X-Ray polarization: RHESSI results and POLAR prospects

SUAREZ GARCIA, Estela

Abstract
Une grande partie de nos connaissances actuelles de l'Univers a été acquise en étudiant le rayonnement électromagnétique qui arrive sur Terre produit par des objets astronomiques. L'étude de ces émissions est traditionnellement basée sur l'analyse de seulement trois propriétés de ces photons: leur énergie, la direction d'où ils viennent, et le temps de détection. Les résultats obtenus sont utilisés pour élaborer des modèles qui permettent d'expliquer l'origine de la radiation observée en terme de sources astronomiques connues ou inconnues. Bien qu'une grande quantité d'information puisse être obtenue à partir de ces trois propriétés des photons, on arrive souvent à une situation dans laquelle deux ou plusieurs modèles théoriques très différents peuvent expliquer les mêmes observations avec succès. Des mesures de polarisation permettraient de distinguer entre différents modèles théoriques, car elles fournissent deux caractéristiques supplémentaires: le degré de polarisation et la direction de polarisation des photons observés. Dans la région du spectre électromagnétique à basse [...]
X-Ray Polarization: RHESSI Results and POLAR Prospects

THÈSE

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pour obtenir le grade de Docteur ès sciences, mention physique

par

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Résumé

Une grande partie de nos connaissances actuelles de l’Univers a été acquise en étudiant le rayonnement électromagnétique qui arrive sur Terre produit par des objets astronomiques. L’étude de ces émissions est traditionnellement basée sur l’analyse de seulement trois propriétés de ces photons: leur énergie, la direction d’où ils viennent, et le temps de détection. Les résultats obtenus sont utilisés pour élaborer des modèles qui permettent d’expliquer l’origine de la radiation observée en terme de sources astronomiques connues ou inconnues. Bien qu’une grande quantité d’information puisse être obtenue à partir de ces trois propriétés des photons, on arrive souvent à une situation dans laquelle deux ou plusieurs modèles théoriques très différents peuvent expliquer les mêmes observations avec succès. Des mesures de polarisation permettraient de distinguer entre différents modèles théoriques, car elles fournissent deux caractéristiques supplémentaires: le degré de polarisation et la direction de polarisation des photons observés. Dans la région du spectre électromagnétique à basse énergie, des observations de polarisation sont systématiquement effectuées. Par contre, pour des photons X et gamma, les données de polarisation restent jusqu’à présent très rares. Cette disparité est due principalement à de grandes difficultés expérimentales dans la construction de polarimètres pour photons de haute énergie, et dans leur utilisation dans l’espace. Néanmoins, l’étude de la polarisation peut fournir des informations essentielles sur le mécanisme d’émission des rayons X dans l’univers, la géométrie, la taille, et l’uniformité de ces sources, et même sur la structure du champ magnétique impliqué. Cette thèse présente une étude de polarimétrie de photons de haute énergie du point de vue de l’observation et du point de vue instrumental.

En utilisant les données collectées par le satellite RHESSI (Reuven Ramaty High Energy Solar Spectroscopic Imager), nous avons effectué des mesures de polarisation pendant sept éruptions solaires dans la gamme d’énergie entre 100 et 350 keV. Les résultats obtenus sont en accord avec les mesures de polarisation des photons X effectuées à des énergies inférieures et supérieures pendant des éruptions solaires. La comparaison avec les prévisions des différents modèles théoriques nous montre qu’un détecteur de meilleure précision est nécessaire pour distinguer entre les théories disponibles.

POLAR est un polarimètre Compton qui vise à mesurer avec précision le degré de polarisation de la radiation émise par les sursauts gamma (Gamma Ray Bursts (GRBs)) entre 50 et 500 keV. POLAR utilise des scintillateurs en plastique et des
photomultiplicateurs à plusieurs canaux pour mesurer la distribution azimutale des photons qui interagissent à l’intérieur du détecteur. Le degré et la direction de la polarisation du flux de photons incidents peuvent être obtenus à partir de l’analyse de cette distribution.

Cette thèse décrit la conception de la mécanique et de l’électronique du détecteur POLAR. Des simulations Monte Carlo ont été effectuées avec GEANT4 pour évaluer la performance de POLAR en tant que polarimètre pour GRB. Les résultats des mesures expérimentales réalisées avec le modèle de démonstration POLAR (une portion 1/25 du détecteur final) dans le laboratoire et auprès de l’ESRF (European Synchrotron Radiation Facility) à Grenoble, sont également présentés. L’accord entre les résultats expérimentaux et les prédictions des simulations GEANT4 témoigne de la bonne compréhension des performances du détecteur, et valide le “package” de simulation de POLAR. Finalement, ce code de simulation nous a permis de prédire l’influence sur POLAR des sources de bruit de fond aux quelles il sera exposé dans l’espace.

Les résultats expérimentaux et les simulations présentés dans cette thèse sont une preuve de la capacité de POLAR à mesurer le degré de polarisation des rayons X. La prochaine étape dans le développement du détecteur POLAR sera l’assemblage du modèle de qualification (16/25 du détecteur final), suivie par une campagne d’essais avec des sources radioactives et auprès des accélérateurs de rayonnement synchrotron. L’attention se concentrera sur l’étude de la réponse du détecteur aux rayons X de faible énergie, pour déterminer son seuil et sa précision pour la mesure de polarisation aux environs du seuil. En plus, une série complète de tests thermiques, de vibrations, et des tests sous vide seront réalisés pour qualifier le détecteur POLAR pour son utilisation dans l’espace. Le modèle de vol POLAR (avec 1600 barreaux de scintillateur) sera construit en prenant en compte les résultats de tous ces essais. Prêt à voler en 2012, POLAR a le potentiel pour devenir le premier détecteur à déterminer avec haute précision le degré de polarisation dans l’émission des GRBs, ce qui constituerait un pas en avant fondamental dans la recherche des sursauts gamma.
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Especially important in the last two years of the thesis has been Dr. Silvio Orsi. Without his contribution to the POLAR project, our countless discussions both on experimental and simulation results, and his thorough reading of the final manuscript the present thesis would not be now in your hands.

I would like to show my gratitude to Dr. Laurent Desorgher, for his work on the PLANETOCOSMICS code, its adaption to the POLAR needs, and all the discussions and advice that allowed me to perform the analysis of the X-ray albedo background. Also of big help has been the work of Maciek Jaworski preparing the BATSE catalog to be used for the determination of the number of GRBs annually visible for POLAR. Thanks as well to Franck Cadoux for his contribution to the POLAR project and for producing all the technical drawings of the POLAR detector presented in this thesis, facilitating the description of the mechanical design and highly improving the quality of its presentation. Special thanks go also to Prof. Catherine Lechanoine-Leluc for her correction of the text in French, and to Peggy Argentin for her help in so many administration issues, not the least time consuming task during a thesis.
Not only this thesis, but the whole POLAR project would not have been possible without the contribution of all the members of the POLAR collaboration. In addition to the ones already mentioned, I would like to cite Dr. Nicolas Produit, Prof. Divic Rapin, Dr. Daniel Haas, Radoslaw Marcinkowski, Dominik Ribka, Prof. Jean-Pierre Vialle, Dr. Giovanni Lamanna, and Prof. Thierry J.-L. Courvoisier.

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Introduction

Much of our actual knowledge of the Universe has been acquired studying the electromagnetic radiation arriving to Earth from astronomical objects. The investigation of those emissions is traditionally based on the analysis of only three photon parameters: the energy, the incoming direction, and the time of detection. The results obtained are used to elaborate models that allow to explain the origin of the observed radiation in terms of known, or unknown astronomical sources. Although a lot of information can be collected with the three mentioned properties, we often arrive to a situation in which two or more very different models can successfully explain the observations [1]. Polarization measurements have the diagnostic potential to differentiate between different theoretical models, since they provide two more parameters: the polarization level and the polarization direction of the incoming photon flux. The low energy regimes of the electromagnetic spectrum routinely benefit from polarization observations. However, at X- and γ-ray photon energies the polarization data remain until now very scarce [2]. This disparity is mostly due to great experimental difficulties in the construction of high energy polarimeters and their operation in space. As polarization signatures are clearly distinctive, studying them can provide essential information on both the emission mechanism and the source geometry with its size, uniformity, and even the structure of the magnetic field. In addition, polarization can sample the extreme physics, basic symmetries and invariants, as well as the nature of gravity [3]. Therefore it has a great potential in answering the fundamental questions on the physics of the universe.

Outline of this thesis

This thesis presents a study of hard X-ray polarimetry from the observational and instrumental points of view.

Chapter 1 is an introduction to the thesis subject, giving an overview of the actual situation of the high energy photon polarimetry in astronomy. First of all a brief description of various physical processes producing polarized hard X-ray fluxes is given. In §1.2 the commonly used measuring principles applied in high energy photon polarimetry are explained. Some of the most significative astronomical sources of polarized high energy radiation are described in §1.3, together
with the results of the measurements performed up to date. The last section of this chapter, §1.4, presents some examples of instruments used in the past or currently under development to measure polarization of astronomical sources.

Chapter 2 presents the results of the polarization measurements performed with the satellite Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) on seven solar flares observed in the period July 2002 to August 2005. The content of this chapter has been extracted from the article in reference [4]. RHESSI, although capable of measuring polarization, has not been designed for this purpose and has strong limitations. Taking advantage of the knowledge of these limitations, we embark on the design and construction of POLAR, an instrument devoted to accurately measuring the polarization of gamma-ray bursts. From chapter 3 on, all chapters from this thesis are devoted to the description and characterization of the POLAR instrument.

Chapter 3 describes the POLAR design, both regarding its mechanical and electronic characteristics, as well as its working principle. The last part of this chapter presents the various POLAR models constructed along the development phase of the instrument, from the demonstration model to the flight model, passing by the engineering qualification model.

An important part of this thesis was dedicated to the construction of the POLAR Monte Carlo simulation package, whose description is given in chapter 4. This simulation package has been used to evaluate the POLAR capabilities, allowing to improve and validate its mechanical design. It has also been fundamental for the development of new capabilities like the method to localize GRBs using POLAR alone.

To validate the results obtained with the simulations, various series of experiments have been performed with the POLAR demonstration model. Those experiments are detailed in chapter 5. The first series of experiments were performed with an in-house laboratory setup in which we can produce partially polarized 511 keV photons. Measurements with 100% polarized hard X-rays in the range between $\sim 45$ keV and 511 keV were finally performed in the ID15 beamline of the European Synchrotron Radiation Facility (ESRF), in Grenoble. The results of this thorough study of the POLAR performance are presented also in chapter 5. The final section of this chapter describes the space qualification tests that have been performed till now to validate the detector components and to demonstrate its thermic and mechanical stability.

Chapter 6 presents the study of the space environment surrounding POLAR, once it will be installed on a satellite. A detailed simulation of the main background sources present in the expected POLAR orbital configuration allows us to predict which will be the final performance of the instrument in space.

Finally, chapter 7 presents the conclusions of this thesis.
The Author’s Contribution

My first contact with the field of high energy polarimetry was at the Paul Scherrer Institute, Switzerland (PSI), when I made my first analysis of the RHESSI data. This very interesting experience lead to the publication of an article [4] and two book chapters [2, 5] reviewing the status of high energy polarization in astronomy. At the same time, the results obtained with RHESSI, added to the results from other authors obtained with other non polarimeter instruments, lead to the conclusion that for doing accurate polarimetric studies a specifically polarimeter detector is needed. This was the main reason for a small group of scientists to develop and construct POLAR.

I arrived to the POLAR project almost at the very beginning of its life. This allowed me to be present in the first development phases, actively participating in the first laboratory tests where various detector configurations, sizes, and components were considered and tested. Once the various tasks associated with the development of the POLAR engineering-qualification model were defined, they were distributed between the members of the POLAR collaboration. I took the responsibility of writing and developing the POLAR Monte Carlo simulation package, under GEANT4. This included the accurate description of all its volumes and materials, the evaluation of its polarimetric capabilities, and the comparison of the laboratory results with the simulations predictions. Finally, it lead also to the development of a new POLAR property: its capability to determine the position of the observed GRB in the sky. In addition, I actively took part in the beam test at the European Synchrotron Radiation Facility (ESRF), in Grenoble. This involved not only participating in the shifts, but also the previous preparation of the online monitoring, the routines needed for the detector alignment, and parts of the software for the posterior analysis of the data. Finally, being part of the POLAR collaboration allowed me to present both the instrument and the simulations results in several international conferences around the world.

Publications by the author related to the thesis:

  X-Ray Polarization of Solar Flares Measured with RHESSI.
  DOI: 10.1007/s11207-006-0268-1

- E. Suarez-Garcia and W. Hajdas, "X-ray polarization and electron angular distribution", Section 7.5.5 of the book chapter:
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POLAR: a novel gamma-ray burst polarimeter.
Conf. Record of the IEEE Nuclear Science Symposium, Dresden, October 2008

• E. Suarez-Garcia, and W. Hajdas, for the POLAR collaboration.

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Localization of gamma-ray bursts using POLAR.


A method to localize gamma-ray bursts using POLAR.
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Papers by others where I am co-author:


Wide-field compact detector for hard x-ray polarization measurements.
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  Chapter 6 of the book "Observing Photons in Space"
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  Conf. Proc. of "Polarimetry days in Rome: Crab status, theory and prospects",
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  E. Suarez-Garcia, and J.-P. Vialle
  POLAR – space-borne Gamma Ray Burst polarimeter.
  Conf. Proc. of the 31st International Cosmic Ray Conference, Lodz, July
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Chapter 1
High energy photon polarimetry in astronomy

Polarized high energy photon fluxes can be produced in nature by many physical processes like Compton and inverse Compton scattering, cyclotron and synchrotron emission, bremsstrahlung, and photon splitting in extreme magnetic fields [6]. The measuring principle applied to measure the level of polarization of an observed photon flux depends on the energy region of interest. For instance, in the energy range from about 30 keV to around 1 MeV, the standard procedure takes advantage of the polarization dependence of Compton scattering. The list of astronomical targets for polarization observation includes black holes, pulsars, X-ray binaries and flare emitters, and exotic objects such as GRBs, Soft Gamma Repeaters (SGRs), and magnetars [7]. The actual level of polarization of the large majority of those objects could not yet be determined. Most of the instruments that have been used for this purpose had been designed to measure some other quantities, and presented only limited polarimetric capabilities. With the goal of accurately measuring high energy photon polarimetry in astronomy, many new polarimeter detectors are currently under design or construction around the world (see §1.4).

This chapter of the thesis follows the reviews from Lei, Dean, and Hills [1] and Hajdas and Suarez-Garcia [2] on high energy photon polarimetry for astronomy. When other bibliographic sources have been used the explicit references are given.

1.1 Physical processes producing polarized X-ray fluxes

The photon polarization is defined as the orientation of the electric vector inside the plane perpendicular to the photon direction of propagation. When the electric vector rotates during the propagation, the photon is said to be circularly polarized. Otherwise, when the direction of its electric vector is constant, the photon is linearly polarized. Along this thesis we speak always of linear polarization, unless stated otherwise. Each individual photon has a certain polarization (keeping
quantum effects aside). The level or degree of polarization of a photon flux is determined by the proportion of its photons whose polarization vector is aligned, ranging from totally unpolarized when the orientation is random, to totally polarized when all electric vectors point to the same direction. We speak of polarized photons, or polarized X-rays when a certain degree of polarization alignment is present in the photon fluxes.

Polarized hard X-rays are produced mainly by non thermal processes far from equilibrium, such as the extreme magnetic field environments present in many astronomical sources. Some of the processes leading to polarized X-rays are described in this section, namely: cyclotron emission, synchrotron emission, curvature radiation, bremsstrahlung radiation, Compton scattering, and magnetic photon splitting.

**Cyclotron** emission is the kind of radiation emitted by non-relativistic charged particles due to the constant acceleration that they experience when moving in a constant magnetic field. The rate of cyclotron radiation emitted by a charged particle is inversely proportional to the particle’s mass. Therefore, electrons will be most frequently the particles responsible from this kind of emission. In the following we will consider only electron-produced cyclotron emission. The electron emits radiation in a dipolar form with the maximum intensity in the direction perpendicular to its acceleration. The direction of the photon electric vector is contained in the plane described by the electron acceleration vector and the photon momentum vector. An observer far away from the source and looking at it from a direction parallel to the magnetic field, will see the acceleration vector rotating as the electron describes a circular orbit. The photons arriving to him will be therefore circularly polarized. If, on the other hand, the line of sight is perpendicular to the magnetic field, the acceleration vector will seem to perform an harmonic motion, and the photons will be linearly polarized. It can be demonstrated that the magnetic field strength needed to produce a photon of $E$ keV via cyclotron emission is

$$B[T] = 8.64 \times 10^6 E \text{ [keV]}.$$  

Given that the largest magnetic fields found in nature are $\sim 10^9 \text{ T}$, the cyclotron emission is likely to be limited to energies $E < 100$ keV.

**Synchrotron** radiation is equivalent to cyclotron emission, but for relativistic particles. When the electron moves with $v \approx c$, although in his rest frame the radiation is emitted in a dipolar form as before, when transformed to the reference frame of the observer the radiation is beamed in the forward direction. In this process significant amounts of radiation are only seen when the emission beam points towards the observer. Only electrons with beams within an angle $\gamma^{-1}$ to the line of sight will contribute to the observed intensity. The magnetic field strength needed to produce a photon of $E$ keV is given by:

$$B[T] = \frac{1.99 \times 10^7}{\gamma^2 \sin \chi} E \text{ [keV]}.$$  

(1.1)

For example, to produce a 1 MeV photon in a $10^9 \text{ T}$ magnetic field, a Lorentz factor of $\gamma = 4.46$ is required. The electron energy spectrum can often be approximated
by a power law, in which case the emitted photon energy spectrum presents also a power law shape. The level of linear polarization ($\Pi$) of the synchrotron emission increases with the electron velocity, and can be expressed in function of the power law index ($\alpha$) of the electron energy spectrum:

$$\Pi = \frac{\alpha + 1}{\alpha + 7/3}$$ (1.2)

For the range of power law indices $1.5 < \alpha < 5.0$ observed in astronomical objects, the expected level of linear polarization in the photon emission is $65% < \Pi < 80%$. Any inhomogeneities in the magnetic field structure will lead to lower values of $\Pi$.

Curvature radiation is the kind of synchrotron radiation emitted in a curved magnetic field. The power emitted in this case is a factor $\gamma$ greater than from standard synchrotron radiation. The polarization characteristics are similar, except that the polarization vector will be now parallel to the local magnetic field, instead of perpendicular as it was in the case of synchrotron radiation.

When an accelerated charged particle moves in the electrostatic field of an ion or an atom nucleus, electro-bremsstrahlung (or simply bremsstrahlung) is emitted. Similar as in the three previously mentioned emission processes, the intensity of the photon emission is inversely proportional to the mass of the charged particle, so that electrons are the most frequent cause of its emission. Bremsstrahlung radiation is indicative of a hot gas. In the hard X-ray and $\gamma$-ray range the hot gas is optically thin to the radiation, and the emitting power does not depend strongly on the frequency, producing a continuous spectrum. The degree of polarization from electron-proton bremsstrahlung can reach high levels of $\sim 80\%$. The polarization vector tends to be parallel to the direction of acceleration and the photons tend to be emitted perpendicular to the electron’s plane of motion. The maximum degree is reached for a scattering angle which is dependent on the incident electron energy.

Compton scattering occurs when the momentum and energy of a high energy photon is modified by its elastic interaction with a free electron, which receives some recoil energy and momentum. The probability of a photon to scatter at an angle $\theta$ off an electron at rest is given by the Klein-Nishina formula, that in the non-polarized case is:

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2} \left( \frac{E'}{E} \right)^2 \left( \frac{E}{E'} + \frac{E'}{E} - 2 \sin^2 \theta \right)$$ (1.3)

where $r_0$ is the classical electron radius and $E$ and $E'$ are the initial and final photon energies, respectively. The degree of linear polarization of the scattered photons is:

$$\Pi_U = \frac{\sin^2 \theta}{\frac{E}{E'} + \frac{E'}{E} - 2 \sin^2 \theta}$$ (1.4)

where the subindex $U$ refers to unpolarized. For example, for 100 keV unpolarized incoming photons, the degree of linear polarization of a flux scattered at 90° can theoretically reach almost 100%.
The azimuthal scattering distribution of a 100% polarized photon beam is not isotropic, but dependent on the angle of polarization. Section 1.2 presents the application of this dependency for measuring hard X-ray polarization. The degree of linear polarization of the scattered photons in that case can be calculated with:

\[
\Pi_P = 2 \frac{1 - \sin^2 \theta \cos^2 \eta}{E + \frac{E'}{E} - 2 \sin^2 \theta \cos^2 \eta}
\]

where \( \eta \) is the azimuthal scattering angle. For example, for a 100 keV incoming fully polarized beam, the level of polarization after a 90° scattering can decrease down to \( \sim 10\% \).

In summary, Compton scattering reduces the degree of polarization of initially polarized beams, and increases the level of polarization of initially unpolarized beams. The later effect is often used to create partially polarized beams in the laboratory using radioactive sources. The source produces a non-polarized flux which is directed towards a scatterer. By selecting only the photons exiting from the scatterer after a \( \sim 90° \) Compton scattering process, one obtains a partially polarized beam. The level of polarization achieved after the scattering depends on the energy of the source and on the exact geometry of the experiment.

**Inverse Compton scattering** is the opposite effect to the standard Compton scattering, i.e. instead of a high energy photon scattering off a free electron, it is a high energy electron which interacts with a low energy photon. The polarization features of this process are the same as previously described for the standard Compton scattering.

**Magnetic photon splitting** is a quantum electrodynamic process occurring at very strong magnetic fields, by which a photon is split into two lower energy photons (\( \gamma \rightarrow \gamma\gamma \)). Such strong magnetic fields are present in astronomical objects as magnetars and Soft Gamma Repeaters (SGRs). The photons produced in this cascade are predicted to be 20% to 30% polarized, with an energy dependent angle of polarization that reverts at the peak position of their energy spectrum. This feature could allow to distinguish magnetic photon splitting emission from synchrotron radiation.

### 1.2 Measuring principles of hard X-ray polarization

Given the energy dependence of the kind of interaction undergone by photons in their interaction with matter (see figure 1.1), the selection of detection techniques applied to determine the level of the linear polarization of photons is strongly related with their energies. Thomson scattering, photo-electric effect and Bragg reflection are utilized at energies of about few to few tens of keV. To measure the polarization degree from tens of keV up to a few MeV, the Compton scattering dependence on the photon polarization is applied. At even higher energies the electron-positron pair production is exploited.
In the Bragg reflection technique, photons of wavelength $\lambda$ reflect off a crystal undergoing a constructive interference at the glancing angle ($\theta_B$), satisfying Bragg’s law:

$$n\lambda = 2d \sin \theta_B$$  \hspace{1cm} (1.6)

where $d$ is the lattice spacing and $n$ is an integer. The maximum reflectivity occurs for photons having their electric vectors parallel to the crystal planes while it is zero if the direction of electric vectors is normal. The Bragg crystal method, although highly efficient as polarization analyzer, can suffer from systematic effects and a narrow energy range strictly selected by the Bragg law.

Another technique in the same energy regime is based on the photoelectric effect. It analyzes the angular distribution of electrons emitted from the atom shell after absorption of the photon. The cross section depends on the azimuth angle $\zeta$ between the photon electric vector and the direction of the electron emission. The formula for electrons ejected from the K-shell [9] is:

$$\frac{d\sigma}{d\Omega} \approx \frac{\sin^2 \theta_e \cos \zeta}{(1 - \beta \cos \theta_e)^4}$$  \hspace{1cm} (1.7)

where $\Omega$ is the solid angle, $\theta_e$ is the electron ejection angle and $\beta$ is its velocity divided by the speed of light. In order to maximize their efficiency, polarimeters based on the photo-effect employ high-$Z$ materials as detectors and work in the energy range where the photo-absorption cross section is the highest (see figure 1.1).

The Thomson scattering technique is also used at the energies below $\sim 30$ keV. Its cross-section for scattering is:

$$d\sigma_T = \frac{e^2}{16} \frac{1 - \sin^2 \theta \cos^2 \eta}{(1 - \sin^2 \theta \cos^2 \eta)}$$  \hspace{1cm} (1.8)
Figure 1.2: Scheme of Compton Scattering process. The incoming photon (blue; energy \( E \), polarization \( \vec{p} \)) scatters off a free electron deviating (red; energy \( E' \)) by an angle \( \theta \) from its original trajectory. \( \eta \) is the angle between the infall polarization and the outfall direction. \( \xi \) is the azimuthal angle of scattering measured with respect to the detector X-axis.

where \( r_0 \) is the classical electron radius, \( \theta \) is the angle between photon infall and outfall direction, and \( \eta \) is the azimuth angle between the infall polarization and the outfall direction.

The method commonly applied to measure the degree of linear polarization of hard X-ray photons is based on Compton scattering. The cross-section of a hard X-ray photon to interact with a free electron (see figure 1.2) is given by the Compton scattering cross section as described by the Klein-Nishina equation:

\[
\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2} \left( \frac{E'}{E} \right)^2 \left( \frac{E}{E'} + \frac{E'}{E} - 2 \sin^2 \theta \cos^2 \eta \right),
\]

where \( E \) and \( E' \) are the initial and final photon energies, respectively, and the remaining variables have the same meaning as for the Thomson cross-section. The Compton and Thomson scattering are equivalent in the classic limit, when the photon energy is much smaller than the electron mass and there is conservation of photon energy (\( E' \cong E \)), in which case the Klein-Nishina formula reduces to equation 1.8. For a given angle \( \theta \) the Klein-Nishina cross section is highest for \( \eta = 90^\circ \), i.e. photons tend to scatter to the direction that is perpendicular to their initial polarization vector. Making use of that relation one can determine the level of linear polarization of hard X-ray photons by measuring the azimuthal distribution that they present when they scatter.
At energies above some tens of MeV the electron-positron pair production becomes a dominating process in the interaction of photons with matter. The cross section for pair production with a polarized photon can be written as [10]:

\[ \sigma(\delta) = \frac{\sigma_0}{2\pi} \left(1 + \Pi R \cos(2\delta)\right) \]  

where \( \sigma_0 \) is the total cross section for pair production, \( \delta \) is the angle between the electron-positron plane and the incident direction of the photon electric vector. \( \Pi \) is the initial polarization degree of the photons and \( R \) specifies the asymmetry ratio for the pair creation process. The typical construction of pair production polarimeters makes use of layers of heavy element materials maximizing the probability of pair production. They are followed by position sensitive detectors that measure the electron and positron tracks.

As explained in §1.1, a flux of photons is said to be polarized when their polarization vectors are preferentially aligned in a certain direction. For each of the above processes, the angular distribution of the measured observable, either photon or electron, is a function of the azimuth angle cosine [11]. The azimuthal distribution of polarized photons is also called modulation curve and presents the form of the curve shown in figure 1.3. To study the ensemble of photons that constitute the measured flux, let us introduce the new variable \( \xi \), which is the azimuthal scattering angle measured with respect to the X-axis of the laboratory reference system (see figure 1.2). The angle \( \eta \) presented in equations 1.8 and 1.9 is the scattering angle of each individual photon defined with respect to the photon polarization vector, which may be different for the thousands of photons involved in the flux. Using \( \xi \) to construct the modulation curve establishes the overall reference system. Since from a polarized flux the largest number of photons should be scattered at \( \eta \sim 90^\circ \), the minimum of the modulation curve constructed with \( \xi \) corresponds to the most frequent orientation of the photons polarization vectors, i.e., the polarization angle of the incoming flux. Frequently, \( \xi \) is not defined in the literature, and the variable used to construct the modulation curve is said to be \( \eta \). Notice though that \( \xi \), as defined in figure 1.2, is a variable that we can measure for each photon individually, while \( \eta \) is not, unless we already know the direction of polarization of each incoming photon.

The modulation curve can be fitted with the following function:

\[ f(\xi) = A \cos (2(\xi - C + \pi/2)) + B \]  

where \( A, B, \) and \( C \) are the fitting parameters. The polarization angle \( (\phi_\Pi = C) \) of the incoming flux corresponds to the phase of the modulation curve fit.

The main experimental challenge is to obtain the modulation curve with the highest possible accuracy. Polarimetric capabilities of any instrument based on the measurement techniques described above are determined by a single parameter called modulation factor. The modulation factor is extracted from the parameters \( A \) and \( B \) from equation 1.11 as:
Figure 1.3: Ideal modulation curve pattern from the Compton scattering of polarized photons.

\[ \mu = \frac{A}{B} \]  

(1.12)

It describes the response of the polarimeter to a photon flux with a polarization degree of \( \Pi \). Given a maximum modulation factor for fully polarized photons \( \mu_{100} \), the degree of polarization \( \Pi \) (also called level of polarization) of the incoming photons is equal to:

\[ \Pi = \frac{\mu}{\mu_{100}} \]  

(1.13)

The polarization degree is defined as a positive quantity with a non-Gaussian statistics spanned between 0 and 1. For a given source counting rate \( R_{\text{src}} \) and background counting rate \( R_{\text{bg}} \), the Minimum Detectable Polarization (MDP) at the significance level \( n_\sigma \) is defined as:

\[ MDP = \frac{n_\sigma}{\mu_{100}} \sqrt{\frac{R_{\text{src}} + R_{\text{bg}}}{T}} \]  

(1.14)

where \( T \) is the observing time. Another quantity used to characterize an operational performance of the polarimeter is its figure of merit, defined as the product of the effective area of the detector and its response to 100% polarized photons \( (A_{\text{eff}} \cdot \mu_{100}) \).

The modulation factor derived from analytical calculations using the Compton cross section formula overestimates in most cases the instrumental one. The rea-
son for it lies in the extreme difficulty of including all polarimeter aspects into the analytical calculation. Therefore, the determination of the polarimeter 100% modulation factor ($\mu_{100}$) and its effective area ($A_{\text{eff}}$) must rely on both Monte Carlo simulations and laboratory calibrations.

Polarization sensitive codes of photon tracking (e.g., GEANT4 [12], EGSnrc [13] or MCNP [14]) are necessary for the construction of the instrument mass-model. Together with an accurate description of the geometry and materials that constitute the instrument and its surroundings (spacecraft, balloon...), it is also important to introduce in the simulation the numerous sources of background that will affect the polarimeter in the flight. The cosmic ray particles, the cosmic X-ray background, and the photons that arrive to the polarimeter either after being scattered in the materials of the spacecraft or in the Earth’s atmosphere are only some of the most significant examples of background that have to be considered.

Independently of the simulation packages chosen, it is always necessary to verify the Monte Carlo results with proper laboratory tests and calibration procedures. These tests have to be done in a wide range of energies paying special attention to the extremes of the spectral range designed for the polarimeter. The laboratory calibration of $\mu_{100}$, its angular variability as well as the effective area, detection thresholds or counting rate dependence etc., are essential for the polarimeter in-flight success. Studies must be done both with polarized and unpolarized beams, to properly verify the zero polarization response of the instrument and discover possible systematic effects causing false polarization patterns or responses. Synchrotron light is commonly used to obtain fully polarized photon fluxes. For somewhat lower levels of polarization a simple laboratory option is to build a setup where $\gamma$-rays from a radioactive source (e.g. Cs$_{137}$) are applied to the polarimeter after being Compton scattered in some material. The Compton process will partially polarize the reflected photons, with the maximum polarization level for the scattering angles around $90^\circ$. In addition, it is recommended to test the polarimeter in particle beams to study the influence of the background particles (e.g. protons from radiation belts and cosmic rays or neutrons from the nuclear reactions).

Both simulations and laboratory verification help in the elimination and correction of systematic effects and spurious signals. For example sensitivity variations between individual channels of the photomultiplier can be diminished after adjustment of their discriminator thresholds. For those effects which are inherent characteristics of the detector, a specific data analysis technique must be applied. An example is the pipellation effect, inherent to any pixelled geometry of the polarimeter. It can be eliminated by randomizing the position of the hit inside of each pixel, or by applying the decoupled ring technique. For further description of data analysis techniques useful in different situations see, e.g. [1].
1.3 Polarized sources in the Universe

Most of the emission processes leading to the creation of hard X-rays produce this radiation with some level of polarization. Their expected degree of polarization depends on the physical process involved in the photon emission, on the physical and magnetic geometry of the source, and on the conditions of the observation. Many of the astronomical objects that we detect at high energies are expected to be sources of polarized emission. Some of them are permanently present in the sky (persistent sources), while others appear only during a short time period suddenly disappearing afterwards (transient sources). We present here a brief description of some examples.

1.3.1 Solar Flares

Solar flares are explosions in the atmosphere of the Sun, which occur when a large amount of magnetic energy is suddenly released. The largest flares can release up to $10^{32}$ ergs and last from some minutes to more than 3 hours [1, 15]. Smaller flares are detected down to $10^{27}$ ergs. The magnetic energy is built up in active regions around sunspots. Both the number of sunspots and solar flares in the Sun depend on the overall solar activity. The largest number of sunspots and solar flares is observed in the maximum of the solar cycle, i.e. with a periodicity of $\sim$11 years. The structure of a solar flare can be very complex. Simplified models describe them as a simple column or as a semicircular loop joining two foot points, but multiple loops with three or more foot points are frequent.

During a solar flare radiation is emitted along the entire electromagnetic spectrum. In addition, as the magnetic energy is being released, particles including electrons, protons, and heavy nuclei are heated and accelerated in the solar atmosphere. The hard X-ray emission from solar flares has its origin mainly in the foot
points region, as shown in figure 1.4, and in the region just above the top of the loop. The foot points are regions where the plasma density is the highest, favoring electron bremsstrahlung and the subsequent production of X-rays [15]. The production of hard X-rays above the soft X-ray loop indicates that the magnetic field lines that continue above the flare top may open up to the interplanetary medium, allowing for energetic flare particles to easily escape.

The hard X-ray emission from electron bremsstrahlung can be highly polarized. Thermal distributions of electron velocities, even for temperatures of a few keV, result in small polarization values produced mainly by the conduction-driven anisotropy of the electrons in the primary source [16] with some contribution from photons backscattered in the photosphere. Higher polarization levels are expected from non-thermal anisotropic distributions of electrons that are accelerated in well-ordered magnetic fields. Many non-thermal models predict polarization levels > 10% (see chapter 2 of this thesis for more details, or e.g. [17] and references therein). The degree of polarization is usually a complex function of the strength and topology of the magnetic field. In addition the observed polarization degree is related to the photon directivity (i.e. the anisotropy of the emitted radiation), which depends both on the electron beaming parameters and on the viewing angle [18].

The first solar flare polarization measurements were done in the seventies at energies around 15 keV [19–21] using polarimeter instruments on board of several Intercosmos satellites. Although initial results [19] showed a linear polarization of around 40% ± 20%, the later flare measurements [20, 21] found polarization degrees always compatible with zero. Moreover, the data suffered from limited photon statistics and systematic errors related with the detector calibration.

Recent measurements at energies below 100 keV (ranges 20-40, 40-60 and 60-100 keV) have been performed with the SPR-N instrument on board of the Coronas-F satellite [22]. From a sample of 25 solar flares, one could determine the upper limits of the polarization degree from 8 to 40% (3σ). Only for the single case of the flare on 29 October 2003 a significant polarization degree was found. The polarization values increased from about 50% at energies 20 – 40 keV, up to more than 70% for the energy channel 60 – 100 keV.

The polarization characteristics of two X-class solar flares in the energy range between 200 keV and 1 MeV have been studied [23] using the RHESSI satellite. The two flares were observed on 23 July 2002 (close to the solar limb), and on 28 October 2003 (close to the solar center). The polarization degrees found were 21% ± 10% and -11% ± 5% in 1σ, respectively. Regarding the direction, they measured a radial polarization direction for the flare close to the solar centre, and an azimuthal one for the flare in the limb.

The results of the hard X-ray polarization analysis that we performed using the RHESSI data of the 23 July 2002 flare and six other strong solar flares will be
thoroughly described in chapter 2.

1.3.2 Gamma Ray Bursts

Gamma Ray Bursts (GRBs) are short flashes of $\gamma$-rays likely produced during the creation of a black-hole at cosmological distances. In a few seconds a huge amount of energy between $10^{51}$ and $10^{53}$ erg is released such that GRBs are the most violent explosions in the Universe. This prompt emission presents a great variability of lightcurves and its spectrum follows a broken power law function, often described using the Band model [24]. The Band model (equation 1.15) fits the spectrum using four parameters: an amplitude ($A$), the low- and high-energy spectral indexes ($\alpha$ and $\beta$, respectively), and the peak energy ($E_{\text{peak}}$) of the power density spectrum $\nu F_\nu$, which represents the total energy flux per energy band:

$$f(E) = A \begin{cases} (E/100)^\alpha \exp\left(-E/(2+\alpha)E_{\text{peak}}\right), & \text{for } E \leq (\alpha - \beta)E_{\text{peak}}^{2+\alpha}, \\ (E/100)^\beta \exp(\beta - \alpha) \left[ (\alpha-\beta)E_{\text{peak}}^{100}/(2+\alpha) \right]^{(\alpha-\beta)}/(\alpha-\beta)E_{\text{peak}}^{2+\alpha}, & \text{for } E \geq (\alpha - \beta)E_{\text{peak}}^{2+\alpha} \end{cases}$$

(1.15)

The flux in this equation is expressed in units of photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$, which are the units of the amplitude $A$.

After the prompt $\gamma$-ray emission has finished, a long lasting afterglow can be observed at various longer wavelengths. The current theoretical picture is that GRBs are produced when a massive star collapses at the end of its life or when two compact objects merge, giving birth in either case to a black hole. The collapsar scenario would be responsible for the long duration [25] and the merger scenario for short duration GRBs [26]. The separation line between short and long GRBs was traditionally taken at 2 seconds [27], but recently suggested rather at 5 seconds [28]. For recent reviews on GRBs, see e.g. [29–31].

Several theoretical models have been proposed to explain which processes are responsible for the GRB emission. In the standard synchrotron with random field model [32] (also called fireball model) the explosion produces a jet in which expanding baryon shells cause internal shocks when a fast shell overtakes a slower moving one. In these shocks relativistic electrons are accelerated, generating through synchrotron emission the X- and $\gamma$-ray photons that we see as the GRB prompt emission. The resulting photon polarization is typically low reflecting the hydrodynamic nature of the model. However, if the magnetic field in the shock is not completely random and the observer sees the jet from an off-axis angle, a high level of polarization (up to 80%) is possible [33]. In the synchrotron with ordered field model [34] (or electromagnetic model) the energy is extracted from the central engine by a rotation-created electromagnetic field, transported in a plasma to large distances by strongly magnetized wind, and dissipated through fast magnetic
reconnections that generate the GRB radiation. Photons emitted in this process can present polarization above 50%. The maximum level of polarization obtained from this model is 80%, attained in a particular model configuration [33]. In the compton drag model [35, 36] (or cannonball model) the γ-ray emission is generated by inverse Compton scattering of soft primary GRB photons that hit previously ejected material. The polarization level depends on the opening angle and Lorentz factor of the jet, predicting therefore all possible values between 0 and 100% polarization.

Although a single measurement might be in agreement with the predictions of the three theoretical models mentioned above, a statistical study of the polarization degree in a larger sample of GRBs can distinguish between different models [33]. Therefore, precise polarimetry measurements of the GRB prompt emission offer unique information on the emission mechanism of the GRBs and on the composition and geometric structure of their jets [7]. To date, only a few measurements of the prompt GRB polarization have been performed, all of them with instruments that had not been designed for this purpose and lacked in many cases a good characterization of their systematic effects, enough effective area, or good background rejection mechanisms for polarimetry. Using data from the RHESSI satellite an 80% ± 20% linear polarization level from GRB 021206 was reported [37], but disproved afterwards [38, 39]. By simulating the scattering of GRB photons off the Earth’s atmosphere, the polarization levels of two BATSE bursts (GRB 930131 and GRB 960924) could be obtained [40] as >35% and >50% respectively, but the result could not be constrained beyond systematics. Also inconclusive were the two measurements [41, 42] obtained using INTEGRAL data from the GRB 041219A. Although they found a high level of polarization (~60% and 98% ± 33%, respectively) they could not statistically claim a polarization detection.

In view of the potential and the lack of precise polarization studies of GRBs, several X- and γ-ray polarimeters have been proposed and are under development. Some examples are given in §1.4.

1.3.3 Crab

The Crab nebula (see figure 1.5), located in the constellation of Taurus, is the remnant of a supernova observed by Chinese and Arab astronomers in AD 1054. At the center of the nebula lies the Crab Pulsar (PSR B0531+21), a neutron star rotating with a ~ 33 ms period, and emitting pulses of radiation in the range from gamma rays to radio waves. Its pulse profile is dominated by two pulses separated by a bridge phase interval, and followed by an off pulse region [43].

The polarization degree of the Crab nebula at low X-ray energies has been reported [45] as 19.2% ± 1.0% at 2.6 keV, and 19.5% ± 2.8% at 5.2 keV. In the energy range from 0.1 to 1 MeV the polarization of the unpulsed emission from Crab nebula was measured as 46% ± 10% by the SPI instrument onboard the INTEGRAL satellite [46]. Also onboard INTEGRAL, the IBIS telescope has been used to measure the polarization of the Crab between 200 keV and 800 keV, in different phase intervals [47]: the peaks, the off-pulse, and the bridge. The polarization signal was
found to be $47^{+19}_{-13}\%$ when considering the average over all the phase intervals.

### 1.3.4 Pulsars

Pulsars are rapidly rotating neutron stars whose rotational and magnetic axes are misaligned. A very intense and narrow jet of light is emitted from the magnetic poles. While the neutron star is rotating, an observer on the Earth sees a pulsed source with typically two peaks of intensity observed when each of the jets is pointing towards the Earth, in a similar way as when one looks at the light emitted by a lighthouse.

Several hundreds of pulsars have been detected to date, mostly in the radio wavelengths. Only a few tens of pulsars emitting high energy radiation are known, including the two most prominent gamma-ray galactic point sources, the Crab and Vela pulsars. Pulsars can be classified in three different categories: rotation-powered, accretion-powered, and magnetars. In the first case the loss of rotational energy powers the pulsar, while in the second case it is the accretion of matter at the star surface. Finally, magnetars are powered by the decay of an extremely intense magnetic field that makes them the most magnetic objects in the universe. Soft gamma repeaters, detected as transient sources with sporadic periods of high γ-ray activity, are thought to be a special type of magnetars.

Two main groups of theoretical models explain the production of γ-rays from pulsars: the polar cap and the outer gap models (see [48] and references therein). In the polar cap models particles are accelerated in the magnetic field near the polar caps of the neutron star. The high energy emission results from curvature radiation and inverse Compton-induced pair cascades in the presence of a strong magnetic field. An $\sim 80\%$ polarization degree is expected along the whole pulsation period.

Figure 1.5: Crab nebula, extracted from [44]. Left: Image of the Crab nebula in the optical, taken by Hubble. Right: A composite image of the Crab pulsar showing the X-ray (blue, Chandra), and optical (red, Hubble) images superimposed.
of the Crab pulsar according to the polar cap models. Concerning the outer gap models, the hard X-ray emission is produced by synchrotron emission or inverse Compton scattering in charge depletion regions developed in the outer magnetospheres, away from the magnetic poles. In this case photon-photon interactions lead to pair production and to the subsequent hard X-ray emission. The level of polarization of the Crab pulsar in this model is expected to vary along the pulsation period from zero values before the first pulsation peak and after the second pulsation peak, up to 40% to 80% in the bridge between the peaks. A third theoretical model exists, the so-called caustic model, which explains the pulsar profile as a combination of emission from both magnetic poles. It predicts for the Crab pulsar a high level of polarization close to 80% everywhere excepting the pulse peaks. Both the outer gap model and the caustic model fit well the pulse profiles observed for many pulsars by the Fermi-GLAST satellite. The polar cap model remains plausible for some pulsars [49]. Polarization measurements would allow to clearly distinguish between these theoretical models.

1.3.5 Active Galactic Nuclei

Active Galactic Nuclei (AGN) are the most luminous persistent sources in the universe. Located at the center of active galaxies, AGN are supermassive black holes that accrete material emitting most of its energy as optical and ultraviolet radiation, but producing as well high-energy radiation. AGN can appear as a variety of peculiar galaxies as quasars, Seyferts, and blazars. These various types differ in the characteristics of their emission spectrum, like their variability, the width of the emission lines, the presence or not of strong radio emission, etc. Although differences in the nature of the host explain some particular cases, i.e. Active Galactic Nuclei (AGN)-radio-quiet AGN, such variety of spectral shapes is thought to result mostly from looking at the same host through different angles of observation, as represented in figure 1.6.

The radio and optical emissions from blazars, expected to be produced by synchrotron radiation, have been found to be in most cases highly polarized. The X-ray and $\gamma$-ray emission is usually associated with electrons in either the jet or the accretion disk. Given the ordered geometry of both regions it would be natural for the blazar high energy emission to be also polarized. Spectral observations of the active galaxy Centaurus A have been successfully reproduced by a model of beamed hard X-ray emission being Compton-scattered off a cold electron cloud moving along the jet axis [51]. Using their model the authors predicted a high degree of polarization reaching up to 60% for energies below 300 keV but decreasing drastically for higher energies.

The degree of linear polarization expected from the hard X-ray photons emitted by an accretion disk has been theoretically calculated [52]. Low energy photons experience multiple times inverse Compton scattering off hot electrons from the accretion disk, until they reach hard X-ray energies and eventually get out of the disk. The degree of polarization of the emission depends on the optical depth of
the accretion disk, the angle of observation, and the true-absorption to scattering cross-section ratio. The radiation along the normal to the disk plane should be non-polarized due to the symmetry of the problem. For thick disks the absolute value of the degree of polarization is expected lower than 12%, while for optical thin disks it may reach up to 65%. Given the large difference between these two situations, the measurement of the hard X-ray polarization degree would provide an insight into the physical conditions present in the AGN.

### 1.3.6 Accreting Black Holes

In the same way as active galactic nuclei emit X-rays when absorbing matter from their accretion disk, black holes in our galaxy are expected to be bright sources of hard X-ray radiation. Some very bright galactic X-ray sources, like Cygnus X-1, are considered as black hole candidates. The same model applied to the AGN [52] can be applied to this kind of sources, predicting a high degree of polarization in the hard X-ray emission. In a different model of the Cygnus X-1, $\gamma$-ray emission was produced by thermal bremsstrahlung from a cloud of electron-positron pairs surrounding the black hole [1]. The optically thick accretion disk is separated from the pair cloud by an optically thin transition region. Polarization resolved observations should show a low degree of linear polarization from the disk, a higher polarization from the inverse Compton scattered emission of the transition region, and a low polarization from the unscattered thermal bremsstrahlung emission from the pair cloud.

Polarization measurements could be even used to detect black holes. Some models [53] predict that the orientation of the linear polarization should depend strongly on the energy of the radiation emitted by the accretion disk, due to the strong gravitational fields existent at the source. Such changes of the polarization angle would be difficult to explain by other means like inverse Compton scatter-
1.4 Instruments to measure polarization

Hard X-ray photons produced by astronomical sources are absorbed by the Earth atmosphere and cannot reach the Earth surface. Instruments aiming to measure any of the characteristics of these photons, such as their polarization, have to be installed on satellites. The choice of the polarimeter detection technique, the optimization of its parameters and the observation methodology depend both on the objectives of the project and on the constrains imposed by the satellite. This section illustrates the topic with several representative examples of already existing polarimeters.

1.4.1 Past and present polarimeters

1.4.1.1 SXRP and SPN-R

The Stellar X-ray Polarimeter (SXRP) [54] was designed for the SRG mission that has not yet been flown. It is a hybrid consisting of Bragg graphite crystal and low-Z lithium scatterer surrounded by imaging proportional counters (figure 1.7). The instrument covers the energy range from 2 keV to 20 keV. To reduce systematic
effects the polarimeter rotates around its optical axis. An extra anticoincidence shield minimizes the background counting rate. The SXRP has very high values of $\mu_{100}$ and $A_{\text{eff}}$: 99 % and 10 cm$^2$ for the Bragg and 71 % and 65 cm$^2$ for the Thomson processes, respectively. The polarimeter is well understood with thorough laboratory calibration and modeling. Its flight model is still waiting for the next flight opportunity. A similar Thomson polarimeter called SPN-R flies onboard of the Coronas-F satellite. Its scatterer is made of beryllium and is surrounded by three pairs of the CsI(Na) detectors. The active area ($A_{\text{eff}}$) of SPN-R is 1 cm$^2$ only. During five years, between 2001 and 2005 the instrument observed tens of Solar Flares. For only eight of them it was possible to provide just the upper polarization limits: $\Pi_{3\sigma} < 8 \%$ to 40 %.

1.4.1.2 COMPTEL and BATSE

The large area imaging Compton Telescope (COMPTEL) [55] and the Burst and Transient Source Experiment (BATSE) [56] were flown onboard of the NASA Cosmic Gamma-Ray Observatory (CGRO) mission, flying between the years 1991 and 2000. COMPTEL operates at energies from 0.75 to 30 MeV and consists of seven low-Z scintillators as scatterers (liquid NE213, $A=4188$ cm$^2$) followed by fourteen high-Z detectors (NaI(Tl), $A=8620$ cm$^2$) placed 1.5 m below the scatterer plane. Its Field of View (FoV) is equal to 1 sr but $A_{\text{eff}}$ is smaller than 20 cm$^2$ and $\mu_{100}$ is below 8 %. The instrument was not optimized for polarimetry and the analysis of several GRBs revealed very low statistics and serious systematic effects. Even polarimetric observations of the Crab nebula turned out to be impossible. BATSE, on the other hand, has eight large area NaI(Tl) detectors ($A=2000$ cm$^2$ each) placed at the spacecraft corners. It operated between 40 keV and 600 keV and had a full $4\pi$ FoV. BATSE was not a polarimeter but had good directional capabilities to localize GRBs. Polarization measurements of two GRBs, out of the $\sim$3000 observed by BATSE, was possible using the Earth albedo scattering (see results in §1.3).

1.4.1.3 RHESSI

The Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) [57] is a NASA-SMEX mission flying since 2002 and dedicated to make imaging and spectroscopic studies of the Sun at energies between 3 keV and 20 MeV (see §2.2.1 for more details). Its spectrometer, made of nine germanium detectors, is located in the plane perpendicular to the satellite rotation axis. Althought not primarily designed as polarimeter, RHESSI can be used as such in two different modes: passive and active. In the passive mode (30 keV to 80 keV) one measures polarization studying the photons that scatter in the Be-block (see Figure 1.8) and stop in the Ge-detectors surrounding it [11, 58]. In the active mode (100 keV to 2 MeV), the polarization information is extracted from the photons scattered between two neighbor Ge-detectors. As a polarimeter, RHESSI has a wide FoV, but a moderate $\mu_{100}$ and a small $A_{\text{eff}}$ (1 cm$^2$). RHESSI polarimetric capabilities are limited by the
Figure 1.8: The RHESSI spectrometer array with nine Ge-detectors and beryllium scatterer.

high levels of Earth-scattered photons and accidental background.

1.4.1.4 SPI and IBIS

The International Gamma-Ray Astrophysics Laboratory (INTEGRAL) is a European satellite launched in 2002. Its two main instruments, SPI spectrometer and IBIS imager, were not designed for polarization detection, but possess such capabilities [1]. The spectrometer has 19 large hexagonal Ge-detectors covering energies from 20 keV to 8 MeV. Its $\mu_{100}$ is moderate (20 %) but its large effective area reaches 50 cm$^2$. The IBIS imager has two detection layers with CdTl and CsI detector arrays. These detectors can be combined to work as a Compton telescope with $A_{\text{eff}} \equiv 100$ cm$^2$. The major problem of the INTEGRAL polarimetry is the lack of proper calibration of its modulation factors and a large uncertainty of the systematic and instrumental effects.

1.4.2 New polarimeters

In the past, most attempts to measure X- and $\gamma$-ray polarization suffered from various obstacles. The difficulties in the instrument construction and in carrying out the observations came in parallel with beliefs that the expected polarization levels should be quite low. These subjects have been recently challenged by the latest results from several instruments on satellites and by the new theoretical models. It caused a rapid development of novel polarimeters and the perfection of measurement techniques making use of the latest advances in the detection technology [17]. The modern gas micropattern detectors are used at low energies by XPOL [59], Mu-PIC or 1DPSPC [60]. Also the classic types like Thomson and crystal polarimeters are further developed and improved (XPE and PLEXAS [61]). Large
scintillator arrays are the core of the design in the classic Compton energy range for instruments like GRAPE [62], PoGOLite [48] and POLAR [63]. For polarimetry at even higher energies, either Si or Ge microstrip detectors are applied as for MEGA [64], TIGRE [65] and NCT [66] detectors. Novel semiconductor pixel detectors (CdTl, CdZnTl) are planned for the SGD and CIPHER polarimeters [67], and a time projection chamber filled with liquid xenon is adopted for the high energy polarimetry in the LXeGRIT detector [68]. For all the above instruments a large emphasis is given to maximize the values of $A_{\text{eff}}$ and $\mu_{100}$ and optimize the signal to noise ratio. Current developments and modern detection techniques are described below for three energy regions. For this purpose few novel polarimeters are selected as typical examples.

1.4.2.1 Energies up to 10 keV - XPOL (IXO)

New polarimetric techniques based on the photoelectric effect have been recently developed to study polarization at lower energies. An example of such instrument is the X-ray Polarimeter (XPOL)$^2$ under design for the ESA International X-ray Observatory (IXO) mission [59,69]. XPOL measures the tracks of the photoelectrons ejected from the atom after the absorption of the photon. From the angular distributions of the tracks one can deduce the photon polarization. At energies around 10 keV the length of the electron track in matter is very short. Thus, its precise visualization requires the micro-pattern gas detectors as a photon absorption medium. The image of the ionization pattern is made using a Gas Electron Multiplier (GEM) as represented in figure 1.9. In the typical operational energy range between 2 keV and 10 keV, the $\mu_{100}$ reaches values of about 50 %. The total active area of the GEM is $15 \times 15 \text{ mm}^2$ while its pixel size is of the order 50 $\mu\text{m}$.

$^2$Previously called Micro-Pattern Gas Detector (MPGD) [69], and Gas Pixel Detector (GPD).
The thickness of the gas chamber is about 10 mm only. For efficient operation the detector is mounted behind a large photon concentrator: the IXO mirror with 3 m² effective area. Further challenges are related with a precise modeling and advanced reconstruction techniques of the complex 3D electron tracks. Despite of such obstacles the prototype was constructed and its polarimetric potential has been successfully demonstrated [59, 70].

1.4.2.2 Energies around 100 keV - GRAPE, POLAR and PoGOLite

Not only the energies but also the field of view that a polarimeter has to cover depend on the sources that one would like to study. For persistent astronomical sources like Crab nebula a pointing instrument with a narrow field of view is preferable as its background levels are smaller. In the case of transient sources that can appear in any position of the sky, like GRBs, the field of view must be as large as allowed by external constrains related e.g. with the satellite or Earth shadow.

When a large FoV is required at energies around 100 keV, the classical design consists of an array of low-\(Z\) plastic scatterers where photons experience Compton scattering, and high-\(Z\) absorbers where they undergo photoelectric reaction. This is the concept of the Gamma-Ray Polarimeter Experiment (GRAPE) [62], constituted by a 64x64 array of plastic and Bismuth Germanate (BGO) scintillators (see figure 1.10). An alternative design is being developed for POLAR [63] (see chapter 3 for details), where all elements are low-\(Z\) plastic scintillators and Compton scattering is the main effect. In this case a photon produces usually several energy depositions and the two largest ones are selected to establish the azimuthal angle. Despite the difference in their designs, both GRAPE and POLAR detect photons in the range 50 to 500 keV with high \(\mu_{100} \approx 40\%\) to 60\% and large \(A_{\text{eff}} \approx 100\) cm². Both instruments have also very good off-axis performance that makes them perfect for GRBs polarimetry. The demonstration model of GRAPE has already...
been tested in a balloon flight and the proposal for a new space mission dedicated to the $\gamma$-ray polarimetry has been submitted to NASA.

The Polarized Gamma-Ray Observer - Light Weight (PoGOLite) [48] is a soft $\gamma$-ray polarimeter designed to study persistent sources. It is constituted by 217 well-type phoswich counters with fast and slow scintillators placed on top of BGOs (see figure 1.11). PoGOLite is able to accurately measure polarization in the energy range between $\sim 25$ keV and 80 keV within a very small FoV $\approx 1.25$ msr (FWHM), strongly reducing the impact of the background. Its good signal to noise ratio, together with its large effective area for polarization measurements ($A_{\text{eff}} \approx 228$ cm$^2$ at 40 keV), and its large modulation factor ($\mu_{100} \sim 33\%$) maximizes PoGOLite’s figure of merit ($A_{\text{eff}} \times \mu_{100}$). This instrument is suitable for long duration balloon flights with pointing capabilities. Within 6 hours it can reach a 10% polarization level from 200 mCrab sources. A small version of PoGOLite, the PoGOLite pathfinder (61 detector units), is scheduled to fly from northern Sweden in August 2010.

1.4.2.3 Energy around and above 1000 keV - MEGA

Astrophysical $\gamma$-ray polarimetry at energies where electron-positron pair production starts to dominate is to date fully untouched. Negative analysis of data from both the COS-B and the EGRET CGRO instruments in the past as well as a limited sensitivity of the present Fermi-GLAST mission indicate high levels of difficulty. In order to succeed, the future instruments have to assure very high detection efficiency and superior tracking precision. Both parameters are intensely optimized for the Medium Energy Gamma-Ray Astronomy Experiment (MEGA) [64, 71]. This instrument consists of a silicon tracker and a calorimeter made of the three-dimensional CsI(Tl)/PIN diode arrays as shown in figure 1.12. The pro-
The 4\(\pi\) anticoincidence shield reduces the charged particle background.

totype tracker is made of 11 layers of double-sided silicon strip detectors (wafers, 6\(\times\)6 cm\(^2\) each), being each layer built as a 3\(\times\)3 wafer matrix. The tracker for the flight model is planned to contain 32 layers with 36 wafers each. MEGA operates between 0.4 MeV and 50 MeV although measurements of polarization (at least with Compton scattering) are feasible only up to 5 MeV. The \(\mu_{100}\) values, measured with the prototype detector using the Compton mode, span between 17% at 0.7 MeV and 6% at 5 MeV [72]. The instrument has a large field of view accepting polar angles below \(\sim 50^\circ\) and is equipped on the sides and on top with an anticoincidence shielding. Its dimensions of 1.2 m width and 1.3 m height are relatively large in comparison with the other polarimeters mentioned. Nevertheless, it would be a suitable polarimeter for both a satellite mission and a long duration balloon flight.
Chapter 2

X-ray polarization of solar flares measured with RHESSI

The degree of linear polarization in solar flares has not yet been precisely determined despite multiple attempts to measure it with different missions. The high energy range in particular has very rarely been explored, due to its greater instrumental difficulties. We approached the subject using the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) satellite to study 6 X-class and 1 M-class flares in the energy range between 100 keV and 350 keV.

2.1 Introduction

Measurements of the linear X-ray polarization in solar flares can provide essential information needed to identify the processes responsible for the acceleration of particles and the emission of radiation. For photon energies in the hard X-ray region, polarization is produced either through electron bremsstrahlung or Compton scattering. The degree of polarization is usually a complex function of the strength and topology of the magnetic field.

Starting in the late seventies, several non-thermal models of X-ray emission from solar flares were developed (see [11] and references therein). Generally the authors assume a uniform magnetic field perpendicular to the solar surface and electrons being accelerated towards the chromosphere [73–77]. These electrons, spiraling downwards along the magnetic field lines, produce bremsstrahlung radiation in collisions with hot plasma. The polarization in the emitted X-rays is a function of the energy spectra of the electrons, their pitch angles (angle between their velocity vector and the magnetic field), and the column density distribution of the ambient plasma. Studying the spectral characteristics of the detected X-rays provides information about the electron energies, while the polarization is a very sensitive tool to sample the electrons pitch angle distribution. Both for very small pitch angles, corresponding to high electron beaming, and for very large ones, the polarization degree can be equally high. The two cases can be distinguished by

31
their polarization direction: parallel and perpendicular to the magnetic field line, respectively. The predicted polarization values can reach up to 60% at energies above 50 keV, being even higher at low energies [74]. After introducing more realistic pitch angle distributions and taking into account photon backscattering processes in the photosphere, the expected polarization is reduced down to 20% or 30% [75, 76].

Several more complex non-thermal models have been developed as well. In one of them the magnetic field structure was defined as a semicircular loop anchored in the chromosphere [78]. This approach allowed studying the X-ray emissions separately from different parts of the loop. The highest polarization could be produced at the top (up to 85%), while the photons observed from the foot-points (in the region of the dense chromosphere) would be polarized to the level of around 20%.

In general, lower energies are predicted to yield stronger polarization signals [74, 76, 78], although the strength of this relation can vary depending on the model. In some recent theories an opposite trend has also been reported [77]. Experimental verification is usually difficult because the low-energy part of the spectrum is strongly contaminated by a non-polarized thermal emission.

In all the cases the observed value of flare polarization is strongly dependent on the viewing angle. The highest polarization values are expected for large angles of view, when the line of sight is perpendicular to the magnetic field line. Thus, most theories predict higher polarization for flares located near the solar limb. Similar behavior is also expected for the directivity of the flare emission: the intensity of the emitted radiation should depend on the angle of view [79, 80]. Constraints related to the model assumptions favor two possible directions of the polarization vector: either parallel to the plane defined by the magnetic field lines and the line of sight or perpendicular to it [76–78].

Contrary to the intense theoretical work, only a few polarization measurements have been conducted in hard X-rays (see §1.3.1). In this energy range, the commonly used technique is based on Compton scattering [1]. In measurements of solar flare polarization with RHESSI, Compton scattering can occur in a specially installed beryllium scatterer. This method can only be used at low energies (20–100 keV). Its details, together with RHESSI’s polarimetric features, are described in references [11] and [58]. In this thesis, we present results in the energy range from 100 keV to 350 keV, obtained for seven solar flares (X and M classes) also selected from the RHESSI instrument database. We used a method based on the scattering of photons from detector to detector of RHESSI that has previously been applied for polarization studies of gamma ray bursts [37–39].

In §2.2 we explain how RHESSI can be used as a Compton polarimeter to study linear X-ray polarization at energies $\geq 100$ keV. The flares selected for analysis, and the criteria used for their selections are detailed in §2.3. Monte Carlo simulations were performed to calculate the response of the instrument, and their results are discussed in §2.4. The final polarization results are described and compared with previous measurements in §2.5. The interpretation of the results is done in
§2.6 by comparing with theoretical predictions. Finally, a brief summary of the conclusions of our work is given in §2.7.

2.2 Method description

2.2.1 Instrument

The Reuven Ramaty High Energy Solar Spectroscopic Imager [57] was designed to observe solar flares from 3 keV up to 17 MeV. It is capable of making spatially, spectrally and temporally resolved images of the Sun [81] using the rotation modulation principle [82, 83]. The spacecraft is rotating with a period \( T \approx 4 \) seconds. The RHESSI angular position in the solar coordinate system is calculated using the satellite roll angle, which is continuously monitored by the spacecraft aspect systems [84, 85].

The RHESSI spectrometer [86] consists of 9 cooled Germanium detectors which are split in a thin front and a thick rear segment. Low-energy photons are mostly stopped in the front segments while high-energy photons can pass through and reach the rear segments. The energy resolution is in the order of a few keV. The arrangement of the 9 detectors in the spectrometer is sketched in figure 2.1.

![Figure 2.1: RHESSI detectors seen from the Sun. The grey lines indicate the possible scattering directions in the RHESSI fixed coordinate system (§2.2.4).](image-url)
Each photon recorded by RHESSI is characterized by its arrival time, deposited energy, detector number and segment. These parameters are stored in the RHESSI event list. The time resolution of RHESSI is equal to one binary microsecond ($1\mu s = 2^{-20}$ sec).

Polarization measurements are possible using photons that are Compton-scattered from one detector into another one, making a signal in both of them. For such events, the effective area is very small, as most of the photons are either completely absorbed (in photopeak reactions) or scattered off the spectrometer [87]. Therefore, only a small percentage of all photons observed by RHESSI produces more than one entry in the event list. The fact that RHESSI rotates allows reducing the systematic errors in the polarization analysis.

### 2.2.2 Compton coincidences

The Compton scattering probability of photons on free electrons is given by the Klein-Nishina cross section (equation 1.9). The dependence of this cross section on $\eta$ is most pronounced if $\theta = 90^\circ$. As the RHESSI axis is pointing to the Sun, the detectors plane is perpendicular to the photon infall direction, and therefore $\theta \approx 90^\circ$ for detector-to-detector scattering.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time interval</td>
<td>Between 1 min. and 4 min. around the flare peak</td>
</tr>
<tr>
<td>Coincidence width</td>
<td>1 $\mu$s</td>
</tr>
<tr>
<td>Single event energy</td>
<td>$25 \text{ keV} &lt; E_i &lt; 300 \text{ keV}$</td>
</tr>
<tr>
<td>Coincidence energy (sum)</td>
<td>$100 \text{ keV} &lt; E_i + E_j &lt; 350 \text{ keV}$</td>
</tr>
<tr>
<td>Kinematical cut</td>
<td>$\theta = 90^\circ \pm 45^\circ$</td>
</tr>
<tr>
<td>Detector segments</td>
<td>Rear segments (without detector 2)</td>
</tr>
<tr>
<td>Pairs selection</td>
<td>Neighbor detectors</td>
</tr>
<tr>
<td>Multiplicity</td>
<td>Two-event coincidences only</td>
</tr>
</tbody>
</table>

Table 2.1: Selection of cuts introduced to extract Compton scattered photons from the event list.

In order to extract Compton scattered photons from the RHESSI event list, several cuts were applied (see table 2.1). As most of the high energy photons pass through the front segments without any interaction, only the rear segments were used for the polarization analysis. This condition ensures that Compton scattering events happen within the same $\mu s$ (see figure 5 and equation 8 from reference [39]). Detector 2 was not taken into account as it operates in a different way than the others [86].

When more than two events happen at the same time, information about the polarization direction is lost. Therefore we selected photons which were registered in exactly two detectors, calling them coincidences. Furthermore, only coincidences between neighboring detectors were chosen, due to the very low probability of direct scattering between remote detectors (see figure 2.1).
The sum of the two energies of the coincidence ($E_i$ and $E_j$) had to fall into our selected range between 100 and 350 keV. In addition, the energy cut imposed on the individual detectors was in the range 25–300 keV. Below this region, the detector noise and the level of accidental coincidences (see §2.2.3) increased very strongly. A final constraint was applied by introducing the so-called kinematical cut which excludes coincidences that are incompatible with Compton scattering, using the kinematical relation between the scattering angle $\theta$ and the observed energies. The kinematical cut was especially useful to reject photons scattered from the Earth atmosphere (see §2.4).

Applying the above cuts, we obtain a raw list of coincidences which is still contaminated by background events of different origin.

### 2.2.3 Background subtraction

Two major sources of background were taken into account in the following analysis. The first are accidental coincidences which occur when two independent solar photons are simultaneously detected. The second kind of background is not related to the flare itself but produced by cosmic rays and the cosmic gamma ray background.

The rate of accidental coincidences is proportional to the square of the incoming photon flux. In order to obtain the number of accidental coincidences ($N_{\text{acc}}$) we repeated the same procedure that was used to find the raw list of coincidences (table 2.1), but taking pairs of events which are time delayed by $20 \text{ b\mu s} < |t| < 30 \text{ b\mu s}$ [39]. As the typical detector dead time is in the order of several microseconds, the delay length was chosen to be longer than this. The rate of accidental coincidences over this range is approximately constant and was used for background subtraction.

The second kind of background was determined either before or after the flare. For this purpose we selected time intervals shifted by 18 orbits, i.e. 24 hours, before or after the flare peak. In this way, the spacecraft geomagnetic coordinates were similar (see first part of table 2.2 for an example), and the systematic effects coming from the background variations along the orbit were strongly reduced. Proper subtraction of this background requires some additional conditions: no other flare or high energy event should be present in that period, and the spacecraft operational status regarding attenuator state and decimation logic should be close to the one in the moment of the flare observation. The total number of background coincidences obtained in this way is denoted by $N_{\text{bg,tot}}$. The period selected for background subtraction contains a (usually negligible) number $N_{\text{bg,acc}}$ of accidental coincidences. It has to be subtracted from $N_{\text{bg,tot}}$ because it is already included in $N_{\text{acc}}$ calculated during the flare peak. The number of coincidences produced by the non-flare related background is then $N_{\text{bg}} = N_{\text{bg,tot}} - N_{\text{bg,acc}}$. As an example, the time evolution of the background signal observed one day before the 20 January 2005 flare is displayed together with the flare in figure 2.2. It reproduces very well the background levels observed before and after the flare peak.
Table 2.2: Geomagnetic coordinates of RHESSI satellite and numbers of coincidences determined at the peak of the flare on 20 January 2005 and during the background measurement period. The data collecting time was 240 seconds.

<table>
<thead>
<tr>
<th></th>
<th>PEAK OF FLARE</th>
<th>BACKGROUND</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starting time</td>
<td>06:43:00</td>
<td>06:42:59</td>
</tr>
<tr>
<td>RA(°)</td>
<td>-76.07</td>
<td>-80.26</td>
</tr>
<tr>
<td>Dec(°)</td>
<td>37.91</td>
<td>37.91</td>
</tr>
<tr>
<td>Total coincidences</td>
<td>43313 ± 208</td>
<td>5874 ± 77</td>
</tr>
<tr>
<td>Accidental coincidences</td>
<td>26907 ± 35</td>
<td>66 ± 2</td>
</tr>
<tr>
<td>Solar flare Compton scattering coincidences</td>
<td>10598 ± 225</td>
<td></td>
</tr>
</tbody>
</table>

Finally, the rate of Compton Scattering events was calculated for any time \( t \) according to

\[
N_C(t) = N_{tot}(t) - N_{acc}(t) - N_{bg}(t + \Gamma),
\]

(2.1)

where \( \Gamma \) is chosen such that both the geomagnetic coordinates and the orientation (roll angle) of RHESSI are in the background period as close as possible to the ones during the flare peak. \( N_{tot} \) is the number of coincidences in the flare peak according to table 2.1, \( N_{bg} \) is the corresponding number of background events from flare-unrelated photons, and \( N_{acc} \) is the number of accidental coincidences.

2.2.4 Polarization analysis

For each coincidence, the line connecting the two detectors involved in the Compton scattering process defines the angle used to construct the modulation curve. According to the RHESSI fixed coordinate system, there are four possible scat-
tering directions \(d\) (labeled \(0^\circ, 45^\circ, 90^\circ, \text{and} 135^\circ\)) between neighboring detectors (figure 2.1). In each direction, the number \(N_d(\tau_i)\) of coincidences per time bin \(\tau_i\) (with \(\tau_i = t_i \mod T\)) was divided by their sum in the same direction \((n_d(\tau_i) = \frac{N_d(\tau_i)}{\sum \eta_d(\tau_i)})\). Such normalization is needed in order to eliminate the dependence on the number of detector pairs which is different for each direction (see figure 2.1).

The RHESSI roll period \(T\) was measured using the spacecraft roll aspect system [84, 85] which provides the RHESSI angular position with an accuracy of 1 arcmin. We obtained the satellite rotation period for each flare using a linear fit. In order to verify its stability and check for possible drifts, \(T\) was calculated in 1 sec steps over a 720 sec interval containing the flare. The maximum variations between the measurements were below 1 ms, thus negligible comparing with the bin size used in the polarization analysis (\(\approx 167\) ms). It was also found that the drift of the period is smaller than \((2.1 \pm 2.0) \cdot 10^{-7}\). It corresponds to a change in the rotation period by less than 0.05 ms, giving an upper limit of \(0.53^\circ\) (3\(\sigma\)) on the possible phase shift for the longest time interval used in the analysis.

The asymmetry curve can be constructed as follows:

\[
A_{0-90}(\tau_i) = \frac{n_0(\tau_i) - n_{90}(\tau_i)}{n_0(\tau_i) + n_{90}(\tau_i)}.
\]

The coincidences occurring in the directions \(45^\circ\) and \(135^\circ\) were properly shifted and included in the equation above. Using asymmetry to determine the polarization minimizes the effect of the lightcurve variations. Grouping to have only two directions improves the statistics.

In order to relate the time variable \(\tau\) with angular directions in the Sun, we used the relation: \(\xi_i = -\frac{2\pi}{T} \cdot \tau_i + \xi_0\). By convention, \(\xi = 0\) corresponds to solar West, and \(\xi = \pi/2\) corresponds to the solar North. \(\xi_0\) is the angular position of RHESSI X-axis (0\(^\circ\) direction from figure 2.1) with respect to the solar West in the moment when measurement started. Through this coordinate transformation, we obtained \(A_{0-90}(\tau)\) in heliocentric coordinates: \(A(\xi)\).

Due to the sinusoidal dependence of the Compton cross section for the scattering of a polarized photon (equation 1.9), the asymmetry curve is also a sinusoidal function with period equal to a half of the RHESSI rotation. It can be represented by a function:

\[
A(\xi) = \mu \cdot \cos \left(2(\xi - \phi_{\Pi} + \pi/2)\right),
\]

where the amplitude \(\mu\) is a positively defined value equal to the flare modulation factor. The phase \(\phi_{\Pi}\) is the polarization angle from the flare (corresponds to \(C\) in equation 1.11).

Comparing the experimental amplitude \(\mu\) with the modulation factor \(\mu_{100}\) from Monte Carlo simulations for a 100% polarized flux (§2.4), allows to determine the polarization degree of the solar flare (\(\Pi\)) using equation 1.13. Two parameters,
Π and $\phi_{\Pi}$, fully describe the polarization state of a solar flare and are needed for comparison with theoretical predictions.

### 2.3 Flares selection

The following criteria were applied to select the flares for polarization analysis: large intensity, strong high energy component and negligible contamination with particles (either from the flare itself or from the radiation belts). Also, since theory predicts highest polarization close to the solar limb [75, 76, 78], we focused on limb-close flares. After applying all these conditions, we were able to select six X and one M class flares, five of them located within less than 120 arcsec from the solar limb (figure 2.3).

In order to study polarization in the most explosive part of the energy release,
only the peak of the flare was chosen (see figure 2.4). The time period for analysis varied between one and four minutes depending on the duration of the flare peak.

The spectrum of each flare was analyzed to find the energy ranges of different emission mechanisms. For this purpose, a fit was performed, using the RHESSI OSPEX fitting tool [88], with a combination of a thermal bremsstrahlung curve and a broken power law (figure 2.5). In all cases, the thermal contribution was found to be negligible at energies above 50 keV. For further analysis we selected the non-thermal bremsstrahlung region (100–350 keV). The spectral indices are given in table 2.3 and correspond to a single power law fit of that part of the flare. These values were subsequently used in the simulations performed to determine the instrumental response function and its polarization modulation factor (see §2.4). Although photons with energies between 50 and 100 keV are already in the non-thermal emission region, their interaction in the RHESSI detectors is governed by photoelectric absorption, leaving only a marginal number of Compton scattering events. On the high-energy side, the threshold value was chosen to avoid regions
Figure 2.5: Background-subtracted spectrum of the flare on 19 January 2005. The fit was made for energies between 12 keV and 600 keV combining a thermal curve and a broken power law. Thermal component is negligible above 40 keV, and the background becomes dominant around 500 keV.

dominated by background.

The main parameters that describe the flares selected are summarized in table 2.3.
<table>
<thead>
<tr>
<th>Flare number (RHESSI)</th>
<th>2072301</th>
<th>3110221</th>
<th>4111002</th>
<th>5011710</th>
<th>5011911</th>
<th>5012005</th>
<th>5082502</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start time</td>
<td>00:18:00</td>
<td>17:03:00</td>
<td>01:59:00</td>
<td>09:35:36</td>
<td>07:57:20</td>
<td>06:21:24</td>
<td>04:33:48</td>
</tr>
<tr>
<td>End time</td>
<td>01:15:44</td>
<td>18:00:36</td>
<td>02:36:52</td>
<td>10:38:48</td>
<td>09:03:32</td>
<td>07:27:04</td>
<td>04:55:56</td>
</tr>
<tr>
<td>Duration (s)</td>
<td>3468</td>
<td>3456</td>
<td>2272</td>
<td>3792</td>
<td>3972</td>
<td>3940</td>
<td>1328</td>
</tr>
<tr>
<td>Class</td>
<td>X4.8</td>
<td>X8.4</td>
<td>X2.6</td>
<td>X4.0</td>
<td>X1.4</td>
<td>X7.1</td>
<td>M7.0</td>
</tr>
<tr>
<td>(x, y) (arcsec)</td>
<td>(-875, -226)</td>
<td>(770, -320)</td>
<td>(716, 99)</td>
<td>(424, 312)</td>
<td>(689, 325)</td>
<td>(833, 245)</td>
<td>(-936, 120)</td>
</tr>
<tr>
<td>Radial distance (arcsec)</td>
<td>904</td>
<td>834</td>
<td>723</td>
<td>526</td>
<td>730</td>
<td>868</td>
<td>944</td>
</tr>
<tr>
<td>Start analysis</td>
<td>00:28:00</td>
<td>17:15:40</td>
<td>02:08:30</td>
<td>09:43:20</td>
<td>08:24:40</td>
<td>06:43:00</td>
<td>04:36:00</td>
</tr>
<tr>
<td>Analyzed interval</td>
<td>120</td>
<td>240</td>
<td>150</td>
<td>60</td>
<td>150</td>
<td>240</td>
<td>240</td>
</tr>
<tr>
<td>Counts (s⁻¹) (E &gt; 25 keV)</td>
<td>67421</td>
<td>126440</td>
<td>28296</td>
<td>50001</td>
<td>20798</td>
<td>128520</td>
<td>21804</td>
</tr>
<tr>
<td>Spectral index (100–350 keV)</td>
<td>3.1</td>
<td>3.5</td>
<td>3.4</td>
<td>3.8</td>
<td>2.9</td>
<td>3.2</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Table 2.3: Description of the main characteristics of the flares studied.
2.4 Simulations

Monte Carlo simulations have been performed to calculate the response of the RHESSI polarimeter to a 100% polarized solar flare. For this purpose, the exact mass model of the whole satellite and its germanium spectrometer has been constructed and implemented in the GEANT 3.21 simulation code [89]. The spacecraft was illuminated by a uniform beam of photons coming in parallel to the RHESSI rotation axis. Each incoming photon was tracked down to an energy of 10 keV and all energy depositions made on its path in any of RHESSI detectors were recorded. In this way a simulated event list was created and subsequently used to determine the modulation factors. The procedure to extract the modulation factors from the event list was the same as for the analysis of the solar flares (§2.2), but neglecting the accidental coincidences. We made two sets of simulations:

1. The modulation factors for 100% polarized emissions were determined for each flare using a photon energy distribution with spectral indices as given in table 2.3. The incoming photons were 100% polarized and their energy range was either 100–600 keV or 80–350 keV. It was found that the contribution from photons above 350 keV to the modulation curve in our energy range (100–350 keV) was negligible. An example of a modulation curve is shown in figure 2.6.

2. In the second case we took monoenergetic photons with 100% polarization at thirteen energies between 100 keV and 1000 keV (figure 2.7). The mean modulation factor of each flare was subsequently calculated by averaging the monoenergetic modulation factors. The weights used for the average were proportional to the number of coincidences per energy bin. $\mu_{100}$ is maximum around 170 keV. It decreases for lower energies due to the low
energy threshold (25 keV) which only allows detecting recoil electrons from photons scattered at very large angles. At such angles, the modulation factor of the instrument is very small, in accordance to equation (1.9). Above 170 keV $\mu_{100}$ diminishes with energy following the polarization sensitivity based on equation (1.9) for photons scattered around $90^\circ$. Using two exponential functions with properly chosen coefficients reproduces the above features in a simple way (see fit function in the capture of figure 2.7).

Both approaches gave the same results. For example, for the case of the 23 July 2002 flare, with an spectral index equal to -3.1, we obtained with the first method $\mu_{100} = 32.8 \pm 1.6\%$ and with the second one $\mu_{100} = 32.4 \pm 5.4\%$.

The analysis of the solar flare lightcurves from single detectors revealed periodic structures that can be attributed to photons reaching RHESSI after being scattered by the Earth’s atmosphere. The contamination of the modulation curves by such photons was computed with another set of Monte Carlo simulations. For this purpose a simplified system consisting of the satellite and the Earth with its atmosphere was constructed. The Earth was represented by a solid sphere with twelve layers of atmosphere extending up to about 50 km above the surface. The mass as well as the chemical composition of all the atmospheric sheets were equal, while the density varied in accordance with their height.

Simulations of Earth scattering were performed using unpolarized photons with spectral indices typical for the analyzed flares and their corresponding angular positions between RHESSI, the Earth and the Sun. The largest fraction of photons detected from the atmosphere was found when the Earth reached the angle of $90^\circ$ with respect to the RHESSI-Sun direction. In the energy range 100 keV-350 keV, up to 30% of the observed photons were coming from the Earth, producing a strong modulation in the single-event lightcurves (figure 2.8, solid line). The influence of
Figure 2.8: Simulations of scattering by the Earth’s atmosphere. The figure shows single events with energies between 100 keV and 350 keV arriving at the rear part of detector number 4. The solid line shows the total photon flux, while the flux coming directly from the Sun appears as a dashed line.

such photons on the asymmetry curves, extracted from coincidences, was much smaller. Most of the Earth scattering caused only accidental coincidences or did not pass the kinematical cut. Finally, the contamination of the modulation curves by the Earth-scattered photons was, in the worst case, less than 8%. Considering their low level and flat distribution along the modulation curves, the modifications of the measured modulation factors were negligible compared to the overall statistical error.

The presence of grids above the detectors could produce periodic structures also in the coincidence lightcurves and therefore this effect was carefully studied with Monte Carlo simulations. Those sources which are not in the center of the Sun are, during RHESSI rotation, intermittently obscured by the grids. This produces in their single-event lightcurves a modulated profile with $180^\circ$ periodicity [81] and such a pattern could be mixed up with the real polarization signal. Firstly, the lightcurve modulation is strongly reduced for high energy photons reaching the rear detectors. Secondly, the width of the angular bin used for polarization analysis is large enough to average all count-rate variations caused by the grid modulation. The lightcurve variations further cancel out since the grids of detector pairs used for coincidences are generally aligned in different directions.

We performed simulations of a flare situated in the solar limb where the grid effect would be the strongest. Fine grids have been approximated keeping the slit/slat width ratio while the coarse ones were exactly implemented. The modulation factor obtained for a non-polarized flux of $10^8$ photons in the 100-350 keV energy range and with a power law spectrum index of -3.1, was $2.5\% \pm 1.9\%$. This is similar to the signal measured from a non-polarized source situated in the center of the sun, where grids do not cause any modulation. Therefore, the grids effect can
be neglected.

Notice that due to the positivity of the polarization degree, even an unpolarized signal gives a non-vanishing amplitude in the asymmetry plot when applying to our analysis. From a 0% polarized simulated flare with around 8500 coincidences, we obtained a modulation factor equal to $(3.4 \pm 1.6)\%$.

2.5 Results

2.5.1 RHESSI polarization measurements

The asymmetry curves $A(\xi_i)$ are displayed in figure 2.9, together with the best fit of the function in equation (2.3). These curves have a periodicity of $T/2$ ($T$ equal to RHESSI rotation period). To improve the statistics, the second half of the asymmetry curves was added to their first half, plotting only the range $0^\circ$–$180^\circ$.

The degrees of polarization $\Pi$ were calculated using equation (1.13) with $\mu_{100}$ taken from simulations. The mean value of $\mu_{100}$ was 33.2% and its variations between different flares were below 1.1%. The resulting polarization degrees were found to be between 2% and 54%, with error bars varying from 10% to 26% at the 1$\sigma$ level (see table 2.4). The $\Pi$ values of all the flares are plotted versus the flare class in figure 2.10, where no significant correlation between these two quantities can be observed.
Figure 2.9: Asymmetry curves of all flares analyzed, extracted for photon energies between 100 keV and 350 keV. The thick lines show the best fits with the function from equation (2.3). The angle of the minimum in the fit curve indicates the flare polarization direction in heliocentric coordinates.
<table>
<thead>
<tr>
<th>Flare number (RHESSI)</th>
<th>Date</th>
<th>( N_{tot} )</th>
<th>( N_{acc} )</th>
<th>( N_{bg} )</th>
<th>( N_C )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2072301</td>
<td>23 Jul. 2002</td>
<td>7439 ± 86</td>
<td>2269 ± 10</td>
<td>1758 ± 42</td>
<td>3411 ± 97</td>
</tr>
<tr>
<td>3110221</td>
<td>2 Nov. 2003</td>
<td>34723 ± 186</td>
<td>21427 ± 31</td>
<td>5135 ± 72</td>
<td>8160 ± 202</td>
</tr>
<tr>
<td>4111002</td>
<td>10 Nov. 2004</td>
<td>3816 ± 62</td>
<td>506 ± 5</td>
<td>2047 ± 45</td>
<td>1262 ± 77</td>
</tr>
<tr>
<td>5011710</td>
<td>17 Jan. 2005</td>
<td>2142 ± 46</td>
<td>473 ± 5</td>
<td>733 ± 27</td>
<td>937 ± 54</td>
</tr>
<tr>
<td>5011911</td>
<td>19 Jan. 2005</td>
<td>5688 ± 75</td>
<td>783 ± 6</td>
<td>2784 ± 53</td>
<td>2121 ± 92</td>
</tr>
<tr>
<td>5012005</td>
<td>20 Jan. 2005</td>
<td>43313 ± 208</td>
<td>26907 ± 35</td>
<td>5808 ± 77</td>
<td>10598 ± 225</td>
</tr>
<tr>
<td>5082502</td>
<td>25 Aug. 2005</td>
<td>6139 ± 78</td>
<td>602 ± 5</td>
<td>3717 ± 61</td>
<td>1820 ± 100</td>
</tr>
<tr>
<td>( \mu_p ) (%)</td>
<td></td>
<td>33.0 ± 1.6</td>
<td>9.6 ± 4.5</td>
<td>151 ± 195</td>
<td>2 ± 14</td>
</tr>
<tr>
<td>( \mu_{100} ) (%)</td>
<td></td>
<td>32.4 ± 1.8</td>
<td>9.1 ± 3.9</td>
<td>96 ± 12</td>
<td>28 ± 12</td>
</tr>
<tr>
<td>( \phi_\Pi ) (deg)</td>
<td></td>
<td>32.9 ± 1.7</td>
<td>11.7 ± 8.6</td>
<td>104 ± 24</td>
<td>36 ± 26</td>
</tr>
<tr>
<td>II (%)</td>
<td></td>
<td>33.4 ± 1.9</td>
<td>9.4 ± 8.2</td>
<td>71 ± 29</td>
<td>28 ± 25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>31.6 ± 1.5</td>
<td>17.1 ± 6.5</td>
<td>170 ± 11</td>
<td>54 ± 21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>34.4 ± 1.6</td>
<td>7.2 ± 3.3</td>
<td>66 ± 14</td>
<td>21 ± 10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>34.4 ± 1.6</td>
<td>2.2 ± 8.4</td>
<td>102 ± 104</td>
<td>6 ± 25</td>
</tr>
</tbody>
</table>

Table 2.4: Summary of polarization results for the flares studied. \( \mu_p \) is the observed modulation factor. \( \Pi \) is the polarization degree of the flare, and \( \phi_\Pi \) its polarization angle given in heliocentric coordinates.
The data do not show any preferential direction of polarization. When plotting the polarization angles of the flare sample in heliocentric coordinates (figure 2.11, left), the points appear to concentrate around the North-South solar direction but the error bars are too large to extract a firm conclusion. When the angle between the polarization direction and the line that joins the flare position and the center of the Sun was calculated, no tendency was found (figure 2.11, right).

Despite the very high single-photon count rates of more than 20000 counts per second, the mean number of Compton events found per flare was only around 4000, and the smallest one does not even reach 1000 coincidences. This reflects the small value of the RHESSI effective area for Compton polarimetry as discussed in §2.2. The signal-to-background ratio is on the average only around 0.5. Depending on the flare, the largest background contribution is produced either by accidental coincidences or by cosmic $\gamma$-ray background. The number of counts found with each flare are compiled in the first part of table 2.4, where the errors refer to $1\sigma$ and are purely statistical.

2.5.2 Comparison with other measurements

With respect to the polarization amplitude, our results are consistent with previous measurements made at higher energies by Boggs, Coburn, and Kalemci [23]. In the particular case of the 23 July 2002 flare that they also analyzed, our value ($2\% \pm 14\%$) is smaller than theirs ($21\% \pm 10\%$), but agreement is found at the $1.5\sigma$ level. The difference can be explained by the different time periods and energy ranges used in both cases. Extending the time and energy windows for our analysis towards the values selected by Boggs, Coburn, and Kalemci provide very similar polarization levels. The polarization angles of the two flares that they measured are aligned along the North-South direction in heliocentric coordinate system. However, these authors conclude that polarization is azimuthal for near-limb flares, but radial for those close to the Sun center. We can not confirm this rule from our observations (see figure 2.11, right). The values found in the present work are more uniformly distributed between $35^\circ$ and $85^\circ$, independently of the flare location. Taking into account the values of the error bars and the size of the statistical sample of analyzed flares, further measurements aimed to verify the observed disparity are needed.

Recent polarization data at energies up to 100 keV have became available from measurements with the SPR-N instrument on board of the Coronas-F satellite [22]. From a sample of 25 solar flares, upper limits on the polarization degree were found to be in the range from 8 to 40\% ($3\sigma$). These values are in good agreement with our results (typically within $2\sigma$). In particular, for the flare on 20 January 2005, observed simultaneously by both satellites, the polarization value from RHESSI observations was equal to $21\% \pm 10\%$ while the upper limit in the Coronas-F measurement was equal to 17\%. Again, a more direct comparison is not possible because both the energy range and the time intervals analyzed were different. For one flare (on 29 October 2003), the Coronas-F instrument showed a significant po-
Figure 2.10: Results on the degree of polarization, with their $1\sigma$ error bars.

Figure 2.11: Polarization degree vs. polarization angle plotted in two different reference systems: with respect to solar equator (left) and with respect to the radial line that joins the center of the Sun and the flare position (right).
larization degree that increases from about 50% at energies 20–40 keV, up to more than 70% for the energy channel 60–100 keV. Unfortunately, RHESSI polarization analysis of the 29 October 2003 flare was not possible due to a high contamination of its detectors with charged particles.

2.6 Interpretation

Our results were compared with theoretical predictions for the non-thermal photon emission given by references [76] and [78], and also with the 0% polarization hypothesis. Bai and Ramaty [76] provide the most comprehensive set of theoretical data, covering the whole energy range from 10 to 500 keV. These authors considered primary X-ray emission due to bremsstrahlung of the accelerated electrons moving towards the photosphere, adding also the X-ray Compton backscattering component. The photon polarization was studied for different electron spectra and pitch angle distributions and results were presented as a function of the observing angle. At energies around 200 keV, typical for our analysis, the polarization reaches maximum values between 20 and 30% and decreases quickly for flares located closer to the solar center. Taking this trend into account, the predicted polarization degrees for our sample of flares range from -19% to 1%, where the negative sign indicates a polarization direction parallel to the magnetic field, and the positive one perpendicular to it.

Leach and Petrosian [78] analyzed emissions from more complex, loop-shaped magnetic fields, but most of their polarization prediction is given only for two energies: 16 and 102 keV. As the dependence of the polarization on the energy was weak, we extrapolated their values towards our energy range. The highest polarizations for large energies are expected to come either from the top of the flare loop, or from the transition region above the chromosphere. The latter option roughly corresponds to RHESSI observations in which the high-energy emissions come from the foot-points. Nevertheless, a clear distinction between chromospheric and transition zone emission was not possible. Leach and Petrosian [78] proposed several models depending on the magnetic field gradient, the electron pitch angle distribution and the spectral index. We selected three different cases for comparison purposes: one with a homogeneous magnetic field and a uniform distribution of the electron pitch angles (model 3), another with equally homogeneous magnetic field but pitch angles close to 90° (model 5), and the last one with a large magnetic field gradient and large pitch angles (model 8). After correcting for the flare position on the Sun, the expected polarization degrees of our flares are in the ranges between -7% and 18% for model 3, from -45% to -80% for model 5, and from -6% to 23% for model 8.

The latest theoretical work on polarized emission, with the most advanced electron beam dynamics, was presented by reference [77]. Polarization calculations were done only up to 100 keV (for photon spectral indices typical to our flares), and showed increased values for higher energies. Their predictions, extrapolated to
Table 2.5: Reduced $\chi^2$ from all the flares combined, obtained by comparison of several theories with our measurements.

<table>
<thead>
<tr>
<th>MODEL</th>
<th>Reduced $\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[76]</td>
<td>1.03</td>
</tr>
<tr>
<td>[78] (model 3)</td>
<td>0.86</td>
</tr>
<tr>
<td>[78] (model 5)</td>
<td>2.70</td>
</tr>
<tr>
<td>[78] (model 8)</td>
<td>0.83</td>
</tr>
<tr>
<td>0% polarization</td>
<td>0.82</td>
</tr>
</tbody>
</table>

The energy range used in the present work, are similar to those from reference [76] and cannot be distinguished by the following $\chi^2$ analysis.

The comparison of our observations with the models was done by generating asymmetry curves for the flares polarized in accordance with the theoretical predictions. Monte Carlo simulations were performed for each flare individually, using exactly the same RHESSI mass model as in §2.4. The expected polarization angle and amplitude were properly determined by adjusting the theoretical predictions to the flare position on the Sun. The high number of simulated events allowed to keep the statistical errors on a very low level comparing with the experimental data. Finally, the reduced $\chi^2$ value was calculated using the data points from all seven flares as given by equation (2.4).

$$\chi^2 = \frac{1}{n(m-1)} \sum_{i=1}^{n} \sum_{j=1}^{m} \frac{(N_{i,j}^e - N_{i,j}^t)^2}{(\Delta N_{i,j}^e)^2 + (\Delta N_{i,j}^t)^2}, \quad (2.4)$$

where $i$ is the flare number and $j$ is the angular bin in the asymmetry plot. $N_{i,j}^e$ and $N_{i,j}^t$ are the experimental and theoretical numbers of coincidences respectively, and $\Delta N_{i,j}^e$ and $\Delta N_{i,j}^t$ are their statistical uncertainties. The total number of degrees of freedom was equal to 77. The results for all four models and the 0% polarization hypothesis are displayed in table 2.5.

From the $\chi^2$ values of table 2.5 we can reject the model 5 from reference [78], with a 90% of confidence. For the rest of the models the $\chi^2$ are very close to unity, preventing us from distinguishing between them. Within the error bars, they all agree with the experimental data equally well. The same is also valid for the 0% polarization hypothesis. Further refinement would require a polarimeter able to deliver data with error bars on the level of 1–2 percent.

2.7 Summary and conclusions

Measurements of hard X-ray polarization have been performed for six X-class and one M-class flares from the RHESSI database. Our flare sample was identified after applying selection criteria to the signal strength, background levels and level of contamination by charged particles in RHESSI detectors. The selected energy
range, from 100 to 350 keV, connects the old [19–21]) and new [22] results at low energies with the only measurement reported at a high energy band [23].

We found values for the polarization degree in the range between 2% and 54%, with statistical errors from 10% to 26% at the 1σ level. The polarization angles are distributed between 66° and 170° in heliocentric coordinates. They do not show any preferential orientation of the polarization, neither parallel nor perpendicular, with respect to the radial direction defined by the position of the flare in the Sun. In addition, no significant dependency between the orientation of the polarization and the distance of the flares to the Sun center was found.

The polarization orientation with respect to the line that joins the two major foot-points of the flare was also studied. For this purpose, images of the flares were constructed with RHESSI at different energies. The emission above ~30 keV was found to be produced around the foot-points. However, no correlation between polarization direction and foot-points orientation was found. Similarly, no relationship between solar flare intensity and polarization degree could be observed.

The polarization degree from the 23 July 2002 flare measured by Boggs, Coburn, and Kalemci [23] at high energies is in agreement with our results at the 1.5σ level. Their conclusion about the orientation of polarization respect to the radial direction passing through the flare position (perpendicular to it for flares in the limb and parallel for flares close to center) cannot be confirmed by our measurements. Our angles are distributed between 35° and 85° independently of the flare location. Comparison with theoretical predictions is more complex, as the direction of the polarization is expected by the theory to change around 300 keV [76]. Again, more observations with better accuracy are needed.

Regarding the low energy measurements, our data are in good agreement with the recent results from the SPR-N instruments on board of the Coronas-F satellite [22], typically within 2σ. Their large sample of 25 solar flares reveals low polarization degrees, providing 3σ upper limits from 8 to 40%. Unfortunately, no information is given about the polarization direction. In the 29 October 2003 flare, for which the Coronas-F team claims a polarization of 70%, RHESSI measurements were contaminated by charged particles.

Theoretical predictions of the non-thermal bremsstrahlung emission provide polarization levels of the order of 20%. However, depending on the assumptions used by different authors, the expected polarization can differ not only by its value, but also by its orientation (see, for example, the calculations at 100 keV from references [76] and [78]). As the statistical uncertainties provided by our instrument are in the same order as the model predictions, equally good agreement is found for any of them as well as for the case of 0% polarization. In order to distinguish between different models, polarimetry measurements of at least 2% accuracy are needed. Only model number 5 from reference [78], predicting polarization up to 85%, could be rejected by our RHESSI data. In this model, the magnetic field has the same strength at the top and the bottom of the loop, and the electrons spiral at pitch angles close to 90°.
RHESSI has made the first steps towards the understanding of the polarization phenomena in solar flares above 100 keV, where non-thermal emission dominates. Measurements with accuracy better than 10 to 20% were, however, hardly possible. This is due to its small effective area and high levels of flare-induced background. Continuation of such studies will require a dedicated polarimeter that must solve the problems inherent to the RHESSI design. Emphasis should be put on increasing the effective area and improving the background rejection capabilities. In particular, a better time resolution will reduce the number of accidental coincidences, and the optimization of the detector dimensions will improve the detection efficiency for the Compton scattering.
Chapter 3

POLAR detector

The instrument POLAR [63, 90, 91] is being built to determine the linear polarization of the hard X-rays emitted during the GRBs prompt emission. For this purpose, the polarization of photons in the energy range between $\sim 50$ keV to 500 keV has to be measured. In §1.2 we explained that in this energy range the common approach to measure photon polarization is to make use of the Compton scattering principle. To optimize the probability of photons to interact via Compton scattering, the target of POLAR, i.e. the part of the detector where the incoming photons first interact, is constructed using low-$Z$ plastic scintillator.

The goal of a Compton polarimeter like POLAR is to accurately measure the azimuthal ($\xi$) distribution of the photons when they Compton scatter inside the detector. To measure the $(x, y)$ position of the photon interaction with enough precision, the scintillator target of POLAR is segmented in thin bars. POLAR will detect two hits from the same incoming X-ray photon when it interacts in one scintillator bar via Compton, and then in a second one via either Compton or photoelectric effect. Figure 3.1 shows how the angle $\xi$ is determined from the position of the two activated bars in POLAR. The exact position of the photon interaction inside the scintillator bar cannot be determined. To smooth out the pixellation effect, the position of the photon interaction is taken as a random value $(x_{\text{rand}}, y_{\text{rand}})$ between the coordinates of the bar walls. The angle $\xi$ is then:

$$\xi = \arctan \left( \frac{y_{\text{rand},2} - y_{\text{rand},1}}{x_{\text{rand},2} - x_{\text{rand},1}} \right)$$  \hspace{1cm} (3.1)$$

where the indices 1 and 2 refer to the two bars fired. Since the Compton scattering cross section is symmetric under the transformation $\xi \rightarrow \pi - \xi$, the two bars in the equation are interchangeable.

In a target made out of only low-$Z$ material, the incoming X-ray photons tend to scatter not only once, but multiple times. In the case that more than two bars are activated by the same X-ray photon, the two largest energy depositions are selected offline and their corresponding bars are used to calculate $\xi$. These two largest energy depositions are related with a large angle Compton scattering, which provides
direct information on the incoming polarization of the X-ray photon. Small angle Compton scattering processes, where the direction of the photon electric vector is not substantially modified, tend to leave small energy depositions in the target. Following this procedure, the $\xi$ angle is determined for every photon that interacts at least twice in the POLAR scintillator target, and used to construct the modulation curve, from which the polarization characteristics of the incoming flux can be determined (see §1.2).

![Figure 3.1: Geometry of the large angle Compton scattering between two scintillator bars of POLAR. $\xi$ is the azimuthal angle of scattering, measured with respect to the $X$-axis of the detector. This angle is correlated with the polarization $\vec{p}$ of the incoming photons, and is used to construct the modulation curve. The angles $\theta$ and $\eta$ are related to the Klein-Nishina formula (see equation 1.9). Finally, $E$ and $E'$ are the X-ray photon energies before and after the Compton Scattering process.](image)

Hard X-ray photons produced by GRBs cannot reach the ground because they are absorbed by the Earth atmosphere. Therefore, POLAR will be mounted onto a satellite flying at the top of the atmosphere. A flight opportunity for POLAR on the future Chinese Tian-Gong Space Station is currently under consideration. An alternative option of flying with the International Space Station is evaluated.

Any instrument devoted to observe transient sources is required to have a large Field of View (FoV) allowing to observe a portion of the sky as large as possible. A large effective area ($A_{\text{eff}}$) is desired for any kind of detector, but in the case of space-born instruments, it is always limited by size and weight constrains imposed by the carrying satellite. In addition, its launch inside a rocket and the strong tem-
The core part of the POLAR mechanical design [92] is its scintillator target (see figure 3.2), constituted by 1600 plastic scintillator bars wrapped in highly reflective material. The POLAR scintillator target is divided into 25 modules, each consisting of 64 scintillator bars, optical coupling, one Multianode Photomultiplier (MAPM) (H8500 from Hamamatsu [93]), and its corresponding front-end electronics, all together enclosed in a 1 mm thick carbon fiber socket (see figure 3.2, left). This modular concept, designed by the Département de Physique Nucléaire et Corpusculaire, University of Geneva, Switzerland (DPNC) mechanics group, gives a good mechanical stability and facilitates the interchange of modules during the testing phase of the detector. The 25 modules are kept in place with an aligning frame located at the bottom of the carbon fiber sockets. The overall volume of the target is \( \sim 30 \times 30 \times 30 \, \text{cm}^3 \), its mass \( \sim 30 \, \text{kg} \), and its power consumption below 50W. The whole target, together with the central computer, the power supplies and the rest of the electronics, is further enclosed in a 3 mm thick carbon fiber box that serves not only as container but also as shield against low energy charged particles.

### 3.1.1 The scintillation element

The plastic bars used to construct the POLAR scintillator target are made out of the scintillating material BC404 (Saint-Gobain [94]). The plastic scintillator material has been chosen because of its fast response and its low atomic number that favors Compton scattering as the interaction process for hard X-ray photons (see figure 1.1). In addition to that, BC404 has been widely used in particle physics experiments and its mechanical and chemical stability are well known, as well as its radiation hardness. The plastic scintillator absorbs hard X-ray photons and isotropically emits optical photons from the point where the X-ray interacted. The number of optical photons emitted is proportional to the energy deposited by the incoming X-ray, with a light yield of about 1 photon per 90 eV. In the case of BC404, the wavelength of maximum emission is 408 nm (see figure 3.3). In the right hand side of figure 3.3 we show the typical spectral response of the photomultiplier that we are using (H8500). Note that the scintillator maximum emission wavelength falls in the plateau region where the MAPM presents its maximum sensitivity. The main characteristics of the BC404 plastic scintillator have been summarized in table 3.1.

The scintillator bars were manufactured in the shape of square prisms with dimensions \( \sim 6 \times 6 \times 200 \, \text{mm}^3 \), which fit with the typical ranges of recoil electrons and match the pitch of the selected MAPM (6.08 mm). If an optical photon pro-
Figure 3.2: Schematic of POLAR detector. Left: Exploded view of one module from POLAR target. Right: Complete POLAR target, i.e., the assembly of 25 modules, with its approximate dimensions. The enclosure box has been cut to show the modules inside.

Figure 3.3: Left: Emission spectra of the plastic scintillator BC404, extracted from [94]. Right: Spectral response from the MAPM H8500, extracted from [93]
### Properties of BC404

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse Width, FWHM [ns]</td>
<td>2.7</td>
</tr>
<tr>
<td>Wavelength of maximum emission [nm]</td>
<td>408</td>
</tr>
<tr>
<td>Light attenuation length [cm]</td>
<td>140</td>
</tr>
<tr>
<td>Density [g cm$^{-3}$]</td>
<td>1.032</td>
</tr>
<tr>
<td>Refractive index</td>
<td>1.58</td>
</tr>
<tr>
<td>Ratio H:C atoms</td>
<td>1.100</td>
</tr>
</tbody>
</table>

Table 3.1: Main characteristics of the plastic scintillator BC404, manufactured by Saint-Gobain [94].

duced in a certain bar exits this bar with a large angle, it can be detected by the photocathode below a neighbor bar. This effect is often called *optical cross-talk* and can make it very difficult to identify the X-ray interaction position inside the scintillator target. With the scintillator bars in the above mentioned square prism shape the optical cross-talk was measured to be as high as 20%. To reduce the cross-talk it was decided to reduce the cross-section of the bottom end of the scintillator bars, shaping that part as a truncated square pyramid (see figure 3.4). For mechanical reasons also the top of the bars was shaped in the same way. To reach the right shape keeping a very good surface quality, a very fine polishing machine was used. The draw-back of this approach is that the number of photons collected at the MAPM photocathode decreases. With the shaped bars, a signal reduction of $\sim 30\%$ has been measured with respect to the prism bars. However, the cross-talk was measured to be $\sim 10\%$, what constitutes a 50% reduction when comparing with the non-shaped bars.

![Figure 3.4](image.png)

Figure 3.4: Scheme of the bottom of one scintillator bar shaped as a truncated square pyramid. The corresponding optical coupling, MAPM photocathode and glass window are also represented.
Let us define the *light collection efficiency* as the number of optical photons arriving at the MAPM divided by the number of optical photons originally produced in the X-ray interaction with the scintillator. The light collection of POLAR scintillator bars has been carefully studied as function of the distance from the photomultiplier, for different grades of scintillator surface polishing [95]. These studies have been performed at the Andrej Soltan Institute for Nuclear Studies, Poland (IPJ) using a 500 MBq Cs$^{137}$ source and two sample POLAR bars. Measurements with naked, roughly polished bars, showed variations in light collection efficiency between far ends of the bars exceeding one order of magnitude. Fine polishing of the bar surfaces reduced those difference to values in the order of 30%. Wrapping the bars with highly reflective foil further improved the result, obtaining finally differences of only 11% to 18% for finely polished, wrapped bars. This results were the reason for selecting the wrapping material for the POLAR scintillator bars presented in §3.1.2.

The procedure used to select the scintillating bars to be used for the construction of the POLAR target involves several criteria. First of all, all bars are subject to a careful visual inspection to reject those with macroscopic defects. Then the bar width is measured with a Vernier caliper at 6 points (3 per side, at the middle and close to both extremities), accepting only those widths between 5.90 mm and 6.00 mm. After that, the bar length is also measured and only those within the range 199.9 mm to 200.1 mm are kept. Finally they are cleaned with isopropanol and those with permanent spots are rejected. These steps are performed for all the scintillator bars at their arrival from the manufacturer.

### 3.1.2 The reflective wrapping material

The square prism length of each single plastic scintillator bar from the POLAR target is enveloped by a enhanced specular reflector (Vikuiti Enhanced Specular Reflector (ESR), 3M [96]) of 65 µm thickness, keeping a thin air gap between the foil and the scintillator surface. The air gap guarantees total reflexion for all angles below $68^\circ$ due to its lower refractive index, and the wrapping contributes by reflecting back into the scintillator some of the optical photons that had been refracted. The very high (98%) reflective index of the ESR relative to the ~ 80% of, for instance, standard aluminum foil, makes it the best choice for our purpose. After several tests, the wrapping procedure presented in figure 3.5 for the assembly of the POLAR modules has been selected. From the various techniques tested, this was the one technically easiest to perform, at the same time as it provides a good performance in terms of light collection. In this configuration the ESR is cut into $50 \times 192 \text{ mm}^2$ wide sheets (green lines in figure 3.5) and $6 \times 192 \text{ mm}^2$ thin strips (red lines in figure 3.5). The wide sheets are located between two neighbor columns, i.e. along 8 scintillator bars, and the thin strips are perpendicularly located in between single bars from neighbor rows. In this way a ESR sheet is present in all directions between the faces of neighbor bars. Although it was estimated that a mismatch between the thin strips and the bar surface could be up to
1%. measurements have shown that the cross-talk between neighbor bars does not significantly depend on the direction, indicating that there is not more light leakage between the thin strips than between the wide ones.

![Figure 3.5: Scheme of the Vikuiti ESR wrapping procedure: top view of the 64 bars (blue squares) of one POLAR module. Wide sheets are represented by the green vertical lines, while short strips are the horizontal red lines.](image)

The standard applications for which ESR foils have been developed use only one of the ESR faces. Therefore the manufacturer warranties the high reflective of one of the ESR faces ("good" side), while no data are provided for the other. To confirm the information provided in the ESR data-sheet and to characterize the unknown face of the foil we measured in the laboratory the reflectivity of both sides of the Vikuiti ESR sheets. Using a laser system (wavelength 470 nm) we obtained for both sides of the sheet values around 99%. The reflectivity has been measured at various incident angles between 15° and 70°. No angular dependance was found within the ∼ 1% systematic uncertainties. To study the aging effect on the ESR material a 1-year old ESR foil was also tested on its both sides. No difference was found with respect to the new sheets. Studies of the ESR reflectivity have been also performed with an ellipsometer [97] at a wider wavelength range between 200 and 1000 nm. For wavelengths above ∼370 nm we obtained reflectivity values higher than 98%.

### 3.1.3 The optical coupling

The optical coupling between the scintillators and the MAPM is assured by a 50 × 50 × 0.5 mm³ wide soft optical pad made of insulating and transparent silicon (Dow Corning DC93-500 [98]). The refractive index of the pad (n=1.41) matches quite well with the ones of the scintillator bars (n=1.58) and the borosilicate glass window of the MAPM (n=1.52). An alternative solution of directly gluing the scintillator bar to the MAPM window using optical cement was considered, but rejected.
since it would make the whole target assembly more sensitive to vibrations, to the
point that it could be damaged during the launch. The optical pad partially absorbs
the vibrations and protects the MAPM window from the impact of the scintillators,
at the same time as it reduces the risk of sparks between the MAPM photocathodes
and the Vikuiti ESR sheets.

3.1.4 The MAPM

The H8500 from Hamamatsu [93] (see left side of figure 3.6) is a Multianode
Photomultiplier (MAPM) developed mostly for Positron Emission Tomography
(PET) applications. However, its spectral response in the same energy range as the
BC404 scintillators, together with its relatively high quantum efficiency (24%),
its small dead space (11%), and its fast time response, make the H8500 ideal
for the POLAR application. The 64 pixels from the MAPM, each one with size
5.8×5.8 mm², are arranged in a 8×8 matrix. The main characteristics of the H8500
MAPM are summarized in table 3.2.

![Image of the H8500 MAPM from Hamamatsu.](image)

Figure 3.6: Left: Image of the H8500 MAPM from Hamamatsu. Right: Example
of uniformity map, as presented in the MAPM data sheet [93].

The sensitivity of each of the 64 anodes in one MAPM is not the same, due
to small differences in their construction. The right hand side of figure 3.6 shows
one example of uniformity map measured with a power supply of -1000 V, as
given by the MAPM data sheet. All values are normalized to the pixel with the
maximal gain, to which the value 100 is assigned. The factory predicts sensitivity
differences up to a factor 3 between channels. Our measurements in various of
the MAPM used for the POLAR tests have revealed differences up to a factor
2. The sensitivity differences can be at least partially compensated by applying
slightly different thresholds to their output signals (see §3.2.1.2). The final POLAR
uniformity map, including the variations of response between scintillator bars and
the whole electronic chain after the MAPM, has to be measured and taken into
account in the further data analysis.
### Properties of H8500

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of pixels</td>
<td>64 (8×8 matrix)</td>
</tr>
<tr>
<td>Pitch [mm]</td>
<td>6.08</td>
</tr>
<tr>
<td>Pixel active area [mm²]</td>
<td>5.8×5.8</td>
</tr>
<tr>
<td>Total volume [mm³]</td>
<td>52×52×27.4</td>
</tr>
<tr>
<td>Effective area [mm²]</td>
<td>49×49</td>
</tr>
<tr>
<td>Thickness of borosilicate glass window [mm]</td>
<td>1.5</td>
</tr>
<tr>
<td>Quantum efficiency</td>
<td>24 %</td>
</tr>
<tr>
<td>Wavelength of maximum sensitivity [nm]</td>
<td>400</td>
</tr>
<tr>
<td>Typical anode uniformity</td>
<td>1:2</td>
</tr>
<tr>
<td>Number of dynode stages</td>
<td>12</td>
</tr>
<tr>
<td>Gain</td>
<td>$1.5 \times 10^6$</td>
</tr>
</tbody>
</table>

Table 3.2: Main characteristics of the MAPM H8500 from Hamamatsu [93].

#### 3.1.5 Construction of one module

To fix the scintillator bars and properly align them on top of the MAPM photocathodes, two polyurethane guides (baffles) have been constructed. They present 64 holes in the shape of a truncated pyramid, to match with the scintillator bars profile (see figure 3.7). The baffle located at the bottom of the module aligns the 64 bars with their corresponding photocathodes at the same time as it holds the DC93-500 optical coupling and the MAPM in their position and decouples them from the scintillators weight load. The baffle at the top of the module warranties a better mechanical stability keeping the bars together and in place (see figure 3.8).

![Figure 3.7: Left: Picture of the two baffles from a POLAR module. Right: One POLAR module during its mounting process. The single bars are inserted in the baffle and ESR stripes are placed between them.](image)

The assembly of the 64 scintillator bars with the interstitial Vikuiti ESR foils,
kept together with kapton tape and held with the optical coupling and the MAPM by the two baffles, is further introduced in a 1 mm thick carbon fiber socket to form one POLAR module (see figure 3.8). The lower part of this socket contains as well the front-end electronics, connected to the MAPM. The carbon fiber socket is too thin to directly screw it to the overall POLAR enclosure. To have enough mass to fix the single modules to the rest of the POLAR structure a 4 mm thick carbon fiber plate has been located inside the carbon fiber socket, on top of the upper baffle (see figure 3.9). It will be attached to the socket and the outer enclosure with a steel screw. More details on the modules assembly process performed to build the POLAR target will be given in the following section (§3.1.6). The vibrations produced during the launch and the thermal expansion of the materials inside the carbon fiber socket could push the scintillator block with a strong force against the upper part of the socket and the MAPM window on the other end. To reduce this force a 3.4 mm thick ring-like cushion (*back seal*) is located between the fixation plate and the upper baffle. The carbon fiber plate with its screw and the back seal have been carefully simulated to study their influence on POLAR performance. When simulating a standard GRB (see §4.3.1) it was found that only few of the X-ray photons with energy below 100 keV interacted in the plate. The total number of hits recorded in the POLAR scintillator target with deposited energy above
5 keV was reduced by about 13%. However, the number of events in the modulation curve was only 1% lower, and the value of the modulation factor was the same independently of the presence or not of the plate and the back seal. In conclusion, the presence of these mechanical elements has no influence on the POLAR polarimetric performance, affecting only the detector response to low energy photons which do not contribute to the modulation curve.

Figure 3.9: Top: Scheme showing the plate used to fix the module to the external POLAR enclosure, and the back seal to absorb the impact from the scintillators block. The example shown here is for a one module assemble (POLAR demonstration model, see §3.3). The same technique will be used in the construction of the whole POLAR detector.

Some of the elements used in the construction of one POLAR module are shown in figure 3.10.

3.1.6 Assembling of the scintillator target

Once all the modules of POLAR are prepared, it remains to mount them in the overall structure to build the complete POLAR target. The modules are fixed with screws to an aluminum frame, placed in the lower part of the modules, which is responsible for holding the carbon fiber sockets together (see figure 3.11). There is a distance of \(\sim 4\) mm between the outer surface of neighbor sockets, because the side of the MAPM case is slightly larger than the 64 bar scintillator block. This separation, summed to the thickness of the two sockets (1+1 mm) and some unavoidable interstitial gaps, makes a total distance from scintillator block to neighbor scintillator block of about 7 mm.

The POLAR target is further placed inside the upper part of a carbon fiber box, to which the carbon fiber sockets are screwed (see figure 3.9 for an example with one single module). The lower part of the overall enclosure box, screwed to the upper one at the target aluminum frame, has room for the central computer, the
power supplies, and all the remaining electronics and cabling. According to the latest discussions with the Tiang Gong Space Lab group, a window will be open in the satellite wall to install POLAR. The aluminum frame will be fixed at the Space Lab opening so that only the POLAR scintillator target will be in the outer space (see right side of figure 3.11). The bottom part of the POLAR enclosure box, containing the front-end electronics, power supply, central computer, etc. will be in vacuum, but shielded by the outer cover of the Space Lab to limit temperature changes.

3.2 Electronics

The optical photons produced when a hard X-ray photon interacts with the POLAR scintillator target are collected at the MAPMs where they are transformed into electrical signals. These electrical signals have to be amplified and processed to extract all the information needed to measure the polarization characteristics of the incoming X-ray flux. In this section we describe the electronic elements that POLAR needs for such purpose.

The size and weight constrains of a space instrument like POLAR, together with the specific needs of the instrument, forced us to develop a specific electronic design for POLAR. The most important components of the POLAR electronics are the front-end, the Low Voltage (LV) and High Voltage (HV) power supplies, and the central computer. They will be connected with cables, and placed inside the lower part of the POLAR enclosure box, as shown in figure 3.11. In the same line as the POLAR mechanical design, the front-end electronic design has been developed in a modular way, in which the electric signal coming from each MAPM is processed by its corresponding front-end electronics, which is mechanically con-
Figure 3.11: Left: View of the POLAR detector. The whole target is enclosed in a carbon fiber enclosure box that is divided into two parts: an upper part to contain the target and a lower part containing the central computer, power supply and the rest of the electronics. The carbon fiber box is shown open and cut in half, to allow for visualization of the content. The aluminum frame holds the carbon fiber sockets together and serves as mechanical interface with the satellite. Right: Scheme showing the POLAR detector, mounted on the Tiangong Space Lab. Only the upper part of the detector (the scintillator target) is external to the Space Lab shielding.

3.2.1 Front-end electronics

The front-end [99] is the ensemble of electronic components that is directly connected to the MAPM. It is responsible of the signal readout from the corresponding POLAR module and implementing a simple trigger functionality at the module level, at the same time as it communicates with the central computer participating in the multi-module triggering. In addition, the front-end provides the MAPM with the appropriate HV. Since the front-end is part of the structure that electronically and mechanically connects the MAPM to the rest of the POLAR structure, issues...
like mechanical stability and heat conduction have been carefully taken into account during its design phase. The design of the front-end electronics has been supervised by the POLAR collaboration members from the Paul Scherrer Institute, Switzerland (PSI), the Andrej Soltan Institute for Nuclear Studies, Poland (IPJ), and the ISDC Data Centre for Astrophysics, Switzerland (ISDC), in collaboration with local electronic companies. The mechanical integration of the front-end electronics within the rest of the POLAR design has been coordinated by the DPNC mechanics group. In this thesis we will describe only the most important functions and characteristics of the POLAR front-end. The complete electronic schemes describing all the elements constituting the POLAR front-end are available in references [99–102].

The front-end consists of three Printed Circuit Boards (PCBs) superimposed and mechanically fixed to each other using side aluminum plates, as shown in figure 3.12. These plates serve also to transfer the thermal load coming from the MAPM and the one generated by the three PCBs. Since the front-end assembly is located inside the carbon fiber socket, its surface is limited by the MAPM surface. The front-end total volume is $\sim 52 \times 52 \times 26 \text{ mm}^3$. From upper to lower PCB, starting at the MAPM position, the three PCBs are named: High Voltage Divider PCB (PMTRC), Application-Specific Integrated Circuit (ASIC) PCB, and Interface PCB (IF PCB).

![Figure 3.12: Left: Exploded view of the assembly that constitutes the front-end electronics. Right: Picture of the front-end (shown here upside down).](image)

### 3.2.1.1 High Voltage Divider PCB (PMTRC)

The High Voltage Divider PCB (PMTRC) provides the HV for the MAPM and an Resistor-Capacitor (RC) coupling for its 64 outputs and its dynode signal. The MAPM is usually provided with a voltage divider chain, built in the base of the MAPM. The original Hamamatsu voltage divider chain contains active components, reason for which it is not recommended to use it in space. To avoid this problem, we have substituted the factory base by a custom voltage divider chain.
that does not make use of any active components, and which, contrary to the Hamamatsu base, is AC coupled and terminated. The PMTRC is connected to the bottom of the MAPM by about 80 tulip type connector pins. Figure 3.13 shows the upper (close to the MAPM) and lower (close to the ASIC PCB) layers of the PMTRC, as well as the PCB after integration with the MAPM.

Figure 3.13: High Voltage Divider PCB (PMTRC). Left: View of the upper layer of the PMTRC before the tulip type pins had been soldered. Middle: View of the lower face of the PMTRC, where most of the RC components are mounted. Right: View of the PMTRC connected to one MAPM, seen from the bottom. Here the tulip type pins and the two signal output connectors have been already installed. The red cable is the HV cable, soldered to the PCB.

The PMTRC receives the HV from the HV system through a cable directly soldered to the PCB, and distributes it to the MAPM. The signal coming from each of the 64 MAPM channels passes through a (50 Ω-100 pF) RC chain to remove the DC component of the signal. The clean 64 anode signals are transmitted, together with the ground lines and a common dynode signal (analog sum of the 64 channels), to the next stage of the front-end via two identical 40-pin connectors.

The PMTRC has a small power consumption which, together with the MAPM, makes ~ 0.160 W.

3.2.1.2 ASIC PCB and Interface PCB (IF PCB)

Although the ASIC PCB and the IF PCB are logically just one piece, the electronic components needed to be distributed between two PCBs given the space limitations imposed by the MAPM surface. The components that naturally should be close to the PMTRC, such as ASIC and Field-Programmable Gate Array (FPGA), were included in the ASIC PCB, while others, like digital isolators, were placed in the IF PCB. The exchange of signals between the two mentioned PCBs is done via two micro terminal board stacker connector. A picture of the ASIC PCB is shown in figure 3.14. The IF PCB is shown in figure 3.15.

The group ASIC PCB-IF PCB has, among other duties, to process the analogue and digital signals arriving from the PMTRC, perform the trigger at the single module level, prepare the input for the overall trigger generation, and transfer this
input, together with the analogue and digital data, to the central computer. The block diagram of this two PCBs is shown in figure 3.16.

The 64 analog signals arriving from the PMTRC get to the ASIC via a golden bonding. In the ASIC the incoming signals are amplified, shaped (with peaking time between 50 and 70 nsec), and fed to 64 discriminators. The ASIC selected for the front-end of POLAR was the VA-PMT chip, produced by the company IDEAS, which is usually applied in PET systems that often work with the same kind of MAPM H8500 that we are using. The VA is a low noise and low power consumption unit with input capacitance of $\sim 10$ pF and linear range from 0 to -1350 fC. Its lower threshold, corresponding to a $\sim 5$ keV energy deposition in one scintillator bar, can be set between 2 and 10 fC, depending on the counting rate and noise levels. A limited capability to adjust each channel discriminator individually is possible using 1 mV steps and the 3 trimming bits of its register. When the signal amplitude crosses the discriminator level, the VA generates a digital signal at the trigger output. All these triggered signals are summed together via a wired-or open collector output called T_OUT. The T_OUT is an analog signal proportional to the number of channels that were above the discriminator thresholds, which is a measure of the event multiplicity and is used for the trigger level 0 logic.
After the discriminators, the 64 digital trigger outputs, containing the information of which channel was hit, are further directed to the bonded level shifter (Level Shifter LS64 from IDEAS). This level shifter was specifically designed to work with the IDEAS VA. We need to include it in the POLAR front-end because the VA works with non standard -1.5 V and +2 V logic, while the ASIC PCB requires 1.5 V and 3.3 V for the FPGA and ancillary electronics. After the level shifter, the 64 signals arrive to the FPGA.

We selected the FPGA model AGLP060V5(-FCG201) IGLOO, from the Actel company, due to its very low power consumption and its small size. The front-end FPGA is responsible for generating the trigger, processing the analogue signal, and communicate with the VA and the Central Computer (CC). In POLAR electronics, we call an event the ensemble of signals collected in one ~ 70 nsec long time window. The FPGA implements various counters that monitor the total num-

Figure 3.16: Joint block diagram of the two lower stages of the front-end electronics: the ASIC PCB and the IF PCB. Please, refer to the acronyms chapter for the meaning of the acronyms used both in the figure and in the text.
ber of hits in the MAPM, the number of single events (events with one hit) and double events (events with two hits), etc. The typical event size is 200 bytes. The FPGA has a First In, First Out (FIFO) memory, enough to store a few events.

Regarding the dynode signal incoming from the PMTRC, it is directly fed to a discriminator. If it is too high, the event was most likely produced by a background source like cosmic protons (a minimum ionizing particle releases \( \sim 2 \text{ MeV/cm} \) in plastic scintillator), and the whole event is rejected by the trigger logic. Note that rejecting cosmic rays when the dynode signal is too high is faster than doing it with the FPGA logic unit (see below). Using the signals from the MAPM dynode and a dedicated flash Analog to Digital Converter (ADC), the FPGA can produce histograms of the spectra, which might be used in the level 1 trigger, as well as for test purposes. The dynode signal can also be used to localize GRB with POLAR (see §4.4), attaching a scaler to count the number of events whose dynode output is above a \( \sim 50 \text{ keV} \) threshold.

The voltage and current signals that the VA needs for its operation are generated by a dedicated Digital to Analog Converter (DAC) and controlled by the FPGA. DACs are also used to set the VA common threshold and to generate the voltage signals needed for the level 0 trigger logic. The trigger logic DAC signals are compared with the T_OUT signal from the VA and with the amplified dynode signal to obtain the number of MAPM anodes that were activated. The POLAR level 0 trigger has to select only events that produced at least two hits above 5 keV in the scintillator target. For this purpose three logic lines are created: ONE_IN, TWO_IN, and TOO_MANY_IN. If the event multiplicity in one module is exactly equal to 1 (ONE_IN), this information is transfered to the central computer where it will be checked if other modules in POLAR registered at least another hit, in which case the event is accepted. If the multiplicity is between 2 bars and 8 bars (TWO_IN), the event is immediately accepted and the analogue readout can be started. The optical cross-talk between channels will increase the multiplicity of the events, so that a photon interacting two times in a module can be detected in more than two channels. The range of the TWO_IN logic line from 2 to 8 bars ensures the acceptance of good events with high multiplicity due only to cross-talk. Finally, if the multiplicity is very large (TWO_MANY_IN), the event is most likely a cosmic ray and is rejected by the trigger logic.

At the level 0 trigger the decision is made within \( \sim 60 \text{ ns} \). The full propagation time of the signal till the FPGA is \( \sim 12.5 \text{ ns} \). The trigger has to come within 50–70 ns after the event arrival. If it does not, the analog signals inside the VA are frozen by using the Sample and Hold (S/H) function until the trigger decision is taken. These signals are subsequently sent to the analogue buffer to be further processed in the VA. The readout of the analogue buffer depends on the clock frequency, which is 5 MHz. The analog signals are then digitized using a 14 bits bipolar ADC. The FPGA manages all the commands needed for the readout and stores the ADC output values in a FIFO, releasing the S/H as soon as possible. The typical dead time for a 64 channel readout with a 5 MHz frequency is 12.5 \( \mu \text{s} \).

The three front-end PCBs have been mounted and are currently under test. The
total power consumption of the front-end of one POLAR module will be around 900 mW.

3.2.1.3 Possible improvements

The modularity of the front-end design allows to substitute any PCB with a new one with different components, provided the interfaces are kept constant. This gives freedom to include, if desired, improvements on the basic-line front-end electronics at a later stage of the design. One possible improvement would be the substitution of the IDEAS VA by the Multianode POLAR Readout ASIC (MAPRA) [103] 2-level ASIC, under construction at the Laboratoire d’Annecy-le-vieux de Physique des Particules, France (LAPP), which could be available for the POLAR flight model (see §3.3). If the final POLAR electronics design includes a 2-level ASIC, it is possible to define a low energy single channel threshold of 5 keV to use in the trigger logic, and a higher energy threshold of 50 keV per channel, useful for the GRB localization method implementation (see §4.4). The actual FPGA logic capability is at the limit with the currently implemented functionalities. Another improvement in the front-end design, which is under consideration to add further functionalities to the system, would be the substitution of the current FPGA by a slightly larger one with a bigger size logic, i.e. with more macrocells.

3.2.2 Voltage Supplies and Central Computer

The low and high voltage supplies, and the central computer for POLAR have not yet been developed. At the actual stage of development of the POLAR detector, the high voltage is emulated by a standard laboratory HV power supply. The low voltage and the central computer are at the moment substituted by a specifically built Electrical Ground Support Equipment (EGSE) (see reference [99] for details), connected to a PC.

3.3 Model policy

POLAR is being constructed in a step-by-step process, where each element is being tested individually before it is integrated in the detector design. The detector design and construction phases involve several steps, in which different models of the same instrument have been used. In this section we present the three versions of the detector that will be discussed along this thesis: the POLAR DM, EQM, and FM.

3.3.1 Demonstration Model (DM)

The POLAR Demonstration Model (DM) is a reduced version of the final design, consisting of one single POLAR module, i.e. one MAPM with its corresponding
64 scintillator bars. The first versions of the DM were built using simple square-prism-shaped scintillator bars, wrapped in Vikuiti ESR as shown in §3.1.2, and placed inside an aluminum housing, as it can be seen in figure 3.17. This kind of construction has been used to perform many laboratory tests, including the measurements with the partially polarized beam from a radioactive source described in §5.1. In the latest phase of development of the DM the 64 scintillator bars had their extremities shaped and polished as truncated square pyramids, as presented in §3.1.1. The bars were also wrapped in Vikuiti ESR and assembled inside a carbon fiber box, following the complete module construction description given in §3.1.5. This advanced mechanical design was the one used during the beam tests performed at ESRF (§5.2).

![Figure 3.17: The POLAR demonstration model (DM), consisting of one POLAR module.](image)

Both for the laboratory measurements and the ESRF beam test have been performed while the front-end electronic was still under tests. Therefore, a combination of Computer Automated Measurement And Control (CAMAC) and Nuclear Instrumentation Module (NIM) electronics was put together in the laboratory to read the DM. This system will be explained in detail in chapter 5. The MAPM was plugged into a small electronic box (see figure 3.17) which provides the LEMO connectors needed to plug in the cables that link the POLAR DM with the CAMAC and NIM electronic modules. As soon as the front-end electronic is finalized and tested, one front-end unit will substitute the CAMAC electronic rack for the DM readout.

### 3.3.2 Engineering-Qualification Model (EQM)

The POLAR Engineering-Qualification Model (EQM) is constituted by 16 modules, assembled in a $4 \times 4$ matrix, and fixed together with a metallic frame as shown
in §3.1.6. In fact, the mechanical structure needed to assemble the 16 modules will be equal to the one used for the POLAR FM, even if some of the places available in the fixation plate will be left empty. The decision of building the POLAR EQM in a smaller size than the FM is due to budget limitations. Despite its smaller size, the EQM, currently under construction, will allow us to test the electronic and logic related with the multi-module POLAR operation, and to address mechanical issues such as resistance to vibration, thermo-vacuum performance, etc. All the necessary tests to qualify POLAR as a satellite instrument will be carried out using the POLAR EQM.

3.3.3 Flight Model (FM)

Finally, the POLAR Flight Model (FM) is the detector that will be mounted in a satellite and perform the GRB polarization measurements. It consists of 25 modules, assembled in a $5 \times 5$ matrix, fixed together and placed inside a carbon fiber enclosure box, as represented in figure 3.11. The final mechanical and electronic designs used in the construction of the POLAR FM will follow the main lines described in §3.1.6 and §3.2.1, respectively. Small modifications may be included, based on the results obtained during the DM and EQM testing and qualification phases.
Chapter 4

Monte Carlo simulation package

A detailed Monte Carlo model of POLAR has been made using GEANT4 [12], in its version 9.0.p01. GEANT4 is an open source toolkit widely used in particle and astroparticle physics for the simulation of the passage of particles through matter. Programmed in the object oriented language C++, GEANT4 provides the frame in which the user can develop the simulation of his specific detector. In most cases, one only needs to describe well the detector characteristics, and to decide which from the wide set of GEANT4 classes are necessary to describe the particles that are going to interact with the detector. The GEANT4 version that we are using is not the latest release of the code. The tests that have been performed with the version 9.2.p02 have given polarization results with a modulation factor systematically larger than the ones obtained with version 9.0.p01. The reason for the new release to provide larger modulation factors could not be precisely determined. We have observed that in the new GEANT4 version the recoil electron is in most cases the particle responsible for the energy deposition, while in the old version at low energies the photon deposited the energy directly. Although the new release seems to describe more accurately the energy transfer between the particles involved in the Compton scattering process, we suspect that the modifications included might have affected the angular distribution of the Compton interactions. Given the good agreement found between the experimental data and the GEANT4–9.0.p01 simulations (see §5.1.4 and §5.2.4), we have decided to keep using this old version. The data used both for the input and the output of the POLAR GEANT4 simulation package have the structure of a ROOT [104] tree.

A simplified description of the overall POLAR simulation package, conceived as a combination of ROOT and GEANT4 code, is depicted in the left side of figure 4.1. Several routines have been written in the ROOT data analysis framework to reproduce the various inputs needed for the GEANT4 simulation. These ROOT routines are called generators, and have been created to reproduce the sources that POLAR is susceptible to detect, such as a GRB, diffuse X-ray background, neutron background, etc. The input is fed to the GEANT4 simulation in the form of a ROOT tree (called t0) providing a list of events. This list contains for each in-
coming particle its run and event number, the kind of particle, initial time, position, momentum, energy, and polarization. The POLAR GEANT4 simulation extracts the information on the incoming particles from the input tree (t0), passes the particles through the POLAR geometry keeping track of all the undergone interactions, and generates a ROOT file (called t1) containing all the information necessary for the subsequent analysis: the incoming photon energy, the number and position of the bars fired, the energy deposited at each bar, etc. This output tree (t1) is further analyzed using specific routines written under ROOT.

Figure 4.1: Simplified flowchart of the POLAR simulation package. *Left*: overall concept of the POLAR simulation, based on a combination of ROOT and GEANT4 code. ROOT routines are used to produce the input data for GEANT4 and to analyze the output data. GEANT4 itself is used to simulate the passage of the particles through the POLAR detector. *Right*: zoom on the GEANT4 simulation, describing its basic working principle.

The right hand side of figure 4.1 is a zoom on the GEANT4 simulation part. In fact, it is a simplification of the full POLAR GEANT4 simulation flowchart diagram, where we have focused in the part of the code that deals with the particle interactions (other parts of the GEANT4 simulation are responsible for the visualization, managing all the information between classes, etc). Each particle contained in t0 is generated by a Particle Generator class with its incoming characteristics: type of particle, arrival time, incoming energy, initial position and momentum, polarization, etc. Taking into account those characteristics, its associated physical processes are obtained from the Physics List class. The cross sections for each physical process are combined with the detector information, which is extracted from the Detector Constructor class, to track the particle through POLAR detector and evaluate if some interaction occurs. If it does not, the particle incoming data are stored in the output t1 and the next particle is extracted from
t0. If the particle interacts in POLAR, the interaction information, i.e. the position and the time of the interaction, the POLAR volume where it happened, the energy deposited, etc., are stored in t1. The particle is further tracked and may interact in POLAR several times, until it either looses all its energy\(^1\) or escapes the detector. In some interaction processes a part of the incoming particle energy is transfered to a secondary particle. If that is the case, the secondary particle is processed in the same way as the incoming one, combining its associated physical processes and the detector characteristics to determine whether an interaction happens or not. The secondary particle is tracked until it escapes or releases all its energy, at which moment the tracking of the incoming or parent particle goes on from the interaction point. The whole simulation process is performed for all the particles present in the t0 input file. Finally, the t1 tree containing the information of the incoming particle characteristics, and all the interactions, is written into the output root file. Further data reduction and analysis of the file with ROOT functions allow to obtain the simulation results.

The data reduction routines prepare the data for the final analysis, creating a tree (t2) with all the information needed to construct the modulation curve. First of all, they store in t2 only the interactions recorded in the POLAR sensitive part, i.e., in the scintillator bars from its target. Furthermore, multiple interactions produced in one bar by a single incoming particle are summed, and the obtained hits (maximum one per bar) are ordered by decreasing energy deposition. The hit position inside the bar is taken as a random number between the coordinates of the bar walls \((x_{\text{rand}}, y_{\text{rand}})\). The random position of the two first hits, corresponding now to the two largest energy depositions, are used to calculate the azimuthal angle of scattering \((\xi)\). The data analysis routines need only to draw and fit the modulation curve to get the polarization characteristics of the simulated data.

4.1 Detector Construction

Special care has been taken to accurately describe the POLAR geometry and materials in its GEANT4 simulation code. The geometry described in the POLAR Monte Carlo simulation package corresponds to the POLAR Flight Model (FM), i.e., 25 modules in a 5×5 matrix arrangement. A visualization of the POLAR simulation geometry is given in figure 4.2. The 1600 bars of the POLAR scintillator target have been simulated with their two ends shaped as truncated pyramids and inserted in the corresponding baffle cavity. The material of the baffles has been described as polyurethane. Each bar is surrounded by a ESR-like foil of 65 μm thickness, leaving a vacuum gap of 10 μm between the scintillator wall and the wrapping. An assembly of 64 identical bars is placed together inside a hollow carbon fiber socket of 1 mm thickness. A 20 μm thin vacuum layer is left between the carbon fiber socket and the block of scintillators in its interior. The carbon fiber plate and the back seal needed to fix the module to the outer enclosure have been

\(^1\)Particles are tracked down to a certain low energy threshold, which for photons is 250 eV.
also simulated inside the carbon fiber socket, just above the block of 64 scintillator bars. Also inside the socket, but below the scintillator bars, the 0.7 mm thick DC93-500 optical coupling has been included. Immediately under the optical coupling the MAPM has been described as an aluminum structure with a 1.5 mm thick borosilicate glass window on its top.

Figure 4.2: POLAR target, as simulated in the Monte Carlo package. The axis of the coordinate system and the numbers associated with some bars are also shown.

The carbon fiber socket with all the contents mentioned above constitutes one POLAR module. 25 replicas of this module are constructed and placed keeping an spacing of 4 mm between sockets. The 25 modules are installed inside a hollow enclosure box made of 3 mm thick carbon fiber, leaving a 1 cm vacuum gap between the sockets and the box. The simulated enclosure box contains only the POLAR target, and no space is left for the electronics. These have not been simulated since their volumes and materials are not yet known.

In the POLAR simulation package, the center of the coordinate system is the center of the scintillator target. The $z$-axis is parallel to the scintillator bars length, with its positive side towards the top of the detector, and the negative towards the MAPM. The scintillator bars have a number associated, from 1 to 1600, as shown in the top view of the detector, in figure 4.2.

Many of the dimensions of the volumes involved in the simulation of POLAR may be defined by the user at run time. These input parameters, which include the exact scintillator dimensions, the thickness of the sockets and the enclosure box, the distance between neighboring sockets, etc., may be written in a macro or in the command line and the GEANT4 simulation will take them into account to construct the detector volumes. Giving the inputs in a macro removes the necessity
of recompiling the GEANT4 code each time that a parameter needs to be changed. This feature has been specially useful when testing various detector configurations to find out which provides the best detector performance.

The exact composition of some of the POLAR components, like the Vikuiti ESR foil and the optical coupling DC93-500, is not provided by their manufacturers. In those cases an approximated description has been made. A summary of the most important materials that constitute the POLAR detector is given in table 4.1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density [g/cm$^3$]</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scintillator (BC404)</td>
<td>1.032</td>
<td>C(0.5), H(0.5)</td>
</tr>
<tr>
<td>Wrapping (ESR)</td>
<td>1.29</td>
<td>C(0.33), H (0.66)</td>
</tr>
<tr>
<td>Baffles (Polyurethane)</td>
<td>1.15</td>
<td>N(0.2), C(0.2), O(0.4), H(0.2)</td>
</tr>
<tr>
<td>Carbon Fiber</td>
<td>1.170</td>
<td>C(0.42), H(0.42), N(0.16)</td>
</tr>
<tr>
<td>Back Seal</td>
<td>2.3</td>
<td>C(1)</td>
</tr>
<tr>
<td>Optical Coupling (DC93-500)</td>
<td>1.08</td>
<td>Si(0.33), O(0.66)</td>
</tr>
<tr>
<td>Borosilicate Glass</td>
<td>2.23</td>
<td>B(0.04), O(0.54), Na(0.03), Al(0.01), Si(0.37), K(0.01)</td>
</tr>
<tr>
<td>Aluminum</td>
<td>2.7</td>
<td>Al(1)</td>
</tr>
<tr>
<td>Steel</td>
<td>7.85</td>
<td>Fe(0.98), C(0.02)</td>
</tr>
</tbody>
</table>

Table 4.1: Description of the materials used in the POLAR Monte Carlo simulation package. The elements used in the composition of each material are given in the third column. The numbers in brackets represent the percentage of each element that has been added to the final compound.

4.2 Physics description

To simulate the response of the polarimeter to different kinds of particles a realistic particle gun has been defined. The incoming direction, the spectrum, and the type of particles can be generated following the user instructions. The most important physical processes that photons can undergo in the detector are taken into account, including polarized Compton scattering, photoelectric effect, and pair production, among others. The scintillation and optical light collection processes have not been considered in the standard POLAR simulation, given their high computational time consumption. Simulations of one single scintillator bar have been done separately to study optical effects and evaluate statistical fluctuations in light collection (see §4.4.3.5).

Specific libraries are available in GEANT4 to reproduce the most important physical process at each particular energy range. The POLAR simulation package, in its Physics List function, calls the relevant libraries for each simulated particle and evaluates which is the most probable process to occur, taken the cross sections into account. The physical processes are classified in GEANT4 according to their nature: electromagnetic processes, hadronic processes, transportation, etc. Gamma
photons, electrons, and positrons interact via electromagnetic processes. To ade-
quately simulate the behavior of photons in the energy range of our interest (keV
to MeV region), we have selected the low energy electromagnetic physics library
from GEANT4 [105]. The functions on this library describe the interactions of
photons and electrons down to 250 eV, taking photon polarization into account.
For the simulation of background particles such as protons and neutrons, we have
substituted our user-made Physics List by the GEANT4-made QGSP_BERT_HP
physics list, stored in the G4NDL3.11 library. The QGSP_BERT_HP physics list
is recommended for the simulation of linear collider neutron fluxes, shielding ap-
lications at all energies, low energy dosimetric applications, and medical and in-
dustrial applications [106]. The functions applied to each of the particles involved
in the simulation of the POLAR signal and background sources are summarized in
table 4.2, where the library from where they are extracted is also specified.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Library</th>
<th>Main Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>gamma</td>
<td>Low Energy Electromagnetic</td>
<td>G4LowEnergyPolarizedCompton</td>
</tr>
<tr>
<td></td>
<td></td>
<td>G4LowEnergyGammaConversion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>G4LowEnergyPhotoElectric</td>
</tr>
<tr>
<td>e-</td>
<td>Low Energy Electromagnetic</td>
<td>G4MultipleScattering</td>
</tr>
<tr>
<td></td>
<td></td>
<td>G4eIonisation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>G4eBremsstrahlung</td>
</tr>
<tr>
<td>e+</td>
<td>Low Energy Electromagnetic</td>
<td>G4MultipleScattering</td>
</tr>
<tr>
<td></td>
<td></td>
<td>G4eIonisation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>G4eBremsstrahlung</td>
</tr>
<tr>
<td></td>
<td></td>
<td>G4eplusAnnihilation</td>
</tr>
<tr>
<td>neutron</td>
<td>QGSP_BERT_HP</td>
<td>G4HadronElasticProcess</td>
</tr>
<tr>
<td></td>
<td></td>
<td>G4HadronFissionProcess</td>
</tr>
<tr>
<td></td>
<td></td>
<td>G4HadronCaptureProcess</td>
</tr>
<tr>
<td></td>
<td></td>
<td>G4NeutronInelasticProcess</td>
</tr>
<tr>
<td>proton</td>
<td>QGSP_BERT_HP</td>
<td>G4HadronElasticProcess</td>
</tr>
<tr>
<td></td>
<td></td>
<td>G4ProtonInelasticProcess</td>
</tr>
</tbody>
</table>

Table 4.2: GEANT4 libraries and classes utilized for the simulation of the physical
processes associated to each particle. In addition to the functions applied specific-
ally to each particle, the transportation process is taken into account for all of
them.

In the simulation of a typical spectrum of GRB photons we observed that in
\(~67\%\) of the cases the X-ray photon interacts via Compton scattering with the
POLAR scintillator target (see table 4.3). In \(~12\%\) of the interactions the photon
experiences photoelectric effect, and in \(~17\%\) of the cases the recoil electron is the
particle responsible of the energy release, via either ionization or multiple scatter-
ing. Given that these interactions are summed inside each scintillator bar, several
processes can be involved in the same hit. For instance, this is often the case when
the photon is absorbed by photoelectric effect, where energy is transfered directly
by the photon, but also via the following electron ionization. When considering
the hits selected for the construction of the modulation curve the main interaction process is Compton scattering.

<table>
<thead>
<tr>
<th>Interaction Process</th>
<th>All interactions</th>
<th>Highest energy hit</th>
<th>Second highest energy hit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compton Scattering</td>
<td>67%</td>
<td>79%</td>
<td>98%</td>
</tr>
<tr>
<td>Photoelectric Effect</td>
<td>12%</td>
<td>16%</td>
<td>1%</td>
</tr>
<tr>
<td>Electron ionization</td>
<td>12%</td>
<td>12%</td>
<td></td>
</tr>
<tr>
<td>Multiple Scattering</td>
<td>9%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3: Main interaction processes responsible of the energy deposition, as obtained from the GEANT4 the simulation of one GRB. The remaining hits to make 100% of the interactions in the last two columns (5% and 1%, respectively) are a combination of several processes in a high multiplicity interaction within the same scintillator bar.

The physics libraries mentioned in table 4.2 describe the interaction of the particles with the detector and are used to calculate, based on the cross sections, where and via which process the interaction happens, as well as how much energy was released. Due to the so-called Birks effect \cite{107} only a fraction of the energy released in plastic scintillator is transformed into scintillation light, and only this fraction of energy is visible for a photomultiplier. Since the GEANT4 version that we are using (9.0.p01) does not take the Birks effect into account, we have implemented it ourselves.

### 4.2.1 Implementation of the Birks Effect

The Birks effect might be explained by a combination of undamaged molecules (they release the absorbed energy via scintillation) and damaged molecules (they dissipate the absorbed energy via non-radiative processes like heating) along the recoil particle path. Assuming the density of damaged molecules to be proportional to the energy loss ($dE/dx$), the light output ($L$) is \cite{108}:

\[
\frac{dL}{dx} = \frac{S \frac{dE}{dx}}{1 + kB \frac{dE}{dx}}
\]

where $S$ is the normal scintillation efficiency, and $kB$ is treated as a single parameter that varies with the kind of scintillator, and is usually measured by fitting the previous expression to experimental data. For BC-400 scintillator material (similar to the BC-404 used for POLAR) its value has been calculated \cite{109} to be $kB = 0.020$ cm/MeV.

Plastic scintillators present a linear response (see figure 4.3, left) to photons above $\sim 100$ keV, i.e. the amount of energy converted into light is proportional to the electron recoil energy. This is not the case for photons below $\sim 100$ keV \cite{110, 111}. To understand well the response of POLAR at low energies a thorough calibration campaign, using photon beams in the range from 5 to 100 keV, is
Figure 4.3: Left: Response of plastic scintillator (NE-102) in equivalent electron energy (MeV_{ee}) to electrons (dotted line) and protons (open circles) [116]. The electron response is linear in the figure. The proton data below 1 MeV have been fitted (solid line) with the first part of equation 4.2. Right: Response of plastic scintillator to ^{12}\text{C} recoils [113]. The data (open circles) have been fitted using equation 4.3 (solid line).

planned for the future at the Swiss Light Source from PSI. The calibration obtained in this way will not be just a proportional constant, but a polynomial function to take the non-linearity into account. In the Monte Carlo simulations we have assumed that once this process is done, the visible energy (E_{vis}), i.e. the amount of energy that we measure in the MAPM, is equivalent to the electron recoil energy.

We have considered in the simulation of the Birks effect that incoming (or external) electrons produce in POLAR the same response than recoil (or internal) electrons. Note, however, that the signal from low energy external electrons is expected to be significantly lower than that from internal electrons [112], due to the escape of primary optical radiation near the crystal surface [110]. Since the amount of this loss depends on the scintillator size and geometry, specific measurements with the POLAR scintillator bars would be needed to evaluate it. The introduction of this correction in the Monte Carlo simulations is expected to reduce the impact of the electron background (§6.2.3), without affecting the rest of the results presented in this thesis. Since the electron background produces only ~1% of the counts in the modulation curve, the correction for the external electrons linearity is not applied.

The response to heavy charged particles is not linear even for relatively high energies and the amount of light produced is always less than the one from an electron of the same energy. To calculate the visible energy for nuclear recoils one needs to consider their electron equivalent energy, often expressed in eV equivalent (eV_{ee}) units. The relative efficiency \( \varepsilon_{rel} \) is defined as the light output \( L [\text{eV}_{ee}] \) divided by the recoil energy [eV]. For recoil energies below 1MeV, the efficiency is less than \(~10\%\) for hydrogen (protons) and \(~1\%\) for carbon nuclei [113], which are the most important recoil nuclei in plastic scintillator. Nuclear recoils are negligible in the interaction of \( \gamma \) photons and electrons, but are important for neutron
interactions.

The relative light response of plastic scintillator (NE-102) to protons in the energy region from about 0.3 MeV to 30 MeV has been parametrized [114, 115] with an accuracy better than 5%. To describe the relative light response to protons below 0.3 MeV we have fitted the measurements from O’Rielly et al., [116] reproduced here in the left side of figure 4.3. The final expression to calculate the visible energy corresponding to proton recoils is the following:

\[
E_{\text{vis}} = \begin{cases} 
0.0187E_{\text{dep}}^2 + 0.1639E_{\text{dep}} & \text{for } E_{\text{dep}} < 0.3 \text{ MeV} \\
0.95E_{\text{dep}} - 8.0 \left( 1.0 - \exp(-0.1E_{\text{dep}}^{0.9}) \right) & \text{for } E_{\text{dep}} > 0.3 \text{ MeV} 
\end{cases}
\] (4.2)

where both the deposited \(E_{\text{dep}}\) and the visible energy \(E_{\text{vis}}\) are expressed in MeV.

When the recoil particle is a \(^{12}\)C nucleus in the scintillator material, the corresponding correction for the Birks effect needs to be applied. Hong et al. [113] reported the scintillation efficiency of carbon recoils in an organic liquid scintillator relative to the electron recoil efficiency. Their results are shown in the right side of figure 4.3, where they have been fitted with a function of the same type used for fitting protons above 300 keV:

\[
E_{\text{vis}} = 0.0667E_{\text{dep}} - 1.0 \left( 1.0 - \exp(0.0607E_{\text{dep}}^{1.0623}) \right)
\] (4.3)

where both the deposited and the visible energy are expressed in MeV. Given the small amount of points available for the fit, this function constituted only a first approximation of the Birks effect for carbon. Nevertheless, it is evident that only a very small amount of the deposited energy is visible.

Finally, a heavy incoming particle can break a carbon nucleus and produce alpha particles. The light output of alpha recoils, relative to the electron recoil, has been described by Cecil et al. [115] with the function:

\[
E_{\text{vis}} = 0.41E_{\text{dep}} - 5.9 \left( 1.0 - \exp(-0.065E_{\text{dep}}^{1.01}) \right)
\] (4.4)

where both the deposited and the visible energy are expressed in MeV.

We can neglect any other nuclei since they are very improbable to be present in the interactions inside the POLAR scintillator target.

The Birks correction formulas 4.2, 4.3, and 4.4 have been systematically applied in the Geant4 Monte Carlo simulations, to calculate the visible energy when the corresponding particles had been responsible for the energy deposition in the POLAR target. When the particle depositing the energy was a photon, an electron, or a positron, all the deposited energy was considered to be visible. The whole correction procedure is equally applied independently of the cosmic source that is being simulated. All the analysis performed on the output data from the Geant4 simulations is done in terms of the visible energy, which allows us to treat all data in exactly the same way, no matter which kind of particles were shot against the detector.
4.3 POLAR performance as predicted by Monte Carlo

The POLAR Monte Carlo simulation package allows us to predict the performance of the detector, even before it is constructed. The capability of POLAR to accurately detect and measure polarization signatures can be evaluated using the parameters presented in §1.2. Here, we will present the results obtained from the analysis of those parameters in a realistic case study. For this purpose, we have simulated the flux arriving to POLAR from a typical, but rather strong, GRB. This is what we call a standard GRB.

4.3.1 Measurement of a standard GRB

We define the standard GRB as a burst with total energy fluence above 5 keV $F_{\text{tot}} = 10^{-5}$ erg cm$^{-2}$ and Band (see equation 1.15) spectral parameters $\alpha = -1.0$, $\beta = -2.5$, and $E_{\text{peak}} = 200$ keV. These spectral parameters correspond roughly to the average from a selection of strong GRBs observed by BATSE [117–119], while the chosen fluence is characteristic of a rather strong GRB. We consider in this section the case of a short GRB, with duration equal to one second, located at the zenith of POLAR detector.

To imitate the flat illumination that a GRB will produce in POLAR, the photons initial positions have been randomly distributed inside a circle with radius $R_{\text{circ}} = 30$ cm. For a GRB at the zenith, the plane of the circle is parallel to the detector top face, and the circle center is at the point (0.0,+50 cm) in the simulations coordinate system. The momentum vectors of all the photons are parallel to the $z$-axis and oriented towards the detector. In this way, POLAR is illuminated from above and all its scintillator bars present equal probability of receiving a GRB photon. A standard GRB produces $\sim 93.47$ photons cm$^{-2}$ s$^{-1}$ in the energy range between 5 keV and 1000 keV. The total number of photons to be generated for the simulation is calculated as the total rate multiplied by the duration of the measurement, and by the area of the circle ($\pi R_{\text{circ}}^2$). Figure 4.4 shows the simulated incoming spectrum corresponding to a one second duration GRB.

The distribution of hits in the POLAR target, and the number of hits produced per each event are drawn in figure 4.5. The numerical results obtained from the simulation of a one second duration standard GRB are summarized in table 4.4. Since the circle where the incoming photons are generated has a larger area than POLAR, only 83 068 photons from the 264 373 simulated photons were actually illuminating (passing through with or without interaction) the detector. The scintillator target recorded 41 799 hits, i.e. in average 26.2 hits bar$^{-1}$ s$^{-1}$, with energy deposition above 5 keV.

4.3.2 Modulation Curve

Not all the photons detected by POLAR are used in the construction of the modulation curve. The minimal requirement for an event to be accepted in the modulation
Table 4.5 is a summary of the criteria applied to select the events in the modulation are summed, and events with total energy deposited above 250 keV are rejected. The energies of all the hits in one event are summed, and events with total energy deposited above 250 keV are rejected. In all scintillator bars along their path. On the other hand only hits, typically traversing the whole target from side to side and depositing energy in all scintillator bars along their path. On the other hand only hits where \( E_{\text{vis}} > 5 \) keV have been included.

The curve is that it must contain at least two hits, each one with energy deposition above 5 keV. This energy threshold corresponds to the minimal energy expected to be detectable with the final POLAR detector and electronics design. In addition, some other selection criteria have been implemented, to favor the selection of GRB events against the background events. For instance, some background sources, such as cosmic ray and trapped protons, tend to produce a large number of hits, typically traversing the whole target from side to side and depositing energy in all scintillator bars along their path. On the other hand only \( \sim 1 \) in 10 000 GRBs photons (see figure 4.5), produce more than 10 hits above 5 keV in the POLAR target. An additional selection cut has been introduced to reduce the impact of the positron background (see §6.2.5 for details): the energies of all the hits in one event are summed, and events with total energy deposited above 250 keV are rejected. Table 4.5 is a summary of the criteria applied to select the events in the modulation.
Table 4.4: Counting rates produced in POLAR by a standard GRB of 1 second duration.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated particles [Hz]</td>
<td>264,373</td>
</tr>
<tr>
<td>Particles illuminating POLAR [Hz]</td>
<td>83,068</td>
</tr>
<tr>
<td>Particles interacting at least once in POLAR ($E_{dep} &gt; 5$keV) [Hz]</td>
<td>25,842</td>
</tr>
<tr>
<td>Hits above 5keV in POLAR [Hz]</td>
<td>41,799</td>
</tr>
<tr>
<td>Counts in modulation curve [Hz]</td>
<td>7,759</td>
</tr>
<tr>
<td>Counts in modulation curve (excluding neighbors) [Hz]</td>
<td>64,53</td>
</tr>
<tr>
<td>Effective area for hits [cm$^2$]</td>
<td>276</td>
</tr>
<tr>
<td>Effective area for Polarization [cm$^2$]</td>
<td>81.2</td>
</tr>
<tr>
<td>Effective area for Polarization (excluding neighbors) [cm$^2$]</td>
<td>69.0</td>
</tr>
</tbody>
</table>

Table 4.5: Selection cuts applied to choose the events for the construction of the modulation curve. In addition to these criteria, an additional cut to reject the events where the two largest energy depositions happen in neighboring bars has been considered.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of hits ($n_h$)</td>
<td>$2 \leq n_h &lt; 10$</td>
</tr>
<tr>
<td>Energy per hit</td>
<td>$E_{vis} &gt; 5$keV</td>
</tr>
<tr>
<td>Sum of energy of all hits</td>
<td>$E_{tot} &lt; 250$keV</td>
</tr>
</tbody>
</table>

In addition to the selection criteria mentioned, we have considered the introduction of a further cut rejecting all events where the two largest energy depositions happen in neighboring bars. For each event, the precision in the determination of the angle $\xi$ is directly proportional to the distance between the two bars where the event largest energy depositions have been recorded. This is so because the further apart are the bars, the smaller is the angle subtended by one bar at the position of the other. The worst case is for neighboring bars, for which the uncertainty of $\xi$ can be as large as $90^\circ$ for horizontally or vertically neighboring bars, and as large as $45^\circ$ for diagonally neighboring bars. In addition, neighboring bars are also influenced by optical cross-talk, making difficult to distinguish a real signal from a response induced by a neighboring bar hit. Both the poor angular resolution and the cross-talk reduce the amplitude of the modulation curve. Constructing the modulation curve histogram excluding all the events with the two largest energy depositions in neighboring bars provides a better polarimetric performance, but with less statistical power. We have systematically made the analysis of the data with and without excluding neighboring bars. From the simulation of a standard GRB, about 9.1% of the photons illuminating the detector fulfill all the conditions to be accepted in the modulation curve (see table 4.4). When rejecting the events with the two largest
energy depositions in neighboring bars, the fraction of accepted photons reduces to 7.8%. For these selected photons, the spectra of their incoming energy and the distance between their two largest energy depositions are presented in figure 4.6. Photons with incoming energy below 30 keV do not contribute to the modulation curve. Note that the position of the Compton edge (see equation 5.5) for a 30 keV incoming photon is around 3 keV, i.e. below the POLAR 5 keV threshold. The maximum of the spectrum corresponds to energies around 50 keV. The distance between the two largest energy depositions may be fit with an exponential function \( f(x) = \exp(p_0 + p_1 \times x) \). The inverse of the slope \((1/p_1)\) provides the typical distance between those two hits and corresponds in our case to 54.9 mm.

![Figure 4.6](image)

Figure 4.6: Left: Spectrum of incoming energies from the GRB photons that contribute to the modulation curve. Right: Distribution of the distance between the two largest energy hits in each event, i.e., the ones included in the modulation curve. In both cases neighboring bars have been excluded.

With the events fulfilling all the selection requirements, the modulation curve is constructed as a histogram of the azimuthal scattering angle \( \xi \). To select the bin size for the histogram, we need to find a compromise between small bins, which provide a larger modulation factor, and large bins whose statistical error is smaller. We have studied the modulation factor and the average statistical error of the modulation curve bins for various bin sizes. Figure 4.7 shows the results obtained when analyzing the data of a standard GRB simulated as 100% polarized along POLAR x-axis \((\phi_{\Pi} = 0)\). We observe that the modulation factor decreases slightly for bins larger than 20°. The average relative error of the bins, i.e. the average of the ratio \(1/\sqrt{N_i}\), with \(N_i\) the number of events in the \(i^{th}\) bin, is also sharply decreasing with the bin size. Values between 15° and 30° appear to be acceptable. We have selected a bin size of 15°, corresponding to 24 bins per modulation curve and leading to 21 degrees of freedom in the modulation curve fits, given that the fit function (equation 1.11) has 3 parameters.

We present in figure 4.8 the modulation curve histograms (red dots) obtained from the simulation of a 100% polarized standard GRB. In the left hand side we show the result when including all bars, while in the right hand side the neighboring
Figure 4.7: *Left*: Modulation factor from a 100% polarized standard GRB calculated for various bin sizes. *Right*: Average value of the relative error in the bins, plotted against the bin size.

Figure 4.8: Modulation curve obtained from simulations of a 100% (red) and a 0% (blue) polarized strong GRB, located at the POLAR zenith. *Left*: All events have been included. *Right*: Events with the two largest energy deposition in neighboring bars have been excluded.

bars have been rejected. The red lines represent the fit of the histogram to the function in equation 1.11.

In the characterization of a polarimeter it is important to describe its response not only to polarized, but also to unpolarized signals. For a perfectly uniform and symmetric instrument the modulation curve from a 0% polarized signal should be totally flat. In the case of POLAR, its square geometry already introduces an asymmetry, since there are more material in the diagonal directions than along the x and y axis. This leads to a modulation curve with four peaks. Although the fit of such curve with a sinusoidal function of period π leads in general to a rather flat response, it is important to correct the signal from this component. We correct the measured modulation curve from the instrument response to a non-polarized signal by applying the following expression [1]:
Figure 4.9: Corrected modulation curve, obtained when combining the 100% and 0% polarized curves from figure 4.8. Left: All events have been included. Right: Events with the two largest energy depositions in neighboring bars have been excluded.

\[ N_{\text{corr}}(\xi) = \frac{N_{\text{sig}}(\xi)}{N_{\text{np}}(\xi)} N_{\text{np}}^{\text{max}} \]  \hspace{1cm} (4.5)

where \( N_{\text{corr}}(\xi) \) is the corrected modulation curve, \( N_{\text{sig}}(\xi) \) is the measured modulation curve, \( N_{\text{np}}(\xi) \) is the non-polarized modulation curve, and \( N_{\text{np}}^{\text{max}} \) is the maximum of the non-polarized curve. Applying this expression bin by bin to the modulation curve histograms from figure 4.8 we obtained the points from figure 4.9.

4.3.3 Modulation Factor

The modulation factor (\( \mu \)) is obtained from the fit of the modulation curve to the function in equation 1.11. The value \( \mu \) is the ratio of the two first fitting parameters (Amplitude/Offset), as described in equation 1.12. The third fit parameter is the phase and provides the polarization angle. The values obtained from the fit lines in figure 4.8 and figure 4.9 are summarized in table 4.6. The correction of the response to a non-polarized signal improves the determination of the polarization angle remarkably, which corresponds in the corrected case (last column of the table) to the input value used in the simulation of the GRB photons. Although the modulation factor from a standard GRB is only 0.7\( \sigma \) higher when excluding neighboring bars, an increase on \( \mu_{100} \) of the order of 2% has been confirmed in the simulation of higher statistic signals. Note that here we are not taking the cross-talk into account, which would further enhance the difference between excluding and non-excluding neighbors.

Along this section we have discussed the example of a standard GRB located at the POLAR zenith. If the detector would be spherical its response would be in principle independent on the direction of the incoming photons, expressed by the polar angle \( \theta_\gamma \), and the azimuthal angle \( \phi_\gamma \). With the POLAR parallelepiped
Table 4.6: Modulation factor obtained from the fits in figures 4.8 and 4.9.

<table>
<thead>
<tr>
<th></th>
<th>100% polarized</th>
<th>0% polarized</th>
<th>Corrected</th>
</tr>
</thead>
<tbody>
<tr>
<td>All events</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu(%)$</td>
<td>28.55 ± 1.72</td>
<td>0.65 ± 1.61</td>
<td>26.96 ± 2.32</td>
</tr>
<tr>
<td>$\phi_{\Pi}(%)$</td>
<td>164 ± 2</td>
<td>122 ± 2</td>
<td>178 ± 2</td>
</tr>
<tr>
<td>No neighbors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu(%)$</td>
<td>30.89 ± 1.88</td>
<td>0.59 ± 1.78</td>
<td>28.82 ± 2.51</td>
</tr>
<tr>
<td>$\phi_{\Pi}(%)$</td>
<td>164 ± 2</td>
<td>12 ± 2</td>
<td>177 ± 2</td>
</tr>
</tbody>
</table>

Figure 4.10: Modulation factor obtained from simulations of a 100% polarized standard GRB, located at various positions in the sky. The zenith of POLAR corresponds to $\theta_{\gamma} = 0^\circ$, $\phi_{\gamma} = 0^\circ$. In the right plot neighboring bars have been excluded in the construction of the modulation curve, while on the left side this condition was not requested.

geometry, the shape of the modulation curve is strongly influenced by the incoming photon direction, due to the dependence of the detector area with respect to the photon flux inclination. The modulation curve sinusoidal shape, which is lost as soon as $\theta_{\gamma} \neq 0$, can be restored applying equation 4.5. However, this manipulation does not avoid the reduction of the modulation factor. The dependence of the modulation factor from a 100% polarized standard GRB, with respect to the GRB location, is shown in figure 4.10.

4.3.4 Effective Area

The effective area ($A_{\text{eff}}$) of a detector is the geometrical area ($A$), multiplied by the probability ($\varepsilon$) of an incoming photon to interact in the detector. In the case of POLAR, this probability can be calculated as the number of photons that fulfill all the conditions to be accepted in the modulation curve, divided by the number of photons that were illuminating the detector. However, to do so one needs to consider the area $A$ as the detector exposed area, which is dependent on the incoming photon direction. The calculation is easier if one considers the area ($A = \pi R_{\text{circ}}^2$).
of the circle where we have simulated photons, in which case the probability $\varepsilon$ is the ratio between the number of photons accepted in the modulation curve, divided by the number of photons that were initially simulated. The effective area has been calculated from the simulation of a standard GRB, located at various positions. The result is shown in figure 4.11. The effective area is maximal for GRB at the position $\theta_\gamma = 45^\circ, \phi_\gamma = 30^\circ$.

### 4.3.5 Figure of Merit

The ability of a detector to measure polarization is better the higher are its $\mu_{100}$ and effective area. The product of both quantities is often called the figure of merit of the polarimeter. The task of maximizing the figure of merit in the design phase of a polarimeter is challenging, since the features that may improve the value of $\mu_{100}$ are likely to reduce the $A_{\text{eff}}$, and vice versa. We present in figure 4.12 the POLAR figure of merit for various positions of a standard GRB.

### 4.3.6 Field of View

POLAR is an open-eyed detector with no mechanical elements that could limit its field of view. Therefore, POLAR is in principle able to see photons coming from the whole $2\pi$ steradians sky above the detector. However, its ability to measure photon polarization is not constant along this solid angle. We define the POLAR field of view as the region of the sky where the detector is able to measure polarization with enough accuracy. In figures 4.10 and figure 4.12 we observed that both the POLAR modulation factor and in consequence its figure of merit decrease sharply for large polar angles $\theta_\gamma$. The $\mu_{100}$ value is falling below 20% for $\theta \approx 50^\circ$. Measurements of polarization for GRBs below that angle become hardly possi-
The value of solid angle representing the region of the sky with $\theta_\gamma < 50^\circ$ is $\Omega = 2\pi(1 - \cos \theta_\gamma) = 2.24$ sr. It constitutes 36% of the half-sky available for an instrument flying at the top of the atmosphere, for which the lower half-sky is blocked by the Earth. In other words, the POLAR field of view corresponds to about 1/3 of the visible sky.

### 4.3.7 Minimum Detectable Polarization

The Minimum Detectable Polarization (MDP), calculated using equation 1.14, is the minimum polarization level that a given photon flux would need so that POLAR is able to distinguish it from a 0% polarized flux. To calculate the MDP for a standard GRB we need its duration, the number of events in its modulation curve (from table 4.4), the detector $\mu_{100}$, and the number of events produced by the background which contribute to the modulation curve. The POLAR response to the most important background sources that will affect it in flight will be discussed in chapter 6. We have summed the number of events arriving to the modulation curve from diffuse photon background, neutrons, electrons, positrons, and the Crab nebula. The result is 1570 Hz when considering all the events in the modulation curve, and 1298 Hz when excluding neighboring bars. Including these values as $R_{\text{deg}}$ in equation 1.14, and taking the statistical significance as $n_{\sigma} = 1$, we obtained the results presented in figure 4.13. In this calculation of the MDP we have not considered the X-ray backscattering produced by both the Earth atmosphere and the satellite on which POLAR will be mounted. Both contributions complicate the calculation because they modify the value of $\mu_{100}$. For a proper evaluation of their influence on the MDP precise simulations of the spacecraft geometry on top of the Earth atmosphere would be necessary, what would require very large amounts of
computational time. The estimations presented in §6.2.7 allow us to predict a relative reduction on $\mu_{100}$ of less than 20%, what would increment the MDP by the same amount. For instance, a value of MDP=5% would become not more than 6% when considering the contribution of the X-ray albedo.

4.3.8 GRB yearly detections

The number of GRBs that POLAR is expected to observe in one year of operation has been estimated using the data from the BATSE catalog, which are available online [120]. The catalog is divided in various lists containing information such as the trigger number, the position in geographic and galactic coordinates, the energy fluence, the duration, etc, for each GRBs detected by BATSE. From the list of 2135 bursts for which the total fluence has been measured, the spectra of the 350 strongest ones have been analyzed [118,119]. The fit parameters obtained from the study are also available online [121].

We have selected for our study the GRBs observed by BATSE in the year 1996. The number of burst observed in this year (215) is close to the value (212) obtained when averaging the total number of burst observed by BATSE over the whole duration of the mission. BATSE was flying in a Low Earth Orbit (LEO) orbit, at about 450 km altitude. Assuming the FoV of BATSE to be $2\pi$ at any given time, i.e. all the sky not occulted by the Earth, to evaluate the POLAR response to the selected GRBs their position has been randomly generated on the $2\pi$ solid angle above POLAR. The 66 bursts with generated polar angle $\theta_p<50^\circ$ correspond to the expected POLAR yearly GRB polarization measurements. The Band spectral parameters ($\alpha$, $\beta$, $E_{peak}$, see equation 1.15) from the weak GRBs have been generated after performing a study of the parameters provided for the 350 strongest bursts of the
Figure 4.14: Minimum Detectable Polarization (MDP) vs. the total fluence given in the BATSE catalog for photons with energy above 20 keV. The figure represents the results obtained from the simulation of the GRBs with generated $\theta_{\gamma} < 50^\circ$ observed by BATSE in 1996. The red color corresponds to short bursts (duration < 2 sec) and blue color to long bursts (duration > 2 sec). In the right plot neighboring bars have been excluded in the construction of the modulation curve, while on the left side this condition was not requested.

catalog. Each Band parameter has been plotted vs. the logarithm of the burst total fluence and the distribution obtained has been fitted with a straight line. The function obtained was used to calculate by extrapolation the average value of each parameter for GRBs with low fluences. The parameters used in the simulation of weak GRBs were determined generating a random number with this mean value and with sigma given by the statistical fluctuations of the Band parameters from the analysis of 350 strong bursts. Finally, the spectrum offset ($A$) has been set so that the integral of the Band function provides a value in agreement with the total fluence provided in the BATSE catalog.

The MDP, calculated using equation 1.14 taking $n_{\sigma} = 1$ and $R_{bg} = 1570$ Hz (1298 Hz when excluding neighboring bars) is plotted against the bursts total fluence ($F_{tot}$ given in the BATSE catalog for photons with energy above 20 keV) in figure 4.14. Considering the plot on the right hand side of the figure, where neighboring bars have been excluded in the construction of the modulation curve, there are six bursts (all of them lasting more than 2 seconds) with MDP < 10%. The number of GRB with MDP < 20% is 25, from which 2 are short bursts. It is important to notice that the MDP value obtained is strongly dependent on the estimated level of background. The value of $R_{bg}$ used to produce figure 4.14 has been calculated taking into account the counts in the modulation curve induced by the sum of diffuse photon background, neutron background, electron background, positron background, and the Crab nebula. Given that for the simulation of these sources (see chapter 6) we have always selected the experimental results providing the highest background fluxes, the value of $R_{bg}$ used here constitutes an upper limit. Assuming the level of background to be, for instance, half of this upper limit, i.e. $R_{bg} = 785$ Hz (649 Hz excluding neighboring bars), the number of GRBs to
be observed by POLAR with a MDP<10% in one year of operation increases to 13, from which one is short and 12 are long GRBs.

### 4.4 Method to localize GRBs

The large field of view of POLAR and its lack of imaging capability would in principle force the detector to rely on other instruments to provide the location of the observed GRBs. Such a limitation would reduce the number of GRBs to be measured by POLAR depending on whether another GRB detector would be observing the same portion of the sky or not. To minimize this drawback we have used the GEANT4 Monte Carlo simulation to develop a method with which POLAR is able to localize GRBs with the precision needed to correctly calculate their polarization.

The mechanical design from §3.1 was under development by the time when the GRB localization method was implemented. In particular, the material and dimensions of several components were not yet known. For this reason, the detector design in the Monte Carlo simulations performed along this section is a simplification of the setup detailed in §4.1. The 1600 scintillator bars (6 × 6 × 200 mm³) were wrapped in a 50 µm foil of aluminum, and placed side by side with neither carbon fiber sockets nor physical separation between modules. Given that the GRB localization method is based in relative, not absolute, comparisons of simulation results, the performance of the localization model is not expected to change when substituting the simplified target by the final design.

#### 4.4.1 Description

Monte Carlo simulations have demonstrated that there exists a relation between the direction of the incoming X-ray photons and the hit pattern, i.e., the distribution of the hits in the POLAR scintillator target. A GRB located at POLAR zenith will produce more hits in the central modules of the target (see figure 4.5, left), while a GRB at a large polar angle (θγ) will present more counts in the modules located at a similar azimuthal angle (φγ) than the GRB. This behavior is due to the photon exponential interaction probability combined with the POLAR size, which corresponds to several absorption lengths. To measure the hit pattern, a scaler is attached to the output of each MAPM for counting the number of photons that produced at least one hit (with deposited energy above 50 keV) in the corresponding POLAR module. The output of the 25 Scaler Outputs (SOs) is finally compared with a database of hit patterns measured at known GRB positions to obtain the position of the observed GRB.

In the POLAR front-end electronics design (§3.2.1.3) including a 2-level ASIC, it is possible to define a low energy single channel threshold of 5 keV to use in the trigger logic, and a higher energy threshold of 50 keV per channel useful for the GRB localization method implementation. A simple OR operation on the MAPM signals above the high level threshold, and a scaler attached to the OR output would
serve to count the number of GRB photons producing some hit above 50 keV in this MAPM. An alternative option for the case where a single level ASIC is used, would be to attach a scaler to the dynode output of each MAPM and count for each event if the dynode signal is above a \( \sim 50 \) keV threshold. All the results presented in this section have been obtained with Monte Carlo simulations that reproduced the 2-level ASIC approach. Nevertheless, independently of which approach is taken, the algorithm to accumulate the SOs and compare the final result with a database of patterns at known GRB positions is relatively simple and suitable to be implemented in the central computer. The needed computing power is negligible as the algorithm has to run only infrequently when a candidate GRB has been detected.

A database of SOs has been created using the POLAR Monte Carlo simulation package. Non-polarized GRBs have been simulated at numerous incoming angles. To get enough statistics for the comparison with future GRB measurements, we simulated very strong bursts for the database, with a total energy fluence \( F_{\text{tot}} = 10^{-4} \) erg cm\(^{-2}\) and the spectral shape of a standard GRB (Band: \( \alpha = -1.0, \beta = -2.5 \), and \( E_{\text{peak}} = 200 \) keV, see §4.3.1).

Defining in spherical coordinates the positions of the simulated GRBs in the sky would imply an indetermination of the incoming photon azimuthal angle (\( \phi \)) when its polar angle (\( \theta \)) approaches 0. To avoid this numerical problem the database has been produced in Cartesian coordinates:

\[
\begin{align*}
x &= (1 - \cos \theta) \cdot \cos \phi \\
y &= (1 - \cos \theta) \cdot \sin \phi
\end{align*}
\]  

(4.6)

Simulations were uniformly distributed in the \((x,y)\) plane, for \( x \) and \( y \) running between -1 and 1 in steps of 0.02. We obtain in this way a grid with 10201 nodes. Note that, since the detector is symmetric and the influence of the satellite behind it is negligible (see §4.4.3.4), it is enough to simulate one quadrant of the grid. The SOs of the other three quadrants can be inferred from the simulated ones. The selection of the coordinate system from equation 4.6 guarantees a uniform grid where all points are equally distant from each other and the center of the coordinate system corresponds to the zenith of the detector.

The output of the scalers was calculated considering only hits with more than 50 keV deposited energy. Although there are no intrinsic limitations that prevent the detection of weaker energy depositions, the inclusion of this threshold is necessary to reduce the spectral dependence of our localization method (see §4.4.3.3 for details). Furthermore, a normalization of the simulated SOs is needed due to the dependency of the absolute number of counts registered in each MAPM on the total flux that the source produced. We scaled the rates dividing by the sum of all counts in the given SO. The result is a Normalized Scaler Output (NSO) like the ones graphically represented in figure 4.15. The final database is constituted by 10201 text files containing the NSO and its statistical error for each of the 25 MAPM of POLAR target.
Figure 4.15: Graphical representation of two of the Normalized Scaler Output (NSO) patterns that constitute the database.

The process to localize the GRBs detected by POLAR is based on the minimization of the Pearson’s $\chi^2$ [122, 123]:

$$\chi^2 = \sum_{i=1}^{n} \frac{(c_i - m_i)^2}{m_i},$$  \hspace{1cm} (4.7)

where $n$ is the number of MAPMs, $c_i$ is the number of counts observed in the $i^{th}$ MAPM, and $m_i$ is the number of counts predicted by a given model for the same MAPM. When POLAR observes a GRB, we calculate $c_i$ as the $i^{th}$ entry of its measured SO, and $m_i$ is obtained from the database of simulated NSOs. Supposing that the GRB was at coordinates $(x,y)$, the predicted number of counts in the $i^{th}$ MAPM is the $i^{th}$ entry of the database file at this position of the sky ($m_i(x,y)$) multiplied by the total number of entries ($c_{tot}$) in the measured SO:

$$\chi^2(x,y) = \frac{1}{25} \sum_{i=1}^{25} \frac{(c_i - c_{tot} \cdot m_i(x,y))^2}{c_{tot} \cdot m_i(x,y)}.$$  \hspace{1cm} (4.8)

To localize a GRB we calculate all of 10201 $\chi^2$ values, one at each point of the database grid, obtaining a 2-dimensional $\chi^2$ distribution (see upper part of figure 4.16 for an example done with a burst of same spectral shape as the database, but fluence $F_{tot} = 10^{-5}$ erg cm$^{-2}$). The minimum of the distribution is found selecting the node of the grid with the lowest $\chi^2$ and fitting two parabolas around it, one in the $x$-direction and the other in the $y$-direction, using 5 points in each case. The grid is fine enough so that the result obtained in this way, less computation demanding than a two-dimensional fit, is a good approximation to the absolute minimum of the two-dimensional distribution. To perform the parabolic fits with ROOT one needs to assign an error to each of the points. Since the $\chi^2$ itself has no associated error we assigned a fixed value, equal for all the points. We have chosen this value equal to 23, which is the number of degrees of freedom of our
experiment. On the horizontal axis the error of each point is the half-width of the bin, in our case 0.01. The positioning of the minimum of the parabolas $\chi^2_{\text{min}}(x)$ and $\chi^2_{\text{min}}(y)$ corresponds to the estimated position of the source. The error on the estimation is calculated with the values of the abscissa located at $\chi^2_{\text{min}}(x) + 1$ and $\chi^2_{\text{min}}(y) + 1$ respectively. Figure 4.16 shows an example of the two-dimensional distribution of $\chi^2$ values, and the two fitted parabolas.

In figure 4.16 one can notice that the $\chi^2$ values do not grow monotonously from the minimum, but decrease at the four corners of the plane. These four corners of the Cartesian space correspond to situations where the GRB is below the POLAR detector, i.e. $\theta_\gamma > 90^\circ$. The $\chi^2$ decreases there because POLAR cannot measure the point of interaction of the photons along the length of its bars, and
is therefore incapable of distinguishing a GRB at $(\theta_\gamma, \phi_\gamma)$ from one at $(180^\circ - \theta_\gamma, \phi_\gamma)$. To avoid this ambiguity, and since GRBs will never appear below POLAR, we have introduced an extra condition in the localization method that takes it into account. Namely, every time that the method gives an output below POLAR it will be transformed into the equivalent position above POLAR and only this one will be given as final result. In practice one would actually not need to simulate those points of the database. Our reason to do it is the numerical advantage of working with a uniform and square grid that can be treated as a regular matrix.

4.4.2 Method verification

Simulations were made to produce example measurements with which we could test the localization method. The GRBs simulated as examples were non-polarized standard GRBs. Note that the spectral shape, i.e. the Band parameters, is the same as the one used for the database bursts, but the total fluence is here ten times smaller. To facilitate the visualization we present only GRB positions above POLAR and in the quadrant of the space where $x > 0$ and $y > 0$. The behavior on the other three quadrants is equivalent due to the symmetry of the detector.

We compared the $x$ and $y$ values taken as input in the measurements with the ones reconstructed using the $\chi^2$ minimization method. Ten samples were run at each selected $(x,y)$ position to study the repeatability and the spread of the reconstructed results around each input value. Figure 4.17 shows the performance of the GRB localization method. The localization procedure works well reconstructing both $x$ and $y$ within a root-mean-square (r.m.s.) smaller than 0.07, and without apparent bias. The average minimum $\chi^2$ obtained for the 380 measurements simulated to produce figure 4.17 was $\chi^2_{\text{min}}(x,y) = 22.9$. Taking into account that there are 23 degrees of freedom, this corresponds to a reduced $\chi^2_{\text{red}}(x,y) = 0.996$. When performing the equivalent GRB localization in spherical coordinates $\theta_\gamma$ could be determined within a r.m.s. $< 4^\circ$ and $\phi_\gamma$ within a r.m.s $< 5^\circ$ for $\theta_\gamma > 30^\circ$ (see appendix A). As comparison, the localization accuracy of the Fermi-GRB burst monitor (GBM) [124] is for bright bursts $< 1.5^\circ$ using a detailed offline analysis, and the Swift Burst Alert Telescope (BAT) [125] provides positions to an accuracy of 1’ – 4’ within 20 seconds of GRB observation.

When a GRB is detected by POLAR its level of polarization ($\Pi$) is determined as the ratio of the measured modulation factor ($\mu$) and the 100% modulation factor ($\mu_{100}$). The error on the polarization level can be calculated as:

$$\sigma_\Pi \Pi = \sqrt{\left(\frac{\sigma_{\mu_{100}}}{\mu_{100}}\right)^2 + \left(\frac{\sigma_\mu}{\mu}\right)^2},$$

(4.9)

where $\sigma_\Pi$, $\sigma_\mu$ and $\sigma_{\mu_{100}}$ are the errors on $\Pi$, $\mu$ and $\mu_{100}$, respectively.

The second term in equation 4.9 depends only on the strength and level of polarization of the observed GRB. Since $\mu_{100}$ varies with the burst position and spectral shape, $\Pi$ must be calculated using a $\mu_{100}$ derived from simulations of a
Figure 4.17: Results from simulated non-polarized standard GRBs. Top left: Linearity plot in $x$, i.e. reconstructed $x$ vs. input $x$ for several fixed $y$ values. Each point on this graph represents the average of the 10 simulations made at each position. Middle left: Spread of the reconstructed $x$, i.e. the standard deviation of the 10 reconstructed $x$ values. Bottom left: Bias in the reconstruction, i.e. the difference between the reconstructed average $x$ value and the input $x$. The plots on the right are the equivalent to the left ones, but calculated for $y$ at several fixed $x$ positions. In all the plots lines of different styles have been drawn to guide the eye.
GRB with the same spectrum (see §4.4.3.3) and position in the sky as the observed one. The highest $\mu_{100}$ is obtained when the GRB is located at POLAR zenith and it diminishes when photons come from POLAR side (see figure 4.18). When the location of the GRB is unknown, the value of $\mu_{100}$ needed to calculate $\Pi$ is also unknown. Therefore the uncertainty on the position of the GRB is translated to an uncertainty in the value of $\mu_{100}$ and, through the first term of equation 4.9, further into an error on the resultant level of polarization.

Figure 4.18: Distribution of 100% modulation factor ($\mu_{100}$) vs. $x$ and $y$, calculated for a standard GRB (see text). The empty area at the right of the image corresponds to positions where the GRB would be below POLAR. Such a situation will never happen during flight and therefore was not considered in the analysis.

One can calculate the error of $\mu_{100}$ with standard error propagation:

$$
\sigma_{\mu_{100}} = \sqrt{\left(\frac{\partial \mu_{100}}{\partial x} \sigma_x\right)^2 + \left(\frac{\partial \mu_{100}}{\partial y} \sigma_y\right)^2}
$$

(4.10)

For each of the positions simulated as examples, the spread and bias of the reconstructed values were determined. When the spread of the reconstructed coordinates was larger than their bias, the spread was introduced as $\sigma_x$ and $\sigma_y$ in equation 4.10. Otherwise, the value of the bias was taken. To calculate the partial derivatives of the $\mu_{100}$ with respect to $x$ and $y$ we fit the 2-dimensional distribution from figure 4.18 with the following polynomial function:

$$
\mu_{100}(x, y) = a_0 + a_1 x + a_2 x^2 + a_3 y + a_4 y^2 + a_5 x y
$$

(4.11)

whose partial derivatives are:
From equations 4.12 and 4.10 one can calculate the error induced on $\mu_{100}$ by the uncertainty in the location of the GRB. The final result can be seen in figure 4.19 and represents the value of the first term in equation 4.9 ($\sigma_{\mu_{100}}/\mu_{100}$) at various source locations. The error caused to $\mu_{100}$ is always smaller than 6% of its absolute value.

The total error in the measured polarization is given by equation 4.9. Its second term ($\sigma_\mu/\mu$) depends on the strength and level of polarization of the GRB. In figure 4.20 we present an example calculated for standard GRBs, located at POLAR zenith, and with various levels of polarization. For this calculation we have substituted $\sigma_{\mu_{100}}/\mu_{100} = 0.10$ in equation 4.9, instead of the 0.06 previously mentioned, because 10% was the maximal error found on $\mu_{100}$ for GRBs of total fluence $F_{\text{tot}} = 10^{-5}$ erg cm$^{-2}$ s$^{-1}$ when variations of the spectral shape were taken into account (see §4.4.3.3). One can notice that the error due to the position uncertainty is negligible for low levels of polarization, with respect to the error associated to the modulation factor itself. At large levels of polarization the localization contribution to the error is more important. The final error in $\Pi$ is in that case $\sigma_\Pi \leq 15\%$ of the absolute polarization level. The values represented in figure 4.20 should be considered for bursts of total fluence $F_{\text{tot}} = 10^{-5}$ erg cm$^{-2}$ as upper limits to the error on the polarization level.
4.4.3 Systematic effects

The results presented in figure 4.17 represent the best case example, since the measurements to which the method was applied were produced in the same conditions as the localization database, and considering POLAR as an instrument with a perfectly uniform response. During a real observation there are several issues that could influence the outcome of the GRB localization method. We will discuss here the most important ones: asymmetries produced by GRB polarization, diffuse cosmic X-ray background, GRB spectral variations, satellite backscattering, fluctuations in light-collection efficiency, and MAPM non-uniform sensitivity.

4.4.3.1 GRB polarization

The database of the localization method was constructed simulating unpolarized sources. Although the polarization introduces an asymmetry in the POLAR hit pattern, it does not strongly affect the output of the scaler used for the localization procedure. Some examples were made with simulations of standard GRBs, 100% polarized in the direction parallel to POLAR x-axis, to confirm that statement. As with the non-polarized examples, 10 simulations were produced at each position of the sky and the spread and bias in the reconstruction of their locations were calculated. Both the spread of the reconstructed values and the bias of their average

Figure 4.20: Upper limits to the error on the polarization level for a GRB of total fluence $F_{\text{tot}} = 10^{-5}$ erg cm$^{-2}$. These plots have been calculated using the upper limit of the error inflicted to $\mu_{100}$ due to the localization procedure. Left: Relative error of the modulation factor for different levels of polarization (dotted), together with the final relative error on $\Pi$ (solid), where $\sigma_{\mu_{100}} / \mu_{100} = 0.1$ has been included. The increase due to the localization uncertainty is visible at high polarization values. Right: Calculated polarization level (points), together with the simulation input values (line), plotted as a reference. For polarization levels above 60% the uncertainty in the GRB position is the largest source of error.
were within the errors equal to the non-polarized case. In conclusion, the outcome of the localization procedure was not affected by the polarization of the source.

4.4.3.2 Diffuse cosmic X-ray background

Outside of the South Atlantic Anomaly the largest source of background [63] that will affect POLAR in orbit is the diffuse Cosmic X-ray Background (CXB) (§6.2.1). This source of background is constant and illuminates approximately isotropically the POLAR instrument. Since the surface of the most external MAPMs is more exposed, the SO produced by the CXB presents higher number of counts for the external MAPMs and lower in the internal ones. When analyzing the SO of the total signal, i.e. GRB+background, the result of the localization method may be different than the one obtained from the GRB alone. POLAR will store data from before, during, and after the GRB, making possible the subtraction of the CXB. We will discuss here how accurately the interpolation and subtraction need to be made so that the localization method is not affected.

To study the background influence it is important to consider the duration of the burst. Unlike GRBs, where for a constant fluence the flux diminishes when the duration increases, the diffuse background produces a flux approximately constant with time. Since we accumulate the output of the scaler during the whole GRB, the shape of its lightcurve has no influence on the localization method. For simplicity we considered both the lightcurves of the burst and the background as flat. Figure 4.21 shows the lightcurve and spectra of the diffuse photon background together with a short standard GRB of one second duration, located at POLAR zenith. The equivalent plots for a 20 seconds long GRB are presented in figure 4.22.

Figure 4.21: Comparison between the flux of a short (1 sec) standard GRB and the diffuse photon background. Left: Assumed lightcurve of the GRB signal (solid) and the diffuse photon background (dotted). All photons producing a hit above 5 keV in POLAR target have been included. Right: Spectrum for the same two sources.
Figure 4.22: Comparison between the flux of a long (20 sec) standard GRB and the CXB. Left: Assumed lightcurve of the GRB signal (solid) and the diffuse photon background (dotted). All photons producing a hit above 5 keV in POLAR target have been included. Right: Spectrum for the same two sources.

We have simulated the CXB using equation 6.1 with a 10% higher normalization factor as suggested in [127], and we calculated its SO. The result was added to the SOs of a series of standard GRBs as the ones presented in figure 4.17. Then, a second CXB was simulated and its SO was subtracted from the previous data successively with an excess of 8%, 10%, 20%, and 30% over its average value. The whole procedure was performed twice, using a 1 second and 20 seconds duration GRB, to reproduce a short and long GRB, respectively.

We observed that, while for a short GRB the background did not influence the performance of the localization method, its contribution was very important in the case of the long GRB, inducing an error of \( \sim 50\% \) in \( \mu_{100} \) if not subtracted. If the background is overestimated by a 8\% of its real level, the error transmitted to \( \mu_{100} \) was \( \sigma_{\mu_{100}} \leq 10\% \), increasing to \( \sigma_{\mu_{100}} \leq 14\% \) for a 10\% overestimation, and to \( \sigma_{\mu_{100}} \sim 20\% \) and \( \sigma_{\mu_{100}} \sim 30\% \) for a 20\% and 30\% overestimation, respectively.

As a conclusion, background subtraction is important not only for the polarimetric performance of POLAR, but also for its capability of localizing GRBs. In the case of short GRBs the CXB can be neglected, but for a 20 seconds long GRBs the background calculation must not differ from the real background level by more than 8\%. When the background is not strongly variable, it is sufficient to average two background measurements one taken immediately before and the other immediately after the GRB.

### 4.4.3.3 Variations of the GRB spectral shape

The GRBs used for the NSO database have been simulated taking the Band parameters corresponding to a standard GRB, summarized in the first row of table 4.7. The NSOs and SOs depend on the spectrum since the penetration length of photons
in the POLAR target is an exponential function of their energy. To study the possible influence of different GRB spectra on the localization method, several series of simulations have been performed. We selected from the BATSE catalog [118] the bursts with energy fluence \( F_{\text{tot}} \approx 10^{-5} \text{ erg cm}^{-2} \) which had the Band parameters most different from our standard ones. The selection of GRBs studied is presented in table 4.7.

<table>
<thead>
<tr>
<th>GRB</th>
<th>( F_{\text{tot}} \times 10^{-5} ) [erg cm(^{-2})]</th>
<th>( \alpha )</th>
<th>( \beta )</th>
<th>( E_{\text{peak}} ) [keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>1.0</td>
<td>-1.0</td>
<td>-2.5</td>
<td>200</td>
</tr>
<tr>
<td>911104</td>
<td>1.1</td>
<td>-0.6</td>
<td>-1.95</td>
<td>265</td>
</tr>
<tr>
<td>920718</td>
<td>1.1</td>
<td>-1.09</td>
<td>-3.06</td>
<td>192</td>
</tr>
<tr>
<td>930922</td>
<td>2.0</td>
<td>-1.40</td>
<td>-2.88</td>
<td>94</td>
</tr>
<tr>
<td>951016</td>
<td>1.4</td>
<td>-1.61</td>
<td>-2.02</td>
<td>118</td>
</tr>
<tr>
<td>980828</td>
<td>1.7</td>
<td>-0.25</td>
<td>-2.08</td>
<td>223</td>
</tr>
<tr>
<td>981130</td>
<td>1.1</td>
<td>-0.54</td>
<td>-2.25</td>
<td>649</td>
</tr>
</tbody>
</table>

Table 4.7: Details of the spectrum of the standard GRB compared to the bursts from BATSE catalog selected for studying the influence of the spectral shape into the localization procedure. From the BATSE catalog we selected the six bursts that, having a similar total energy fluence, presented the most different Band parameters with respect to our standard GRB.

We made a series of simulations locating each BATSE burst at several positions in the sky and applied to them the localization method to study the spread and bias of the reconstructed values, in the same way as presented in §4.4.2. With the scaler energy threshold at 50 keV we largely reduce the dependence of the method output on spectral variations, so that the bias of the reconstructed coordinates is below 0.15 and the error inflicted into \( \mu_{100} \) is below 10% for all GRBs from table 4.7. We show in figure 4.23 the case of GRB 981130, for which the method performance was the worst of the six examples (the absolute values of the coordinates bias were the largest). Analysis of the same burst in spherical coordinates is presented in appendix A.

Unfortunately, when reducing the method sensitivity to spectral variations, we cut out a large number of counts from the SOs and NSOs, diminishing the statistical power. As a consequence, the error produced on \( \mu_{100} \) from the uncertainty in the localization of GRBs with fluence \( F_{\text{tot}} = 10^{-6} \text{ erg cm}^{-2} \) and same spectral parameters as the database bursts, can reach 14%. For weaker GRBs our technique will not be able to provide the position of the source with sufficient accuracy, especially taking into account the spectral variability.

We have also applied the localization method to the GRBs in table 4.7 using a very low 5 keV energy threshold to the scalers. It was observed that the modification of the GRB spectral parameters introduced in some cases a large bias on the reconstructed \( x \) and \( y \) coordinates. The sign of the bias changed from GRB
Figure 4.23: Results from GRB 981130, simulated non-polarized and without background. **Top left:** Linearity plot in $x$, i.e. reconstructed $x$ vs. input $x$ for several fixed $y$ values. Each point on this graph represents the average of the 10 simulations made at each position. **Middle left:** Spread of the reconstructed $x$, i.e. the standard deviation of the 10 reconstructed $x$ values. **Bottom left:** Bias in the reconstruction, i.e. the difference between the reconstructed average $x$ value and the input $x$. The plots on the right are the equivalent to the left ones, but calculated for $y$ at several fixed $x$ positions. In all the plots lines of different styles have been drawn to guide the eye.
to GRB, and its absolute value was the largest (taking values up to 0.25) when $\alpha$ and $E_{\text{peak}}$ strongly differed from the values used for the database, while variations on $\beta$ did not affect it significantly. The main reason is that most of the photons that POLAR detects, and which mostly define the shape of the SO, have low energies. Low energy photons do not penetrate far inside POLAR target, producing hits only on the side where the GRB is coming from. Although this makes them in principle very good to localize a GRB, the fact that POLAR cannot measure the spectral shape precisely enough makes it impossible to correct for the bias in the reconstructed coordinates for GRB spectrally very different from our standard one. One possible alternative would be to measure the GRB spectrum with a small spectrometer that could be mounted somewhere close to POLAR. In such a case it would be enough to produce a new NSO database with the observed burst spectrum and apply the localization method to determine the GRB position with a few degrees uncertainty.

### 4.4.3.4 Satellite backscattering

Photons coming from the GRBs can reach POLAR indirectly after being backscattered in the spacecraft where the polarimeter is mounted. We have simulated a very simple description of the Chinese Tiang-Gong Space Lab as a bottle-like assembly of two cylinders (1.65 m radius, 4 m high, and 1.4 m radius, 3.2 m high, respectively) joint by a 1.4 m long truncated cone (see figure 6.35). All volumes were simulated in aluminum with a thickness of 4 cm, so that the total mass of the spacecraft is $\approx$8 tons. POLAR was placed outside the Space Lab at 12.5 cm from its trunked cone part, pointing with the front of its target to the zenith. The GRB photons were uniformly illuminating an area of 2 m radius with POLAR at its center. A series of simulations with standard GRBs at several positions in the sky, as done for figure 4.17, were produced and the localization method was applied. The results were found to be within errors the same as when the satellite was not considered. The 50 keV energy threshold applied in the scalers is rejecting most of the photons coming to POLAR from the satellite, since they have lost energy in the backscattering process.

### 4.4.3.5 Statistical fluctuations in light collection

Plastic scintillators are a good choice to perform hard X-ray polarimetry because the probability that a photon of this energy range experiences Compton scattering in the target is very high. The price one pays in exchange is a low energy resolution. GEANT4 simulations of optical photon tracking show that about $\approx$60% of the optical photons produced in a POLAR scintillator bar never reach the MAPM [91]. The detector will be calibrated taking this into account but, due to the statistical fluctuations in the number of optical photons collected, the spectral resolution will be poor. We have simulated the scintillation process in a single bar and fired it with bunches of photons at various energies. For each run a gaussian fit of the photo-
peak spectral line was performed. We found an expression to relate the $\sigma$ of this gaussian fit with the incoming energy of the photon, i.e., the broadening ($\sigma$) of the lines as a function of the deposited energy ($E_{\text{dep}}$, expressed in keV):

$$\sigma = 0.215 \cdot E_{\text{dep}}[\text{keV}] + 2.953 \text{ keV}. \quad (4.13)$$

The main consequence of this line-broadening for POLAR measurements is that the signal collected at the MAPM anode does not correspond exactly to the deposited one. Therefore, the 50 keV threshold introduced at the scalers will be blurred.

The influence of the spectral line broadening into the GRB localization method has been studied. Standard GRBs were simulated at different positions in the sky as it was done to produce figure 4.17. Before applying the localization method to these GRBs, each value of the energy deposition $E_{\text{dep}}$ was substituted by a number that had been randomly generated following a Gaussian distribution with mean $E_{\text{dep}}$ and sigma the result from equation 4.13. The application of the localization method to the modified data gave the same results as when $E_{\text{dep}}$ was perfectly determined, with no increment on the coordinates uncertainty.

### 4.4.3.6 Sensitivity variations between MAPM anodes

Two photons of the same energy can produce different signals if they come to two MAPM channels that do not have the same sensitivity. According to the H8500 MAPM data-sheet [93] sensitivity differences up to a factor three can exist between the anodes of the same MAPM. The threshold of the POLAR 1600 channels will be calibrated to reduce these sensitivity variations and obtain a uniform output. However, such a correction is not possible on the dynode signal. We have decided to study the influence of the MAPM non-uniform response into the GRB localization method to warranty that the method will work in the case that the final front-end has only a 1-level ASIC, in which case the needed electronic counter would be connected to the dynode signal.

We have observed that the sensitivity usually varies following a smooth function with a maximum close to one of the corners of the MAPM, and monotonously decreases when moving away from that point. We have assigned to each of the 64 elements of a MAPM a number in the range from 0.4 to 1, distributed according to an example data-sheet, but with variations of the order of 5% at each channel. Such a sensitivity mask was produced for each of the 25 MAPMs of POLAR, taking random orientations so that the corner with maximum sensitivity was not always at the same side of the target. In this study we have assumed that the average sensitivity is the same for all 25 MAPMs. The $40 \times 40$ mask created in this way was applied as a multiplicative factor to the energy depositions of a series of standard GRBs like the ones from figure 4.17. No change in the localization uncertainty with respect to the results shown in figure 4.17 was found.
Chapter 5

Experimental measurements

There are several possibilities to produce "human-made" polarized X-rays for testing the performance of a polarimeter. Naturally radioactive sources emit isotropically non-polarized X-rays. However, it is possible to produce partially polarized X-rays when assuring that the photons emitted by the radioactive source perform Compton scattering before reaching our polarimeter detector (the maximum level of polarization is attained for a scattering angle $\theta \sim 90^\circ$). A drawback of this technique is that the efficiency is very low (most of the photons will not scatter in the direction that we want). To increase the counting rate it is preferable to use a rather strong radioactive source, but taking care that the polarimeter under test is well shielded from the direct source emission. Furthermore, the place where the photons scatter, i.e. the scatterer, should be constructed in a low-Z material to inhibit the photons from being absorbed via the photoelectric effect (see figure 1.1). Using a detector as scatterer, acting as a trigger for the polarimeter, allows in addition to reduce the background.

An alternative option to produce partially polarized X-rays is to use a special radioactive source which produces positrons in its decay. If this positrons couple to the electrons of the source or some surrounding material, they form an atom of positronium that very rapidly decays into two photons emitted in opposite directions (see §5.1). The special feature of those photons is that they are correlated (also called entangled). It means that if one can detect the polarization of one photon, its companion will be polarized in the direction exactly perpendicular to the first one. Using a similar principle as in the previous case, one can locate a scatterer detector in front of the source and a tag detector at a 90° scattering angle from it on one side of the setup. Placing the polarimeter to be tested on the opposite side of the setup to receive the correlated photons, and using the scatterer as a trigger, we can select from the total sample of photons produced by the source those which are polarized in the direction of the tag. A great advantage of this setup with respect to the previous one is that it is possible to increase the number of tags and measure photons at different angles of polarization within the same run, increasing in this way the efficiency of the experiment. In addition, selecting all the photons
independently if they were or not tagged, a flux of unpolarized photons is selected, allowing to study also the response of the polarimeter to an unpolarized source. For this reason we have selected this kind of setup to carry out several laboratory measurements with the POLAR DM, which will be repeated with the EQM, and later with the POLAR FM.

Using radioactive sources in a specially designed setup allows to produce only partially polarized photons. To obtain a 100% polarized photon flux the only alternative is to use the radiation produced by a synchrotron. Several synchrotron facilities are available around the world, providing a limited amount of beam-time under request and approval of the proposal by a scientific council. Taking into account that the energy range in which POLAR is operating is rather high and cannot be produced by most of middle and small-size synchrotron facilities, the high energy beam-line ID15A at the European Synchrotron Radiation Facility (ESRF) located in Grenoble, was selected to perform of a beam-test with POLAR.

The setups utilized for the radioactive source and the synchrotron experiments, the results obtained with them, and the comparison of these results with simulations are presented in this chapter. In addition, last section of this chapter is dedicated to describe some of the space qualification tests to be performed with the POLAR EQM.

5.1 Partially polarized photons from radioactive source

The radioactive source $^{22}\text{Na}$ emits positrons [130] during its decay:

$$^{22}\text{Na} \rightarrow ^{22}\text{Ne} + e^+ + \nu_e$$ (5.1)

This positron, captured by an electron of the surrounding matter, forms an exotic atom called positronium. The positronium has a very short lifetime (less than a microsecond) before it decays into photons. Since $e^-$ and $e^+$ have spin $1/2$, the positronium exists in two spin configurations:

- **para-positronium** (total spin $S=0$): is the fundamental state and it decays into two correlated photons with energy 511 keV that travel in opposite directions. The spins of the two photons are in this case anti-parallel.

- **ortho-positronium** ($S=1$): it decays into 3 photons.

The geometry of our experimental setup (see §5.1.1) selects the para-positronium ($S=0$) decay type. The two photons produced in this decay are said to be entangled. This means that their polarization directions is unknown, but measuring the polarization direction of one photon fixes the direction of the other to be perpendicular to the first one. The phenomenon has been used to test the so-called Einstein-Podolsky-Rosen paradox [128].

The probability $f(\theta_1, \theta_2, \Delta \phi)$ of the photon 1 to scatter to a direction $\phi_1$ and the photon 2 to do it towards $\phi_2$ has been calculated [129, 130] to be:
\[ f(\theta_1, \theta_2, \Delta \phi) = \frac{d\sigma}{d\Omega_{nopol}}(\theta_1, \eta_1) \cdot \frac{d\sigma}{d\Omega_{nopol}}(\theta_2, \eta_2) \cdot \left[ 1 - m(\theta_1)m(\theta_2) \cos(2(\phi_2 - \phi_1)) \right] \] (5.2)

where the indices 1 and 2 refer to the two photons emitted, \( \phi \) is the azimuthal angle of scattering, \( \frac{d\sigma}{d\Omega_{nopol}}(\theta, \eta) \) is the Klein-Nishina cross-section (equation 1.3) for randomly-polarized photons, and:

\[ m(\theta_i) = \frac{\sin^2(\theta_i)}{\frac{E_i}{E_i'} + \frac{E_i'}{E_i} - \sin^2 \theta_i} \] (5.3)

with \( E \) and \( E' \) the photon energy before and after the scattering, and \( \theta \) the Compton scattering angle.

### 5.1.1 Experimental Setup

A \(^{22}\)Na source (25MBq activity and 2.6 years half life) is placed inside a lead container that acts as a shielding as shown schematically in figure 5.1. In two of the faces of the container, opposed to each other, there are two opening holes with 30 mm diameter. In front of the left side hole and at a distance of about 180 mm a plastic scatterer (S1) with the shape of a truncated cone is located. The length of S1 is 30 mm, and its small and large diameters are 5 mm and 20 mm, respectively. Perpendicular to it and at 200 mm distance 4 cylindric NaI detectors are placed as tags (see figure 5.2). The 4 tags are identical and their sensitive part has 50.8 mm length and 25.4 mm radius. On the right hand side of the setup the POLAR demonstration model (DM) target is placed facing the source. The azimuthal distribution of the tags might be varied, as well as the distance between the S1-tags assembly and the \(^{22}\)Na source, and the distance of the POLAR DM to the source. All the results shown here have been obtained with the detectors at the positions schematized in figure 5.1, and the four tags (from number 1 to 4) at the azimuthal angles 0°, 30°, 90°, and 180°, respectively.

The positrons emitted by the \(^{22}\)Na source interact with an aluminum target, where they annihilate emitting two 511 keV photons back-to-back. Most of the photons are stopped by the lead shielding and only those that pass through the opening holes can exit the container. Photons emitted to the left can interact in the scatterer S1, which is used to define the trigger for the POLAR DM, where the correlated photons arrive. The ensemble of all the photon-couples detected by S1 and the DM is unpolarized, since no preferential direction is defined through the scattering. On the other hand, the photons that are Compton-scattered in S1 and further detected in one of the tags are preferentially polarized in the direction orthogonal to the tag position. Their correlated photons, entering in the DM, are therefore polarized in the direction of the tag.
Figure 5.1: Scheme of the laboratory setup, shown here with only one tag detector at $\phi = 90^\circ$. The red and grey areas of the scatterer (S1) and the tag represent the sensitive part and the photomultiplier, respectively. For the POLAR demonstration model the sensitive target is represented in blue and the mechanical support in gray. All the distances given in the figure are expressed in mm.

Figure 5.2: Left: Distribution of the tags in the laboratory setup. In the laboratory coordinate system TAG1 is situated along the X-axis ($\phi = 0^\circ$) and TAG3 along the Y-axis ($\phi = 90^\circ$). TAG2 and TAG4 are then located at $\phi = 30^\circ$, and $\phi = 180^\circ$, respectively. The polar angle $\theta = 90^\circ$ for all the tags. Right: POLAR DM placed in front of the radioactive source container.

5.1.2 CAMAC readout electronics

To operate the POLAR DM before the front-end electronics presented in §3.2.1 was ready, an electronic rack (see figure 5.3) was mounted in the laboratory at DPNC. A combination of Nuclear Instrumentation Module (NIM) and Computer Automated Measurement And Control (CAMAC) modules installed in the rack and connected to a Personal Computer (PC) performed the readout of the POLAR
The block diagram explaining the logic of the CAMAC electronics used in the laboratory measurements is presented in figure 5.4. The 64 signals registered in the anodes of the POLAR MAPM are fed to four 16-channel CAMAC ADCs through 200 ns delay lines. The time window has been chosen to be 180 ns, long enough to read the signals from the NaI detectors, whose decay time (∼ 250 ns) is much longer than the one from plastic scintillators (< 3 ns). To construct the ADC logic gate the signals from both the MAPM dynode and the S1 detector are split into two lines each. One of the dynode lines and one of the S1 lines are fed into a logic unit whose purpose is to perform an \textit{AND} operation in a time window of ∼ 100 ns. Some delay (∼ 30 ns) is required in the dynode line so that it arrives at the same time as the S1 signal to the coincidence unit. The result of the logic operation is the gate for the CAMAC ADCs. We say that an event \textit{triggered} when the ADC gate is equal to one, i.e. when the MAPM dynode has a signal above 25 keV at the same time as S1 has a signal above 50 keV. The second dynode and S1 lines produced at the splitter are fed to a fifth ADC module, together with the signal from the tags, for further processing. All the events with signal in one of the TAG detectors (so-called \textit{tagged} events) are stored in the output data file. The probability of an event to be detected by a TAG is very small, compared with the probability of it to interact only with S1. We are mainly interested in tagged events, but we want to collect a sample of unpolarized events to study the detector response. Therefore, one in 20 non-tagged events are stored in the output data file. We name \textit{saved} events the group constituted by the tagged events together with the sample of triggered (but non-tagged) events that we store. Note that to construct an unpolarized sample of events we need the saved events together with 5% of the events tagged by each TAG detector. Finally, the output of the 5 ADCs, containing the information of the MAPM anodes and dynode, and the S1 and TAG detectors, is sent via a CAMAC controller to the computer, where it is saved on disk and analyzed offline. The dead-time to read one event with the CAMAC system used for the laboratory tests is 80 ms, which corresponds to a maximum readout rate of 12 Hz. The system performance increases when reading only a fraction of the non-tagged events. The limiting factor of the acquisition system is the data transfer from the CAMAC crate to the PC that drives the acquisition.

The outputs from the ADCs provide the \textit{raw} ADC values. They need to be corrected for \textit{pedestals} and for the gain differences between MAPM channels. Both corrections are done offline. The pedestal value of an ADC is an offset in the ADC output. The ADC pedestal is defined by the integration of the excess signal from the gate pulse which allows current to pass into the ADC. In order to correct for this offset, pedestal runs are taken periodically in between the data acquisition runs. In a pedestal run, taken without shielding the source, the pedestal values are measured and recorded by using a 1 kHz pulser as the trigger, which avoids the acceptance of data signals from the corresponding MAPM anode. Then, during the data processing, these pedestals are subtracted from their respective ADC channels, on an event by event basis. Concerning the gain differences between MAPM channels,
Figure 5.3: Electronic rack filled with CAMAC and NIM electronics.

Figure 5.4: Block diagram of the CAMAC electronics as it was installed in the DPNC lab, for the tests with the partially polarized source (see §5.1).
they are corrected by multiplying the signals in each channel by the sensitivity map provided in the MAPM data sheet. A more sophisticated gain correction might be done when calibrating POLAR by studying the response of each MAPM channel to the same kind of incoming photons (see §5.2.2.3 for details). After both pedestal subtraction and gain correction procedures have been applied, one obtains the corrected ADC values. The last step of the data reduction consists on the application of a procedure to remove noisy channels on individual runs. After this process is done the data are ready for analysis.

5.1.3 Laboratory Results

We have taken several runs of measurements keeping all the detectors at the positions schematized in figure 5.1. The spectrum of energy measured by S1 is presented in the top-left side of figure 5.5. The black line represents the spectrum taking all the saved events into account, while the blue line is only for those events that were also detected in TAG1.

Given the rather high energy of the photons and the low-Z material of S1, the most common interaction process in this detector is Compton scattering. The energy of the photon before \((E)\) and after \((E')\) the Compton scattering process are related by the expression:

\[
E' = \frac{E}{1 + \frac{E}{m_e c^2} (1 - \cos \theta)}
\]  

(5.4)

where \(m_e\) is the electron mass, \(c\) is the speed of light, and \(\theta\) is the angle of scattering. To be detected both in S1 and in one of the tags, the \(E=511\) keV photons have to experience Compton scattering in S1 at an angle \(\theta \approx 90^\circ\). In consequence, the photon energy after the scattering must be \(E' \approx 255.5\) keV. The difference \(E - E' = 255.5\) keV is the energy that they deposit in the S1 detector, which corresponds to the peak in the blue spectrum of figure 5.5. This peak has been fitted with a gaussian function of mean \(299.4 \pm 0.5\) ADC channels. Therefore, for the S1 detector 1 ADC channel corresponds to 0.85 keV. The spectrum of the scattered photons is measured in TAG1 (see top-right plot in figure 5.5), where the highest energy peak (fitted with a gaussian function of mean \(269.7 \pm 0.1\) ADC channels) corresponds to the absorption via photoelectric effect. We can conclude that for the TAG1, 1 ADC channel corresponds to 0.95 keV (the calibration for the other tags can be calculated in the same way). The very low part of the TAG1 spectrum shows saved events without activity in TAG1. To reject this noise we set a software threshold to the tags at 25 keV. The bottom part of figure 5.5 shows the correlation between the spectrum measured at S1 and TAG1. As expected from equation 5.4, the large majority of events are concentrated in the region where half of their 511 keV incoming energy is left in the S1 and the other half in TAG1.

At the same time as photons arrive to S1, their correlated photons are directed towards the POLAR DM. To further clean the data, a software cut on the minimum
total energy deposition at 25 ADC channels (almost equivalent to the dynode discriminator threshold) is applied. This cut rejects less than 1% of the total 1,055,703 saved events, leaving 1,055,343 to work with. In each of those events, the signals on all 64 channels of the POLAR DM have been stored. We consider that a POLAR channel has been hit if its signal is higher than 10 ADC channels. The total number of hits produced in the POLAR target amounts to 7,647,697. The spectrum obtained accumulating the energy of all those hits is shown in the left side of figure 5.6. The blue line on the same figure represents the same kind of spectrum, but calculated only for the events leaving more than 25 keV in TAG1. These 66,736 tagged events produce 498,288 hits on the POLAR DM. Taking into account that only 5% of the non-tagged events have been saved, from the total number of triggered events only 4.2% are tagged by TAG1. Taking all tags into account, ~1.7% of all triggered events are tagged. The spectra of the hits produced in the channel 29 (one of the bars at the center of the scintillator target) is shown in the right
side of the same figure. Saved and tagged events present the same spectral shape in the POLAR DM.

Figure 5.6: Spectrum of energy deposited in the POLAR DM. **Left**: Energy deposited per hit (taking all 64 bars into account). The black line corresponds to the saved events, while the blue line represents the events tagged by TAG1. **Right**: Energy measured in bar number 29 of the POLAR DM, both for saved and tagged events.

The distribution of hits in the POLAR DM target, and the number of hits produced per each event are drawn in figure 5.7. The beam of 511 keV photons seems to have a radius of about 1 cm and is approximately centered on the POLAR module. The distribution of the number of hit bars shows a maximum ∼10, due to the optical cross-talk between neighboring channels. A special analysis technique has been applied to eliminate the crosstalk offline. This method consists in identifying the clusters or groups of bars related to the same photon interaction.

Figure 5.7: **Left**: Distribution of hits produced by the source in the POLAR DM. **Right**: Number of hits produced per event in the POLAR target.

The cluster finding algorithm searches for the bars with the highest energy release separated by at least one bar using the following procedure:

1. Look for the channel with the highest energy release, which constitutes the first cluster (discard the event if the energy is lower than 50 ADC channels).
2. Look for the second largest energy release, excluding from the search the 8 channels surrounding the first highest energy release. Note that if the highest energy release is at the edge of the MAPM the number of neighbors is lower.

3. In the case that the second highest energy release found is lower than some of its immediate neighbors (possible if its neighbor is also a neighbor of the largest energy deposition), the hit and its 8 neighbors are discarded and the search for the second largest energy deposition starts again. Otherwise the found second largest energy release is identified as the second cluster.

With this procedure one identifies a number of clusters that can be 0 (when no channel is above 50 ADC channels), 1 (if no second cluster can be identified), or 2. In fact there can be more than two clusters which may be identified by iterating the process, but this step is not necessary since only the position of the two largest energy clusters is needed for the construction of the modulation curve. Figure 5.8 shows the modulation curve constructed with the events tagged by TAG1 (red line) and the non-polarized (blue line) events. We remind here that to construct the non-polarized sample one needs to take not only the non-tagged events, but also 1 in 20 of the events detected in each of the four TAG detectors. The distribution of the distance between the two largest energy hits for each of the events included in the non-polarized modulation curve is shown in the right-hand side of the same figure. When fitting it with an exponential function, the typical distance of interaction was found to be $8.3 \pm 0.1$ mm. The events in the modulation curves are selected with the two largest energy depositions above 30 ADC channels. We obtain 82 421 non-polarized events and 6687 tagged events in the modulation curves. The tagged events are expected to be preferentially polarized in the direction of the tag, i.e. in the $0^\circ$ direction for TAG1.
We see that the modulation curve of the non-polarized sample is far from being flat. Important factors influencing the shape of this curve are the geometrical shape of the detector, the malfunction of one channel close to the center of the target, and the cross-talk between channels which cannot be 100% eliminated. The modulation factor can be best measured when correcting the polarized curve with the non-polarized one (see equation 4.5), in which case all those effects disappear. The corrected modulation curves obtained with the four TAG detectors are presented in figure 5.9, and the results of their fits are summarized in table 5.1. The POLAR DM is able to reconstruct well the polarization angle of the tagged photons.

Figure 5.9: Corrected modulation curves obtained in the laboratory from the tagged events. The amplitudes of the curves, the degree and orientation of the polarization are presented in table 5.1.

Simulations have been performed to evaluate the $\mu_{100}$ expected from 511 keV photons arriving to the POLAR DM. For this purpose $10^6$ photons have been generated towards the POLAR DM in a beam of $2^\circ$ opening angle. This simulation was performed with photons both 100% polarized along the detector $x$-axis, and 0% polarized. The corrected modulation curve (calculated neglecting neighboring bars) is shown in figure 5.10. Events were selected with the two highest energy depositions in the POLAR DM above 30 keV. The value obtained from the fit was $\mu_{100} = 31.3 \pm 0.7\%$. When comparing the $\mu$ values measured in the laboratory with the $\mu_{100}$ obtained from the simulations, we obtained a level of polarization of $\sim$55%.
Table 5.1: Results obtained in the laboratory with the tagged events. The final polarization values have been obtained comparing with the $\mu_{100}$ calculated from simulations (see figure 5.10 and leading text).

<table>
<thead>
<tr>
<th>TAG#</th>
<th>TAG position</th>
<th>$\mu$(%)</th>
<th>$\phi_{\Pi}$(°)</th>
<th>$\Pi$(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0°</td>
<td>16.2±1.8</td>
<td>180±3</td>
<td>51.8±5.9</td>
</tr>
<tr>
<td>2</td>
<td>30°</td>
<td>18.4±1.8</td>
<td>29±3</td>
<td>58.8±5.9</td>
</tr>
<tr>
<td>3</td>
<td>90°</td>
<td>17.6±1.8</td>
<td>90±3</td>
<td>56.2±5.9</td>
</tr>
<tr>
<td>4</td>
<td>180°</td>
<td>18.5±1.8</td>
<td>175±3</td>
<td>59.1±5.9</td>
</tr>
</tbody>
</table>

Figure 5.10: Corrected modulation curve obtained from the simulation of a 100% polarized radioactive source emitting 511 keV photons. The modulation factor obtained from the fit is $\mu_{100} = 31.3 \pm 0.7\%$.

5.1.4 Comparison with simulations

A Monte Carlo model of the laboratory setup has been constructed to reproduce the results obtained in the previous section. The skeleton of the GEANT4 simulation remains the same as presented in chapter 4, but the geometry has been slightly modified to take only one module of the detector into account, and to introduce the laboratory elements. The volumes implemented in the GEANT4 simulation are the lead container that shields the radioactive source, the POLAR DM, and the active areas of the S1 and the four tag detectors. A picture of the Monte Carlo laboratory setup is presented in figure 5.11. The materials, dimensions, and the distance between these volumes have been reproduced as they are in the laboratory. The lead container is sealed and the detail structure of its interior is unknown. We have simulated it as a block of lead where only a cylinder of 30 mm radius is empty, i.e. made of air. This tube joins the two opening holes from where the source radiation can escape. The source is supposed to be point-like, isotropically
producing unpolarized photons. Since in the large majority of the solid angle the photons are absorbed by the shielding and never exit the container, it is enough to simulate the solid angle illuminating the container windows. Therefore, photons are simulated in a beam with circular profile and $3^\circ$ opening angle towards the exit. This leaves sufficient margin to fully cover the window surface and still simulate some photons which are stopped in the walls near the exit.

![Diagram](image)

Figure 5.11: Setup used in the Monte Carlo simulations for comparison with the measurements performed with the partially polarized radioactive source.

The main difficulty associated with the construction of the laboratory Monte Carlo simulation was to accurately reproduce the photon entanglement. GEANT4 was designed for traditional particle simulation when there are no collective effects during tracking, i.e. each particle is transported independently of the transportation of the other particles. In the laboratory Monte Carlo simulation we split the photon tracking process into two parts: a step-1 where 511 keV randomly polarized photons are directed towards S1, and a step-2 where only the photons seen by S1 above its 50 keV threshold are re-directed towards the POLAR DM. In the second step, 511 keV photons are generated with random polarization, but each one is generated at the same initial position and with opposite initial momentum to its correlated photon produced in the first step of the simulation. The cross section \( \frac{d\sigma}{d\Omega} \) for the step-1 photon to interact with S1 and the cross section \( \frac{d\sigma}{d\Omega} \) for its correlated photon to interact with the POLAR DM are related by equation 5.2. To accurately describe the photon entanglement we have to take the third term of the equation into account. Therefore we need to save the characteristics of the first interaction of the step-1 photon \((\theta_1, \phi_1, \text{ and } m_1)\) and the first interaction of the step-2 photon \((\theta_2, \phi_2, \text{ and } m_2)\). The modulation curve measured by the POLAR DM is constructed weighting all the step-2 photons whose two largest energy hits are above 30 keV by a factor \(W = 1 - m(\theta_1)m(\theta_2)\cos[2(\phi_2 - \phi_1)]\) corresponding to the third term in equation 5.2. One may think of doing the simulation without taking this term into account. The first thing that one would try is to produce randomly polarized photons in step-1, and generate the step-2 photons with a polarization direction exactly perpendicular to the one from the correlated step-1 photons. However, this procedure does not reproduce the quantum entanglement correctly, because it treats the Compton scattering process from the step-1
and step-2 photons separately. The result obtained in this way presents a value of the modulation factor which is approximately half of the one experimentally measured.

![Graphs showing deposited energy spectra](image)

Figure 5.12: Simulated spectra of deposited energy. Top left: Spectra measured in S1. The black line takes all events into account, while the blue line corresponds to the events that had been tagged in TAG1. Top right: Spectra of events measured by TAG1. Bottom: Spectra of photons detected in both S1 and TAG1: blue line from top left vs. the TAG1 spectrum from top right. It is evident that there exist a correlation between the peak in the S1 spectrum and the one in the TAG1 spectrum.

The spectrum measured in S1 and TAG1 with the simulated data is presented in figure 5.12. The blue line in the left plot is the spectrum measured in S1 for photons detected by TAG1. The peak of this spectrum has been fitted with a gaussian function with mean $262.6 \pm 0.6$ keV, which is slightly larger than the $255.5$ keV value obtained analytically (§5.1.3). The reason is that some photons experience more than one Compton scattering in S1 before arriving to TAG1. The sum of the energy deposited by this multiple interactions shifts the spectrum towards higher energies. Fitting the observed peak in the spectrum of the TAG1 detector (right plot) we obtained a mean $247.2 \pm 0.7$, which represents the remaining photon energy after the interaction in S1. Many of the events appearing below the peak of the TAG1 spectrum correspond to photons which, before interacting in S1, are scattered off the lead container in the region near its opening hole.
The spectrum of energy deposited per hit in the 64 bars of the POLAR DM, calculated from the Monte Carlo simulation, is presented in figure 5.13, both for the triggered events (releasing more than 50 keV in S1) and for the TAG1-tagged events (those which in addition left more than 25 keV in TAG1). Also the spectra measured in the bar number 29 are presented. In both cases we see a typical Compton spectrum. The few events appearing in the right side of the Compton edge correspond to multiple energy depositions in the same bar, whose accumulated energy reaches values above 340 keV (which is the position for 511 keV incoming photons). Note that the poor scintillator energy resolution smoothes out the spectrum so that in the laboratory (see figure 5.6) one cannot observe such sharp structures as the edge shown here by the simulation. Regarding the triggered events selection, we consider in these plots (and in the rest of this section) only 1.5% of the total events simulated. This selection contains 445 199 triggered events with more than 25 keV total energy deposition in the POLAR DM, producing a total of 652 271 hits in the target. On the other hand, the selection of 83 337 events tagged by TAG1 (with total energy deposited above 25 keV in the POLAR DM) has been obtained taking all simulated photons into account. When considering all the simulated photons, from the 31 163 930 triggers obtained, only 2.7%, were tagged in TAG1.

![Figure 5.13: Simulated spectra of energy deposited in the POLAR DM. Left: Energy deposited per hit (taking all 64 bars into account). The black line corresponds to the events triggered (seen by S1). The blue line corresponds to events triggered and tagged by TAG1. Right: Energy deposited in bar number 29 of the POLAR DM, both for non-tagged and tagged events.](image)

The distribution of hits in the POLAR DM target, and the number of hits produced per each event are drawn in figure 5.14. We see how the beam illuminates mostly the four central bars of the detector, which are facing the lead container opening. The difference between the distribution of the number of hits from the laboratory (figure 5.7), and the one from the simulations (figure 5.14) is due to the fact that the latter do not contain any cross-talk.

The modulation curves of the tagged and non-polarized events are shown in figure 5.15. In both cases the events have been selected with energy depositions above
30 keV and excluding neighboring bars. The non-polarized modulation curve contains 70 206 events, while the tagged modulation curve contains 14 697. The 4-peak structure observed in the non-polarized curve is due to the square surface of the detector. The distribution of the distance between the two largest energy hits selected for the modulation curve, also shown in figure 5.15, has been fitted with an exponential function. The typical distance of interaction was found to be 8.2±0.1 mm, in good agreement with the value obtained in the laboratory. The corrected modulation curves obtained with the events tagged by the four TAG detectors, are presented in figure 5.16. The polarization results obtained from the fit of those modulation curves are summarized in table 5.2.

![Figure 5.14: Simulation of non-tagged events. Left: Distribution of hits produced by the source in the POLAR DM. Right: Number of hits produced per event in the POLAR target.](image)

![Figure 5.15: Left: Modulation curve of polarized (tagged by TAG1, red) and unpolarized (blue) events, constructed using the position of the identified clusters. The curve of tagged events has been scaled up to the level of the non-polarized curve. The fit parameters correspond to the red curve. Right: Distribution of the distance between the two largest energy hits in each triggered event, i.e. the ones included in the blue modulation curve.](image)
Figure 5.16: Modulation curves obtained by the Monte Carlo simulations from the tagged events. The amplitudes of the curves, the degree and orientation of the polarization are presented in table 5.2.

<table>
<thead>
<tr>
<th>TAG#</th>
<th>TAG position</th>
<th>$\mu$ (%)</th>
<th>$\phi_\Pi$ (°)</th>
<th>$\Pi$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$0^\circ$</td>
<td>15.6 ± 1.4</td>
<td>0 ± 3</td>
<td>49.8 ± 4.6</td>
</tr>
<tr>
<td>2</td>
<td>$30^\circ$</td>
<td>16.8 ± 1.4</td>
<td>27 ± 2</td>
<td>53.7 ± 4.6</td>
</tr>
<tr>
<td>3</td>
<td>$90^\circ$</td>
<td>17.0 ± 1.4</td>
<td>94 ± 2</td>
<td>57.2 ± 4.7</td>
</tr>
<tr>
<td>4</td>
<td>$180^\circ$</td>
<td>17.2 ± 1.4</td>
<td>3 ± 2</td>
<td>55.0 ± 4.6</td>
</tr>
</tbody>
</table>

Table 5.2: Results obtained in the Monte Carlo simulations for the tagged events. The polarization level ($\Pi$) is the result of comparing $\mu$ with the value $\mu_{100}$ from figure 5.10.

The values of $\mu$ obtained with the Monte Carlo simulations (table 5.2) agree well with the ones from the laboratory (table 5.1). A comparative graph is presented in figure 5.17.
5.2 Tests with synchrotron radiation

In December 2009 the POLAR DM\(^1\) was tested at the high energy diffraction and scattering beam line ID15A from the European Synchrotron Radiation Facility (ESRF), in Grenoble. This beam line provides 100% polarized X-rays in the energy range between about 30 keV and \(\sim 500\) keV [131], providing ideal conditions for the calibration of a hard X-ray polarimeter as POLAR.

5.2.1 Experimental Setup

The beam had a square shape of size \(\sim 500 \times 500\) \(\mu\)m\(^2\). The standard beam flux, normally \(\sim 10^{15}\) photons s\(^{-1}\), was reduced by about 10 orders of magnitude to avoid damage in the detector, and to set an acceptable photon rate for the POLAR DM electronics. For this purpose a wedge made out of aluminum was placed in the beam path, in a small room before the experimental hutch, so that most of the photons scattered off the wedge could not enter in the experimental area. However, photons which scatter forward and interact in the walls of the hutch constitute a source of low energy background which arrive to the detector from all directions. Concerned about the possibility that this background would prevent us from performing clean measurements, a brass socket of 5 mm thickness was placed around the POLAR DM scintillator target to act as shielding (see figure 5.18). Previous to its construction, Monte Carlo simulations were performed to confirm that its

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\(^{1}\)The POLAR DM used in the laboratory measurements from the previous section had square prism bars, no baffles, and it was enclosed in an aluminum socket. The DM used in the beam test was in its final design, equal to one POLAR FM module, i.e. scintillator bar extremes shaped as truncated pyramids, baffles for bar alignment, and carbon fiber socket enclosing the module.
presence would not influence the measurement results.

Figure 5.18: Photographs of the POLAR DM installed for the beam test at ESRF. The panel in front of POLAR was installed to shield from background photons scattering forward off the wedge. A hole is opened on this panel to let the beam pass through. On the right picture, one wall of the POLAR shielding has been removed to show the carbon fiber socket inside.

The POLAR DM was installed on an Eulerian cradle which allows to make rotations around the beam axis (angle $\chi$) and has a small range for translations along the three cartesian axis. To translate the detector by larger distances, the Eulerian cradle was installed on top of a translation table with a larger displacement range. For consistency with the coordinate system used along this thesis, we will consider the beam to be along the $z$-axis, and the $y$-axis to be vertical and positive towards the hutch ceiling for $\chi = 0^\circ$. The whole coordinate system is fixed to the POLAR DM and rotates with it when the Eulerian cradle rotates in $\chi$. The polarization orientation of the beam is always horizontal. Since we define the measured polarization respect to the POLAR $x$-axis, for us the relation between the angle of polarization ($\phi_\Pi$) and the Eulerian cradle ($\chi$) is $\phi_\Pi = -\chi$.

The POLAR DM was connected via 8 m-long LEMO cables to the electronic rack, which was located outside the hutch. Also the power supply cable was passed through the rack chicane window. Although the kind of CAMAC-NIM electronic modules used for the laboratory tests with a radioactive source and at the ESRF beam test was the same, the logic had to be slightly modified. The main difference in the CAMAC electronics setup is that at the synchrotron no external trigger is applied. The block diagram of the CAMAC electronics used at the ESRF beam test is shown in figure 5.19. The MAPM dynode output is split to generate the logic gate that controls the ADCs. In this way, the POLAR module is self-triggered, and the 64 anode data lines, together with the dynode line, are processed at the 5 ADCs and sent to the readout computer for storage and offline analysis.

A remarkable improvement of the CAMAC electronics readout speed, respect to the system described in §5.1.2, was achieved by changing the CAMAC con-
controller. The Ethernet CAMAC controller used for the laboratory tests with radioactive source was substituted by an older EISA CAMAC controller, increasing the maximum readout rate to $\sim$500 Hz. The reason for the Ethernet controller to be much slower is the time that it spends in converting the data to Ethernet format, while the old EISA controller transfers the data directly, without conversion. In the laboratory measurements a low acquisition rate was acceptable, given the low trigger rate from the radioactive source.

The movement of all motors, which allow for rotations and translations of the detector, is remotely controlled by the beam line computer. This computer was synchronized with our data acquisition PC so that the running of the experiment could be automatized. Various macros were written to perform series of runs in which all the data taking periods and the necessary movements of the motors were defined, stopping always the motors during data taking to avoid electronic noise. In this way the user needed only to start the run and supervise the procedure, without direct intervention unless in case of problems, and the efficiency on using the available beam time for measurements was optimized. In six days of beam test we were able to collect $\sim$80 million events. Runs were performed at eight energies (46.5, 59, 88, 122, 200, 288, 356 and 511 keV), and at angles $\chi = 0^\circ$ and $\chi = 90^\circ$ for all those energies. The energy values were selected to be close to the ones available from radioactive sources, so that later some studies could be reproduced in the in-house laboratory, if necessary. In this thesis we will concentrate on the study of the high energy 64-bar scans, in which we collected 20 000 events with the beam centered on one bar of the POLAR DM, then moved to the next bar, and performed the same kind of measurement for the 64 bars of the target. Putting the 64 runs together allows to approximately reproduce the flat illumination expected from a GRB.
5.2.2 Data Reduction

Before the analysis could begin, a thorough process of data reduction was carried out. The following steps, mentioned in chronologic order of application, are involved in the data reduction process: mapping correction, pedestal subtraction, cross-talk correction, energy calibration, and hits selection.

5.2.2.1 Mapping correction and pedestal subtraction

As mentioned above, the signals coming from the POLAR DM are fed to CAMAC ADCs, whose output is read by the data acquisition PC. To avoid electronic cross-talk between neighboring channels, the distribution of signals to the ADC input lines was not done in correlative order. The mapping correction consists simply on re-arranging the collected data so that the 64 MAPM output signals constitute the ordered entries of a 64-element array.

Several runs have been taken in between physics runs at the ESRF to measure the pedestal for posterior subtraction. A typical pedestal spectrum, taken for one of the MAPM channels, is shown in the left side of figure 5.20. For each channel, the mean of its pedestal spectrum is calculated. The values obtained are subtracted from the ADC values obtained during physics runs. After the subtraction, all the measured spectra start close to the first ADC channel. The spectrum measured in one MAPM channel is shown in the right side of figure 5.20 before (black line) and after (blue line) pedestal subtraction.

5.2.2.2 Cross-talk correction

Although shaping the bottom of the scintillator bars as a truncated pyramid reduces the optical cross-talk between neighboring MAPM channels, the effect cannot be completely eliminated. The data collected show \(\sim 10\%\) cross-talk, for which we have made a correction offline. When the beam illuminates one bar, the signal registered in the other 63 bars can be produced either by cross-talk, by the back-
ground, or by a secondary interaction of the photon when it scatters on the initial bar.

Figure 5.21: Energy measured in bar fired by the beam vs. energy in its neighbor. Left: Before cross-talk correction. Right: After cross-talk correction.

We studied the relation between the energy measured in the fired bar, and the energy measured in its neighbors. On the left side of figure 5.21 is shown an example of this distribution (energy in fired bar vs. energy in neighboring bar), before the cross-talk correction. The distribution shows a thick blob, whose large width is mostly due to the poor energy resolution of plastic scintillator. The events outside of the blob are caused by either background or scattered photons. Excluding the outskirts, the blob may be fitted with a line, whose slope (∼10%) indicates the amount of cross-talk between the two channels. The same kind of fit may be done considering all the bar-pairs constituted by the bar fired and each one of the 64 bars of the target. This gives 64 numbers (one is the bar with itself, whose value should be 1) that provide information on the probability of a bar-couple to be simultaneously active. The same study, reproduced with the beam on the other bars, provides a $64 \times 64$ matrix ($M$), named cross-talk matrix (see left side of figure 5.22). The cross-talk matrix has been constructed using the information of the 64-bar scans performed at beam energies 511 keV and 356 keV, where the cross-talk is most visible. The data taken at $\chi = 0^\circ$ and $\chi = 90^\circ$ have been put together, so that no preferential direction of polarization is present in the sample.

Let us consider the signals measured by the POLAR DM as 64-entries array ($X$), and the data without cross-talk as another one ($Y$). Then, the relation between the data with cross-talk and the data without it is given by the cross-talk matrix: $X = M \cdot Y$. Since we have measured $X$ and we are interested in calculating $Y$, we just need to multiply $X$ by the inverse of the cross-talk matrix: $Y = M^{-1} \cdot X$. Performing this operation will remove the signal observed in the neighboring bars due to cross-talk and add it to the fired bar. The right plot in figure 5.22 shows the inverted matrix $M^{-1}$. Figure 5.23 shows an example of the POLAR response before (left side) and after (right side) cross talk correction. The signal detected by all the other bars is added to the hit bar, so that after the correction its output is $> 70\%$ larger. The right hand side plot in figure 5.21 shows the distribution of energy between neighbors after the correction has been applied.
Figure 5.22: Left: Cross-talk matrix ($M$). The energy measured in all 64 POLAR DM channels is plotted for all the runs of a 64 bar-scan. The diagonal shows the energy in the bar where the beam was located. Outside the main diagonal one can observe the signal detected by the closest neighbors. Right: Inverse of the cross-talk matrix ($M^{-1}$).

Figure 5.23: Energy deposited in the POLAR DM, when the beam was over bar number 20. The $z$-axis represents the energy measured in each bar (in ADC channels) accumulated for 1000 events. Left: Before cross-talk correction. Right: After cross-talk correction.

This correction removes most of the optical cross-talk observed between channels. However, due to the spread of the distribution in figure 5.21, it is not possible to guarantee that the effect is totally eliminated, and a small cross-talk residual may still be present in the corrected data.

5.2.2.3 Energy calibration

Until this point, we have expressed the spectral information of the data collected at ESRF in ADC channels. With the data almost clean from cross-talk information, the next step in the data reduction process is to calibrate it in energy. We used the 64-bar scans performed at high energies to fit the spectra of each channel and find the position of the Compton edge, whose value in keV can be analytically calculated.

The position of the Compton edge ($E_{ce}$) corresponds to the maximum energy
deposited in the detector by the Compton scattering process of an incoming photon. It can be calculated taking $\theta = \pi$ in equation 5.4:

$$E_{ce} = \frac{2E^2}{m_ec^2 + 2E} \quad (5.5)$$

where, as before, $E$ is the photon energy before the interaction, $m_e$ is the electron mass and $c$ is the speed of light. The Compton edge values expected for the beam energies that we have studied are summarized in table 5.3.

<table>
<thead>
<tr>
<th>$E$ (keV)</th>
<th>46.5</th>
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<th>88</th>
<th>122</th>
<th>200</th>
<th>288</th>
<th>356</th>
<th>511</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{ce}$ (keV)</td>
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<td>11</td>
<td>23</td>
<td>39</td>
<td>88</td>
<td>153</td>
<td>207</td>
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</tr>
<tr>
<td>Prob. Compton (%)</td>
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<td>92</td>
<td>98</td>
<td>99</td>
<td>99</td>
<td>99</td>
<td>99</td>
<td>∼100</td>
</tr>
<tr>
<td>Prob. Photoelectric (%)</td>
<td>21</td>
<td>8</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>∼0</td>
<td>∼0</td>
<td>∼0</td>
</tr>
</tbody>
</table>

Table 5.3: Expected position of the Compton edge for the beam energies used at the ESRF beam test. The lower part of the table shows the probability of the incoming photons to interact with the POLAR target via either Compton scattering or Photoelectric effect (calculated from Monte Carlo simulations).

Figure 5.24: Left: Spectrum measured in bar number 39 with the 511 keV beam. Right: Same spectrum, smoothed and fitted with the function in equation 5.6 to find the Compton edge position.

The left side of figure 5.24 shows the spectrum measured in bar number 39 with the 511 keV beam. We observe the typical shape of a Compton spectrum, except in the low energy part, where the efficiency loss of the detector due to the proximity of its threshold affects the shape of the spectrum. To find out the position of the Compton edge we have made a fit of the spectrum using the following function:

$$f(x) = a_0 + a_1 \cdot Erfc((x - a_2) \cdot a_3) \quad (5.6)$$
where the function $Erfc(x)$ is the complementary error function, defined as:

$$Erfc(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-t^2} dt$$  \hspace{1cm} (5.7)

The function in equation 5.6 is a step-like function, whose parameter $a_2$ provides the $x$ coordinate where the value of $f(x)$ is half the value obtained in the plateau. In other words, when fitting the spectrum with $f(x)$, the parameter $a_2$ gives the Compton edge position. Since we are only interested in the Compton edge area, we have smoothed out the left part of the spectrum to facilitate the fitting procedure. For this purpose we have searched the maximum of the spectrum excluding the 50 first ADC channels, where some peaks may appear. The spectrum at the left side of the maximum has been considered to be constant and equal to the maximum value, with a 10% error per bin. Note that this is only a mathematical trick to improve the fit performance in the edge area, which otherwise would have problems due to the high statistics and variability of the first bins in the spectrum. An example of the smoothed spectrum is provided in the right hand side of figure 5.24, where the red line is the fitted curve.

The Compton edge values expressed in units of ADC channel, obtained from the fit of the 64-bar scan performed at 511 keV, is shown in the left side of figure 5.25. On the right plot of the figure we present the gain map of the same MAPM provided by the manufacturer. It is evident that the response of the detector is closely related with the MAPM sensitivity variations. However, the Compton edge position plot includes more effects than the photomultiplier gain, such as differences in the optical coupling between bars and MAPM, differences in the electronic chain followed by each channel signal, etc. The ratio between the maximum and minimum values in the Compton edge distribution is 2.5. The same ratio calculated for the gain map gives 2.2 as a result.

![Figure 5.25: Left: Compton edge values obtained from the 511 keV scan. Right: Values of the MAPM gain provided by the manufacturer.](image)

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To calibrate each bar of the POLAR DM individually, we have performed the fit of their spectra measured at various energies. Taking into account that the fit is performed on the Compton edge, it can only be applied for the four highest beam energies (200, 288, 356, and 511 keV). At lower energies the probability that the photons interact via photoelectric effect increases, and the spectral shape is modified by the photo-absorption peak. Given the low energy resolution, this peak is mixed with the Compton spectrum and, at even lower energies, further modified by the influence of the threshold. To estimate the goodness of the spectral fits, the probability for their $\chi^2$ to be less than the value obtained has been evaluated. The probability distribution obtained when accumulating the values from the 64 spectral fits at the four highest beam energies is shown in the left side of figure 5.26. For very good fits this distribution should be flat. The fits performed at lower energies (200 and 288 keV) are mostly responsible for the large number of counts observed in the first bin of the distribution. At these energies, the photoelectric absorption peak starts to appear in some channels, reducing the quality of the fits.

![Figure 5.26: Left: Probability for the $\chi^2$ of the spectral fit to be larger than the value obtained. Right: Calibration line for bar number 4.](image)

Drawing for each POLAR bar the value of the fit parameter $a_2$ vs. the theoretically calculated ($E_{ce,teo}$) Compton edge position (see table 5.3) at all energies, we obtain the kind of plot presented in the right side of figure 5.26. The fitting procedure applied to the low energy points provide overestimated values, due to the influence of the photoelectric absorption peak. The four high energy points can be fit using a polynomial of the form $E_{ce,teo}[\text{keV}] = m \cdot E_{ce}[\text{ADCch}]$. The slope ($m$) gives the calibration, i.e. the equivalence between keV and ADC channels, for this particular POLAR bar. The error on the Compton edge found from the spectral fits is very small (usually less than 1%). Since the error of the calibration method itself is much larger, we have performed twice the linear fit of figure 5.26. The first time we have evaluated the residuals of the fit. The second time, the standard deviation of the residuals distribution was assigned as the error of the data points, and
the linear fit was performed taking those errors into account. Finally, the energy calibration of the data is done multiplying the amount of energy (in ADC channels) deposited in each bar by the \( m \) associated to the bar.

The energy calibration method has been tested using Monte Carlo simulations. The 64 runs of each scan have been reproduced by illuminating each POLAR DM bar with a \( 0.5 \times 0.5 \text{ mm}^2 \) photon beam at the selected energies. To apply the spectral fit method in the same way as we have done for the experimental data, we need to introduce the energy resolution of plastic scintillator in the simulated data. The energy resolution is related with the slope of the spectrum at the Compton edge position. The derivative of the fit function in equation 5.6 is given by:

\[
\frac{df(x)}{dx} = -\frac{2a_1a_3}{\sqrt{\pi}} \cdot e^{-\left[\frac{(x-a_2)a_3}{a_3\sqrt{2}}\right]^2}
\]

which has the shape of a gaussian function \( g(x) = \exp\left(-\frac{(x-x_0)^2}{2\sigma^2}\right) \). The width of our gaussian-like function \( \sigma_{ce} = \frac{1}{a_3\sqrt{2}} \) provides the energy resolution in the spectrum, expressed in ADC channels. This value depends on the beam energy. To obtain the relative energy resolution, we divided it by the value of the Compton edge (also in ADC channels).

The energy resolution \( \sigma_{ce}/E_{ce} \), calculated for the 64 POLAR DM channels using the experimental data at the four largest energy beams, is presented in the left side of figure 5.27. The resolution values oscillate between 18\% and 25\%. Variations in resolution are in the same order as the light collection variations which depend on the depth of the photon interaction inside the scintillator bars. The precise energy releases obtained from the simulation have been randomized using a gaussian function with \( \sigma \) corresponding to the \( \sigma_{ce}/E_{ce} \) values obtained from the 64-bar scan at 356 keV. One example of the simulated spectrum obtained before (black line) and after (blue) the randomization is shown in the right side of figure 5.27 together with the spectrum measured experimentally (red) in the same channel and at the same energy. A good agreement is found in the Compton edge zone between the smoothed simulated and the experimental spectra. In the low energy region the experimental spectrum is modified by the loss of efficiency close to the detector threshold.

The simulation of the low energy beam data (46.5, 59, 88, and 122 keV) has served to verify the presence of the photoelectric absorption peak in the measured spectra, confirming the non applicability of the Compton edge fitting procedure at these energies. Applying the method to data simulated at high beam energies (200, 288, 356, and 511 keV) has given as a result a 5\% overestimation in the determination of the Compton edge position. Our interpretation is that the 5\% difference between the position calculated analytically and the value obtained from the simulations is due to the sum of multiple interactions in the same bar, which slightly shifts the spectrum towards higher energies. The overestimation has been found consistently at the four high beam energies considered. To correct for this effect we multiply by a factor 1.05 the calibration slopes \( (m) \) obtained from the
Figure 5.27: Left: Resolution in energy calculated at the Compton edge position, for the four highest energy beams. Right: Comparison of the spectrum simulated (with and without introduction of the energy resolution) and measured in one POLAR bar with a 356 keV photon beam. The simulated spectra have been normalized to the maximum of the experimentally measured spectrum.

experimental data, before using them to execute the energy calibration.

The spectrum experimentally measured using a 511 keV beam in one POLAR DM channel is shown in figure 5.28 before and after the energy calibration.

Figure 5.28: Spectrum of one POLAR DM channel before (left plot) and after (right plot) the energy calibration (511 keV beam energy). The peak at 511 keV is hardly visible because photons of this energy Compton scatter in plastic scintillator instead of being absorbed via photoelectric effect.

5.2.2.4 Hits selection

The last step of the data reduction consists in selecting the two largest energy hits to be considered for the calculation of the azimuthal angle of scattering $\xi$. We have executed this procedure rejecting neighboring bars, both to increase the angular resolution and to avoid the influence of possible cross-talk residuals. Once $\xi$ is determined, we are ready to analyze the polarization of the signal.
5.2.3 Polarization results

The analysis of the data collected at the ESRF beam test is at present undergoing. The first polarization results available, which are presented in this thesis, have been obtained from the high energy beams applying a 50 keV off-line threshold to the energy deposition per bar. Detailed studies of the data taken at low energy beams and lowering the off-line threshold will follow and their results will be published elsewhere.

The modulation curve measured from a 100% polarized beam (see red points in left plot from figure 5.29) has to be corrected by the response of the detector to a non-polarized signal, to obtain a good fit with function 1.11. There are various ways in which we can calculate the 0% polarization response to correct the data measured at the ESRF beam test. First of all, we can put together the data measured at $\chi = 0^\circ$ and $\chi = 90^\circ$. Those two sets of data present perpendicular directions of polarization, and the sum of both is equivalent to a 0% polarization signal. This approach has been taken to produce the blue modulation curve in the left plot of figure 5.29. Unfortunately, in real GRB observations we will not have two sets of perpendicularly polarized data taken at exactly the same conditions, as we have from the beam test. An alternative to this approach is to obtain the 0% polarized response from Monte Carlo simulations. In the right side of figure 5.29 we present the comparison between the 0% polarized modulation curve obtained experimentally (black points) and the one obtained from the simulations (blue points) using 511 keV photons. Both curves agree well within errors.

Figure 5.29: Left: Modulation curve obtained from the 511 keV beam data using a 50 keV threshold per POLAR channel. The red points have been calculated with the photon beam 100% polarized along the POLAR x-axis. The blue points correspond to the 0% polarized signal obtained from the mixture of two data sets perpendicularly polarized. Right: Comparison between the 511 keV 0% polarized modulation curve obtained from the experimental data (black points) and from the simulation (blue points). The simulated curve has been normalized to the maximum of the experimental data. Both curves have been fitted with the function in equation 5.9.
Another possibility to avoid the need of performing this correction is to fit the measured modulation curve with a function of the form:

$$f(\xi) = a_0(1 + a_1 \cos(2\xi - a_2) + a_3 \cos(4\xi - a_4)) \quad (5.9)$$

where $a_0$ is the curve offset. The fit parameters $a_1$ and $a_2$ provide the information on the signal polarization. The parameter $a_1$ is the modulation factor ($\mu$) and $a_2$ is the angle perpendicular to the polarization direction ($a_2 = \phi_\Pi + \pi/2$). Finally, the last two fit parameters provide the information on the 0% polarization response of the detector, due to its geometry: $a_3$ is the amplitude of the non-polarized component of the signal, and $a_4$ is its phase. The black and blue lines in the right side of figure 5.29 correspond to the result of performing this kind of fit on the non-polarized curves. The amplitude of the non-polarized response ($a_3$) has been found to be 10.2±0.3% in the experimentally obtained curve, and 10.2±0.5 in the simulated curve.

Using the mentioned 5-parameter fit function to fit the 100% polarized modulation curve has the advantage of sparing us the work of calculating the non-polarized modulation curve. However, we have decided to calculate the corrected modulation curve using equation 4.5. This method is able to take a 0% signal with an arbitrary shape into account, even a non sinusoidal one, what may happen in case of dead or malfunctioning single channels. Note, however, that the simulation needs as input the spectral characteristics of the incoming flux. If the spectrum cannot be accurately measured, such as in the case of a GRB observation, selecting a standard spectral shape will introduce some systematics in the modulation curve. Analyzing the modulation curve both using the simulation and the 5-parameter fit would be recommended in that case.

Figure 5.30 shows the corrected modulation curves measured at $\chi = 0^\circ$ with the beam energies 511, 356, 288, and 200 keV. The polarized data have been here corrected using at each energy the mixture of two sets of experimentally measured 100% perpendicularly polarized data. The upper part of table 5.4 summarizes the polarization results obtained from the 3-parameter fit of those curves. We have included also the results from the analysis of the data measured at $\chi = 90^\circ$. The lower part of the table 5.4 provides the results obtained when analyzing the same data, but correcting for the non-polarized response using the 0% polarized modulation curves obtained from Monte Carlo simulations. Note that a polarization angle $\phi_\Pi$ is equivalent to $\phi_\Pi + 180^\circ$. The agreement between the results in the two halves of table 5.4 gives us confidence to use the POLAR simulation package to calculate the 0% polarization response, when this information is not available from the experimental data.

As expected from the Compton scattering cross section [1] the modulation factor decreases when increasing the beam energy. For a perfect polarimeter the 100% modulation factor can be calculated as:

$$\mu_{100}^{\text{analytic}} = \frac{d\sigma(\eta = 90^\circ) - d\sigma(\eta = 0^\circ)}{d\sigma(\eta = 90^\circ) + d\sigma(\eta = 0^\circ)} = \frac{\sin^2 \theta}{E' + E' - \sin^2 \theta} \quad (5.10)$$
Figure 5.30: Modulation curves (corrected for the experimentally calculated non-polarized response) obtained from the experimental data applying an offline threshold of 50 keV per hit. Top left: 511 keV. Top right: 356 keV. Bottom left: 288 keV. Bottom right: 200 keV.

where $d\sigma$ represents the Klein-Nishina cross-section. In the left side of figure 5.31 we present the calculation of $\mu_{100}$(analytic) for various incoming energies, at two fixed scattering angles ($\theta = 90^\circ$ and $\theta = 60^\circ$). The modulation factor is decreasing monotonously for all scattering angles.

The modulation factor also decreases when we lower the off-line software threshold applied to each energy deposition (fixed until now at 50 keV). We present in the right side of figure 5.31 a preliminary study of the experimental data using lower software thresholds, at 20 and 30 keV. The values of $\mu$ shown in the plot have been obtained with data taken at $\chi = 0^\circ$. The 0% response needed for the correction of the modulation curve was derived from perpendicularly polarized experimental data. It is evident that for a given beam energy the lower the software threshold, the lower the modulation factor obtained. This is explained taking into account the dependence between the energy deposited ($E - E'$) in the Compton interaction and the scattering angle $\theta$ (see equation 5.4). Large scattering angles correspond to large energy depositions. Since $\mu$ also increases with $\theta$, rejecting low energy depositions from the analysis leads to higher modulation factors. However, the software threshold shall not be too high to avoid losing too many events. Its value should be set according to the incoming photon energy. In the cases where
0% polarized curve produced with experimental data

<table>
<thead>
<tr>
<th>( E ) (keV)</th>
<th>( \chi = 0^\circ )</th>
<th>( \chi = 90^\circ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>511</td>
<td>( 34.5 \pm 0.5 ) 181.5 ± 0.4</td>
<td>( 35.1 \pm 0.5 ) 89.6 ± 0.4</td>
</tr>
<tr>
<td>356</td>
<td>( 44.4 \pm 0.6 ) 179.9 ± 0.4</td>
<td>( 45.0 \pm 0.6 ) -90.3 ± 0.4</td>
</tr>
<tr>
<td>288</td>
<td>( 51.2 \pm 0.7 ) 179.9 ± 0.4</td>
<td>( 50.3 \pm 0.6 ) 89.7 ± 0.4</td>
</tr>
<tr>
<td>200</td>
<td>( 51.0 \pm 0.9 ) 0.6 ± 0.5</td>
<td>( 49.8 \pm 0.8 ) 90.6 ± 0.5</td>
</tr>
</tbody>
</table>

Simulated 0% polarized signal

<table>
<thead>
<tr>
<th>( E ) (keV)</th>
<th>( \chi = 0^\circ )</th>
<th>( \chi = 90^\circ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>511</td>
<td>( 35.3 \pm 0.6 ) 179.8 ± 0.5</td>
<td>( 34.3 \pm 0.6 ) 91.6 ± 0.5</td>
</tr>
<tr>
<td>356</td>
<td>( 45.2 \pm 0.8 ) 181.2 ± 0.5</td>
<td>( 44.0 \pm 0.8 ) 89.6 ± 0.5</td>
</tr>
<tr>
<td>288</td>
<td>( 51.2 \pm 0.9 ) 179.5 ± 0.5</td>
<td>( 50.1 \pm 0.9 ) -90.1 ± 0.5</td>
</tr>
<tr>
<td>200</td>
<td>( 51.2 \pm 1.4 ) 178.2 ± 0.7</td>
<td>( 49.7 \pm 1.4 ) 92.9 ± 0.7</td>
</tr>
</tbody>
</table>

Table 5.4: Polarization results obtained of the ESRF data applying a 50 keV threshold on the energy deposited per hit. Corrected modulation curves have been fitted. The 0% polarized modulation curves have been constructed using experimental data (in the upper part of the table), and using simulated data (in the lower part of the table).

the incoming energy is unknown, such as in future GRB observations, the position of the software threshold for each event may be set studying the total energy deposited in the POLAR scintillator target.

![Figure 5.31](image.png)

Figure 5.31: Left: Analytical calculation of the modulation factor for a perfect polarimeter, done at two Compton scattering angles (\( \theta = 90^\circ \) and \( \theta = 60^\circ \)). Right: Modulation factor plot against the off-line threshold on the energy deposition per hit, for various beam energies. The modulation factors here presented have been obtained with the experimental data taken at \( \chi = 0^\circ \). The 0% polarized modulation curve, needed for the modulation curve correction, was constructed using the combination of data taken at \( \chi = 0^\circ \) and \( \chi = 90^\circ \).
5.2.4 Comparison with simulations

Monte Carlo simulations have been performed to reproduce the polarization results obtained at the synchrotron beam test. We have used the same simulated data as for the energy calibration method (see §5.2.2.3), putting the 64 files from each energy scan together. The whole process was performed twice: with 100% and 0% polarized incoming photons.

The modulation curves of both the polarized and non-polarized scans have been constructed rejecting neighboring bars, and applying a 50 keV threshold to the energy deposited at each bar. The corrected modulation curves presented in figure 5.32 are the result of applying equation 4.5 to the 100% and 0% simulated modulation curves calculated with the 511, 356, 288, and 200 keV energy scans. The fit of these curves to the function in equation 1.11 provides the $\mu_{100}$ for monochromatic photon fluxes of the energies selected at the ESRF beam test. Table 5.5 presents the fit results.

<table>
<thead>
<tr>
<th>Entries</th>
<th>χ²/ndf</th>
<th>Offset</th>
<th>Amplitude</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top left: 511 keV</td>
<td>33.02 / 21</td>
<td>4212 ± 20.2</td>
<td>-1517 ± 27.1</td>
<td>3242 ± 0.5</td>
</tr>
<tr>
<td>Top right: 356 keV</td>
<td>40.81 / 21</td>
<td>2270 ± 17.2</td>
<td>1329 ± 22.8</td>
<td>1790 ± 0.5</td>
</tr>
<tr>
<td>Bottom left: 288 keV</td>
<td>39.48 / 21</td>
<td>1866 ± 13.6</td>
<td>1594 ± 17.4</td>
<td>230 ± 0.5</td>
</tr>
<tr>
<td>Bottom right: 200 keV</td>
<td>33.22 / 21</td>
<td>717.9 ± 717.9</td>
<td>405.2 ± 11.3</td>
<td>87.4 ± 87.4</td>
</tr>
</tbody>
</table>

Figure 5.32: Modulation curves (corrected for the non-polarized response) obtained from the experimental data applying a 50 keV offline threshold per hit. Top left: 511 keV. Top right: 356 keV. Bottom left: 288 keV. Bottom right: 200 keV.

The comparison between the experimental and the simulated modulation factors is presented graphically in figure 5.33. The results are in good agreement for the three highest energy points. However, at 200 keV the simulation predicts a higher value than the one measured experimentally. This discrepancy points out
Table 5.5: Polarization results obtained from Monte Carlo simulations. As done with the experimental data, a 50 keV threshold was applied to the energy deposited per hit.

The need of a deeper study of the detector response at low energies. Lowering the off-line software threshold on the energy deposition per hit has also shown some unexpected features in the experimental data, probably related to the influence of some remaining cross-talk, the MAPM sensitivity variations, and the proximity to the detector threshold. The analysis of all these issues is at present ongoing.

![Figure 5.33](image)

Figure 5.33: Comparison between the modulation factors obtained from the ESRF data (upper part of table 5.4) and the Monte Carlo simulations of the POLAR DM beam test (table 5.5.)

The response of the POLAR detector at high energy, where the data are clean from systematics, is well understood and can be reproduced with Monte Carlo simulations. The results of the measurements performed with synchrotron radiation at ESRF, together with the laboratory experiments performed with the radioactive source, provide very valuable information on the performance of the POLAR detector, and validate the predictions of the GEANT4 Monte Carlo simulation package.
5.3 Space Qualification Tests

To guarantee that the POLAR detector will survive the launch inside a rocket and that it will be fully operational in the environmental conditions present in orbit, a series of space qualification tests have to be performed with the POLAR EQM. We present here only a general overview of the space qualification tests planned for the POLAR EQM. More details are given in reference [132]. The POLAR EQM will be qualified at the module level, followed by a final test with the complete EQM assembly. The central computer and power supply modules, which are important parts of the POLAR FM, need to be qualified as well.

The Hamamatsu MAPM H8500, a key component of the POLAR experiment, has already passed preliminary space qualification tests: it has been tested in thermo-vacuum (temperature range from -25°C to 55°C) as well as on a vibration table (up to around 13 Grms in random vibration mode). In addition, a destructive compression test has been performed on a non-working MAPM to see if it supports the stress of the scintillator target on its surface e.g. during vibration or thermal expansion. Tests have been performed applying a force up to 900 N (300 N correspond to 50 G). The MAPM glass window only broke after applying this very high stress level over several hours. This test proves that the MAPM will sustain the scintillator target load expected during launch. In the near future many other qualification tests with the MAPM and the rest of the POLAR EQM components will be performed. The most important ones are described below.

5.3.1 Environmental Stress Screening (ESS)

The Environmental Stress Screening (ESS) consists of a thermal cycling of the POLAR EQM within operational and non-operational temperature ranges, followed by vibration tests, and a second thermal cycling. At each of these steps, functional tests will be performed. The maximum and minimal operational and non-operational temperatures are platform dependent and will be discussed with the corresponding space agency. For the moment we assume standard limits often used for low Earth orbit missions: between -45°C and +85°C for non-operational, and between -25°C and +55°C for operational cycles.

Vibration tests will be performed with a random distribution of the frequencies during test and in full operation mode. Although the detector will be switched off during launching, operational vibration tests provide valuable information on the kind of electric problems that the launching process may cause. The vibration ranges have to be established together with the space agency responsible of the platform on which POLAR will be mounted. At present we assume a maximum of 10 Grms.
5.3.2 Electromagnetic inductance and conductivity tests

The goal of these tests is to detect the possible interference with other modules on the platform. Emission and inductance tests are usually performed. Detailed test procedures depend on the flight platform.

5.3.3 Thermo-Vacuum Test (TVT)

A thermal cycling of the full POLAR detector in vacuum, including operational and non-operational temperature ranges will be performed. This test usually serves as reference for the space qualification process. The POLAR EQM will be tested to higher limits than the final flight model. More and longer cycles during thermal tests and vibration will be performed, selecting a range $\sim 5^\circ C$ over and under the final qualification temperature range.

Finite element models have been created for the POLAR EQM and thermal as well as mechanical load studies have been performed. The results of theses studies give confidence in the current design.
Chapter 6

Background sources in space

The Monte Carlo simulation package allows to predict the performance of the detector in space, long before its launch. We have already described (§4.3.1) the expected response of POLAR to a GRB flux. In that occasion we considered that GRB photons would be the only particles arriving to the POLAR detector during the measurement. The main ingredient that may affect the predicted result, is the presence of background sources when the detector is flying around the Earth. In this chapter we describe the influence on POLAR of the most important background sources present in orbit. The data necessary for the characterization of these sources have been extracted from literature. Given that the level of background depends strongly on the orbit in which the detector is installed, we will discuss first of all the two possible orbits that have been considered for POLAR.

6.1 Orbital studies

The small size of POLAR allows it to be easily mounted as a piggy-back on a platform. The only restriction for the platform is that it must provide POLAR with a free-space observation, without any element in its construction to limit the POLAR field of view. In addition, it is important that the background rates in the platform orbit are controlled, and that they do not create problems for the polarization measurements.

Depending on the satellite purpose, there are various possible orbits for its location. We consider here the most common orbits: the Geostationary Orbit (GEO) and the Low Earth Orbit (LEO). Most of the satellites, including communication, weather observation, military, and research satellites, fly in one of these two orbits. For instance, communication satellites are often in the GEO, which allows them to stay all the time over the same region of the Earth. On the other hand, scientific satellites, specially those which study the Earth, are often flying on the LEO. Some scientific satellites, such as INTEGRAL, are located in a highly eccentric orbit where its closest position to Earth is about 10 000 km. In this way they can avoid the high background close to the Earth constituted by charged particles.
trapped by the geomagnetic field.

During the development of the POLAR detector two orbits have been under consideration: the GEO and the LEO.

### 6.1.1 Geostationary Orbit (GEO)

The Geostationary Orbit (GEO) is a geosynchronous orbit where the satellite is located above the equator and rotates around the Earth with the same period of rotation as the Earth. In this way the satellite position is almost constant, always above the same equatorial region of the Earth. The altitude of the orbit is usually around 35 000 km above the Earth surface. As already mentioned, this is the kind of orbit preferred for communication satellites. Since this kind of satellites is mainly dedicated to study or communicate with the Earth, an opportunity for POLAR would be to use the free place on the upper part of the satellite, facing deep space, to study GRBs.

The still position of the satellite above the Earth in the GEO orbit has as consequence that the background rate due to trapped charged particles is almost constant all along the orbit. We have calculated the expected electron and proton fluxes in the GEO using the data provided by the Space Environment Information System (SPENVIS) [133]. SPENVIS is a free-access tool created by the European Space Agency (ESA) to provide space environment data with a user-friendly interface. It includes models for charged particles which allow to calculate the spectrum of electrons and protons in different orbits and at the minimum or maximum solar activity. We have selected a GEO at 35 793 km altitude and 0° geographic latitude. The spectra from electrons and protons obtained from the average of a one day duration flight during the solar minimum are shown in figure 6.1.

![Spectra of charged particles in the GEO obtained from SPENVIS](image)

**Figure 6.1:** Spectra of charged particles in the GEO obtained from SPENVIS *Left:* Electrons spectrum. *Right:* Protons spectrum.

Trapped particles arrive to POLAR approximately randomly from the $2\pi$ space above it, since the platform shields from most of the upward going particles. To reproduce such a distribution we randomly select a point over a half sphere of 50 cm
radius above POLAR. The coordinates of the selected point give the momentum of the particle, always directed towards the center of the sphere. Then, in the same point a circle with radius $R_{\text{circ}} = 30$ cm is defined tangent to the sphere. The initial position of the particle is a point randomly taken from this circle. The total number of particles to be generated is calculated as the total rate in the considered energy range ($9.4 \times 10^7$ electrons cm$^{-2}$ s$^{-1}$ between 40 keV and 7 MeV, and $1.4 \times 10^7$ protons cm$^{-2}$ s$^{-1}$ between 600 keV and 400 MeV), multiplied by the duration of the measurement, and by the area of the circle ($\pi R_{\text{circ}}^2$). Due to the extremely large flux we have simulated only a 5 µsec and a 50 µsec measurement of electron and proton background, respectively. The number of particles obtained in each case are randomly generated with an energy following the spectra from figure 6.1. Table 6.1 summarizes the counting rates obtained in POLAR using the Monte Carlo simulation.

<table>
<thead>
<tr>
<th>GEO</th>
<th>Electrons</th>
<th>Protons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated particles (correspond to 5 µsec and 50 µsec, resp.)</td>
<td>$1.3 \times 10^9$</td>
<td>$1.9 \times 10^9$</td>
</tr>
<tr>
<td>Particles illuminating POLAR [Hz]</td>
<td>$1.2 \times 10^{11}$</td>
<td>$1.7 \times 10^{10}$</td>
</tr>
<tr>
<td>Particles interacting at least once in POLAR ($E_{\text{vis}} &gt; 5$keV) [Hz]</td>
<td>$5.2 \times 10^7$</td>
<td>0</td>
</tr>
<tr>
<td>Hits above 5keV in POLAR [Hz]</td>
<td>$5.8 \times 10^7$</td>
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</tr>
<tr>
<td>Counts in modulation curve [Hz]</td>
<td>$4.4 \times 10^6$</td>
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</tr>
<tr>
<td>Counts in modulation curve (excluding neighbors) [Hz]</td>
<td>$3.8 \times 10^6$</td>
<td>0</td>
</tr>
<tr>
<td>Effective area for hits [cm$^2$]</td>
<td>0.55</td>
<td>0</td>
</tr>
<tr>
<td>Effective area for Polarization [cm$^2$]</td>
<td>0.05</td>
<td>0</td>
</tr>
<tr>
<td>Effective area for Polarization (Far bars) [cm$^2$]</td>
<td>0.04</td>
<td>0</td>
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</tbody>
</table>

Table 6.1: Counting rates produced by electrons and protons in the GEO. We simulated only the flux in 5 µsec for electrons and 50 µsec for protons. All the rates have been scaled up to reproduce the expectations from a 1 sec measurement.

All protons have been stopped by the carbon fiber enclosure from POLAR, which has a thickness of 3 mm. However, the rates expected from electrons are extremely high. With such a high level of background, three orders of magnitude larger than the GRB flux, it would be impossible for POLAR to perform any polarization measurement. We can conclude that the GEO is an unacceptable orbit for POLAR.

### 6.1.2 Low Earth Orbit (LEO)

Any orbit in the altitude range $\sim 200-2000$ km is considered as a Low Earth Orbit (LEO). The inclination of the orbit, defined as the angle between the orbit plane and the Earth equator, can take any value between 0° (equatorial orbit) and 90° (polar orbit). The LEO is located below the inner Van Allen radiation belt, a band of high energy electrons and protons trapped by the Earth magnetic field. Since the magnetic dipole that is responsible for the Earth magnetic field is not at the center of the Earth, the magnetic axis does not coincide with the rotation axis. In con-
sequence, the altitude of the Van Allen radiation belts varies with the geographic latitude. The region where the inner radiation belt is the lowest is called the South Atlantic Anomaly (SAA), and is characterized by large fluxes of trapped electrons and protons.

Figure 6.2: Geographical distribution of charged particles in a 350 km altitude and 42° inclination LEO, obtained from SPENVIS Left: Electron distribution. Right: Proton distribution.

We consider a LEO with 350 km altitude and an inclination of 42°, which is the kind of orbit planned for the Chinese Tiang-Gong Space Lab. The orbit of the International Space Station (ISS) has similar characteristics. The typical rotational period of satellites in this kind of orbit is around 90 minutes. In figure 6.2 we show the distribution of particles along the orbit for a 1-day mission, obtained from SPENVIS selecting the conditions of a solar minimum. From the figures is evident that the fluxes of particles are everywhere negligible, excepting in the SAA region. High fluxes of electrons are also expected in the polar cap regions (polar horns), but for a 42° orbit this region is hardly ever reached.

We have studied the fluxes of trapped particles inside the SAA, to evaluate if the detector would be able to perform GRB polarization measurements in this part of the orbit.

6.1.2.1 SAA particles

Using the data provided by SPENVIS we have calculated the average flux inside the SAA. We defined the SAA as the region where $1.9 < B < 2.4$ and $0.23 < L < 0.29$, plus the region where $1.2 < B < 1.9$ and $(0.10 \times B + 0.10) < L < (0.03 \times B + 0.17)$. The coordinates $(B, L)$ are the geomagnetic McIlwain coordinates [134], in which the SPENVIS data are provided. Figure 6.3 represents the particle distribution maps from figure 6.2 in the geomagnetic coordinate system. The definition of the SAA frontiers has been chosen so that all the colored area ($\text{flux} \gtrsim 1 \text{ cm}^{-2} \text{ s}^{-1}$) is contained. In average, the time spent in the SAA constitutes 6% of the total time.
The spectra of electrons and protons, averaged for the selected SAA region, are depicted in figure 6.4. Particles have been randomly generated on the surface of a circle ($R_{circ} = 30$ cm), in the same way as it was done to simulate the particles in the GEO (§6.1.1). We have simulated electrons corresponding to a 1 msec duration measurements, due the high flux ($4.5 \times 10^7$ electrons cm$^{-2}$ s$^{-1}$ between 40 keV and 7 MeV). Regarding trapped protons, a 1 sec duration measurement was simulated (proton flux $\sim400$ protons cm$^{-2}$ s$^{-1}$ between 600 keV and 400 MeV).

The energy deposited by protons in the POLAR scintillator target has to be corrected by the Birks effect (§4.2.1). Figure 6.5 shows the spectra of energies recorded in the detector by the simulated SAA particles. Figure 6.6 shows the incoming energy spectra from all the simulated SAA particles, and the incoming energy spectra from those who interacted in the POLAR scintillator target. We
consider that the particle interacted if it produced at least one hit with $E_{vis} > 5$ keV. From figures 6.5 and 6.6 we deduce that a large amount of electrons are stopped by the POLAR carbon fiber enclosure. The electrons that reach the POLAR sensitive area produce hits with less than 100 keV deposited energy. Protons below 20 MeV do not reach the scintillator target, but higher energy protons can produce very large energy depositions (up to 70 MeV) in the detector.

The numerical results of the simulation of SAA trapped particles are presented in table 6.2. The numerical values confirm our observation from the spectra: less than 1% electrons reach the POLAR scintillator target. However, given the very high electron flux, the amount of events that pass all the conditions (table 4.5) to be accepted in the construction of the modulation curve is very high. Taking into account that we expect around 7000 counts/sec from a standard GRB, such a high level of background would overwhelm our signal.

Around 17% of all the protons illuminating POLAR reach its scintillator target. A typical proton will pass through the whole target, releasing some energy in
The flux has been calculated as an average of the fluxes inside the anomaly. (*) Given the large amount of electrons, we simulated the flux corresponding to a 1 msec measurement. All the counting rates have been scaled to reproduce the expectations from a 1 sec measurement.

In conclusion, even if most of the particles are stopped by the POLAR enclosure, the on-line trigger, and the off-line selection cuts, the high electron flux reaching the POLAR scintillator target will prevent us from performing GRB polarization measurements. Simulations performed with the electron rates provided by SPENVIS for the region of the polar horns give also too high fluxes for POLAR to perform measurements. For this reason, the detector will not collect data during the passages through the SAA and the polar horns. A decision whether POLAR will be switched off or not in the SAA will be taken at a later stage. However, these regions constitutes only a small fraction (6%) of the whole orbit. Since the fluxes of trapped particles in the rest of the LEO is very small, this kind of orbit constitutes the best option to fly POLAR.

### 6.2 Background sources outside the SAA

Once selected the LEO as the orbit where POLAR will be flying, we focus on characterizing the background sources expected in this region. We discuss here the most important background sources: the diffuse cosmic X-rays, cosmic particles such as neutrons, electrons, protons, and positrons, and finally the strongest...
persistent X-ray source: the Crab nebula.

6.2.1 Diffuse cosmic X-ray background

Outside of the SAA the POLAR background is dominated by the diffuse Cosmic X-ray Background (CXB) [63]. The diffuse sky background, produced by the integrated emission of extragalactic sources, was discovered in the sixties by rocket borne X-ray counters [135]. Since then, CXB has been measured and studied in a very wide energy range from below 1 keV to about 100 GeV (see [126] and references therein). The emission below $\sim$5 keV can be accounted for by resolved AGNs [136]. AGNs are thought to still dominate the CXB emission up to hundreds of keV, but difficulties related with the resolution of individual sources at high energies [127, 137] hinder the proof of this hypothesis. From $\sim$300 keV to 10 MeV the CXB is attributed to Type Ia supernovae [138], and above 30 MeV to unresolved blazars [139].

The spectrum of the diffuse cosmic hard X-ray background, measured by the High Energy Astronomical Observatory 1 (HEAO1) and the Cosmic Gamma-Ray Observatory (CGRO), has been parametrized [126] using the function:

$$
\begin{align}
3–60\text{ keV} & : \\
\quad f(E) & = 7.877E^{-0.29}e^{-E/41.13} \\
\text{> 60 keV} & : \\
\quad f(E) & = 0.0259 \left(\frac{E}{60}\right)^{-5.5} + \\
& \quad + 0.504 \left(\frac{E}{60}\right)^{-1.58} + \\
& \quad + 0.0288 \left(\frac{E}{60}\right)^{-1.05}
\end{align}
$$

with $f(E)$ in units of $\text{keV cm}^2\text{s sr}$. Later measurements [127] of the CXB, performed in the 5–100 keV energy range with the INTEGRAL satellite, required an increment of 10% in the absolute normalization factor to fit their results. A new analysis [140] of INTEGRAL data in the 20–200 keV provides results which, although compatible with the ones previously published, disfavor the need of the mentioned 10% scaling. For our calculations of the diffuse CXB we have decided to consider the highest rates reported, i.e. those from reference [127]. The predictions presented in this section constitute therefore an upper limit on the expected diffuse background to affect the POLAR detector.

Photons from diffuse cosmic X-ray background are distributed in the same energy range as GRB photons and their interaction inside the POLAR target is indistinguishable from them. As GRBs are generally not longer than a few seconds, the CXB level can be considered as constant during a GRB measurement. POLAR will measure before, during, and after each GRB observation to evaluate the level of background and subtract it from the signal. The duration of the measurement outside the burst determines the precision to which we know the level of the background.
Even if we will be able to precisely subtract the diffuse X-ray background, it is important to evaluate how POLAR reacts to this emission. We have simulated the CXB using equation 6.1 with a 10% higher normalization factor as suggested in [127]. Diffuse background illuminates POLAR isotropically arriving from all directions except from the bottom, where POLAR will be protected by the Earth and the satellite. This distribution is reproduced in the same way as we did for the GEO particles (§6.1.1), defining a half sphere of 50 cm radius and a circle with radius $R_{circ} = 30$ cm. The total number of photons to be generated is calculated as the total rate in the considered energy range (6.71 photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ between 5 keV and 1000 keV), multiplied by the duration of the measurement (1 sec), by the area of the circle ($\pi R_{circ}^2$), and by the solid angle (2\pi). Figure 6.7 shows the simulated incoming spectrum corresponding to a one second measurement. Figure 6.8 shows the distribution of hits inside the POLAR scintillator target, and the number of hits produced by each incoming CXB photon. Due to the relatively low energy of this background photons, they are mostly detected in the outer layers of the target.

The numerical results obtained from the simulation of the CXB are summarized in table 6.3. The scintillator target recorded 8674 hits s$^{-1}$, i.e. 5.4 hits bar$^{-1}$ s$^{-1}$ in average. From the 54 606 incoming CXB photons, only 746 s$^{-1}$ produced two hits fulfilling all conditions to be accepted in the modulation curve$^1$. These photons constitute the real background source for polarization measurements, smoothing the eventual modulation from the GRB signal. The spectra of their incoming energy and the distance between their two largest energy depositions are presented in figure 6.9. The rate of events in the modulation curve induced by the diffuse CXB

---

$^1$In the discussions along this chapter, and unless stated otherwise, we will always consider the modulation curve where events with the two largest energy hits in neighboring bars have been rejected.
Figure 6.8: *Left: Distribution of hits produced by the CXB in the POLAR target. Right: Number of hits produced in the POLAR target per event. In both cases only hits with $E_{\text{vis}} > 5$ keV have been included.*

<table>
<thead>
<tr>
<th>Diffuse Cosmic X-ray Background (CXB)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated particles [Hz]</td>
<td>119 780</td>
</tr>
<tr>
<td>Particles illuminating POLAR [Hz]</td>
<td>54 606</td>
</tr>
<tr>
<td>Particles interacting at least once in POLAR ($E_{\text{vis}} &gt; 5$keV) [Hz]</td>
<td>8674</td>
</tr>
<tr>
<td>Hits above 5keV in POLAR [Hz]</td>
<td>10 223</td>
</tr>
<tr>
<td>Counts in modulation curve [Hz]</td>
<td>891</td>
</tr>
<tr>
<td>Counts in modulation curve (excluding neighbors) [Hz]</td>
<td>746</td>
</tr>
<tr>
<td>Effective area for hits [cm$^2$]</td>
<td>205</td>
</tr>
<tr>
<td>Effective area for Polarization [cm$^2$]</td>
<td>21.0</td>
</tr>
<tr>
<td>Effective area for Polarization (Far bars) [cm$^2$]</td>
<td>17.6</td>
</tr>
</tbody>
</table>

Table 6.3: Counting rates produced in POLAR by CXB.

is 10 times lower than the expected rate from strong short GRBs.
Figure 6.9: Left: Spectrum of incoming energies from the CXB photons that contribute to the modulation curve. Right: Distribution of the distance between the two largest energy hits, i.e., the ones included in the modulation curve. In both cases neighboring bars have been excluded.
6.2.2 Neutrons

An instrument like POLAR, mounted on a satellite flying on the upper part of the Earth atmosphere, is continuously being hit by neutrons. The neutron radiation environment is produced mostly by the collision of cosmic charged particles either with nuclei in the atmosphere (albedo neutrons) or with the material of the spacecraft (local neutrons) [141]. Neutrons are dangerous for POLAR because in their interaction with the scintillator target they can produce couples of hits undistinguishable from photon Compton interactions. If such events happen during a GRB observation, they will contribute to the modulation curve and can blur the polarization measurement. Therefore, it is important to evaluate the POLAR neutron radiation environment and its influence on the POLAR performance [142].

The neutron radiation environment in the LEO has been measured with nuclear photoemulsion detectors inside and outside the MIR station [141, 146] as well as with $^3$He proportional counters inside the International Space Station [147]. Being POLAR a detector to be located on the external side of a satellite, the results from Lyagushin et al. [146] reproduced in figure 6.10 represent the closest description of POLAR neutron radiation environment that we can implement without a precise knowledge of the spacecraft. The orbit of the MIR station had during the measurements an inclination to the equatorial plane of $i \approx 52^\circ$ and an altitude of $\sim 400$ km. Along the orbit the largest counting rate is observed during the SAA passages, followed by the high latitude regions, while equatorial regions present the lowest neutron rates. We have selected the neutron spectrum at high latitude regions (line 2 in figure 6.10) to describe the POLAR neutron radiation environment since this is the upper limit of the neutron induced background when excluding the SAA. POLAR will not take measurements inside the SAA due not only to the large neutron rate, but mostly to very high rates of electrons (§6.1.2.1) which do not allow for GRB observations. The total neutron rate in the 0–15 MeV energy range was found to be 0.3 neutrons cm$^{-2}$ s$^{-1}$ (0.076 neutrons cm$^{-2}$ s$^{-1}$) in the high latitude (equatorial) regions of the orbit. When using the data obtained when the detector was inside the MIR station, the rate rose to 6.02 neutrons cm$^{-2}$ s$^{-1}$.

A specific routine has been implemented in ROOT to generate the POLAR neutron background. Several points have been extracted from curve number 2 in figure 6.10 and a histogram with 15000 bins in the range from 0 to 15 MeV was made by inter/extra-polation from the extracted values. The energies of the neutrons in the output event list are randomly generated following the distribution given by the previous histogram. Neutrons come to POLAR from all sides. To reproduce this distribution neutrons were randomly generated as we did with the GEO particles (§6.1.1), with the difference that here we considered not only half, but the whole sphere to produce the momentum vectors. The total number of neutrons to be generated is calculated as the total rate (0.3 neutrons cm$^{-2}$ s$^{-1}$), multiplied by the duration of the measurement and by the area of the circle ($\pi R_{circ}^2$) where the neutrons were distributed. The left plot in figure 6.11 shows the incoming neutron spectrum corresponding to a 100 second measurement.
Fig. 1. Neutron energy spectra inside the Mir station. Fissionable foils (SPECTR-N), nuclear emulsions (TDP): (—–) SPECTR-N, 20 g = cm^2, (- - - - -) SPECTR-N, 30 g = cm^2, (•; •; •) TDP, 40 g = cm^2.


Fig. 2 shows the energy spectra of neutrons outside the station. They were measured by the "Granat-S" instrument by means of the organic scintillator (stilbene) in the Earth equator region, at the high latitudes, as well as in the region of South Atlantic Anomaly. The ratio of the neutron fluxes in the region of the high latitudes at the equator is 4–6. The fluxes of the neutrons in the South Atlantic Anomaly exceed those at the high latitudes by 10–20 times. Besides, there is the peak in the energy region of 6–12 MeV, which is probably caused by the straight processes of the proton interactions with the nucleus neutrons of the station matter. It is characteristic for the spectrum of neutrons generated in "thick" targets while the protons of tens-hundreds MeV energy interact with the targets mentioned. In the figure there is the monthly average-weighted energy neutron spectrum, which is in good agreement with the shape of the spectra obtained by means of passive spectrometers in the same region of energy.

Figs. 3 and 4 show the results of the experiments on the measurements of the neutrons and spectra of high-energy neutrons (E¿ 20 MeV) which were obtained by using the scintillator detectors on the basis of the inorganic crystals.

Figure 6.10: Neutron energy spectra measured outside the MIR station with organic scintillator GRANAT-S [146]. The curve numbers correspond to: 1-Equatorial region, 2-High latitude region, 3-South Atlantic Anomaly, 4-Average monthly spectrum. Excluding the South Atlantic Anomaly, where POLAR will not take measurements, we have selected curve number 2 as an upper limit to the neutron rates affecting POLAR during GRBs observations.

Figure 6.11: Left: Simulated spectrum of neutrons reproducing curve 2 from figure 6.10. The number of entries corresponds to the total number of neutrons arriving in 100 seconds on a surface of 30 cm radius. Right: Simulated spectrum of energies deposited by neutrons on the POLAR scintillator target (before the correction for the Birks effect had been applied, see text) during a 100 sec measurement. The total spectrum is the sum of the energy deposited when the neutron interacted with Carbon atoms, and when it did with Hydrogen atoms (proton).
We have used the high precision neutron tracking QGSP_BERT_HP physics list [106] from GEANT4 to accurately describe the neutron interaction cross sections (stored in the G4NDL3.11 library). Figure 6.11 (right) represents the energy deposited in the POLAR target by the neutron background whose incoming spectrum was shown in the left side of the same figure. We can see that the largest contribution to the total energy deposited comes from neutron interactions with the hydrogen of the scintillator material, being the interactions with Carbon ($^{12}\text{C}$) only important at lower energies.

Plastic scintillators are compounds of hydrogen (H) and carbon (C) atoms in a ratio approximately 1:1. The cross section for neutron scattering on H and C is presented in figure 6.12. Neutrons below 5 MeV scatter elastically in either H or C nuclei. At higher energies the cross section for inelastic scattering in C increases, becoming the scattering in C atoms the most probably interaction undertaken by the incoming neutrons. The cross sections for neutrons and photons with energies of few MeV are similar, so that they cannot be distinguished by their interaction depth in the considered energy range [144].

![Figure 6.12: Differential cross section for the different processes that neutrons can undertake when interacting with plastic scintillator, a material composed by about 50% carbon and 50% hydrogen. Taken from [143].](image)

The energy lost by a neutron in each of its interactions can be expressed [145] as:

$$\frac{E'}{E} = \frac{A^2 + 1 + 2A \cos \theta}{(A + 1)^2}$$

(6.2)
where $E$ and $E'$ are the energies of the neutron before and after the scattering, respectively. $A$ is the atomic number of the nucleus in which the neutron scattered, and $\theta$ is the scattering angle. The deposited energy ($E_{dep}$) is fully absorbed by the recoil nucleus (H or C) and can be calculated as:

$$E_{dep} = E - E' = E \left(1 - \frac{E'}{E}\right) = E \left(\frac{2A(1 - \cos \theta)}{(A + 1)^2}\right)$$  \hspace{1cm} (6.3)

The neutron deposits the maximum energy when it backscatters, i.e. $\cos(\theta) = -1$, and the minimum when it continues its path without deviation, i.e. $\cos(\theta) = 1$.

$$E_{dep,\text{min}} = E - E'_{\text{max}} = 0$$  \hspace{1cm} (6.4)

$$E_{dep,\text{max}} = E - E'_{\text{min}} = \frac{4A}{(A + 1)^2}E$$  \hspace{1cm} (6.5)

For $E < 10\text{MeV}$, the scattering is mostly s-wave, thus independent of $\theta$. In that case $E'$ and $E_{dep}$ are uniformly distributed in the ranges:

- for H ($A = 1$) : $E_{dep} \in [0, E]$
- for C ($A = 12$) : $E_{dep} \in [0, 0.28E]$

This effect can be seen in figure 6.13.

Figure 6.13: Energy deposited vs. incoming energy for the neutrons detected in the POLAR target in a 100 sec measurement. Left: Result when the neutron interacts with a proton. One can clearly see the uniform distribution of deposited energies from 0 to the incoming energy of the neutron. Right: Result when the recoil particle is a $^{12}\text{C}$ atom. Here the deposited energy is uniformly distributed between 0 and $\sim 0.28E_0$. The line appearing at $E_0 > 5000 \text{ keV}$ in the lower part of the graph corresponds to inelastic interactions of neutrons with $^{12}\text{C}$ atoms.

When neutral particles as $\gamma$-rays or neutrons arrive to a scintillator material, light is emitted in response to the ionization produced by the recoil particle (electron, proton, or heavier nuclei [116]). The recoil particles when neutrons interact
with the atoms of the plastic scintillator are either protons or $^{12}\text{C}$ atoms. In either case, the energy deposited by the neutron in the scintillator ($E_{\text{dep}}$, figure 6.11, right) must be corrected for the Birks effect to calculate the amount of energy ($E_{\text{vis}}$) that is transformed into light and is therefore detectable. We have calculated the visible energy for protons, carbon nuclei, and alpha particles using expressions 4.2, 4.3, and 4.4, respectively. For electrons and gamma the visible energy is equal to their deposited energy.

Figure 6.14: Comparison between the spectrum before ($E_{\text{dep}}$) and after ($E_{\text{vis}}$) the correction for the Birks effect. The result with protons as the recoil particle is shown in the left and with $^{12}\text{C}$ atoms in the right side. It is evident that after the correction the carbon recoil energy is strongly shifted to lower energies. The inset in the right hand side figure show a zoom of its Birks corrected corrected spectrum.

Figure 6.15: Left: Distribution of hits produced by neutrons in the POLAR target. Right: Number of hits produced in the POLAR target per event. In both cases only hits with $E_{\text{vis}} > 5$ keV have been included.

The result of applying the correction for the Birks effect on the spectra from figure 6.11 is presented in figure 6.14. Figure 6.15 shows the distribution of hits inside the target, and the number of hits produced by each neutron. Table 6.4 summarizes the response of POLAR to the neutron background. According to it, 409 hits s$^{-1}$ will be produced by the neutron background in the POLAR target. The
number of neutrons that scatter in the target producing two hits indistinguishable from a photon Compton interaction amounts to 47 Hz (when excluding neighboring bars). These are the neutrons that can blur the polarization measurement. For these dangerous neutrons, the incoming energy and the distance between the two highest energy hits has been plotted in figure 6.16.

<table>
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<tr>
<th>Neutrons</th>
<th></th>
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</thead>
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<td>892</td>
</tr>
<tr>
<td>Particles illuminating POLAR [Hz]</td>
<td>379</td>
</tr>
<tr>
<td>Particles interacting at least once in POLAR ($E_{\text{vis}} &gt; 5\text{keV}$) [Hz]</td>
<td>169</td>
</tr>
<tr>
<td>Hits above 5keV in POLAR [Hz]</td>
<td>409</td>
</tr>
<tr>
<td>Counts in modulation curve [Hz]</td>
<td>66</td>
</tr>
<tr>
<td>Counts in modulation curve (excluding neighbors) [Hz]</td>
<td>47</td>
</tr>
<tr>
<td>Effective area for hits [cm$^2$]</td>
<td>536</td>
</tr>
<tr>
<td>Effective area for Polarization [cm$^2$]</td>
<td>209.2</td>
</tr>
<tr>
<td>Effective area for Polarization (Far bars) [cm$^2$]</td>
<td>150.0</td>
</tr>
</tbody>
</table>

Table 6.4: Counting rates produced in POLAR by the neutron background.

Figure 6.16: Left: Incoming energy of the neutrons which are dangerous for POLAR, i.e., those that increment the number of counts in the modulation curve. Right: Distance between the two highest energy depositions produced by the "dangerous" neutrons.

The rate of events in the modulation curve induced by neutrons, obtained simulating the neutron background measured outside the MIR station [146], is 100 times lower than the expected rate from strong short GRBs, and 15 times lower than the expected from the diffuse X-ray background. The results here presented constitute the upper limit for the POLAR neutron background, since the input data used for the analysis corresponds to the maximum neutron flux measured outside the SAA. A more detailed knowledge of the neutron radiation environment where
POLAR will be involved is only possible when having access to a detailed model of the spacecraft carrying the polarimeter.

6.2.3 Electrons

Electrons able to fake a photon Compton interaction in POLAR are in the energy range from \( \sim 50 \text{ keV} \) to \( \sim 5 \text{ MeV} \), while protons are in the range from \( \sim 20 \text{ MeV} \) to \( \sim 150 \text{ MeV} \). The geomagnetic cutoff along the orbit considered for POLAR is always \( \gtrsim 1 \text{ GV} \), so that the direct cosmic ray flux is not relevant for us. In the SAA the fluxes are very high and POLAR will not take data. We therefore consider sub-cutoff particles as possible constituents of the POLAR charged particle background.

We have searched in the literature for measurements of cosmic electrons, either from reentrant albedo electrons, or produced by primary cosmic rays that interact with the residual atmosphere, giving electrons and protons which are below the geomagnetic cutoff rigidity [148]. In particular, protons interacting with the Earth atmosphere produce pions that decay producing electrons and positrons: \( \pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm \). The intensity of secondary electrons can be of the same order of magnitude as the one of the primary cosmic flux [149]. Reentrant albedo particles, on the other hand, are cosmic particles that come towards the Earth, are then deflected upwards by the magnetic field, and then deflected downwards again. They enter the detector from above but they are not coming directly from outer space.

The Payload for Antimatter-Matter Exploration and Light-nuclei Astrophysics (PAMELA) and the Alpha Magnetic Spectrometer (AMS-01) experiments have performed measurements of cosmic rays over a wide energy range. In particular, they have measured leptons at energies above about 100 MeV [148], below or around the geomagnetic cutoff. Electrons of such a high energy can be rejected by POLAR when applying an upper limit on the total energy deposited, or on the number of bars fired by each incoming particle. Measurements of low energy electrons have been performed by the instrument MARIA-2\(^2\) [149] on board the MIR station, and EXPLORER XVIII [150] on the IMP-1 satellite. The MARIA-2 energy range spans from about 20 MeV to about 80 MeV, just above our region of interest. The EXPLORER XVIII energy range, between 2.7 and 7.5 MeV, would be more suited. Unfortunately for us, the IMP-1 satellite was an interplanetary mission taking data at a distance of about 125 000 km from the Earth. We cannot assume such fluxes to be the same in the POLAR orbit, only \( \sim 400 \text{ km} \) high.

We have selected the data from AMS-01 and MARIA-2 to estimate the POLAR electron background. Those instruments were flying in orbits (\( \sim 350 \text{ km height, } \sim 50^\circ \text{ inclination} \)) close to the one expected for the Chinese Tiang-Gong Space Lab (§6.1.2). In addition, AMS-01 and MARIA-2 were flying almost simultaneously (in 1998, and from 1995 to 1997, respectively) so that the solar activity was similar.

\(^2\)Also spelt as MARYA, MARIYE, or MARIYA in the literature.
during both measurements. They flew during a solar minimum, when the cosmic ray flux on the Earth atmosphere should be largest, and their measured intensity is larger than the ones observed from PAMELA. Therefore, using the AMS-01 and MARIA-2 data allows us to set an upper limit on the expected electron rates for POLAR.

In figure 6.17 we present the data of the four experiments extracted from the literature, together with a power law fit of the AMS-01 and MARIA-2 results (black line) whose mathematical expression is the following:

\[ f(E) = 9113 \cdot E^{-2.30} \]  

(6.6)

where the energy \( E \) is given in keV and the \( f(E) \) in units of electrons cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) keV\(^{-1}\).

We have used equation 6.6 to estimate the POLAR electron environment in the energy range from 40 keV to 10 MeV. This constitutes a one order of magnitude extrapolation of the measured data towards lower energies. Although we cannot guarantee that the tendency observed by MARIA-2 instrument is kept, it can give an idea of the expected rates in our energy range, where no measurements have been reported. With our extrapolation, the total rate expected from electrons in the 40 keV – 10 MeV window is about 58 electrons cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\).

We have simulated a flux of electrons uniformly distributed in a 2\(\pi\) solid angle above POLAR, in the same way as we did for the diffuse photon background. Electrons are expected to come from all directions, but the presence of the satellite will
shield POLAR from the upcoming ones. The simulated initial energy distribution, following equation 6.6, is shown in the left side of figure 6.18. In the right side of the same figure one can see the spectrum of energies measured in the POLAR scintillator target. Simulations show that most of the incoming flux is absorbed by the 3 mm thick carbon fiber enclosure box. The distribution of the hits produced by electrons in the POLAR target is presented in figure 6.19. It is clear that electrons do not usually penetrate far inside the detector, being the outermost scintillator bars the most often fired. If on flight the electron background would turn out to be higher than expected, the “walls” of the POLAR target could be used as an anticoincidence shield.

![Figure 6.18: Spectra from simulated electrons. Left: incoming energies, produced following equation 6.6. Right: energy detected in the POLAR scintillator bars.](image)

![Figure 6.19: Left: Distribution of hits produced by electron in the POLAR target. Right: Number of hits produced in the POLAR target per event. In both cases only hits with $E_{vis} > 5$ keV have been included.](image)

Table 6.5 reflects the numerical results of the simulation of electrons. From the high flux arriving to the detector, only $3484 \text{ hits s}^{-1}$ are produced in the POLAR target. This corresponds in average to $\sim 2.2 \text{ hits bar}^{-1} \text{ s}^{-1}$ so that the probability of

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measuring a two bar accidental coincidence due to electrons is very low. The num-
ber of electrons that produce two hits indistinguishable from a photon Compton
interaction amounts to 61 Hz. For those electrons the incoming energy distribution
and the distance between the two largest energy hits has been plotted in figure 6.20.

<table>
<thead>
<tr>
<th>Electrons</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated particles [Hz]</td>
<td>1 027 250</td>
</tr>
<tr>
<td>Particles illuminating POLAR [Hz]</td>
<td>467 201</td>
</tr>
<tr>
<td>Particles interacting at least once in POLAR ($E_{\text{vis}} &gt; 5\text{keV}$) [Hz]</td>
<td>1682</td>
</tr>
<tr>
<td>Hits above 5keV in POLAR [Hz]</td>
<td>3484</td>
</tr>
<tr>
<td>Counts in modulation curve [Hz]</td>
<td>78</td>
</tr>
<tr>
<td>Counts in modulation curve (excluding neighbors) [Hz]</td>
<td>61</td>
</tr>
<tr>
<td>Effective area for hits [cm$^2$]</td>
<td>4.7</td>
</tr>
<tr>
<td>Effective area for Polarization [cm$^2$]</td>
<td>0.21</td>
</tr>
<tr>
<td>Effective area for Polarization (Far bars) [cm$^2$]</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Table 6.5: Counting rates produced in POLAR by the electron background.

Figure 6.20: Left: Spectrum of incoming energies from the electrons contribut-
ing to the modulation curve. Right: Distribution of the distance between the two
largest energy hits, i.e., the ones included in the modulation curve. In both cases
neighboring bars have been excluded.
6.2.4 Protons

The AMS-01 instrument has observed fluxes of protons at various geomagnetic latitudes [151] in the energy range from 100 MeV to 200 GeV (see figure 6.21, left). We have selected the values corresponding to the equatorial region and to the highest geomagnetic latitude reached in a 42° inclination orbit to estimate the proton background for POLAR. The spectra obtained are presented on the right side of figure 6.21. The rate expected from protons in the energy range from 10 MeV to 500 MeV amounts to $5.6 \times 10^{-5}$ protons cm$^{-2}$ s$^{-1}$ sr$^{-1}$. This corresponds, scaled to a $R_{circ} = 30$ cm surface and a $2\pi$ solid angle above POLAR, to less than 1 proton s$^{-1}$. We can conclude from that result that the expected flux of protons is negligible for POLAR.

Figure 6.21: Left: Spectrum of protons as observed by the AMS-01 experiment [151]. Right: Extrapolation of the spectrum of sub-cutoff protons towards lower energies. The data corresponding to the equatorial region and to the maximal geomagnetic latitude reached in a 42° orbit have been selected since they represent the two extreme values in the expected POLAR orbit.
6.2.5 Positrons

In the interaction of primary cosmic rays with the Earth atmosphere not only electrons and protons, but also positrons are produced. The MARIA-2 instrument, already mentioned in section 6.2.3, has measured the positron in the energy range from 20 MeV to 80 MeV [149]. We have fitted their observed data with the power law function:

\[ f(E) = 11.14 \cdot E^{-1.70} \]  \hspace{1cm} (6.7)

where \( E \) is given in keV and \( f(E) \) has units of positrons cm\(^{-1}\) s\(^{-1}\) sr\(^{-1}\) keV\(^{-1}\). The fit is shown in figure 6.22.

![Figure 6.22: Positron spectrum as measured by the MARIA-2 instrument [149]. The solid line is a power law fit of the form of equation 6.7.](image)

We have simulated positrons in the energy range from 40 keV to 10 MeV, where according to equation 6.7 the rate expected is 1.17 positrons cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\). Positrons lose all their kinetic energy via multiple scattering in the first layers of material that they encounter, which corresponds in the case of POLAR to the carbon fiber outer enclosure box. In this sense positrons behave in a similar way to electrons. But unlike them, once positrons are at rest they annihilate with local electrons giving birth to two 511 keV photons emitted back to back. One of these photons travels away from the detector, but the other enters the POLAR target where it likely Compton scatters producing two hits that fulfill all criteria to enter in the modulation curve. This fact is reflected in the spectrum of the total energy deposited per each incoming positron (figure 6.23) where a Compton edge around 400 keV is clearly distinguishable.

Figure 6.24 shows the spectra of a standard GRB (\( F_{\text{tot}} = 10^{-5} \) erg cm\(^2\), \( \alpha = -1, \beta = -2.5, E_{\text{peak}} = 200 \) keV, duration=1 sec) compared with the spectra of various background sources. We can see that, while the incoming spectra (left) presents in all cases an exponential decay, the spectra of total deposited energy (right) by positrons is clearly distinguishable from the rest of the sources. This difference can be used to reject a large portion of the events produced by positrons. Given the power law shape of the GRB spectrum, only a few GRB photons leave
Figure 6.23: Spectrum of the total energy deposited by positrons in the POLAR target. **Left:** For all events. **Right:** Only for the events that contribute to the modulation curve (neighboring bars rejected).

Figure 6.24: Spectra of the events in the modulation curve: comparison between a standard GRB and the background sources. **Left:** Spectra of incoming energies. **Right:** Spectra of total deposited energies.

A total energy deposition above around 200 keV. This was the reason for rejecting all the events with a total energy deposition over 250 keV, as already mentioned in table 4.5. In table 6.6 we summarize the effect of this cut on various sources. It is evident that the cut is efficient in reducing the incidence of positron background. Figure 6.25 illustrate the dependence of the number of events arriving to the modulation curve (neighboring bars excluded) as function of the cut applied to the total energy deposited. When the total $E_{\text{vis}}$ cut is fixed at 250 keV we reduce the GRB signal by only $\sim$5%, while the total background is reduced by about 50%. The rates of counts in the modulation curves discussed in the present chapter, and the modulation curves from chapter 4, have been calculated already applying this cut.

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Table 6.6: Number of counts in the modulation curve from the GRB and various background sources, before and after the cut on the total energy deposition was applied (neighboring bars have been rejected).

<table>
<thead>
<tr>
<th>Source</th>
<th>No cut on total $E_{vis}$</th>
<th>Total $E_{vis} &lt; 250$ keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRB</td>
<td>6891</td>
<td>6453</td>
</tr>
<tr>
<td>CXB</td>
<td>764</td>
<td>746</td>
</tr>
<tr>
<td>Neutrons</td>
<td>73</td>
<td>47</td>
</tr>
<tr>
<td>Electrons</td>
<td>175</td>
<td>61</td>
</tr>
<tr>
<td>Positrons</td>
<td>1356</td>
<td>420</td>
</tr>
<tr>
<td>Crab</td>
<td>27</td>
<td>24</td>
</tr>
<tr>
<td>Total Background</td>
<td>2405</td>
<td>1298</td>
</tr>
<tr>
<td>SNR</td>
<td>2.87</td>
<td>4.97</td>
</tr>
</tbody>
</table>

We have simulated the positrons uniformly distributed in a $2\pi$ solid angle above POLAR. The spectrum of incoming energies simulated according to equation 6.7 is presented in the figure 6.26 together with the spectrum of the energy deposited. The left side of figure 6.27 shows the distribution of the hits inside the POLAR target. It is clearly visible that the hits are not preferentially distributed on the walls of the detector, as it happened with the electrons, but they are uniformly distributed in the target, as expected from the 511 keV photons produced by annihilation.

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which corresponds in average to 4.7 hits bar\(^{-1}\) are summarized in table 6.7. Positrons produce 7556 hits s\(^{-1}\) conditions to contribute to the modulation curve is 420 s\(^{-1}\) double hit events is present. The number of positron events which fulfill all hits with \(E_{vis} > 5\) keV have been included.

The final numerical results obtained with the Monte Carlo simulation of positrons are summarized in table 6.7. Positrons produce 7556 hits s\(^{-1}\) in the POLAR target, which corresponds in average to 4.7 hits bar\(^{-1}\) s\(^{-1}\), so that no danger of accidental double hit events is present. The number of positron events which fulfill all conditions to contribute to the modulation curve is 420 s\(^{-1}\). Therefore, positrons constitute the second most important source of background for POLAR, with an amount of counts approximately half of the number obtained from the diffuse CXB. The incoming energy and the distance between the two largest energy hits of the events contributing to the modulation curve have been plotted in figure 6.28.

We plan to apply the cut on the total energy deposited on the data offline. This cut might be applied online if the levels of low energy positrons turn out to be much larger than the ones we obtained by extrapolation of the MARIA-2 data. The total
### Positrons

<table>
<thead>
<tr>
<th>Entry</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Simulated particles [Hz]</td>
<td>20876</td>
</tr>
<tr>
<td></td>
<td>Particles illuminating POLAR [Hz]</td>
<td>9508</td>
</tr>
<tr>
<td></td>
<td>Particles interacting at least once in POLAR (E_{\text{vis}} &gt; 5\text{keV}) [Hz]</td>
<td>3190</td>
</tr>
<tr>
<td></td>
<td>Hits above 5keV in POLAR [Hz]</td>
<td>7556</td>
</tr>
<tr>
<td></td>
<td>Counts in modulation curve [Hz]</td>
<td>507</td>
</tr>
<tr>
<td></td>
<td>Counts in modulation curve (excluding neighbors) [Hz]</td>
<td>420</td>
</tr>
<tr>
<td></td>
<td>Effective area for hits ([\text{cm}^2])</td>
<td>432</td>
</tr>
<tr>
<td></td>
<td>Effective area for Polarization ([\text{cm}^2])</td>
<td>68.7</td>
</tr>
<tr>
<td></td>
<td>Effective area for Polarization (Far bars) ([\text{cm}^2])</td>
<td>56.9</td>
</tr>
</tbody>
</table>

| Table 6.7: Counting rates produced in POLAR by the positron background. |

**Figure 6.28:** *Left:* Spectrum of incoming energies from the positrons contributing to the modulation curve. *Right:* Distribution of the distance between the two largest energy hits, i.e., the ones included in the modulation curve. In both cases neighboring bars have been excluded.

Energy deposited might be obtained from the sum of the dynode signal from all 25 MAPM. A threshold at 250 keV to this sum would be equivalent to our offline cut.
6.2.6 Crab

The Crab nebula (see section 1.3.3 for details) is one of the brightest persistent sources in the sky, reason for which it is frequently used as calibration source. Its spectrum has been described [152, 153] as a power law:

\[ f(E) = 9.59E^{-2.108} \]

in units of photons cm\(^{-1}\) s\(^{-1}\) keV\(^{-1}\). According to this spectral shape, the Crab produces a flux of \(~1.5\) photons cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) in the energy range from 5 keV to 1000 keV.

To estimate the effect of the Crab into the POLAR performance, we simulated the Crab nebula as if it would be located at the zenith of POLAR. The initial position of the photons was taken uniformly distributed over the area of a circle with radius \(R_{\text{arc}} = 30\) cm, located above POLAR in the \(xy\)-plane. The polarization level was defined to be 46\%, according to the INTEGRAL measurements [46], fixed at an angle of 123\(^\circ\) with respect to the POLAR \(x\)-axis.

Figure 6.29: Simulated spectra from Crab. \(Left\): incoming energies, produced following equation 6.8. \(Right\): energy deposited in the POLAR scintillator bars.

The numerical results obtained from the simulation of the Crab at the POLAR zenith are summarized in table 6.8. The scintillator target registers 239 hits s\(^{-1}\), i.e., 0.15 hits bar\(^{-1}\) s\(^{-1}\) in average. The number of events contributing to the modulation curve is 24 s\(^{-1}\), only 4\% of the rate observed from the diffuse cosmic X-ray background. This makes Crab negligible as background source, but also hardly possible to be considered as a target for measuring its level of polarization.
Figure 6.30: *Left:* Distribution of hits produced by the Crab in the POLAR target. *
*Right:* Number of hits produced in the POLAR target per event. In both cases only hits with $E_{\text{vis}} > 5$ keV have been included.

<table>
<thead>
<tr>
<th>Crab</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated particles [Hz]</td>
<td>4100</td>
</tr>
<tr>
<td>Particles illuminating POLAR [Hz]</td>
<td>1287</td>
</tr>
<tr>
<td>Particles interacting at least once in POLAR ($E_{\text{vis}} &gt;5$ keV) [Hz]</td>
<td>180</td>
</tr>
<tr>
<td>Hits above 5keV in POLAR [Hz]</td>
<td>239</td>
</tr>
<tr>
<td>Counts in modulation curve [Hz]</td>
<td>28</td>
</tr>
<tr>
<td>Counts in modulation curve (excluding neighbors) [Hz]</td>
<td>24</td>
</tr>
<tr>
<td>Effective area for hits [cm$^2$]</td>
<td>124</td>
</tr>
<tr>
<td>Effective area for Polarization [cm$^2$]</td>
<td>19</td>
</tr>
<tr>
<td>Effective area for Polarization (Far bars) [cm$^2$]</td>
<td>17</td>
</tr>
</tbody>
</table>

Table 6.8: Counting rates produced by the Crab nebula when placed at the POLAR zenith.
6.2.7 X-ray albedo

The photon flux produced by a GRB will interact not only with POLAR, but also with the Earth atmosphere that is below the detector. A part of those photons scatter via Compton effect, and can interact with POLAR in their way back into space. Both their level and the direction of their polarization changes in the backscattering process. Their contribution to the POLAR rates constituted therefore another source of background, specially dangerous because its intensity is not constant, but proportional to the GRB, and its signal may be polarized.

The X-ray albedo has been evaluated using an adaptation of the PLANETOCOSMICS simulation package. PLANETOCOSMICS [154] is a simulation framework based on GEANT4 which contains a detailed description of the Earth, its atmosphere and its magnetic field, allowing to compute the hadronic and electromagnetic interactions of cosmic rays and X-rays with the ∼200 km-thick atmosphere of our planet. For our study, the standard code has been slightly modified to introduce a GRB incoming spectrum, and to provide as an output the kind of ROOT tree (t0) that we need as input for the POLAR Monte Carlo simulation.

A 200 km radius detecting sphere has been defined with its center at 412 km altitude over the Earth surface. The characteristics (momentum, position, polarization, etc.) of the photons that enter the sphere are saved in a t0-like ROOT tree. This tree is then fed to the POLAR simulation package that generates the corresponding photons and tracks them through the POLAR detector. The size of the detecting sphere is very small compared with the ∼6500 km radius of the Earth, so that the atmosphere is almost flat and the flux characteristics almost constant in the sphere scale. This allows us to scale the incoming position of the photons down to a 27 cm radius sphere, which is just enough to contain the detector. In this way the efficiency of the simulation is highly improved. All the photon characteristics are saved in t0 using the coordinate system of the detecting sphere, which has the z-axis in the direction joining the sphere with the Earth center. For simplicity, the GRB photons are simulated as coming parallel to the Earth axis. To simulated different GRB positions the latitude of the detecting sphere is modified. Therefore, the relation between the incoming polar angle (θγ) of the GRB photons and the latitude of the detecting sphere is: \( \theta_\gamma = 90^\circ - \text{latitude} \). Notice that this simulation procedure is valid because our particles of interest, the GRB photons, are neutral and therefore not affected by the Earth magnetic field and its asymmetries. In the same way, the results are independent of the longitude geographic coordinate, reason for which we have considered it equal to 0° in our simulations.

In the left side of figure 6.31 we show the incoming spectra of the photons that enter in the detecting sphere, for a GRB simulated at the POLAR zenith. The black line represents the total flux. The blue line is the incoming spectra of the photons that come directly from the GRB, and the red spectra is the one from the photons that enter the sphere after scattering in the Earth atmosphere. In the right plot from the same figure we show the spectra of energies measured in the POLAR scintillator target. Photons coming directly from a GRB located at the
Figure 6.31: Spectra obtained in the simulation of a GRB at the POLAR zenith (detecting sphere at latitude 0°). Left: Incoming spectrum. Right: Spectrum of detected energy. In both cases the black line represents the total flux, the blue line the flux coming directly from the GRB, and the red line the flux that arrives to POLAR after scattering in the Earth atmosphere.

POLAR zenith enter in the detecting sphere with $\theta_\gamma = 0^\circ$. Figure 6.32 shows the incoming angles ($\theta_\gamma$ and $\phi_\gamma$) from the photons that enter in the detecting sphere after interacting with the Earth atmosphere. As expected, Earth-scattered photons present $\theta_\gamma > 90^\circ$, while the distribution of azimuthal angles is flat.

Figure 6.32: Incoming direction of the photons that come to POLAR after being backscattered from the Earth atmosphere. The direction from the photons that come directly from the GRB was $\theta_\gamma = 0^\circ$ (zenith). Left: Polar angle ($\theta_\gamma$). Right: Azimuthal angle ($\phi_\gamma$).

We have simulated a GRB 100% polarized along the POLAR $x$-axis and with the spectral characteristics of a standard GRB. To reproduce the behavior for different GRB positions we have performed the simulation several times, locating the detecting sphere at six different latitudes. At each position of the sphere, a total of $5 \times 10^8$ GRB photons have been randomly generated on the surface of a circle with 7100 km radius, placed at 1000 km above the Earth surface. In this way, all the Earth atmosphere is illuminated. Table 6.9 shows the results of the analysis, performed separately with the photons that arrive to POLAR directly from the GRB,
and with the photons that interacted with the atmosphere. Finally, in the lower part of the table we show the results obtained when considering all the photons entering the detecting sphere. From the total amount of photons simulated, only \( \sim 1\% \) arrive to the 200 km radius detecting sphere. The rates recorded in the POLAR target have been obtained after re-scaling the size of the detecting volume down to a 27 cm radius sphere, containing the detector.
### Direct GRB flux

<table>
<thead>
<tr>
<th>$\theta_\gamma$ [°]</th>
<th>0</th>
<th>15</th>
<th>30</th>
<th>45</th>
<th>60</th>
<th>75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons arriving to detecting sphere</td>
<td>416 477</td>
<td>401 421</td>
<td>397 591</td>
<td>403 898</td>
<td>398 285</td>
<td>398 624</td>
</tr>
<tr>
<td>Particles illuminating POLAR</td>
<td>159 436</td>
<td>181 323</td>
<td>170 207</td>
<td>140 388</td>
<td>96 632</td>
<td>49 076</td>
</tr>
<tr>
<td>Particles interacting at least once in POLAR ($E_{vis} &gt; 5$keV)</td>
<td>51 414</td>
<td>54 036</td>
<td>48 151</td>
<td>38 129</td>
<td>25 019</td>
<td>11 937</td>
</tr>
<tr>
<td>Hits above 5keV in POLAR</td>
<td>84 023</td>
<td>86 536</td>
<td>76 574</td>
<td>59 769</td>
<td>40 042</td>
<td>18 882</td>
</tr>
<tr>
<td>Counts in modulation curve</td>
<td>15 977</td>
<td>15 527</td>
<td>13 890</td>
<td>10 563</td>
<td>7 331</td>
<td>3 267</td>
</tr>
<tr>
<td>Counts in modulation curve (excluding neighbors)</td>
<td>13 574</td>
<td>13 205</td>
<td>11 852</td>
<td>9 080</td>
<td>6 305</td>
<td>2 858</td>
</tr>
<tr>
<td>$\mu_{100}$ (%) (excluding neighbors)</td>
<td>33.9 ± 1.8</td>
<td>32.9 ± 1.3</td>
<td>26.2 ± 1.9</td>
<td>21.4 ± 2.1</td>
<td>19.0 ± 2.5</td>
<td>17.7 ± 3.7</td>
</tr>
<tr>
<td>$\phi_{11}$ (excluding neighbors)</td>
<td>0 ± 2</td>
<td>179 ± 1</td>
<td>1 ± 2</td>
<td>177 ± 3</td>
<td>5 ± 4</td>
<td>168 ± 6</td>
</tr>
</tbody>
</table>

### GRB flux backscattered from the Earth atmosphere

<table>
<thead>
<tr>
<th>$\theta_\gamma$ [°]</th>
<th>0</th>
<th>15</th>
<th>30</th>
<th>45</th>
<th>60</th>
<th>75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons arriving to detecting sphere</td>
<td>89 980</td>
<td>86 880</td>
<td>81 688</td>
<td>73 829</td>
<td>60 995</td>
<td>39 414</td>
</tr>
<tr>
<td>Particles illuminating POLAR</td>
<td>52 588</td>
<td>48 839</td>
<td>43 747</td>
<td>37 138</td>
<td>25 530</td>
<td>13 211</td>
</tr>
<tr>
<td>Particles interacting at least once in POLAR ($E_{vis} &gt; 5$keV)</td>
<td>15 546</td>
<td>14 798</td>
<td>13 360</td>
<td>11 390</td>
<td>8 279</td>
<td>4 425</td>
</tr>
<tr>
<td>Hits above 5keV in POLAR</td>
<td>25 816</td>
<td>24 419</td>
<td>21 970</td>
<td>18 553</td>
<td>13 459</td>
<td>7 256</td>
</tr>
<tr>
<td>Counts in modulation curve</td>
<td>58 79</td>
<td>54 56</td>
<td>48 83</td>
<td>40 55</td>
<td>29 60</td>
<td>15 48</td>
</tr>
<tr>
<td>Counts in modulation curve (excluding neighbors)</td>
<td>49 71</td>
<td>46 56</td>
<td>41 75</td>
<td>34 68</td>
<td>25 13</td>
<td>13 19</td>
</tr>
<tr>
<td>$\mu_{100}$ (%) (excluding neighbors)</td>
<td>5.4 ± 2.8</td>
<td>5.2 ± 2.1</td>
<td>4.9 ± 3.1</td>
<td>3.3 ± 3.1</td>
<td>10.5 ± 4.2</td>
<td>12.3 ± 4.7</td>
</tr>
<tr>
<td>$\phi_{11}$ (excluding neighbors)</td>
<td>0 ± 15</td>
<td>168 ± 11</td>
<td>58 ± 18</td>
<td>4 ± 44</td>
<td>-3.6 ± 11</td>
<td>-18 ± 13</td>
</tr>
</tbody>
</table>

### Total

<table>
<thead>
<tr>
<th>$\theta_\gamma$ [°]</th>
<th>0</th>
<th>15</th>
<th>30</th>
<th>45</th>
<th>60</th>
<th>75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons arriving to detecting sphere</td>
<td>506 457</td>
<td>488 301</td>
<td>479 239</td>
<td>477 727</td>
<td>459 280</td>
<td>438 038</td>
</tr>
<tr>
<td>Particles illuminating POLAR</td>
<td>212 024</td>
<td>230 162</td>
<td>213 954</td>
<td>177 526</td>
<td>122 162</td>
<td>62 287</td>
</tr>
<tr>
<td>Particles interacting at least once in POLAR ($E_{vis} &gt; 5$keV)</td>
<td>66 960</td>
<td>68 834</td>
<td>61 511</td>
<td>49 519</td>
<td>33 298</td>
<td>16 362</td>
</tr>
<tr>
<td>Hits above 5keV in POLAR</td>
<td>109 839</td>
<td>110 955</td>
<td>98 544</td>
<td>78 322</td>
<td>53 501</td>
<td>26 118</td>
</tr>
<tr>
<td>Counts in modulation curve</td>
<td>21 856</td>
<td>20 983</td>
<td>18 773</td>
<td>14 618</td>
<td>10 291</td>
<td>4 815</td>
</tr>
<tr>
<td>Counts in modulation curve (excluding neighbors)</td>
<td>18 545</td>
<td>17 861</td>
<td>16 027</td>
<td>12 548</td>
<td>8 818</td>
<td>4 177</td>
</tr>
<tr>
<td>$\mu_{100}$ (%) (excluding neighbors)</td>
<td>24.5 ± 1.1</td>
<td>25.1 ± 1.1</td>
<td>21.0 ± 1.2</td>
<td>15.9 ± 1.8</td>
<td>14.1 ± 2.1</td>
<td>16.1 ± 3.1</td>
</tr>
<tr>
<td>$\phi_{11}$ (excluding neighbors)</td>
<td>179 ± 1</td>
<td>179 ± 1</td>
<td>177 ± 3</td>
<td>179 ± 4</td>
<td>168 ± 6</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.9: Comparison between results observed with and without X-ray albedo
In figure 6.33 we show the influence of the X-ray albedo in the modulation curve. The left plot from the figure shows the percentage of events in the modulation curve that have been produced by photons arriving to POLAR after scattering in the Earth atmosphere. The plot on the right side of the same figure shows the relative decrease of the 100% modulation factor $\mu_{100}$. In average, for GRB at positions with $\theta_\gamma < 50^\circ$, the value of $\mu_{100}$ is around 25% of the value expected if there would be no atmosphere (absolute reduction $\sim$8%). Responsible for this decrease are $\sim 27\%$ of the modulation curve events, that are produced by photons arriving to POLAR after interacting with the atmosphere. A slight increase of the $\mu$ measured from an unpolarized GRB is also expected, due to the partial polarization level acquired by the photons through the Compton scattering process.

The influence of the X-ray albedo in the POLAR performance turns out to be of great importance. However, we shall not forget that POLAR will not be flying alone on the top of the atmosphere, but mounted on a satellite. This volume below the detector will also scatter photons (see §6.2.8) back to POLAR but, to compensate, it will shield from a part of the albedo X-ray photons. Considering a big satellite like the Tiang-Gong Space Lab into the PLANETOCOSMICS simulations would make the simulation very inefficient, since the detecting sphere would need to be re-scaled to a sphere of $\sim 5$ m radius, lowering dramatically the probability for any photon to be seen by the POLAR detector.

There are two ways in which photons can arrive to POLAR from the Earth atmosphere, considering the presence of the Space Lab: either they can reach POLAR passing through the satellite, or they can do it from around the satellite. We have calculated the spectrum from the photons entering the detecting sphere after scattering on the atmosphere (red line in the left plot from figure 6.31). Following this energy distribution we have simulated $10^6$ photons illuminating the bottom the Tiang-Gong Space Lab (made of 4 cm thick aluminum) from $\theta_\gamma = 180^\circ$. The photons were generated over the surface of a circle with 3 cm radius, so that all of
them would be seen by POLAR if the spacecraft would not be present in between. Only 1.5% of the photons simulated interacted with POLAR producing some hit above 5 keV. Taking into account that only \( \sim 25\% \) of the GRB photons are seen as X-ray albedo, the percentage of GRB photons that are able to traverse the Space Lab is less than 4\%, and therefore negligible.

The dimensions of the Tiang-Gong Space Lab have been included in figure 6.35, which is a visualization of the GEANT4 simulation setup where the Space Lab has been implemented. The position of POLAR is planned to be on the central part of the satellite, looking towards the zenith. The volume below the polarimeter is a truncated cone with \( \sim 1.5 \) m radius at the POLAR location. The probability for a X-ray albedo photon to arrive to POLAR without passing through the satellite depends on its incoming direction, but also on the position where it enters the detecting sphere, in whose center POLAR is located. Taking this position into account, we can estimate how many photons are blocked by the satellite. The shortest dimension of the Tiang-Gong Space Lab is its 1.5 m radius, and its longest dimension is its \( \sim 4.3 \) m half length. Considering the radius of the Space Lab, all photons entering the sphere at \( \theta_{\text{pos}} > 110^\circ \) will be stopped\(^3\). Considering the half-length of the Space Lab, photons entering at \( \theta_{\text{pos}} > 93^\circ \) are stopped. Let us consider the average between these two values, i.e. \( \theta_{\text{pos}} > 102^\circ \), as the region where all photons are stopped by the Tiang-Gong Space Lab. The analysis of the X-ray albedo, performed for the photons fulfilling \( \theta_{\text{pos}} < 102^\circ \), has provided the results summarized in table 6.10. For a GRB located at the POLAR zenith only \( \sim 4\% \) of the Earth-scattered photons that interacted in the POLAR detector fulfill \( \theta_{\text{pos}} < 102^\circ \). However, the number of photons backscattered from the Earth atmosphere increases with \( \theta_\gamma \). We consider the POLAR field of view for polarization analysis for GRB with \( 0^\circ < \theta_\gamma < 50^\circ \). In this region, the number of backscattered photons contributing to the modulation curve is in average \( \sim 10\% \). The influence of its contribution to the modulation curve is shown in figure 6.34, where we see that the \( \mu_{100} \) may be reduced in average by 12\% of its value, i.e. an absolute \( \mu_{100} \) reduction of \( \sim 3\% \).

\(^{3}\)Notice that \( \theta_{\text{pos}} \) is related to the position where the photon enter the sphere, while \( \theta_\gamma \) is related to the photon incoming momentum.
### Direct GRB flux

<table>
<thead>
<tr>
<th>$\theta_\gamma$ [°]</th>
<th>0</th>
<th>15</th>
<th>30</th>
<th>45</th>
<th>60</th>
<th>75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons arriving to detecting sphere</td>
<td>416 477</td>
<td>401 421</td>
<td>397 591</td>
<td>403 898</td>
<td>398 285</td>
<td>398 624</td>
</tr>
<tr>
<td>Particles illuminating POLAR</td>
<td>159 436</td>
<td>181 323</td>
<td>170 207</td>
<td>140 388</td>
<td>96 632</td>
<td>49 076</td>
</tr>
<tr>
<td>Particles interacting at least once in POLAR ($E_{vis} &gt; 5$keV)</td>
<td>51 414</td>
<td>54 036</td>
<td>48 151</td>
<td>38 129</td>
<td>25 019</td>
<td>11 937</td>
</tr>
<tr>
<td>Hits above 5keV in POLAR</td>
<td>84 023</td>
<td>86 536</td>
<td>76 574</td>
<td>59 769</td>
<td>40 042</td>
<td>18 882</td>
</tr>
<tr>
<td>Counts in modulation curve</td>
<td>15 977</td>
<td>15 527</td>
<td>13 890</td>
<td>10 563</td>
<td>7 331</td>
<td>3 267</td>
</tr>
<tr>
<td>Counts in modulation curve (excluding neighbors)</td>
<td>13 574</td>
<td>13 205</td>
<td>11 852</td>
<td>9 076</td>
<td>6 305</td>
<td>2 858</td>
</tr>
<tr>
<td>$\mu_{100}$ (%) (excluding neighbors)</td>
<td>33.9±1.8</td>
<td>32.9±1.3</td>
<td>26.2±1.9</td>
<td>21.4±2.1</td>
<td>19.0±2.5</td>
<td>17.7±3.7</td>
</tr>
<tr>
<td>$\phi_11$ (excluding neighbors)</td>
<td>0±2</td>
<td>179±1</td>
<td>1±2</td>
<td>177±3</td>
<td>5±4</td>
<td>168±6</td>
</tr>
</tbody>
</table>

### GRB flux backscattered from the Earth atmosphere

<table>
<thead>
<tr>
<th>$\theta_\gamma$ [°]</th>
<th>0</th>
<th>15</th>
<th>30</th>
<th>45</th>
<th>60</th>
<th>75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons arriving to detecting sphere</td>
<td>22 244</td>
<td>22 318</td>
<td>23 687</td>
<td>25 199</td>
<td>26 699</td>
<td>22 998</td>
</tr>
<tr>
<td>Particles illuminating POLAR</td>
<td>7290</td>
<td>8363</td>
<td>12 624</td>
<td>16 086</td>
<td>15 292</td>
<td>10 183</td>
</tr>
<tr>
<td>Particles interacting at least once in POLAR ($E_{vis} &gt; 5$keV)</td>
<td>1897</td>
<td>2949</td>
<td>5227</td>
<td>6677</td>
<td>6412</td>
<td>4121</td>
</tr>
<tr>
<td>Hits above 5keV in POLAR</td>
<td>2804</td>
<td>4704</td>
<td>8487</td>
<td>10 808</td>
<td>10 510</td>
<td>6773</td>
</tr>
<tr>
<td>Counts in modulation curve</td>
<td>554</td>
<td>991</td>
<td>1818</td>
<td>2350</td>
<td>2316</td>
<td>1450</td>
</tr>
<tr>
<td>Counts in modulation curve (excluding neighbors)</td>
<td>466</td>
<td>835</td>
<td>1533</td>
<td>1983</td>
<td>1980</td>
<td>1243</td>
</tr>
<tr>
<td>$\mu_{100}$ (%) (excluding neighbors)</td>
<td>3.0±9.7</td>
<td>4.6±7.1</td>
<td>10.7±5.2</td>
<td>0.4±4.3</td>
<td>15.3±4.6</td>
<td>12.6±5.8</td>
</tr>
<tr>
<td>$\phi_11$ (excluding neighbors)</td>
<td>35±92</td>
<td>109±43</td>
<td>-110±13</td>
<td>109±360</td>
<td>-32±8</td>
<td>-18±13</td>
</tr>
</tbody>
</table>

### Total

<table>
<thead>
<tr>
<th>$\theta_\gamma$ [°]</th>
<th>0</th>
<th>15</th>
<th>30</th>
<th>45</th>
<th>60</th>
<th>75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons arriving to detecting sphere</td>
<td>438 721</td>
<td>423 739</td>
<td>421 278</td>
<td>429 097</td>
<td>424 984</td>
<td>421 622</td>
</tr>
<tr>
<td>Particles illuminating POLAR</td>
<td>166 726</td>
<td>189 686</td>
<td>182 831</td>
<td>156 474</td>
<td>111 924</td>
<td>59 259</td>
</tr>
<tr>
<td>Particles interacting at least once in POLAR ($E_{vis} &gt; 5$keV)</td>
<td>53 311</td>
<td>56 985</td>
<td>53 378</td>
<td>44 806</td>
<td>31 431</td>
<td>16 058</td>
</tr>
<tr>
<td>Hits above 5keV in POLAR</td>
<td>86 827</td>
<td>91 240</td>
<td>85 061</td>
<td>70 577</td>
<td>50 552</td>
<td>25 655</td>
</tr>
<tr>
<td>Counts in modulation curve</td>
<td>16 531</td>
<td>16 518</td>
<td>15 708</td>
<td>12 913</td>
<td>9 647</td>
<td>4 717</td>
</tr>
<tr>
<td>Counts in modulation curve (excluding neighbors)</td>
<td>14 040</td>
<td>14 040</td>
<td>13 385</td>
<td>11 063</td>
<td>8 285</td>
<td>4 101</td>
</tr>
<tr>
<td>$\mu_{100}$ (%) (excluding neighbors)</td>
<td>32.7±1.8</td>
<td>28.6±1.7</td>
<td>22.3±1.7</td>
<td>17.4±1.9</td>
<td>15.6±2.2</td>
<td>16.4±3.1</td>
</tr>
<tr>
<td>$\phi_11$ (excluding neighbors)</td>
<td>0±2</td>
<td>1±2</td>
<td>2±2</td>
<td>176±3</td>
<td>179±4</td>
<td>168±6</td>
</tr>
</tbody>
</table>

Table 6.10: Analysis of the X-ray albedo when considering only photons with $\theta_{pos} < 102^\circ$, i.e. those which may arrive to POLAR without interacting in the Tiang-Gong Space Lab.
Figure 6.34: Influence of the X-ray albedo on the modulation curve, taking only photons with \( \theta_{\text{pos}} < 102^\circ \) into account. Left: Ratio between the number of Earth-scattered photons contributing to the modulation curve, and the total number of events in the modulation curve (we consider the curve where neighboring bars have been rejected). Right: Relative reduction in \( \mu_{\text{100}} \).

In conclusion, considering GRBs in the POLAR field of view, the presence of the Tiang-Gong Space Lab behind POLAR shields in average from \( \sim 90\% \) of the X-ray albedo. The maximum effect is for GRBs located at the POLAR zenith, for which only 4% of the GRB photons arrive to POLAR after being scattered off the Earth atmosphere.
6.2.8 Satellite backscattering

We have presented in the previous section the advantage of having the large volume of the Tiang-Gong Space Lab behind POLAR. We will address now its negative consequence, namely, that in the same way as the atmosphere, the satellite also backscatters GRB photons. For this study we have implemented an approximate description of the Space Lab into our POLAR Monte Carlo simulations. The geometry is shown in figure 6.35. The Space Lab is constructed using 4 cm thick aluminum and has a total weight of $\sim 8$ tones.

Figure 6.35: Visualization of the simulation geometry where POLAR is mounted on the Tiang-Gong Space Lab, constructed in 4 cm thick aluminum. The target is facing the outer space while the front end and the rest of the electronics are kept inside. The wall of the spacecraft is located at the height of the MAPM.

We have simulated a one second duration standard GRB located at various positions above POLAR. The GRB photons have been uniformly generated over the surface of a circle with radius 2 m. In this way not only the detector but also a large portion of the Tiang-Gong Space Lab is illuminated, allowing to take the scattered photons into account. In figure 6.36 we present the spectra of incoming ($E_0$) and detected ($E_{\text{vis}}$) energies for the photon flux coming directly from the GRB, from the flux backscattered from the satellite, and from the sum of both.

Table 6.11 summarizes the results obtained when analyzing the events arriving to POLAR directly from the GRB, and the photons that interacted first with the Tiang-Gong Space Lab. Finally, in the lower part of the table we show the results obtained when considering both sources together.
Figure 6.36: Spectra of the photons producing at least one hit with more than 5 keV on the POLAR target. The data corresponds to the simulation of a GRB at the POLAR zenith ($\theta_{\gamma} = 0^\circ$). *Left:* Incoming spectrum. *Right:* Spectrum of detected energy. In both cases the black line represents the total flux, the blue line the flux coming directly from the GRB, and the red line the flux that arrives to POLAR after scattering in the Tiang-Gong Space Lab.
### Direct GRB flux

<table>
<thead>
<tr>
<th>θγ [°]</th>
<th>0</th>
<th>15</th>
<th>30</th>
<th>45</th>
<th>60</th>
<th>75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated particles</td>
<td>(1.2 \times 10^6)</td>
<td>(1.2 \times 10^6)</td>
<td>(1.2 \times 10^6)</td>
<td>(1.2 \times 10^6)</td>
<td>(1.2 \times 10^6)</td>
<td>(1.2 \times 10^6)</td>
</tr>
<tr>
<td>Particles illuminating POLAR [Hz]</td>
<td>88092</td>
<td>106301</td>
<td>112020</td>
<td>108719</td>
<td>97010</td>
<td>77115</td>
</tr>
<tr>
<td>Particles interacting at least once in POLAR ((E_{\text{vis}} &gt; 5\text{keV})) [Hz]</td>
<td>25753</td>
<td>29270</td>
<td>29721</td>
<td>29553</td>
<td>28482</td>
<td>26272</td>
</tr>
<tr>
<td>Hits above 5keV in POLAR [Hz]</td>
<td>41518</td>
<td>46313</td>
<td>46527</td>
<td>46033</td>
<td>44190</td>
<td>40932</td>
</tr>
<tr>
<td>Counts in modulation curve [Hz]</td>
<td>7534</td>
<td>8356</td>
<td>8217</td>
<td>8155</td>
<td>7568</td>
<td>7100</td>
</tr>
<tr>
<td>Counts in modulation curve (excluding neighbors) [Hz]</td>
<td>6462</td>
<td>7152</td>
<td>7031</td>
<td>7014</td>
<td>6494</td>
<td>6144</td>
</tr>
<tr>
<td>(\mu_{100}) (%) (excluding neighbors)</td>
<td>31.4 ± 2.5</td>
<td>28.3 ± 2.4</td>
<td>25.1 ± 2.4</td>
<td>26.0 ± 2.5</td>
<td>16.8 ± 2.5</td>
<td>22.0 ± 2.6</td>
</tr>
<tr>
<td>(\phi_{1}) (excluding neighbors)</td>
<td>177 ± 3</td>
<td>179 ± 2</td>
<td>-177 ± 3</td>
<td>178 ± 3</td>
<td>180 ± 4</td>
<td>-174 ± 3</td>
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</tbody>
</table>

### GRB flux backscattered from the Tiang-Gong Space Lab

<table>
<thead>
<tr>
<th>θγ [°]</th>
<th>0</th>
<th>15</th>
<th>30</th>
<th>45</th>
<th>60</th>
<th>75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated particles</td>
<td>(1.2 \times 10^6)</td>
<td>(1.2 \times 10^6)</td>
<td>(1.2 \times 10^6)</td>
<td>(1.2 \times 10^6)</td>
<td>(1.2 \times 10^6)</td>
<td>(1.2 \times 10^6)</td>
</tr>
<tr>
<td>Particles illuminating POLAR [Hz]</td>
<td>3788</td>
<td>3869</td>
<td>3709</td>
<td>3507</td>
<td>3236</td>
<td>2236</td>
</tr>
<tr>
<td>Particles interacting at least once in POLAR ((E_{\text{vis}} &gt; 5\text{keV})) [Hz]</td>
<td>3228</td>
<td>3315</td>
<td>3201</td>
<td>3036</td>
<td>2832</td>
<td>1964</td>
</tr>
<tr>
<td>Hits above 5keV in POLAR [Hz]</td>
<td>6012</td>
<td>6264</td>
<td>6151</td>
<td>5842</td>
<td>5388</td>
<td>4040</td>
</tr>
<tr>
<td>Counts in modulation curve [Hz]</td>
<td>1394</td>
<td>1458</td>
<td>1402</td>
<td>1134</td>
<td>1034</td>
<td>740</td>
</tr>
<tr>
<td>Counts in modulation curve (excluding neighbors) [Hz]</td>
<td>1181</td>
<td>1218</td>
<td>1194</td>
<td>1134</td>
<td>1034</td>
<td>740</td>
</tr>
<tr>
<td>(\mu_{100}) (%) (excluding neighbors)</td>
<td>11.4 ± 5.8</td>
<td>12.3 ± 5.5</td>
<td>4.0 ± 6.2</td>
<td>6.1 ± 6.2</td>
<td>6.1 ± 6.2</td>
<td>2.5 ± 7.3</td>
</tr>
<tr>
<td>(\phi_{1}) (excluding neighbors)</td>
<td>181 ± 15</td>
<td>10 ± 14</td>
<td>-62 ± 40</td>
<td>-40 ± 28</td>
<td>176 ± 30</td>
<td>-172 ± 92</td>
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</table>

### Total

<table>
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<th>θγ [°]</th>
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<th>30</th>
<th>45</th>
<th>60</th>
<th>75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated particles</td>
<td>(1.2 \times 10^6)</td>
<td>(1.2 \times 10^6)</td>
<td>(1.2 \times 10^6)</td>
<td>(1.2 \times 10^6)</td>
<td>(1.2 \times 10^6)</td>
<td>(1.2 \times 10^6)</td>
</tr>
<tr>
<td>Particles illuminating POLAR [Hz]</td>
<td>91880</td>
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<td>112226</td>
<td>100246</td>
<td>79351</td>
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<td>Particles interacting at least once in POLAR ((E_{\text{vis}} &gt; 5\text{keV})) [Hz]</td>
<td>28981</td>
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<td>32922</td>
<td>32588</td>
<td>31314</td>
<td>28236</td>
</tr>
<tr>
<td>Hits above 5keV in POLAR [Hz]</td>
<td>47530</td>
<td>52577</td>
<td>52678</td>
<td>51875</td>
<td>49578</td>
<td>44972</td>
</tr>
<tr>
<td>Counts in modulation curve [Hz]</td>
<td>8928</td>
<td>9814</td>
<td>9619</td>
<td>9466</td>
<td>8802</td>
<td>7981</td>
</tr>
<tr>
<td>Counts in modulation curve (excluding neighbors) [Hz]</td>
<td>7643</td>
<td>8370</td>
<td>8225</td>
<td>8148</td>
<td>7528</td>
<td>6884</td>
</tr>
<tr>
<td>(\mu_{100}) (%) (excluding neighbors)</td>
<td>27.6 ± 2.3</td>
<td>25.5 ± 2.2</td>
<td>21.2 ± 2.1</td>
<td>23.2 ± 2.3</td>
<td>15.4 ± 2.3</td>
<td>20.4 ± 2.5</td>
</tr>
<tr>
<td>(\phi_{1}) (excluding neighbors)</td>
<td>176 ± 2</td>
<td>-1 ± 3</td>
<td>4 ± 3</td>
<td>-2 ± 3</td>
<td>0 ± 4</td>
<td>4 ± 3</td>
</tr>
</tbody>
</table>

Table 6.11: Comparison between results observed with and without the Tiang-Gong Space Lab.
Figure 6.37 presents the influence of the satellite backscattering in the modulation curve. In average, 15% of the events in the modulation curve have been detected in POLAR after interacting in the Tiang-Gong Space Lab. Their contribution reduces the $\mu_{100}$ by about 12% of the value obtained without backscattering.

The Tiang-Gong Space Lab scatters back to POLAR a number of photons that is, in average, around the same amount of Earth-scattered photons than it stops. For GRBs in the region of the sky $0^\circ < \theta_\gamma < 50^\circ$, the mean value of GRB photons detected either after being scattered back from the Space Lab or from the Earth atmosphere, constitutes around 18% of the total GRB-induced events contributing to the modulation curve. Note, however, that the number of photons scattering back from the satellite depends strongly on the geometry and materials used in the satellite construction. A more accurate description of the platform will be required to precisely calculate the final rate of backscattered photons.

Figure 6.37: Left: Ratio between the number of photons backscattered by the Space Lab contributing to the modulation curve, and the total number of events in the modulation curve (we consider de curve where neighboring bars have been rejected). Right. Relative reduction in $\mu_{100}$ due to the satellite backscattering.
Chapter 7

Conclusions

This thesis presents a study of hard X-ray polarization in astronomy through observations of solar flares with the satellite RHESSI, and through simulations and experiments with the instrument POLAR.

The RHESSI satellite has allowed us to measure the level of linear polarization of the 100–350 keV photons emitted during the impulsive phase of seven solar flares. Values for the polarization level were found in the range between 2% and 54%, with statistical errors from 10% to 26% at the 1σ level. The angles of polarization were distributed between 66° and 170° in heliocentric coordinates. They do not show any preferential orientation of the polarization, neither parallel nor perpendicular, with respect to the radial direction defined by the position of the flare in the Sun. In addition, no significant dependency between the orientation of the polarization and the distance of the flares to the Sun center was found. Also no correlation appeared between the polarization orientation and the line that joins the two major foot-points of the flare. Similarly, no relationship between solar flare intensity and polarization degree could be observed.

Our results have been compared with previous observations and with various theoretical predictions [76, 78]. We found an agreement with the low energy measurements from the SPR-N instruments on board of the Coronas-F satellite [22], typically within 2σ. The polarization degree from the 23 July 2002 flare measured by Boggs, Coburn, and Kalemci [23] at high energies is in agreement with our results at the 1.5σ level. Their conclusion about the orientation of polarization with respect to the radial direction passing through the flare position (perpendicular to it for flares in the limb and parallel for flares close to center) cannot be confirmed by our measurements. Regarding the theoretical predictions, a χ² analysis allowed to reject one of the models from reference [78] with 90% confidence. In this model, predicting very high polarization values up to 85%, the magnetic field strength is constant along the loop and the electrons spiral at pitch angles close to 90°. Due to the statistical uncertainties, for the rest of the models the χ² values were very close to unity, making it impossible to distinguish between them. Polarimetry measurements with better accuracy are therefore needed.
The POLAR experiment is a Compton polarimeter aiming to accurately measure the level of polarization of the (50–500 keV) hard X-ray photons emitted by GRBs. The detector design makes use of well-known technology, based on plastic scintillators and multi-anode photomultipliers, assembled in a modular construction which provides a very good mechanical stability. The fast response of the electronics specifically developed for POLAR, the small $\sim$70 ns time window to look for coincidental hits, and the programmed trigger logic, make negligible the probability of measuring accidental coincidences between independent GRB photons.

Using GEANT4, a detailed Monte Carlo simulation has been written to characterize the POLAR performance. POLAR has a large field of view (2.24 sr) and a large effective area ($\sim$90 cm$^2$) for polarization measurements, which combined with a large modulation factor for 100% polarized GRBs ($\mu_{100} \sim 30\%$) constitute the best qualities for a GRB polarimeter. All together these features provide POLAR with a Minimum Detectable Polarization (MDP) for the measurement of a standard GRB taking values between 4% and 7% ($1\sigma$ level), depending on the GRB position. The number of GRBs observed by POLAR during one year has been evaluated using data from the BATSE catalog. We expect at least 6 long GRBs to be detected with a MDP lower than 10%, and 25 GRBs (from which two are short bursts) with MDP<20%. This values depend strongly on the background level estimation, which in our case has been done assuming the highest levels found in the literature.

The position of the GRBs is needed to correctly determine their level of polarization. The POLAR simulation package has allowed us to develop a method by which POLAR is able to estimate the position of GRBs. We can determine the coordinates of a strong GRB ($10^{-5}$ erg cm$^{-2}$ sec$^{-1}$) with accuracy such that the error transmitted to the 100% modulation factor due to the location uncertainty is kept below 10%. Several effects that could potentially modify the performance of the GRB localization technique have been studied. It was found that the influence of the diffuse photon background will be negligible for short GRBs, but it needs to be subtracted from long ones. Its estimation in the later case should be done with a precision better than 8% around the real value. Neither the level of polarization of the source, nor the presence of a spacecraft behind POLAR show any influence in the output of the localization method. Furthermore, the limited energy resolution due to light collection inefficiencies and the MAPM non-uniformities will not diminish the localization capabilities of our method. This localization procedure provides enough accuracy to perform good polarization measurements. It will be useful for cases when no other GRB localization instrument simultaneously observes the same field of view as POLAR.

The POLAR demonstration model (one POLAR module constituting a 1/25 portion of the whole detector) has been tested using partially polarized X-rays and 100% polarized synchrotron radiation. The values of the polarization level and polarization angles obtained in both cases are according to the expectations. For instance, the $\mu_{100}$ values obtained at the synchrotron beam line increase when
decreasing the beam energy, and when increasing the threshold on the energy deposited per bar, as expected from the Compton cross-section. The experimental results obtained both with the radioactive source and at the synchrotron beam are in good agreement with the output from the GEANT4 simulations, what constitutes the validation of the POLAR Monte Carlo simulation package.

Finally, the most important sources of background to which POLAR will be exposed when flying along the LEO orbit have been simulated. From the persistent background sources, i.e. those independent from the presence or not of a GRB, the most important one is the diffuse X-ray photon background producing around 750 Hz counts in the POLAR modulation curves, followed by the positron background producing 420 Hz. These two sources, together with the neutron, electron, and the Crab, induce \( \sim 1300 \) Hz in the POLAR modulation curve, which is rather high when compared with the \( \sim 6500 \) Hz produced by a short GRB. However, since these sources are constant along the GRB duration, they can be subtracted by measuring them immediately before and after the GRB observation. More dangerous are the rates induced by the GRB photons backscattered from the satellite where POLAR is mounted, or by the Earth atmosphere behind it. The amount of counts that they produce in the modulation curve depend both on the strength and on the position of the GRB above POLAR. For GRBs in the POLAR field of view for polarization measurements, they constitute in average 18% of the total GRB counts in the modulation curve, reducing the POLAR \( \mu_{100} \) from \( \sim 30\% \) to around 25%. These results can only be considered as approximations to the real value. A more accurate description of the platform in which POLAR will be flying is required to precisely calculate the exact rate of backscattered photons. The background levels presented in this thesis constitute upper limits to the POLAR background, since for the simulation of the various sources we have always selected the experimental results or the theoretical predictions providing the highest fluxes.

The experimental and simulation results presented in this thesis proof the capability of POLAR to measure the level of polarization of hard X-rays. The next step in the development of the POLAR detector will be the assembly of a scintillator target with 16 modules. Using this assembly a series of experimental measurements both with radioactive sources and synchrotron radiation will be performed, allowing to test the inter-module communication and all the elements of the POLAR trigger logic. The attention will be focused in studying the response of the detector to low energy X-rays. In addition a full series of thermal, vibration, and vacuum tests will be carried out to space-qualify the POLAR detector. The POLAR flight model will be constructed taking the output of all those tests into account. Ready to fly in 2012, POLAR has the potential to be the first detector to precisely determine the level of polarization on the prompt emission of GRBs, which would constitute a milestone for the GRB research.
Appendix A

Localization of GRBs in \((\theta_\gamma, \phi_\gamma)\) coordinates

The method to localize GRBs (§4.4) has been developed in Cartesian coordinates because the \((x, y)\) coordinates are well defined in all the space, while in spherical coordinates the azimuth \(\phi_\gamma\) is not defined for \(\theta_\gamma = 0^\circ\). However, results are easier to interpret in spherical coordinates since most people are familiar with angular variables expressed in degrees. We present here the figures equivalent to figures 4.17 and 4.23 when using spherical coordinates. Note that new GRB positions have been chosen here so that the simulated GRBs are uniformly distributed in the \((\theta_\gamma, \phi_\gamma)\) space, while the positions chosen to generate figures 4.17 and 4.23 were uniformly distributed in \((x, y)\) coordinates. The localization method has been applied in the same way as in §4.4, using the data base created in \((x, y)\) coordinates, but both the input and the output of the localization method have been translated into spherical coordinates.

Figure A.1 shows that the polar coordinate \(\theta_\gamma\) of a standard GRB could be determined within a r.m.s. smaller than 5\(^\circ\). The azimuthal coordinate \(\phi_\gamma\) could be determined with similar accuracy where \(\theta_\gamma > 30^\circ\), but its value was undetermined at positions close to the zenith \((\theta_\gamma=0)\). The slight positive bias on \(\theta_\gamma\) in the zenith region is due to the fact that this coordinate is defined positive. Regarding GRB 981130, we observe in figure A.2 a bias in \(\theta_\gamma\) and \(\phi_\gamma\) below 10\(^\circ\).
Figure A.1: Results in \((\theta_\gamma, \phi_\gamma)\) coordinates from simulated non-polarized standard GRBs. *Top left:* Linearity plot in \(\theta_\gamma\), i.e. reconstructed \(\theta_\gamma\) vs. input \(\theta_\gamma\) for several fixed \(\phi_\gamma\) values. Each point on this graph represents the average of the 10 simulations made at each position. *Middle left:* Spread of the reconstructed \(\theta_\gamma\), i.e. the standard deviation of the 10 reconstructed \(\theta_\gamma\) values. *Bottom left:* Bias in the reconstruction, i.e. the difference between the reconstructed average \(\theta_\gamma\) value and the input \(\theta_\gamma\). The plots on the right are the equivalent to the left ones, but calculated for \(\phi_\gamma\) at several fixed \(\theta_\gamma\) positions. In all the plots lines of different styles have been drawn to guide the eye.
Figure A.2: Results from a GRB 981130, simulated non-polarized and without background. Top left: Linearity plot in $\theta_\gamma$, i.e. reconstructed $\theta_\gamma$ vs. input $\theta_\gamma$ for several fixed $\phi_\gamma$ values. Each point on this graph represents the average of the 10 simulations made at each position. Middle left: Spread of the reconstructed $\theta_\gamma$, i.e. the standard deviation of the 10 reconstructed $\theta_\gamma$ values. Bottom left: Bias in the reconstruction, i.e. the difference between the reconstructed average $\theta_\gamma$ value and the input $\theta_\gamma$. The plots on the right are the equivalent to the left ones, but calculated for $\phi_\gamma$ at several fixed $\theta_\gamma$ positions. In all the plots lines of different styles have been drawn to guide the eye.
Acronyms

AC  Alternating Current
ADC  Analog to Digital Converter
AGN  Active Galactic Nuclei
AMS-01  Alpha Magnetic Spectrometer
ASIC  Application-Specific Integrated Circuit
BATSE  Burst and Transient Source Experiment
BGO  Bismuth Germanate
CAMAC  Computer Automated Measurement And Control
CC  Central Computer
CGRO  Cosmic Gamma-Ray Observatory
COMPTEL  Compton Telescope
CXB  Cosmic X-ray Background
DAC  Digital to Analog Converter
DC  Direct Current
DM  Demonstration Model
DPNC  Département de Physique Nucléaire et Corpusculaire, University of Geneva, Switzerland
EGSE  Electrical Ground Support Equipment
EQM  Engineering-Qualification Model
ESA  European Space Agency
ESR  Enhanced Specular Reflector
**ESRF** European Synchrotron Radiation Facility

**ESS** Environmental Stress Screening

**FE** Front-End

**FIFO** First In, First Out

**FM** Flight Model

**FoV** Field of View

**FPGA** Field-Programmable Gate Array

**FWHM** Full Width at Half Maximum

**GEO** Geostationary Orbit

**GEM** Gas Electron Multiplier

**GRAPE** Gamma-Ray Polarimeter Experiment

**GRB** Gamma Ray Burst

**HEAO1** High Energy Astronomical Observatory 1

**HV** High Voltage

**HXT** Hard X-ray Telescope

**IF PCB** Interface PCB

**INTEGRAL** International Gamma-Ray Astrophysics Laboratory

**IPJ** Andrej Soltan Institute for Nuclear Studies, Poland

**ISDC** ISDC Data Centre for Astrophysics, Switzerland

**IXO** International X-ray Observatory

**I/O** Input-Output

**ISS** International Space Station

**MAPM** Multianode Photomultiplier

**MAPRA** Multianode POLAR Readout ASIC

**MDP** Minimum Detectable Polarization

**MEGA** Medium Energy Gamma-Ray Astronomy Experiment

**NIM** Nuclear Instrumentation Module
**NSO**  Normalized Scaler Output

**LAPP**  Laboratoire d’Annecy-le-vieux de Physique des Particules, France

**LEO**  Low Earth Orbit

**LV**  Low Voltage

**LS**  Level Shifter

**PAMELA**  Payload for Antimatter-Matter Exploration and Light-nuclei Astrophysics

**PC**  Personal Computer

**PCB**  Printed Circuit Board

**PET**  Positron Emission Tomography

**PMTRC**  High Voltage Divider PCB

**PoGOLite**  Polarized Gamma-Ray Observer - Light Weight

**PSI**  Paul Scherrer Institute, Switzerland

**RC**  Resistor-Capacitor

**RHESSI**  Reuven Ramaty High Energy Solar Spectroscopic Imager

**SAA**  South Atlantic Anomaly

**SGR**  Soft Gamma Repeater

**S/H**  Sample and Hold

**SNR**  Signal-to-Noise Ratio

**SO**  Scaler Output

**SPENVIS**  Space Environment Information System

**SXR**  Stellar X-ray Polarimeter

**SXT**  Yohkoh Soft X-ray Telescope

**TVT**  Thermo-Vacuum Test

**XPOL**  X-ray Polarimeter
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5.1 Scheme of the laboratory setup, shown here with only one tag detector at $\phi = 90^\circ$. The red and grey areas of the scatterer (S1) and the tag represent the sensitive part and the photomultiplier, respectively. For the POLAR demonstration model the sensitive target is represented in blue and the mechanical support in gray. All the distances given in the figure are expressed in mm.

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A.2 Results from a GRB 981130, simulated non-polarized and without background. Top left: Linearity plot in \(\theta_\gamma\), i.e. reconstructed \(\theta_\gamma\) vs. input \(\theta_\gamma\) for several fixed \(\phi_\gamma\) values. Each point on this graph represents the average of the 10 simulations made at each position. Middle left: Spread of the reconstructed \(\theta_\gamma\), i.e. the standard deviation of the 10 reconstructed \(\theta_\gamma\) values. Bottom left: Bias in the reconstruction, i.e. the difference between the reconstructed average \(\theta_\gamma\) value and the input \(\theta_\gamma\). The plots on the right are the equivalent to the left ones, but calculated for \(\phi_\gamma\) at several fixed \(\theta_\gamma\) positions. In all the plots lines of different styles have been drawn to guide the eye.
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