ability to store a large amount of data and remotely control the All-Sky equipment, despite the great difficulties that the equipment installation site presents for remote data transmission.
- The super resolution image processing algorithm used to process the acquired images, added to their super position, successfully generate better quality images, which allow the effective detection of a large number of objects present in the sky, thus as it also allows the observation and positioning of transitory objects.
- Through the use of specific software it was possible to establish and confirm the passes of the national satellite over the Magallanes region. But given the adverse weather conditions, the Fasat Charlie's passing times, the low amount of light reflected by the satellite at these times, and of course the health emergency caused by COVID-19, influenced the development of the research and did not allow the capture of the satellite with the All-Sky system built.
- Finally, the base purpose of learning and generating experience in the field of Space Situational Awareness, supported by AFOSR, was fulfilled by successfully implementing the system in this southern region of the planet and by establishing solid links with specialist researchers in the area. as is the work team of Dr. Holzinger, allowing us to establish a basis for future research that the Institution and the scientific community need to carry out in the area.

A Appendix: Details on the OmniSSA Mk. 3 Array

All three (3) Electro-optical (EO) sensor modules each contain a Rokinon 10mm F/2.8 ED AS IF NCS lens, a SBIG FW5-8300 5-position filter wheel (presently with Johnson filters), an SBIG STF- 8300M CCD, and an ODROID single-board computer (SBC). A block diagram of this configuration is depicted in Figure 1(a), while a photo of all three EO sensor modules is shown in Figure 1(b). The STF-8300M has a cooled CCD with 3326 x 2504 pixels, each with a pixel pitch of $5.4 \mu\text{m}$, bit-depth of 16 bits, and read noise of 0.02 e⁻/pixel/sec at -15C. The EO sensor module design preserves the capability of simultaneous triggering through the synchronization port. 3. The approximate pixel FoV is 106 arcsec (at the boresight) and the Rokinon lens has an effective collecting diameter of 3.75mm. It provides an ultra-wide FoV for each EO sensor module of 66 deg × 82 deg (103 deg corner-to-corner; verified in calibration). The ODROID units each have real-time clock shields, allowing the EO sensor modules to synchronize with one another and use either network time or GPS time to trigger exposures.

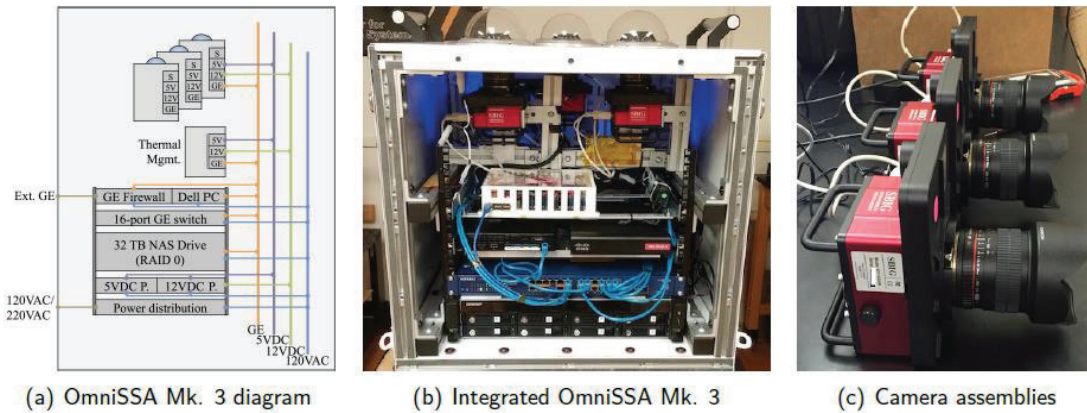


Figure 1: OmniSSA Mk. 3 Functional Operation and Camera Assemblies.

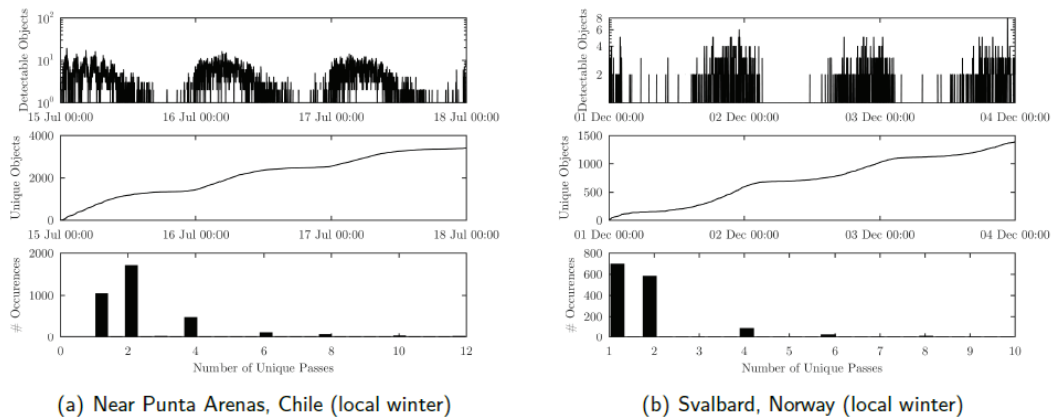


Figure 2: Expected Performance at Chilean and Norwegian Sites in a 72-hour period (single camera; no image fusion)

B Appendix: OmniSSA Mk. 4 Overview and Bill of Materials

All-Sky Sensor Array. All three (3) Electro-optical (EO) sensor modules each contain a Kowa Prominar MFT 8.5 mm f/2.8 lens and a ZWO ASI 1600MM Pro MFT CMOS sensor with 7nm H-alpha filter. The ZWO ASI 1600MM Pro has a cooled CMOS sensor with 4656 x 3520 pixels, each with a pixel pitch of 3.8 μ m, bit-depth of 12 bits, and read noise of 1.2e at 30 db gain. The quantum efficiency of the sensor is 60% with a full well capacity of 20 ke. The Kowa Prominar is a wide-angle lens with a field of view of 114 deg and an aperture diameter of 3.03 mm. The instantaneous FoV / pixel FoV is 82 arcsec/pixel at boresight. Even though the lens has a very wide field of view, the distortion is only -0.12% which is significantly lower than other wide field of view lenses. Each sensor will be communicating to the main computer via USB 3.0 cables. An on-board GPS module (supporting GPS and GLONASS constellation) is used for determining accurate location of the sensor as well as sync the clock using GPS time, allowing the sensors to synchronize and take simultaneous exposures. Software Defined Radio. Ettus Research B210 Universal Software Radio Peripheral (USRP) provides an RF coverage from 70 MHz to 6 GHz with 56 MHz of real-time bandwidth and a noise figure of less than 8 dB. Two receiver inputs enable the connectivity of two externally mounted antennas. First, Diamond D3000N discone antenna provides wideband reception from 25 to 3000 MHz, covering VHF, UHF and L satellite bands. The second antenna, Garmin GA38 is used for enhanced GNSS connectivity and possible Inmarsat reception. Both antennas can be replaced in case a specific frequency coverage is needed. The expected SDR system performance for VHF/UHF bands received SNR in a sample scenario is shown in figure below.

C Appendix: GRANT FA9550-19-1-0028 P00001

Grant/Cooperative Agreement Modification				
1. AWARD NO. FA9550-19-1-0028	2. MODIFICATION NO. P00001	3. EFFECTIVE DATE 23 OCT 2019	4. PURCHASE REQUEST NO. See Block 9	PAGE OF 1 2
5. ISSUE BY AFRL/RBKR2 USAF, AFRL DUNS 143574726 AF OFFICE OF SCIENTIFIC RESEARCH 875 NORTH RANDOLPH STREET, RM 3112 ARLINGTON VA 22203-1954 VALENCIA R. THORNTON 703-696-7337 valencia.thornton@us.af.mil			CODE FA9550 6. AWARDED TO ACADEMIA POLITECNICA AERONAUTICA CAGE CODE SUE87 GRAN AV. JOSE MIGUEL CARRERA, 11087 PARADERO 36 1/2 SANTIAGO	
9. ALLOCATED FUNDING: The following funds with associated Accounting Classification reference number(s) (ACRNs) are allotted to this agreement:				
<u>ACRN</u>	<u>FUND CITATION (=)</u>			<u>AMOUNT</u>
FOREIGN GRANT				
SPECIAL INSTRUCTIONS: N/A PAYING OFFICE INSTRUCTIONS: N/A PAYMENT SCHEDULE (if applicable): N/A				
10. FUNDING HISTORY:		Government Share	11. Recipient Share	12. Total
Previously Obligated:		\$30,000.00	\$0.00	\$30,000.00
Obligated by this Action:		\$0.00	\$0.00	\$0.00
Total Obligated to date:		\$30,000.00	\$0.00	\$30,000.00
13. TOTAL AWARD AMOUNT CHANGE		\$0.00	\$0.00	\$0.00
14. DESCRIPTION OF MODIFICATION This modification incorporates by reference Academia Politecnica Aeronautica letter dated 4 SEP 2019 to change the grant duration from 12 to 18 months and extend the period of performance through 31 May 2020, with final reports due 29 Aug 2020. The reporting requirements are revised as shown on page 2. All other terms and conditions remain unchanged as a result of this modification. RESEARCH TITLE: "Detection and Classification of Various Astronomical Events Near the Earth, Using an OmniSSA Sensor Arrays in Subantarctic Skies" PI: Dr. Roberto Solis PO: Dr. Geoffrey Andersen				
FOR THE RECIPIENT			FOR THE UNITED STATES OF AMERICA	
15. SIGNATURE			16. SIGNATURE	
 			//signed//	
17. NAME AND TITLE		18. DATE SIGNED	19. NAME AND TITLE	
 		 	ELEANOR A. ZACHERY	
			GRANTS OFFICER	
			20. DATE SIGNED	
			23 OCT 2019	

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SCHEDULE

(BLOCK 14 CONTINUATION) REVISED REPORTING REQUIREMENTS

The following reports must be submitted. Reports are due on or before the following dates.

TYPE OF REPORT	DUE DATE	SUBMIT TO
Annual Performance Report	30 NOV 2019	Pgm Mgr** & http://afosr.reports.sgizmo.com/s3/
Final Performance Report, including SF 298 Report Documentation Page	29 AUG 2020	Pgm Mgr** & http://afosr.reports.sgizmo.com/s3/
Final Invention Report	29 AUG 2020	afri.afosr.pkcontracting@us.af.mil & http://afosr.reports.sgizmo.com/s3/
Final Federal Financial Report, including line item 11	29 AUG 2020	Grant Admin Office (Block 12 of Grant Award Form) & afri.afosr.pkcontracting@us.af.mil
Quarterly Federal Financial Report (SF 425)	*See below	Grant Admin Office (Block 12 of Grant Award Form)

* SF 425 Quarterly Federal Financial Reports are required if any payment is made by an advance. The quarterly end dates that must be used are 31 Mar, 30 Jun, 30 Sep, and 31 Dec. The reports must be submitted within thirty (30) days after the end of each reporting period.

Quarterly Federal Financial Reports (SF 425) are not required if all payments are by reimbursement.

** The Program Manager/Officer is shown on page 1 of the basic Grant award in Block 15.

AFOSR prefers Performance Reports be submitted electronically, however, if the awardee does not have access to electronic means, send paper copies of Performance Reports to the appropriate Program Manager and office symbol listed in Block 15 of page 1 of the basic grant award at the following address: 875 N. Randolph Street Room 3112, Arlington VA 22203-1954.

All records pertinent to this award must be retained for a period of at least three years from the date of submission of the Final Federal Financial Report.

D Appendix: C Appendix: GRANT FA9550-19-1-0028 P00002

Grant/Cooperative Agreement Modification				
1. AWARD NO. FA9550-19-1-0028	2. MODIFICATION NO. P00002	3. EFFECTIVE DATE 30 MAY 2020	4. PURCHASE REQUEST NO. See Block 9	PAGE OF 1 2
5. ISSUE BY AFOSR/PKR USAF, AFRL DUNS 143574726 AF OFFICE OF SCIENTIFIC RESEARCH 875 NORTH RANDOLPH STREET, RM 3112 ARLINGTON VA 22203-1954 ELAINE UBAS 7035888391 Elaine.Ubas@us.af.mil			6. AWARDED TO ACADEMIA POLITECNICA AERONAUTICA GRAN AV. JOSE MIGUEL CARRERA, 11087 PARADERO 36 1/2 SANTIAGO	
9. ALLOCATED FUNDING: The following funds with associated Accounting Classification reference number(s) (ACRNs) are allotted to this agreement:				
<u>ACRN</u>	<u>FUND CITATION (s)</u>	<u>AMOUNT</u>		
SPECIAL INSTRUCTIONS: N/A PAYING OFFICE INSTRUCTIONS: N/A PAYMENT SCHEDULE (if applicable): N/A				
10. FUNDING HISTORY:				
	Government Share	11. Recipient Share		12. Total
Previously Obligated:	\$30,000.00	\$0.00		\$30,000.00
Obligated by this Action:	\$0.00	\$0.00		\$0.00
Total Obligated to date:	\$30,000.00	\$0.00		\$30,000.00
13. TOTAL AWARD AMOUNT CHANGE				
		\$0.00	\$0.00	\$0.00
14. DESCRIPTION OF MODIFICATION				
COVID-19 NO COST EXTENSION 12 MONTHS				
This modification incorporates by reference Academia Politecnica Aeronautica letter dated 4 APR 2020 to change the grant duration from 18 to 30 months and extend the period of performance through 31 May 2021, with final reports due 29 Aug 2021. The reporting requirements are revised as shown on page 2. All other terms and conditions remain unchanged as a result of this modification.				
RESEARCH TITLE: "Detection and Classification of Various Astronomical Events Near the Earth, Using an OmniSSA Sensor Arrays in Subantarctic Skies"				
PI: Dr. Roberto Solis				
PO: Dr. Geoffrey Andersen				
FOR THE RECIPIENT			FOR THE UNITED STATES OF AMERICA	
15. SIGNATURE			15. SIGNATURE	
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17. NAME AND TITLE		18. DATE SIGNED	19. NAME AND TITLE	
			ELEANOR A. ZACHERY	
			GRANTS OFFICER	
			20. DATE SIGNED	
			30 MAY 2020	

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SCHEDULE

(BLOCK 14 CONTINUATION) REVISED REPORTING REQUIREMENTS

The following reports must be submitted. Reports are due on or before the following dates.

TYPE OF REPORT	DUE DATE	SUBMIT TO
Annual Performance Report	30 NOV 2019	Pgm Mgr** & http://afosr.reports.sgizmo.com/s3/
Annual Performance Report	30 NOV 2020	Pgm Mgr** & http://afosr.reports.sgizmo.com/s3/
Final Performance Report, including SF 298 Report Documentation Page	29 AUG 2021	Pgm Mgr** & http://afosr.reports.sgizmo.com/s3/
Final Invention Report	29 AUG 2021	afri.afosr.pkcontracting@us.af.mil & http://afosr.reports.sgizmo.com/s3/
Final Federal Financial Report, including line item 11	29 AUG 2021	Grant Admin Office (Block 12 of Grant Award Form) & afri.afosr.pkcontracting@us.af.mil
Quarterly Federal Financial Report (SF 425)	*See below	Grant Admin Office (Block 12 of Grant Award Form)

* SF 425 Quarterly Federal Financial Reports are required if any payment is made by an advance. The quarterly end dates that must be used are 31 Mar, 30 Jun, 30 Sep, and 31 Dec. The reports must be submitted within thirty (30) days after the end of each reporting period.

Quarterly Federal Financial Reports (SF 425) are not required if all payments are by reimbursement.

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All records pertinent to this award must be retained for a period of at least three years from the date of submission of the Final Federal Financial Report.

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