



Matteo Dodero

Space Based Infrared Observations for Space Situational
Awareness

School of Aerospace, Transport and Manufacturing

MSc Astronautics and Space Engineering
Academic Year: 2024–2025

Supervisors: Dr Nicola Garzaniti, Dr Marta Ceccaroni,
Dr Dario Spiller (external)
September 2025



School of Aerospace, Transport and Manufacturing

MSc Astronautics and Space Engineering

Academic Year: 2024–2025

Matteo Dodero

Space Based Infrared Observations for Space Situational
Awareness

Supervisors: Dr Nicola Garzaniti, Dr Marta Ceccaroni,
Dr Dario Spiller (external)

September 2025

This thesis is submitted in partial fulfillment of the
requirements for the degree of MSc Astronautics and Space
Engineering.

© Cranfield University 2025. All rights reserved. No part of
this publication may be reproduced without the written
permission of the copyright owner.

Academic Integrity Declaration

I declare that:

- the thesis submitted has been written by me alone.
- the thesis submitted has not been previously submitted to this university or any other.
- that all content, including primary and/or secondary data, is true to the best of my knowledge.
- that all quotations and references have been duly acknowledged according to the requirements of academic research.

I understand that to knowingly submit work in violation of the above statement will be considered by examiners as academic misconduct.

Abstract

This thesis explores the feasibility of using infrared sensors for space-based situational awareness in low earth orbit. The goal is to assess if the thermal radiation of targets can be detected, therefore rendering them visible, even under unfavourable illumination conditions i.e. during eclipse. This thesis is done in collaboration with Arca Dynamics. After a literature review, the relevant sensor requirements are outlined and bolometer cameras are chosen because of their cost effectiveness. INO's High-Definition Infrared Space Camera Core is selected as the chosen sensor. Next, the radiometric signatures of targets are modelled and a simplified model to assess detectability is constructed. This model is used to assess the limitations of the technology showing that detectability is highly dependent on target temperature and detection is feasible only for large objects (at least larger than 8 m^2) at temperatures reached during eclipse. Next, a more complete bolometer model is developed that includes important effects such as point spread function, thermal time constant, integration and amplification, and a noise model. This model is then used in the simulation pipeline that allows us to simulate different target and observer scenarios, assess detectability, and generate synthetic images. A case study is presented using the satellite Cartosat-1 which shows that the object is detectable at distances up to 238 km. This study shows that detection of objects during eclipse is feasible, but only for relatively large objects at limited ranges. Target temperatures and relative kinematics are also crucial factors that influence detection. The model still needs to be validated to ensure its fidelity to reality. However, the behaviour of this model is in agreement with similar work in the literature.

Keywords:

Bolometer, object detection, synthetic images, sensor model, SST, Signal-to-noise ratio

Acknowledgments

I would like to thank Dario, Rebecca, and the whole team at Arca Dynamics for welcoming me in Rome and supervising me throughout this thesis. It was amazing to be part of the incredible work you are doing.

I would also like to thank Tim from the Institut National d’Optique for meeting with me and providing valuable feedback about bolometers.

A very special thanks goes to my supervisors, Marta and Nicola. Nicola, your willingness to innovate is inspiring. Thank you for always being present and for the precious support you have given me. Thank you for opening the doors to incredible projects and opportunities. Marta, your concreteness always brought things down to earth (often needed in space engineering). Thank you for offering invaluable guidance, both professionally and personally. It has been a pleasure to work with you both.

I would like to thank my family for always being there through highs and lows. Thank you for allowing me to go on this journey.

To the Mediterranean squad and all the friends I shared laughs, dinners and study sessions at Cranfield I could not have hoped for a better group of people.

Thank you to the ones of the jazz on the beach for always being there during all these years.

Finally thank you Brett, for always believing in me and always showing up with grace and kindness. Thank you for putting up with countless hours of me talking about space debris and cameras.

I would also like to acknowledge the use of AI (ChatGPT-4), which assisted with grammar and syntax corrections as well as with resolving some coding issues.

Matteo

“Look again at that dot. That’s here. That’s home. That’s us.”
– Carl Sagan, *Pale Blue Dot*

Contents

Academic Integrity Declaration	i
Abstract	ii
Acknowledgments	iv
Contents	v
List of Figures	viii
List of Tables	xi
List of Abbreviations	xii
1 Introduction	1
1.1 Background and motivation	1
1.2 Infrared sensing for SSA	1
1.3 Research question and objectives	2
1.4 Thesis outline	3
2 Literature review	5
2.1 The LEO environment	6
2.1.1 Increase LEO operations risks	7
2.1.2 Mitigation	9
2.1.3 Space based optical observations for SSA	10
2.2 Arca Dynamics Operations	11
2.2.1 Object detection and orbit determination	11
2.2.2 Inspection	14
2.3 Space-based Infrared observation for SSA	15
2.3.1 Infrared observation for SSA	15
2.3.2 Infrared observation for NEO	16
2.3.3 Infrared observations for proximity operations	16
2.4 Resistive Bolometers	18
2.4.1 Operating Principle	18
2.4.2 Figures of merit	20
2.4.3 Noise sources	21
2.5 Photon Detectors	22

2.5.1	Operating principle	22
2.6	Literature gap	23
3	Requirements	24
3.1	ConOps	24
3.2	Requirements	25
3.2.1	Size requirements	25
3.2.2	Observation requirements	26
3.2.3	Payload performance requirements	27
3.2.4	Design requirements	27
3.3	Un-cooled bolometer selection	29
3.4	Telescope Trade-off	31
4	Radiometric modeling of the target signatures	33
4.1	Thermal radiation	33
4.1.1	Radiant exitance	34
4.1.2	Real emission	35
4.1.3	View factor	35
4.1.4	Power at Aperture	36
4.2	Power incident on the sensor	37
4.2.1	Optical throughput	38
4.3	Signal to Noise Ratio	39
4.3.1	Testing	40
4.3.2	SNR	41
5	Technology limitations	42
5.1	Assumptions	42
5.2	SNR vs Distance	43
5.3	Minimum Area vs Range	45
5.3.1	High temperatures	46
6	Bolometer Response	47
6.1	Diffraction limited power distribution	48
6.1.1	Power distribution	49
6.2	Thermal power map	50
6.2.1	Membrane's model	50
6.3	Rolling shutter and integration	53
6.3.1	Shutter	53
6.3.2	Integration	54
6.4	Noise	55
6.5	Signal conversion	57
7	Simulation	58
7.1	Target	59
7.1.1	Projected area	59
7.1.2	Temperature and Emissivity	60
7.2	Orbits and geometry	62

7.2.1	Orbit	62
7.2.2	Reference frames	64
7.2.3	Pointing	66
8	Results	70
8.1	Simplified model performance	70
8.1.1	SNR vs Range	70
8.1.2	Range vs Temperature	71
8.2	Results of the full simulation pipeline	72
8.2.1	Simulated image frames	72
8.2.2	SNR analysis	74
8.2.3	Model comparison	75
9	Conclusion	78
9.1	Limitations	79
9.2	Future Work	80
	References	82
A	CURES	89
B	Image plane coordinates	91

List of Figures

2.1	LEO population from ESA's Annual Space Environment Report 2025 (European Space Agency (ESA), 2025b)	6
2.2	Launch traffic from ESA's Annual Space Environment Report 2025 (European Space Agency (ESA), 2025b)	7
2.3	Number of cumulative collisions in LEO from ESA's Annual Space Environment Report 2025 (European Space Agency (ESA), 2025b)	8
2.4	Total Object Area in LEO from ESA's Annual Space Environment Report 2025 (European Space Agency (ESA), 2025b)	8
2.5	Right ascension and declination angles from Stoker et al. (2020). The red dots represent the trajectory of the object in the field of view. α_0, δ_0 are the right ascension and declination of the pointing direction of the camera. α_1, δ_1 are the right ascension and declination of the target at time t	12
2.6	Example of sidereal tracking image from Haussmann et al. (2021)	13
2.7	Temperature variation of a LEO object during the course of one orbital period from Yilmaz et al. (2019)	17
2.8	Radiance emitted by target from Yilmaz et al. (2019)	17
2.9	Bolometer diagram from Kruse (2001)	19
2.10	Signal generation from a thermal camera system using bolometers from Vollmer and Möllmann (2018)	20
3.1	Focal length vs FOV	32
4.1	Black body spectral radiance for relevant temperatures	34
4.2	Geometry of radiative exchange between two surfaces	36
4.3	Power that reaches the aperture VS temperature for a 1 m^2 emitting area parallel to the aperture, $\varepsilon = 0.8$, distance 100 km	37
4.4	Radiation pipeline before reaching the sensor. (Généreux et al., 2024)	38
4.5	Typical transmittance of a coated germanium lens from Edmund Optics (Edmund Optics, n.d.)	39
4.6	Noise equivalent power for MWIR (left) and LWIR (right)(Généreux et al., 2024)	40
4.7	Signal Transfer Function (Généreux et al., 2024)	41
5.1	SNR vs Distance for different emissivities for a 1 m^2 projected area at $T = -90^\circ\text{C}$	43
5.2	SNR vs Distance for different emissivities for a 1 m^2 projected area at $T = -60^\circ\text{C}$	43

5.3	SNR vs Distance for different emissivities for a 1 m^2 projected area at $T = -30^\circ\text{C}$	44
5.4	SNR vs Distance for different emissivities for a 1 m^2 projected area at $T = 0^\circ\text{C}$	44
5.5	SNR vs Distance for different emissivities for a 1 m^2 projected area at $T = 30^\circ\text{C}$	44
5.6	SNR vs Distance for different emissivities for a 1 m^2 projected area at $T = 60^\circ\text{C}$	44
5.7	Minimum area vs temperature that results in an $\text{SNR} = 5$ at a distance of 100 km	45
5.8	Zoomed minimum area vs temperature that results in an $\text{SNR} = 5$ at a distance of 100 km	46
6.1	Diffraction pattern (Airy disk) produced by a circular, diffraction-limited aperture. Bright rings correspond to constructive interference; dark rings correspond to destructive interference (Nave, n.d.).	48
6.2	Fine gaussian kernel with a fine grid (30×30) (left), pixel intensity distribution once binned on to original pixels (right) in normalised units . . .	49
6.3	Example of empirical testing of the response of a bolometer's pixel (Généreux et al., 2018)	50
6.4	Example of the response of a pixel to two step inputs lasting 10 ms and 20 ms of the same magnitude of 100 pW using the membrane's model . .	52
6.5	Example of thermal power map of the focal plane due to a fast moving object across the FOV	53
6.6	Noise distribution on the focal plane in pW	56
6.7	Noise distribution on the focal plane in pW plotted in 3D in pW	56
7.1	Simulation pipeline overview.	58
7.2	Simplified model of the target, based on Table 7.1 with the x-axis in red, y-axis in green, and z-axis in blue (left). Projected cross sectional area as a function of viewing direction, Azimuth and Elevation are the spherical coordinates defining a direction in the body frame (right) made using DRAMA CROC (European Space Agency (ESA), 2025a)	60
7.3	Solar panel temperature of a LEO satellite from Kim and Han (2010b) . .	62
7.4	Target and observer orbit, 22/07/2025, 02:35:37.869 (UTC)	64
7.5	Camera frame and world frame, adapted from Hartley and Zisserman (2003) .	65
7.6	Pinhole camera model from Hartley and Zisserman (2003)	66
7.7	Relative distance between target and observer at time $t_{obs} = 22\text{-Jul-2025 } 03:49:00$ (UTC). The blue line indicates the time in which the target stays in the FOV with the chosen attitude.	67
7.8	Target and observer position at t_{obs}	68
7.9	Object in the field of view, full coordinates in Appendix B	69
8.1	SNR vs Range for Cartosat-1, highlighting the SNR at ranges reached during the observational scenario and the maximum achievable (black dotted line)	71
8.2	Maximum range vs. temperature for Cartosat-1	71

8.3	Stacked image of 582 frames with noise.	72
8.4	Image of the object 10 seconds after the object enters the FOV (frame number 300), color-bar in counts.	73
8.5	Zoomed-in image of the object 10 seconds after the object enters the FOV (frame number 300) color-bar in counts (left), 3D plot of the image counts made using MATLAB's surf function (right).	73
8.6	Brightest pixel SNR in every frame	74
8.7	Comparison of the two models	75
8.8	Comparison of complete model and simplified model with efficiency factors. 76	
8.9	SNR vs Range including efficiency factors, dotted black line showing the maximum detectable range.	77

List of Tables

2.1	Cross sectional areas of current LEO large constellation. Data from ESA's DISCOS.	9
3.1	Summary of Payload Requirements.	29
3.2	Comparison of two uncooled microbolometers. Data from Généreux et al. (2024) (INO) and Dartois et al. (2017) (ULIS)	30
3.3	Summary of camera system parameters (INO bolometer).	32
7.1	Physical characteristics of Cartosat-1 from DISCOS.	59
7.2	Classical Orbital Elements of the Target	63
7.3	Classical Orbital Elements of the Observer	63
8.1	Main input parameters for the observational scenario	70
B.1	Pixel coordinates and ranges over time	91

List of Abbreviations

CTIA	Capacitive Trans-Impedance Amplifier
ESA	European Space Agency
FOV	Field of View
GEO	Geosynchronous equatorial orbit
HDISCC	High-Definition Infrared Space Camera Core
INO	Institut national d'optique
IOD	Initial orbit determination
JAXA	Japan Aerospace Exploration Agency
LEO	Low Earth Orbit
NASA	National Aeronautics and Space Administration
NEO	Near Earth Object
NEP	Noise Equivalent Power
OD	Orbit determination
PSF	Point Spread Function
ROIC	Read-out integrated circuit
SiTF	Signal-Transfer Function
SNR	Signal to Noise Ratio
SSA	Space Situational Awareness

Chapter 1

Introduction

1.1 Background and motivation

The number of objects in low Earth orbit (LEO) is increasing rapidly, driven both by the deployment of large satellite constellations and by the accumulation of orbital debris (European Space Agency (ESA), 2025b). As traffic in LEO grows, the need for accurate and timely information on the state of orbiting objects is becoming of greater importance. Such information is critical to reduce collision risk and minimise the number of avoidance maneuvers, which would otherwise shorten the operational lifetime of active satellites.

At present, space object catalogues rely primarily on ground-based sensors. While these sensors make up the backbone of current Space Situational Awareness (SSA), they are limited by geographical location, atmospheric conditions, and time of the day – all of which constrain coverage and observation opportunities. In this context, space-based observation systems are becoming increasingly attractive as a complementary solution. Arca Dynamics, the Italian company in collaboration with whom this thesis was carried out, is actively exploring and specialising in space-based sensing services.

Although most existing space-based sensors rely on optical payloads operating in the visible spectrum, these are restricted by illumination conditions and are ineffective during eclipse. To overcome this limitation, this work investigates the feasibility of using infrared sensors as an alternative for space-based SSA.

1.2 Infrared sensing for SSA

In recent years, interest has grown in the use of space-based infrared (IR) sensors for both object detection and object characterisation (Bianchi et al., 2025; Okada et al., 2017).

Such sensors have been employed in the context of proximity operations with resident space objects, as well as for asteroids exploration such as the Hayabusa mission (Kawaguchi et al., 2008).

For object detection, infrared sensors offer a key advantage: they are capable of operating without external illumination. This makes them effective during eclipse or in geometries where reflected sunlight does not reach the observer. If sufficiently sensitive, and if they operate in the appropriate wavelength bands, infrared sensors can detect the thermal radiation naturally emitted by a spacecraft. Infrared measurements are also valuable for characterisation since the observed radiance can be used to infer object temperature, providing insight into both physical properties and operational states.

There are two main classes of infrared detectors that could be considered for this application: photon detectors and bolometers. Photon detectors provide excellent sensitivity but require cryogenic cooling, typically to temperatures on the order of 77K (Vollmer & Möllmann, 2018), to operate effectively in the relevant wavelengths. This makes them suitable only for large spacecraft with the necessary cooling infrastructure. Bolometers, on the other hand, have been widely used in Earth observation missions as well as in asteroid and comet studies. While traditionally limited by their sensitivity, bolometer technology has advanced significantly in recent years (Boudou et al., 2019; Génereux et al., 2024). Notably, uncooled bolometers have become increasingly sensitive and can operate at or near room temperature (Vollmer & Möllmann, 2018), making them a promising candidate for cost-effective space-based SSA applications.

Despite this potential, relatively little research has been conducted on the use of infrared sensors for LEO-to-LEO object detection outside the context of proximity operations. This gap is due in part to the unique challenges posed by this application, but ongoing advances in detector technology suggest that using these sensors might be possible.

1.3 Research question and objectives

The guiding research question of this thesis is:

How effective are infrared sensors for space-based space situational awareness (SSA) under unfavorable illumination conditions?

To address this, the work has been developed in line with Arca Dynamics' operations, and, in particular, with the aim of using space-based observation for orbit determination. The specific objectives are as follows:

- **Sensor modelling.** Develop a sensor model to assess whether resident space objects are detectable under different observational conditions. This model should capture the relevant physics and instrument characteristics while remaining suitable for an early feasibility study.
- **Early Feasibility assessment.** Use the sensor model to perform an early feasibility study of infrared technology for SSA. The goal is to highlight under what conditions objects are detectable and to identify the main limitations that constrain performance.
- **Simulation pipeline development.** Construct a general simulation pipeline capable of simulating representative observational scenarios and generating synthetic infrared observations. The pipeline should be flexible enough to simulate arbitrary target–observer scenarios and provide estimates of detectability.

From these objectives, the following guiding research sub-questions are derived:

- What are the main infrared detector technologies suitable for SSA, and what are their limitations?
- Once bolometers are selected, in particular INO’s The High-Definition Infrared Space Camera Core (Généreux et al., 2024) as the most practical option, are objects detectable during eclipse, and if so:
 - What types of objects (in terms of size and effective radiating area) are detectable?
 - At what ranges are detections feasible?
 - What are the main challenges affecting detectability (thermal response, point spread function, noise)?

Special emphasis is placed on the eclipse regime, since this is where infrared sensors can provide unique value compared to visible light payloads. The central aim is therefore to determine whether objects are detectable in eclipse, which types of objects can be observed, and under what conditions detection is achievable.

1.4 Thesis outline

To address the research question and objectives, the thesis is organised as follows:

- **Chapter 2** presents the literature review. It introduces the LEO environment, space-based SSA, infrared technologies, and previous studies on infrared object detection. This evidences the theoretical background for the work.
- **Chapter 3** defines the application context and sensor payload requirements, based on discussions with Arca Dynamics.
- **Chapter 4** develops the methodology to derive the radiometric signatures of the target using the selected bolometer sensor, and introduces a simplified model to assess technology limitations.
- **Chapter 5** applies the simplified model, evaluates the first technology limitations, and establishes the upper bound on achievable performance.
- **Chapter 6** introduces a more complete bolometer model, including the effects of the point spread function (PSF), thermal transient response, detector integration, amplification, and noise. This model serves as the foundation for generating synthetic infrared images.
- **Chapter 7** describes the simulation pipeline, which defines a plausible observational scenario using the target Cartosat-1. The pipeline is designed to be general enough to reproduce arbitrary observer–target geometries.
- **Chapter 8** presents and analyses the results of the chosen observational scenario. The findings are interpreted in a broader context, highlighting the main factors that affect detectability.
- **Chapter 9** summarises the work, outlines the key limitations of the study, and proposes directions for future research.

Chapter 2

Literature review

In recent years infrared imaging has been applied in a variety of ways in space. Earth observation missions, comet and asteroid inspection, as well as asteroid detection and astronomy missions have all contributed to the development of this technology (Proulx et al., 2017; Zengilowski et al., 2022).

At the same time the LEO environment has become more and more crowded. Large constellations dominate the LEO region and the number of debris has increased exponentially. Therefore, the development of Space Situational Awareness services has become increasingly important. In particular, LEO to LEO optical space-based observation has become newly feasible and valuable. This is partially demonstrated by the success of Arca Dynamics, which offers SSA services with space-based observations.

Infrared imaging for non-astronomy missions allows us to do two main operations: first, to derive the temperatures of objects or surfaces and second, if the sensitivity permits, to be able to detect and observe targets from thermal emissions even in adverse illumination conditions.

There are two infrared detector technologies that allow for large focal-plane arrays: (1) Resistive bolometer arrays (microbolometers), which sense a temperature rise from absorbed radiation, and (2) photon detectors which generate charge carriers directly from incident photons.

This chapter summarises the state-of-the-art of space-based SSA and thermal imaging technology. It also provides the theoretical background upon which this thesis is based.

2.1 The LEO environment

In recent years, Low Earth Orbit (200–2000 km altitude) has experienced a significant growth in orbital population. First, large communication constellations have expanded rapidly. Launch costs — driven down primarily by the Falcon 9 — have decreased to under 3000 USD per kilogram (Jones, 2018), opening the space market to smaller actors.

Second, fragmentation events, the deliberate destruction of satellites, and collisions — most notably the 2009 collision between Iridium 33 and Cosmos 2251 (Kelso et al., 2009) — are an increasing driver of the growth in orbital population. Loose regulations on aspects like end-of-life requirements in previous decades have allowed the situation to become unsustainable.

According to ESA’s Annual Space Environment Report in 2025 (European Space Agency (ESA), 2025b), there are now approximately 54,000 objects larger than 10 cm and more than 1 million between 1 and 10 cm currently in orbit. Figure 2.1 shows the number of objects in LEO, indicating a clear upward trend in recent years. Figure 2.2 shows the launch traffic in LEO, demonstrating the unprecedented number of launches in recent years.

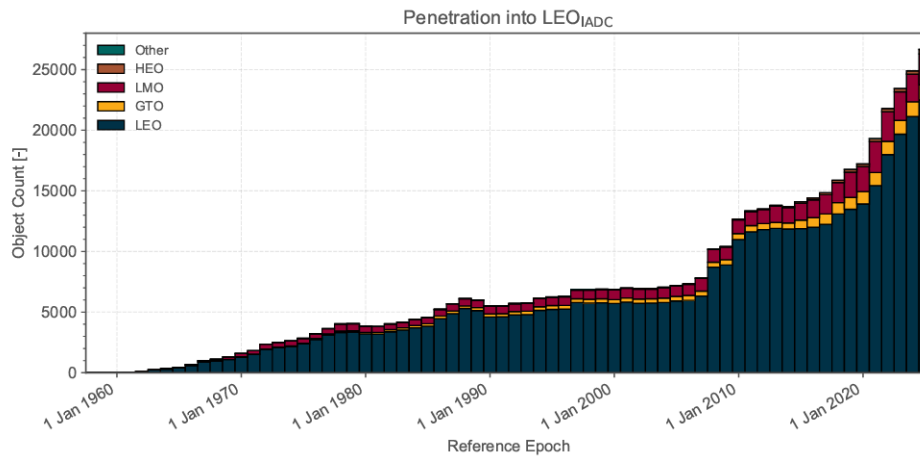


Figure 2.1: LEO population from ESA’s Annual Space Environment Report 2025 (European Space Agency (ESA), 2025b)

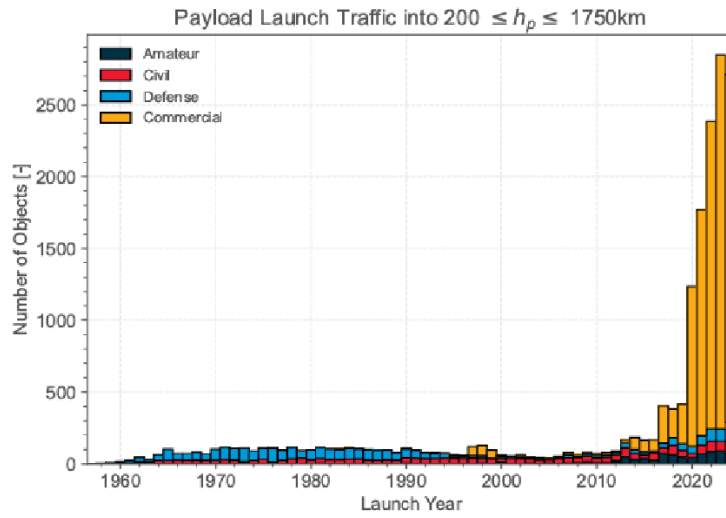


Figure 2.2: Launch traffic from ESA’s Annual Space Environment Report 2025 (European Space Agency (ESA), 2025b)

2.1.1 Increase LEO operations risks

The increased crowding of the LEO environment has made operations in LEO more risky. Large constellations, like Starlink, now have to perform a reported 275 maneuvers per day (Pultarova, 2024) to avoid collisions with other objects. ESA predicts a significant increase in collisions – see Figure 2.3 – in the coming decades if current trends continue. This scenario paints an alarming picture of the situation, highlighting the danger posed to sustainable access of some of the most useful orbits.

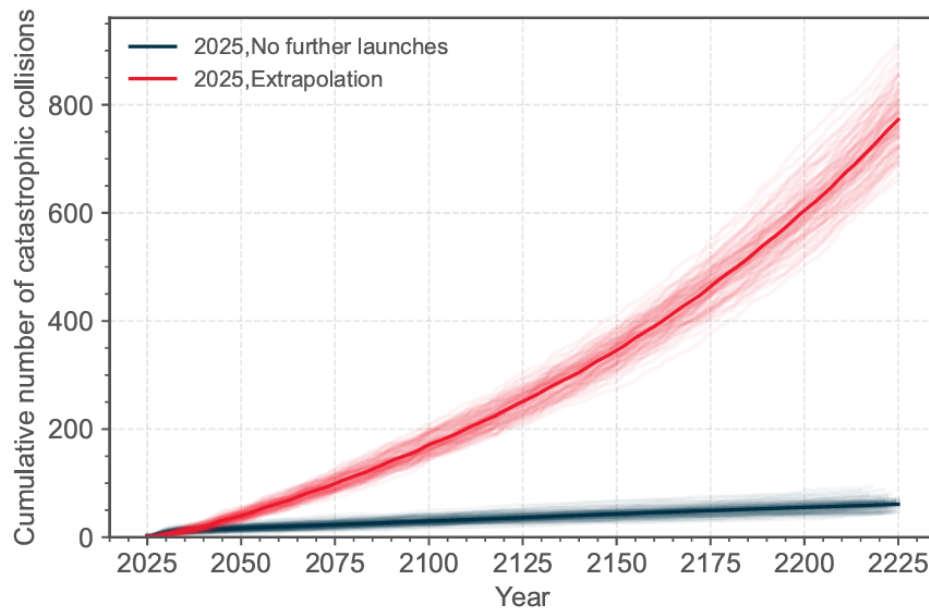


Figure 2.3: Number of cumulative collisions in LEO from ESA's Annual Space Environment Report 2025 (European Space Agency (ESA), 2025b)

A notable trend is the substantial growth in the total object area in low Earth orbit (LEO), as illustrated in Figure 2.4. The cross-sectional area of resident space objects (RSOs) is a critical parameter influencing collision probability (Krier, 2017). Specifically, in close approaches, the combined cross-sectional area of the interacting objects is directly correlated with collision likelihood; larger aggregate areas correspond to an increased probability of impact.

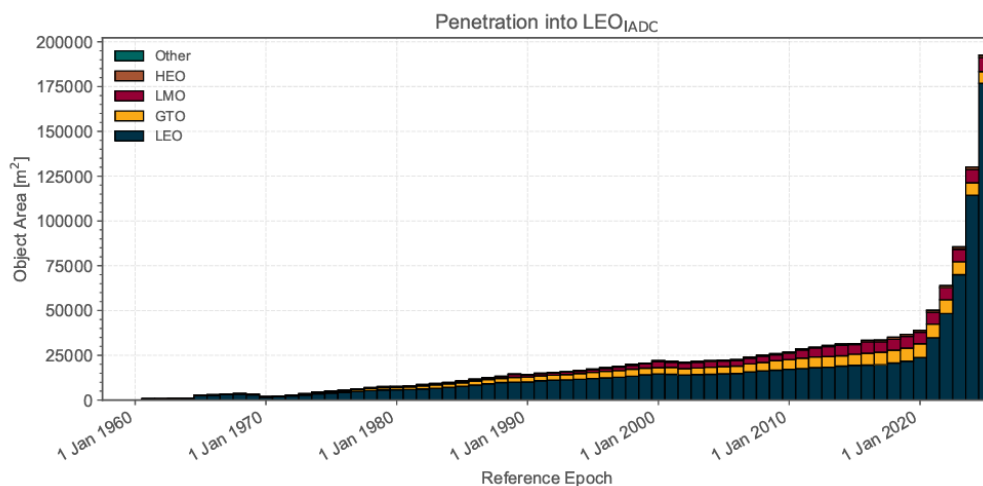


Figure 2.4: Total Object Area in LEO from ESA's Annual Space Environment Report 2025 (European Space Agency (ESA), 2025b)

One contributing factor to this trend is the growth in the cross-sectional area of satellites within large communication constellations, which can reach values upwards of 90 m^2 . This increase is primarily attributable to the deployment of expansive solar arrays (Caddy & Spitler, 2024) designed to meet the substantial power requirements of these platforms. Table 2.1 shows the cross sectional area of the satellites in some of the largest LEO constellation. This will have an impact on the results of this thesis as will be discussed in later chapters. The data to make this table has been taken from ESA's DISCOS¹.

Table 2.1: Cross sectional areas of current LEO large constellation. Data from ESA's DISCOS.

Constellation	Launch years	Number of Objects	Max cross-sec Area (m^2)	Average Area (m^2)
Starlink-G1-P1-group4	2021-2025	1584	23.657	13.562
Starlink-G2-P1-group6	2023 - 2025	1800	92.84	33.884
Iridium-NEXT	2017-2023	66	14.459	10.154
OneWeb	2019-2023	588	4.989	3.464

2.1.2 Mitigation

There are a number of mitigation measures that are being considered or have already been implemented to tackle the problem of space debris. Some of the ones receiving the most attention are the following.

First, there has been a push to introduce new regulations and policies to ensure that end-of-life requirements (European Space Agency (ESA), 2023b) reduce the risk of generating additional debris. An example is the ESA Zero Debris approach (European Space Agency (ESA), 2023a), which, through policies, regulations, and updated end-of-life requirements, aims to set an example and significantly decrease the amount of new debris in orbit. Second, efforts have focused on active debris removal, such as the ClearSpace mission (European Space Agency (ESA), 2025c) and similar projects. These missions aim to capture and de-orbit inactive satellites. Finally, there is a strong interest in Space Situational Awareness (SSA).

¹For showing this data we are using information from ESA DISCOS (Database and Information System Characterising Objects in Space), a single-source reference for launch information, object registration details, launch vehicle descriptions, as well as spacecraft information for all trackable, unclassified objects. We acknowledge ESA's efforts to maintain and operate this database with its APIs.

NASA defines SSA as “the requisite current and predictive knowledge of the space environment and the operational environment upon which space operations depend” (Newman, 2024). SSA consists of observing resident space objects (RSOs), characterizing them, cataloging them, and predicting their future positions. Accurate knowledge of the current and future state of the orbital population is essential for predicting collisions and enabling effective mitigation actions.

These catalogs, which contain precise position data for objects at given times, are built using observations from networks of sensors around the world. The main public provider of such a catalog is the U.S. military through the NORAD catalog (Speretta et al., 2017). One of the main challenges is that the uncertainty in an object’s state grows over time (Gondelach, 2019), requiring it to be re-observed after several orbits.

Currently, most observations are made using ground-based radars and telescopes (Yunpeng et al., 2021). However, these systems are limited by weather, geographic location, and, in the case of ground-based telescopes, the time of day, since they can only operate at night. Furthermore, because objects must be observed multiple times to maintain accurate orbital data, it is sometimes impossible to re-observe them before uncertainties grow too large, leading to a loss of track (Yunpeng et al., 2021). A promising solution is space-based optical observation, which is not restricted by weather or daylight. An orbital observation payload could continuously monitor space objects throughout its entire orbit, offering a significant advantage over ground-based systems.

2.1.3 Space based optical observations for SSA

Several missions have already demonstrated the value of space based observations. For example, in 2010 the United States Air Force launched the SBSS-1 satellite (NASA National Space Science Data Center (NSSDC), 2025). The observation payload is a telescope placed on a gimble to track the objects. Since the beginning of the mission it has made observations that have contributed to the United States’ catalogue (Office of the Director, Operational Test & Evaluation (DOT&E), U.S. Department of Defense, 2011). Another notable mission is Canada’s Sapphire satellite, in orbit since 2013 (Scott et al., 2013). All of the current missions operate with visible light sensors. In addition to operational missions a growing body of literature has proposed concepts and studied how catalogs can be created with space-based optical payloads (Du et al., 2019) (D’Anniballe et al., 2025).

In this context companies like Arca Dynamics have started to use space-to-space observations to provide services to public catalogs and private actors.

2.2 Arca Dynamics Operations

Arca Dynamics is an Italian company that offers services with space-based observations. In particular, two of their operations are of interest in this work: orbit determination and inspection. The former has the goal of deriving, from an optical observation, the state vector of a target RSO and accurately predicting its future trajectory. Inspection has the goal of characterizing the purpose of the observed target and its operations. From a sensor perspective these two operations have different requirements and constraints.

2.2.1 Object detection and orbit determination

Observations from a space-based optical payload for the purposes of orbit determination need to provide images that are then turned into precise, time-stamped line-of-sight measurements of targets. Practically, from each image two angles are derived: right ascension and declination as showed in Figure 2.5. Orbit determination (Milani & Gronchi, 2010) relies on a series of angle measurements to find the full state – position and velocity – of the target.

There are two main factors affecting the success and uncertainty of the orbit determination process: the uncertainty on the angle measurements and the observation time, which is directly proportional to the length of the observed arc (Pirovano, 2020). Once the state of the target is found, together with its error, it is possible to propagate the state in the future and check for possible collisions with other objects.

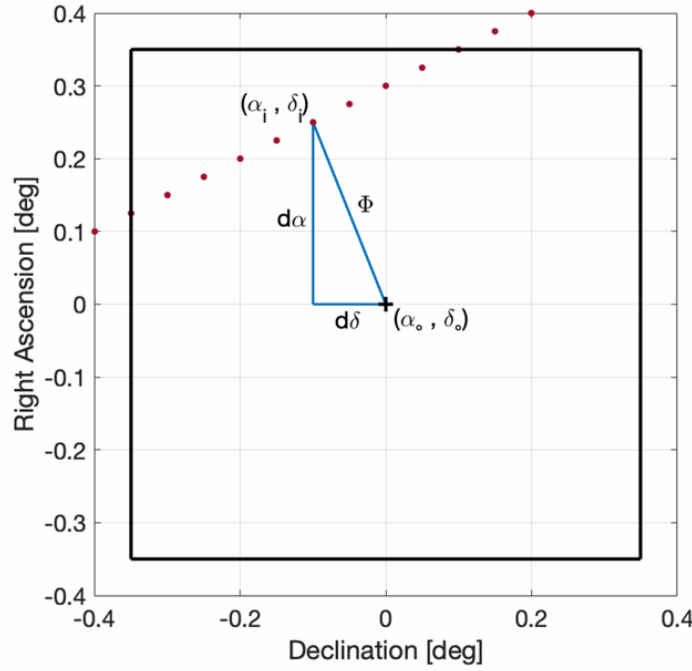


Figure 2.5: Right ascension and declination angles from Stoker et al. (2020). The red dots represent the trajectory of the object in the field of view. α_0, δ_0 are the right ascension and declination of the pointing direction of the camera. α_1, δ_1 are the right ascension and declination of the target at time t

There are two main ways to gather the necessary images from an optical payload. These two strategies have an effect on the payload requirements and design.

The first one is sidereal tracking. It involves pointing the telescope at a known inertial direction and waiting for the object to pass across the field of view (shown in Figure 2.6). In the resulting images, the stars will appear as dots and the targets as streaks. The length of the streak depends on the integration time and the relative velocity of the two objects.

It is worth discussing – even if qualitatively – the effect of this strategy on the quality of the orbit determination process. As mentioned before, the two main figures of merit here are the uncertainty on the measured angles and the time of observation – essentially, how long the object stays in the FOV.

The angular error depends mainly on the streak’s centroiding error and on the pointing (attitude) knowledge of the observing spacecraft (D’Anniballe et al., 2024), which in turn determines the fidelity of the reference frame from which the angles are measured. By using the stars visible in each frame to refine the attitude solution, the pointing error can be reduced, which can be a significant advantage (Abbasi et al., 2019).

The other important factor is the time of observation. This can vary depending on the relative orbital velocities of the observer and the target. However it is always constrained by the FOV of the camera as the pointing direction is fixed. This means that a higher FOV will allow longer orbital arcs to be observed.

Finally, an important aspect of this strategy is that, as the payload is pointing at a fixed direction (sidereal tracking), the energy falling on any given pixel from the target is determined by the target's apparent kinematics across the focal plane. A faster apparent rate spreads the target's flux over more pixels (a longer streak), reducing the per-pixel signal; if the target is fast enough, the peak signal — and thus the Signal to Noise ratio (SNR) — can drop below the detection threshold and the target may not be visible.

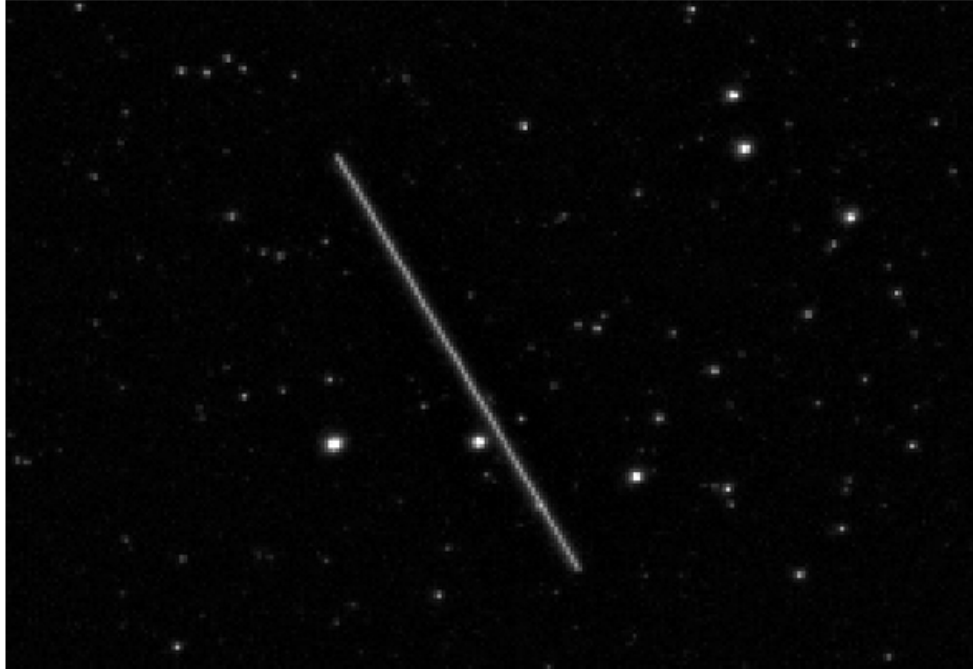


Figure 2.6: Example of sidereal tracking image from Haussmann et al. (2021)

The second observational strategy is object tracking. It involves tracking the object once it enters the FOV. This can be done either by gimbal-ed telescope mounted on a satellite or by changing the attitude of the satellite to track the target, keeping it in the FOV. With this strategy the object tracked will appear as a dot in the image and the stars will appear as steaks. The length of these streaks, again, will depend on the integration time.

One characteristic of this strategy is that the observation time is not bounded by the instrument's FOV; it is limited by the spacecraft's ability to slew and keep the target within the FOV. Because relative angular rates in LEO-to-LEO geometries are high, maintaining

track often requires rapid slews and substantial control authority, which is challenging for small satellites. As a result, this mode is used primarily for LEO-to-GEO observations (Abbasi et al., 2019), though LEO-to-LEO tracking has also been proposed even for small satellites (Felicetti & Emami, 2018) (D’Anniballe et al., 2025)

Another key characteristic is that, if the attitude-control loop is sufficiently fast, the target’s apparent motion can be compensated so it remains at a fixed location on the focal plane. This can allow for higher signal to noise ratios.

2.2.2 Inspection

Inspection consists of producing images with resolved targets in them. This is done for two main reasons: (1) to identify the purpose of the target satellite and (2) to characterize its operations. To do this, information about the shape of the satellite, its attitude, its structure and components etc. is necessary.

For example, a company trying to assess previous satellite malfunctions might be interested in receiving high-definition images of their satellites. There they would be able to see, for instance, whether or not a solar panel deployed. On the other hand, a government might want to see if the antenna of another country’s satellite is pointing towards earth or towards space and is therefore performing a satellite relay.

High definition images of these kinds require very high resolutions. In order to yield images capable of displaying the information previously discussed, Arca Dynamics suggests that resolutions should be in the order of 10 cm. This is achieved in the visible spectrum of light by using high resolution focal planes (large number of pixels). To achieve such high resolutions at large distances (i.e. hundreds of km for LEO to LEO observations) the pixels need to be quite small, in the order of a few micrometers to keep the focal length from increasing too much. The high relative velocities of objects within the LEO environment mean that objects move quickly across the field of view. Payloads for this application need to have fast integration times and high sensitivity to avoid either smeared pictures or being unable to detect the objects at all.

This application is not explored in this work for three main reasons: (1) uncooled bolometers, which will be the chosen technology as discussed in later chapters, do not achieve the required size – state-of-the-art bolometers today can only reach up to a maximum of around 1000 x 1000 pixels (Vollmer & Möllmann, 2018) –, (2) the pixel pitch of the bolometers is impractically large, requiring focal lengths that are too large for this application, and (3) current uncooled bolometers lack substantial sensitivity.

2.3 Space-based Infrared observation for SSA

Current optical space-based SSA operations, such as the ones previously discussed rely on detecting reflected sunlight in the visible part of the electromagnetic spectrum. This allows for detection of objects at ranges well over 1000 km (Simms et al., 2013).

Almost all objects in LEO orbits have a period of eclipse that can last up to 35 minutes (RM, 2019). Targets in eclipse cannot be observed by visible light sensors. This can be a significant limitation. To solve this problem, Arca Dynamics is exploring different passive space based solutions. One interesting candidate is using infrared sensors.

Infrared observations can exploit the intrinsic thermal emission of space objects. Any object at a finite temperature emits thermal radiation, and for satellites in LEO this emission lies primarily in the infrared. If this thermal emission is detected targets can be observed during eclipse without relying on sunlight. This capability makes infrared sensing especially valuable for the need of continuous detection and tracking of space objects.

The thermal emission of a body at temperature T can be described by Planck's law of blackbody radiation (Rees, 2013), which gives the spectral radiance as a function of wavelength:

$$L_{\lambda}(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/(\lambda kT)} - 1}. \quad (2.1)$$

Where, $L_{\lambda}(T)$ is the spectral radiance, h is Planck's constant, c is the speed of light in vacuum, λ is the wavelength of the emitted radiation, k_B is Boltzmann's constant, and T is the absolute temperature of the emitting body.

Very few public study exist on exploiting thermal emission to observe satellites and debris. This section explores the main advancements on this topic.

2.3.1 Infrared observation for SSA

A number of authors have investigated the potential of infrared observations for SSA. Schubert et al. (2022) examined the detectability of LEO space debris using a ground-based infrared sensor. They first developed a simplified thermal model to characterize the light curves of debris targets, and then coupled this with a sensor model to assess whether the emitted radiation could be detected. Their analysis considered a range of detector technologies, from low-performance devices to state-of-the-art systems.

The results indicate that infrared detection offers an advantage over visible-light sensors

only when very sensitive detectors are employed—comparable in performance to those used on observatories such as the James Webb Space Telescope.

Other authors have focused on developing high fidelity thermal models to characterize the targets signatures. Demars et al. (2023) use a high fidelity thermal simulator to predict the long-wave infrared light curves (radiance values) of a 3U CubSat during the course of an orbit in LEO. Packard et al. (2024) have used the same methodology for a larger satellite in geostationary orbit.

Another contribution on this topic has been made by the study of the serendipitous detection of satellites in the NASA’s WISE mission images. The WISE spacecraft was launched in 2009 in a sun synchronous orbit with the goal of surveying the entire sky with its four infrared detector which span from the near to the far infrared (Wright et al., 2010).

The wise spacecraft uses state of the art cryocooled photon detectors. During its operation the sensors detected a number of space debris and satellites particularly in the GEO region. Fitzmaurice et al. (2021) analyzed the observations to find and characterize satellites and space debris. Krezan et al. (2015) used the observations to find previously uncataloged space debris to improve the knowledge of the GEO debris population. With this they present a revised GEO collisional risk assessment.

2.3.2 Infrared observation for NEO

Another relevant area of research is the use of infrared detectors for detecting Near-Earth Objects (NEOs). Infrared observations are particularly valuable because asteroids typically have high emissivity and radiate strongly at thermal infrared wavelengths. The WISE spacecraft, during its extended mission, demonstrated this capability by detecting and characterizing asteroids (Wright et al., 2010). Building on this success, NASA is now developing the NEO Surveyor mission, which is specifically designed to detect and characterize asteroids and comets in the solar system using state of the art infrared photon detectors (Mainzer et al., 2023).

2.3.3 Infrared observations for proximity operations

A number of studies have explored the use of infrared detection for proximity operations. While for a different application they model the target signatures and the thermal properties of objects in Low Earth Orbit (LEO).

Bianchi et al. (2025) present a methodology for modeling the infrared signatures of space

targets as observed by a bolometer detector. Their approach focuses on accurately predicting the radiometric signal by accounting for the detector's characteristics and thermal state of the target. It provides a practical framework for simulating sensor performance in realistic observation scenarios.

Yilmaz et al. (2019) investigate the thermal environment of LEO debris and its implications for infrared detection. They show that the temperature ranges for a LEO object span between 30°C and -90°C as showed in Figure 2.7.

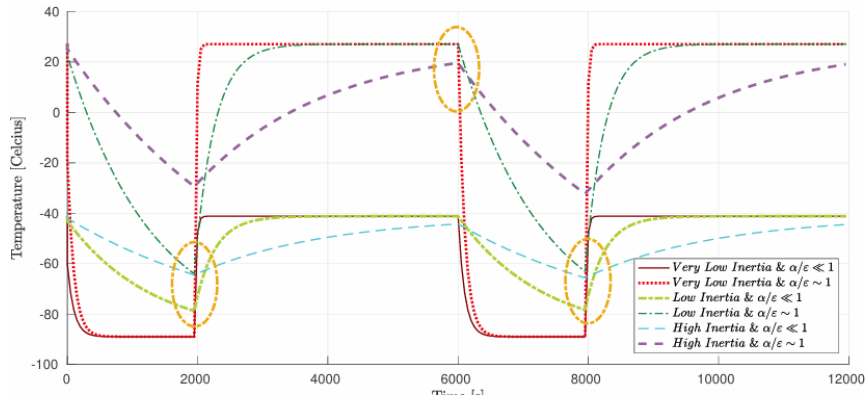


Figure 2.7: Temperature variation of a LEO object during the course of one orbital period from Yilmaz et al. (2019)

From these temperature ranges they show that observing in the long-wave infrared (LWIR, $8\text{--}14\text{ }\mu\text{m}$) band is optimal to maximize the detected signal as showed in Figure 2.8

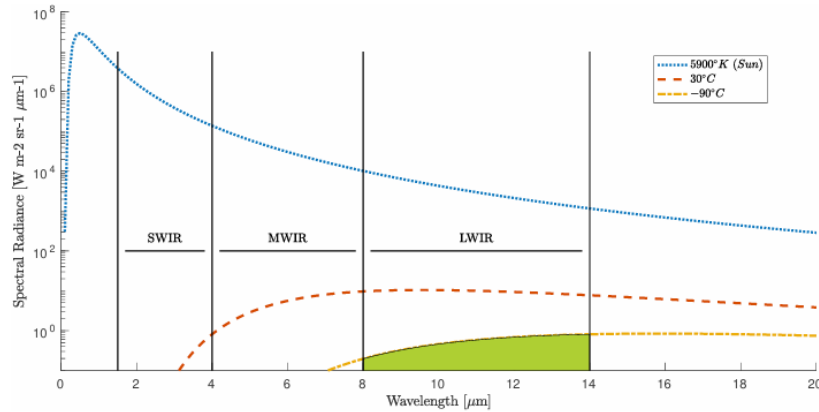


Figure 2.8: Radiance emitted by target from Yilmaz et al. (2019)

2.4 Resistive Bolometers

There are two main types of infrared detectors that can be suitable for this application and have significant space heritage: thermal detectors (bolometers) and photon detectors. This section and the next highlights the main characteristics of both and outline the theoretical background of this study. The thesis will then focus on bolometers as they are a more cost effective solution and more suitable for Arca Dynamics operations and this application. This choice will be explored in more detail in Chapter 3

Using resistive bolometers in focal plane arrays has an extensive space heritage. They have been used in earth observation and exploration missions such as ESA's EarthCare mission (Wehr et al., 2023) and JAXA Hayabusa2 mission (Arai et al., 2017). Bolometer arrays are particularly attractive because they can operate at room temperature, eliminating cryocoolers and greatly simplifying the payload (e.g. reducing mass, volume, power, and complexity) making them especially suitable for small satellites.

2.4.1 Operating Principle

A bolometer consists of a temperature-sensitive resistance. Radiation incident on the bolometer causes the temperature to rise. A temperature rise causes the resistance to change, which can then be measured (Kruse, 2001). When the radiation ends, the temperature returns to thermal equilibrium with the environment.

A bolometer is made of a thin sensing membrane upon which a detecting layer, usually made of vanadium oxide (VO_x), is deposited (Kruse, 2001). This membrane is held up by a series of small supporting legs, as shown in Figure 2.9. These legs are the largest contributors to the decrease in fill factor. Underneath the membrane a reflective material ensures that the radiation not absorbed is reflected back on the membrane.

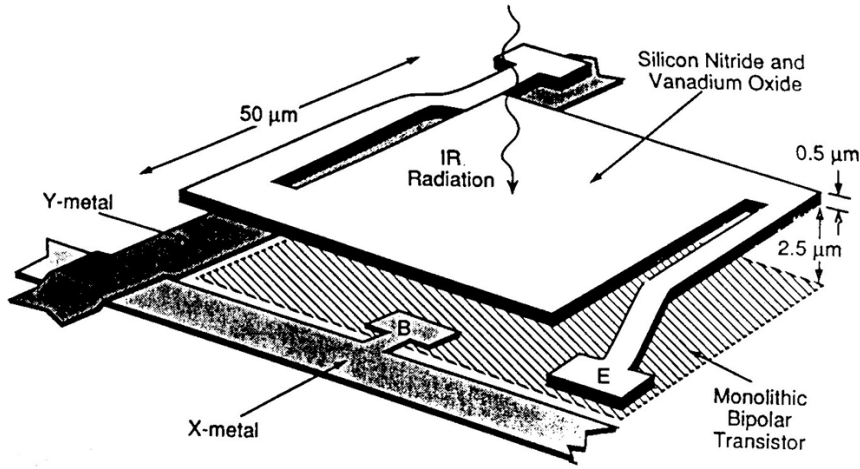


Figure 2.9: Bolometer diagram from Kruse (2001)

The temperature change ΔT of the membrane is described by the following equation (Vollmer & Möllmann, 2018):

$$\eta \Phi_0 = C_{th} \frac{d\Delta T}{dt} + G_{th} \Delta T \quad (2.2)$$

Where Φ_0 is the power transferred to the detector from the radiation. $\eta = \frac{\Phi_{absorbed}}{\Phi_{incident}}$ is the absorption efficiency – the fraction of absorbed power by the membrane compared to the incident power from the target. C_{th} is the heat capacitance and G_{th} is the heat conductance of the detector.

The temperature change from a square impulse of $\eta \Phi_o$ is (Vollmer & Möllmann, 2018):

$$\Delta T = \frac{\eta \Phi_o}{G_{th}} (1 - e^{-\frac{t}{\tau_{th}}}) \quad (2.3)$$

Where τ is the thermal time constant. This is a fundamental figure of merit of the bolometer design. It represents how quickly a bolometer can respond to an input signal. It is dependent on the heat conductance and capacitance of the detector:

$$\tau_{th} = \frac{C_{th}}{G_{th}}. \quad (2.4)$$

Eq.2.4 can also be expressed as:

$$\tau_{th} = C_{th} R_{th} \quad (2.5)$$

where $R_{th} = \frac{1}{G_{th}}$ and R_{th} is the thermal resistance.

A bolometer focal plane array is made up of two components: (1) the sensing element comprised of a number of bolometer units (Figure 2.9) and (2) a read-out integrated circuit (ROIC). The latter reads the signal and contributes to the signal processing by amplifying it (Vollmer & Möllmann, 2018). In practice, the ROIC measures the resistance value of each bolometer by biasing the membrane with a set voltage. The signal is then transferred to a Capacitive Trans-Impedance Amplifier (CTIA) where the current passing through the bolometer is accumulated in a capacitor for the duration of the integration time. This last step converts the current into a voltage and sets the gain of the ROIC (Boudou et al., 2019). Figure 2.10 illustrates the whole camera system.

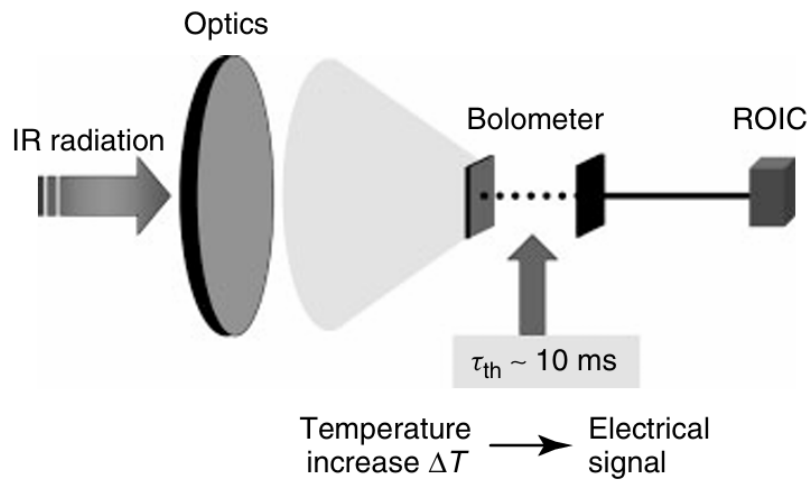


Figure 2.10: Signal generation from a thermal camera system using bolometers from Vollmer and Möllmann (2018)

2.4.2 Figures of merit

The performance of a bolometer's detectors is characterized by a set of parameters referred to as figures of merit. These quantify the detectors' sensitivity and noise performance.

Responsivity. Responsivity measures how well a bolometer transforms the radiation power incident on the bolometer into signal. The signal V_s is usually measured as a voltage (Volts) but can sometimes be in counts or current (Ampere). The incident power is measured in watts. The responsivity R can be expressed as (usually in $[\frac{V}{W}]$) (Kruse, 2001) :

$$R = \frac{V_s}{P_0} \quad (2.6)$$

Noise Equivalent Power (NEP). This figure of merit quantifies the level of power incident on the bolometer that gives rise to a signal equivalent to the root mean square (rms) noise of the pixel (Kruse, 2001). NEP represents the the incident power necessary to produce a signal-to-noise ratio of one ($SNR = 1$). This is expressed in units of power (Watts) by Eq 2.7:

$$NEP = \frac{V_n}{R} \quad (2.7)$$

where V_n is the rms noise voltage.

2.4.3 Noise sources

In a bolometer array there are three types of fundamental noise sources: Johnson noise, temperate fluctuation noise, and and flicker or $f/1$ noise (Bianchi et al., 2025)(Gao et al., 2011). Together, these determine the minimum detectable power and therefore define the noise-equivalent power (NEP) of the detector.

Johnson noise. This type of noise is caused by random fluctuation of the charge carriers in the resistive membrane. These carriers generate a voltage noise V_j (signal noise). The rms voltage caused by this noise can be approximated with Equation 2.8 (Bianchi et al., 2025)(Gao et al., 2011)

$$V_j^2 = 4k_b T_b R_b B_j \quad (2.8)$$

where k_b is Boltzmann constant, T_b is the temperature of the resistive bolometer, R_b is the bolometers impedance, and B_b is the frequency bandwidth of the system. B_b is dependent on the type of biasing on the membrane. For a bolometer with continuous bias, the noise bandwidth will be related to its time constant τ (Gao et al., 2011), shown in 2.9

$$B = \frac{1}{2\tau} \quad (2.9)$$

Temperature fluctuation noise. This is the noise from the heat exchange of the bolometer with its environment through conduction and radiation. This exchange is irregular and has a statistical nature causing temperature fluctuations. The rms voltage caused by this effect can be approximated with Eq.2.10(Bianchi et al., 2025)

$$V_{th}^2 = \frac{4k_B T_b^2}{G_{th}} V_{bias} \beta^2 B_{th} \quad (2.10)$$

where β is the thermal coefficient of resistance and V_{bias} is the voltage bias. The frequency

bandwidth for this noise B_{th} can be found in Eq. 2.11.

$$B_{th} = \frac{1}{4\tau} \quad (2.11)$$

Flicker noise. This type of noise is also known as low frequency noise or pink noise. It has the characteristic of decreasing as the frequency increases ($1/f$) (Bianchi et al., 2025). For a specific frequency f , the rms voltage can be found in Eq.2.12

$$V_{1/f}^2 = v_{bias}^2 \frac{n}{f} \quad (2.12)$$

where n is the $1/f$ noise constant of the bolometer array (Gao et al., 2011).

2.5 Photon Detectors

Infrared photon detector technology has been the subject of increasing interest in recent years due to its central role in astronomy missions. These technologies have recently been used in the James Webb telescope (Glasse et al., 2015) and the WISE mission (Wright et al., 2010). They offer low NEP and fast frame rate (Vollmer & Möllmann, 2018), however they need to be cooled down to cryogenic temperatures, particularly to detect the mid- and long-wave infrared section of the spectrum. This can drive up the complexity as well as mass and power of a potential payload.

2.5.1 Operating principle

Photon detectors differ fundamentally from resistive bolometers as they rely on the direct interaction between the incoming radiation and the semiconductor material of the pixel. Incoming infrared photons interact with the semiconducting material and they change its energy distribution. This creates a signal – usually a current – that can then be amplified (Vollmer & Möllmann, 2018). In practice, a photon needs to have enough energy to move a charge carrier, this sets a minimum energy threshold ΔE that photons need to have to be detected. The energy of a photon is dependent on its wavelength therefore the detector will be sensitive only until a certain cut off wavelength λ_{cutoff} as showed in Eq.2.13:

$$\lambda_{cutoff} = \frac{hc}{\Delta E} \quad (2.13)$$

Where h is Plank's constant and c is the speed of light in a vacuum.

The optical energy however is not the only one capable of exciting charge carriers. For detectors sensitive to longer wavelengths (above $3\ \mu m$), and as a consequence with low energy thresholds, thermal transitions contribute significantly to change the charge distribution in the material. This effect makes the detectors very noisy (Rogalski, 2003). To prevent the thermal generation of charge carriers these focal plans need to be cooled to at least $77^\circ K$ (Vollmer & Möllmann, 2018) for mid-wave infrared (3 to $5\ \mu m$) and long-wave infrared (8 to $14\ \mu m$).

2.6 Literature gap

While several studies have examined the use of infrared sensors for SSA, most have focused on characterizing target light signatures, supporting proximity operations, or detecting objects in GEO or from the ground. The literature does not yet address whether state-of-the-art uncooled bolometers are suitable for space-based SSA, particularly for orbit determination under adverse illumination conditions (e.g., during eclipse).

In this context, the specific case of deploying a bolometer thermal camera on a space platform in LEO to observe other LEO targets remains largely unexplored. Bolometers are attractive because they are cost-effective, can be mounted on small satellites without the need for cryogenic cooling, and could complement larger sensor networks by filling observational gaps when objects are not visible in reflected sunlight. To date, there has been little investigation into the feasibility and limitations of employing uncooled bolometers in space for this purpose. This gap highlights the need for a systematic assessment of their performance in the space environment, including sensitivity, noise characteristics, and operational constraints.

Chapter 3

Requirements

The main contribution of the thesis is the development of a sensor model and the related simulation pipeline. This model is developed in the context of Arca Dynamics operations. The payload under study has to meet the some specific needs of stakeholder – Arca Dynamics.

This Chapter delineates the constraints and requirements decided and agreed upon with Arca Dynamics that contextualize the project and justify some initial decisions. First the ConOps of the the mission this payload would be used for are outlined, then the payload requirements are presented. Finally, a trade-off is conducted to (1) choose a sensor available on the market and (2) size the telescope to meet the requirements.

3.1 ConOps

The observation strategy chosen is sidereal tracking as outlined in Section 2.2.1. The reason for its choice is its simplicity compared to object tracking. The simpler control loop makes it more suited for small satellites.

In any case, the orbit of the object is either not known before hand or not known precisely enough to calculate the attitude maneuver to track the object before it enters the FOV. In object tracking the maneuver would need to be done with an image based control loop such as the one proposed by Felicetti and Emami (2018). Therefore the target needs to be first visible in the image in a sidereal tracking configuration. This makes this strategy more suitable for an early feasibility assessment.

With this strategy for an observation to take place a series of actions need to happen. A standard observation sequence consists of the following steps.

1. **Tasking.** First the satellite is tasked to point at specified direction. The direction

is chosen depending on the target. If it is a known target the observation needs to update its position error in a catalogue, for example, the pointing direction is determined by the predicted position of the target. This is done to then perform orbit determination with the observations. The other possibility is often called survey mode. The observations serve to find new objects to add to the catalogue. To do this, the process is called initial orbit determination, which can be defined as the process of deriving the state of the target without prior information about its orbit.

2. **Observation.** Images are taken either continuously or during the time the objects is know to pass in the FOV.
3. **Pre-processing.** Subsequently the images are pre-processed to check if any object can be detected in them. This is usually done thresholding techniques based on the deviations from the mean background intensity, applied either at the line level or across the entire frame (Spiller et al., 2020). depending on the communication and computing capabilities of the spacecraft this can be done either on board or on the ground. The image is then analyzed to derive the two angles defined in Section 2.2.1.

3.2 Requirements

This section explores the initial requirements and constraints developed with the company to meet they needs.

3.2.1 Size requirements

The payload must be compatible with a CubeSat platform, with the constraint in this case set to a 16U configuration. This inherently imposes limitations on the payload's size, mass, and power consumption. The reason for these constraints comes from the total cost that the market for an application like this could support. While a precise figure is not provided in this work, the cost should be consistent with that of building and launching a 16U platform.

There are two reasons for this: (1) for space-based SSA to be effective, a number of satellites must be deployed to maintain observability of a large number of spacecraft. This means that the payload should be considered as part of a constellation rather than as a single expensive satellite. (2) The main advantage lies in being able to observe targets even during eclipse, reducing uncertainties when visible-light optical sensors are not oper-

ational. However, if the cost increases enough, alternative solutions such as ground-based radars become more attractive, raising the issue of opportunity cost.

The following requirements are derived from the available mass volume and power of the EnduroSat 16U platform (EnduroSat, 2025).

- The payload mass should be lower than 18 kg
- The payload volume should be smaller than $197 \times 197 \times 350 \text{ mm}^3$
- The average power needed should be smaller than 27 Watts

These requirements already rule out the possibility of using cryo-cooled detectors. With these constraints it is not possible to cool the sensor down to 77 K, the temperature usually needed for a photon detector to work in the infrared – Section 2.5.1.

3.2.2 Observation requirements

In order to explore the feasibility of an infrared payload for this application it is necessary to establish the fundamental observation requirements that the sensor must satisfy. If observations made with this payload meet these requirements the observation can be considered useful.

The first requirement concerns the duration for which a target object remains within the sensor's FOV. This parameter is critical, as it directly influences the success of the initial orbit determination process, which is the more demanding of the two intended applications of this payload—initial orbit determination and orbit determination. According to Arca Dynamics' algorithm, reliable initial orbit determination can be achieved if the object remains in the FOV for a minimum of 20 seconds:

- The target should remain in the field of view for a minimum of 20 seconds for the initial orbit determination to succeed.

The second requirement relates to the distance between the observer and the target. To ensure a sufficient number of targets can be observed a minimum useful distance of 100 km is set. In the context of LEO-to-LEO observations, closer encounters are relatively rare unless dedicated maneuvers are performed to reduce the separation. Conducting such maneuvers would defeat the purpose of the payload which is to conduct passive observations of targets without conducting target oriented orbital adjustment. The requirement is:

- The payload should be able to make observations of targets at distances greater than 100 km.

3.2.3 Payload performance requirements

In addition to observation requirements, the payload must also satisfy a set of performance requirements. These requirements specify the level of capability the sensor must achieve in order to work for this application and to generate useful data for orbit determination.

The first performance parameter concerns the spectral band in which the payload operates. According to the work of Yilmaz et al. (2019), the long-wave infrared (LWIR) region is the most effective for observing LEO objects, as their thermal emissions fall predominantly within this range. Consequently, the sensor must, at minimum, be capable of operating in the 8–14 μm wavelength band.

- The payload shall include an operational wavelength band in the range of 8–14 μm .

A second requirement addresses the spatial resolution of the detector, defined by the number of pixels in the focal plane array. Arca Dynamics is able to perform initial orbit determination from LEO to LEO observations with arrays of at least 800x800 pixels, which therefore sets the lower bound for this payload.

- The sensor shall employ an array of no fewer than 800x800 pixels.

Finally, the sensitivity of the sensor is determined by its detection threshold. A successful observation requires that the detected signal exceed the noise floor by a sufficient margin. Consistent with similar studies (Pineau & Felicetti, 2023), a signal-to-noise ratio (SNR) greater than 5 is adopted as the minimum criterion for detection.

- A target shall be considered detected when the observation achieves an SNR of at least 5.

3.2.4 Design requirements

The payload must also comply with a set of design requirements. These requirements specify the optical configuration in terms of field of view, aperture size, and focal ratio (F).

As mention in Section 2.2.1 the time of observation is constrained by the FOV. Therefore minimum FOV is set to ensure that the required observation time might be achievable. This is in accordance to previous payload design for the same application (Pineau & Felicetti, 2023).

- The minimum payload FOV should be of 5 degrees.

The Cub-sat constrain affects the maximum size of the aperture area of the telescope. Due to the volume constraints (Section 3.2.1), a maximum aperture area o 20 cm has been selected.

- The aperture diameter should not exceed 20 cm.

The final design constraint concerns the focal ratio, defined as the ratio between the focal length and the aperture diameter. To ensure the feasibility of manufacturing the telescope, the focal ratio is constrained to a minimum value of 1. Ratios below this threshold are uncommon in practice and significantly increase the complexity of the optical design.

- The focal ratio should not be lower than 1.

Table 3.1: Summary of Payload Requirements.

Req. #	Type	Derivation	Requirement
S-1	Size	Cost	The payload mass shall be lower than 18 kg.
S-2	Size	Cost	The payload volume shall be smaller than $197 \times 197 \times 350 \text{ mm}^3$.
S-3	Size	Cost	The average power consumption shall be lower than 27 W.
O-1	Observation	Orbit determination process	The target shall remain in the field of view for at least 20 seconds for initial orbit determination to succeed.
O-2	Observation	LEO-to-LEO application constraints	The payload shall be able to observe targets at distances greater than 100 km.
P-1	Performance	(Yılmaz et al., 2019)	The payload shall include an operational wavelength band in the range of 8–14 μm .
P-2	Performance	Orbit determination process	The sensor shall employ an array of no fewer than 800x800 pixels.
P-3	Performance	Pre-processing chain (Pineau & Felicetti, 2023)	A target shall be considered detected when the observation achieves an SNR of at least 5.
D-1	Design	O-1	The payload shall provide a field of view of at least 5° .
D-2	Design	S-2	The aperture diameter shall not exceed 20 cm.
D-3	Design	Optical manufacturing	The focal ratio shall not be lower than 1.

3.3 Un-cooled bolometer selection

While un-cooled bolometers have been used extensively for space application, large focal plane arrays that meet the requirements are more rare. One constraint that came up during the formulation of this work is the availability of performance data upon which a model can be based on. Therefore, in addition to the previously stated requirements another one is added on that has affected the sensor choice which is availability of public information about the bolometer.

In particular three crucial information were needed to build a model are (1) NEP values or data to calculate it from its noise components (1/f Noise, Jhonson noise, thermal fluctuation noise), (2) responsivity curve – relating input power to output signal in volts or counts –, and (3) thermal time constant.

There are two currently available sensors suitable to space applications that have been found to meet the requirements and at the same time have enough data availability: the Lynred ULIS PICO 1024 bolometer (Dartois et al., 2017) and The High-Definition Infrared Space Camera Core (HDISCC) by INO (Généreux et al., 2024). Table 3.2 summarizes the characteristics of the two sensors. It should be noted that the NEP for the PICO1024 is not explicitly given in Dartois et al. (2017) but has been derived by the author from the given mean temporal noise expressed in millivolt and the responsivity curve expressed in $\frac{V}{W}$.

Table 3.2: Comparison of two uncooled microbolometers. Data from Généreux et al. (2024) (INO) and Dartois et al. (2017) (ULIS)

Name	Size	Pixel pitch	Spectral band	NEP (pW)	Responsivity	τ (ms)	Power	Mass
INO HDISCC	1024×768	14 μm	2–14 μm	5.2 / 4.2	provided	10	1.7 W	1545 g
ULIS PICO1024	1024×768	17 μm	8.5–17.2 μm	6.3	provided	12	-	-

Both sensors satisfy the performance and size requirements. To choose between them, three key performance parameters are compared: operating spectral-band width, NEP, and thermal time constant.

A wider spectral band is desirable because it integrates more signal from a target of a given temperature, improving detectability. A lower NEP is preferable because it lowers the noise floor and enables detection of fainter signals; the detection criterion is set at $SNR \geq 5$. Finally, a smaller thermal time constant is advantageous, as it represents the time a pixel needs to approach its peak signal (approximately 5τ to reach about 99% of steady state). For fast LEO-to-LEO relative kinematics, this can be a limiting factor, as a target may not dwell on a pixel long enough to reach thermal equilibrium.

INO's sensor performs better in all three of these parameters as showed in Table 3.2. Furthermore extensive information are provided on how the testing campaign was conducted. This allows to make less assumptions in the model. It has very good space heritage as it is currently being used on earth observation missions.

3.4 Telescope Trade-off

With the sensor selected, the optical system must be sized to ensure that the payload can meet its performance and observation requirements. Within the constraints set by the requirements the sizing has the goal of finding a suitable focal length (f), aperture diameter (D) and field of view (ϕ). There are two competing design drivers:

Maximize field of view (FOV). A larger FOV increases the probability that a target remains within the sensor FOV for at least 20 seconds, the observation requirement.

Maximize aperture diameter. A larger aperture increases the amount of radiation collected by the telescope, thereby improving the signal level.

The field of view in each direction ($\phi_{1,2}$) can be expressed using a pinhole camera model (Pineau & Felicetti, 2023)0.25, where f is the focal length and $b_{1,2}$ are the sensor dimensions in the two axes. The sensor dimensions are obtained as the product of the pixel pitch and the number of pixels along each direction. Equation 3.1 shows that FOV is related to the focal length: reducing f increases the FOV.

$$\phi_{1,2} = 2 \arctan\left(\frac{b_{1,2}}{2f}\right) \quad (3.1)$$

The aperture diameter D is related to the focal length through the focal ratio $F = f/D$. The optical design is set at the minimum allowed focal ratio, $F = 1$. This ensures that, for a given focal length, the aperture is as large as possible, and conversely, for a given aperture, the FOV is as wide as possible. In this configuration, $f = D$, meaning that the focal length equals the aperture diameter.

This relationship creates a trade-space: decreasing the focal length increases the FOV but simultaneously reduces the aperture (since $f = D$). The telescope sizing problem therefore reduces to finding the balance between these two competing drivers. Figure 3.1 shows the tradespace.

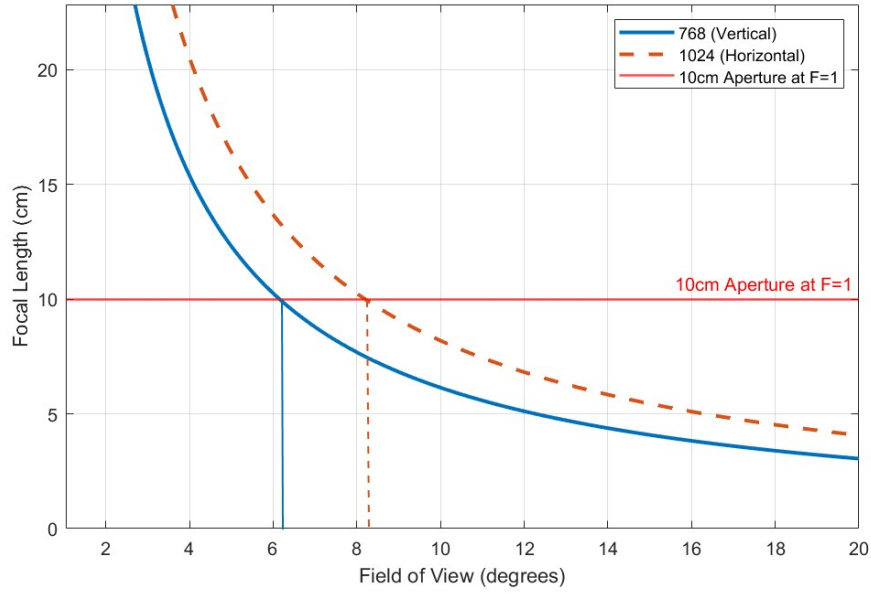


Figure 3.1: Focal length vs FOV

An aperture size of 10 cm was chosen to be a good balance between the need of maximizing FOV and aperture. This choice gives two directional FOV of $\phi_1 = 6.1$ and $\phi_2 = 8.2$ meeting the design requirement.

Table 3.3: Summary of camera system parameters (INO bolometer).

Parameter	Value
Detector size (pixels)	1024×768
Pixel pitch	$14 \mu\text{m}$
Spectral band	$2\text{--}14 \mu\text{m}$
Noise-equivalent power (NEP)	5.2 pW (MWIR), 4.2 pW (LWIR)
Thermal time constant	10 ms
Field of view (horizontal / vertical)	$8.2^\circ \times 6.1^\circ$
Focal length	10 cm
Aperture diameter	10 cm
F-number (F)	1

Chapter 4

Radiometric modeling of the target signatures

The electrical signal generated by a bolometer is directly proportional to the temperature variation of its sensing membrane. When a target object emits thermal radiation, a portion of this energy is absorbed by the bolometer, leading to an increase in the membrane's temperature and consequently altering the sensor's output.

This chapter is dedicated to quantitatively characterizing the amount of radiative power that effectively reaches the bolometric sensor from a given target. This analysis is essential for characterizing the Signal to Noise Ratio (SNR) of different observational scenarios and accurately modeling the bolometer's thermal behavior under radiative loading.

4.1 Thermal radiation

Every object with a temperature above absolute zero emits radiation. An ideal black body – defined as an object that absorbs all incident radiation – will emit radiation only depending on its temperature. The spectral radiance L_λ [$\text{W m}^{-2} \text{sr}^{-1} \text{m}^{-1}$] of a black body can be found using Planck's law (Rees, 2013):

$$L_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/(\lambda kT)} - 1}. \quad (4.1)$$

Where λ is the wavelength [m]; T is the absolute temperature [K]; $h = 6.62607015 \times 10^{-34}$ Js is Planck's constant; $c = 2.99792458 \times 10^8$ ms⁻¹ is the speed of light in a vacuum; and $k_B = 1.380649 \times 10^{-23}$ JK⁻¹ is Boltzmann's constant.

Figure 4.1 shows the spectral radiance of a black body at four different temperatures: 30

°C (303 K), 0 °C (273 K), −80 °C (193 K)—which span the range of surface temperatures of a LEO satellite—and 5778 K (solar temperature). It can be seen that, for most of the temperatures of interest, the radiance peaks in the long-wave infrared (LWIR) region of the spectrum, which spans from 8 to 14 μm . This region is fully included in the transmittance window of the sensor (Généreux et al., 2024).

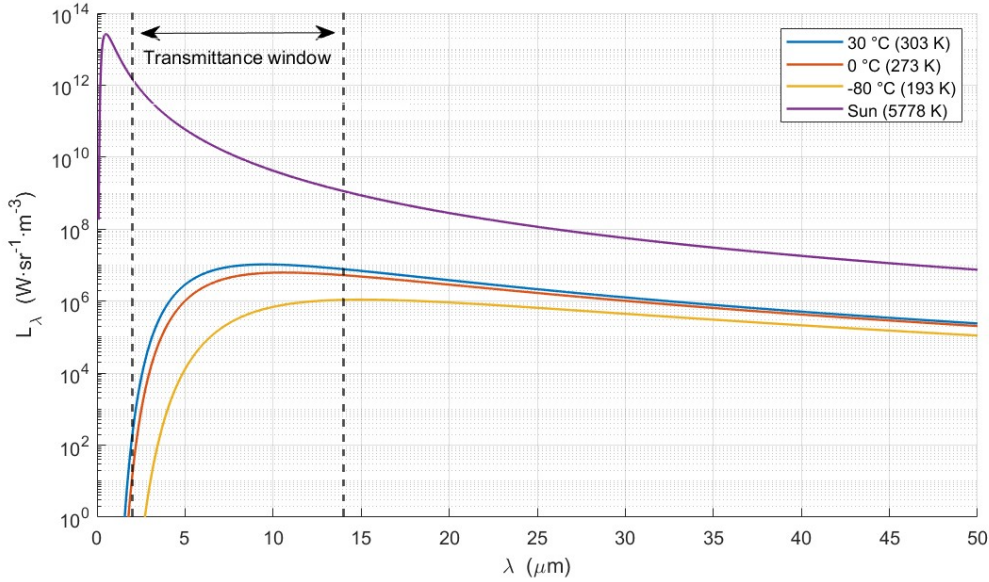


Figure 4.1: Black body spectral radiance for relevant temperatures

Equation 4.1 can be integrated over the entire wavelength spectrum to obtain the total radiance $L(T)$, which represents the total power emitted per unit area per unit solid angle:

$$L(T) = \int_0^{\infty} L_{\lambda}(\lambda, T) d\lambda \quad (4.2)$$

Radiance is a property of radiation and it stays constant as it propagates through a non absorbing and non scattering medium. It does not only represent outgoing radiation but also incoming radiation depending on the application (Rees, 2013).

4.1.1 Radiant exitance

To determine the total power emitted by the target surface, we introduce the spectral radiant exitance $M_{\lambda}(\lambda, T)$, which represents the radiant power emitted per unit area, per unit wavelength, into a hemispherical solid angle (Rees, 2013). Assuming the surface behaves as a Lambertian (perfectly diffuse) emitter the spectral radiance is independent of direction. Therefore the spectral radiant exitance can be found by the following relation

(Vollmer & Möllmann, 2018)

$$M_\lambda(\lambda, T) = \pi L(\lambda, T) \quad (4.3)$$

and integrating again over the whole spectrum the spectrum yields Stefan Boltzmann law

$$M(T) = \int_0^\infty M_\lambda(\lambda, T) d\lambda = \sigma T^4 \quad (4.4)$$

where $\sigma = 5.670374419 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$.

4.1.2 Real emission

Most materials do not behave as ideal black bodies; their emission depends on the surface properties of the material. The efficiency with which a material emits thermal radiation is characterized by its spectral emissivity, $\varepsilon(\lambda)$, defined as the ratio of the material's spectral radiant exitance $M_\lambda(\lambda, T)$ to that of a black body $M_{\lambda,bb}(\lambda, T)$ at the same temperature (Vollmer & Möllmann, 2018):

$$\varepsilon(\lambda) = \frac{M_{\lambda,real}(\lambda, T)}{M_{\lambda,ideal}(\lambda, T)} \quad (4.5)$$

Some materials exhibit behavior in which emissivity varies with wavelength; others, however, display grey-body behavior, meaning their emissivity does not deviate significantly from a constant value over the spectrum (or the wavelength band of interest). In this work, the target material is assumed to behave as a gray body, with a constant emissivity. Therefore relation 4.3 becomes

$$M_\lambda(\lambda, T) = \varepsilon \pi L_\lambda(\lambda, T). \quad (4.6)$$

4.1.3 View factor

Radiation from a diffuse surface is emitted in in an hemispherical solid angle, the aperture of the observing telescope only receives a fraction of the the total power emitted by the target. In order to find the fraction of radiant power emitted by the target surface into an hemisphere that reaches the cameras aperture a view factor can be applied to Eq 4.6. This dimensionless coefficient takes into account the geometry of the scene and represents the fraction of power emitted by an infinitesimal surface dA_1 that reaches another

infinitesimal surface dA_1 . It can be calculated with eq.4.7 (Vollmer & Möllmann, 2018):

$$F_{12} = \frac{1}{A_1} \int_{A_i} \int_{A_j} \frac{\cos \theta_1 \cos \theta_2}{\pi r^2} dA_1 dA_2 \quad (4.7)$$

Where r is the distance between the two surfaces and θ_1 , θ_2 are the angles between the normal to the surfaces and the line traced between the two surfaces as showed in fig.4.2

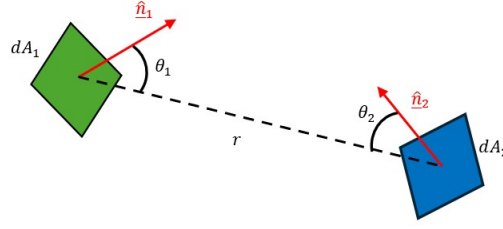


Figure 4.2: Geometry of radiative exchange between two surfaces

From the geometry of the scene, the Eq.4.7 can be expressed as Eq.4.9 (Bianchi et al., 2025). Furthermore, assuming that the surface receiving the radiation is the telescope's aperture area A_D and the distances between the surfaces are large enough, the view factor can be approximated to Eq.4.9.

$$F_{12} = \frac{1}{A_1} \int_{A_1} \int_{A_2} \frac{(\mathbf{n}_1 \cdot \mathbf{r}_{12})(\mathbf{n}_2 \cdot \mathbf{r}_{21})}{\pi \|\mathbf{r}\|^4} dA_1 dA_2 \quad (4.8)$$

$$F_{12} = \frac{(\mathbf{n}_1 \cdot \mathbf{r}_{12})(\mathbf{n}_2 \cdot \mathbf{r}_{21})}{\pi \|\mathbf{r}\|^4} A_D \quad (4.9)$$

4.1.4 Power at Aperture

Assuming the target's distance is sufficiently large, the radiant power intercepted by the optical aperture is obtained by integrating the gray body spectral exitance in Eq.4.6 over the detector pass-band and scaling the result by both the target area A_t and the corresponding view factor $F_{t \rightarrow lens}$. Because the bolometer focal-plane array is sensitive only in the $2 \mu m$ and $14 \mu m$ range (Généreux et al., 2024), wavelengths outside this window do not contribute to the measured signal; consequently, the integral is evaluated only between the lower and upper cut-off wavelengths λ_1 and λ_2 :

$$P_{aperture} = A_t F_{t \rightarrow lens} \epsilon \pi \int_{\lambda_1}^{\lambda_2} L_\lambda(\lambda, T) d\lambda. \quad (4.10)$$

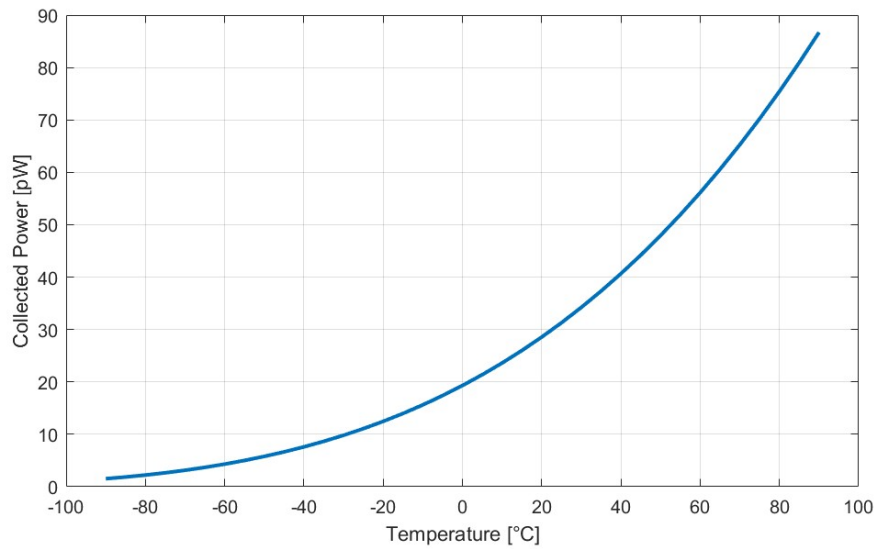


Figure 4.3: Power that reaches the aperture VS temperature for a 1 m^2 emitting area parallel to the aperture, $\varepsilon = 0.8$, distance 100 km

4.2 Power incident on the sensor

Once the radiation reaches the aperture, it propagates through a set of lenses — in the case of a refractive telescope — or is reflected by a series of mirrors if the telescope is reflective. In both cases, radiation is focused onto the focal-plane array.

Thermal cameras frequently incorporate additional optical filters designed to transmit radiation within specific wavelength band (Okada et al., 2017). Such filtering is employed to enhance signal quality. Depending on the specific application, isolating particular wavelength bands can be crucial either to exclude unwanted radiation or to accurately derive temperature measurements after appropriate camera calibration. Furthermore, the bolometer's pixels do not absorb all incident power, a portion gets reflected or it is lost in inefficiencies (Généreux et al., 2018). All these factors contribute to dampening the signal.

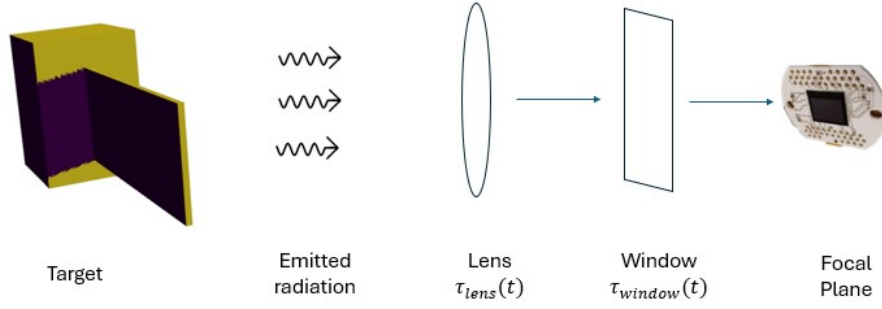


Figure 4.4: Radiation pipeline before reaching the sensor. (Généreux et al., 2024)

This application is dedicated to detecting objects traversing the field of view; consequently, no optical filters have been included in the imaging chain, since the primary objective is to maximise overall optical throughput within the broad transmittance window of the bolometer. Moreover, because the sensor is pointed toward the cold dark sky (2.725 K (Fixsen, 2009), most of the power falls outside the transmittance window), the only significant radiation reaching the detector will originate from the target objects. The incident power at sensor – defined as the power that reaches the detector after the optical pipeline – is (Bianchi et al., 2025):

$$P_{inc} = A_t F_{t \rightarrow lens} \epsilon \pi \int_{\lambda_1}^{\lambda_2} L_{\lambda}(\lambda, T) \tau_{lenses}(\lambda) \tau_{window}(\lambda) d\lambda, \quad (4.11)$$

where $\tau_{lenses}(\lambda)$ is the optical throughput of the lenses and $\tau_{window}(\lambda)$ is the optical transmittance of the Germanium window in front of the focal plane.

4.2.1 Optical throughput

In any imaging system, each optical element (lenses, mirrors, windows, coatings, etc.) absorbs or reflects a fraction of the incoming radiation. The combined effect of these losses is described by the optical transmittance (or throughput) function, $\tau(\lambda)$, which represents the fraction of power at wavelength λ that reaches the detector. A system with perfectly lossless optics would have $\tau(\lambda) = 1$ for all λ , whereas real systems exhibit $\tau(\lambda) < 1$, often varying across the spectral band of interest.

Infrared optics are typically made from germanium, which provides high transmittance in the infrared. With an anti-reflective coating—to minimize reflectance (the fraction of photons reflected when radiation strikes the optic)—transmittance can exceed 90 %, covering most of the wavelength band of interest (Edmund Optics, n.d.). Figure 4.5 shows

the typical transmittance of a coated germanium lens from Edmund Optics and illustrates a mostly constant behavior of transmittance across the spectrum of interest. Therefore, for this analysis, a constant value of $\tau(\lambda) = 0.9$ has been chosen as an approximation.

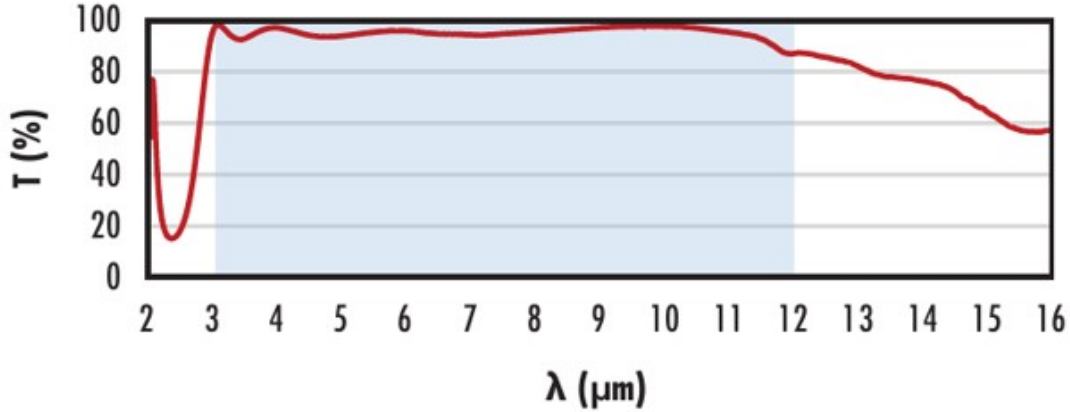


Figure 4.5: Typical transmittance of a coated germanium lens from Edmund Optics (Edmund Optics, n.d.)

Furthermore High-Definition Infrared Space Camera Core (HDISCC) is packaged by INO in a vacuum behind a germanium window. This window has typical transmittance of 92% and always greater than 85% in the band of interest (Généreux et al., 2024). Because the transmission curve is not available, a value of $\tau_{window}(\lambda) = 0.85$ has been chosen as a conservative approximation. This analysis assumes that the telescope is a refractive one, but similar considerations and results can be achieved by a reflective telescope using gold coated mirrors. It is important to note that there are other factors that contribute to decreasing the signal, however, at this stage, they are not taken into account because of how the testing campaign of the bolometer is conducted (which will be explained in the following Section).

4.3 Signal to Noise Ratio

The Signal to Noise Ratio can be a powerful tool that informs whether or not an object can be seen and how well. This section explores how SNR is calculated in this analysis using the parameters provided by the manufacturer. It should be noted that this methodology is only valid given these parameters. In other testing campaigns the same parameters (eg. Noise Equivalent Power) could be defined in different ways or calculated at different stages of the optical chain.

4.3.1 Testing

To correctly determine SNR it is first necessary to outline how the testing campaign was done in regards to two main parameters measured by INO (Généreux et al., 2024):

- **Noise Equivalent Power:** INO defines and measures NEP as the power incident on the detector that gives rise to a $\text{SNR} = 1$. During the laboratory test the array is mounted in its vacuum package; a temperature-controlled black-body illuminates the detector while a fixed-diameter baffle sets an f-number of 1. The temperature of the black body is changed and the value of that incident power which gives a pixel-level $\text{SNR} = 1$ is calculated, counting for the baffle geometry and the transmission.

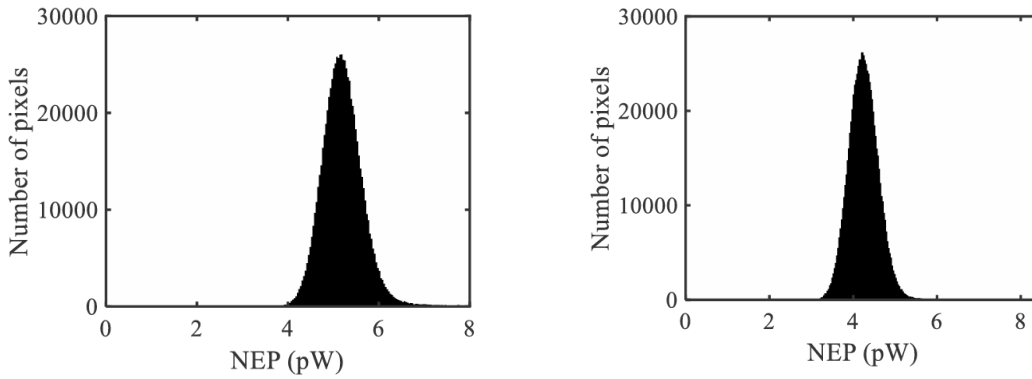


Figure 4.6: Noise equivalent power for MWIR (left) and LWIR (right)(Généreux et al., 2024)

Figure 4.6 shows the distribution of the NEP on the pixels of the focal plane array. The median NEPs are $NEP_{MWIR} = 5.2$ pW and $NEP_{LWIR} = 4.2$ pW. This suggests that the NEP is dependent on the wavelength probably due to the spectral absorption of the detector. However it does not deviate much from the given values (approximately 1 pW across the transmittance window (INO, 2025)). Therefore an average NEP of $NEP_{window} = 4.7$ pW has been used as an approximation of the NEP over the whole transmittance window.

- **Signal-Transfer Function (SiTF)** is the per-pixel responsivity curve that links a bolometer's digital output (counts) to the optical power that actually arrives at the membrane; its slope ($\frac{\text{counts}}{\text{nW}}$ in this case) represents how many counts are generated per watt of incident radiation once the pixel has reached thermal equilibrium. INO measures this slope in a laboratory setup where the packaged focal-plane array (with its germanium window but no external imaging lens) views a temperature-controlled

black-body through an f/1 baffle. For each of the black-body temperatures they acquire 30 frames with the shutter closed (to capture drift) and 30 with it open, subtract the closed-frame average from the open-frame average to obtain a “differential signal” map, and then perform a linear regression of that differential signal versus the known irradiance reaching the detector plane; accounting for geometry and transmission they are able to determined the SiTF in Figure4.7. Therefore, the power considered is relative to the power incident on the membrane.

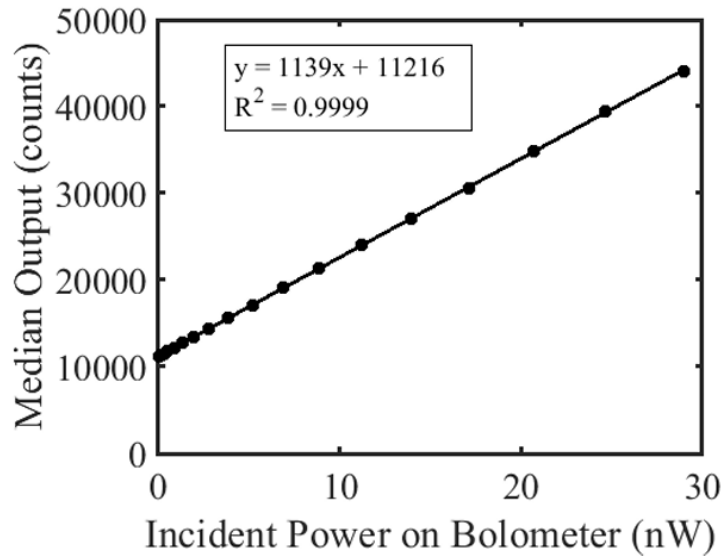


Figure 4.7: Signal Transfer Function (Généreux et al., 2024)

Because of how these two parameters are calculated the Eq. 4.11 does not account for the bolometer absorption and other inefficiencies as they are included in the NEP and the slope of the SiTF.

4.3.2 SNR

Finally, with the assumption that the signal is concentrated on only one pixel and that the object stays on the pixel for at least 5 time constants (1 % error on the thermal equilibrium), the Signal to Noise ratio can be determined by the Eq. 4.12

$$SNR = \frac{P_{inc}}{NEP_{window}} \quad (4.12)$$

Chapter 5

Technology limitations

With the model developed in Chapter 4, it is possible to perform preliminary analyses—under certain assumptions—to determine the capabilities and limitations of the technology. This analysis aims to identify the conditions under which INO’s uncooled bolometer is effective for object detection.

5.1 Assumptions

For the analyses in the following sections, some additional assumptions are made beyond those introduced previously. Understanding the effects of these assumptions is crucial to appreciating the limitations of the study. The assumptions are as follows:

- **Single-pixel illumination.** All incident power is assumed to fall onto a single pixel. Since the field of view is relatively large and the optics fast ($F/1$), the point-spread function concentrates most of the energy on one pixel. This approximation slightly overestimates the SNR but allows for a tractable preliminary analysis.
- **Thermal equilibrium.** Each pixel is assumed to reach thermal equilibrium, meaning the target remains within the pixel’s field of view long enough (at least 5τ to be considered in thermal equilibrium). This scenario corresponds to relatively slow-moving objects and may not hold for all space-based observations. It depends on the relative motion between observer and target, but it simplifies the calculations for this initial evaluation. This assumption will be revisited in later sections.
- **Projected target area.** The target area is taken to be the object’s projected area, i.e., the area effectively seen by the detector. Depending on the object’s shape and viewing angle, this may overestimate or underestimate the true emitting area. From a numerical prospective this means that the angle θ_1 defined in Section 4.1.3 is

$\theta_1 = 0$. Furthermore, it is assumed that $\theta_2 = 0$ as well. This angle represent the angle from the vector exiting the center of the camera frame. This angle is limited by the FOV, and it will have values that will not deviate from 0 substantially.

- **Uniform temperature.** The target's temperature is assumed constant over the projected area, representing an average temperature.
- **Thermal radiation only.** Because the study focuses on adverse illumination conditions—specifically, situations in which the target is either in eclipse or viewed at an unfavorable phase angle—the signal is therefore treated as arising solely from the target's thermal emission.

All of these assumptions influence the bolometer's performance results and they must be interpreted in light of the assumptions made. However this simplified model provides a useful overview of the technology's capabilities.

5.2 SNR vs Distance

The first set of results show how the signal-to-noise ratio (SNR) changes with distance for given temperatures in the temperature range of a LEO satellite and a 1 m^2 projected target area. In Figures 5.1 to 5.6 The different colored lines represent the different possible emissivities of the materials and the SNR thresholds of 1 and 5 are highlighted. A SNR of 5 is chosen as the minimum to label the object as visible (Pineau & Felicetti, 2023). The black dotted lines show the maximum distance at which an object is visible for the minimum emissivity (black) and maximum emissivity (pink).

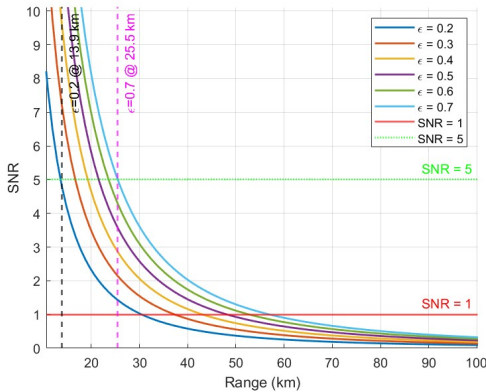


Figure 5.1: SNR vs Distance for different emissivities for a 1 m^2 projected area at $T = -90^\circ\text{C}$

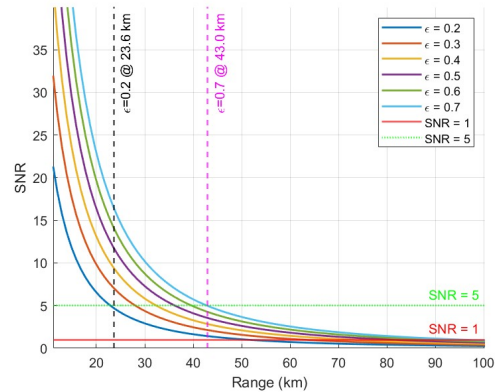


Figure 5.2: SNR vs Distance for different emissivities for a 1 m^2 projected area at $T = -60^\circ\text{C}$

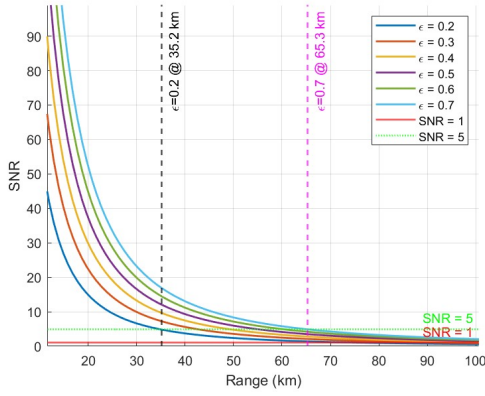


Figure 5.3: SNR vs Distance for different emissivities for a 1 m^2 projected area at $T = -30^\circ\text{C}$

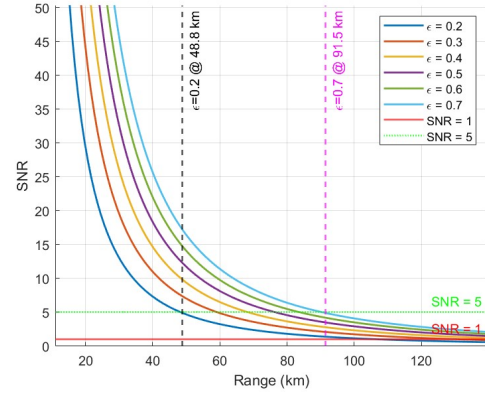


Figure 5.4: SNR vs Distance for different emissivities for a 1 m^2 projected area at $T = 0^\circ\text{C}$

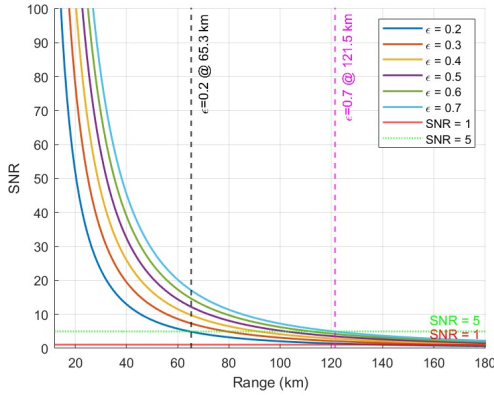


Figure 5.5: SNR vs Distance for different emissivities for a 1 m^2 projected area at $T = 30^\circ\text{C}$

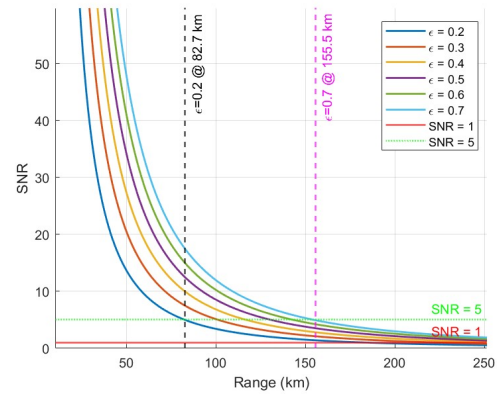


Figure 5.6: SNR vs Distance for different emissivities for a 1 m^2 projected area at $T = 60^\circ\text{C}$

The data in Figures 5.1 to 5.6 show that the SNR obeys an inverse-square dependence on the Observer–target separation r ,

$$\text{SNR}(r) \propto r^{-2},$$

as anticipated from the view-factor expression in Eq.4.9. The same figures further indicate that, for target surface temperatures below 0°C — a range typical of photovoltaic arrays in eclipse, which are usually the dominant contributors to the optical cross-section (Kim & Han, 2010a) — the practical observation distance is limited to less than 100 km.

Encounters at such short ranges are relatively infrequent, because they require the observer and target either (i) to share nearly identical orbital elements or (ii) to reach the

line of nodes simultaneously. Therefore, the proposed sensing configuration is most effective for detecting spacecraft in eclipse whose projected area exceeds 1 m^2 .

5.3 Minimum Area vs Range

The second set of results coming from this simplified model show what is the minimum projected area necessary for the object to be considered visible at a distance of 100 km. The distance of 100 km has been chosen because it is considered as the minimum useful distance for this application. Detectability, as mentioned before, is defined at $\text{SNR} = 5$. Figure 5.7 Show the minimum detectable area for the temperatures range that a LEO satellite might have.

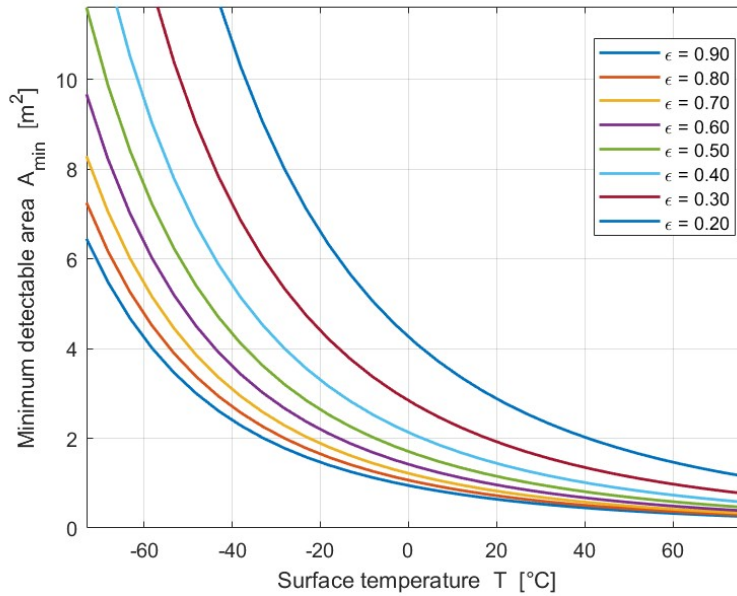


Figure 5.7: Minimum area vs temperature that results in an $\text{SNR} = 5$ at a distance of 100 km

During eclipse solar panel's temperatures can reach $T = -70^\circ\text{C}$ (Kim & Han, 2010a). Their emissivity in the infrared can be as low as 0.7 depending on surface properties and degradation. Taking this emissivity value –represented by the yellow line – it can be seen that in order to have visibility over the full time in eclipse the minimum detectable area needs to be upwards of 8 m^2 . Thus suggests that only large satellites are fully visible over the full duration of the eclipse if the geometry allows.

5.3.1 High temperatures

It is instructive to examine the minimum detectable area at elevated temperatures (right side of Figure 5.7). Although this technology is inherently more limited than visible-light detectors, it remains effective when the target is illuminated. Under such conditions, surface temperatures can reach up to 70°C . With proper camera calibration, it is possible to estimate the target's temperature—at least differentially relative to other observation of the same object—enabling the identification of active payloads. This capability is valuable even at night, when a satellite may continue to operate certain subsystems. For instance, some antennas can reach 80°C during operation.

Figure 5.8 illustrates the minimum required area at higher temperatures. For high emissivity values, this area falls below 0.5 m^2 . Such projected areas are achievable even in CubeSats equipped with comparatively large solar panels.

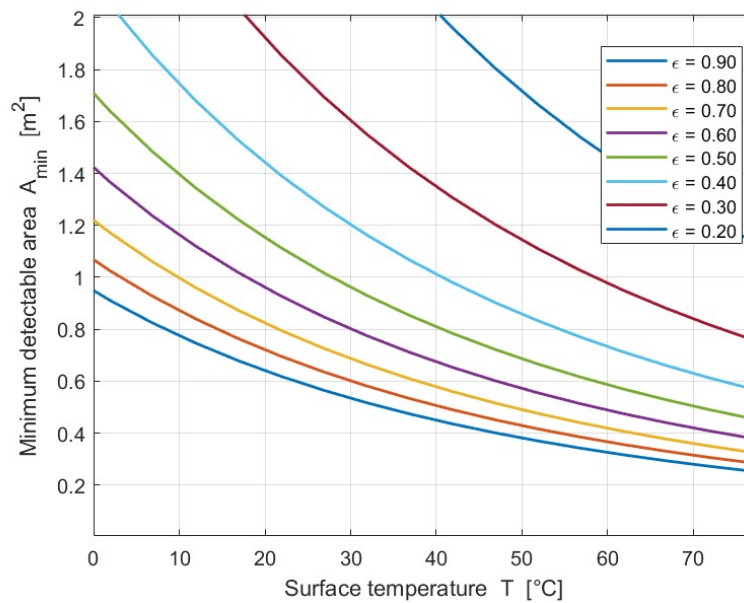


Figure 5.8: Zoomed minimum area vs temperature that results in an $\text{SNR} = 5$ at a distance of 100 km

Chapter 6

Bolometer Response

The model presented in Chapter 4 enables rapid estimation of signal-to-noise ratios (SNR) for various target sizes and distances. However, it does not account for two effects that can significantly influence the SNR: the thermal behavior of the bolometer membrane and the impact of the readout architecture on the measured signal.

First, if a pixel does not reach thermal equilibrium the SNR could significantly decrease, the recorded signal will not correspond to the instantaneous power incident on the focal plane. Given the potentially high relative velocities between observer and target in space-based applications, this transient response can become a critical factor. Second, the focal plane is read out not instantaneously but over a finite integration time in a rolling-shutter configuration; during the thermal transient, this readout scheme further modifies the captured signal.

This Chapter introduces an extended model that incorporates these dynamics to generate realistic synthetic images complete with diffraction spreading, transient thermal response, readout timing, and noise modeling. The modeling pipeline consists of the following steps:

1. **Diffraction-limited spreading.** The incident radiant power is spatially distributed according to the system's point-spread function.
2. **Thermal transient response.** The membrane thermal state is modeled accounting for the time-dependent response, thereby accounting for the detector's thermal time constant.
3. **Rolling-shutter and integration.** The focal plane readout is simulated in a rolling-shutter configuration, coupled with a CTIA integration model to capture pixel-wise exposure timing.

4. **Noise addition.** Noise is added with a simplified noise model that keeps SNR evaluations consistent.
5. **Signal conversion.** The analog temperature signals are converted to digital counts via the calibrated signal-transfer function provided by the manufacturer.

Together, these steps produce synthetic frames whose spatial, temporal, and noise characteristics closely emulate those of an actual spaceborne bolometer array. This methodology enables a more accurate, time-varying SNR characterization for fast-moving objects and permits robust prediction of target detectability under realistic operating conditions.

6.1 Diffraction limited power distribution

When parallel electromagnetic plane waves encounter a finite circular aperture and are subsequently imaged onto a focal plane, they are not brought to a single geometric point. The spatially varying phase across the aperture introduces phase differences; the radiation interferes with itself and generates a characteristic diffraction pattern (Rees, 2013)(Goodman, 2005).

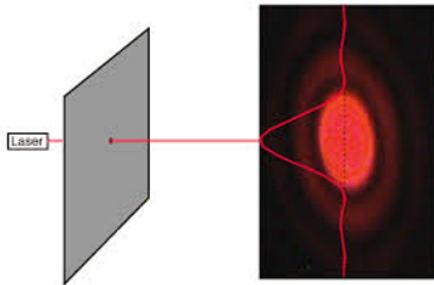


Figure 6.1: Diffraction pattern (Airy disk) produced by a circular, diffraction-limited aperture. Bright rings correspond to constructive interference; dark rings correspond to destructive interference (Nave, n.d.).

Figure 6.1 shows the intensity distribution recorded on the detector for a distant point source due to diffraction. This distribution is known as the point spread function (PSF) (Song et al., 2024). Because diffraction is fundamental to wave propagation, a diffraction-limited PSF places a hard limit on the spatial resolution of any imaging system (Goodman, 2005). For a circular pupil of radius a , the monochromatic, diffraction-limited PSF is called the Airy pattern (Wertz et al., 2011). In many engineering analyses the Airy pattern is approximated by a two-dimensional Gaussian having a similar energy distribution (Wang & Atkinson, 2017):

$$\text{PSF}_G(x,y) = \frac{1}{2\pi\sigma^2} \exp\left[-\frac{x^2+y^2}{2\sigma^2}\right], \quad (6.1)$$

where (if using pixel coordinates) σ can be expressed as (Lee et al., 2022):

$$\sigma \simeq 0.45 \frac{F/\#\lambda}{p}. \quad (6.2)$$

Here, $F/\#$ is the focal ratio of the system, λ is the mean operating wavelength, and p is the pixel pitch of the focal-plane array.

6.1.1 Power distribution

Assuming the radiation coming from the target satellite is in parallel rays (the far field assumption (Rees, 2013)) and the radiation can be approximated as coming from a point source (the satellite's projected areas are often much smaller than the projected instantaneous field of view of the pixel), it is possible to spread the power in Eq. 4.11 on the focal plane using a gaussian kernel constructed with Eq. 6.1. Furthermore, to maintain sub pixel accuracy of the centroid, the kernel is constructed with an over-sampled grid of smaller virtual pixels that are then binned into the original pixels as showed in Figure 6.2

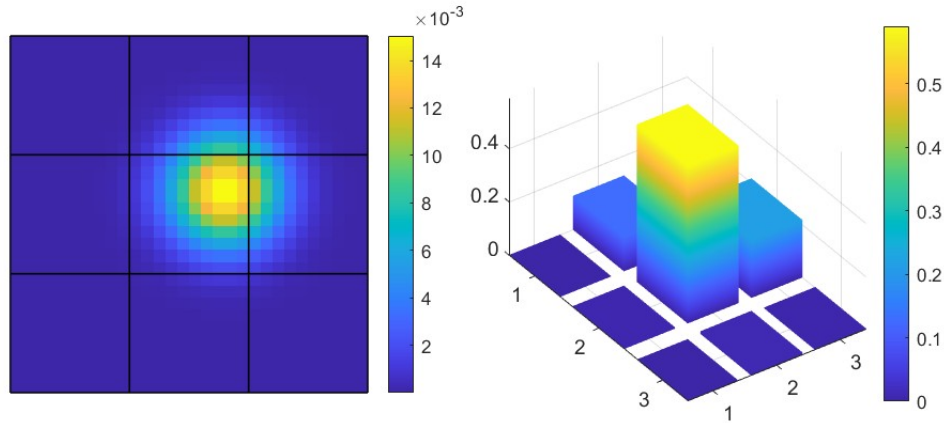


Figure 6.2: Fine gaussian kernel with a fine grid (30 x 30) (left), pixel intensity distribution once binned on to original pixels (right) in normalised units

6.2 Thermal power map

Bolometers derive the temperature of each pixel by applying a voltage bias to the pixel's membrane and measuring the resulting change in current or voltage, since the electrical resistance of the membrane is temperature-dependent. This distinguishes bolometers from photon detectors: when a bolometer pixel is read out, it is not reset. Therefore, aside from self-heating due to the Joule effect from the bias, the pixel's membrane thermal state evolves independently of the readout circuit. To accurately simulate the signal measured by the bolometer, a model of the membrane is presented in this section.

6.2.1 Membrane's model

Because of the thermal inertia of each sensing element, a change in the incident power on a pixel does not produce an equivalent instantaneous change in signal (Ramanagopal et al., 2020). Instead, a micro-bolometer behaves as a first-order dynamic system whose transient follows an exponential response as illustrated in Figure 6.3 (Généreux et al., 2018).

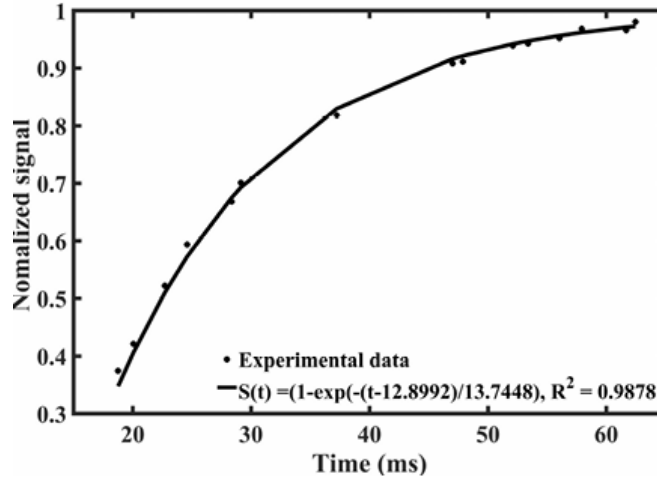


Figure 6.3: Example of empirical testing of the response of a bolometer's pixel (Généreux et al., 2018)

To model this behavior each pixel can be approximated by a heat sink with thermal capacity C that exchanges heat with its surroundings and has a resistance R – just as multiple authors have employed in their work (Krapeza, 2025; Lee et al., 2022; Ramanagopal et al., 2020). The temperature change $\Delta T(t)$ of the membrane due to a change in power absorbed $P(t)$ on the detector can be found by solving the following equation (Krapeza, 2025):

$$C \frac{d\Delta T}{dt} = P(t) - \frac{\Delta T(t)}{R} \quad (6.3)$$

Assuming that the joule effect is perfectly compensated the solution can be expressed as follows (Krapeza, 2025) :

$$T(t) = \frac{1}{C} \int_{-\infty}^t P(t') \exp\left[-\frac{t-t'}{\tau}\right] dt', \quad (6.4)$$

where τ is the bolometer time constant which is equivalent to:

$$\tau = RC \quad (6.5)$$

INO's HDISCC in particular has a time constant of $\tau = 10ms$ (Généreux et al., 2024). Equation 6.4 suggests that the thermal state of the membrane at time t is dependent on the current power being absorbed by the bolometer and its previous history.

Assuming that the signal has a linear relation to the temperature of the sensing membrane, the signal $S(t)$ can be expressed as (Krapeza, 2025):

$$S(t) = \frac{\alpha}{\tau} \int_{-\infty}^t P(t') \exp\left[-\frac{t-t'}{\tau}\right] dt' + \beta, \quad (6.6)$$

With α and β the coefficients that relate absorbed power to the output signal that can be found through calibrating the camera. The signal transfer function that is provided (the camera calibration) – as detailed in Section 4.3.1 – relates the signal $S(t)$ in counts to the incident power on the membrane $P_{inc}(t)$ (Généreux et al., 2024):

$$S(t)_{counts} = 1139 P_{inc}(t) + 1126 \quad (6.7)$$

This relation is valid when the membrane is in thermal equilibrium. It is therefore convenient to use the power incident on the bolometer $P(t)_{inc}$ in Eq.6.6 instead of the power absorbed $P(t)$. This can be done without changing the physics with the assumption that the efficiency factor η that differentiates the incident and absorbed power is constant. This efficiency factor is included in the slope of the signal transfer function in Eq.6.7. It is then possible to define the variable $\Phi(t)$ [W] which represent the equivalent thermal equilibrium power incident on the membrane.

$$\Phi(t) = \frac{1}{\tau} \int_{-\infty}^t P_{inc}(t') \exp\left[-\frac{t-t'}{\tau}\right] dt' \quad (6.8)$$

To be able to implement Eq.6.8 numerically, we can discretise the time in uniform interval Δt and assume that the power incident $P_{inc}(t)$ is constant within each interval:

$$t_k = k\Delta t, \quad P_{inc}(t) = P_{k-1}, t \in [t_{k-1}, t_k).$$

Finally $\Phi(t)$ at time step t_k can be found by solving the integral in Eq. 6.8:

$$\Phi_k = a\Phi_{k-1} + (1-a)P_{k-1}, \quad a = e^{-\Delta t/\tau}. \quad (6.9)$$

Using Eq.6.9 is possible to simulate a thermal power map in units of power [W] that represents the thermal state of the bolometer membrane at any time t that depends on the current power incident on it and its history. It is possible to extend $\Phi(t)$ to represent the focal plane state with a 2 dimensional temperature power map that is updated at every time step: $\Phi(x, y, t)$, where x and y are the pixel coordinates.

Figure 6.4 Shows an example of the effective power that is transformed into signal due to the evolving state of the membrane of a pixel. It can be noticed that for inputs lasting one or two times the time constant (10 or 20 ms) there is a significant decrease in peak power recorded. This can significantly affect the SNR. It should be noted that that this behavior is in line with other works regarding bolometers (G  n  reux et al., 2018; Krapeza, 2025; Oswald-Tranta et al., 2010; Ramanagopal et al., 2020; Vollmer & M  llmann, 2018). Figure 6.5 also shows an example of a fast moving object in the FOV. It can be noticed that the streak the object leaves is comet-like. This is due to the fact that once the source of radiation stops illuminating a pixel, due to the thermal inertia, the pixel still outputs a signal. This is also in line with the works presented by Lee et al. (2022) and Oswald-Tranta et al. (2010).

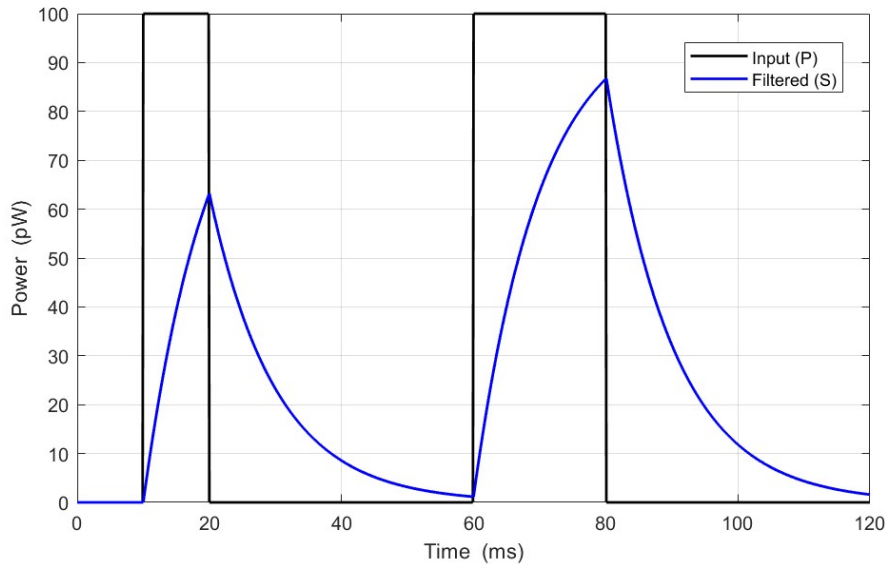


Figure 6.4: Example of the response of a pixel to two step inputs lasting 10 ms and 20 ms of the same magnitude of 100 pW using the membrane's model

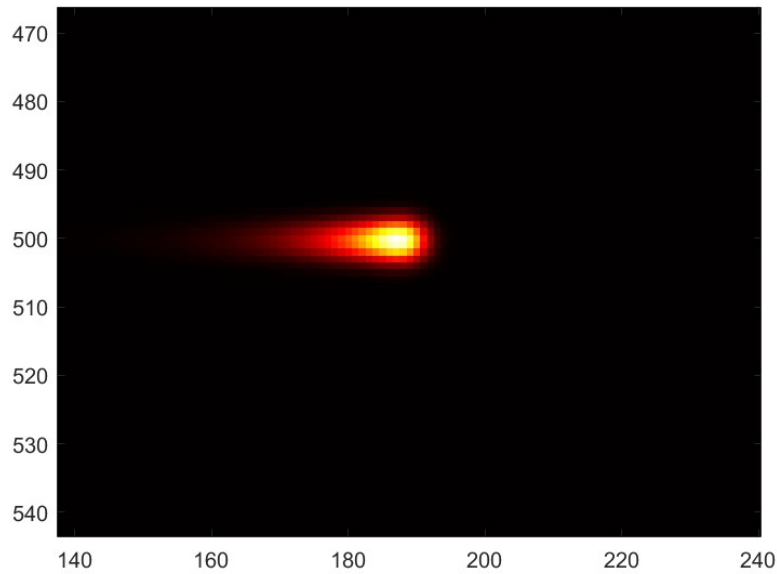


Figure 6.5: Example of thermal power map of the focal plane due to a fast moving object across the FOV

6.3 Rolling shutter and integration

A bolometer camera employs a read-out integrated circuit (ROIC) with a capacitive transimpedance amplifier (CTIA) to convert each pixel’s temperature-dependent resistance change into a measurable signal (Boudou et al., 2019). By applying a bias voltage across the bolometer (the pixel), a small sensing current flows and is integrated onto a capacitor within the CTIA; the resulting voltage on that capacitor is then digitized as the raw pixel signal.

To remove any offsets introduced, for example, by the temperature of the pixel without incoming radiation and Joule self-heating when the bias is applied, a blind pixel—shielded from incoming infrared—is read out in the same way and its voltage output is subtracted from each active pixel’s voltage, isolating the true thermal response of the scene (Dartois et al., 2017).

6.3.1 Shutter

INO’s camera operates in a rolling-shutter configuration. The pixels in each line are biased simultaneously, one line at a time. As soon as the biasing of one line ends, the next line is biased, its current is read, and the signal is digitized. Rolling shutter affects the image—especially when imaging fast-moving objects—and, while it doesn’t directly

impact SNR, it can produce distorted or blurred scenes (Peeters et al., 2017).

Therefore, to simulate a frame from the thermal power map described in the previous section, the map is sampled one line at a time to include this effect. Consequently, the time required to capture one frame equals the time needed to bias all of the lines. The camera's frame rate is configurable; however, changing it alters the integration time and, thus, the camera's responsivity and noise (Boudou et al., 2019; Dartois et al., 2017). It should also be noted that while it is configurable, it is constrained by physical limits: if too high the integration time would be very low, significantly reducing responsivity, if too low biasing would produce a significant amount of heat affecting the image and increasing noise. In addition, if the frame rate is adjusted, the camera must be re-calibrated. For this analysis, the frame rate is kept at the manufacturer's specified 30 Hz in order to keep the the provided values of noise and SiTF consistent.

6.3.2 Integration

The integration time – the time each pixel is biased with a set voltage – depends on the frame rate and it is found for this specific camera and frame rate with with Eq. 6.10 (Boudou et al., 2019):

$$t_{int} = \frac{1}{n_{line} f_{ps}} = \frac{1}{768 \times 30} = 43.4 \mu s \quad (6.10)$$

Where n_{line} is the number of pixel's lines in the focal plane and f_{ps} is the frame rate.

During integration time the pixels are biased and the charge from the bias current is accumulated in a capacitor. Later the corresponding voltage across the capacitor is measured. This has an effect on the effective signal and it therefore needs to be modeled accordingly. The output of the CTIA can be described by Eq. 6.11 (Généreux et al., 2016).

$$V_{out}(t_i) = \frac{1}{C_f} \int_0^{t_i} \left[\frac{V_a}{R_a(t)} - \frac{V_b}{R_b(t)} \right] dt \quad (6.11)$$

Where $V_{out}(t_i)$ is the pixel voltage sampled at the end of the integration window t_i ; C_f is the feedback capacitance that accumulates charge; V_a and V_b are the bias voltages values across the active and the blind pixel respectively and $R_a(t)$ and $R_b(t)$ the time and temperature dependent resistances.

The integral represents the total differential charge collected over t_i . The resulting current is integrated in the capacitor, for this reason the resulting voltage is proportional to the

average difference between the active-pixel and blind-pixel currents. When the pixel is in thermal equilibrium, the peak output voltage simply tracks the peak incident power, so integrating over the window does not change the measured value. During a thermal transient, in contrast, the CTIA sums the varying current across the entire integration time; the output voltage therefore represents the time-averaged bolometer temperature over that period and is proportional to the corresponding average effective radiant power $\Phi(t)$ (Section 6.2.1) reaching the bolometer.

To model this behavior every pixel in the temperature power map described in Section 6.2.1 is sampled twice during the integration time and the average of these two values is stored as the incident power signal for that frame $F(x, y, t)$ [W]

6.4 Noise

There are three main sources of noise in bolometers cameras (Bianchi et al., 2025)(Ringqvist et al., 2018)(Vollmer & Möllmann, 2018):

- **Johnson noise:** It is caused by fluctuations of the charge carriers in any resistor at temperature T . It can be modeled as a gaussian distribution $N(0, \sigma_{johnson})$ (Ringqvist et al., 2018)
- **Thermal-fluctuation:** Caused by Random heat flow between the membrane and the substrate. It also follows a Gaussian distribution $N(0, \sigma_{th})$ (Bianchi et al., 2025).
- **Pink (1/f) noise:** It is present in most electrical circuits, it has a power spectral density inversely proportional to the frequency creating slow drift and frame-to-frame correlation (Ringqvist et al., 2018).

The value of NEP provided includes the contribution of all of these noises. A simplified model has been chosen to represent the total noise in the image. It is modeled as a Gaussian distribution with mean 0 and standard deviation $\sigma = NEP$. Spatially it correctly models Johnson noise and thermal fluctuation noise. The slow drift effect however it is not captured. Nevertheless it keeps SNR evaluation constant and still allows to determine whether an object is visible. Figures 6.66.7 show the noise distribution in units of power.

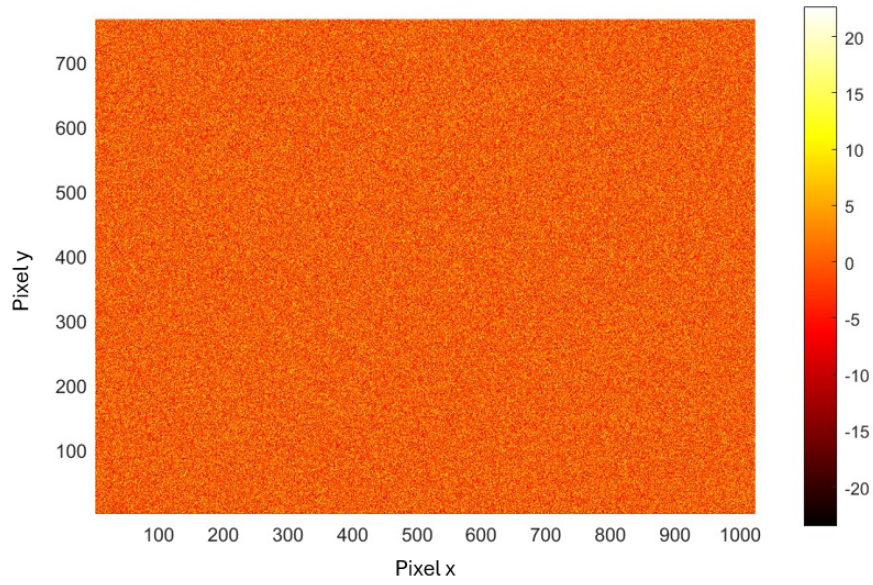


Figure 6.6: Noise distribution on the focal plane in pW

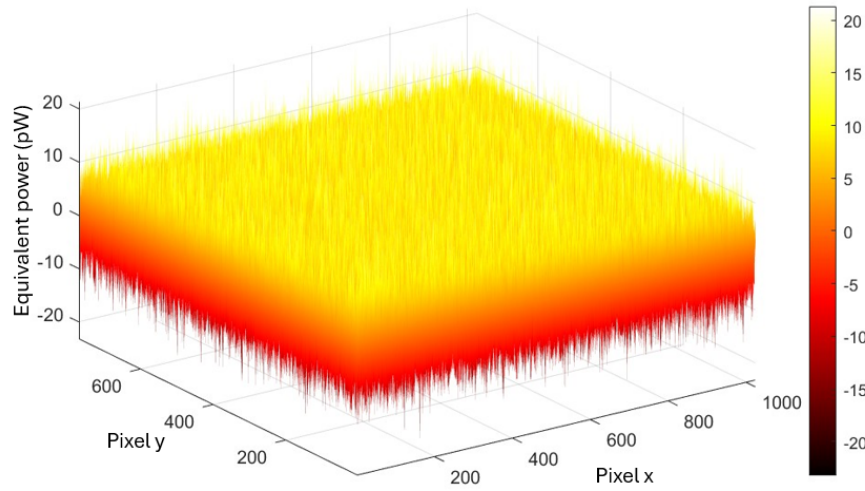


Figure 6.7: Noise distribution on the focal plane in pW plotted in 3D in pW

To make the final synthetic images noise is added to the frames after the the thermal power map is sampled. The signal in units of power is equal to:

$$S(x,y,t)_{power} = F + Noise \quad (6.12)$$

6.5 Signal conversion

Finally the signal in units of power can be converted onto digital counts with the SiTF.

$$S(t)_{counts} = 1139 S(t)_{power} + 1126 \quad (6.13)$$

With this final step this extended model allows us to do two things. First, depending on the target trajectory in the field of view it allows us to estimate the SNR when thermal equilibrium is not reached, accurately accounting for the thermal state and integration effects. Second, it generates synthetic images in counts – the digital output of the detector – of the target moving across the field of view correctly accounting for rolling shutter distortions.

Chapter 7

Simulation

To generate synthetic images that account for all the factors treated in the previous chapter, it is necessary to construct a simulation that follows defined steps to make sure that the images are representative of a plausible scenario. This chapter presents the full simulation pipeline.

First, a target is selected together with a description of its physical characteristics. Then the orbits of the target and observer spacecraft are defined and their relative positions propagated over time. The positions can be projected onto the image plane using a pinhole camera model to derive the pixel coordinates. The radiometric chain described in Chapter 4 is used to derive the radiation power incident on the sensor. Finally, the sensor model explained in Chapter 6 can be used to obtain synthetic images.

The following methodology, while it is aimed at detecting a specific target satellite (the Cartosat-1), includes general enough parameters such that it may be easily reproduced to analyze and determine detection of various types of targets and used with various kinds of observers in a given scenario. The Cartosat-1 satellite was chosen, in particular, for this simulation due to its large size and its orbit in LEO.

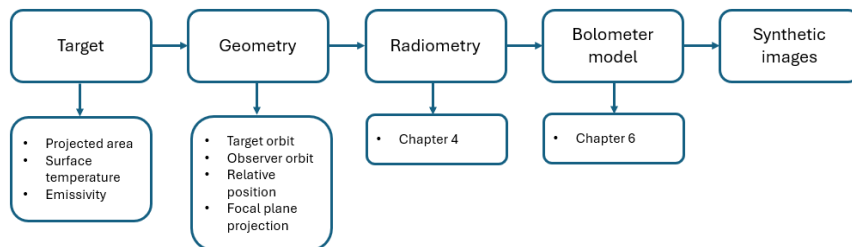


Figure 7.1: Simulation pipeline overview.

Figure 7.1 shows an overview of the simulation pipeline. The next sections will outline the pipeline and the main assumptions for each step, particularly with regard to the first two sections.

7.1 Target

To characterize the radiation emitted by the target, it is necessary to first establish a set of assumptions regarding its behavior. Here, we assume that the emission is diffuse, meaning that the surface radiates uniformly in all directions, and that the observation is direct such that the radiation reaches the sensor without intermediate reflections from other surfaces. Under these conservative assumptions, only the portion of the satellite directly visible to the sensor contributes to the measured signal. With this framework, the radiometric signature of the target can be fully described by three fundamental properties, as discussed in Chapter 4: the projected area visible to the sensor, the temperature of the object, and its emissivity.

7.1.1 Projected area

To compute the thermal signal, we first need to determine the portion of the target's surface that both emits radiation and is visible to the observer — the apparent (projected) emitting area (as defined in Section 5.1). Estimating this area requires a geometric model of the satellite.

Table 7.1: Physical characteristics of Cartosat-1 from DISCOS.

Name	Cartosat-1
Mass (kg)	1560
Shape	Box + 2 Pan
Width (m)	2
Height (m)	2.8
Depth (m)	2
Span (m)	12
Maximum Cross Section (m ²)	24
Minimum Cross Section (m ²)	4
Average Cross Section (m ²)	12.977

The approximate dimensions of most active satellites can be found on ESA’s DISCOS¹ database (European Space Agency (ESA), Space Debris Office, 2025). Table 7.1 shows the geometric proprieties of Cartosat-1. It also shows the projected minimum, maximum, and average cross section of the satellite (Sanchez-Ortiz et al., 2013).

The projected cross-sectional area of a satellite is a function of the viewing direction in the spacecraft body frame. Consequently, it depends both on the target’s attitude at the time of observation and on the relative position of the observer. Figure 7.2 illustrates this effect for a simplified target geometry, showing how the apparent area changes with viewing direction.

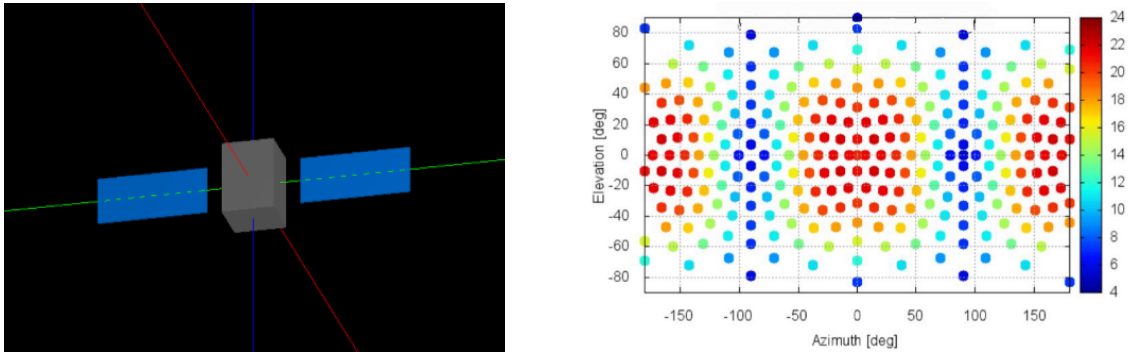


Figure 7.2: Simplified model of the target, based on Table 7.1 with the x-axis in red, y-axis in green, and z-axis in blue (left). Projected cross sectional area as a function of viewing direction, Azimuth and Elevation are the spherical coordinates defining a direction in the body frame (right) made using DRAMA CROC (European Space Agency (ESA), 2025a)

Figure 7.2 shows that the projected area can vary significantly depending on the viewing angle. However, it reaches its lowest values at very specific orientations and rises quickly as soon as the viewing direction moves away from those angles.

Since the target’s attitude is not known for this simulation, we approximate the projected area using the average cross-sectional area of Cartosat-1, which is 12.977 m^2 .

7.1.2 Temperature and Emissivity

In order to estimate the thermal infrared signal detectable by a bolometer, a complete thermal model of the target spacecraft would in principle be required. Such a model

¹For this simulation we are using information from ESA DISCOS (Database and Information System Characterising Objects in Space), a single-source reference for launch information, object registration details, launch vehicle descriptions, as well as spacecraft information for all trackable, unclassified objects. We acknowledge ESA’s efforts to maintain and operate this database with its APIs.

would need to account for the emissivity of every surface material, the thermal properties of all components, and their respective power dissipation. Due to the lack of detailed thermal information about the target, we introduce two simplifying assumptions.

First, we assume that the effective temperature of the satellite is equal to the temperature of its solar panels. This choice is motivated by the fact that solar panels typically constitute the largest radiating surface and dominate the projected area from most viewing directions. However, since radiated power scales with the fourth power of temperature ($P \propto T^4$), even a small difference in temperature can lead to a significant change in emitted power.

The spacecraft main body is likely to operate at higher temperatures for two reasons: (i) if the payload is active, internal dissipation and battery discharge maintain elevated temperatures even during eclipse, and (ii) the main bus generally has higher thermal inertia than the solar panels, further contributing to higher mean temperatures.

Here, we assign the solar panel temperature to the entire spacecraft, and this will probably significantly underestimate the radiated signal. We make this simplifying conservative assumption to forecast the least optimal scenario (with the hope that scenarios might be better in reality).

Second, we assume that the emissivity of the spacecraft surfaces are equal to that of the solar panels. While this simplification may either overestimate or underestimate the true signal, the effect is limited because emissivity scales linearly with radiated power (Chapter 4) and the solar panel constitute the larger emitting area. Thus, although approximate, this assumption does not strongly bias detectability.

Based on these considerations, we adopt the thermal model presented by Kim and Han (2010b), which describes the transient temperature evolution of a LEO satellite during eclipse as shown in Figure 7.3. In this approach, the satellite temperature is taken as a function of the elapsed time since eclipse entry, thereby capturing the thermal transient in a simplified but representative manner. For the emissivity, we assume a constant value of $\varepsilon = 0.8$ (Alonso-Álvarez et al., 2019; Kim & Han, 2010b), representative of typical solar panel surfaces. This choice is consistent with our earlier assumption that the solar panels dominate the radiating area and provides a reasonable first-order estimate.

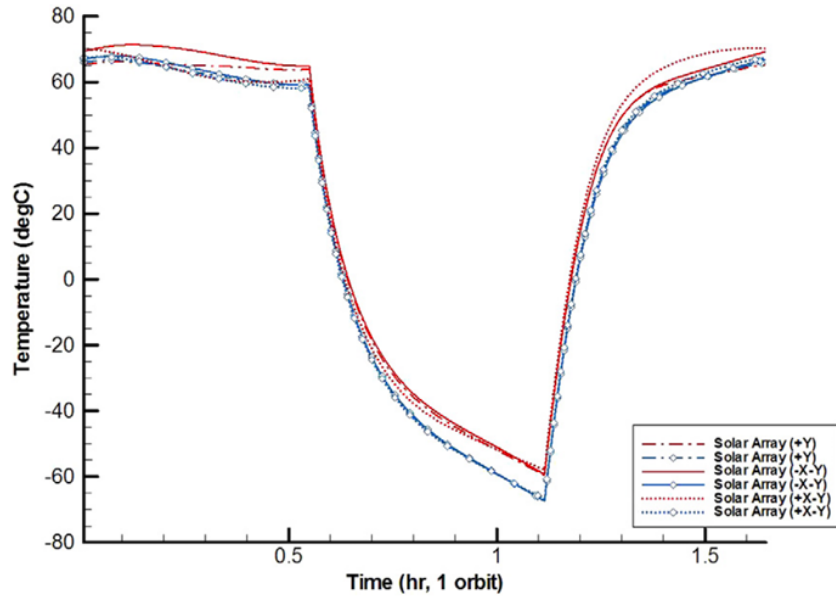


Figure 7.3: Solar panel temperature of a LEO satellite from Kim and Han (2010b)

7.2 Orbits and geometry

This section first describes how the orbits of the target and the observer are derived for the scenario under study. Once the trajectories are available in the Earth-Centered Inertial (ECI) frame, the necessary reference frame transformation is introduced in order to map the three-dimensional relative geometry of the target onto the two-dimensional focal plane of the camera. Finally, the criteria for selecting a suitable observation epoch are discussed, and a specific time of observation is defined when the target will be imaged under favourable conditions.

7.2.1 Orbit

The orbit of the target satellite was obtained from publicly available Two-Line Element (TLE) data provided by CelesTrak (CelessTrak.org, 2025). A TLE is a standard two-line data format that encodes the orbital parameters of an Earth-orbiting object at a given epoch. While TLEs are commonly propagated with the SGP4 model, in this work they are instead converted into classical Keplerian orbital elements and propagated using a two-body (Keplerian) propagator. This choice is sufficient for the present feasibility analysis as the goal is to achieve plausible relative positions not long-term state accuracy.

The TLE of Cartosat-1 retrieved from CelesTrak (CelessTrak.org, 2025) on 22/07/2025 was selected, from which its orbit was reconstructed and propagated for the analysis.

Table 7.2 shows the classical orbital elements and the epoch at which these elements were generated. It can be noticed that Cartosat-1 has a polar orbit at 605 km altitude.

Table 7.2: Classical Orbital Elements of the Target

Parameter	Symbol	Value
Epoch (UTC)	–	2025-07-22 02:35:37.869
Semi-major axis	a	6976.811 km
Eccentricity	e	0.0002626
Inclination	i	97.565200°
RAAN	Ω	235.785800°
Argument of perigee	ω	86.702100°
Mean anomaly	M	273.449700°
True anomaly	f	273.419662°

The orbit of the observer satellite was not chosen to reflect a detailed mission design, but rather to provide a plausible geometry for demonstrating the detection model. In particular, the observer orbit was defined such that its nodes intersect with those of the target orbit near eclipse. This configuration ensures that the closest point of approach occurs under conditions where bolometer-based detection is most advantageous compared to visible-light sensors. It was also chosen so that the two objects would arrive at the nodes at similar times. This is to reflect the conditions under which space-based detections are possible. The choice is therefore illustrative, aimed at simulating a plausible scenario that highlights feasibility. Table 7.3 shows the classical orbital elements of the observer orbit.

Table 7.3: Classical Orbital Elements of the Observer

Parameter	Symbol	Value
Epoch (UTC)	–	2025-07-22 02:35:37.869
Semi-major axis	a	6908.137 km
Eccentricity	e	0.0002626
Inclination	i	97.400000°
RAAN	Ω	250.000000°
Argument of perigee	ω	266.702100°
True anomaly	f	91.419662°

Figure 7.8 shows the observer and target orbit together with the sun direction at 02:35:37.869 (UTC) on the 22/07/2025. It also shows the portion of those orbits that are sunlit for the next orbit revolution.

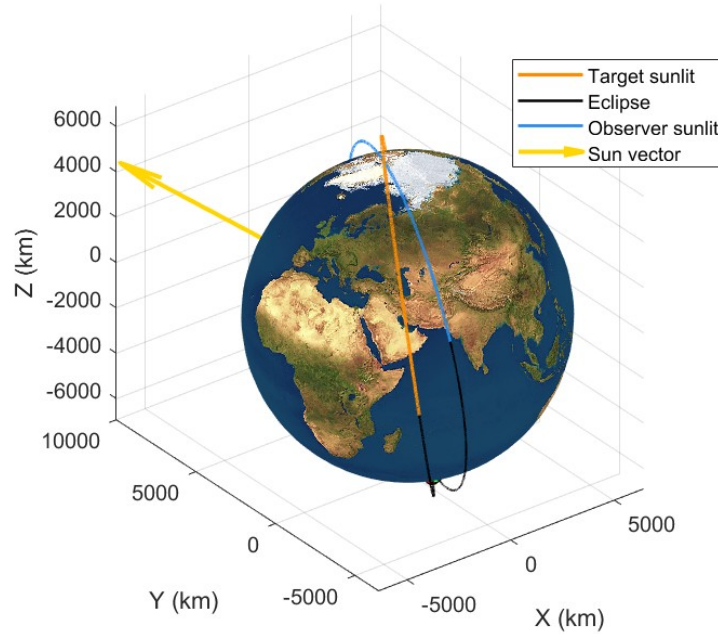


Figure 7.4: Target and observer orbit, 22/07/2025, 02:35:37.869 (UTC)

7.2.2 Reference frames

Once the orbits are defined it is necessary to trace the path of the target in the camera field of view. This requires mapping the object's trajectory in three-dimensional space onto the two-dimensional image plane. The projection is performed using the pinhole camera model (Hartley & Zisserman, 2003).

First, it is necessary to change the reference frame from the inertial world frame (ECI) to the camera frame. This is done with a roto-translation as shown in Figure 7.2.

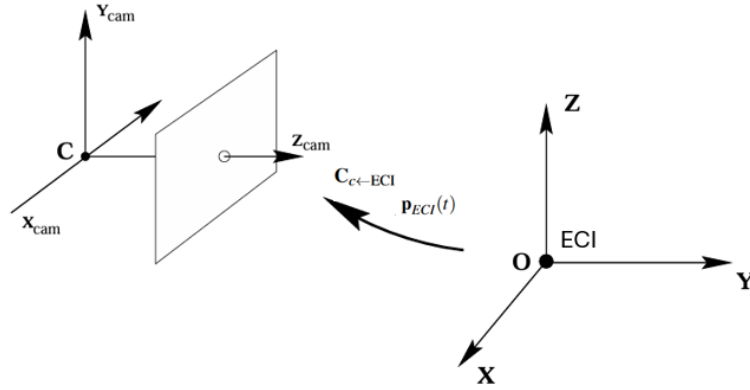


Figure 7.5: Camera frame and world frame, adapted from Hartley and Zisserman (2003)

Let $\mathbf{r}_{tar}(t)$ and $\mathbf{r}_{obs}(t)$ be the position vectors of the target and observer, respectively, expressed in the Earth-Centered Inertial (ECI) frame. The relative position of the target with respect to the observer can be expressed with Equation 7.1:

$$\mathbf{p}_{ECI}(t) = \mathbf{r}_{tar}(t) - \mathbf{r}_{obs}(t). \quad (7.1)$$

The transformation from ECI to the camera reference frame is completed by a rotation matrix, $\mathbf{C}_{c \leftarrow ECI}$. The coordinates of the target in the camera frame are then obtained with Equation 7.2:

$$\mathbf{p}_c(t) = \mathbf{C}_{c \leftarrow ECI} \mathbf{p}_{ECI}(t), \quad (7.2)$$

where $\mathbf{p}_c(t) = [X_c(t), Y_c(t), Z_c(t)]^\top$.

In the camera frame it is possible to use the pinhole camera model to map the positions onto the image plane as shown in Figure 7.6.

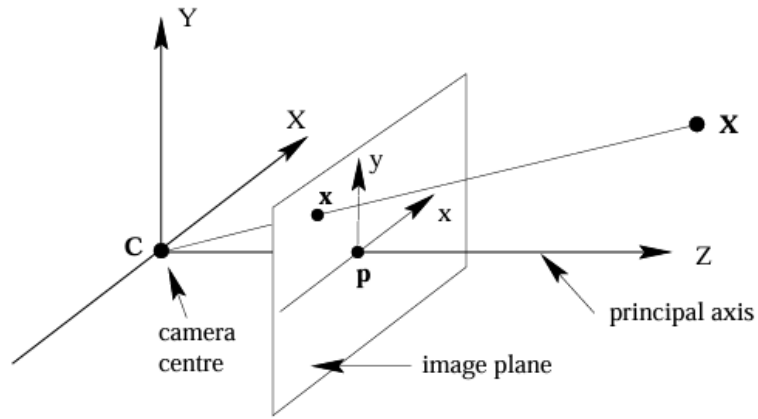


Figure 7.6: Pinhole camera model from Hartley and Zisserman (2003)

The coordinates in the camera frame can be transformed into coordinates in the image frame – defined by the conventions in Figure 7.6 with Equation 7.3

$$u(t) = f_{pix} \frac{X_c(t)}{Z_c(t)}, \quad v(t) = f_{pix} \frac{Y_c(t)}{Z_c(t)}, \quad (7.3)$$

where $u(t)$ and $v(t)$ are the coordinates in the image frame in pixels with the origin at the centre of the image. f_{pix} is the focal length expressed in pixels and can be found by dividing the focal length f by the pixel pitch p : $f_{pix} = \frac{f}{p}$

7.2.3 Pointing

In this study, the observational strategy is based on sidereal tracking, meaning that the spacecraft attitude is kept fixed with respect to the Earth-Centered Inertial (ECI) frame for the duration of the observation. The reference attitude is defined at a chosen epoch t_{obs} in the following way:

- The boresight direction z_c is aligned with the relative position vector from the observer to the target, expressed in the ECI frame.
- The y_c axis is orthogonal to z_c and aligned with the instantaneous along-track direction of the observer at t_{obs} (i.e. with the projection of the velocity vector onto the focal plane).
- The x_c axis completes a right-handed reference system.

Once defined, this attitude is maintained throughout the observation interval, thereby simulating a true sidereal tracking mode.

The selection of the observation time - and consequently the attitude - must satisfy the following conditions:

- The target must be observed during eclipse as this is the scenario in which infrared detection maintains an advantage over visible light sensors. For the considered case, the target enters eclipse on 22-Jul-2025 at 03:46:12 and exits on 22-Jul-2025 at 04:11:26.
- The target must remain within the instrument field of view for at least 20 seconds, ensuring the possibility for IOD (Chapter 3).
- The observation should be chosen as close as possible to the instant of closest approach, which occurs at 03:47:59.650, to minimise the observer–target range and maximise the SNR.
- The Sun and Earth must remain outside the instrument’s field of view to avoid contamination by direct or scattered light.

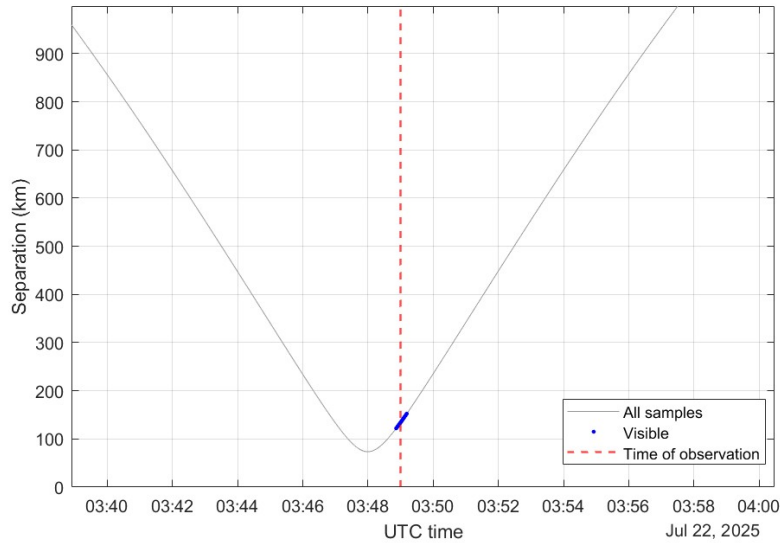


Figure 7.7: Relative distance between target and observer at time $t_{obs} = 22\text{-Jul-2025 } 03:49:00$ (UTC). The blue line indicates the time in which the target stays in the FOV with the chosen attitude.

Taking these constraints into account, the reference epoch t_{obs} is selected as the earliest instant after closest approach for which the target remains visible for at least 20 seconds, the entire interval is contained within eclipse, and the exclusion conditions are satisfied. Figure 7.7 shows the relative distance and the chosen time at which the attitude is fixed.

This instant defines where the fixed attitude will be in the ECI frame, and this attitude is then maintained throughout the observation in accordance with the adopted sidereal tracking strategy.

Figure 7.8 shows the target and observer positions at the time of observation which happens on 22-Jul-2025 at 03:49:00 (UTC), around 3 minutes after the target enters eclipse.

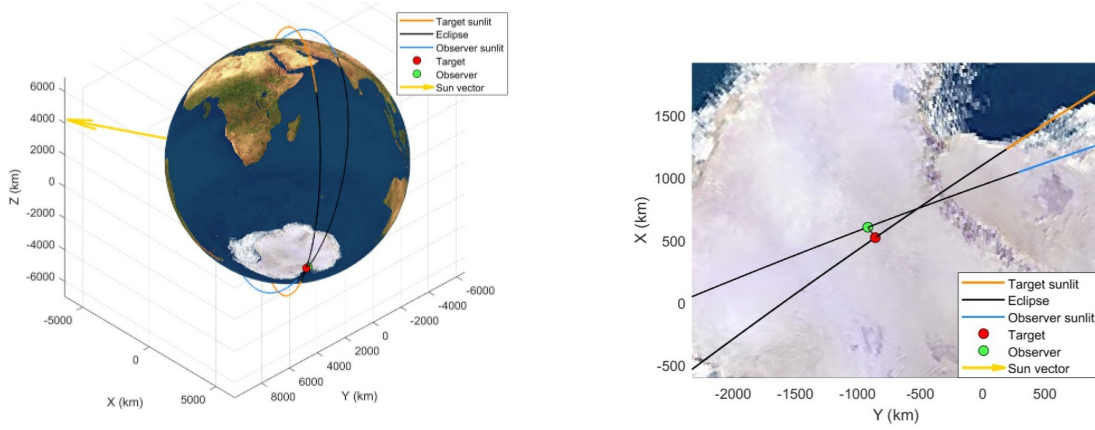


Figure 7.8: Target and observer position at t_{obs}

Finally, the trajectory of the target projected onto the focal plane is shown in Figure 7.9. The distance between successive points decreases as the target crosses the field of view (from right to left), which makes it appear as though the target slows down. This effect is consistent with the fact that the target is receding from the observer, as illustrated in Figure 7.7. More generally, objects that are farther away traverse the field of view more slowly, since a larger relative path corresponds to the same angular displacement as the relative distance increases.

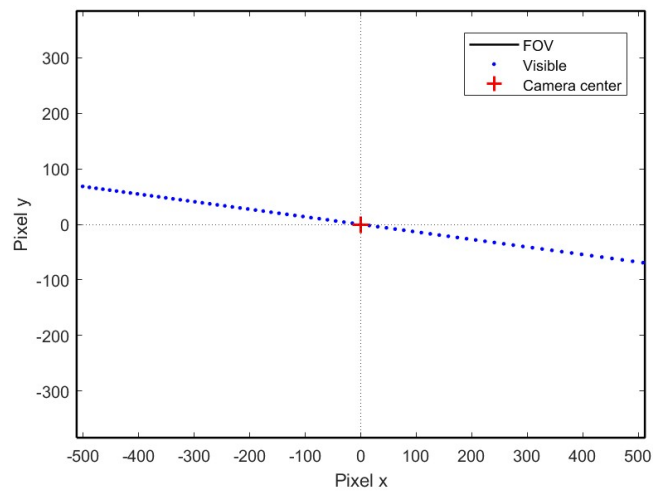


Figure 7.9: Object in the field of view, full coordinates in Appendix B

It is now possible to run a full simulation with the model constructed in Chapter 4 and 6.

Chapter 8

Results

This chapter presents the results of the simulation for the specific scenario and target described in Chapter 7. It evaluates the performance of the bolometer in the selected observational scenario. The analysis is structured in three stages. First, the performance is assessed using the simplified model introduced in Chapter 4 in order to provide an initial understanding of the main limitations of the scenario. Next, the results of the full end-to-end simulation are presented, offering a more realistic representation of the instrument response. Finally, both sets of results are analysed together, and the key findings are discussed in a broader context. This comparison highlights the impact of the additional physical effects captured by the more complete model, especially their influence on the achievable signal-to-noise ratio (SNR).

8.1 Simplified model performance

The simplified model in Chapter 4 requires the inputs in Table 8.1. A surface temperature of 0°C is chosen because the observation happens 3 minutes after entering eclipse. From Figure 7.3 it is possible to derive an approximate solar panel temperature of 0°C.

Table 8.1: Main input parameters for the observational scenario

Target	Surface temperature	Surface area	Emissivity	Range
Cartosat-1	0 °C	12.977 (m^2)	0.8	122–152 (km)

8.1.1 SNR vs Range

Figure 8.1 shows how the signal-to-noise ratio (SNR) changes with range. At the ranges reached throughout the observation, the SNR goes from 40 to 26. The maximum range is also shown.

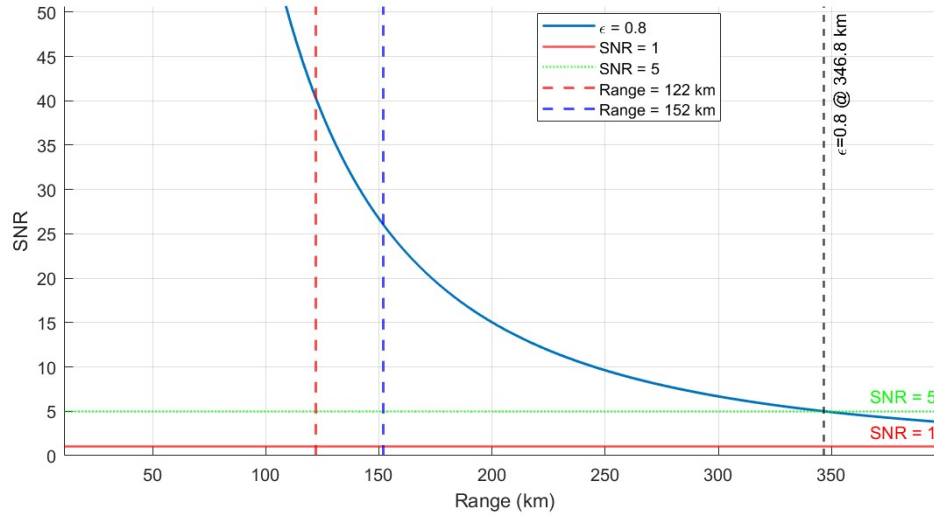


Figure 8.1: SNR vs Range for Cartosat-1, highlighting the SNR at ranges reached during the observational scenario and the maximum achievable (black dotted line)

It should be noted that the simplified model neglects two important effects: the thermal transient response of the bolometer and the instrument point spread function (PSF). As a result, the full simulation is expected to yield lower SNR values. Nevertheless, the simplified model remains valuable as it provides an order-of-magnitude estimate that can be used as a sanity check for the more complete simulation and effectively represents an upper bound on the achievable performance.

8.1.2 Range vs Temperature

It is also interesting to see how the maximum range changes depending on the temperature assuming an SNR threshold of 5.

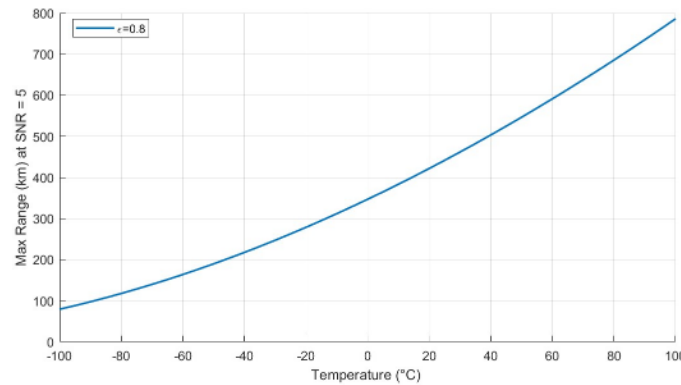


Figure 8.2: Maximum range vs. temperature for Cartosat-1

Figure 8.2 shows that the detectable range, and therefore detection, is very dependent on temperature. At the lowest temperatures sometimes reached during eclipse the range is very limited.

8.2 Results of the full simulation pipeline

Having established the limitations of the scenario through the simplified model, we now turn to the results obtained with the complete end-to-end simulation pipeline. This model incorporates all relevant physical effects and instrument characteristics discussed in Chapter 6, providing a more realistic representation of the observational performance.

The following subsections present the outputs of the full pipeline in the following manner. First, the evolution of the target in the field of view is examined. Then, the radiometric response of the bolometer is evaluated, with particular emphasis on the resulting signal-to-noise ratio (SNR). These results are then compared against the simplified estimates in order to highlight the impact of the additional modeling fidelity.

8.2.1 Simulated image frames

The simulation pipeline produces synthetic images of the target as it would be recorded by the bolometer. A total of 582 frames were generated for the selected observation, with pixel values expressed in detector counts. .

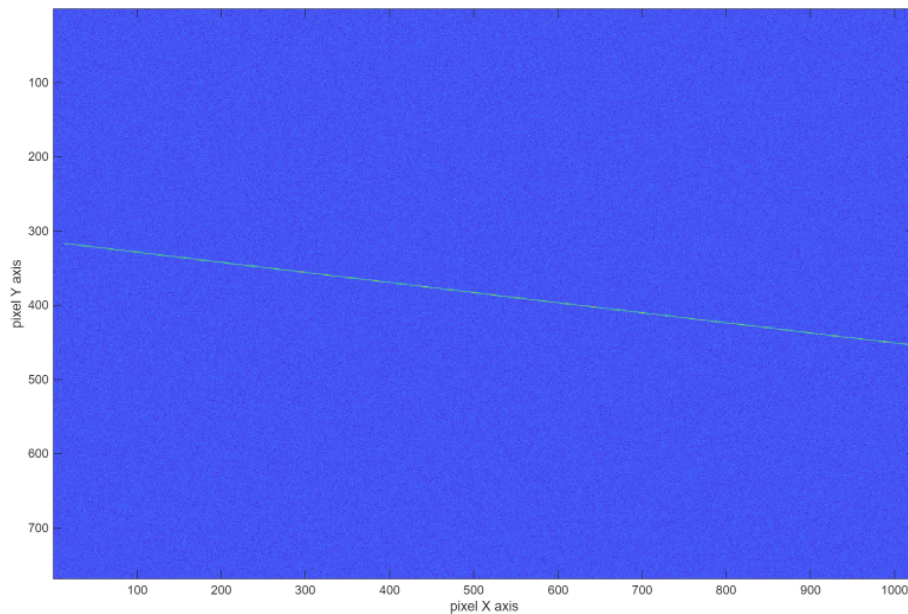


Figure 8.3: Stacked image of 582 frames with noise.

Figure 8.3 shows the 582 simulated frames stacked together to illustrate the trajectory of the target across the field of view. In each individual frame the target occupies only a few pixels, owing to the wide field of view (FOV) of the instrument, the small footprint of the PSF, and the faint nature of the signal. As an example, Figure 8.4 displays frame number 300, corresponding to approximately 10 seconds after the target first enters the field of view.

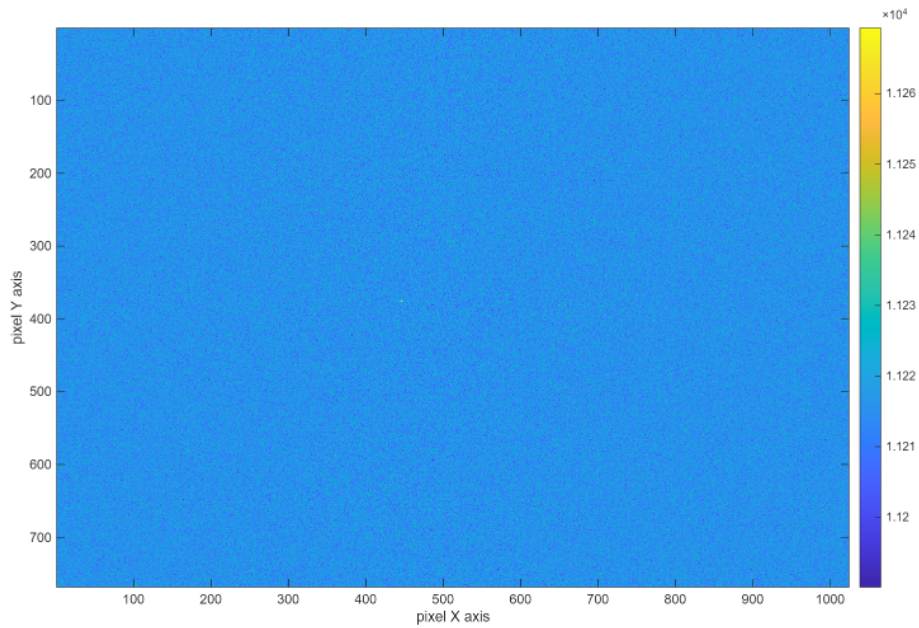


Figure 8.4: Image of the object 10 seconds after the object enters the FOV (frame number 300), color-bar in counts.

Figure 8.5 provides a zoomed-in view of frame 300 together with a three-dimensional surface plot of the image. The latter representation highlights how the target signal rises comfortably above the noise floor, making the detection possible.

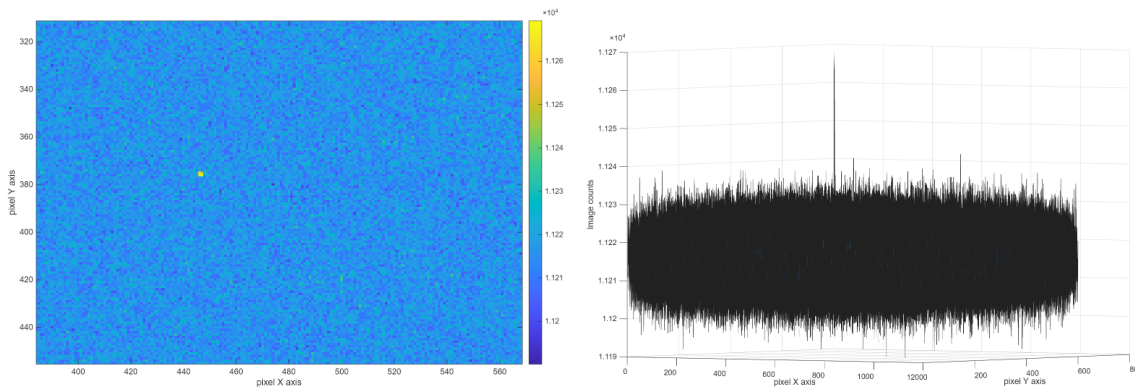


Figure 8.5: Zoomed-in image of the object 10 seconds after the object enters the FOV (frame number 300) color-bar in counts (left), 3D plot of the image counts made using MATLAB's surf function (right).

8.2.2 SNR analysis

Figure 8.6 shows the signal-to-noise ratio (SNR) of the brightest pixel in each frame over the duration of the observation.

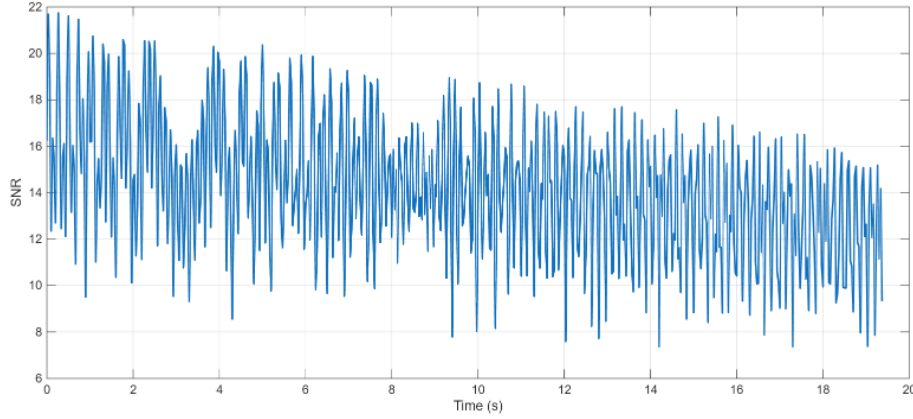


Figure 8.6: Brightest pixel SNR in every frame

It can be observed that the SNR fluctuates significantly from frame to frame. This behaviour is driven by two main effects:

1. **Point spread function (PSF) sampling.** The fraction of the total power received by the brightest pixel depends strongly on the exact position of the PSF relative to the pixel grid. Owing to the large field of view, the diffraction-limited PSF constructed for this simulation extends slightly beyond a single pixel. As a result, the recorded signal is highly sensitive to the precise location of the PSF centre on the pixel grid.
2. **Thermal transient response of the bolometer.** The finite thermal response time of the detector introduces a lag between the incident power and the measured output. When the target moves from one pixel to the next, the previous pixel begins to cool down while the new pixel starts heating up. Depending on when the line of pixels is read during this transition, the measured signal can vary significantly between consecutive frames.

Together, these two mechanisms explain the large frame-to-frame variations in the brightest-pixel SNR observed in the simulation.

This behavior may pose a challenge for detection algorithms, as in some frames the signal could fall below the detection threshold. Such frame-to-frame variability can hinder reliable object association across frames.

This effect could be mitigated by slightly defocusing the sensor so that the PSF spreads

over several pixels. However, this comes at the expense of signal-to-noise ratio (SNR), since the collected energy is distributed more broadly across the detector.

However, because the target follows an approximately linear trajectory over short observation times, modern detection algorithms (Spiller et al., 2020) can exploit motion models to predict the object’s future position, even several frames ahead. This enables the trajectory to be reconstructed and tracked consistently, even if individual frames do not yield a positive detection when thresholding techniques (Gonzalez, 2009) are applied.

8.2.3 Model comparison

Figure 8.7 shows per frame brightest pixel SNR compared to the simplified model.

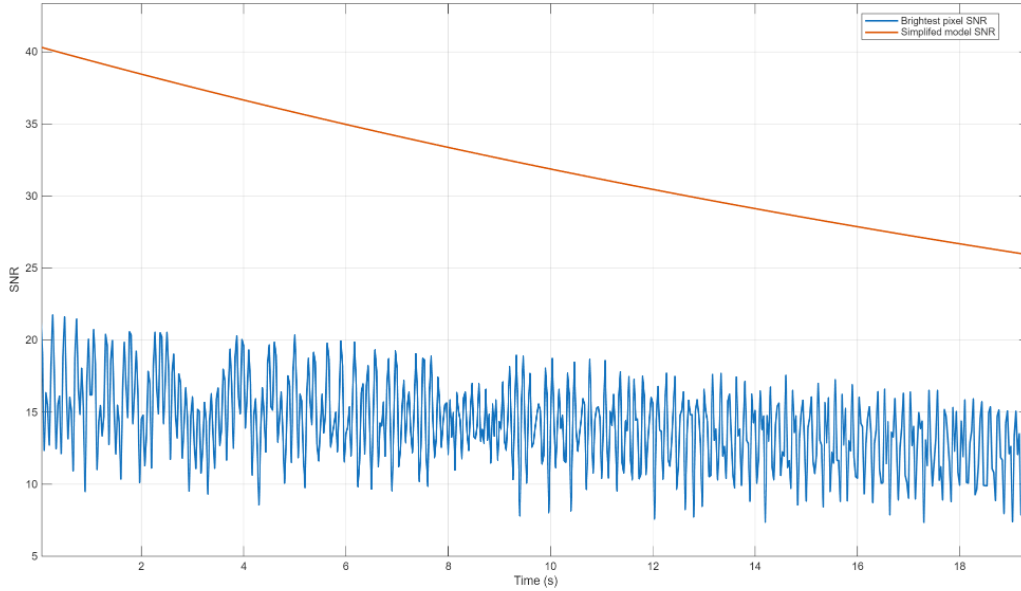


Figure 8.7: Comparison of the two models

The results demonstrate a clear reduction in signal-to-noise ratio (SNR) when moving from the simplified model to the full end-to-end simulation. This decrease can be attributed primarily to two factors: the thermal transient response of the bolometer and the spatial distribution of the point spread function (PSF).

Thermal transient response. In the simplified model the detector is assumed to be in thermal equilibrium. In reality, the bolometer exhibits a finite thermal time constant, and the signal builds up gradually as the target traverses a pixel. This effect can be quantified by comparing the dwell time of the target on a pixel with the bolometer time constant.

The time on pixel can be estimated by dividing effective observation time t_{total} by the number of pixels crossed N_{pix} as shown in Equation 8.1. The observation time is approx-

imately 20 s and the number of pixels can be estimated with the number of horizontal pixels in the sensor since the observation crosses the FOV horizontally ($N_{\text{pix}} = 1024$).

$$t_{\text{pix}} \approx \frac{t_{\text{total}}}{N_{\text{pix}}} \approx \frac{20 \text{ s}}{1024} = 0.0195 \text{ s} \quad (8.1)$$

The corresponding response relative to thermal equilibrium follows the exponential behaviour

$$\eta_{\text{thermal}} = 1 - e^{-t_{\text{pix}}/\tau} \approx 0.86, \quad (8.2)$$

where τ is the thermal time constant of the bolometer. This means that in this scenario the output signal will be reduced to around 14 % due to the dynamics of the observation.

Point spread function effects The second contributing factor to the reduction in SNR is the diffraction-limited PSF. Because the PSF footprint spans only slightly more than a single pixel, the fraction of total power received by the brightest pixel depends strongly on the exact alignment of the PSF with the pixel grid. This fraction can vary between approximately 25% and 78%, with an average around 55% for this specific scenario. Consequently, the PSF not only introduces frame-to-frame fluctuations in the brightest-pixel SNR, but also reduces the mean signal level compared to the simplified assumption in which all the power is concentrated into one pixel.

It is possible to define two efficiency $\eta_{\text{thermal}} = 0.86$ and $\eta_{\text{PSF}} = 0.55$ and reconstruct the Figure 8.7 by applying them to the received signal in the simple model.

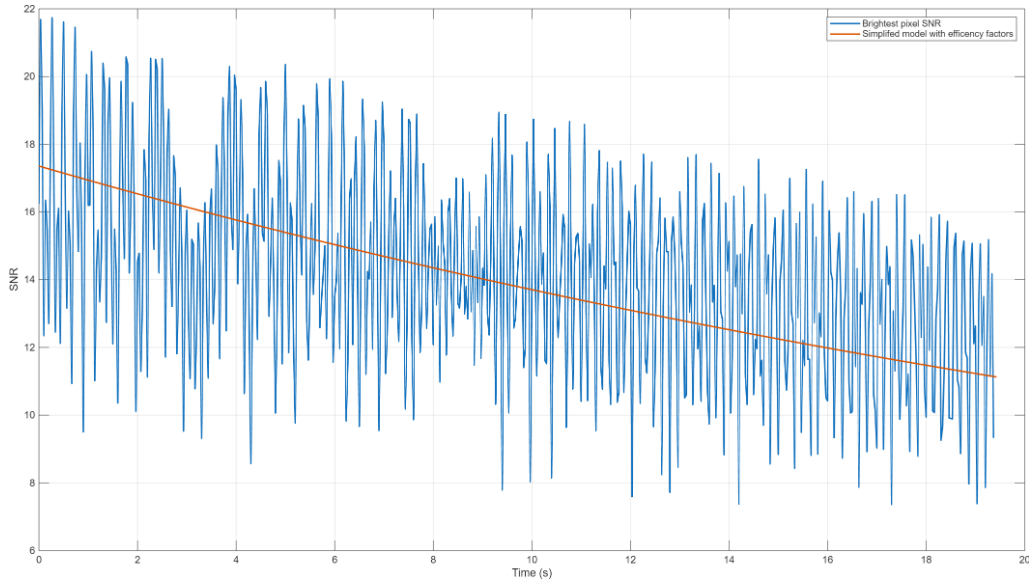


Figure 8.8: Comparison of complete model and simplified model with efficiency factors.

Figure 8.8 shows that the simplified model, once corrected for the efficiency factors, fol-

lows the results of the full simulation much more closely. A slight difference in slope remains visible, which can be attributed to the fact that the target slows down as it crosses the field of view. This increase in dwell time enhances the measured signal in the simulation, whereas the simplified model does not capture this dynamic effect.

Assuming similar observation conditions — namely a comparable time within the field of view, an approximately horizontal trajectory across the detector, and equal temperature — it is possible to plot the SNR as a function of range as shown in Figure 8.9. By including the efficiency factors, this provides a more realistic estimate of the detection limits for Cartosat-1. The Figure shows that, in these conditions, Cartosat-1 is visible up to 238 km.

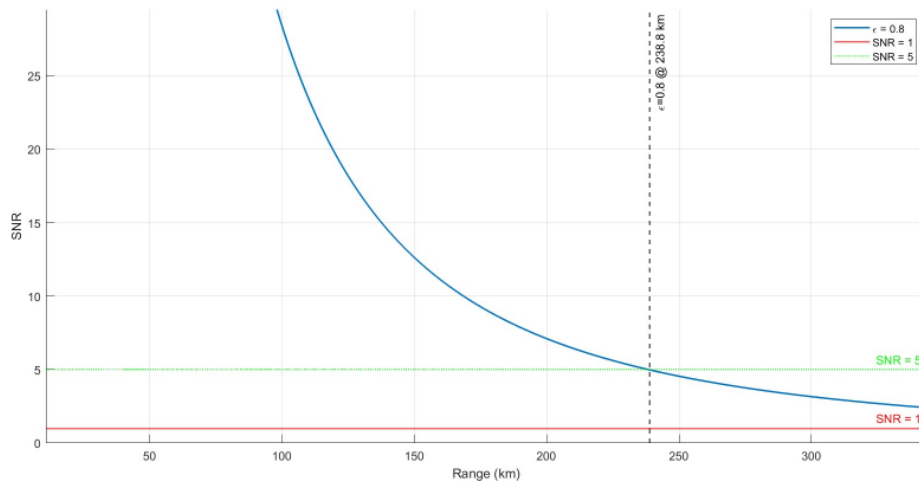


Figure 8.9: SNR vs Range including efficiency factors, dotted black line showing the maximum detectable range.

Chapter 9

Conclusion

The guiding research question of this thesis was: **How effective are infrared sensors for space-based space situational awareness under unfavorable illumination conditions?** To address this question, the work proceeded in several stages, moving from conceptual analysis to detailed simulation.

First, the application — space-based observation for orbit determination — was defined, and corresponding requirements were established for an infrared sensor payload suitable for SSA within the context of Arca Dynamics’ operations. These requirements were set with the aim of identifying practical and cost-effective solutions for small satellite platforms. Bolometers were therefore identified as a suitable candidate, with particular focus on the INO HDISCC camera. The goal was to conduct a feasibility study to evaluate whether such a payload could enable object detection from a space-based platform for the purpose of orbit determination.

Next, the radiometric signatures of a representative target were modelled, and a simplified bolometer model was developed. Although idealised, this model provided an upper bound on performance. The results showed that under eclipse conditions — when target temperatures are low — only relatively large spacecraft with effective radiating areas of at least 8 m^2 are detectable during the full duration of the eclipse. This part established the maximum achievable performance and highlighted the first key limitation of the technology.

Building on this foundation, a full bolometer model was constructed. This model incorporates the thermal transient response, the diffraction-limited point spread function (PSF), detector integration and amplification, and relevant noise sources. It enabled the generation of synthetic image sequences for arbitrary observational scenarios. A simulation pipeline was then developed to propagate the orbits of a target and an observer, transform

the relative geometry into the camera frame, and produce realistic infrared images of the target. Although a specific case study was conducted using the satellite Cartosat-1, the pipeline is general and can be applied to other spacecraft.

Analysis of the simulated images revealed that the fast apparent motion of the target across the field of view, combined with the PSF footprint on the detector grid, significantly reduces the effective signal-to-noise ratio compared to the simplified model. Furthermore, the image shows a large frame-to-frame signal variability caused by these effects which presents a challenge for association algorithms, though modern tracking methods can mitigate this by exploiting motion continuity.

Finally, the results demonstrated that detection range is strongly dependent on target temperature and geometry. When accounting for thermal response and optical effects, the achievable range is substantially limited: for Cartosat-1, detection was found to be possible up to approximately 238 km in the simulated scenario. Nevertheless, successful detection during eclipse is achievable, provided that target conditions and geometry are favourable.

In summary, this thesis has shown that, while infrared sensors can contribute to space-based SSA, particularly by enabling observations during eclipse when other modalities are less effective, their performance is constrained. Detection is limited primarily to larger objects, and fast target dynamics reduce sensitivity due to the thermal response of the detector. Ranges are restricted, but detection of resident space objects under eclipse conditions remains feasible. The methods developed here, especially the end-to-end simulation pipeline, provide a framework for assessing the detection capabilities of future infrared payloads for SSA applications.

9.1 Limitations

The model developed in this thesis is subject to several limitations. Most importantly, it has not been formally validated against experimental data. The modelling process relies on a number of assumptions, which are clearly stated at each step of the work. Where possible, intermediate results were used to establish upper and lower bounds or to provide order-of-magnitude estimates, ensuring that subsequent stages remained consistent. In addition, the behaviour of the model has been compared with similar approaches in the literature and found to be in agreement.

A full validation was not possible due to the lack of publicly available infrared imagery

or reference software specifically tailored to space-to-space infrared detection of resident space objects. Nevertheless, steps were taken to strengthen the credibility of the methodology. In particular, the bolometer model was reviewed with a representative from the sensor manufacturer (INO), who confirmed that all the principal physical effects have been included. While these measures cannot replace full experimental validation, they provide confidence that the results presented are meaningful within the stated assumptions.

9.2 Future Work

The work presented in this thesis can be extended in several directions to further assess and validate the use of infrared sensors for space-based SSA:

1. **Experimental validation.** A key next step is to validate the bolometer model experimentally. This could be achieved by reproducing the simulated scenario in a laboratory setting, with controlled infrared sources moving across the field of view, and comparing the measured frames against model predictions. Such validation would provide confidence in the applicability of the model to real-world conditions.
2. **High-fidelity thermal target modelling.** In this thesis, the target's thermal state was simplified by assuming one representative temperature for the whole object. A more detailed thermal model of the spacecraft would allow a precise assessment of how long a target remains visible during eclipse and under what conditions. This would also enable investigations into temperature contrasts between different operational states — for example, comparing an active payload with one that is switched off, or assessing whether solar panels are operational or not. Such modelling could determine whether thermal differences are detectable, even in sunlit conditions.
3. **Inclusion of external radiative sources.** The current modelling focuses on self-emission of the target. Extending it to include Earth infrared radiation as well as reflected sunlight would allow performance to be assessed under illuminated conditions. This would clarify whether infrared sensors could remain effective outside eclipse and therefore broaden their operational envelope.
4. **Refined noise modelling.** The present bolometer uses a simplified noise model but could be expanded to include additional factors for greater realism, such as readout, lens thermal drift, $1/f$ noise or calibration uncertainties. A more complete noise model would improve the reliability of detection limit estimates.

5. **Observation accuracy and orbit determination.** While this work has focused on detectability, orbit determination ultimately depends on the accuracy of the measured positions. Bolometers exhibit significant delays compared to photon detectors due to their thermal time constant. Future work should examine how this affects centroiding accuracy, positional uncertainty, and consequently orbit determination performance. Questions such as whether the thermal response introduces systematic biases in the measured trajectory remain open and highly relevant.

Together, these extensions would both strengthen the validity of the present results and expand the applicability of infrared sensors for operational space-based SSA.

References

- Abbasi, V., Thorsteinson, S., Balam, D., Rowe, J., Laurin, D., Scott, L., & Doyon, M. (2019). The neossat experience: 5 years in the life of canada's space surveillance telescope. *1st NEO and Debris Detection Conference*, 22.
- Alonso-Álvarez, D., Augusto, A., Pearce, P., Llin, L. F., Mellor, A., Bowden, S., Paul, D., & Ekins-Daukes, N. (2019). Thermal emissivity of silicon heterojunction solar cells. *Solar energy materials and solar cells*, 201, 110051.
- Arai, T., Nakamura, T., Tanaka, S., Demura, H., Ogawa, Y., Sakatani, N., Horikawa, Y., Senshu, H., Fukuhara, T., & Okada, T. (2017). Thermal imaging performance of tir onboard the hayabusa2 spacecraft. *Space Science Reviews*, 208(1), 239–254.
- Bianchi, L., Bechini, M., Quirino, M., & Lavagna, M. (2025). Synthetic thermal image generation and processing for close proximity operations. *Acta Astronautica*, 226, 611–625. <https://doi.org/https://doi.org/10.1016/j.actaastro.2024.10.061>
- Boudou, N., Durand, A., Tinnes, S., Cortial, S., Gorecki, A., Cueff, M., & Viro, A. (2019). Ulis bolometer improvements for fast imaging applications. *Infrared Technology and Applications XLV*, 11002, 366–375.
- Caddy, S., & Spitler, L. (2024). A surprising boost in starlink satellite brightness at optical wavelengths during the day. *Proceedings of the 6th Advanced Maui Optical and Space Surveillance (AMOS) Technologies Conference*, 6.
- CelesTrak.org. (2025). The celesstrak.org [Accessed: 2025-09-22]. *CelesTrak*.
- D'Anniballe, A., Felicetti, L., & Hobbs, S. (2025). Preliminary analysis and design of an optical space surveillance and tracking constellation for leo coverage. *Acta Astronautica*, 231, 47–63.
- D'Anniballe, A., Felicetti, L., & Hobbs, S. (2024). Cooperative tracking strategies for optical space-to-space surveillance constellations. *IAC 2024 congress proceedings*.
- Dartois, T., Manolis, I., Bézy, J.-L., Meynart, R., & Tisse, C.-L. (2017). Environmental evaluation of the ulis pico1024 microbolometer. *Sensors, Systems, and Next-Generation Satellites XXI*, 10423, 323–333.

- Demars, C., Packard, C., Tyler, D., & Rodgers, C. (2023). High-fidelity simulation of dynamic thermal satellite signatures with muses. *Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS)*.
- Du, J., Chen, J., Li, B., & Sang, J. (2019). Tentative design of sbss constellations for leo debris catalog maintenance. *Acta Astronautica*, 155, 379–388.
- Edmund Optics. (n.d.). *Germanium (ge) windows*. Retrieved July 21, 2025, from <https://www.edmundoptics.com/f/germanium-ge-windows/13137/>
- EnduroSat. (2025, August). *Endurosat 16u platform – 16u cubesat bus* [Accessed: 15 August 2025]. <https://satsearch.co/products/endurosat-16u-platform>
- European Space Agency (ESA). (2023a). ESA’s Zero Debris approach [Introduces ESA’s commitment to significantly limit the production of debris in Earth and lunar orbits by 2030.]. https://www.esa.int/Space_Safety/Clean_Space/ESA_s_Zero_Debris_approach
- European Space Agency (ESA). (2023b, October). *Esa space debris mitigation requirements (essb-st-u-007, issue 1, revision 0)* (Technical Standard No. ESSB-ST-U-007) (Includes requirements to support ESA’s “Zero Debris” policy (via Agenda 2025) to mitigate space debris and improve long-term orbital sustainability). European Space Agency. <https://technology.esa.int/upload/media/ESA-Space-Debris-Mitigation-Requirements-ESSB-ST-U-007-Issue1.pdf>
- European Space Agency (ESA). (2025a). Debris risk assessment and mitigation analysis (drama) [Space Debris User Portal]. <https://sdup.esoc.esa.int/drama/>
- European Space Agency (ESA). (2025b, March). *ESA’s Annual Space Environment Report* (tech. rep. No. ESA ESOC-EOP-SER-ENV-005-REP) (Issue 12, 31 March 2025). European Space Agency. https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf
- European Space Agency (ESA). (2025c, August). Clearspace-1: Earth’s first space debris removal mission [Describes ESA’s ClearSpace-1 mission aimed at rendezvousing with, capturing, and deorbiting the PROBA-1 satellite—an uncooperative, derelict object—to demonstrate active debris removal using robotic arms]. https://www.esa.int/Space_Safety/ClearSpace-1
- European Space Agency (ESA), Space Debris Office. (2025). Discosweb: Database and information system characterising objects in space [Accessed: 15 August 2025].
- Felicetti, L., & Emami, M. R. (2018). Image-based attitude maneuvers for space debris tracking. *Aerospace science and technology*, 76, 58–71.
- Fitzmaurice, J., Bédard, D., Lee, C. H., & Seitzer, P. (2021). Detection and correlation of geosynchronous objects in nasa’s wide-field infrared survey explorer images. *Acta Astronautica*, 183, 176–198.

- Fixsen, D. J. (2009). The temperature of the cosmic microwave background. *The Astrophysical Journal*, 707(2), 916.
- Gao, Y.-t., Chen, H.-m., Xu, Y., Sun, X.-n., & Chang, B.-k. (2011). Noise research of microbolometer array under temperature environment. *International Symposium on Photoelectronic Detection and Imaging 2011: Advances in Infrared Imaging and Applications*, 8193, 222–228.
- Généreux, F., Picard, F., Spisser, H., Tomas, A., Letourneau, A., Fisette, B., Proulx, C., Martin, L., Pope, T., Alain, C., et al. (2024). Ultra-broadband uncooled infrared camera core for multi-spectral and far-infrared earth, lunar, and planetary observation.
- Généreux, F., Tremblay, B., Gay, D., Deshaies, S., Briand, M., Poirier, M., Caron, J.-S., Paultre, J.-E., Béland, D., Provençal, F., et al. (2018). Small uncooled bolometers with a broad spectral response. *Infrared Technology and Applications XLIV*, 10624, 142–150.
- Généreux, F., Tremblay, B., Girard, M., Paultre, J.-E., Provençal, F., Desroches, Y., Oulachgar, H., Ilias, S., & Alain, C. (2016). On the figure of merit of uncooled bolometers fabricated at ino. *Infrared Technology and Applications XLII*, 9819, 478–486.
- Glasse, A., Rieke, G., Bauwens, E., García-Marín, M., Ressler, M., Rost, S., Tikkanen, T. V., Vandenbussche, B., & Wright, G. (2015). The mid-infrared instrument for the james webb space telescope, ix: Predicted sensitivity. *Publications of the Astronomical Society of the Pacific*, 127(953), 686.
- Gondelach, D. J. (2019). *Orbit prediction and analysis for space situational awareness*. University of Surrey (United Kingdom).
- Gonzalez, R. E. W., Rafael C. (2009). *Digital image processing*. Pearson education.
- Goodman, J. W. (2005). *Introduction to fourier optics*. Roberts; Company publishers.
- Hartley, R., & Zisserman, A. (2003). *Multiple view geometry in computer vision*. Cambridge university press.
- Hausmann, R., Wagner, P., & Clausen, T. (2021). Streak detection of space debris by a passive optical sensor. *8th European Conference on Space Debris*, 8.
- INO. (2025). *Spec sheet high-definition infrared space camera core* [Accessed July 20, 2025].
- Jones, H. (2018). The recent large reduction in space launch cost. *48th International Conference on Environmental Systems-ICES 2018-81*.
- Kawaguchi, J., Fujiwara, A., & Uesugi, T. (2008). Hayabusa—its technology and science accomplishment summary and hayabusa-2. *Acta Astronautica*, 62(10-11), 639–647.

- Kelso, T., et al. (2009). Analysis of the iridium 33-cosmos 2251 collision. *Advances in the Astronautical Sciences*, 135(2), 1099–1112.
- Kim, H. K., & Han, C. Y. (2010a). Analytical and numerical approaches of a solar array thermal analysis in a low-earth orbit satellite. *Advances in Space Research*, 46(11), 1427–1439.
- Kim, H. K., & Han, C. Y. (2010b). Analytical and numerical approaches of a solar array thermal analysis in a low-earth orbit satellite. *Advances in Space Research*, 46(11), 1427–1439.
- Krapeza, J.-C. (2025). How to reduce the memory effect in microbolometer cameras? *Proc. of SPIE Vol 13469*, 13469, 134690D–1.
- Krezan, J. M., Howard, S., Dao, P. D., & Surka, D. (2015). Geo collisional risk assessment based on analysis of nasa-wise data and modeling.
- Krier, G. (2017). Satellite collision probability for long-term encounters and arbitrary primary satellite shape. *7th European conference on space debris*, 7(1).
- Kruse, P. W. (2001). *Uncooled thermal imaging: Arrays, systems, and applications* (Vol. 51). SPIE press.
- Lee, K., Ban, Y., & Kim, C. (2022). Motion blur kernel rendering using an inertial sensor: Interpreting the mechanism of a thermal detector. *Sensors*, 22(5), 1893.
- Mainzer, A., Masiero, J. R., Abell, P. A., Bauer, J., Bottke, W., Buratti, B. J., Carey, S. J., Cotto-Figueroa, D., Cutri, R., Dahlen, D., et al. (2023). The near-earth object surveyor mission. *The Planetary Science Journal*, 4(12), 224.
- Milani, A., & Gronchi, G. (2010). *Theory of orbit determination*. Cambridge University Press.
- NASA National Space Science Data Center (NSSDC). (2025). Sbss (space based space surveillance), usa 216, cospar 2010-048a [Launch date: 26 September 2010; provides spacecraft specifications and mission overview. Accessed 15 August 2025.]. <https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=2010-048A>
- Nave, C. R. (n.d.). *Circular aperture diffraction [illustration]* [Image on HyperPhysics web site]. HyperPhysics, Department of Physics & Astronomy, Georgia State University. Retrieved July 31, 2025, from <http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/cirapp.html>
- Newman, L. K. (2024, August). Nasa space situational awareness (ssa) overview [“SSA is defined as ‘the requisite current and predictive knowledge of the space environment and the operational environment upon which space operations depend.’”]. https://nescacademy.nasa.gov/video/8f412b2643514f1abb9bc0bab9ffb1711d?utm_source=chatgpt.com

- Office of the Director, Operational Test & Evaluation (DOT&E), U.S. Department of Defense. (2011, —). *Fy 2011 annual report: Early operational test & evaluation of the space-based space surveillance (sbss) satellite* (Operational Test & Evaluation Report) (Reports the discovery of a data formatting problem during integrated testing that limited full utilization of SBSS mission data by a user. Accessed 15 August 2025.). U.S. Department of Defense, DOT&E. <https://www.dote.osd.mil/Portals/97/pub/reports/FY2011/af/2011sbss.pdf?ver=2019-08-22-112334-427>
- Okada, T., Fukuhara, T., Tanaka, S., Taguchi, M., Imamura, T., Arai, T., Senshu, H., Ogawa, Y., Demura, H., Kitazato, K., et al. (2017). Thermal infrared imaging experiments of c-type asteroid 162173 ryugu on hayabusa2. *Space Science Reviews*, 208(1), 255–286.
- Oswald-Tranta, B., Sorger, M., & O’Leary, P. (2010). Motion deblurring of infrared images from a microbolometer camera. *Infrared physics & technology*, 53(4), 274–279.
- Packard, C., Demars, C., Canull, L., Tyler, D., Rodgers, C., Edel, Z., & Golubev, T. (2024). Dynamic eo/ir satellite signature prediction with high-fidelity muses simulation. *Advanced Maui Optical and Space Surveillance (AMOS) Technologies Conference*, 124.
- Peeters, J., Louarroudi, E., De Greef, D., Vanlanduit, S., Dirckx, J., & Steenackers, G. (2017). Time calibration of thermal rolling shutter infrared cameras. *Infrared Physics & Technology*, 80, 145–152.
- Pineau, D., & Felicetti, L. (2023). Design of an optical system for a multi-cubesats debris surveillance mission. *Acta Astronautica*, 210, 535–546.
- Pirovano, L. (2020). *Cataloguing space debris: Methods for optical data association* [Doctoral dissertation, University of Surrey].
- Proulx, C., Allard, M., Pope, T., Tremblay, B., Williamson, F., Julien, C., Larouche, C., Delderfield, J., & Parker, D. (2017). Performance characterization of the earthcare bbr detectors. *International Conference on Space Optics—ICSO 2010*, 10565, 47–51.
- Pultarova, T. (2024). SpaceX starlink satellites made 50,000 collision-avoidance maneuvers in the past 6 months. what does that mean for space safety? [Published July 23, 2024].
- Ramanagopal, M. S., Zhang, Z., Vasudevan, R., & Johnson-Roberson, M. (2020). Pixel-wise motion deblurring of thermal videos. *arXiv preprint arXiv:2006.04973*.
- Rees, G. (2013). *Physical principles of remote sensing*. Cambridge university press.

- Ringqvist, C., Mele, G., Carlsson, H., Marta, M. B. S., Runborg, O., Enqvist, P., & Wallgren, U. (2018). Flir project-modeling noise in bolometer signal. *KTH Royal Institute of Technology, Stockholm, Sweden*.
- RM, S. (2019). Computation of eclipse time for low-earth orbiting small satellites. *International Journal of Aviation, Aeronautics, and Aerospace*, 6(5), 15.
- Rogalski, A. (2003). Infrared detectors: Status and trends. *Progress in quantum electronics*, 27(2-3), 59–210.
- Sanchez-Ortiz, N., Dominguez-Gonzalez, R., Correia De Oliveira, J., Gelhaus, J., Kerschull, C., & Krag, H. (2013). Computation of cross section of complex bodies in esa drama tool. *6th European conference on space debris*.
- Schubert, M., Böttcher, L., Gamper, E., Wagner, P., & Stoll, E. (2022). Detectability of space debris objects in the infrared spectrum. *Acta Astronautica*, 195, 41–51.
- Scott, A., Hackett, J., & Man, K. (2013). On-orbit results for canada’s sapphire optical payload. *Advanced Maui Optical and Space Surveillance Technologies*.
- Simms, L. M., Phillion, D., De Vries, W., Riot, V., Bauman, B. J., & Carter, D. (2013). Orbit refinement with the stare telescope. *Journal of Small Satellites*, 2(2), 235–251.
- Song, F., Chen, Q., Tang, X., & Xu, F. (2024). Analytical model of point spread function under defocused degradation in diffraction-limited systems: Confluent hypergeometric function. *Photonics*, 11(5), 455.
- Speretta, S., Sundaramoorthy, P., & Gill, E. (2017). Long-term performance analysis of norad two-line elements for cubesats and pocketqubes. *11th IAA Symposium on Small Satellites for Earth Observation*, 1–6.
- Spiller, D., Magionami, E., Schiattarella, V., Curti, F., Facchinetti, C., Ansalone, L., & Tuozi, A. (2020). On-orbit recognition of resident space objects by using star trackers. *Acta Astronautica*, 177, 478–496.
- Stoker, K., Johnson, J., Abercromby, K., Liam, S., & Morgan, Y. (2020). Angles-only orbit determination accuracies with limited observational arc. *Advanced Maui Optical and Space Surveillance Technologies Conference*.
- Vollmer, M., & Möllmann, K.-P. (2018). *Infrared thermal imaging: Fundamentals, research and applications*. John Wiley & Sons.
- Wang, Q., & Atkinson, P. M. (2017). The effect of the point spread function on sub-pixel mapping. *Remote Sensing of Environment*, 193, 127–137.
- Wehr, T., Kubota, T., Tzeremes, G., Wallace, K., Nakatsuka, H., Ohno, Y., Koopman, R., Rusli, S., Kikuchi, M., Eisinger, M., et al. (2023). The earthcare mission—science and system overview. *Atmospheric Measurement Techniques*, 16(15), 3581–3608.

- Wertz, J. R., Everett, D. F., & Puschell, J. J. (2011). Space mission engineering: The new smad. (*No Title*).
- Wright, E. L., Eisenhardt, P. R., Mainzer, A. K., Ressler, M. E., Cutri, R. M., Jarrett, T., Kirkpatrick, J. D., Padgett, D., McMillan, R. S., Skrutskie, M., et al. (2010). The wide-field infrared survey explorer (wise): Mission description and initial on-orbit performance. *The Astronomical Journal*, 140(6), 1868.
- Yilmaz, Ö., Aouf, N., Checa, E., Majewski, L., & Sanchez-Gestido, M. (2019). Thermal analysis of space debris for infrared-based active debris removal. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, 233(3), 811–822.
- Yunpeng, H., Kebo, L., Yan'gang, L., & Lei, C. (2021). Review on strategies of space-based optical space situational awareness. *Journal of Systems Engineering and Electronics*, 32(5), 1152–1166.
- Zengilowski, G. R., Wong, A. F., Wong, S., Mainzer, A. K., Carey, S., Vachier, I. D., Dorn, M., Eisenhardt, P. R., Farris, M., Horne, C. T., et al. (2022). Status update on the neo surveyor detector development. *X-Ray, Optical, and Infrared Detectors for Astronomy X*, 12191, 671–679.

Appendix A

CURES



7 April 2025

Dear Mr Dodero ,

Reference: CURES/24757/2025

Project ID: 28214

Title: Optical sensors for space based SSA

We are pleased to inform you that you have successfully declared that your research project is a **Literature Review – based solely on openly available literature which is in the public domain, and you are undertaking desk-based research not involving any other form of data or information.**

You have also confirmed that your project **does not meet** any of the literature review specified exceptions, listed both within the relevant section of the CURES form and below:

1) Your supervisor has requested that you apply for approval through CURES because:

- The journals or data are in a sensitive area (please discuss this with your supervisor)
- The project will be embargoed i.e. **will not be publicly available via the Cranfield library immediately or longer term**

2) Approval is/will be specifically required by another external body e.g. journal publishers

Therefore, **you do not require ethical approval** and your CURES application will be automatically closed.

Please keep a copy of this letter safe, if this exception is in relation to your thesis project, you will need to include a copy with your final thesis submission.

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team

Appendix B

Image plane coordinates

Table B.1: Pixel coordinates and ranges over time

UTC Time	X pixel	Y pixel	Range [km]
22-Jul-2025 03:48:51	508.6068	-68.9485	122.0569
22-Jul-2025 03:48:52	489.8178	-66.4060	122.4877
22-Jul-2025 03:48:52	471.1684	-63.8820	122.9194
22-Jul-2025 03:48:52	452.6571	-61.3764	123.3519
22-Jul-2025 03:48:53	434.2824	-58.8889	123.7853
22-Jul-2025 03:48:53	416.0428	-56.4195	124.2195
22-Jul-2025 03:48:53	397.9369	-53.9678	124.6545
22-Jul-2025 03:48:53	379.9631	-51.5338	125.0903
22-Jul-2025 03:48:54	362.1201	-49.1171	125.5269
22-Jul-2025 03:48:54	344.4064	-46.7177	125.9642
22-Jul-2025 03:48:54	326.8206	-44.3353	126.4024
22-Jul-2025 03:48:55	309.3615	-41.9697	126.8413
22-Jul-2025 03:48:55	292.0275	-39.6208	127.2810
22-Jul-2025 03:48:55	274.8175	-37.2884	127.7215
22-Jul-2025 03:48:55	257.7300	-34.9723	128.1627
22-Jul-2025 03:48:56	240.7639	-32.6724	128.6046
22-Jul-2025 03:48:56	223.9177	-30.3884	129.0473
22-Jul-2025 03:48:56	207.1904	-28.1202	129.4907

Continued on next page

UTC Time	X pixel	Y pixel	Range [km]
22-Jul-2025 03:48:57	190.5805	-25.8677	129.9348
22-Jul-2025 03:48:57	174.0869	-23.6306	130.3796
22-Jul-2025 03:48:57	157.7085	-21.4089	130.8251
22-Jul-2025 03:48:57	141.4439	-19.2023	131.2713
22-Jul-2025 03:48:58	125.2920	-17.0107	131.7182
22-Jul-2025 03:48:58	109.2518	-14.8340	132.1658
22-Jul-2025 03:48:58	93.3219	-12.6720	132.6140
22-Jul-2025 03:48:59	77.5014	-10.5245	133.0629
22-Jul-2025 03:48:59	61.7891	-8.3914	133.5125
22-Jul-2025 03:48:59	46.1838	-6.2725	133.9627
22-Jul-2025 03:48:59	30.6846	-4.1677	134.4136
22-Jul-2025 03:49:00	15.2904	-2.0770	134.8651
22-Jul-2025 03:49:00	0.0000	0.0000	135.3172
22-Jul-2025 03:49:00	-15.1875	2.0633	135.7700
22-Jul-2025 03:49:01	-30.2732	4.1130	136.2234
22-Jul-2025 03:49:01	-45.2580	6.1493	136.6774
22-Jul-2025 03:49:01	-60.1430	8.1724	137.1320
22-Jul-2025 03:49:01	-74.9291	10.1823	137.5872
22-Jul-2025 03:49:02	-89.6174	12.1791	138.0430
22-Jul-2025 03:49:02	-104.2088	14.1631	138.4994
22-Jul-2025 03:49:02	-118.7042	16.1343	138.9563
22-Jul-2025 03:49:03	-133.1045	18.0929	139.4139
22-Jul-2025 03:49:03	-147.4107	20.0389	139.8720
22-Jul-2025 03:49:03	-161.6238	21.9726	140.3307
22-Jul-2025 03:49:04	-175.7445	23.8940	140.7899
22-Jul-2025 03:49:04	-189.7738	25.8032	141.2497
22-Jul-2025 03:49:04	-203.7126	27.7004	141.7100
22-Jul-2025 03:49:04	-217.5616	29.5856	142.1709
22-Jul-2025 03:49:05	-231.3219	31.4591	142.6323

Continued on next page

UTC Time	X pixel	Y pixel	Range [km]
22-Jul-2025 03:49:05	-244.9941	33.3208	143.0942
22-Jul-2025 03:49:05	-258.5792	35.1710	143.5567
22-Jul-2025 03:49:06	-272.0780	37.0096	144.0197
22-Jul-2025 03:49:06	-285.4913	38.8369	144.4832
22-Jul-2025 03:49:06	-298.8198	40.6530	144.9472
22-Jul-2025 03:49:06	-312.0644	42.4579	145.4118
22-Jul-2025 03:49:07	-325.2259	44.2517	145.8768
22-Jul-2025 03:49:07	-338.3049	46.0345	146.3423
22-Jul-2025 03:49:07	-351.3024	47.8066	146.8083
22-Jul-2025 03:49:08	-364.2190	49.5678	147.2748
22-Jul-2025 03:49:08	-377.0555	51.3185	147.7418
22-Jul-2025 03:49:08	-389.8126	53.0585	148.2092
22-Jul-2025 03:49:08	-402.4910	54.7881	148.6772
22-Jul-2025 03:49:09	-415.0915	56.5074	149.1456
22-Jul-2025 03:49:09	-427.6148	58.2164	149.6144
22-Jul-2025 03:49:09	-440.0615	59.9152	150.0837
22-Jul-2025 03:49:10	-452.4324	61.6039	150.5535
22-Jul-2025 03:49:10	-464.7281	63.2826	151.0237
22-Jul-2025 03:49:10	-476.9493	64.9515	151.4944
22-Jul-2025 03:49:10	-489.0968	66.6105	151.9654
22-Jul-2025 03:49:11	-501.1710	68.2598	152.4370