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FROM CONCEPT TO DEVELOPMENT OF ASTROPHYSICS PAYLOADS FOR GAMMA-RADIATION STUDIES

VOLUME 1

Dissertação no âmbito do Mestrado Integrado em Engenharia Física no ramo de Metrologia e Qualidade orientada pelo Professor Doutor Rui Miguel Curado da Silva e apresentada ao Departamento de Física da Faculdade de Ciências e Tecnologia.

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From Concept to Development of Astrophysics Payloads for Gamma-Radiation Studies

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Lastly, to the most important person in my life, my father, José Neves. Thank you for believing and supporting me through these years. It hasn't always been easy, and from the quantity of side-projects I held throughout this time, I believe it wasn't easy to find it feasible; nevertheless your support was unshakable. You taught me some of the most important tools throughout: work ethics, discipline, and good values. This thank you is extended to the rest of my family members: thank you for your support and understanding.

Per Aspera Ad Astra

Resumo

Os CubeSats iniciaram uma revolução espacial ao providenciar uma plataforma de dimensões reduzidas e escalável: potencializando o lançamento de múltiplas unidades destes satélites normalizados. O resultado: uma diminuição no custo de desenvolvimento, lançamento e operação destes satélites, e um avanço nas tecnologias presentes nestes satélites. Neste momento, CubeSats permitem o desenvolvimento satélites que abrangem áreas desde o desenvolvimento de novas tecnologias à realização de investigação científica.

A área de estudo de Astrofísica é um dos ramos científicos com maior potencial de beneficiar da democratização do espaço. As redes Multi-Mensageiro à escuta de Surtos de Raios Gamma e outros eventos podem beneficiar em grande escala desta vantagem.

Neste trabalho são estudadas três missões diferentes com o objetivo de fornecer os *inputs* para futuras missões de CubeSats contendo experiências de polarimetria.

STRATOSPOLCA é um instrumento científico a bordo de um Balão de Grande Altitude. Os seus objetivos: estudar a radiação de fundo Gamma e a multiplicidade dos eventos em função da altitude.

COMCUBE é um projeto pertencente ao portfólio de projetos AHEAD2020 no qual se pretende estudar e definir um satélite protótipo para uma futura constelação deste tipo de satélites para 'caçar' Surtos de Raios Gamma numa perspetiva integrada de instrumentos em rede de Multi-Mensageiro.

ANTAEUS é um conceito de missão que tira vantagem dos novos desenvolvimentos em detetores de estado sólido e dos desenvolvimentos em CubeSats para oferecer uma nova experiência polarimétrica numa plataforma de satélite 2U.

O trabalho aqui realizado procura evidenciar o desenvolvimento de tais tipos de satélites, de conceito à definição preliminar.

Palavras-chave: Astrofísica, CubeSat, Polarimetria, Multi-Mensageiro, Surtos de Raios Gamma

Abstract

CubeSats started a Space Revolution by providing a smaller platform but one that could carry multiple units of the Standardized definition. The result: the decrease in cost, and the increase in the technological advancement of spacecraft. Now, one has the framework to develop from concept to operations of a spacecraft to test new space technology or even to perform scientific studies.

The field of Astrophysics is one of the scientific fields with the most potential benefit from this democratization of Space. The Multi-Messenger networks listening for Gamma-Ray Bursts and other events can benefit greatly from this advantage.

In this work, three different Missions are studied with the effects of providing inputs to future CubeSats transporting polarimetric payloads.

STRATOSPOLCA is a payload instrument on board a High Altitude Balloon. Its objectives are to provide insight into the background gamma radiation and the multiplicity of events as a function of altitude.

COMCUBE is developed under the AHEAD2020 consortium with the goal of studying a spacecraft prototype and baseline for a future constellation hunting for Gamma-Ray Bursts in a Multi-Messenger and integrated perspective.

ANTAEUS is a pathfinder mission concept to take advantage of the new developments in solid state detectors and CubeSat developments to offer a new polarimetric experiment in a 2U satellite.

The work herein provides a study on the development of such satellites, from concept to preliminary definition, providing the framework for future projects.

Keywords: Astrophysics, CubeSat, Polarimetry, Multi-Messenger, Gamma-Ray Bursts

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List of Acronyms

ADCS Attitude Determination and Control System. xv, 24

AMEGO All-sky Medium Energy Gamma-ray Observatory. xv, 1, 12

AMON Astrophysical Multimessenger Observatory Network. xv, 64

CDR Critical Design Review. xv, 40

CIDL Configuration Item Data List. xv

COMCUBE Compton Cube. xv, 1, 3, 4, 50, 72

COTS Commercial Off The Shelf. xv, 68

CZT Cadmium Zinc Telluride. xv

DARPA Defense Advanced Research Projects Agency. xv, 23

DOORS Dynamic Object-Oriented Requirements System. xv, 36

DRD Document Requirements Definition. xv, 35, 71

DSSD Double-sided Silicon Strip Detector. xv, 53–58

ECSS European Cooperation for Space Standardization. xv, 4, 22, 39

EPS Electric Power System. xv, 24

ESA European Space Agency. xv, 12, 22, 68

EU European Union. xv, 18

FEE Front End Electronics. xv, 53

Fermi Fermi Gamma-ray Space Telescope. xv, 12, 13, 16, 22

FoM Figure of Merit. xv, 14, 50, 55, 72

GAM Gamma Astrophysics Payload. xv

GRB Gamma Ray Burst. xv, 1, 9, 14, 18, 20, 64, 65, 68, 69, 76, 77

GW Gravitational Wave. xv, 1, 18

HERMES-SP High Energy Rapid Modular Ensemble of Satellites - Scientific Pathfinder. xv, 20

IAC International Astronautical Conference. xv, 63

IAF International Astronautical Federation. xv

INTEGRAL International Gamma-Ray Astrophysics Laboratory. xv, 1, 12, 13, 22

IUT Item Under Test. xv

IXPE Imaging X-Ray Polarimetry Explorer. xv

LEO Low Earth Orbit. xv, 63

LIP Laboratory of Instrumentation and Experimental Particle Physics. xv, 63

MDP Minimum Detectable Polarization. xv

MDR Mission Definition Review. xv, 69

MEGAlib Medium-Energy Gamma-ray Astronomy library. xv, 27, 28, 30, 53, 69, 71, 76

NASA National Aeronautics and Space Administration. xv

OBDH On-Board Data Handling. xv, 24

PDR Preliminary Design Review. xv, 40, 65, 68

PRR Preliminary Requirements Review. xv, 63, 77

RS Technical Requirement Specification. xv

S/C Spacecraft. xv, 67–69

SAA South Atlantic Anomaly. xv, 16, 23

SE Systems Engineering. xv

SNR Signal to Noise Ratio. xv

SOC Scientific Operation Center. xv, 65, 67

SPENVIS SPace ENVironment Information System. xv, 30

SRR System Requirement Review. xv, 40, 63, 65

SSC Swedish Space Corporation. xv, 3

STRATOSPOLCA Stratospheric Polarimetry with Cadmium Telluride Array. xv, 3, 4, 12

TCS Thermal Control System. xv, 24

TT&C Telemetry, Tracking, and Command. xv, 24

USA United States of America. xv, 18

WP Work Package. xv, 3

1

Introduction

1.1 Motivation

On the 17th of August 2017, a Gravitational Wave, GW170817, was observed by the Virgo and LIGO observatories and this was the first observed GW from a source strong enough to produce detectable electromagnetic signals [1], and these were observed by the Fermi Gamma-ray Burst Monitor $\approx 1.7s$, after the GW detection. This event was then observed by other observatories both on ground and space thus marking the coming of a new age in Multi-Messenger Astronomy. In terms of scientific results, for the first time the same source could be studied with two messengers: gravitational waves, and electromagnetic. This meant that the models under study were now to be subject to more data than before thus allowing for further theoretical and experimental improvements. Several other events have since then been observed on the Multi-Messenger scope.

For events such as Gamma Ray Burst, Active Galactic Nuclei, Pulsar Wind Nebulae, and Compact Object Binaries, there is scientific gain [2] from doing polarization studies in conjunction with the Graviational Waves. However, only a limited amount of polarimetric experiments has been performed, namely on programs such as INTEGRAL [3] and POLAR [4]). Moreover, missions like e-ASTROGAM and AMEGO [5], [2] are proposed for this field of study.

To answer the current scientific needs for electromagnetic observation on a 100 keV to 1 MeV range known as soft γ-ray, studying both the spectroscopy and the polarimetry, covering all-sky and reducing the costs, a nanosatellite constellation of CubeSat-based satellites is proposed by the scientific community of AHEAD2020 as future project on the High Energy Astrophysics and Multimessenger Astronomy fields. However, this mission, dubbed COMCUBE, is merely a technological pathfinder and not optimized for polarimetry. Consequently, ANTAEUS was born out of the need to build a CubeSat (1U to 2U) designed specifically for this purpose.

1.2 Objectives

This thesis combines the work carried out on three projects: STRATOSPOLCA, COMCUBE, and ANTAEUS. An overview of the three projects and my participation is presented on the following sections.

The objective of this work is to lay the ground work for future CubeSat constellations.

1.2.1 STRATOSPOLCA

The STRATOSPOLCA project was submitted and approved for flight on the BEXUS 30/31 Launch Campaign. The project started in August 2019, with a planned launch for October 2020 later delayed due to COVID for October 2021 when it was launched. Formally, the project closed in June 2022 after the scientific analysis and presentation is concluded.

My participation on the project was under the roles of Project Manager and later (when the need was assessed) of Systems Engineer, combining the two positions.

The goal of STRATOSPOLCA was to design, manufacture, assemble, integrate, test, and launch of an experiment for a High Altitude Balloon flight provided by the Swedish Space Corporation (SSC).

The objectives of the project are described in Table 1.1. For the purpose of this thesis, STRATOSPOLCA also serves the role of being the teaching pillar that allowed to gather the knowledge to implement on the next projects, many times due to learning by doing it wrong first on STRATOSPOLCA.

ID	Objective
Obj.1.1.	Measure the level of single, double, and multiple events, as a function of the altitude.
Obj.2.1.	Improve future polarimetric experiments Signal-To-Noise Ratio.
Obj.2.2.	Compare data acquired to pre-flight simulations.
Obj.2.3.	Measure the energy of the interactions.

Table 1.1: STRATOSPOLCA Objectives

1.2.2 COMCUBE

AHEAD2020 is an international community of laboratories financed by the European Union to develop and integrate efforts on high-energy astrophysics. This project is subdivided into Work Packages ranging from Management to Outreach Activities, and more technical packages, such as Work Package (WP) 11 named Space Experiments for HE Astrophysics & Multimessenger Astronomy subdivided into the following tasks:

- Task 11.1 Nanosatellite Infrastructure;
- Task 11.2 Compton Telescope CubeSat Prototype;
- Task 11.3 Optimization/testing of a novel GRB detector and veto system;

– Task 11.4 Future missions - beyond the baseline.

Our work will be focused on these tasks, but specifically on the Design of the Nanosatellite of Task 11.1 and on laying the groundwork of a future proposal for a network (or constellation) of these nanosatellites.

For the scope of this thesis, the scientific results and major conclusions will be presented first on the Results section and the conclusions integrated in the project STRATOSPOLCA and ANTAEUS.

1.2.3 ANTAEUS

ANTAEUS has scientific objectives vary to those of COMCUBE due to being more inclined for the proof of concept of polarimetric missions aboard CubeSats. Moreover, whilst COMCUBE is loosely defined in terms of the subsystems, processes, and life-cycle; ANTAEUS is developed as a whole CubeSat with the collaboration of the University of Beira Interior, and the University of Nottingham a CubeSat mission since the early start, and following the development and lifecycle guidelines of the European Cooperation for Space Standardization (ECSS).

ANTAEUS Mission Objectives with respect to the scientific mission are defined in Table 1.2.

ID	Requirement
MO-01	The scientific experiment shall measure the energy of incoming photons within a range from 100 keV to 1 MeV.
MO-02	The scientific experiment shall identify double-events on the pixels of the detector.
MO-03	The scientific experiment should distinguish a celestial signal from background noise.
MO-04	The scientific experiment should, for non-background events, be capable of identifying the polarization of the incoming source.

Table 1.2: ANTAEUS Main Scientific Objectives

1.3 Thesis Organization

This dissertation is organized through successive chapters following a similar organizational structure as that of the IMRaD used in research papers.

Introduction

This chapter concerns itself with the Motivation and Objectives for the persecution of the dissertation. The organization of the dissertation is also presented.

State of the Art

On this chapter, a definition of the existing research and work in the scientific field and satellite engineering is presented.

Methods

The Methods chapter provides an in-depth overview of the methods employed both for scientific analysis and for the systems engineering approach used.

Results

On this chapter the results obtained and present and some preliminary discussion is held as well as comparison. The evolution of the three projects and directions taken in each are also studied.

Conclusion

Lastly, the outcome of the work performed is described and the conclusions reached are discussed and future research is proposed.

2

State of the Art

2.1 High-Energy Astrophysics

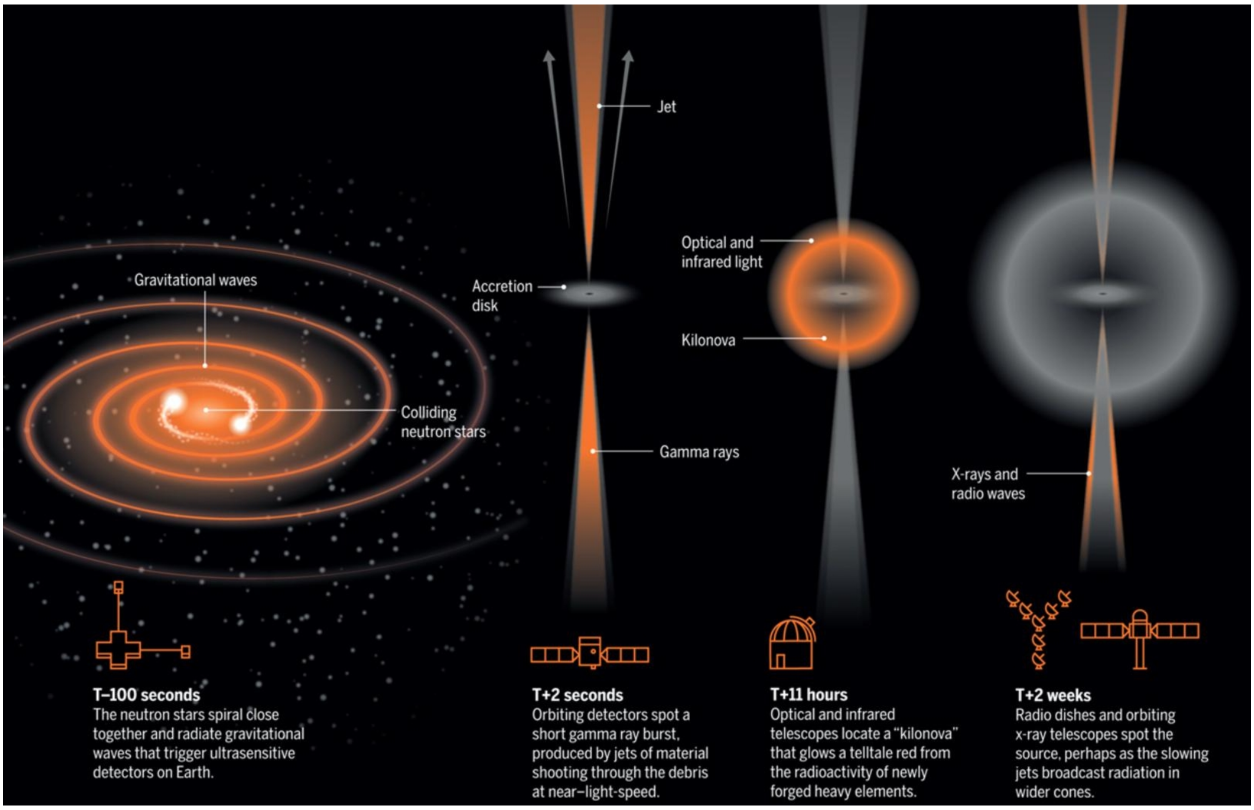

Figure 2.1: Multimessenger concept. Adapted from AHEAD Webpage.

Humanity has long searched the night sky for answers, in wonder of discovery for the objects and phenomena. The scientific community has provided for extensive studies on the composition of Stars and Planets both in our immediate surroundings and farther away. Stars, for example, are very interesting to understand the chemical composition of the Cosmos for it is on the more complex and massive systems that the heavier elements are forged.

More recently, however, we have began to observe gravitational effects that we hadn't foreseen on initial models and concurrently scientists theorized and proved the existence of more atypical objects. Objects with a greater mass, like Neutron Stars, or Black Holes. These objects would challenge some of our initial assumptions and could provide for explanations as well as open the way to new theories and frameworks to explain our Universe.

At this point we could listen to the Cosmos in its Optical and Radio components through observations. The studies occur on wavelengths of 380 to 750 nm for the first on the millimeter scale to the 100 km magnitude on the latter. However, these observations occur for photons of small energy (bellow 1 keV) and therefore correspond to emission mechanisms such as spontaneous emission when electrons move from higher energy states to lower energy states.

In spite of the important information provided by the aforementioned mechanisms, they don't provide with the complete picture of all emission mechanisms and energy ranges on massive objects. Both on Stars and heavier celestial objects, we find the occurrence of nuclear interactions and these emit higher energy photons that can't be observed with Radio or Optical telescopes. Therefore when comparing different models to explain the Cosmos we may find ourselves looking at very different but potentially valid explanations of our observations and to be able to move onto more refined models and choose between the mechanisms available we need to observe in higher energies where we found a gap in our knowledge.

It is in this context of High-Energy Astrophysics that the observation of X-rays and γ-rays is applicable, with the energy range starting in the keV order of magnitude. The photons emitted on the X-ray energy range (from 1 to 100 keV, approximately) are typically emitted from high energy ions or electrons when these hit matter. However, this leaves a gap in our understanding for greater energy bands and eventually moved onto γ-rays, that is, photons emitted from nuclear or arising from photon-particle interactions, typically with energies above 100 keV. Throughout this thesis, we will be interested on such photons and their sources.

The energy range from 100 keV to 1 MeV is of particular interest because it contains binding energies of nuclei, as well as the electron rest energy which is appropriate to tag leptonic processes.

But performing spectroscopic studies is not sufficient to give us the entire picture of a specific massive object. And, like optical electromagnetic radiation can be polarized, so can a beam of γ photons be polarized.

The exact mechanisms and physical properties of these emissions are far from being totally understood and this is the forefront of research in the field. A necessary requirement to push the boundary forward is to build and improve upon the instrumentation available.

2.1.1 Polarized Gamma-Ray Emission Mechanisms

A Polarized Gamma-Ray Photon may be emitted from various mechanisms, such as Magneto-Bremsstrahlung Radiation, Bremsstrahlung Radiation, Compton Scattering, and

Magnetic Photon Splitting ([6]).

For each Emission Mechanism, there is a related set of properties (such as energy and polarization distribution, particle flux, and others) that depend on the celestial object and associated phenomena (may be, for example, a jet stream or an accretion disk).

The sources of this radiation may be GRB, Pulsars, Solar Flares, Active Galactic Nuclei, or even binary systems composed of Neutron Stars and/or of Black Holes and their merger.

Whilst the same sources may be analyzed from Radio, Optical, or X-Ray telescopes, these only provide us with limited information, namely in terms of energy and imaging. To improve upon this, several Gamma-Ray instruments have flown and they make use not only of the energy of incident photons but also of their Compton scattering within the detector thus allowing for two additional parameters of study: the level of linear polarization - also called polarization degree-, and the polarization angle. The first is deeply entangled with the emission mechanism and the latter with both the mechanism and its source.

2.2 Development of Polarization Detectors

Polarization Detectors are based on the properties of the Compton Scattering, a phenomena where a photon interacts with a charged particle - more commonly, an electron on the material of the Detector. A graphical representation is provided in Figure 2.2.

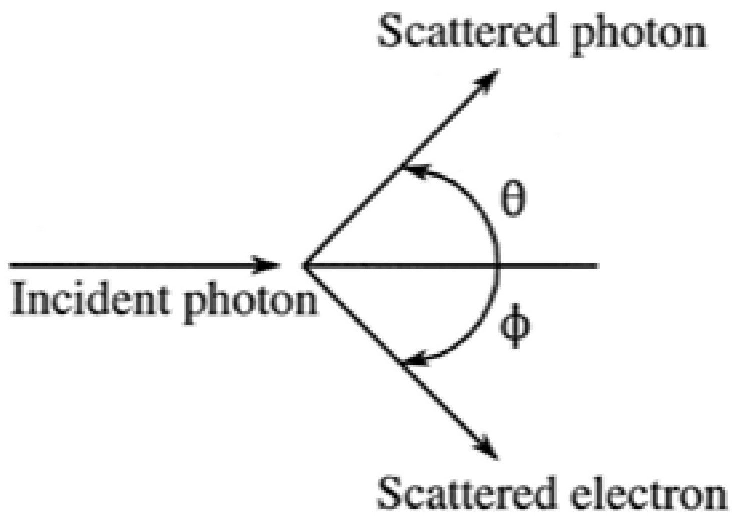

Figure 2.2: Compton Scattering Process, adapted from [6]

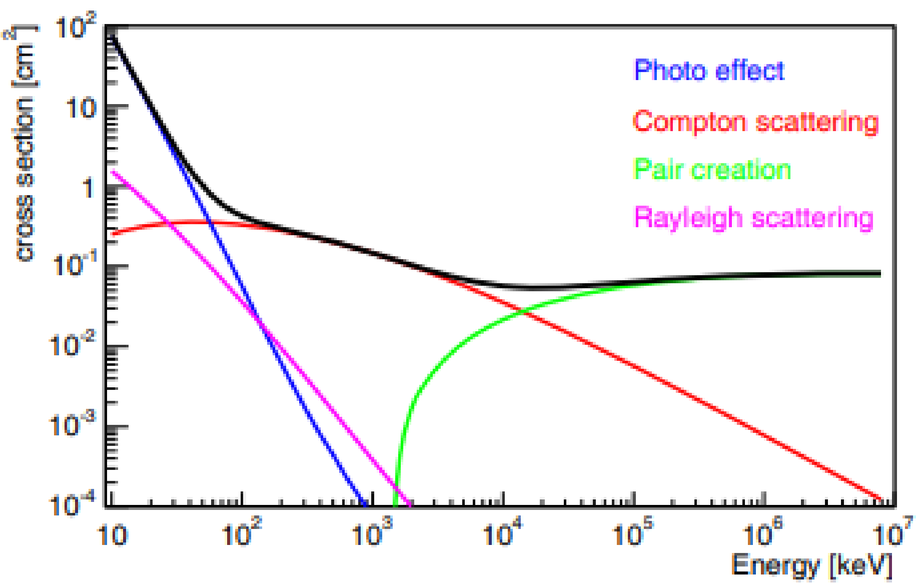

Figure 2.3: Cross-Sections for different phenomena. Adapted from [7]

Compton Scattering follows a known differential cross-section of the Klein-Nishina Distribution defined in equation 2.1 for a beam of linearly polarized photons. In figure 2.3 different cross-sections for different phenomena can be seen across a range of energies. Where r_0 is the classical electron radius, E' and E are defined as the energies after and before the interaction, θ is defined as the angle of the scattered photons, and, lastly, ϕ is the angle between the plane of the scatter and the incident polarization plane.

$$\frac{d\sigma_{KN,P}}{d\Omega} = \frac{r_0^2}{2}\left(\frac{E'}{E}\right)^2\left[\frac{E'}{E} + \frac{E}{E'} - 2sin^2(\theta)cos^2(\phi)\right] \tag{2.1}$$

The relationship between the initial and final energies is found by analyzing the Compton Scattering relations. In equation 2.2 we find the difference between incoming and outgoing photon's wavelength and later on equation 2.3 we have an explicit relationship between the photon's respective energy.

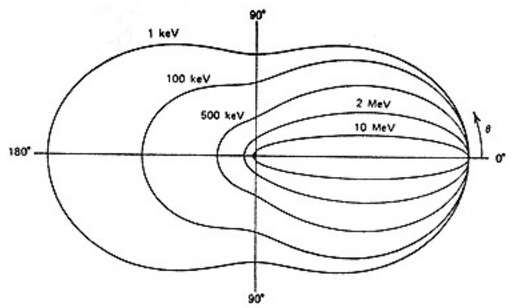

Figure 2.4: Scattering Distribution as a function of the Energy

It can be seen in Figure 2.4 that for higher energy levels, the distribution of the scattering will be mostly directed to a more clearly defined scattering angle.

$$\lambda' - \lambda = \frac{h}{m_e c}(1 - cos\theta) \tag{2.2}$$

$$\frac{E'}{E} = \frac{1}{1 + (E/m_e c^2)(1 - cos\theta)} \tag{2.3}$$

Compton Scattering detectors are often composed of semiconductors crystals arranged in matrix-like configurations where energy is deposited and positions are calculated on the center points of the pixels; and of semiconductors of Silicon in a strip configuration (also known as Silicon Strip Detectors) for tracking of the interactions coupled with calorimeters (for energy deposition). These detectors can only give us a limited spatial resolution.

The Compton Telescope CubeSat Prototype is composed of Silicon Strip Detectors coupled with a Calorimeter. ASTROGAM, and AMEGO are both proposed telescopes following the same architectural concept. Fermi, launched in 2008 and still in orbit as of January 2021, is a Gamma-Ray Satellite Telescope by NASA with a flight-proven track record of a similar geometry, but not optimized for polarimetry.

PoGOLite, and STRATOSPOLCA are balloon-borne experiments for hard X-Ray and Gamma-Ray measurements with matrix-like geometries, however with pixels varying from a hexagonal shape on the first to a square shape on the latter. The INTEGRAL, an ESA satellite mission, uses the IBIS detector as a pixellated Gamma-Ray detector composed of two planes with limited polarimetric capabilities. Like Fermi, INTEGRAL is one of the flight-proven detectors.

INTEGRAL design is based on a Coded Mask telescope design. A graphical representation of this design can be found in Figure 2.5.

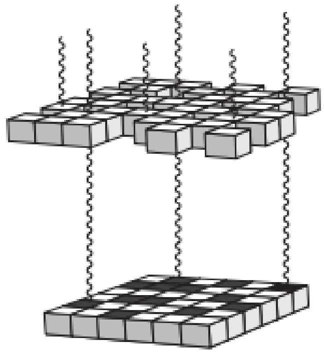

Figure 2.5: Coded Mask simplified design as used on INTEGRAL. Adapted from [7]

2.2.1 Parameters of Interest

In order to qualify the telescopes' capability in achieving results, the communities define scientific requirements ad hoc ahead of and during their design.

One of the figures is the MDP, defined as the Minimum Detectable Polarization for a 100% polarized beam of a type-source with the influence of Background events. The source is usually a choice between a measure of the Crab Nebula (usually either 1 Crab or 10 mCrab) and an observation time of 1 year or 1 Ms. Other sources have been used, such as GRB170817A after 2017. We can find the most general form with resource to equation 2.4. The MDP is a good measure of how little linear polarization a detector can still measure in spite of the influence of background radiation.

$$MDP(100\%) = \frac{n_\sigma}{\epsilon S_F Q_{100} A_{eff}} \sqrt{\frac{\epsilon S_F A_{eff} + B}{T}} \tag{2.4}$$

The $MDP(100\%)$ has as input the n_σ level, the S_F or Source Flux in units of photons/s/cm^2, the Background represented by B expressed in a simple count rate counts/s, the modulation factor, Q for a 100% polarized beam, the Effective Area, or A_{eff}, expressed in cm^2, the ϵ representing the detector efficiency (also seen in literature as double-event efficiency), and lastly the time of the exposure expressed in seconds, T.

Another interesting and similar measure to have is the Sensitivity of the Detector as defined in equation 2.5, with the added parameter of ΔE defined as the Energy Band, in keV. The Sensitivity is the minimum detectable flux of a 100% polarized beam in units of photons/s/cm^2/keV at a significance level of n_σ.

$$S = \frac{n_\sigma}{\epsilon Q_{100}} \sqrt{\frac{B}{A_{eff} T \Delta E}} \tag{2.5}$$

Early authors (such as [6]) call for general parameters such as the Figure of Merit (FoM) defined on equation 2.6 but mostly for pixellated detectors.

$$FOM = \epsilon Q_{100} \tag{2.6}$$

Other parameters are of interest when choosing and designing our detector, namely their Energy Range, Energy Resolution, and Effective Area. These parameters have already been introduced as requirements for our project on Chapter 1.

Another parameter of estimation which will be important on a transient is the capability of providing the location of the emission in the sky.

Location may be used to improve and correct results from off-axis signals. Using a multi-satellite multi-detector configuration we may be able to introduce post-processing factors to refine individual data and cross-examine between individual results and boosting the constellation scientific return in spite of the problems and systemic errors described in the future Section 2.2.2.

However, whilst the aforementioned are parameters based off the detector alone, other important parameters must be considered, namely: their orbital coverage, and availability. It is important to guarantee a high coverage and high availability due to the unpredictability nature of common events like GRB.

2.2.2 Common Problems and Systemic Errors

Compton detectors, because they depend on interactions and the positions of said interactions are inherently pixellated (pixels may be hexagons, squares, or triangles - the trade-off between each of these is well studied in [6]) and therefor have distorted tracking information. In Figure 2.6 you can see the comparison between a "real" event and its detection at the center of the pixel.

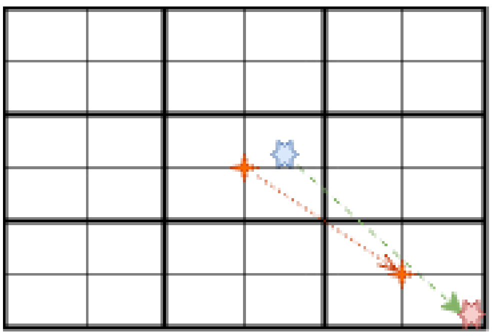

Figure 2.6: Pixellated Detector schematic of first interaction (blue) and second interaction (red). Thicker lines are the boundaries of the pixels whilst the finer lines are the lines connecting the center coordinates. In orange you can find the *detected* positions.

Moreover, due its discrete geometry, the polarimetric response will not be uniform and a previous study of its distribution is necessary to normalize, simulating both non-polarized N_{non} and polarized N_{pol} beams in function of the angle (θ) as described in equation 2.7.

$$N_{true}(\theta) = \frac{N_{pol}(\theta)}{N_{non}(\theta)} N_{max} \tag{2.7}$$

Due to this effect, we may see artifacts on our modulation curve like repeated peaks on the non-polarized incidence.

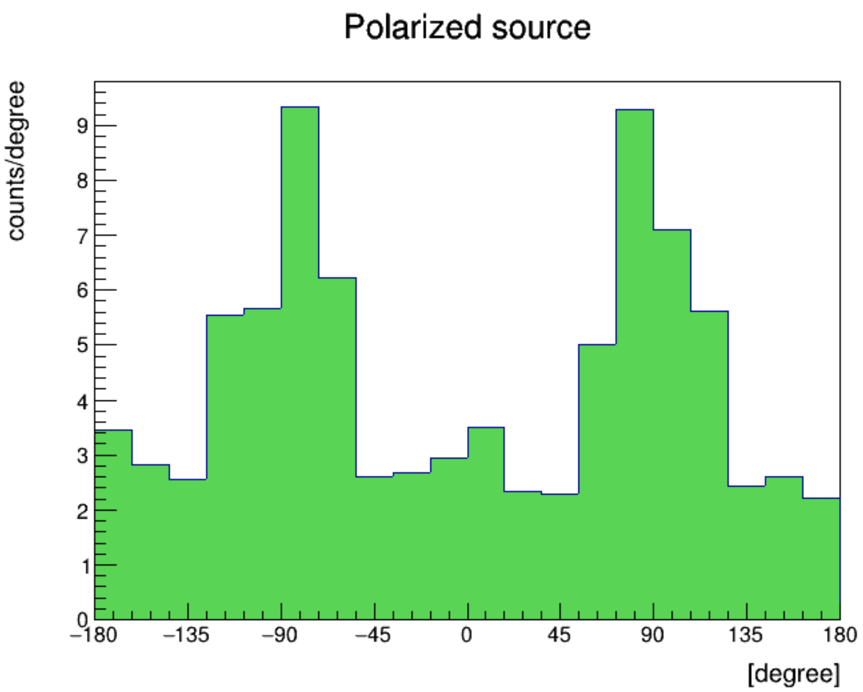

Figure 2.7: Simulated Polarized Beam with modulation artifacts due to the discrete nature of the instrument

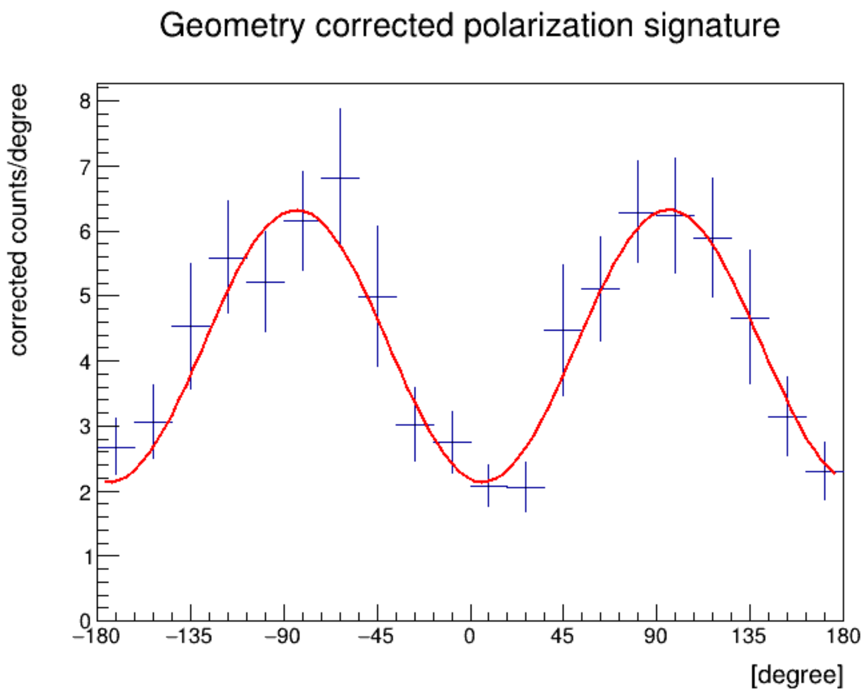

Figure 2.8: Simulated Output with Geometry Correction on MEGAlib

Another problem arises when particles hit the detector off-axis. The Modulation Factor as a function of Energy of the events will reflect aggravating systematic errors. The article [8] does a detailed investigation on this matter.

Background radiation is a common problem for all detectors and moreover for Earth orbiting detectors which may have the influence of intense background regions like the South Atlantic Anomaly (SAA) which is well-known to cause problems when satellites orbit through the region due to the increased flux of energetic particles. Therefore, using a multi-satellite approach to reduce the unavailability of the instruments and have redundancy in case one or more of the satellites is within the SAA when an event occurs. This has famously occurred when observing the GRB170817A, the landmark event for Multi-Messenger Astrophysics, when the Fermi instrument entered the SAA thus raising the background count rate and rendering bellow optimal information for the complete study of an extended emission.

2.3 Multi-Messenger Astrophysics

In spite of the different scientific communities split between the energies of observation, like discussed on Section 2.1, there is a firm belief that the best results will be obtained by combining efforts in what is known as Multi-Messenger Astrophysics.

A typical Neutron Star merger starts when the two Stars begin to spiral close to each other and disrupting the Gravitational field and propagating GW. The emitted GW will be detected by sensitive detectors on Earth, like LIGO, USA, and VIRGO, EU.

Upon merging, jets of particles are emitted and an accretion disk is formed around the new system. These will be sources for GW which should be detected by orbiting satellites around Earth (assuming they will be on the path of incoming particles). Between this and the Gravitational Wave there will be a span of time on the order of one hundred seconds.

A dozen hours after the merger, a transient kilonova will be detected by Optical and Infrared telescopes. These telescopes may be located on Earth or be in orbit.

Within a couple of weeks, radio telescopes and X-ray telescopes will be able to pick up the remnants of the merger by-products.

Other sources may be added to the mix and for some kinds of events it should be possible to detect a neutrino flux coming from the source, using the appropriate observatories.

As one can easily note, it's enchanting to be able to combine the data of the different observations and be able to perform research while looking not just at one specific energy range or parameter, but at the entire spectrum, as if looking at the entire "picture" of the event. This is the interest in Multi-Messenger Astrophysics, and this effort should be rewarded due to the more in-depth revision and selection of the most apt models to describe the Universe and the events as well as mechanisms we are looking after.

The first event of the kind which was simultaneously detected was the Gravitational Wave GW170817, emerging from the elliptical Galaxy NGC 4993, observed on the 17th of August of 2017 and soon after observed as a GRB identified as GRB170817A. Eleven hours after the first observations, optical and near infrared telescopes identified the transient coming from the same galaxy which was referenced as AT 2017gfo.

2.4 Summary of Existent and Future Telescopes

Polarimetry - polarization angle and polarization degree measurements - of gamma-rays is still a recent field of observation and no dedicated observatories are currently in space.

On the polarization point of view, nonetheless, INTEGRAL, since 2002, has served as a polarimeter by necessity and has provided results [9] [10], however, on a smaller range between 200 keV and 600 keV. The COMPTEL space telescope (measuring between 1991 and 2000) did perform measurements on the range of interest but with a low sensitivity when in comparison with observatories on the other energy bands. COMPTEL, in spite of performing on the range of interest, did not perform polarimetric studies.

POLAR, a mission on board the Chinese Space Station, Tiangong 2, was very successful in 2016 measuring over 55 Gamma Ray Bursts. Five of these were selected for having the best statistics and provide data. Their results were very favorable and proved a low polarization level, thus rejecting the hypothesis that all GRB are unpolarized [4]. The results further increase the interest for a deep study of the matters. The Swiss/Chinese colaboration is expected to launch a follow-up mission named POLAR-2.

A graphical description of sensitivity over the energy ranges can be found in Figure 2.9 for both historic, current, and proposed instruments and observatories.

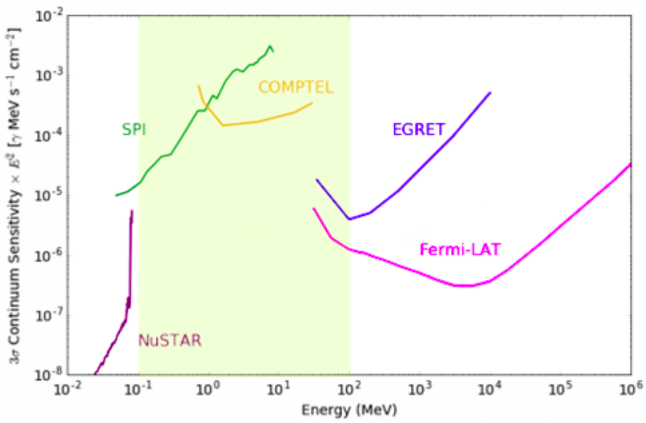

Figure 2.9: Sensitivity as a function of energy for hard X-ray and gamma-ray instruments. Adapted from [11].

An interesting project, the HERMES-SP which is proposed to measure from a few keV to approximately 1 MeV with resort to a smaller and modular approach like the one we propose by using multiple CubeSats of NanoSat categories into a constellation. However, this project focuses more on localization of GRB for direct observation alongside GW observatories.

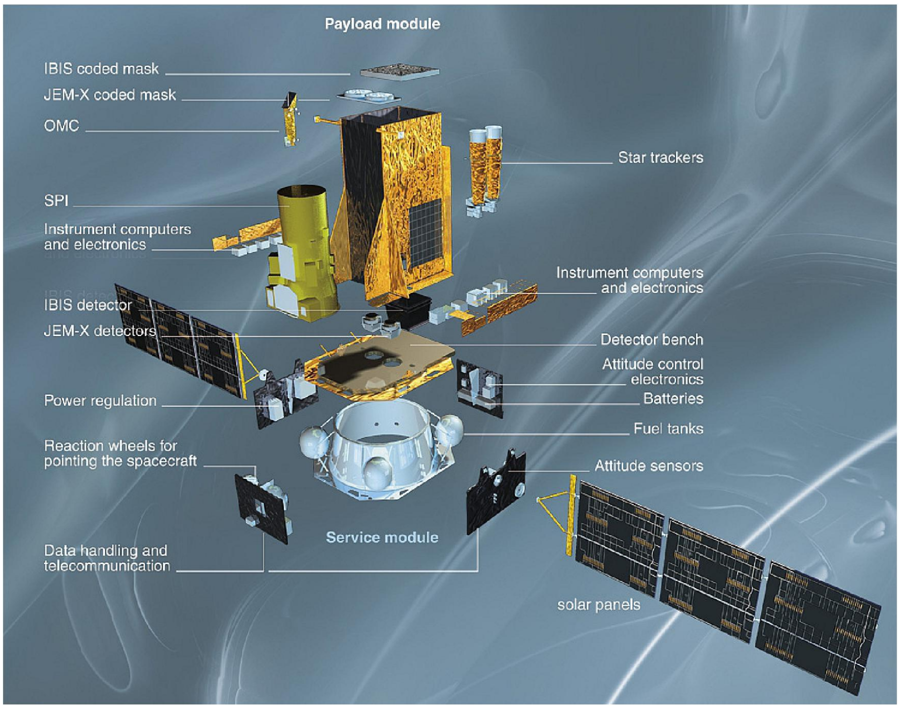

Figure 2.10: INTEGRAL Expanded View. Adapted from eoPortal Directory - INTEGRAL

2.5 Satellites

Satellites have been used for both the benefits of science, communications, navigation and positioning systems, as well as other applications, and serving a multitude of end-users. The first human-made satellite was launched only in 1957, Sputnik-1, and, in spite of having only around 84 kg, the satellites that followed - most notably in communications - have reached weights around tons of kilograms.

In terms of standardization, the processes of designing, building, testing, flying, and decommissioning a satellite are widely standardized through local standards.

In the case of Europe, the European Cooperation for Space Standardization (ECSS) is the joint venture led by European Space Agency (ESA). The standards cover the development of the spacecraft and supporting products such as ground communications, ground support equipment, test facilities, and other. The standards cover Management, Engineering, and Product Assurance and have associated Technical Memoranda and Handbooks which support the user.

2.5.1 Scientific Satellites

The Fermi satellite weighted 4303 kg and had dimensions of 2.8 m x 2.5 m. The INTEGRAL telescope weighted around 3500 kg and had a volume of 45 m^3.

However, due to improvements in electronics, satellites have been miniaturized and it is now possible to launch satellites as small as 10x10x10 cm^3 and weighting less than 1 kg. Smaller satellites are possible but with greater constrains. The unit-size of 10x10x10 cm^3 is commonly called 1U whilst multiples of this size are respectively 2U, 3U, 4U, and so forth, for, respectively, 2, 3, and 4 times the basic unit. A more detailed definition is provided in Section 2.5.2.

For the purpose of scientific instrumentation, as shown in Figure **??**, satellites are typically heavy and voluminous. Therefore, these kinds of laboratories are also expensive due to a number of complex factors such as the precise and sensitive instruments and launch services. A semiconductor crystal, for example, is a common element for gamma-ray detectors and is increasingly difficult to produce maintaining the quality whilst increasing the size.

Type of Satellite	**Mass**
Large	>1000 kg
Medium	500 kg to 1000 kg
Mini	100 kg to 500 kg
Micro	10 kg to 100 kg
Nano	1 kg to 10 kg
Pico	<1 kg

Table 2.1: Satellite Classes

A satellite constellation is an ensemble of satellites that works together to achieve a certain objective. Mostly, these solutions are used to achieve total sky coverage and high availability. These kinds of configurations have already been used for telecommunications and recently one of the most numerous constellations (STARLINK, by SpaceX) promises to provide high-speed internet coverage requiring 41493 satellites, of which 2335 have already been launched as of March 2022. Constellations vary widely from 2 satellite units to many satellite units.

For scientific purposes, satellite constellations may offer a good scientific solution at a lower cost from traditional satellites whilst maintaining or improving some parameters of interest. Another advantage of this solution is that the time frame from design to launch of one of these satellites is considerably smaller which allows to fly newer technology and instruments on board. Lastly, one great scientific and technical advantage is that the system is redundant, both for cases of lack of coverage due to external interference such as SAA or cases of satellite malfunction. Small satellites, nevertheless, still have one major disadvantage which is their failure rate in comparison to other satellites.

2.5.2 CubeSat Definition

The CubeSat history starts in 1998 with a project that Stanford University (Aeronautics and Astronautics Department) had with the Defense Advanced Research Projects Agency (DARPA) and with the Aerospace Corporation [12]. The goal of the project was to launch a picosat size satellite as part of a DARPA program. In spite of having background with small satellites, the students proposed instead that the challenge be the design of a launcher for this picosat. The continued work of these research institutes moved towards defining these satellites and launchers as a standard.

The standard was first released in 1999 by a collaboration of the California Polytechnic State University and Stanford University. The objective of the standard was, at first, to facilitate access to space for university students. However, since then, many students and universities alike as well as private companies have used this standard as the baseline for many satellites. At the time of the writing of this thesis, it's possible to search online for CubeSat parts buy them through online stores.

The smallest unit for a CubeSat is a 1U unit has dimensions of 10 cm x 10 cm x 11.35 cm (counting with rails interface). The different CubeSat sizes are presented in Figure 2.11.

The CubeSat standard allows for the combination (also known as ride-share) of several satellite launches into one flight, by making use of the modularity and common design the launch deployers.

The CubeSat definition (available in cubesat.org) compromises the standardization of:

- Flight Segment Unit Requirements (may be extended to a multiplicative factor, such as 1.5U, 2U, 3U and others) [13];
- Regulatory Requirements;
- Testing Requirements and information [14];

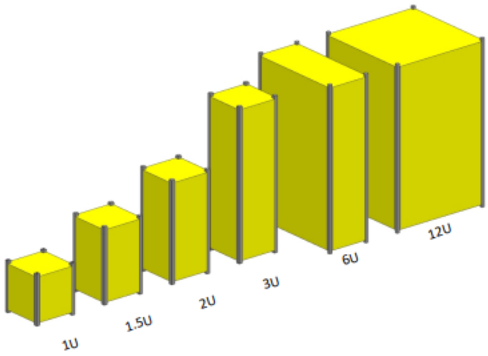

Figure 2.11: CubeSat family of sizes. Adapted from [13].

- P-POD (Launch Segment deployer) [15].

Figure 2.12: P-POD MkIII REV E, image from [15]

CubeSat Subsystems

Due to the relative high demand and need of parts (the customer usually only wants to develop its part, the Payload) common to all spacecraft and with a design easily adaptable to other spacecraft (after all, the dimensions and the electronic interfaces are maintained equal), online stores are able to provide systems such as:

- Electric Power System (EPS);
- On-Board Data Handling (OBDH);
- Telemetry, Tracking, and Command (TT&C);
- Thermal Control System (TCS)
- Propulsion Systems;
- Attitude Determination and Control System (ADCS).

Table 2.2 provides a list of common functions per subsystem.

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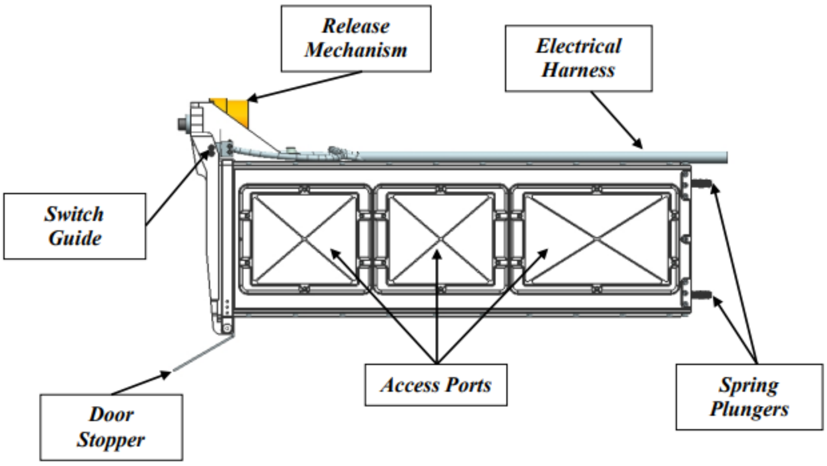


Figure 2.13: P-POD MkIII REV E Main Features from [15]

System	Functions
Electronic Power System	Power Control
	Power Distribution
	Power Generation
Telemetry, Telecommand, and Control	Handling High-Priority Commands
	Communicate with Ground Segment
On-Board Computer	Handle House-Keeping
	Change Operating Modes
	Define out-going packets
Data Bus	Distribute Data Signals
	Distribute Power
Attitude Determination and Control System	Attitude Determination
	Attitude Control

Table 2.2: CubeSat list of most common Systems and their functions

3

Methods

3.1 Scientific Background and Definition

For the scope of the scientific definition, the strategy employed was to perform a gap-analysis to the existing state of the art in the scientific realm in combination with the aspirations of the laboratory associated with this thesis.

The correct and definite outline of the scientific objective for a mission allows to bring clarity on the project and ensure that the science and engineering disciplines stay aligned with one another. While it may not seem clear at the beginning how, but a clear definition of the scientific background and the mission objectives allow for the teams doing the design and execution of the project to make their decisions wisely and taking into consideration "mission return", taking into consideration the solutions and options which offer a greater scientific return to the mission.

Likewise, the arguments supporting the mission concept defined later on the applicable sections must be sound in order to allow for the correct definition of the mission.

The scientific motivations have already been discussed in Section 1.1, as well as sections 2.1, 2.2, 2.3, and 2.4. The missions herein build on this scientific motivation and provide different answers to the different problems arising.

3.1.1 Simulations

Regarding simulations, the tool Medium-Energy Gamma-ray Astronomy library (MEGAlib) was used. MEGAlib [16] is a medium-energy astrophysics tool family that concerns itself with the study of the interaction of particles and radiation with matter and the outcome of these interactions. MEGAlib is divided into:

- Geomega [17] - used for geometry and detector analysis, specifically: geometry overlap, calculation of energy, position, and time resolutions, as well as trigger handling;
- Cosima [17] (Cosmic simulator) – tool employed to use both the simulation input and the detector and geometry specifications and simulating the generated events;
- Revan (Real event analyzer) – software suite handling reconstruction of events after they've been simulated in Cosima or measured data;

- Mimrec [18] - data analysis tool which takes as inputs the results produced with Revan and provides as output the results of the parameters of interest (such as modulation factor, effective area, and other quality factors).

3.1.1.1 MEGAlib workflow

The workflow used for the simulation is summarized in this section. First, a geometry containing the detector and surrounding environment is defined. Secondly, the simulation parameters are defined and the simulation is ran. Lastly, the data is collected and treated.

Geometry Definition

For MEGAlib, a geometry is a file with a ".geo.setup" termination. This file is produced by the user and contains the parameters of the geometry, namely:

- Geometry name, and version;
- Volumes;
- Detector resolution;
- Trigger definition.

A volume is a definition within MEGAlib for a volume of variable size and shape, to which the user can also provide a material type, a mother volume, and the visibility.

The detector resolution was provided from heritage simulations using the same types of detectors.

A trigger is a "signal" provided by the simulation wherein an interaction or set of interactions (depending on how the user defines the trigger) occur and is identified. A trigger is connected to a detector type of volume.

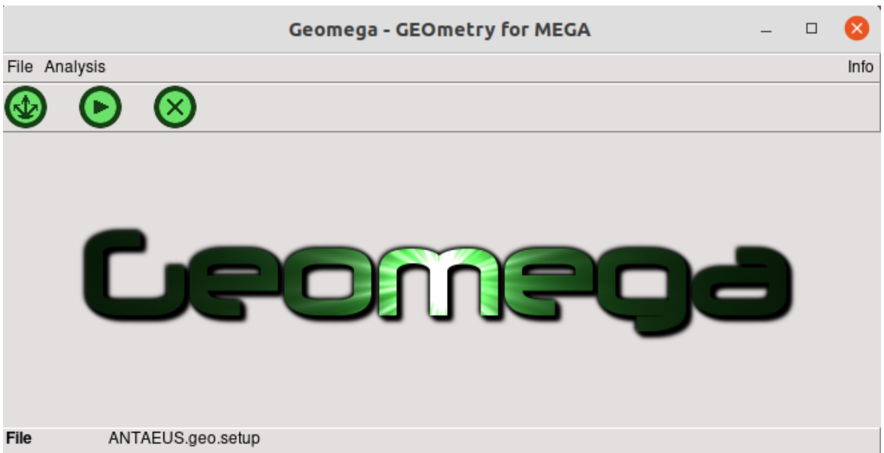


Figure 3.1: Geomega menu from MEGAlib

Simulation Parameters Definition

Simulations are defined through files with termination ".setup". It's common, when calculating the modulation factor for example, the user to create a "simfile.setup" and "randomsimfile.setup" files with similar content. The contents of this type of file are:

- Geometry (".geo.setup" file generated previously);
- Physics lists;
- Simulation name;
- Output file;
- Time, triggers, or events;
- Sources and their definitions.

To maintain repeatability and comparison, some parameters are kept equal on all simulations. Such parameters are: the physics lists for all simulations, and time, trigger, or events, when comparing between successive simulations.

The definition of sources is related to: the type of particles coming from the sources, their flux, beam type, spectrum, and polarization.

For modulation factor calculation, as an example, all parameters are kept equal, and only the polarization parameter related to the defined source is, on one simulation, defined, and on the other, random.

Data Collection

Figure 3.2: Revan menu from MEGAlib

Data collection is obtained by the successive simulation and comparison between results.

To measure the expected modulation factor, two simulations must be performed: one simulation with a polarized source, and an non-polarized source. Upon successful execution of the simulations through Cosima, then Revan must be employed for each of the resulting simulation files.

Afterwards, Mimrec is to be employed on its graphical user interface and the "Polarization Analysis" method shall be selected on the menu. After inserting the correct files for the polarized and non-polarized sources, the program will provide with its calculated results.

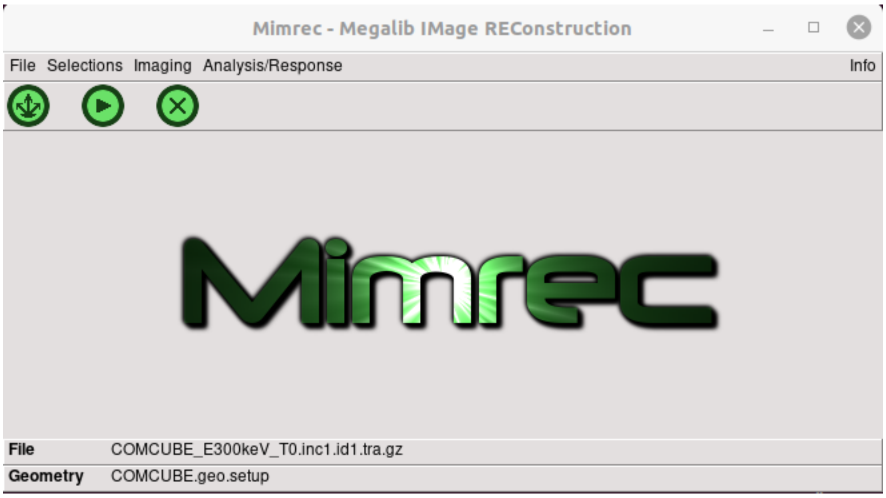


Figure 3.3: Mimrec menu from MEGAlib

One should be aware, however, that MEGAlib and other simulation tools may provide optimistic results.

3.1.1.2 Background Simulations

Background simulations are required to be able to characterize the type of environment the detectors will be subject to. They allow, for example, to give a good approximation of the number of background triggers, and background "noise" expected.

Background simulations further provide input for trade-off analysis when comparing different potential choices for orbits.Performing background simulations follows similar steps to those mentioned before. However, whilst in simpler simulations, the user defines simple sources (such as Monochromatic, Band-Function Spectrum, or Power Law spectrum, or others), background simulations use the input provided by the online software SPENVIS. SPENVIS is ESA's SPace ENVironment Information System, an online platform available on www.spenvis.oma.be, and its task is to model the space environment, namely radiation belts, energetic particles, plasmas, micro-particles, gases, and cosmic rays.

On SPENVIS, the user defines the several orbital parameters, as well as the start and duration of the simulation. The output of SPENVIS can then be used for integration with the "Background Generator" tool which will, in turn, do the spectrum of the background, generating an image for the user to evaluate, and generate the ".setup" files for the following MEGAlib simulations which will be performed following the strategy described before.

3.2 Mission Definition

The Mission Definition process is an iterative process between customer (the scientific proposal) and the platform-provider. The starting point is an exchange of information between the customer and the platform-provider. During this phase, the parties involved exchange their thoughts and their inputs. The platform-provider should provide their opinion as to solutions and the customer will evaluate how the solutions provided cover the scientific requirements. It may be common that the customer wants to achieve a high-number or complex goals not feasible within the project scope.

The phase, according to the applicable standard, ends with the delivery of a Mission Description Document [19]. The document and its supporting documentation, when applicable (such as list of preliminary technical requirements specification, scientific justification, and others), are then subject to the Mission Definition Review.

The Mission Definition Review is a review of the deliverable documentation performed by, preferably, external members with knowledge on the areas under study. For large missions, this is done by a committee of people specialists on the different areas, representing the end-customer (or higher-level customer).

For the scope of STRATOSPOLCA, this phase was not formally performed. Instead, the project team (and for the purpose of this thesis, the supplier) discussed directly with the Endorsing Professor (for this purpose, the customer) and the deliverable documentation was the documentation applicable for submission to the REXUS/BEXUS program.

Figure 3.4: Mission Definition cycle

3.3 Requirements Definition

Technical Requirements Specification (RS) is defined in [20] and the requirements for this document are presented on the same standard. The RS is a document or set of documents containing the requirements for the scope of a given system or subsystem. For example, there can be a RS document for the entire system (these often contain the General Requirements Specifications, GRS, or the General Equipment Requirements Specifications, GERS) of a mission, or only of a specific subsystem within the mission.

In accordance to [20], a Requirement is a provision with a verbal form "shall" wherein the a need is specified. Similarly, the verbal form "should" is used for recommendations, "may" for specifying permissions, and "can" to define possibilities.

Furthermore, the standard in [20] also provides requirements as well as recommendations for writing requirements. As an example, all requirements shall be: described in quantifiable terms (performance), justifiable, traceable to both higher- and lower-level requirements, unambiguous, unique, identifiable, singular, self-contained, and verifiable. For these reasons, some terms are excluded from use in requirements, such as "and", "included but not limited to", "optimize", "maximize", "necessary", "relevant", "typical", "user-friendly", "suitable", "satisfatory", or "state of the art" for they (and others) introduce some form of nonconformance to the aforementioned requirements of requirements.

3.3.1 Requirement Derivation

Derivation, or "flow-down" of requirements, is a process that takes as input the Mission Definition, the chosen Product Tree, and higher-level requirements, and has as its output the requirements for the lower-level system (systems are further described and defined in Section 3.4.

Requirement derivation is performed by the Systems Engineering function at each level. Initially, the Technical Requirements Specifications (usually only down to Segment Level) are derived from the Mission Objectives and a set of requirements are added that are required to perform the mission.

Some requirements, while not being traceable directly from higher-level requirements, may be traceable from other sources. For example, when designing the ground segment or ground support equipment, specific legislation will apply. Likewise, the flight segment can be subject to requirements deriving from legislation – national or international –, the launch provider, or even from other stakeholders (a special component, material, or mechanical part which you are obliged to use). As an example, Contamination & Cleanliness Control Requirements are usually only required for the Flight Segment and its subsystems - although, ground support equipment handling flight equipment shall be cleanable.

An example of the typical flowdown from Mission Objectives to Payload Requirements is available in Figure 3.5.

The Specification Tree is a document containing the tree-structure of the specifications and their association to each other. This kind of structure is useful to clarify rules for superseding requirements, as well as traceability between requirements. The Specification Tree need is defined in [21] and its Document Requirements Definition DRD is present on Annex J of the same standard. An example of the tree structure is available in Figure 3.6.

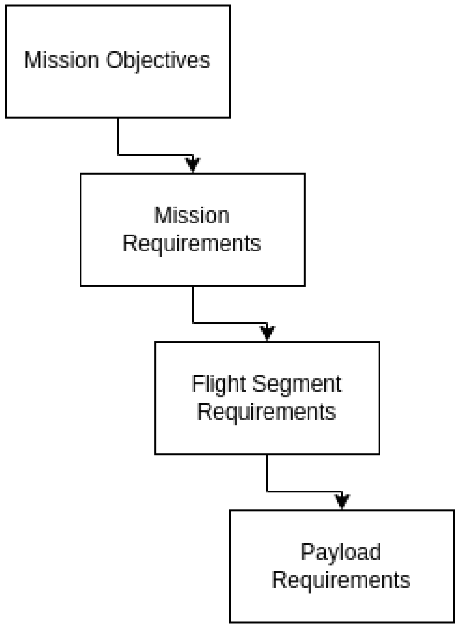


Figure 3.5: Specification tree derivation from objectives to payload requirements

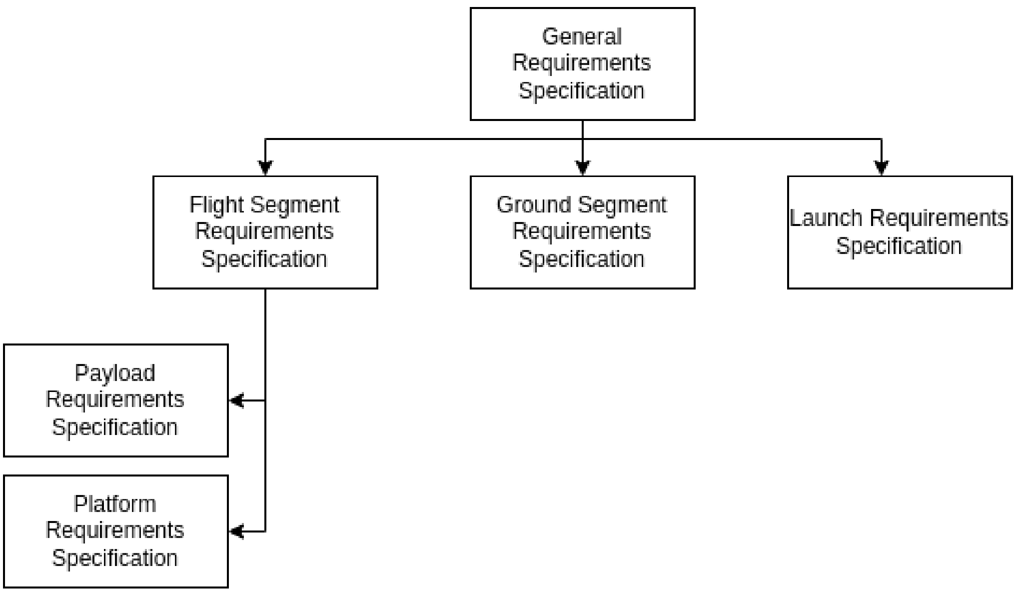


Figure 3.6: Specification tree, reduced to show only level 1 (mission-level), level 2 (segment-level), and an example of level 3 (system-level) requirements flow down.

3.3.2 Types of Requirements

The ECSS standard normalizing Technical Requirements Specification, [20], states that requirements can be categorized as:

- Functional;
- Mission;
- Interface;
- Environmental;
- Operational;
- Human-Factor;
- (Integrated) Logistics Support;
- Physical;
- Product Assurance induced;
- Configuration;
- Design; and,
- Verification.

This categorization occurs at all levels of the requirement specification, and to the different subsystem level architecture. However, these should be tailored to the system under study. As an example, a system with no human interaction whatsoever may not require Human-Factor requirements.

It's important to have this list and norm into consideration when writing requirements to ensure that all areas are fulfilled and that the Technical Requirement Specification covers the requirements necessary for the subsystem to meet its acceptance criteria.

A tempting decision is, and given that the ECSS Standards are written in the form of requirements, to simply download these standards in their requirement form (such as Dynamic Object-Oriented Requirements System (DOORS) format, readily available on the website) and, with little or no tailoring, apply all requirements to the project. This can be burdensome given that requirements ought to be verified, and not all requirements are necessarily applicable to all space projects. With this in mind, it's important that the user of the ECSS reads carefully the scope and understands the scope of each standard and how it applies to the system under development.

3.3.3 Verification of Requirements

Requirements may be verified in one or more of the following:

- Review of Design (R);
- Inspection (I);
- Analysis (A); and,
- Test (T).

Review of Design is a verification method on which the requirement is simply verified by the review of the design proposed to which the requirement is applicable. As an example, suppose the requirement "The system shall have a redundant power subsystem." This requirement may be verified (among others) by Review of Design. When the supplier of this system proposes the design, a validation of its design and verifying that it contains in fact a redundant power system. Should it not, and then its said that the design is non compliant with the requirement. Further, this requirement may be evaluated by Analysis and Test - on the first, by simulation of a failure, and on the latter by testing the failure with the system assembled.

Inspection is a verification method on which the requirement is verified by observation and accompanying judgement of the observation (complaint or not compliant). This observation and judgment are accompanied - as seen fit - by measurement, testing (such as fit-check), or gauging. As an example "The system shall have a mass less than or equal to 2 kg." is a requirement verified by inspection, namely by measuring of the mass of the system and assessing its compliance.

Analysis as a verification method employs computational tools, mathematical models, or other techniques and tools to verify that the design is in accordance to the requirement specification. Similarity Analysis may be employed (for example, if the system under design has similar priorities to systems already designed, tested, and flown). The most common requirements verified by Analysis are those concerning structural analysis (requiring Finite Elements Modeling), thermal analysis, or others. As an example "The system shall withstand the launch vehicle random mechanical loads." is a requirement first verified by Analysis - specifically structural analysis.

For last, Test is a verification method which employs testing techniques to the models and measures their performance, characteristics or other under representative environments. As an example, taking into consideration the requirement used to explain Analysis, the same requirement may be verified by Testing on later stages of the product. Namely by testing the system as-built on a shaker table capable of putting as inputs the random mechanical loads (with Qualification or Acceptance levels as applicable) onto the Item Under Test (IUT) and then measuring the response of the IUT against the inputs. This type of test is also used to validate the Analysis.

3.4 Systems Engineering

Taking into consideration the Systems Engineering Body of Knowledge, [22], Systems Engineering can be defined as the:

> Systems Engineering (SE) is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on holistically and concurrently understanding stakeholder needs; exploring opportunities; documenting requirements; and synthesizing, verifying, validating, and evolving solutions while considering the complete problem, from system concept exploration through system disposal.

When defining a scientific mission, and taking into consideration the interchanging communication (interfaces) between the different disciplines – scientific and engineering -, as well as taking into consideration the technical and programmatic constraints, the Systems Engineering function acts as the "man in the middle" to the solution. Guaranteeing a solution satisfying customer requirements and performing trade-off analysis taking these into consideration and not in spite of.

Throughout the work herein described, the approach was one taking into profound consideration the Systems Engineering holistic approach to systems. In spite of being a commonly misunderstood position within new laboratories making their way into Space, this function preliminary assures that requirements are followed-through and verified, and that the different systems can be integrated and tested, to then finally assure that the Mission Return is positive and that the project is successful.

3.4.1 Product Cycle

Closely related to the concept of Systems Engineering, is the concept of the Product Cycle or Life Cycle, as used in the natural sciences ([22]). The Product Life Cycle is the cycle between the Kick Off of the project (usually starting with the Definition of the Concept) until retirement, or disposal (most commonly used in Space industry to refer to the disposal of Spacecraft) of the system.

The relation between the Phases of the Product Cycle as described in [22] and as described in [19] can be easily identified. Due to the nature of generalization of the Product Life Cycle as described in Figure 3.7 and in [22], the phases therein have corresponding components to those detailed by the ECSS Project Management Standard [19] which also accommodate for the specificity of the Space Industry.

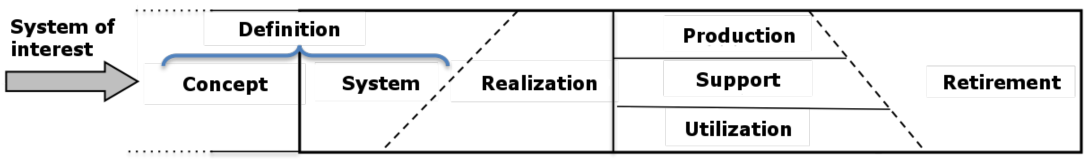


Figure 3.7: Life Cycle of a Product (General Definition). Adapted from [22].

As figure 3.8 demonstrates, throughout the cycle, various activities occur but the work load associated with them varies. As an example, System Requirements & Architecture design is an activity with relevant work load at the earlier stages of the project but less at the later stages. Integration & Validation activities, on the other hand, occurs at all stages of the product life cycle but are not constant.

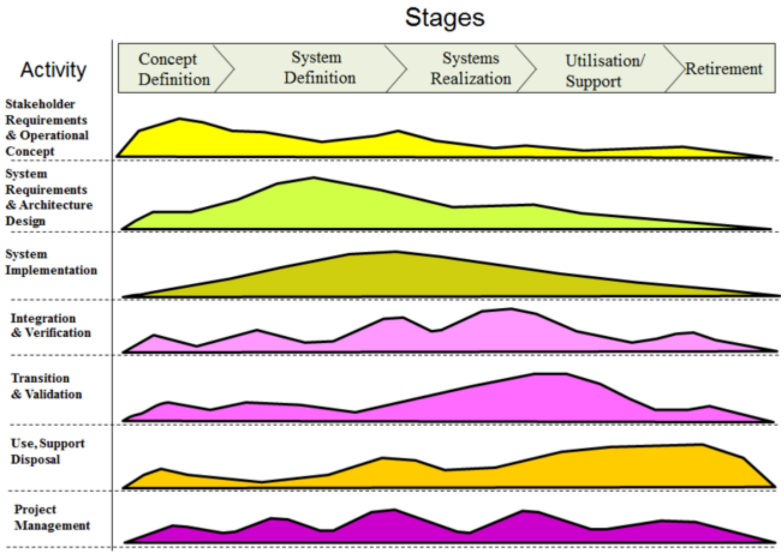


Figure 3.8: Life Cycle of a Product with relative work load. Adapted from [22].

Figure 3.9 presents the activities performed throughout the typical Space product life cycle [19]. Reviews such as the System Requirement Review (SRR) offer moments of reflection and critical questioning of the delivered mission concepts, or requirements. Other reviews such as Preliminary Design Review (PDR) and Critical Design Review (CDR) mark the end of phases and provide the formal authorizations to proceed to the next phases.

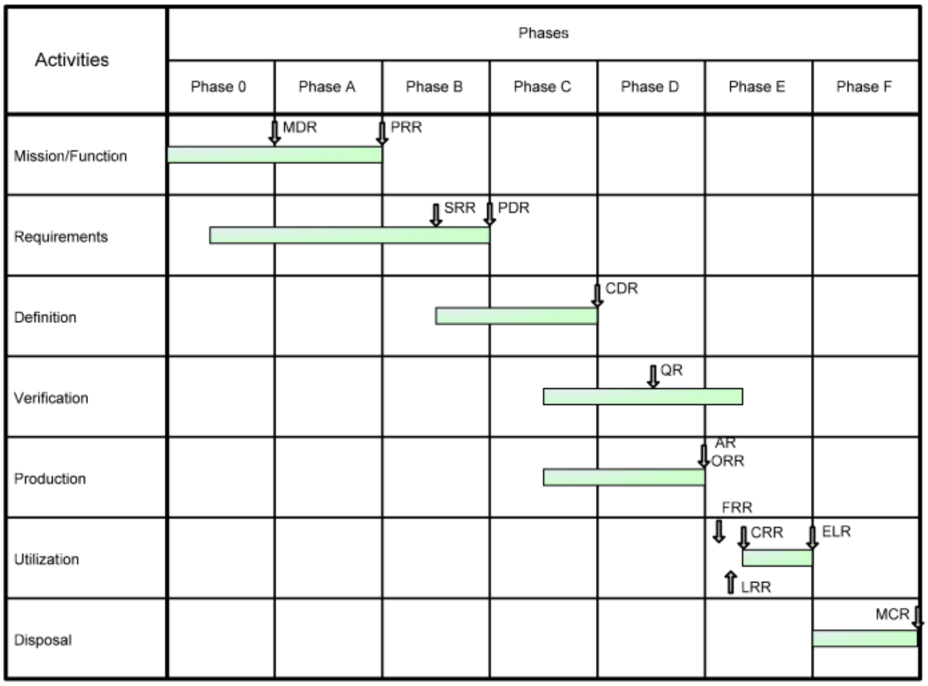


Figure 3.9: Life Cycle for a Space Product, including the major reviews. Adapted from [19].

3.5 Performance Evaluation

Performance evaluation and control is critical to assure that mission success is achieved. Mission success is achieved through the positive evaluation of the Mission Success Criteria as defined at the beginning of the project. Some projects may define this Mission Success Criteria as Mission Goals or Mission Requirements. The scope of the projects under study, we will only employ a limited set of Figures of Merit and Mission Success Criteria.

3.5.1 Scientific Figures of Merit

The identified scientific Figures of Merit (FoM) are:

- Polarization Quality Factor;
- Minimum Detectable Polarization; and,
- Estimation of GRBs per year.

The Polarization Quality Factor is a Figure of Method verified by Analysis through simulation using MEGAlib as described in Section 3.1.1.1. The Minimum Detectable Polarization (MDP) is a Figure of Merit verified by Analysis - namely simulation and the calculation. The equation concerning the Minimum Detectable Polarization has been defined in 2.4. The estimation of Gamma Ray Bursts per year is calculated by taking as inputs the system design parameters, namely the MDP, and comparison with the Polarization Level of historic Gamma-Ray Bursts on the GRB databases of BATSE and Swift.

4

Results

On this section the results achieved on each of the missions are detailed and analyzed. Ony on the next chapter, however, we will draw the conclusions.

4.1 STRATOSPOLCA

The scope of this thesis within the STRATOSPOLCA project only concerns the Systems Engineering aspects of the early Mission Definition and Design of the Mission.

4.1.1 Description of the Payload

STRATOSPOLCA payload is a 5 by 5 matrix of CdTe semiconductors of reduced dimensions bonded and integrated on a Front End Electronics System to be integrated on the main STRATOSPOLCA Flight Segment. The Payload can seen in Figure 4.1.

The Payload was not built nor designed directly for this flight. Therefor, considerations of the constraints imposed by the payload ought to be taken.

4.1.2 Description of the Flight Environment

STRATOSPOLCA is an experiment based of a High-Altitude Balloon platform.

The expected flight profile for STRATOSPOLCA can be found in the BEXUS User Manual [24] and is herein presented in Figure 4.2 and the graphical representations of prior flights' altitude profiles are also available in Figure 4.3. The altitude variations, from [24], found in Figure 4.4. The geometry of the gondola can be found on Figure 4.5. Furthermore, the flight parameters are described in table 4.1 .

Given the Flight Environment, the following constraints are immediately identified:

- In spite of the "High-Altitude", it's expected that many of the photons on the energy range are cut by the higher atmospheric layers (A);
- The altitude variations in Float phase don't allow for observation of a single source;
- The protection of the experiment shall allow for successful recovery of the experiment; and,

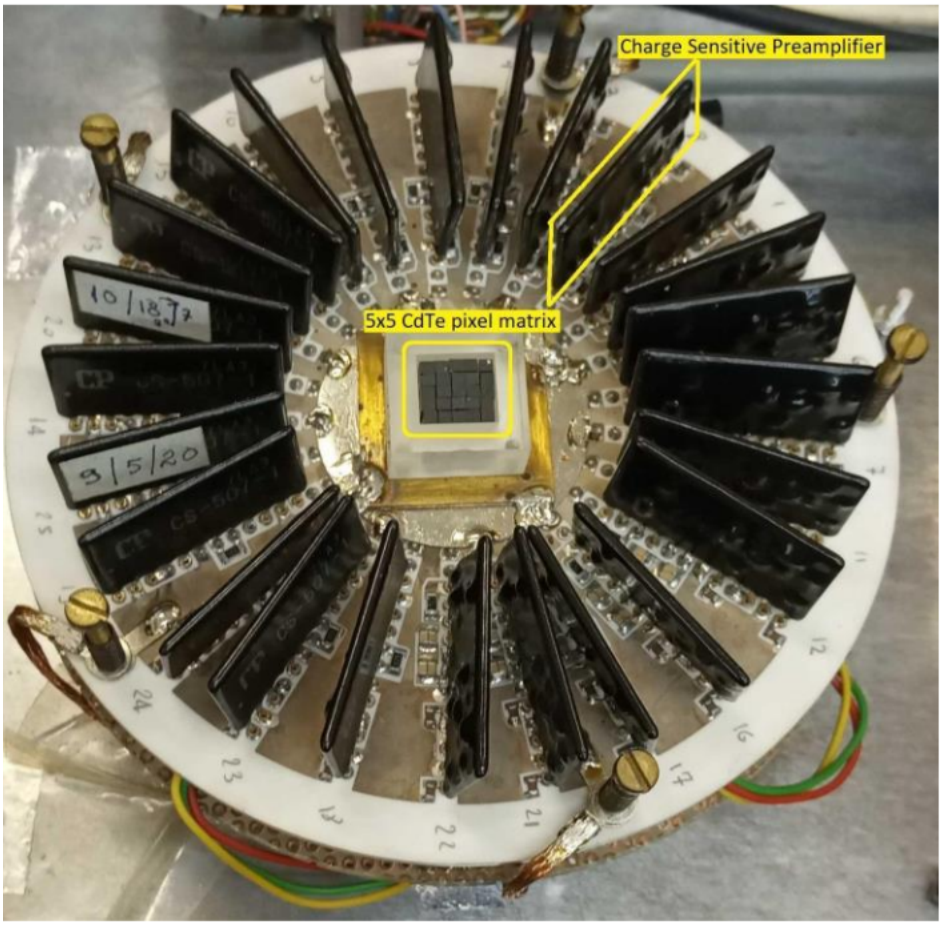


Figure 4.1: STRATOSPOLCA Payload. Adapted from [23].

Flight Phase	Information	Value	Unit
Ascent	Nominal Ascent Speed	5	m/s
Ascent to Float	Variations	3 to 6	m/s
Float	Altitude Changes	±200	m
Float	Minimum Altitude	20	km
Float	Maximum Altitude	30	km
Descent	Stable Descent Speed	-8 to -7	m/s
Descent	Landing Equivalent Drop	3	m
NA	Line of Sight Minimum	200	km
NA	Line of Sight Maximum	300	km

Table 4.1: BEXUS Flight Parameters

- Due to the geometry of the gondola, some ”blind spots” may occur due to the existence of other experiments.

4.1.3 Concept of Operations

The Concept of Operations for STRATOSPOLCA derives directly from the Flight Profile and the constraints imposed by the profile as listed on the prior section. The Concept herein described is also the first proposed. The Concept was further reviewed by the team

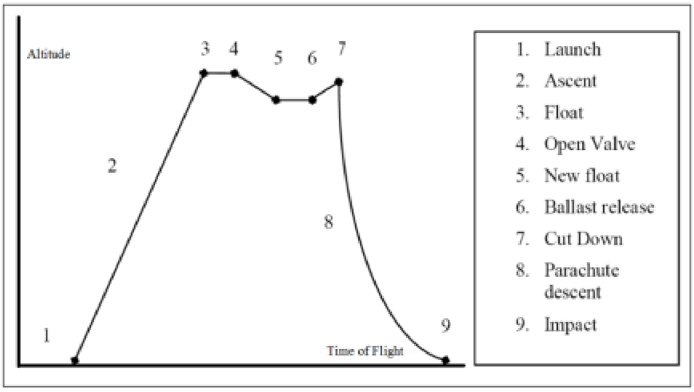


Figure 4.2: BEXUS Flight Profile, adapted from [24]

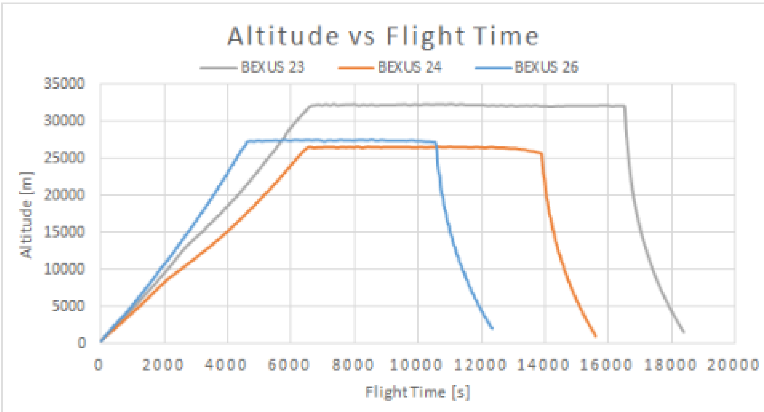


Figure 4.3: BEXUS Altitude Profile, adapted from [24]

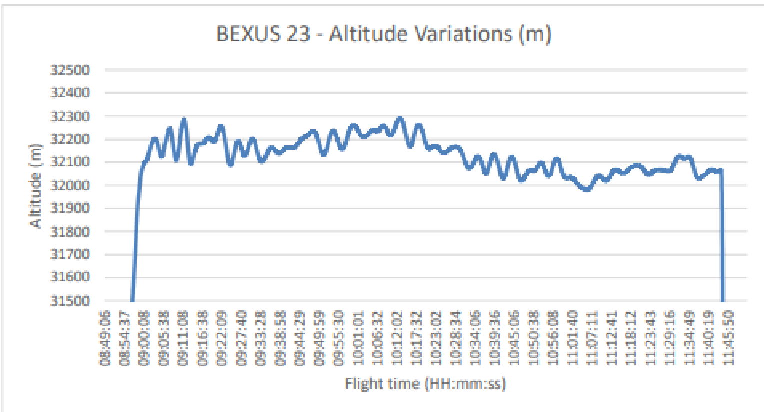


Figure 4.4: BEXUS Altitude Variations, adapted from [24]

afterwards and some of the concept was simplified due to immature technical implementation.

Pre-Flight Operations

On preparation for flight, final checks to the Flight and Ground Segments should be performed. A full systems test comprising of flight segment being irradiated with a radiation source, Ba133, and test of the results on the Ground Segment Graphical User Interface should be performed, allowing to verify the system end-to-end for its major functionalities.

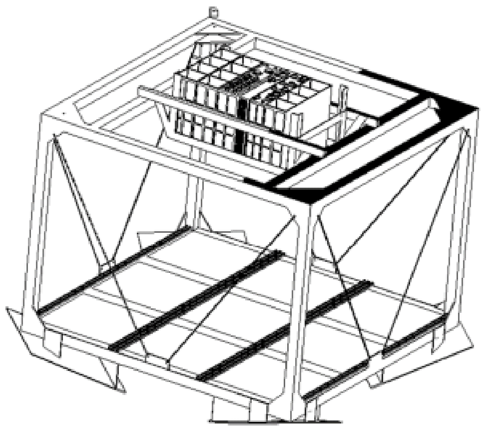


Figure 4.5: BEXUS Gondola Geometry, adapted from [24]

Immediately Before Launch

During the ground phase, the Flight Segment of the experiment shall be in low power mode. Only performing essential health-checks and validating systems. The experiment should not have the detector turned on due to the expensive usage of battery power.

Launch

On Launch, the Ground Segment manually turn on the Flight Segment through telemetry commands. At this point, the detector and signal analysis system is turned on. A shock-type vibration can be expected on this event which may disrupt signals.

From Launch to Recovery, the Flight Segment is designed to communicate with the Ground Segment and transmit simplified scientific data and housekeeping data.

Ascent Phase

During the ascent phase, the experiment shall be registering events (signals) in function of some form of time which can be correlated with its altitude. This will be the major data concentration source due to the ascent phase being slower than the descent phase. The data acquired on this phase should be sufficient to achieve the scientific goals related.

Float Phase

During the float phase, the flight segment will continue to acquire data. During this phase is expected that the number of new events stabilizes over time at the same altitude - in spite of the variance due to the local winds affecting the platform. Moreover, due to the same variations and the short duration of the flight, it is not possible, even in float phase, to acquire data from a given source.

With a more complex experiment, stabilization of the flight segment unit (and a longer flight) would allow for observation of a gamma source (such as the Crab Nebula). However, within this scope it wouldn't be possible.

Descent Phase

During the descent phase, STRATOSPOLCA Flight Segment unit is expected to be recording data. Due to the higher descent velocity (thus increase in altitude uncertainty, and lower acquisition time at each altitude), the validity of the scientific output can be questioned. However, if necessary, this data can be used to correlate with the ascent phase data acquisition.

Recovery

On recovery, the Flight Segment unit is turned off.

4.1.4 Requirements Derivation

Taking into consideration the premises described before, STRATOSPOLCA objectives and requirements are tailored for the flight and for the specificity of the team background and knowledge.

To the best of my abilities, and unknown of the standards stated on the Methods section concerning Technical Requirements Specification, we followed the guidelines promoted by the organization. The general Processes, Inputs, and Outputs used for the Requirement definition process used in STRATOSPOLCA employed can be found in Figure 4.6.

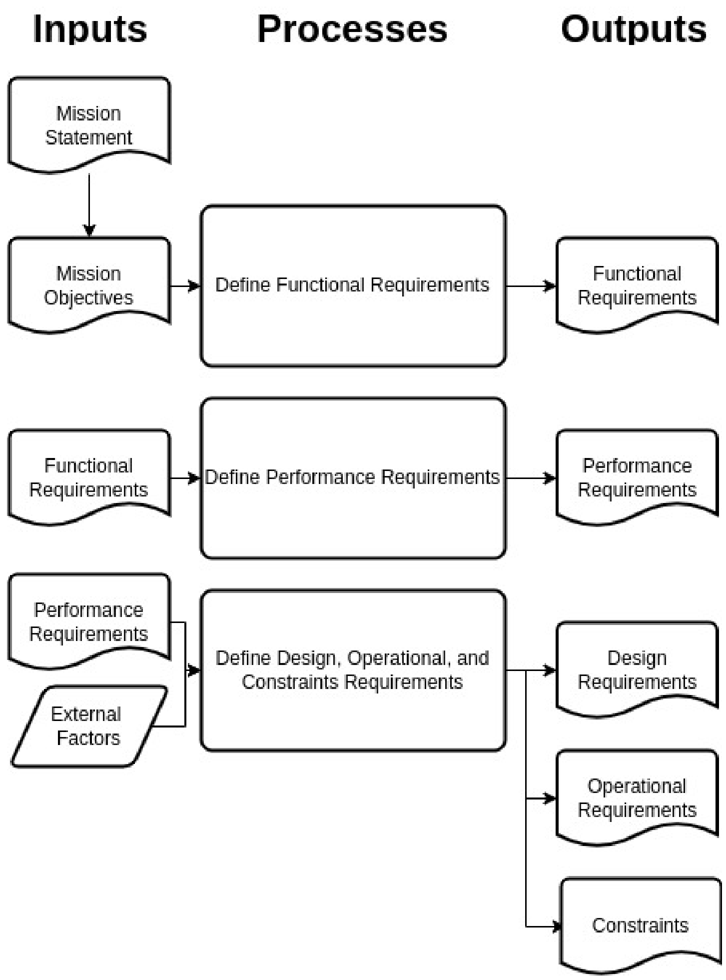


Figure 4.6: STRATOSPOLCA Requirements Process

The major problem with the approach taken was that it was performed only at a System level, not taking into consideration the product decomposition of the STRATOSPOLCA mission. This left room for a paramount quantity of uncertainties, uncontrolled requirements (requirements not written and therefor not validated), inconsistencies, and incorrect flow down of the requirements (no formal flow-down of the requirements was performed).

4.1.5 Performance Evaluation

Performance evaluation was not performed by myself therefor not included within the scope of this dissertation.

4.1.6 Systems Architecture

The Systems Architecture is simplified and defined as an Interface diagram in Figure 4.7.

4.1.7 As-Built System

Due to the limitations on the application of the Systems Engineering function, STRATOSPOLCA was very immature in terms of Requirements Management, Verification Planning, and Model Philosophy, as well as other aspects. This later led to the existence of the Systems Engineering function led to the release of immature requirements without proper flow-down of these.

In figure 4.8 the FlatSat approach to testing of STRATOSPOLCA is shown. During this late stage, embedded systems were used in support to debugging and as ground support equipment.

Furthermore, the Verification and Validation Strategy and the Control of Verification activities was second plan to design and manufacturing. This led to uncontrolled requirements; unverified requirements at the time of Launch; and subsystems led by different people who weren't aware that the requirements were applicable to their subsystem.

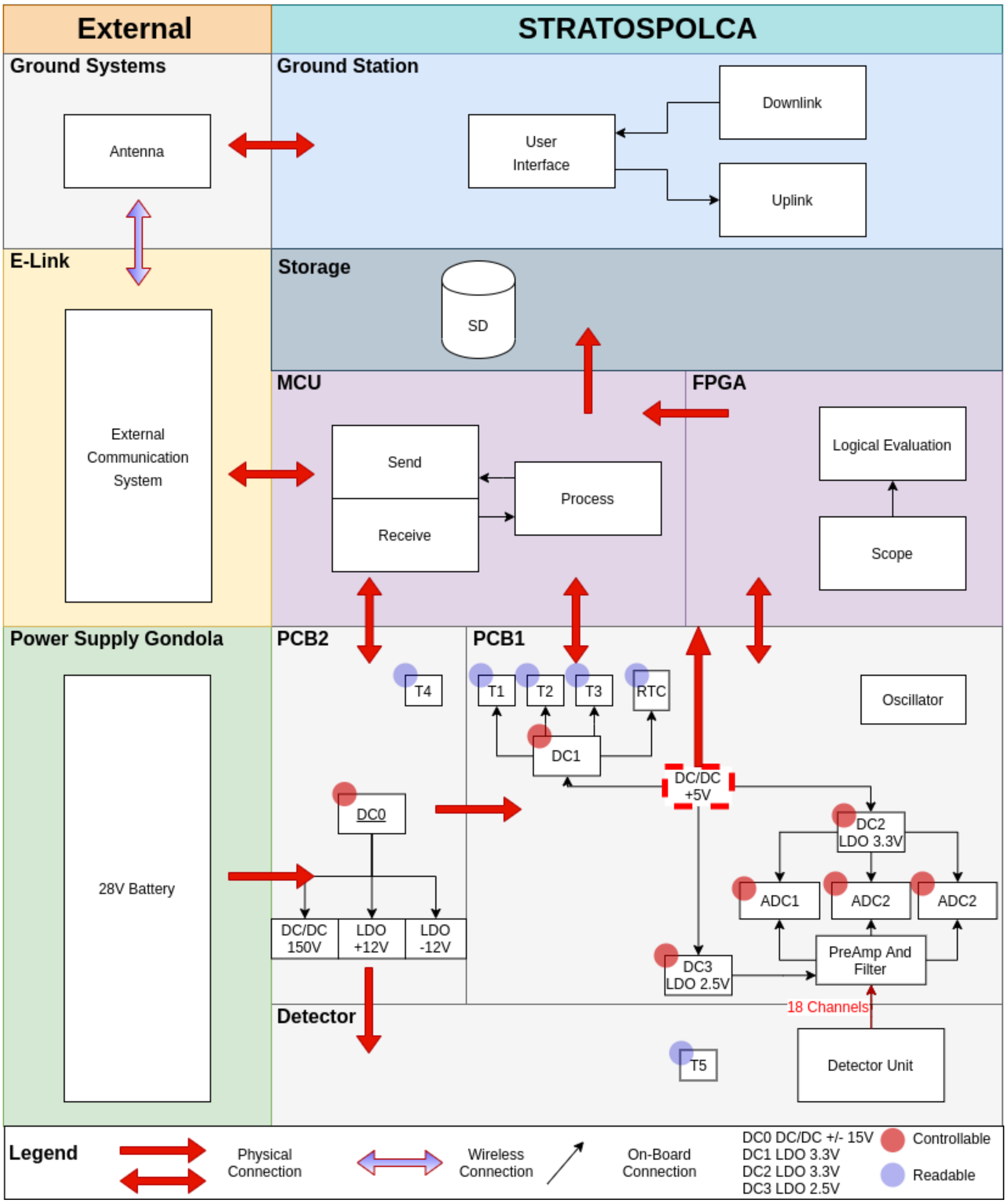


Figure 4.7: STRATOSPOLCA baseline systems architecture with interfaces.

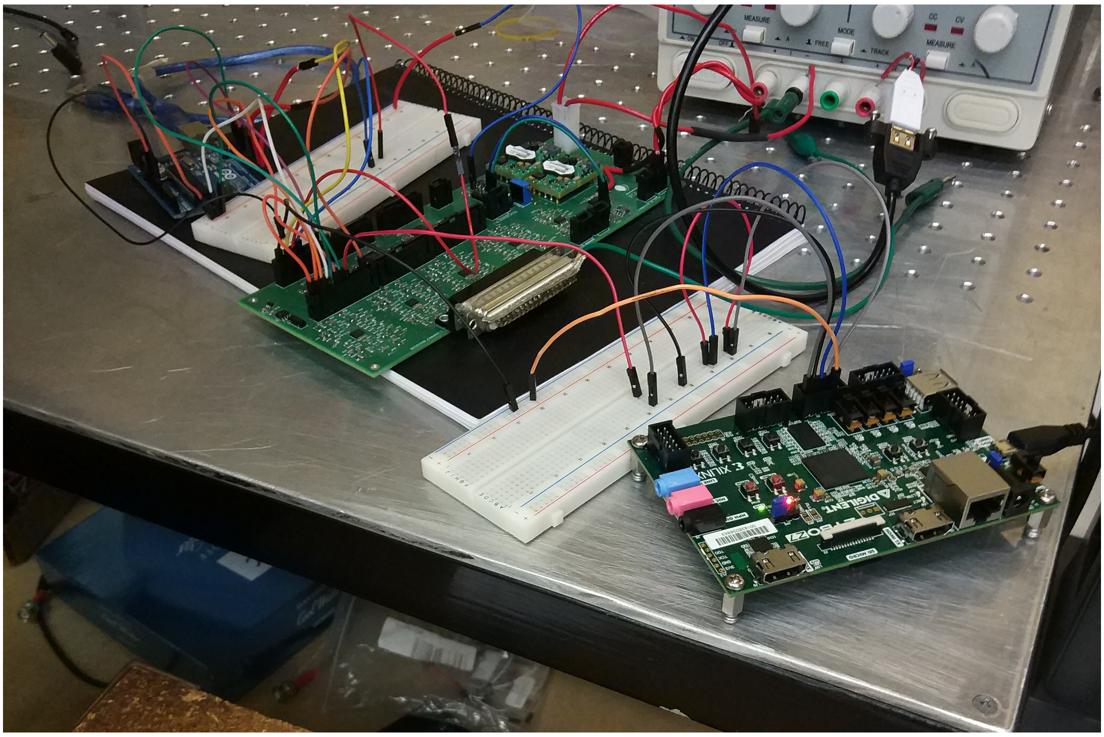


Figure 4.8: STRATOSPOLCA FlatSat testing.

4.2 COMCUBE

COMCUBE allowed to perform a series of trade-off analysis and studies regarding the different kinds of detectors. Given the fast iteration cycles, we were only able to study some of the major FoM in most cycles.

4.2.1 Concept of Operations

The Concept of Operations defined for COMCUBE was only loosely defined by the leadership of the consortium. Having this said, the concept is to fly a CubeSat-like structure capable of observing the sky in medium-energy ranges.

4.2.2 Requirements Derivation

Given the scope of this project, the analysis performed served better the purpose of laying the groundwork for future missions and the trade-offs herein described to support the justification for the design of those missions. Currently, COMCUBE is developing their initial requirements for the future mission. This work falls out of the scope of this document.

4.2.3 Performance Evaluation

The methods employed for COMCUBE are only those concerning the scientific outcome.

The evaluation was performed mostly through analysis of the Modulation Factor.

4.2.3.1 Preliminary Evaluation

Performance evaluation on COMCUBE was performed through iterative design taking into consideration the limitations of the data acquisition systems and detectors, within the space of a CubeSat.

While, initially, COMCUBE was a 1U or 2U CubeSat, the community reached the consensus that a 4 Units of 2U CubeSats would be required to achieve acceptable results for the main scientific objectives. On this section, we provide the initial studies. On the later sections we will challenge the initial definition and study the different solutions.

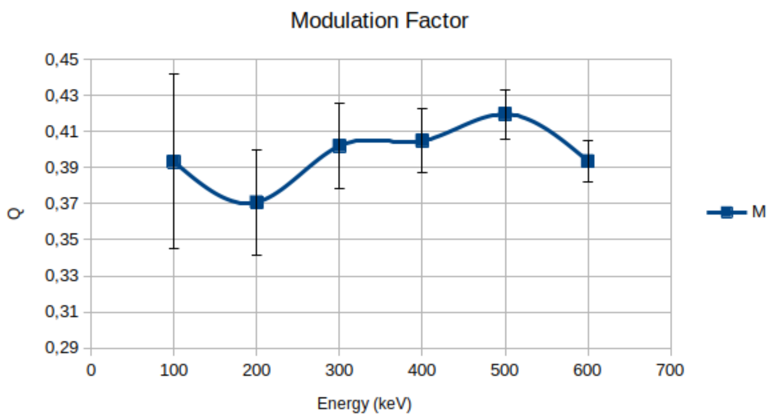


Figure 4.9: Baseline COMCUBE - Q factor

The first calculations of the Modulation Factor (or Quality Factor, Q) for the COMCUBE baseline geometry can be seen in Figure 4.9. While it's expected for this sort of detectors' Modulation factor to decrease with increasing energy, it can be seen a strange behavior for the energy range between 100 keV and 300 keV with a sort of valley at 200 keV.

However, one should further note that the uncertainties herein do provide cause for caution. The uncertainty for the Modulation factor calculated at 100 keV is of 0.0472, covering a wide range of values for the Quality Factor and, indeed, when doing this simulations, the user had difficulties because of this high variability. Attempts at improving this initial result were ultimately unsuccessful.

The angle of polarization as reconstructed as a function of the energy can be seen in Figure 4.10. The Polarization Angle expected is of 90. As it can be seen, all angles' uncertainties range include the expected angle. Therefor this design as analyzed through MEGAlib can be said to have a good polarization angle reconstruction.

As another verification, it's useful to analyze the modulation factor as a function of the angle of incidence with constant energy. The results can be seen in Figure 4.11. The results therein are according to the expected.

Lastly, Figure 4.12 and Figure 4.13 display, respectively, the calculated energy and angular resolution for the baseline detector.

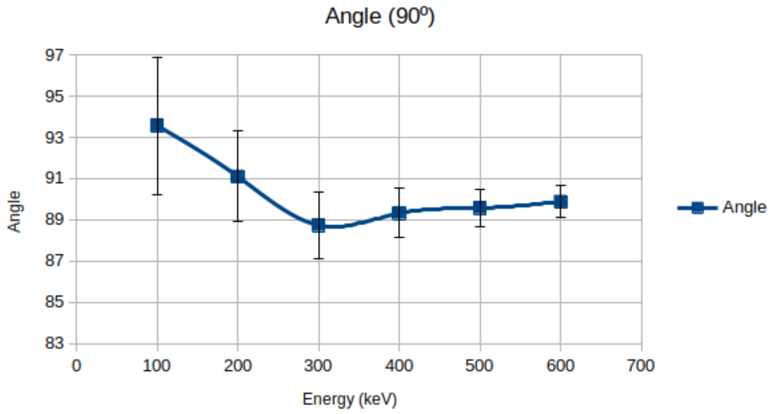


Figure 4.10: Baseline COMCUBE - angle of polarization - from MEGAlib - and its uncertainty

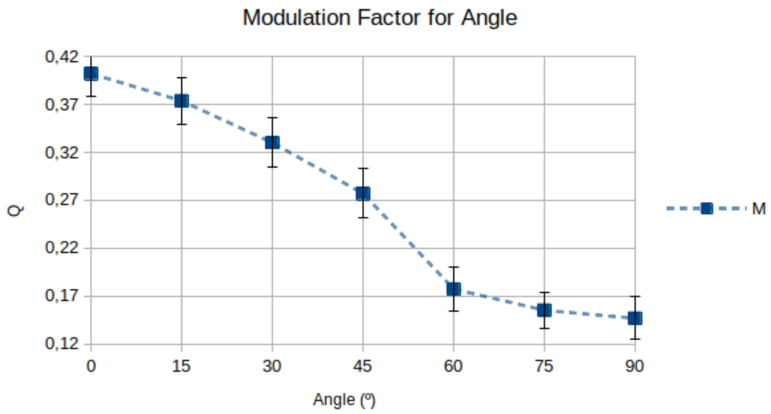


Figure 4.11: Baseline of 300 keV monochromatic with varying angle of incidence.

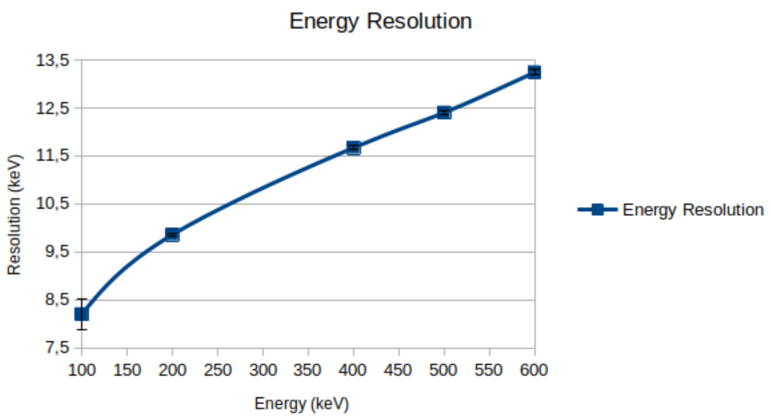


Figure 4.12: Baseline COMCUBE - Energy resolution

4.2.4 Trade-Off Analysis

COMCUBE development allowed for a great deal of interactions and analysis of the modulation factor for detectors in different configurations. Table 4.2 presents the mapping of

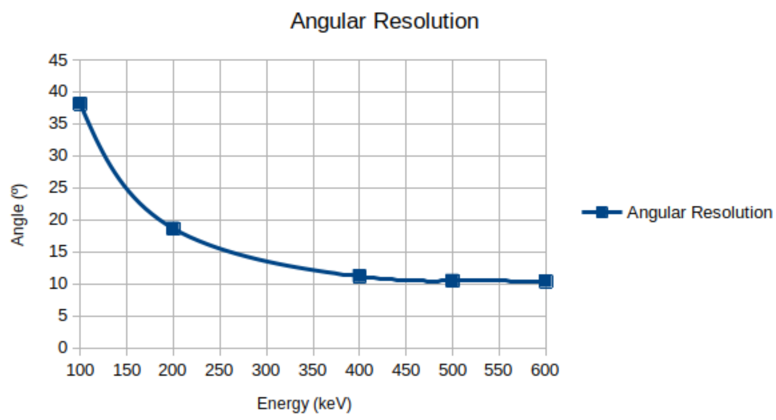


Figure 4.13: Baseline COMCUBE - Angular resolution

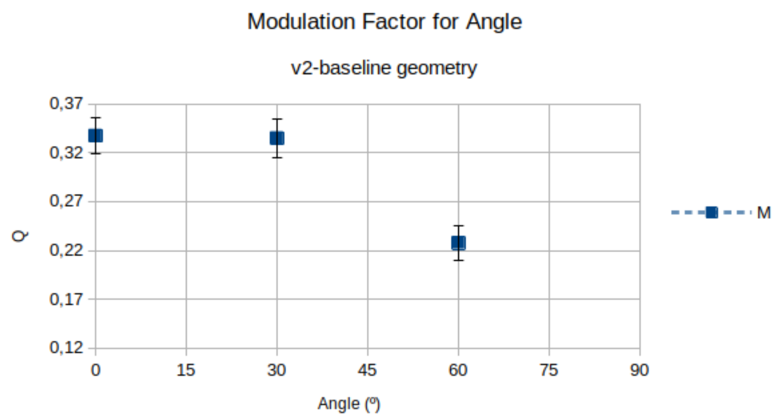


Figure 4.14: Baseline COMCUBE - Crab Simulation

the several configurations studied on this Trade-Off Analysis. In Table 4.3 a summary of the detectors used for the configurations and their high-level information can be found.

Detector Name	**Material**	**A**	**B**	**C**	**D**	**E**
Silicon DSSD (2x)	Si	x	x	x	x	x
Calorimeter	CeBr3	x			x	x
p-Terphenyl plastic scintillator	p-Terphenyl			x		x
Side Detectors	CeBr3		x	x	x	x

Table 4.2: Configurations Mapping

The different configurations maintain the Double-sided Silicon Strip Detector assembly.

The DSSD detector has a total area of 68 x 68 mm^2, however, their active area is only 64 x 64 mm^2 they have a guard ring surrounding which is 2 mm wide.

This assembly of DSSD has two of these detectors, distancing 1 cm between them. These are rotated counterclockwise 180 º around the Z axis between each other. The DSSD detector is surrounded by its Front End Electronics (FEE), which is simulated with the "CircuitBoard" Material as defined in MEGAlib. A real-life example of such detector can be found in Figure 4.15.

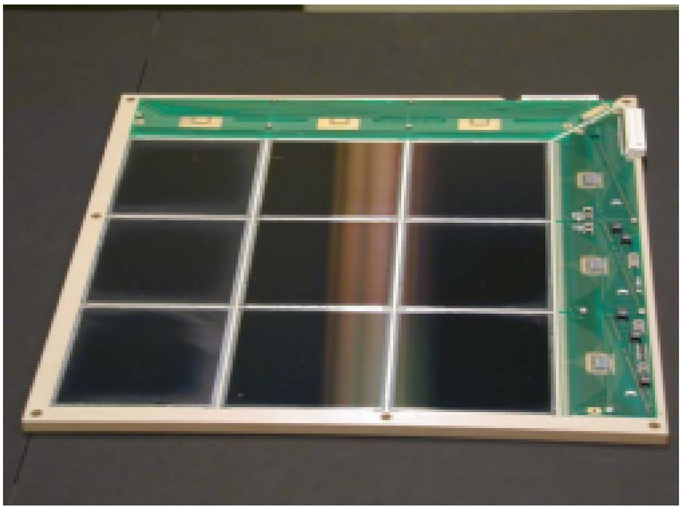


Figure 4.15: DSSD detector example. Adapted from [7].

The second type of detectors used was the configuration named "Calorimeter", made of CeBr3 - Cerium Bromide - for material as well as a p-Terphenyl type detector assembled together as a configuration. These detectors were employed in Configurations A, D, and E. These detectors are used as scintillation detectors in other gamma-ray experiments. Besides the CeBr3 crystal, the detector is wrapped in Millipore (material of the same name in geomega) and have a Silicon photomultiplier array at the bottom (material SiliconPIN).

The p-Terphenyl plastic scintillators - commonly called by "Plastic" detectors - are a material defined on purpose for this simulation within Geomega and not using any of the existing detector, wrapped in Millipore and, like the Calorimeter type of detectors, with a Silicon photomultiplier array at the "bottom" face of the scintillator.

Lastly, the Side Detector configuration is made of the simple configuration of the Calorimeter without the integration of the p-Terphenyl plastic scintillator.

For the simulations herein, the configuration of the instrument is a 2 by 2 matrix of the configurations described on the previous paragraphs. Figures 4.22 and 4.23 show the 4U geometry with all the detectors selected (Configuration E) to provide a better graphical explanation. The side detectors configuration are not only translated but also rotated (avoid having side detectors facing to the inward walls of the instrument).

Trigger Strategy

The trigger strategy employed for all the configurations studied herein has the configurations set to trigger on at least one hit in one detector. For the purpose of the trade-off analysis, the trigger was always on for the Si DSSD detectors, and turned on for each of the active detectors for the given configuration.

This was accomplished by If/EndIf strategy employed directly on the geometry setup file for COMCUBE.

Detector Name	*Silicon DSSD (2x)*	*Calorimeter*	*p-Terphenyl plastic scintillator*	*Side Detectors*
Material	Si	CeBr3	p-Terphenyl	CeBr3
Area [mm^2]	4624	2601	2500	2500
Height **[mm]**	1.5	20	10	10
Energy Resolution **[FWHM @ 662 keV]**	5%	5%	10%	5%
Noise Threshold **[keV]**	30	15	10	15
Trigger Threshold **[keV]**	30	15	10	15

Table 4.3: Detector types and their data

Trade-Off Assumptions

The trade-off analysis performed herein only concerns the comparison of the Scientific Figure of Merit, the modulation factor. However, the author is obliged to recognize that this trade-off analysis, due to the potential mass and system constraints it imposes on the spacecraft, should be taken into consideration with the full instrument trade-off analysis, including the study of the power dispensed for the configurations, the mass budget available, the need for on-board processing of data, and the electronics required to support each of the configurations.

Furthermore, the trade-off analysis, on a future iteration, taking into consideration the new evolution of the design, should also account with a weighted evaluation of the energies under consideration. For example, on the trade-off presented below, the author compares the values obtained for each energy in comparison with the values obtained for the same energy for other configurations, as well as with regards to the values for different energies on the same configuration. However, should it be said that for a given energy the interest in having better values for the modulation factor is greater than for other energies, than the trade-off analysis shall have this into consideration.

A practical example of this is to say that, for example, the Instrument Requirement Specifications detail that the objective is to observe, with greater interest (to support the Mission Requirements), Gamma-Ray Bursts on the energy range between 150 keV to 250 keV. In such case, the researcher should put-forth a weighted trade-off analysis taking such requirement into consideration.

4.2.4.1 Configuration A : Si DSSD + Calorimeter

Configuration A comprises only of the Si DSSD assembly in conjunction with the Calorimeter (CeBr3 combined with the p-Terphenyl configuration). The results shown in Figure

4.16 are relatively poor for the lowest part of the Energy Range (below 150 keV) and for the 500 keV to 600 keV range. However, the configuration offers a relatively good performance fo the range between 200 keV and 400 keV.

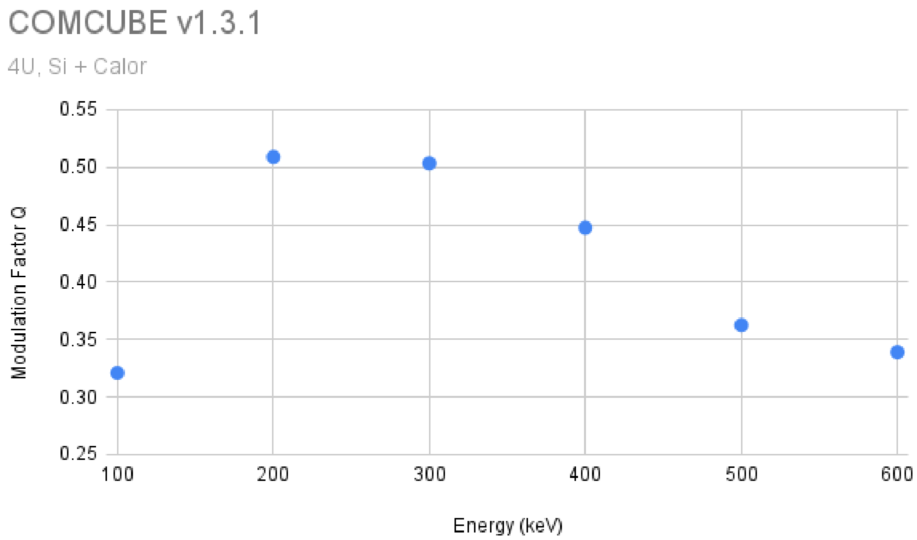


Figure 4.16: COMCUBE V1.3.1 with Si Detector and Calorimeter

Energy [keV]	Modulation Factor Q	U(Q)
100	0.320983	0.222121
200	0.508929	0.019946
300	0.503432	0.015346
400	0.447368	0.037453
500	0.362492	0.049670
600	0.339032	0.015029

Table 4.4: Configuration A Table of Results. U(Q) presents the uncertainty calculated by MEGAlib.

However, this analysis is not complete without the careful analysis of the uncertainties associated. As can be noted in Table 4.4, the uncertainty reported by MEGAlib's mimrec for the Modulation Factor at 100 keV is relatively high (0.22) and on the order of magnitude of the simulated modulation factor. This leads one to believe that the simulation is ultimately unsatisfactory. In spite of efforts to improve this value, this was not possible.

4.2.4.2 Configuration B : Si DSSD + Side Detectors

Configuration B comprises the Si DSSD detectors coupled with the CeBr3 Side detectors. This configuration has a clear disadvantage because, due to the positioning of the detectors. Due to the lack of a detector at the bottom side of the instrument, the energies are not "collected". For that reason, no correlation between the energy can be made with relation to the interactions on the DSSD detectors which can only measure for the position.

Figure 4.17 reveals a generally unsatisfactory performance with a value for lower energies,

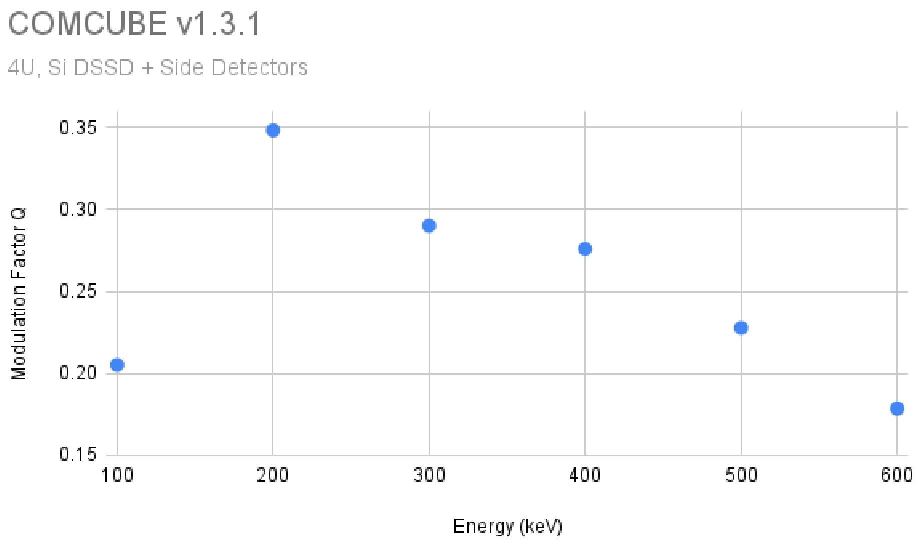


Figure 4.17: COMCUBE V1.3.1 with Si Detector and Side Detectors.

like on Configuration A previously studied, with a very high uncertainty, as reported on Table 4.5. The results reported for higher energies are, however, lower than those reported for Configuration A. These results lead to the dismissal of this architecture.

Energy [keV]	**Modulation Factor Q**	**U(Q)**
100	0.205152	0.2757390
200	0.348230	0.0236887
300	0.290043	0.0177423
400	0.275851	0.0169404
500	0.227631	0.0165542
600	0.178484	0.0166660

Table 4.5: Configuration B results with reported uncertainties.

4.2.4.3 Configuration C : Si + Plastic + Side Detectors

Configuration C is composed of the Si DSSD detectors, coupled with a Plastic detector of p-Terphenyl below, and the Side detectors, as described before. This configuration begins to sustain a more suitable candidate for the selected architecture. The results in graphic form in figure 4.18 and in Table 4.6 put forth a more promising solution to those presented before. In spite of the maximum Modulation Factor being smaller than the values reported for energies 200 keV to 400 keV, they maintain only a small decrease in value across the energies.

Figure 4.18 reports the full instrument configuration, Configuration E, besides Configuration C. This was chosen as such to later provide a comparison.

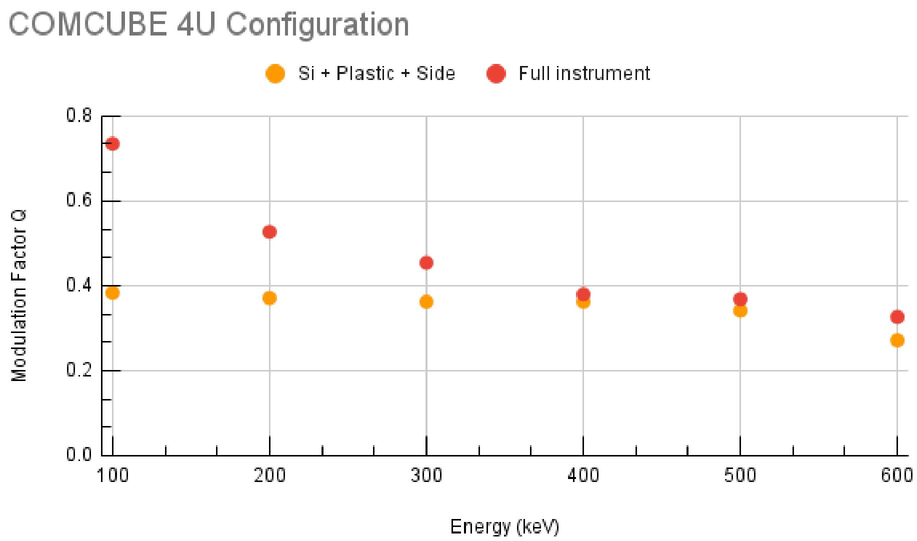


Figure 4.18: COMCUBE V1.3.1 with Si Detector with Pt Detectors and Side Detectors

Energy [keV]	**Modulation Factor Q**	**U(Q)**
100	0.383312	0.1106440
200	0.370767	0.0201324
300	0.362011	0.0158255
400	0.362092	0.0157293
500	0.341161	0.0154501
600	0.271118	0.0155854

Table 4.6: Configuration C results with reported uncertainties.

4.2.4.4 Configuration D : Si DSSD + Calorimeter + Side Detectors

Configuration D is composed of the Si DSSD detectors, coupled with the Calorimeter assembly (a composition of CeBr3 detectors and "Plastic" detectors), and the Side detectors, with the properties reported in previous sections. This configuration differs from Configuration C because the latter does not include the CeBr3 unit.

The results in Table 4.7 and Figure 4.19 provide results for the lower energy ranges, which are an improvement. Nonetheless, the higher energy results, such as 500 keV and 600 keV are less than those reported on the most simple configuration, Configuration A. To be noted, in spite of this, that for the scientific purpose under analysis, the energies in the lower side of the spectrum are of most interest. Therefor, acting purely under this assumption would lead to choosing Configuration D over Configuration A.

4.2.4.5 Configuration E : Full Instrument

Configuration E, also known as the "Full Instrument" configuration, is composed of the same 2 Si DSSD detectors, the Calorimeter assembly (CeBr3 with p-Terphenyl), and the Side Detectors.

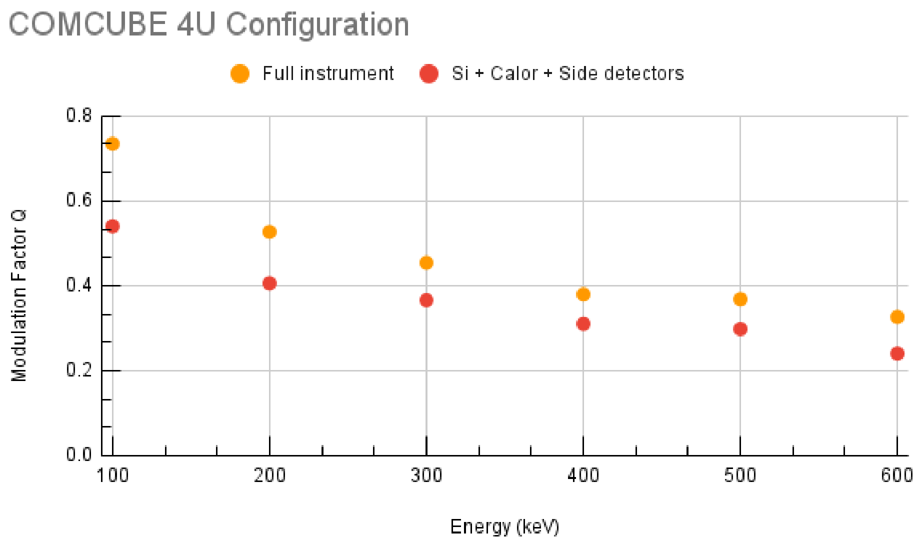


Figure 4.19: COMCUBE V1.3.1 with Si Detector, Calorimeter, and Side Detectors

Energy [keV]	**Modulation Factor Q**	**U(Q)**
100	0.539991	0.1183570
200	0.405571	0.0191839
300	0.365745	0.0150084
400	0.310094	0.0146919
500	0.297713	0.0143892
600	0.240231	0.0147273

Table 4.7: Configuration D results with reported uncertainties.

The simulated results show an increase in the modulation factor for the lower energy ranges and decreases gradually through the energy range under study. Figure 4.20 presents the Configuration E results in conjunction with the results obtained for the other Configurations. There is an overall decrease in the reported uncertainties when in comparison to the previous Configurations.

The results, when compared to the other configurations, are clear that this solution is mostly predominant and offers no discussion on the lower energy ranges. It should be identified, however, that for the energies of 300 keV and 400 keV, Configuration A surpasses Configuration E in terms of the modulation factor.

Taking into consideration the function of a Systems Engineer studying the spacecraft as a whole, however, one is tempted to choose Configuration A over Configuration E. Configuration A offers a less complex system (both in terms of mechanical and thermal interfaces, as well as with regards to the electronics and embedded systems), with a relatively short scientific negative trade-off. This is, of course, unless the Mission Requirements state otherwise. For missions where the Mission Requirements or even the Mission Objectives are stating explicitly to give precedence to better outcomes in the lower energy range, Configuration E takes the preference.

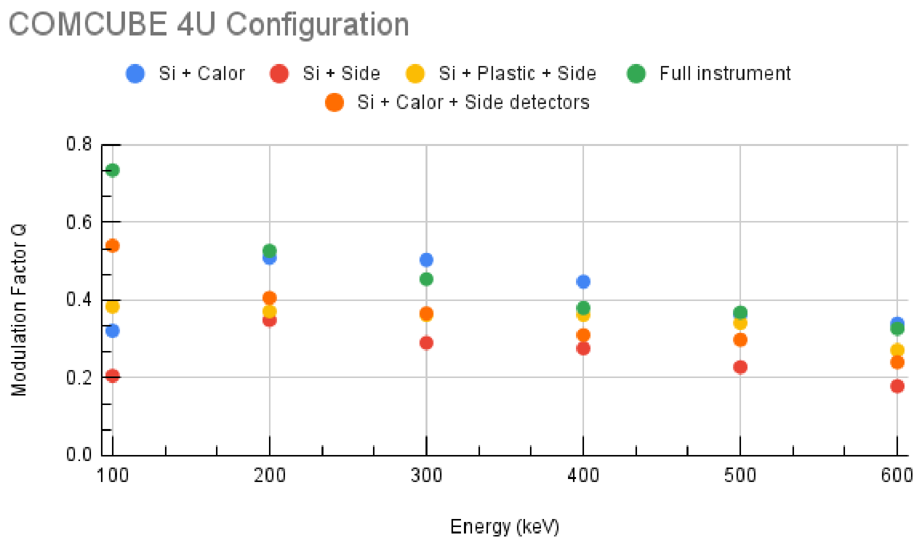


Figure 4.20: COMCUBE V1.3.1 with Full Instruments.

Energy [keV]	Modulation Factor Q	U(Q)
100	0.734099	0.0355719
200	0.526661	0.0148313
300	0.454022	0.0107189
400	0.379548	0.0102003
500	0.368062	0.0096630
600	0.326239	0.0098786

Table 4.8: Configuration E results with reported uncertainties.

4.2.5 Final Design Evaluation

The final design (in version 1.3.1) was evaluated taking into consideration the trade-off analysis described in Section 4.2.4. The selected configuration was Configuration E, in spite of its complex implementation.

The naming of "Final" should be considered with reservations. The COMCUBE project is, if one takes into consideration the phases described in [19], only in the first phase, Phase 0. In which the scientific community is actively identifying the needs and identifying the various mission concepts on the level of the science required to attain a successful mission.

It is not uncommon to see, through Phase A (Feasibility) or even Phase B (Preliminary Definition) a change to the baseline design even if this change affects the initial scientific assessment (with the agreement, however, of both parts).

For the scope of this work, the performance analysis performed delivers an optimal instrument for the assumptions taken into consideration. Figure 4.21 presents a comparison between the initial version ("m_v1") and the final ("m_v2") of the structures. Due to the constraints and decisions taken on the design from the consortium, the last version was chosen as the baseline before proceeding to the next phase of the project.

Future iterations should be held to perform minor improvements to the geometry, including the structure, and a more detailed definition of the electronics surrounding the detectors. However, these should not have major impact in the results presented.

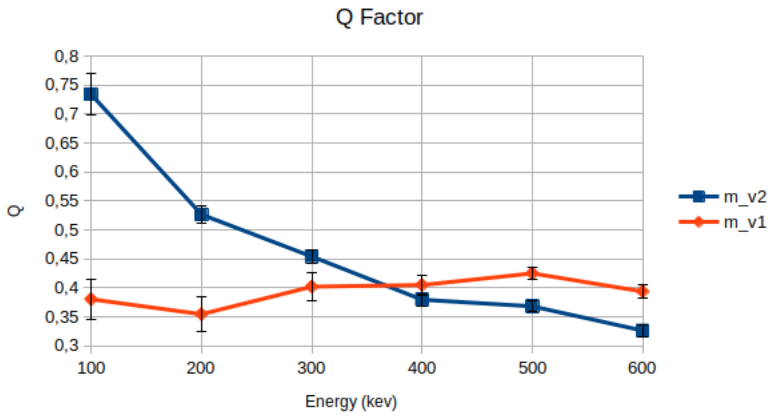


Figure 4.21: COMCUBE V1.3.1 - Q Factor.

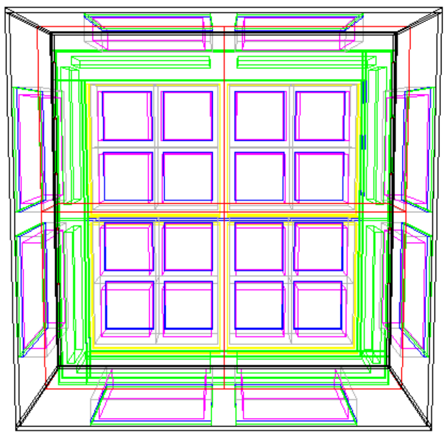


Figure 4.22: COMCUBE V1.3.1 - Top View using MEGAlib / Geomega. In green the FEE, in yellow the Si DSSD, in violet the CeBr3.

Minimum Detectable Polarization

The MDP for a constellation was calculated and presented in Table 4.9.

For the calculation of the MDP, the COMCUBE simulated efficiency was of 0.6008 and the Background Count was calculated at 10 counts/s/cm^{-2}.

The relation between the Minimum Detectable Polarization (Equation 2.4) of the 1U and 4U configurations was calculated. Equation 4.1 reports this relation.

$$MDP_{4U} \approx \left(\frac{Q_{1U}}{Q_{1U}}\right) \frac{MDP_{1U}}{2} \tag{4.1}$$

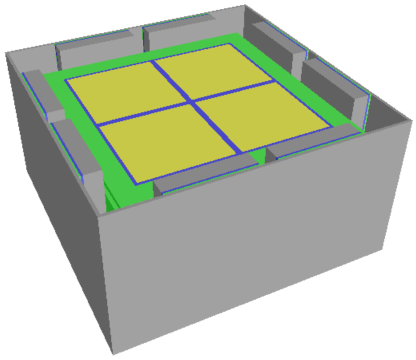


Figure 4.23: COMCUBE V1.3.1 - Ray Tracing using MEGAlib / Geomega.

Source	**Modulation Factor**	**MDP**
GRB170817A	0.35 ± 0.02	≈ 20 %
Crab (from 100 to 2000 keV)	0.30 ± 0.02	≈ 35 %

Table 4.9: COMCUBE MDP calculation for Sources GRB170817A and Crab Nebula, at 20 cm^3 of Area

4.3 ANTAEUS

Figure 4.24: ANTAEUS Mission Logo. Credits to Diogo Marques.

Project ANTAEUS is born from the intent of designing, assemble, and fly on a Low Earth Orbit (LEO) a 1U to 2U CubeSat Spacecraft lead by LIP, with the support of Universities.

For the scope of ANTAEUS, an initial needs assessment was performed by taking as input the discussions held with the principal investigators of the mission (Dr. Rui Silva Curado, and Dr. Jorge Maia).

The first baseline established for the scientific instrument was a 8 by 8 pixel array of Cadmium Telluride, each pixel with dimensions approximately of 2 mm x 2 mm x 5 mm. This detector is not to be developed by the project team - however, the accompanying electronics and system design are.

The work performed herein concerns the initial system definition and study of the preliminary definition of requirements to the level of Preliminary Requirements Review (PRR). A System Requirement Review (SRR) was to occur within the duration of this work, however, due to the underdevelopment of the Platform (the subsystems supporting the Payload), this was not possible.

Nonetheless, for my short participation on the project, the team was successful in achieving various milestones and publishing a Conference Paper at the IAC 2021 in Dubay, [25].

The preliminary logo for the mission can be found in Figure 4.24.

4.3.1 Mission Concept

The Mission Concept initially put forth can be read:

> "The satellite scientific and primary mission is to provide a reliable satellite platform to measure the Compton Scattering generated double-events of incident photons and, if possible, to determine the polarization degree and direction of the celestial gamma-ray emission for the energy between 100 keV to 1 MeV."

The focus of this Mission Concept is to provide the minimum and optimal translation of what the baseline goal for the scientific team is within the scope of this project. Already, many challenges are addressed, and the introduction of the determination of the polarization degree for such a small kind of spacecraft would be a stretch from the current baseline of missions.

4.3.2 Multimessenger Networks

As discussed in Section 2.3, multimessenger networks can be very interesting for this kinds of satellites. In spite of their relatively short size, they have a small orbital period thus capable of having multiple daily short passages on the Line of Sight of their Ground Stations. For this reason, CubeSats present an interesting solution for CubeSat constellations as warnings for the events of GRB or for initial comparison between the different sources (while the complete data can be downloaded through the course of a week).

An initial concept developed within the scope of ANTAEUS is presented in Figure 4.25. This concept has been studied by other organizations such as the Astrophysical Multimessenger Observatory Network (AMON) presented in Figure 4.26.

Figure 4.25: ANTEUS multimessenger concept.

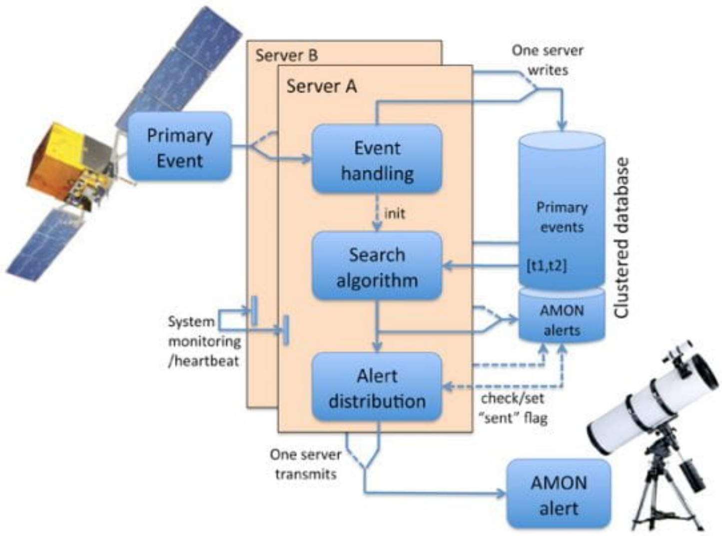


Figure 4.26: AMON System Concept. Adapted from AMON Website.

Having this into consideration, it can be said that a future objective to integrate ANTAEUS in such networks. This work may be performed on a later stage or, if having repercussions on the Flight Segment Architecture, it may be integrated before the Preliminary Design Review (PDR). A simple Ground Segment approach would be to integrate this into the Scientific Operation Center (SOC). Otherwise, special telemetry data packets can be used within the Flight Segment to transmit at the first possible time the information of the new GRB with the accompanying preliminary results.

4.3.3 Mission Objectives

The Mission Objectives were derived from the Mission Concept in section 4.3.1. The objectives presented in Table 4.10 contain two mandatory requirements, MO1 and MO2, as well as two recommendations, MO3 and MO4. The recommendations were left in as supporting requirements but to me reviewed for feasibility in SRR and PDR. It should be noted, nonetheless, that polarization is a byproduct of being able to identify double-events (that is, MO4 is a derived result from successful achieving and processing the data collected in MO2).

ID	Description
MO1	The astrophysics experiment shall measure the energy of incoming photons within a range from 100 keV to 1 MeV.
MO2	The astrophysics experiment shall identify double-events on the pixels of the detector.
MO3	The astrophysics experiment should distinguish a celestial signal from background noise.
MO4	The astrophysics experiment should, for non-background events, be capable of identifying polarization.

Table 4.10: Mission Objectives for ANTAEUS.

4.3.4 System Overview

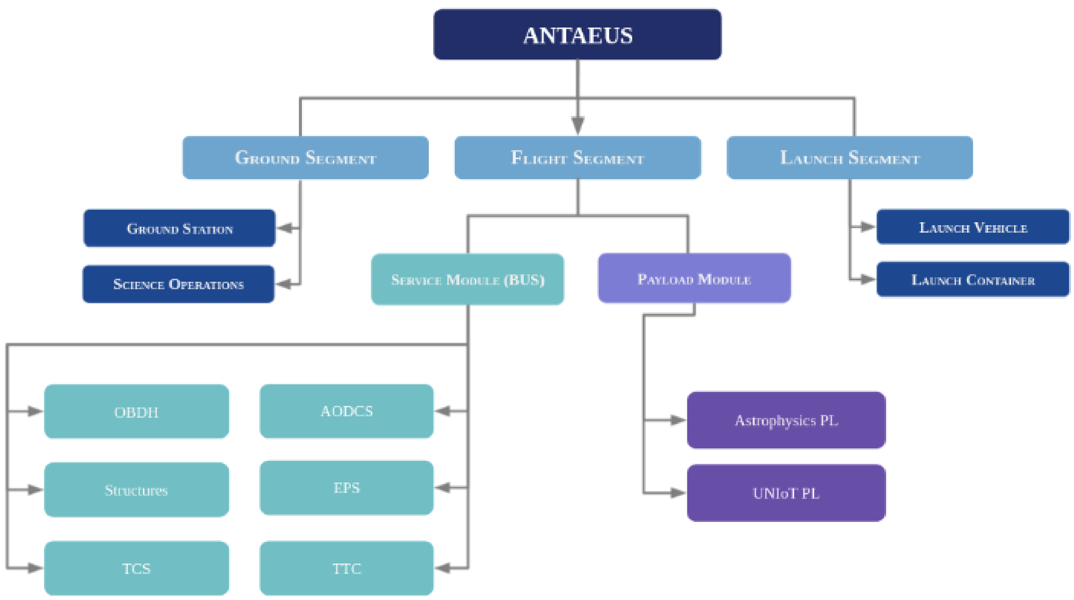


Figure 4.27: ANTAEUS System Overview. Adapted from [25].

The preliminary system design can be seen in Figure 4.27. This systems overview includes the Ground Segment, the Flight Segment, and the Launch Segment.

This system also includes a second payload not covered herein. The second payload is facing NADIR therefor not constraining the Instrument under development.´

4.3.5 Mission Requirements

The defined Mission Requirements (as per Table 4.11) flow-down from the Mission Concept, Mission Objectives, and take into consideration other similar missions and known performance requirements.

ID	**Driver**	**Description**
MR1	Instrument	The payload shall measure gamma radiation within a range from 100 keV to 1 MeV.
MR2	Instrument	The payload shall perform spectroscopic analysis.
MR3	Instrument	The payload shall perform polarimetric analysis.
MR4	Instrument Calibration	The payload shall be able to calibrate itself in orbit when Crab Nebula is visible within 40º deviation maximum from zenith within a 5 min period.
MR5	Instrument	The payload shall identify Gamma-Ray Burst events.
MR6	Instrument	The payload shall be, nominally, pointed to zenith with better than 5º of pointing accuracy.
MR7	S/C Configuration	The S/C shall be compatible with the CubeSat 2U design standard and PC-104.
MR8	Risk Management	Commercial-off-the-shelf (COTS) components, custom solutions and flight heritage will be preferred.
MR9	Legislation	The S/C shall be able to deorbit and disintegrate within 25 years.
MR10	Instrument	The S/C shall be able to operate for at least 2 years.
MR11	Project Management	The mission shall have a procedures manual.
MR12	Project Management	The S/C shall be operational within 3 years.
MR13	S/C Configuration	The astrophysics payload shall not exceed 0.3 kg.
MR14	S/C Configuration	The astrophysics payload shall fit on a 10x10x5 cm3 volume.
MR15	Instrument Attitude	The S/C attitude shall be known with high accuracy, less than 1º.
MR16	Instrument Power	The astrophysics payload shall have a peak operating power consumption of 7 W.
MR17	Instrument Data	The astrophysics payload shall generate a maximum of 15 Mbps of scientific data.
MR18	Instrument Data Rate	The astrophysics payload shall acquire samples from individual detector pixels at a rate of 1 MSPS.
MR19	Instrument Data	The astrophysics payload shall be able to store at least

ID	Driver	Description
		a full week of data.
MR20	Instrument	The astrophysics payload shall have an energy resolution of at least 5 keV @ 511 keV.
MR21	Instrument Temperature	The astrophysics payload shall operate within the temperature range from 0ºC to 20´ºC.
MR22	S/C Operation	The S/C shall be able to store the scientific data and transmit on a weekly basis until end-of-life.

Table 4.11: Mission Requirements for ANTAEUS, Adapted to show only those pertaining to the Scientific Payload, also known as Instrument.

4.3.5.1 Requirements Justification

This section details the Requirement Justification. The inputs used for the justification are: the selected Mission Concept, the environments and constraints, as well as the scientific preliminary figures of merit and acceptable performance levels for the Instrument.

MR1

Derived from Mission Concept and Mission Objective MO1 directly.

MR2

Required to measure energy, as per MO1, supporting the Mission Concept.

MR3

Required to measure polarization, as per MO2 and MO3, supporting the Mission Concept.

MR4

Required to assess the performance evolution of the scientific instrument while in-orbit. The Crab Nebula is also one of the best known sources of gamma-radiation. For that reason, and for its availability, it was chosen as the calibration reference. This in-orbit calibration should allow to change on-board parameters pertaining to the configuration parameters of the algorithms supporting the analysis of the data acquisition.

MR5

Requirement derived from the need to identify the start of this events and record the greatest flux of particles during the event. This requirement is supported and called on due to the assessment that is not feasible to record all data at all times for processing of the raw data on the Ground Segment at the Scientific Operation Center (SOC).

MR6

This requirement puts a limit to the accuracy of the pointing of the S/C and defines the nominal pointing ot the Instrument - to Zenith. The Zenith pointing allows for the instrument to be turned outwards to the celestial sky and avoid radiation coming from the direction of the Earth. The accuracy herein presented is middle-term to the capability of COTS systems and to the needs for a good pointing accuracy. A high pointing accuracy improves the instrument in its capability to correlate the events with the celestial position of the sources.

MR7

Requirement derived from the CubeSat Standard [13].

MR8

Commercial Off The Shelf (COTS) Systems and Components with flight heritage provide a decrease in the Risk index of the support subsystems. The Instrument and Payload, in spite of not being COTS, should employ mostly COTS components in its electronics.

MR9

Requirement flown down from legislation, and Standards pertaining to the maintenance of the space debris. This requirement can only be verified by Analysis until the Phase of Disposal of the Spacecraft.

MR10

The operational time requirement of minimum 2 years supports the assessed need - yet to be numerically evaluated - to observe Gamma Ray Bursts. The two year period should allow the Spacecraft to observe a reasonable number of these events.

MR11

Requirement derived from the need to have a manual containing the in-flight operations procedures for the Instrument, besides the Platform. Given that in spite of its components being COTS, the design is developed by the project and custom made. For that reason, coupled with the fact that Spacecraft Operations are not going to occur at the same physical location as the Science Operations. This relation between the different components of the Ground Segment is still under evaluation and could suffer changes before PDR.

MR12

Requirement derived from the need to participate in the Fly Your Satellite (ESA) program.

MR13

Requirement flow down from preliminary Mass Budget, discussion with the Platform subsystems, as well as the constraints imposed by the mission size.

MR14

Same rationale as for MR13. Requirement flow down from preliminary Volume Allocation Budget, discussion with the Platform subsystems, as well as the constraints imposed by the mission volume (2U).

MR15

Requirement derived from the assessment of accuracy of the attitude to support efficient data analysis for the Payload.

MR16

Requirement derived from different experiments, and preliminary Power Budget calculated by the Payload team.

MR17

Requirement derived from preliminary data budget taking into consideration the types of messages, the expected event count rate, and with positive margins of safety to accomodate potential temporary events with high flux of incoming particles.

MR18

Requirement derived from MO2, and the need to perform coincidence analysis. That is, establishing a baseline for the time in which two successive events are considered a double event. Requirement choice is justified by heritage experiments and MEGAlib common configuration parameters.

MR19

The initiation of this requirement flows-down from a preliminary risk assessment performed at Mission Definition Review (MDR). On the MDR meeting, it was identified that the entire data for one GRB event could not be sent over the course of one passage over the Ground Station. For that reason, it was proposed to use more than one Ground Station.

MR20

Requirement is a constraint from the existing experiments and detectors perfomance. MR20 supports requirements MR1 and MR2 by defining their performance.

MR21

Requirement derived from the acceptable temperature range of operation of most common detectors. Requirement should be revised with the selection of components for the instrument.

MR22

Requirement in support of Mission Objectives and taking into consideration the functionality of the S/C. The definition of a minimum communication periodicity also provides a baseline for the availability of new data. This can be helpful when working in support of Multimessenger Networks or when correlating the data acquired with new observations performed by other observatories.

4.3.6 Function Tree

The Function Tree in figure 4.28 has been derived from the derived functions identified in table 4.12. The functions therein cover the requirements and a one to many correlation assures that the requirements are met through the functions identified.

Function ID	Function Name
F.01.01	GAM Functions
F.01.01.01	Data Acquisition
F.01.01.01.01	Event Detection
F.01.01.01.02	Preamplification
F.01.01.01.03	Pulse Shaping
F.01.01.01.04	Amplification
F.01.01.01.04	Analog to Digital Conversion
F.01.01.02	Data Analysis
F.01.01.02.01	Data Read (from Data Acquisition)
F.01.01.02.02	Coincidence Analysis
F.01.01.02.03	GRB Finder
F.01.01.02.04	Polarization Calculation
F.01.01.02.05	Background Daemon
F.01.01.03	Data Storage
F.01.01.03.01	Time Stamping
F.01.01.03.02	Memory Storage
F.01.01.04	Control
F.01.01.04.01	Communication with OBC
F.01.01.04.02	Firmware Update
F.01.01.04.03	Housekeeping

Table 4.12: Function Tree in Table form for the

4.3.7 Configuration Item List

The Configuration Item List defines the Items under Configuration within the scope of the Instrument (a Configuration Item List containing the other systems exists at Mission-level). The items under configuration are items which the configuration is to be controlled and documented. The Configuration Items were selected taking into account the Standards in Configuration, namely ECSS-M-ST-40C Rev.1 [26].

Configuration Code	Name	Category
01.01.GAM	Astrophysics Payload	Developed
01.01.GAM.01	Gamma Rays Detector	Non-Developed
01.01.GAM.02	Preamplifiers	Developed
01.01.GAM.03	Filters	Developed
01.01.GAM.04	Amplifiers	Developed
01.01.GAM.05	Analog to Digital Conversion	Developed
01.01.GAM.06	Processing Unit	Developed

Table 4.13: Configuration Item List for the ANTAEUS Payload.

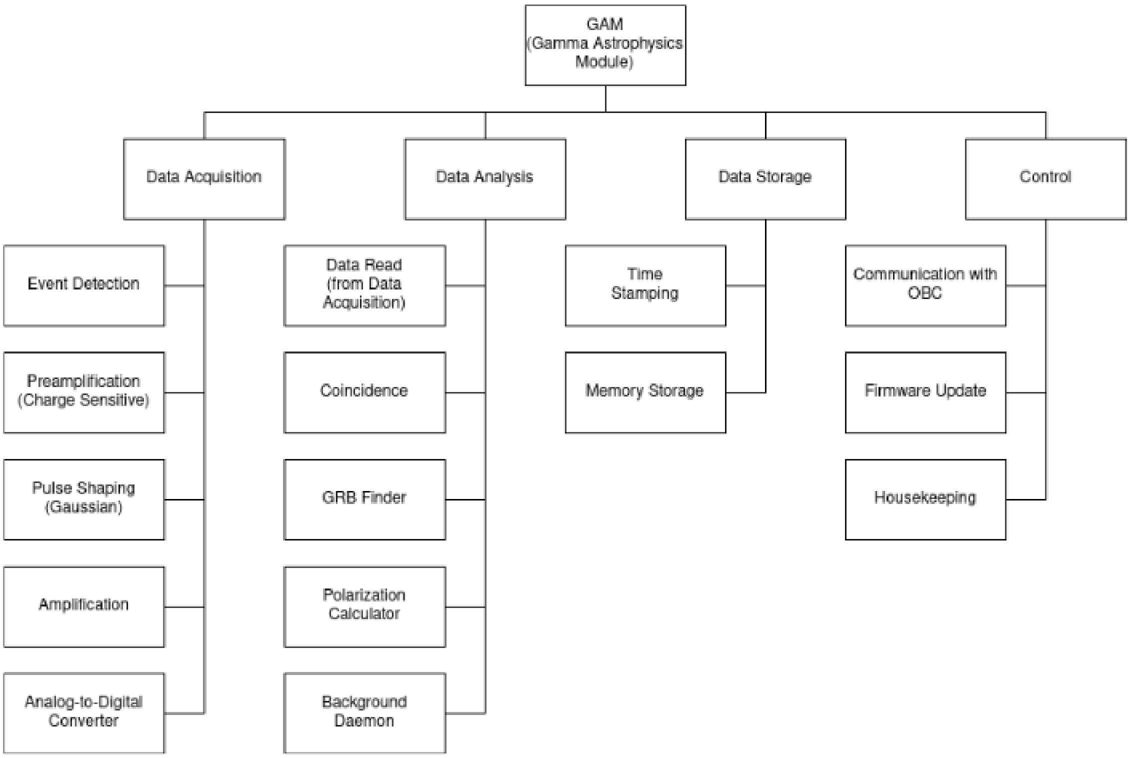


Figure 4.28: ANTAEUS Function Tree

This list supports the future definition of a Configuration Item Data List (DRD from the same standard [26]), as well as an As-Built Configuration List and supporting Subsystem Logbooks for the different models.

4.3.8 Product Tree

The Product Tree is a direct derivation from the Function Tree. The several elements identified in the Product Tree (Figure 4.29) cover at least one function as identified on the Function Tree in Figure 4.28.

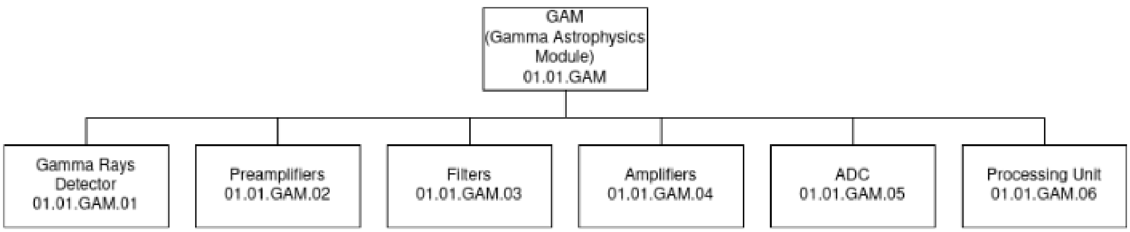
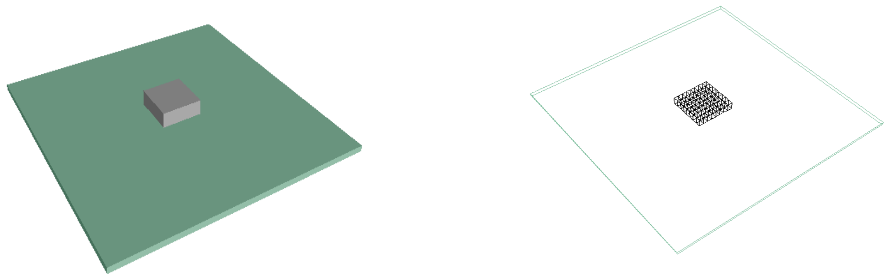


Figure 4.29: ANTAEUS Product Tree.

4.3.9 Geometry Definition

Within the realm of the scientific simulations in MEGAlib, the geometry was simplified to the pixel array detector with a "CircuitBoard" type below. Given that the simulations have been performed with a perpendicular incidence angle, no other geometrical or mechanical factors should impact the detector performance. Given the Mission Requirements, the Platform subsystems should not have any mechanical part blocking the forward view of the instrument.



(a) Ray Tracing **(b)** Regular

Figure 4.30: ANTAEUS Simplified Geometry on Geomega

Figure 4.30 presents the Ray Tracing geometry with the small detector at the middle in gray and the CircuitBoard in gray; on the same figure, the "Regular" geometry of edges is presented. The detail of the pixels edges is more clearly seen on this figure.

4.3.10 Performance Evaluation

The preliminary performance evaluation for ANTAEUS was performed taking into consideration simple assumptions and the only FoM calculated was the modulation factor presented in figure 4.31. The results and reported uncertainties are reported in Table 4.14.

ANTAEUS is the corollary of the work performed in STRATOSPOLCA and COMCUBE. The results therein are used to define and design the ANTAEUS payload geometry and are used as a driver for trade-off analysis.

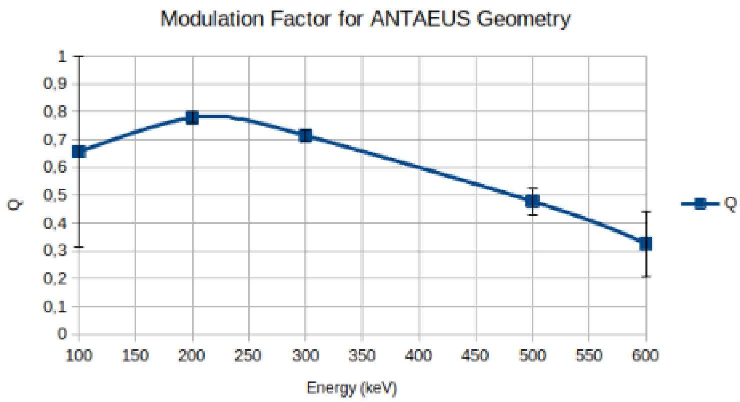


Figure 4.31: ANTAEUS modulation factor.

As it can be noted, the ANTAEUS geometry, in spite of not being as differentiated and massive as COMCUBE's, delivers relatively good results for the modulation factor or quality factor.

Energy [keV]	**Modulation Factor Q**	**U(Q)**
100	0,656148	0,34240900
200	0,779399	0,02080740
300	0,714781	0,01826910
500	0,478592	0,04846260
600	0,325690	0,11747900

Table 4.14: ANTAEUS Preliminary Results.

5

Conclusions

5.1 STRATOSPOLCA

The STRATOSPOLCA mission was the introductory mission to the concepts of Systems Engineering and requirements management.

Student researched and developed projects can bring much to the universities and to the students themselves as well as laboratories, which depend on students for dissertations, thesis, and research positions in the future).

STRATOSPOLCA's lessons learned [23] provide for a much in-depth analysis to identify and address problems and solutions for future projects.

The scientific outcome of these projects may be a a matter under discussion but much is dependent on who is leading and who is supporting these projects.

STRATOSPOLCA was the first of its kind on the University of Coimbra and was successfully completed with students which had no prior background, special academic training, or major support.

The next step to STRATOSPOLCA is very clearly to proceed with a STRATOSPOLCA 2.0, building on the learning curve of the first iteration, and taking on the lessons learned as reported by the first team.

Requirements Management, and Verification Control are two clear areas of investment for future iterations.

The potential for future research is plausible. And these sorts of high-altitude balloon flights can help improve missions for future success. The COMCUBE mission is likely to have a model flying in such types of balloons as part of their verification strategy. ANTAEUS, in spite of its lower budget, may also take such type of opportunity.

5.2 COMCUBE

The objectives of this dissertation within the scope of COMCUBE were successful. The simulations were performed and the results were presented. The next steps to be taken are to improve the geometry definition within the MEGAlib and perform improved geometry analysis.

The next steps should further cover a different range of figures of merit besides the modulation factor, with an improved and more stable baseline. One of the many difficulties working under such rapid iteration of geometries was that it was not feasible to keep up and perform all the analysis.

Nonetheless, a more detailed analysis shall take the measures of:

- Minimum Detectable Polarization;
- Number of GRB over a year; and,
- Background response for various orbits.

There is also the possibility of studying further configurations, such as:

- CubeSat Coordinated Flights;
- CubeSat constellation; and,
- Other types of detectors.

5.3 ANTAEUS

ANTAEUS is on the map to be on the forefront of the next wave of scientific CubeSats delivering results in Astrophysics. The current work lays the foundations at PRR level for a CubeSat mission to be successful in the future.

Having that in mind, it's paramount for the engineering management of the Mission (which encompasses not only the Spacecraft but also the Ground Segment) to have an increased attention to the Requirements management of the System.

In terms of Systems Engineering, the next steps are:

- Improve Maturity of Instrument Requirements;
- Review current Mission, System, and Subsystem-level requirements;
- Prepare a Technological Assessment regarding the Instrument;
- Define the Model Philosophy for the Instrument;
- Define the Model Philosophy for the System;
- Prepare the Verification Plan;
- Release a new and improved issue of the Design Definition File;
- Release a new and improved issue of the Design Justification File;
- Other types of detectors.

In regards to the Scientific Analysis, further analysis should be held. Namely:

- Background Simulations, taking into account different types of Orbits;
- Crab Nebula detection for different Orbits;
- Minimum Detectable Polarization;
- Number of expected GRB's over one year;
- Improved geometry study;
- Instrument constellation; and,
- Other types of detectors' dimensions.

Bibliography

[1] B. P. A. et al, "Multi-messenger observations of a binary neutron star merger," *The Astrophysical Journal*, vol. 848, p. L12, Oct. 2017.

[2] J. McEnery, J. A. Barrio, and et al, "All-sky medium energy gamma-ray observatory: Exploring the extreme multimessenger universe," 2019.

[3] C. Winkler, T. J.-L. Courvoisier, and et al, "The INTEGRAL mission," *Astronomy & Astrophysics*, vol. 411, pp. L1–L6, Nov. 2003.

[4] S.-N. Zhang, M. Kole, and et al, "Detailed polarization measurements of the prompt emission of five gamma-ray bursts," *Nature Astronomy*, vol. 3, pp. 258–264, Jan. 2019.

[5] A. D. Angelis, , V. Tatischeff, and et al, "The e-ASTROGAM mission," *Experimental Astronomy*, vol. 44, pp. 25–82, June 2017.

[6] F. Lei, A. J. Dean, and G. L. Hills *Space Science Reviews*, vol. 82, no. 3/4, pp. 309–388, 1997.

[7] A. Zoglauer, "First light for the next generation of compton and pair telescopes : development of new techniques for the data analysis of combined compton and pair telescopes and their application to the mega prototype."

[8] R. M. C. da Silva, N. Auricchio, E. Caroli, A. Donati, S. D. Sordo, V. Honkimaki, J. M. Maia, F. Schiavone, J. B. Stephen, and A. Trindade, "Polarimetry study with a CdZnTe focal plane detector," *IEEE Transactions on Nuclear Science*, vol. 58, pp. 2118–2123, Aug. 2011.

[9] M. Chauvin, J. P. Roques, D. J. Clark, and E. Jourdain, "POLARIMETRY IN THE HARD x-RAY DOMAIN WITH INTEGRAL SPI," *The Astrophysical Journal*, vol. 769, p. 137, May 2013.

[10] M. Giomi, R. Bühler, C. Sgrò, F. Longo, and W. Atwood, "Estimate of the fermi large area telescope sensitivity to gamma-ray polarization," 2017.

[11] A. M. and, "All-sky medium energy gamma-ray observatory (AMEGO)," in *Proceedings of 35th International Cosmic Ray Conference — PoS(ICRC2017)*, Sissa Medialab, Aug. 2017.

[12] C. Cappelletti, S. Battistini, and B. K. Malphrus, *Cubesat Handbook: From Mission Design To Operations.* Academic Press, 2021.

[13] "Cubesat Design Standard Rev.13," standard, California Polytechnic State University, San Luis Obispo, US, Feb. 2014.

[14] "General Environmental Verification Standard (GEVS) for GSFC Flight Programs and Projects," Standard GSFC-STD-7000 Rev.B, National Aeronautics and Space Administration, Washington DC, US, Apr. 2021.

[15] "Poly Picosatellite Orbital Deployer Mk. III Rev. E User Guide," standard, California Polytechnic State University, San Luis Obispo, US, Mar. 2014.

[16] A. Zoglauer, R. Andritschke, and F. Schopper, "MEGAlib – the medium energy gamma-ray astronomy library," *New Astronomy Reviews*, vol. 50, pp. 629–632, Oct. 2006.

[17] A. Zoglauer, G. Weidenspointner, M. Galloway, S. Boggs, and C. Wunderer, "Cosima - the cosmic simulator of MEGAlib," in *2009 IEEE Nuclear Science Symposium Conference Record (NSS/MIC)*, IEEE, Oct. 2009.

[18] A. Zoglauer, S. E. Boggs, M. Galloway, M. Amman, P. N. Luke, and R. M. Kippen, "Design, implementation, and optimization of MEGAlib's image reconstruction tool mimrec," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 652, pp. 568–571, Oct. 2011.

[19] ECSS Secretariat, "Project planning and implementation," Standard ECSS-M-ST-10C Rev.1, European Cooperation for Space Standardization, 2009.

[20] ECSS Secretariat, "Space engineering technical requirements specification," Standard ECSS-E-ST-10-06C, European Cooperation for Space Standardization, 2009.

[21] ECSS Secretariat, "System engineering general requirements," Standard ECSS-E-ST-10C Rev.1, European Cooperation for Space Standardization, 2017.

[22] SEBoK authors, "Systems Engineering Body of Knowledge (SEBoK), version 1.8," 2017. [Online; accessed 14 Feb 2022 22:41:03 UTC].

[23] H. Neves, R. Gameiro, J. Sousa, I. de Oliveira, J. Pereira, B. Matos, R. Roque, and et al, "Student Experiment Documentation - STRATOSPOLCA," BX31, december 2021.

[24] P. S. Rehal, M. Nürmberger, A. Frenea-Schmidt, M. Snäll, K. Andersson, B. Norendahl, M. Bysell, F. Rosenberg, E. Nordqvist, "BEXUS User Manual 8.0," User Manual, july 2021.

[25] J. Monteiro, H. Neves, D. Marques, R. C. Silva, J. Maia, J. Santos, J. Panagopoulos, Y. Mashtakov, A. Guerman, C. Capelletti, A. A. Gil, and R. Perez, "Preliminary

Mission Design of CubeSat for High Energy Astrophysics Polarimetry," (Dubai), International Astronautical Federation, 2021.

[26] ECSS Secretariat, "Space project management - configuration and information management," Standard ECSS-E-ST-40C Rev.1, European Cooperation for Space Standardization, 2009.