Pre-flight development of the PoGOLite Pathfinder

MÓZSI KISS

Doctoral Thesis in Physics
Stockholm, Sweden 2011
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Pre-flight development of the PoGOLite Pathfinder

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Cover illustration: Stamps issued by the Swedish postal service in January 2009 to commemorate the International Year of Astronomy, which marked the 400th anniversary of Galileo Galilei’s first telescope observations. One depicts a schematic view of the PoGOLite polarimeter as seen from the top and in cross-section, while the other one shows the Taurus constellation, where a star-shaped hole marks the position of the Crab, making it the first Swedish stamp with an (intentional) hole. Image credit: © Posten Frimärken. Designer: Einar Åkerlind.

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Abstract

The Polarized Gamma-ray Observer (PoGOLite) is a balloon-borne instrument that will measure gamma-ray polarization in the energy range 25–80 keV from astronomical sources such as pulsars, accretion discs and jets from active galactic nuclei. The two additional parameters provided by such observations, polarization angle and degree, will allow these objects to be studied in a new way, providing information about their emission mechanisms and geometries.

The instrument measures azimuthal scattering angles of photons within a close-packed array of phoswich detector cells (PDCs) based on coincident detection of Compton scattering and photoelectric absorption. Each PDC comprises three different scintillating components and combines photon detection, active collimation and bottom anticoincidence into one single unit. The three parts are viewed by a photomultiplier tube (PMT) and pulse shape discrimination is used to identify signals from different parts. Surrounding the detector array is a segmented side anticoincidence shield (SAS) made of BGO crystals.

The detector elements of the instrument (PDCs, SAS units, PMTs) have been characterized, resulting in a placement scheme which details where within the detector array each element should be placed in order to maximize the instrument sensitivity and response uniformity. Suitable operating parameters for flight, such as threshold settings and PMT voltages, have also been defined.

Geant4 Monte Carlo simulations have shown that a polyethylene shield is needed around the detector array in order to sufficiently reduce the background from atmospheric neutrons. To validate these simulations, a simple detector array with four plastic scintillators and three BGO crystals shielded with polyethylene was irradiated with 14 MeV neutrons. Measured results were accurately recreated in simulations, demonstrating that the treatment of neutron interactions in Geant4 is reliable.

A Pathfinder version of the PoGOLite instrument has been constructed and tested with unpolarized and polarized photon beams, and results have been compared with simulations. The Pathfinder is being prepared for a maiden flight from northern Sweden in mid-2011. A circumnavigation is foreseen at an altitude of up to 40 km, whereby the instrument travels westwards over Greenland and Canada and returns over Russia after a period of about 20 days. The main observational targets for this flight will be the Crab system and Cygnus X-1.
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Introduction

Measurements of X-rays and gamma-rays have long been central to observational astronomy. Sources of interest are numerous on both hemispheres, and existing as well as currently planned instruments will continue to expand this exciting field. For many of these objects, there are several competing models and theories describing the high-energy emission, but often, the information at hand, such as light-curves and energy spectra, is consistent with several models and thus cannot solve this ambiguity.

Polarimetry is expected to provide decisive information, since photons are characterized not only by their energy, direction and time of detection, but also by their polarization. Measuring polarization in the X-ray and gamma-ray band has proven to be a challenge due to the high levels of background, but since polarimetry provides two new parameters, polarization angle and degree, such measurements could potentially open a whole new observational window on the universe.

PoGOLite, with the logo in Figure 1, is a balloon-borne Compton-based polarimeter. Thanks to its excellent background rejection capabilities, which are achieved using a combination of both active and passive systems, PoGOLite will be able to measure the polarization from a wide variety of astronomical objects. A “pathfinder” version of this instrument, which is being prepared for a flight from northern Sweden in mid-2011, will be the main topic of this thesis.

Figure 1. The “PoGO LoGO” or “PoGOType”.

PoGOLite
The Polarized Gamma-ray Observer

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Outline

An introduction to X-ray and gamma-ray polarimetry is presented in Chapter 1, along with a discussion on the scientific potential of such studies. Chapter 2 will focus on describing the PoGOLite instrument and its constituents in detail. In Chapter 3, tests of the inorganic scintillator crystals of the side anticoincidence shield will be presented. Neutron irradiation tests, conducted in order to evaluate the instrument background rejection capabilities, and simulations thereof are given in Chapter 4, while the process of optimizing the detector array sensitivity and uniformity is described in Chapter 5. The penultimate part of the text, Chapter 6, details the characterization of the PoGOLite instrument through laboratory tests with unpolarized and polarized photon beams as well as Monte Carlo simulations. Finally, some closing words and an outlook are given in Chapter 7.

Author’s contribution

After the completion of my Master of Science thesis, which was based on work with the PoGOLite prototype carried out at the Stanford Linear Accelerator Center (SLAC) between September 2005 and February 2006, I continued working with PoGOLite as a PhD student, starting at the Royal Institute of Technology (KTH) in May 2006. I quickly became heavily involved with the testing and characterization of the BGO crystals to be used for the side anticoincidence shield (SAS). Around this time, the requirements for the flight-version crystals were just being finalized, and most of the specifications ended up being based on my test results from the first set of prototype crystals.

Once the SAS BGO crystals were delivered from the manufacturer, I assumed full responsibility for the testing of these. All 187 crystals were individually inspected, energy spectra were recorded for five irradiation points on each crystal, the light yield and energy resolution were determined for all irradiation points and linear dimensions were measured. The best units were identified for use in the instrument. I studied the reproducibility of the measurements, collimation of the photon beam from the radioactive source, effects of voltage settling in the photomultiplier tubes, changes in light yield when using optical grease from different suppliers, properties of different reflector materials, etc.

To date, there have been three PoGOLite beam tests at the KEK “Photon Factory” in Japan. For all of these, I was actively involved in preparing and testing the instrument used during the tests, and taking shifts with the data acquisition system. Having had the main responsibility for testing the BGO crystals of the side anticoincidence shield, I became strongly involved in the measurements relating to this anticoincidence unit and the data analysis that followed.

For the neutron test which took place at the Nuclear Engineering Department at the Chalmers University of Technology in Gothenburg, I was responsible for the preparation of the SAS BGO units. During the tests, my involvement in the data
acquisition and analysis gradually increased and by the completion of the test, I had assumed full responsibility for the analysis. As for the simulation, I inherited the detector geometry and a basic simulation framework from Masaru Ueno at the Tokyo Institute of Technology. I modified the code to separate between interactions caused by different particles, re-ran all simulations and could then individually include quenching effects for the particles in my analysis, which allowed me to obtain a good agreement between simulated and measured data. The analysis and simulation of the neutron beam test presented here is entirely my work.

My licentiate thesis, entitled “Studies of PoGOLite Performance and Background Rejection Capabilities”, was written about two years into my doctorate studies. The thesis, which I defended in June 2008, detailed my work with the SAS BGO crystals, the photon beam tests at KEK as well as the measurements and simulations of the neutron test conducted in Gothenburg. The BGO and neutron chapters are included here as well. The KEK beam tests are covered in a dedicated chapter in my licentiate thesis and in publications listed at the end of this section. They are only briefly discussed in this work to put the other material into context. All the remaining material has been specifically written for this thesis.

During the second half of 2008, diploma work students Daniel Walldin and Erik Brandrup-Wognsen studied plastic scintillators from ELJEN Technology to be used for flight. From these scintillators and the previously tested BGO crystals, they produced a large number of PDCs and SAS units. Because of my previous experience assembling and testing such detector elements at SLAC, my involvement in this process became something like that of an (informal) supervisor. Following a “workshop” where a majority of the Swedish PoGOLite collaboration participated in cutting, gluing and folding covering materials for the PDCs, I finished the covering procedure of the PDCs (and therefore also enjoyed the privilege of naming each unit).

I conducted Geant4 simulations with a seven-unit detector array in order to determine the activity of a radioactive source required for producing a reasonable count rate of polarized photons in a laboratory measurement. (Tests with such a detector array had previously been carried out at SLAC, where obtaining a clear polarization signal had taken about one week of measurement time.) A radioactive source ($^{241}$Am, 3.7 GBq) was procured based on these results. This study also became the basis of my simulation work regarding the laboratory measurements of unpolarized and polarized beams.

In preparation for the assembly of the PoGOLite Pathfinder detector array, I conducted an extensive testing of all available units: PDCs, SAS segments and photomultiplier tubes. This work resulted in a “placement scheme” detailing where in the detector array each individual detector element should be positioned, and which photomultiplier tube it should be coupled to in order to maximize the sensitivity and uniformity of the detector system. My suggestion was accepted by the collaboration and the detector was subsequently configured according to these specifications.
Construction of the PoGOLite Pathfinder instrument took off around mid-2009. This marked the start of an intensive period where new parts of the instrument were delivered almost daily. My activities during this time became heavily focused on assembling the polarimeter. I have participated in this amazing effort from the very beginning up to the point where the essentially finalized instrument was shipped from the premises in order to be integrated into the gondola assembly – a work which I have documented in over 1000 photographs.

Most of the scientific data that I present here (unpolarized beam and polarized beams recorded with the assembled instrument, measurements with a strong background) was collected during three very intensive weeks in October-November 2010, which was the amount of time available for measurements due to the tight planning involved with preparing the instrument for flight. Although several problems, mainly with the data acquisition system, were encountered (and subsequently solved), this was a very fruitful period which provided data for multiple analyses, several of which are presented here.

The acquired data also became the foundation for my work with the main analysis program. While some software written by Japanese colleagues already existed, this had become increasingly cluttered through repeated modifications and additions by different authors. I therefore decided to re-write the entire analysis code from scratch, with the aim of producing a simple and intuitive program that would be suitable for the analysis of data recorded not only in a controlled laboratory environment, but also in flight. The result is the "MainAnalysis" program, which has proven to be a very powerful tool and will hopefully be used to analyze flight data once the instrument is launched.

Originally, the maiden voyage of the PoGOLite Pathfinder was scheduled to be a short (~24 h) flight taking place in August 2010. Due to circumstances beyond the control of the collaboration, the “High Visibility Type B Mishap”\(^1\) of the balloon-borne Nuclear Compton Telescope in Alice Springs, Australia, on April 29 2010, our flight was postponed while the investigation into this matter was pending\(^2\). As a result, the work plan of my thesis became significantly altered: instead of describing the analysis of flight data, the focus instead became that of testing and characterizing the instrument in a laboratory environment.

The decision was made to change the maiden voyage into a circumnavigational flight. It is worth underlining that several studies presented here can be improved, but that this was not possible due to work on the instrument reconfiguring it for a long-duration flight, which had to take immediate priority.

The work presented here is also discussed in the the following publications, of which I am the author or co-author:

\(^1\)Crash
\(^2\)The 400-page report on this incident is available in its entirety from the Goddard Space Flight Center on the address http://www.nasa.gov/centers/goddard/business/foia/balloon_mishap.html


Chapter 1

X-ray and gamma-ray polarimetry

Polarized X-rays and gamma-rays are expected from a wide variety of astronomical sources, including pulsars, X-ray binary systems, strongly magnetized neutron stars and collimated outflows from active galactic nuclei. Although polarimetric studies of these sources are expected to provide important new insight into the emission mechanisms and geometries of the objects [1], the field is largely unexplored. This chapter gives an introduction to X-ray and gamma-ray polarimetry and its prospects.

1.1 Measurement techniques

When photons interact in a material, several processes can occur, with cross-sections depending on the energy of the incident radiation. At low energies, the photoelectric effect [2] dominates, Compton scattering [3] is most probable in an intermediate energy region, and at high energies the pair production process [4] takes over. Each of these interactions has a dependence on the polarization of the incident radiation and can in principle be used for polarimetry.

To cover the entire X-ray and gamma-ray band, all three processes must be employed, and their polarization-dependent characteristics will briefly be discussed below. Since the processes dominate in different energy regions (see Figure 1.1), their measurement techniques cannot be combined in any straight-forward way: a detector intended for measuring one process is not well-suited for recording another process.
Chapter 1. X-ray and gamma-ray polarimetry

Figure 1.1. Mass attenuation coefficient (cm$^2$/g) for photon interactions in water, adopted from [5]. Multiplying this parameter by a material density (g/cm$^3$) gives the change in intensity per unit length (cm$^{-1}$) for photons traversing the material.

1.1.1 Photoelectric effect

In the photoelectric effect [2], an incident photon is absorbed by the atom it interacts with, and the photon energy is transferred to an electron in the atom. If the photon energy is greater than the binding energy of the electron (which is always the case for X-rays and gamma-rays), the atom is ionized and the electron is emitted with a kinetic energy given by

$$E_{k,e^-} = h\nu - E_b$$  \hspace{1cm} (1.1)

where $h$ is Planck’s constant, $\nu$ is the frequency of the incident radiation and $E_b$ is the binding energy of the electron in question. Electrons populating atomic shells close to the nucleus are more tightly bound than those in outer shells and if the photon has sufficient energy, an electron will most likely be emitted from the inner-most shell, i.e. the K-shell. For linearly polarized radiation, the angular distribution of emitted electrons is not uniform but rather given, in terms of the differential scattering cross-section, by [6]

$$\frac{d\sigma}{d\Omega} = r_0^2 Z^5 \alpha^4 \left( \frac{m_e c^2}{\hbar \nu} \right)^{7/2} \frac{4\sqrt{2} \sin^2 \theta \cos^2 \phi}{(1 - \beta \cos \theta)^4}$$ \hspace{1cm} (1.2)
where $r_0$ is the classical electron radius, $Z$ is the atomic number of the absorbing material, $\alpha$ is the fine-structure constant, $m_e$ is the mass of the electron, $c$ is the speed of light, $\theta$ is the polar emission angle of the electron, $\phi$ is the azimuthal angle of emission from the polarization plane and $\beta = v/c$ with $v$ being the final velocity of the emitted electron. Due to the $\cos^2 \phi$ dependence, the azimuthal electron emission angles will be modulated by the polarization of the incident photons. Thus, by measuring the distribution of azimuthal electron emission angles, the polarization of the incident radiation can be determined.

1.1.2 Compton scattering

In the Compton interaction [3], a photon is scattered off an electron, assumed to be at rest\(^1\). The scattering is at a polar angle $\theta$ relative to the direction of incidence as shown in Figure 1.2, and some of the energy is transferred to the electron. The reverse process called inverse Compton scattering is also possible, whereby a photon scatters off a relativistic electron and instead gains energy.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{compton_scattering.png}
\caption{Geometry of the Compton scattering process [7].}
\end{figure}

The energy of the scattered photon is given by [7]

\[ E'_\gamma = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e c^2} (1 - \cos \theta)} \tag{1.3} \]

where $E_\gamma = h\nu$ is the energy of the incident photon and $\theta$ is the polar scattering angle of the photon, as defined in Figure 1.2.

\(^1\)An electron can be considered to be at rest if the photon energy is large compared to the binding energy of the electron: $h\nu \gg E_b$. This is always the case for X-rays and gamma-rays.
Chapter 1. X-ray and gamma-ray polarimetry

The Compton process is governed by the Klein-Nishina formula [8], which gives the differential cross-section for a photon to scatter at polar angle $\theta$ relative to the direction of incidence and azimuthal angle $\phi$ relative to the polarization vector:

$$\frac{d\sigma}{d\Omega} = \frac{1}{2} e^2 \frac{k^2}{k_0^2} \left( \frac{k}{k_0} + \frac{k_0}{k} - 2 \sin^2 \theta \cos^2 \phi \right)$$

(1.4)

where $k_0$ and $k$ are the momenta of the incident and scattered photon, respectively. The geometry is clarified in Figure 1.3.

Since the negative term in Equation 1.4 decreases as $\phi \to 90^\circ$ (and even vanishes at $\phi = 90^\circ$), photons have a higher probability to scatter perpendicularly to the polarization vector of the incident radiation, i.e. at an angle $\phi$ close to $90^\circ$. Thus, the azimuthal scattering angles of photons from a polarized beam will be modulated and the resulting anisotropy can be used for polarimetry. The polarization studies described in this thesis are entirely based on the Compton scattering process.

1.1.3 Pair production

In the pair production process (see [4] and references therein), a photon interacts with the Coulomb field of an atom and is transformed into an electron-positron pair. The geometry of the process is defined in Figure 1.4.
1.1. Measurement techniques

Figure 1.4. Geometry of the pair production process, adapted from [9]. Vectors $k$, $p_+$, and $p_-$ indicate the momenta of the incident photon, positron and electron, respectively. Angles $\theta_+$ and $\theta_-$ are the polar angles of the positron and electron, defined relative to the direction of the incoming photon. The polarization direction is indicated by $\epsilon$, and $\Psi$ is the angle between this direction and the projection of $p_+$ onto the plane perpendicular to the direction of the incident photon. Finally, $\phi$ is the angle between the projections of $p_+$ and $p_-$ on this plane. In the co-planar case, which is the most common one, $\phi = 180^\circ$, i.e. the electron-positron pair is in the same plane as the incident photon.

For the pair production process be possible, the photon energy must exceed $2m_e c^2 = 1.022$ MeV, and a close proximity to an atom is needed for the conservation of momentum. The process tends to be co-planar ($\phi = 180^\circ$) i.e. the electron-positron pair is mostly in the same plane as the momentum of the incident photon (vector $k$ in Figure 1.4). In this case, $\Psi$ simply becomes the angle between the polarization vector of the incident photon and the plane of the produced electron-positron pair. The differential cross-section for the process is then given by [9]

$$\frac{d\sigma}{d\Psi} = A(1 - \lambda \cos^2 \Psi)$$

(1.5)

where $A \approx 0.8$ is the asymmetric ratio (ratio between number of pairs produced in the plane of polarization and number of pairs produced in the plane perpendicular to the polarization) and $\lambda \approx 0.2$ is the degree of asymmetry in the distribution and is approximately constant at high energy. Thus, since the electron-positron pair plane has a higher probability to be oriented perpendicular to the polarization vector ($\Psi = 90^\circ$), the process will be modulated by the polarization of the incident radiation and pair production can therefore be used for polarimetry.
1.1.4 From modulation to polarization

The processes discussed above all have an angular dependence on the polarization: the azimuthal angle of the emitted electron for the photoelectric effect, the azimuthal photon scattering angle in the Compton process and the angle to the plane of the electron-positron pair for the pair production. Polarimetry based on these processes thus aims to reconstruct the distribution of these angles. If the observed radiation is polarized, the relevant angle will be modulated (anisotropic). An example of such a modulation is shown in Figure 1.5.

![Figure 1.5](image)

**Figure 1.5.** Example of polarization-induced modulation. The “angle” on the abscissa can either refer to the azimuthal electron emission angle (photoelectric effect), the azimuthal photon scattering angle (Compton process) or the angle to the electron-positron pair plane (pair production). Amplitude ($A$) and mean value ($B$) of a fitted sinusoidal modulation curve have been indicated.

The anisotropy is given by the modulation factor $M$, defined as the ratio between the amplitude $A$ and the mean value $B$ of a fitted sinusoidal modulation curve:

$$M = \frac{A}{B} = \frac{C_{\text{max}} - C_{\text{min}}}{C_{\text{max}} + C_{\text{min}}}$$  \hspace{1cm} (1.6)

where $C_{\text{max}}$ and $C_{\text{min}}$ are the maximum and minimum count rates of the angular distribution (ordinate of Figure 1.5).

Polarized radiation is characterized through its polarization degree (fraction of the radiation (photons) with polarization (electric field vector) aligned in a certain direction) and polarization angle (rotation between a chosen frame of reference and the polarization direction). Both of these parameters can be deduced from the modulation curve. The polarization degree $P$ is given by

$$P = \frac{M}{M_{100}}$$  \hspace{1cm} (1.7)
where $M$ is the observed modulation factor and $M_{100}$ is the modulation factor for a 100% polarized beam, obtained either through simulations or by measuring a beam with a known polarization degree and solving for $M_{100}$. The polarization angle is the phase of the modulation curve relative to some fixed reference. Thus, the task of determining the polarization becomes that of measuring the angular distribution relevant for the process in question. This is done in several existing and proposed instruments, some of which will be mentioned throughout this chapter.

1.2 Scientific targets

1.2.1 Pulsars

Pulsars are rapidly rotating neutron stars with strong magnetic fields. As such an object rotates, it will emit dipole radiation with characteristics depending on the angle between the dipole axis and the rotation axis of the system, as well as the orientation of the system relative to the observer. Although pulsars were discovered in 1967 [10], there is still no generally accepted model that can fully explain the observed electromagnetic spectra. For the high-energy emission, there are currently three main models [11]: the polar cap model [12], the (two-pole) caustic model [13] and the outer gap model [14]. These are briefly described here.

The polar cap model: According to this model, an acceleration of electrons and positrons takes place in the open field line regions around the polar caps of the neutron star. These particles emit synchrotron and curvature radiation as they traverse the strong and non-uniform magnetic field in the polar regions. The radiation, along with pair production, causes an electromagnetic cascade, giving rise to the observed spectra.

The caustic model: Here, the particle acceleration and emission are assumed to take place along the edge of the open field region, extending from the surface of the neutron star out to the light cylinder, outside which particles co-rotating with the neutron star would be moving faster than the speed of light.

The outer gap model: Predicts that electrons and positrons are accelerated in vacuum gaps in the outer magnetosphere, between the closed and the open magnetic field lines. As charged particles can escape along the open magnetic field lines, a vacuum gap is formed, with a strong potential difference over the region. This accelerates the particles to high energies, whereby they emit synchrotron and curvature radiation. Undergoing inverse Compton scattering, this radiation can produce secondary electron-positron pairs, which, in turn, cause more synchrotron and curvature radiation. The observed high-energy emission is assumed to be from such pair production-induced cascades.

The pulsar geometry and regions of emission predicted by these three models are shown schematically in Figure 1.6.
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Figure 1.6. Emission regions for the polar cap, caustic and outer gap models [15]. The angular velocity vector $\Omega$ and magnetic field vector $B$ are separated by the angle $\alpha$, i.e. the rotation axis and magnetic field axis are not parallel, causing the pulsed emission observed from these systems. The light cylinder is a region at a certain distance from the rotation axis where material rigidly connected to the rotating object would be moving at the speed of light.

Although the models propose different locations of emission, the predictions for the intensity are very similar. The correct model therefore cannot be identified based on this information only. However, the polarization characteristics predicted by the different models are widely divergent and this information can thus be used to discriminate between models. If all three turn out to be incorrect, polarimetric observations will still serve to put severe constraints on future models. Emission characteristics (intensity, polarization angle and polarization degree) predicted by these models for the Crab pulsar, one of the most prominent pulsars on the northern hemisphere, are shown in Figure 1.7.
Figure 1.7. Intensity (top row), polarization angle (middle row) and polarization degree (bottom row) as a function of the rotation phase of the Crab pulsar (one full revolution is 33 ms) as predicted for the high energy emission by the polar cap model (left column) caustic model (middle column) and outer gap model (right column) [16]. “High energy” here applies to optical emission as well as non-thermal X-ray and gamma-ray emission, and the spectral dependence of the polarization characteristics have been ignored (see [11] for a discussion). Due to the offset between the rotation and magnetic field axes, emission from the two poles of the pulsar cause two peaks in the observed intensity for each complete revolution. Depending on the orientation of the system relative to the line of sight of the observer, one peak is usually more pronounced than the other. Here, vertical lines indicate the first and the second pulse observed in the emission, P1 and P2, respectively.
It is noted, from observations of a large number of pulsars with the Fermi Gamma-ray Space Telescope [17], that the gamma-ray emission seems to appear at high altitude, mainly from the outer magnetosphere in most pulsars, thus favoring outer gap and caustic models, while the polar cap model remains plausible only for a few of the studied objects [18].

1.2.2 Accretion discs

Accretion discs can be formed when matter is falling towards a compact object, for example in binary systems consisting of a neutron star or a black hole and a visible companion star. In such systems, matter can be accreted from the companion onto the compact object, whereupon gravitational energy is emitted as X-rays. Cygnus X-1 on the northern hemisphere is an example of such a system. It exhibits two main spectral states [19, 20, 21], the “hard” and the “soft” state. Most of the time is spent in the hard state. When transitions to the soft state occur, these typically last a few months [22], while the hard state can last for several years. The time scale of the variability is shown in Figure 1.8.

![Figure 1.8. Variability of Cygnus X-1 in energy ranges 3–12 keV (blue) and 20–300 keV (red) as observed by instruments on the Rossi X-ray Timing Explorer (RXTE) and the Compton Gamma-Ray Observatory (CGRO) [23]. The abscissa shows time in Modified Julian Date (MJD), while the ordinate is the photon flux in terms of the spectral index $\Gamma$, as given by a power law on the form $F(E) = kE^{-\Gamma}$ where $F$ is the flux, $E$ is the photon energy and $k$ is a constant.](image)

Transitions between the two are believed to be related to changes in the mass accretion rate of the system. If the accretion rate is low, the inner part of the disc becomes geometrically thick and optically thin, with a hot inner flow or corona region. A primary flux of X-rays arises through multiple Compton up-scattering of photons and is expected to be unpolarized. However, a secondary component, caused by photons that are reflected from the accretion disc, is believed to have a significant polarization. This situation is called the “hard” state and is depicted in Figure 1.9. The observed polarization depends on the inclination of the accretion disc relative to the line of sight and polarimetry can therefore provide information about the geometry of the system, which is difficult to obtain through other measurements [16].
1.2. Scientific targets

Figure 1.9. Emission from an accretion disc in the hard spectral state [23]. The primary component (“Direct soft photons”) is unpolarized, but the secondary component (“Reflected photons”) can have a significant polarization.

If, instead, the accretion rate is high, matter is accreted through a geometrically thin but optically thick disc, which extends to the innermost stable orbit around the compact object. Active regions with energetic electrons are then formed above the disc, and hard X-rays emitted from the accretion disc can undergo Compton up-scattering in these regions. This is the “soft” spectral state, schematically shown in Figure 1.10. A different polarization signature is expected compared to the hard state and a polarimetric study in the X-ray band will provide information about the electron energy distribution in the active regions of the accretion disc [16].

Figure 1.10. Emission from an accretion disc in the soft state [23]. The primary component (“Direct soft photons”) is unpolarized. A secondary component from photons scattering in an active region (“Scattered hard photons”) can be polarized.

1.2.3 Neutron stars

For accreting magnetized neutron stars, X-rays and gamma-rays can be observed from matter flowing along the magnetic field lines onto the polar regions of the star. Due to the strong magnetic field [24], this radiation is expected to be linearly polarized. As the neutron star rotates, the polarization signature will change. By observing these changes, it is possible to determine both the orientation of the rotation and magnetic field axis of the system [16]. The main candidate for such a measurement on the northern hemisphere is Hercules X-1.
1.2.4 Astrophysical jets

Active galaxies which are powered by the accretion of matter onto a super-massive black hole can emit jets – collimated outflows of radiation perpendicular to the plane of accretion [16]. If such a galaxy is viewed through one of these jets, the object is called a blazar. Spectra from blazars typically show two components, one from synchrotron radiation and one caused by photons undergoing inverse Compton scattering. The radiation is known to be polarized in the radio to UV-range, but little is known about the polarization of the X-ray and gamma-ray photons. Here, a polarimetric study could provide important information about the emission mechanisms and the geometry of the magnetic field of the host galaxy. One candidate for such a measurement is Markarian 501.

1.3 Crab polarimetry

One of the most prominent sources in the sky is the Crab system: a pulsar wind nebula and rotating neutron star located some 6500 light-years from Earth, which emits radiation from radio all the way up to gamma-rays (see Figure 1.11).

![Figure 1.11. The measured spectrum of the Crab nebula extends over many orders of magnitude in frequency [25]. Flux shown in Jansky (1 Jy = 10^{-26} W/m²).](image)

The Crab is one of the most studied objects in the galaxy and has been observed in radio with the Very Large Array [26], in infrared with the Spitzer Space Telescope [27], in optical with the Hubble Space Telescope [28] and in X-rays with the X-ray Multi-Mirror Newton instrument [29], to mention a few examples. The emission of the Crab nebula is expected to be steady within a few percent, thus the flux from astronomical sources is commonly quoted in “Crab” units, where 1 Crab is the flux from the Crab in the 2–10 keV band. It is also routinely used to cross-calibrate X-ray and gamma-ray instruments, as well as to study changes in detector performance over time. However, recent studies with the Fermi Gamma-ray Burst Monitor, independently confirmed with instruments on the Swift telescope, RXTE
1.3 Crab polarimetry

(Rossi X-ray Timing Explorer) and INTEGRAL (INTErnational Gamma-Ray Astrophysics Laboratory), show a decline in the 15–50 keV flux from the nebula by about 70 mCrab since August 2008, i.e. a decrease by about \(~3.5\%\)/year, with similar results also seen in the \(~3–15\) keV and \(50–100\) keV bands \([30]\). The fact that the pulsed emission remains stable over this period indicates that the variation arises from the nebula. Furthermore, gamma-ray flares from the Crab nebula, observed with Fermi in energies above 100 MeV, have recently been reported \([31]\). One flare was in February 2009 and lasted about 16 days, during which the gamma-ray flux increased approximately by a factor of four. A second one, lasting around four days, occurred in September 2010, and increased the flux by a factor of six. Neither the decrease in flux over the time scale of years, nor these short flares are fully understood at the time of writing. They indicate, however, that absolute calibration based on the Crab nebula may not be reliable, at least not without cross-reference to other instruments observing the system during the same period.

In 1976, the polarization of 2.6 keV and 5.2 keV X-rays from the Crab nebula was measured with OSO-8 (Orbital Solar Observatory 8) using first and second order Bragg diffraction\(^2\) at an angle of 45\(^\circ\) \([32, 33]\). The instrument had two photon-counting detectors which could be rotated relative to the line of sight towards the Crab, causing a modulation in the count rates, since photons have a higher probability to scatter perpendicularly to the polarization vector. Background was subtracted using data from a measurement when the Crab was occulted by the Earth. At 2.6 keV, the measured polarization degree was \((19.2 \pm 1.0)\%\) at position angle \((156.4 \pm 1.4)\)\(^\circ\), while corresponding values at 5.2 keV were \((19.5 \pm 2.8)\%\) and \((152.6 \pm 4.0)\)\(^\circ\). These results are consistent with radiation arising from synchrotron processes and the measurement remains, to date, the only statistically significant and well-constrained study of the Crab polarization in this energy range.

Optical polarization from the Crab has been studied with OPTIMA (Optical Pulsar TIMing Analyzer) \([34]\), a 3.5 m telescope located in Spain, sensitive in the 450–950 nm range. The system has high timing resolution and thus allows phase-dependent measurements of the polarization angle and degree. Figure 1.12 shows results from such a measurement carried out in 2002: intensity, polarization angle and polarization degree as a function of the phase of the Crab pulsar. The polarization angle exhibits a rapid shift over the peak regions and the polarization degree is anti-correlated to the peaks, indicating that the emission is produced at many different altitudes over the pulsar, i.e. with a multitude of different polarization angles. As the pulsar rotates, the polarization angle will be seen as rapidly swinging and the polarization degree will be averaged to a low value. If the polarization signature is similar in X-rays and gamma-rays, instruments with high sensitivity to polarization and are needed for an observation of the pulsar component.

---

\(^2\)Bragg diffraction (constructive) arises when electromagnetic radiation incident on a crystal lattice satisfies the relation \(2d \sin \theta = n \lambda\), where \(d\) is the distance between parallel planes in the crystal structure, \(\theta\) is the scattering angle, \(\lambda\) is the wavelength and \(n\) is an integer corresponding to the distance between involved crystal layers in units of the length \(d\). First order Bragg diffraction corresponds to \(n = 1\) and happens with two adjacent crystal layers, etc.
Chapter 1. X-ray and gamma-ray polarimetry

Figure 1.12. Optical polarization of the Crab pulsar seen with OPTIMA [34]. Relative intensity (top), polarization angle (middle) and polarization degree (bottom panel) are shown as a function of the pulsar period (33 ms). Vertical red lines have been added to guide the eye, indicating the peak regions, P1 and P2, respectively.

In gamma-rays, the Crab has been studied with INTEGRAL [35], which has two main instruments, IBIS and SPI. IBIS (Imager on-Board the Integral Satellite) [36], is a coded mask pixelized solid-state detector optimized for high angular resolution. It has two position-sensitive layers: one upper layer with a $128 \times 128$ matrix of CdTe (cadmium-telluride semiconductor detectors) for low energies ($15–1000$ keV) and a second layer with a $64 \times 64$ matrix of CsI (cesium iodide inorganic scintil-
lators) for high energies (200 keV–10 MeV). Due to the discrete matrix elements, photons can be tracked as they scatter from one layer to the other, providing some sensitivity to polarization. SPI (SPectrometer on Integral) [37], is a 19-unit coded mask array of hexagonal high-purity germanium detectors, designed to maximize energy resolution in the range 20 keV–8 MeV. By tracking photons scattering from one cell into the other, this instrument also gains polarimetric sensitivity. The two detector systems are shown in Figure 1.13.

Figure 1.13. The INTEGRAL IBIS and SPI detectors are both segmented and can therefore be used for Compton polarimetry. IBIS (top) has a pixelized matrix where photons can scatter from pixel to pixel. SPI (bottom) consists of 19 hexagonal elements where photons can scatter in one element and be absorbed in another.
Between 2003 and 2007, the Crab was observed in the 200–800 keV range with the IBIS instrument [38]. In the peak regions (P1 and P2), no significant polarization was found, which was interpreted as a low polarization degree and/or a rapidly changing polarization angle (as seen in the optical range). For the off-pulse region (between P2 and P1), the result was >72% polarization at an angle of (120.6 ± 8.5)°. When also including the bridge region (between P1 and P2), the corresponding values were >88% and (122.0 ± 7.7)°. The high polarization degree implies synchrotron emission from a region with a well-ordered magnetic field, and the polarization angle is consistent with the pulsar rotation axis, estimated through observations in the X-ray band to be at (124.0 ± 0.1)° [39].

The SPI instrument has also been used to study the polarization of the Crab, collecting over 600 observations in the energy range 100 keV–1 MeV [40] between 2003 and 2006. Simulations were carried out with polarized photons irradiating a computer model of the SPI instrument, and the polarization angle was varied between 0° and 180° in 10° steps. By adding simulated unpolarized photons, a matrix could be generated with results corresponding to any combination of polarization angle and degree, a procedure which is described in [41]. Using a χ² test to compare the observed results with simulated data in the matrix, the best match could be determined. Through this technique, the polarization degree was found to be (46 ± 10)% at (123.0 ± 11)°. The angle is consistent with IBIS results and with the rotation axis of the pulsar, while the relatively high polarization degree again implies a well-ordered magnetic field in the emitting region.

Observational results of Crab polarization studies are summarized in Table 1.1.

|------------|--------|-------------|------------|------|
| OPTIMA     | 450–950 nm,  
            ~1–3 eV (Optical) | Peaks: low polarization,  
            ~5–10% | Peaks: rapidly changing,  
            ~70–170° | [34] |
| OSO-8      | 2.6 keV (X-rays)  
            5.2 keV (X-rays) | (19.2 ± 1.0)%  
            (19.5 ± 2.8)% | (156.4 ± 1.4)°  
            (152.6 ± 4.0)° | [32, 33] |
| INTEGRAL   | 0.2–0.8 MeV  
            (Gamma-rays) | Peaks: little or no polarization  
            Off-pulse:  
            >88% pol. | Peaks:  
            N/A  
            Off-pulse:  
            (122 ± 7.7)° | [38] |
| INTEGRAL   | 0.1–1 MeV  
            (Gamma-rays) | Off-pulse:  
            (46 ± 10)% | Off pulse:  
            (123 ± 11)° | [40] |

Table 1.1. Summarized results of Crab polarization studies, sorted after energy.

Several other instruments aim to measure the X-ray/gamma-ray polarization of the Crab. Examples include the Compton-based instruments PHENEX (Polarimeter of High ENERgy X-rays) [42], the coded mask telescope CIPHER (Coded
1.4 Gamma-ray burst polarimetry

Gamma-ray bursts (GRBs) [44] are short but powerful flashes of gamma-rays, believed to be caused by supernova events or mergers of neutron stars in binary systems. A typical burst lasts a few seconds and is then usually followed by an “afterglow” in the lower energy range: X-rays, ultraviolet, optical, infrared and radio. The occurrence of a gamma-ray burst (and therefore, its arrival direction) cannot be predicted in advance, but when they do occur (on the order of one per day in the visible universe), they are extremely bright, momentarily outshining every other gamma-ray source. An instrument with a wide field of view therefore has a chance of observing these bursts.

The central engine powering this emission and the structure of the magnetic fields associated with gamma-ray bursts are not fully understood. The emission, which is assumed to arise from a spherical shell moving outwards from the central engine, has characteristics depending on the geometry of the magnetic field. There are several models describing this emission: synchrotron with globally ordered magnetic fields (SO model), synchrotron with random variations of the magnetic field on small scales (SR model) and the Compton drag (CD model). Models have proven difficult to constrain through spectral and temporal measurements, but polarimetry is expected to resolve some of the ambiguities [45].

A measurement of $(80 \pm 20)\%$ polarization from gamma-ray burst GRB 021206 with RHESSI (Reuven Ramaty High Energy Solar Spectroscopic Imager) has been reported [46]. A re-analysis showed, however, that the results could not statistically constrain the polarization [47]. Yet another analysis produced, from the same data set, a polarization degree of $(41^{+57}_{-44})\%$, which, within one standard deviation, is consistent with both 0% and almost 100% polarization [48]. Results such as these are potentially affected by large uncertainties and systematic errors, and therefore remain debated. This lack of stringent results illustrates the need for dedicated gamma-ray burst polarimeters. Several instruments have been proposed, e.g. POLAR [49] and GRAPE [50], both active in the energy range 50–300 keV.

In 2004, aforementioned INTEGRAL detected a gamma-ray burst under very favorable conditions. This burst, GRB 041219a, was the brightest one seen by the instrument and occurred only 3.2° from the viewing axis of the detectors. The polarization of the gamma-ray burst was studied both with IBIS [51] and with SPI [52]. This burst featured two bright peaks, both lasting a few tens of seconds, as shown in Figure 1.14.
Figure 1.14. Light curves (observed intensity as a function of time) for GRB 041219a recorded with INTEGRAL IBIS (top) and SPI (bottom).
With IBIS [51], in the energy range 200–800 keV, no polarization was seen in the first of the two peaks (upper limit 4%). This need not imply a low intrinsic polarization degree, but could also result from a rapid change in the polarization angle, producing a low average polarization over the peak region. For the second peak of the burst, the polarization degree was found to be $(43 \pm 25)%$.

The SPI measurement [52] was instead based on measuring polarization between 100 keV and 350 keV in the brightest 66 s and 12 s of the burst. For the longer interval, the measured polarization was $(63^{+31}_{-30})%$ at $(70^{+14}_{-11})^\circ$, while corresponding results were $(96^{+39}_{-40})%$ at $(60^{+12}_{-14})^\circ$ for the shorter time-interval.

The uncertainties in the measured results are considerable, due to the fact that the instruments are not dedicated polarimeters but rather an imager (IBIS) and a spectrometer (SPI) with some sensitivity to polarization. As such, INTEGRAL was never calibrated on ground with polarized beams, and results are therefore completely dependent on simulations based on computer models of the instrument.
Chapter 2

The PoGOLite experiment

2.1 Overview of the PoGOLite instrument

PoGOLite, the Polarized Gamma-ray Observer, is a balloon-borne instrument that will measure the polarization of hard X-rays/soft gamma-rays from astronomical sources in the energy range 25–80 keV.\(^1\) It is optimized for point-sources, with a field of view of \(\sim 1.25 \text{ msr} \ (2.0^\circ \times 2.0^\circ)\). Since radiation is absorbed in the atmosphere [41] and since the X-ray flux from observed objects follows an inverse power-law [53], the high float altitude of the instrument (\(\sim 40 \text{ km}\)) and sensitivity extending as low as possible are crucial, and allow data to be collected with good statistics even in a limited duration flight. The operation is international, involving institutes and universities from Sweden\(^2\), Japan\(^3\) and the United States\(^4\).

The “Lite” in “PoGOLite” is for “light-weight”. Originally, the instrument was foreseen to consist of 397 detector cells [54], but design studies, cost estimates, prototype tests and Monte Carlo simulations demonstrated that a comparable performance could be achieved using a smaller detector array, consisting of 217 units. Such a “light-weight” instrument could reach a float altitude of up to 40 km and be able to measure a polarization degree as low as 10\% from a 200 mCrab source in a six-hour flight [16]. A stepping stone on the way to realizing this goal is the 61-unit PoGOLite “Pathfinder”, which is being prepared for a maiden-flight from northern Sweden in mid-2011. The latter part of this chapter will be devoted to describing the Pathfinder instrument.

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\(^1\)The name “Gamma-ray Observer” is used mainly for historical reasons and it is debatable whether the instrument should be called “PoXOLite” instead, for “X-ray Observer”.

\(^2\)Royal Institute of Technology (KTH), Stockholm University (SU).

\(^3\)Tokyo Institute of Technology, Hiroshima University, Yamagata University, Japan Aerospace Exploration Agency (JAXA).

\(^4\)Stanford Linear Accelerator Center (SLAC), Kavli Institute for Particle Astrophysics and Cosmology (KIPAC), University of Hawaii.
Chapter 2. The PoGOLite experiment

2.1.1 The phoswich detector cell array

The PoGOLite instrument uses an array of plastic scintillators to measure polarization based on the Compton scattering process. This is done by tracking individual photons through coincident detection of Compton scattering and photoelectric absorption in a segmented detector volume of phoswich detector cells (PDCs) [55, 56], surrounded by a segmented side anticoincidence shield (SAS) [57] made of BGO crystals. The PDC units are hexagonal so they can be tightly packed in a honeycomb structure, while surrounding SAS segments have two different pentagonal shapes to fit closely around detector array as shown in Figure 2.1.

Figure 2.1. Computer-generated top view of a 61-unit detector array [58]. The PDCs (purple) are surrounded by a segmented side anticoincidence shield (green).

The honeycomb structure makes the design scalable. The geometric detection area of the instrument can be calculated from the number of detector cells, given by the relation

\[ N(n) = 3(n^2 + n) + 1 \]  \hspace{1cm} (2.1)

where \( N \) is the number of PDCs in the array and \( n \) is the number of rings outside the central unit (which corresponds to the “+1” term). Similarly, the number of pentagonal anticoincidence segments required for enveloping the geometry is

\[ M(n) = 6n + 6 \]  \hspace{1cm} (2.2)

where \( M \) is the total number of segments and \( n \) is the number of PDC rings outside the central unit. In this expression, “6n” corresponds to the number of “edge” pieces and “+6” (a constant) to the number of “corner” pieces, since two geometries are needed for the SAS segments.
Each PDC consists of three active components: a hollow “slow” plastic scintillator\(^5\) (60 cm long), a solid “fast” plastic scintillator\(^6\) (20 cm) and a BGO (bismuth germanate oxide, Bi\(_4\)Ge\(_3\)O\(_{12}\)) crystal\(^7\) (4 cm). The three components are glued together using an optically transparent polyurethane-based adhesive [62]. A sketch of a PDC and pictures of the three scintillating components are shown in Figure 2.2.

**Figure 2.2.** A phoswich detector cell (PDC), consisting of three scintillating components that are glued together, forming one 84 cm long unit.

The slow scintillator tube at the top of the unit acts as an active collimator. Photons within the field of view can pass through the tube without interacting in the walls and reach the fast scintillator, which is where Compton scatterings and photoelectric absorptions are detected. The BGO crystal at the bottom of each unit acts as an anticoincidence shield, allowing photons and charged particles entering the instrument from the rear to be detected. Details on the plastic scintillators are given in [55], while the BGO crystals will be discussed further in Chapter 3.

Both the fast and the slow scintillator are wrapped in VM2000 [63], a reflective material used to minimize the loss of scintillation light through the surfaces of the detectors. Foils of lead and tin, 50 \(\mu\)m thick, surround the slow scintillator. The lead provides additional passive collimation, while the tin prevents characteristic X-rays of lead from entering the scintillator [55]. The BGO crystal is coated with a thin layer of barium sulphate (BaSO\(_4\)), which further enhances the internal reflectivity.

\(^5\)ELJEN Technology “EJ-240” scintillator [59].
\(^6\)ELJEN Technology “EJ-204” scintillator [60].
\(^7\)Nikolaev Institute of Inorganic Chemistry [61] BGO.
“Phoswich” in “phoswich detector cell” (PDC) stands for “phosphor sandwich” and implies that the detector (the fast plastic scintillator) is “sandwiched” between two vetoing components (the slow plastic scintillator and the bottom BGO crystal). All three are viewed by a single photomultiplier tube (PMT), connected to the BGO piece via a silicone pad, which allows the tube to be tightly pressed against the BGO for good optical contact while protecting the PMT window from breaking. Due to the different scintillation decay times of the materials, ~2 ns for the fast plastic scintillator, 285 ns for the slow plastic scintillator and 300 ns for the BGO crystal [55], pulse shape discrimination can be used to identify signals from the different components. A sketch of the PoGOLite detector array can be seen in Figure 2.3. The side anticoincidence shield (SAS), used to detect charged particles and photons incident on the instrument from the side, is also shown.

![Figure 2.3. Simplified sketch of the PoGOLite detector array (not to scale, all units not shown) and different kinds of events.](image)

When the detector array is aimed at an astronomical object, photons from the source can pass through the slow scintillator tubes without interacting and reach the fast scintillators, where they can either be absorbed, scattered into another

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8Hamamatsu R7899 photomultiplier tube [64], optimized for low noise. Described in [55, 65].
cell or escape the detector array entirely. Off-axis photons will deposit energy in the side anticoincidence shield, bottom BGO crystal or slow scintillator and can be rejected. Events of interest are from photons that only deposit energy in the fast scintillators (“Fully contained events” in Figure 2.3). By studying the relative energy depositions in the involved detector cells, the path of such photons can be reconstructed, giving the azimuthal scattering angle of each photon. Since spatial resolution is not achievable within a detector unit, the angular resolution depends on the size of the cells, as well as the distance between the interaction sites.

The mass attenuation coefficient for photons in a plastic scintillator, corresponding to the cross-sections of the photon interactions, is shown in Figure 2.4.

![Figure 2.4. Mass attenuation coefficient for photons in a plastic scintillator, generated based on data from [5]. The PoGOLite energy range has been indicated.](image)

In the PoGOLite energy range, the cross-section is dominated by Compton scattering. The choice to use plastic scintillators as both scatterers and absorbers is therefore a compromise. It is motivated by the fact that plastic scintillators are light-weight, which makes it possible to have an instrument with a large detection area and still reach a high float altitude with a low atmospheric overburden.

Since a photon deposits more energy when absorbed than upon scattering, these events can be distinguished [66], despite the poor intrinsic energy resolution often associated with plastic scintillators. PoGOLite measurements are thus essentially integrated over energy, with limited calorimetric capabilities. A simulation-based study of energy-dependent polarimetry with PoGOLite is presented in [20]. The energy resolution of the PoGOLite plastic scintillators is discussed in [55].

9 The polar scattering angle is not measured, as it does not depend on the polarization (see Section 1.1.2). It is limited to about $90^\circ \pm 30^\circ$ perpendicular to the incident photon due to the length of the fast scintillators and the detector geometry.
As given by Equation 1.3, a photon with an energy of 25 keV will deposit just over 1 keV in a detector cell upon scattering at $\theta = 90^\circ$. The PoGOLite plastic scintillators must therefore be sensitive to energy depositions down to about 1 keV, which dictates the lower energy range of the instrument. Both beam test results and simulations confirm that the modulation of scattering angles can reliably be measured at photon energies as low as 25 keV [65, 67]. The upper limit on the energy range arises from the fact that the background flux estimated from simulations becomes dominating above around 80 keV [21].

### 2.1.2 Event selection technique

Signals from each photomultiplier tube reach charge-sensitive amplifiers on the electronics boards, where they are digitized to 12 bit accuracy with a sampling rate of 37.5 MHz, which corresponds to about 30 ns between sampling points. The boards are equipped with field-programmable gate arrays (FPGAs), which are used to set trigger and threshold levels of individual detector channels and to monitor sampled waveforms. When a waveform is recorded, 50 samples surrounding the trigger are stored, starting 15 samples before the trigger and ending 35 samples after it. At the given sampling rate, this corresponds to storing a waveform with a duration of about 1.3 $\mu$s (0.4 $\mu$s before the trigger and around 0.9 $\mu$s after the trigger). By including pre-trigger data, it is possible to correct for baseline offsets from preceding signals, caused, for example, by large signals from cosmic rays (see Figure 2.5).

![Figure 2.5. Baseline offset due to a large signal by a cosmic ray](image-url)

The storing of pre-trigger data allows the true pulse height (“True PH”) to be reconstructed.
The recorded waveforms are examined in an off-line analysis. Due to the difference in scintillation decay times of the detector components, the output from the charge-sensitive amplifier has different rise times – short (~0.1 \( \mu s \)) for signals in the fast scintillator and longer (~0.3 \( \mu s \)) for signals from the slow scintillator or the bottom BGO crystal – as illustrated in Figure 2.6.

![Figure 2.6. Output from the charge-sensitive amplifier (shown with a negative polarity) [68]. The rise time is shorter for a signal from the fast plastic scintillator than for one from the slow scintillator or BGO crystal.](image)

Quantitatively, the distinction is made by calculating the difference between sampled pulse heights separated by four samples (the “fast” output) and separated by fifteen samples (the “slow” output), and then locating the maximum difference for both of these:

\[
\text{“Fast” output: } \max_{1 \leq i \leq 46} \{ v[i + 4] - v[i] \} \quad (2.3)
\]

and

\[
\text{“Slow” output: } \max_{1 \leq i \leq 35} \{ v[i + 15] - v[i] \} \quad (2.4)
\]

where \( v[i] \) is the pulse height in the \( i \):th sample point and \( 1 \leq i \leq 50 \). These “outputs” are thus not signals from the electronics, but rather mathematical “outputs” calculated from the sampled charge-sensitive amplifier pulses using the two equations above.

\[^{10}\text{For the “fast” output, the maximum value is only calculated for } i \text{ up to 46 since } i + 4 \text{ would otherwise be outside the range of the recorded waveform. Analogously, for the “slow” output, the maximum is taken only for } i \text{ up to 35.}\]
For signals originating from the slow scintillator or BGO crystal, the “slow” output will be significantly greater than the “fast” output, whereas the two are approximately equal for signals from the fast scintillator, as shown in Figure 2.7.

(a) Fast scintillator: “fast” and “slow” outputs are about equal.

(b) Slow scintillator: the “slow” output is greater than the “fast”.

**Figure 2.7.** Examples of waveforms from the fast and the slow scintillator. For each trigger, 50 samples are recorded. A signal in the fast scintillator gives a shorter rise time than one in the slow scintillator or the BGO crystal. If a photon is scattered from one component to the other, the result will be a superposition of the individual waveforms. The pulse height (ordinate) is proportional to the energy deposition.
The separation becomes evident when the fast and slow outputs are plotted in a two-dimensional histogram, such as the one in Figure 2.8.

Figure 2.8. “Fast” and “slow” outputs of one detector cell, calculated using Equations 2.3 and 2.4. Each point corresponds to one recorded event. Two “branches” can be seen: one corresponding to events in the fast scintillator and one for events in the slow scintillator or bottom BGO crystal. The region between the branches contains events from photons that scatter from one component into the other. The “flattening” around 2800 on the ordinate is caused by saturation in the electronics.

Clean events from the fast scintillator are selected as follows:

\[
0.1 \times [“\text{Fast}”] - 40 < [“\text{Slow}”] < 0.1 \times [“\text{Fast}”] + 140
\]

where “Fast” and “Slow” are calculated using Equation 2.3 and Equation 2.4, and the first and last parts correspond to the lower and upper red lines in Figure 2.8, respectively. Analogously, events from the slow branch can be selected as

\[
2.1 \times [“\text{Fast}”] - 300 < [“\text{Slow}”] < 2.8 \times [“\text{Fast}”] + 100
\]

where the first and last parts instead correspond to the lower and upper blue lines in Figure 2.8, respectively. Since the difference between the scintillation decay times of the slow scintillator and the bottom BGO is small (about 15 ns), signals cannot be distinguished between these two detector components. This is, however, not a problem, since events in the slow scintillators and bottom BGO crystals are both rejected in the analysis.
Once clean events from the fast scintillators have been selected for the units involved in an event using Equation 2.5, their relative positions in the detector array yield the azimuthal scattering angle. The distribution of such angles is fitted with a sinusoidal modulation curve

\[ p_0 \left\{ 1 + p_1 \cos \left[ \frac{\pi}{180} (2x + 2p_2) \right] \right\} \]  

(2.7)

where \( p_0, p_1 \) and \( p_2 \) are fitting parameters and \( x \) is the scattering angle. The result is then used to determine the polarization as described in Section 1.1. The 180° symmetry (factor two in the argument of the cosine function) is expected due to the nature of the Compton scattering process, and a Fourier analysis can thus be applied, e.g. with a curve

\[
\begin{align*}
c_0 \left\{ 1 + c_1 \cos \left[ (x - c_2) \right] + c_3 \cos \left[ 2(x - c_4) \right] + 
&+ c_5 \cos \left[ 3(x - c_6) \right] + c_7 \cos \left[ 4(x - c_8) \right] + 
&+ c_9 \cos \left[ 5(x - c_{10}) \right] + c_{11} \cos \left[ 6(x - c_{12}) \right] \right\} 
\end{align*}
\]  

(2.8)

using fitting parameters \( c_0 \) through \( c_{12} \). Since the components are independent, the polarization signal is expected to appear only in the 180° component, and such a curve can thus be used to improve the fit by separating out effects not related to the polarization. For instance, a small contribution in the component with a 60° period may appear as a result of the hexagonal structure of the PDCs and the honeycomb structure of the detector array. The analysis described here is limited to the simple sinusoidal fit (Equation 2.7). A discussion on the full Fourier decomposition is given in [58].

### 2.1.3 Threshold settings

There are five threshold settings that can be individually adjusted for each of the connected detectors in order to reduce the dead time and storage requirements of the instrument, as well as to improve the quality of the recorded data.

**Trigger threshold:** Corresponds to a minimum energy level that must be deposited in the detector unit in order for the data acquisition system to issue a trigger. Conceptually, a photoelectric absorption should initiate the readout of the detector array, and cells neighboring the absorption site should be searched for a coincident Compton scattering event. This level is therefore set such that triggers are issued for photoelectric absorption events but not for Compton scatterings.

**Hit threshold:** When data is stored, all channels with signals above the hit threshold are recorded. This corresponds to a zero-suppression: channels with no activity at the time of trigger need not be read out. The setting should be sufficiently low to accept Compton events but still reject noise from the electronics.
Waveform discrimination threshold: Corresponds to a simple pulse shape discrimination cut performed directly in the hardware and allows events from the slow scintillators or BGO crystals to be immediately rejected.

Upper discrimination threshold: Large energy depositions can be caused e.g. by cosmic ray particles traversing the detector elements. Such events are outside the dynamic range of the instrument and need not be recorded, which can be regulated with this setting.

Histogram threshold: Apart from the complete sampled waveforms, peak values (the highest value within the 50 sampled points) are also separately histogrammed, one histogram for each detector channel, for a simple “quick-look” analysis. This setting corresponds to a “trigger” for storing such peak values in histograms.

The concept of these threshold levels is visualized in Figure 2.9.

![Figure 2.9. Acceptance region defined by the trigger and threshold settings. The “hit” threshold (not shown) is equivalent to the “trigger level” and determines which additional channels are read out when a trigger has been issued.](image)

Once a trigger has been issued, the system waits for several clocks to see if there is a coincident upper discrimination or waveform discrimination signal. These imply that a charged particle or an off-axis event has caused the trigger and the event should thus be vetoed. If no such veto signal is received, all channels with a signal above the hit threshold are read out. Background events can thus be rejected by the trigger logic, instead of being recorded and then discarded in the
off-line analysis\textsuperscript{11}. Data obtained in the two different modes (in-flight versus offline background rejection) will be compared to ensure that an unbiased set of events is used for the polarization analysis. Furthermore, the number of upper discrimination and waveform discrimination signals is counted, so information e.g. about the side anticoincidence shield background rate can still be obtained. Detailed descriptions of the PoGOLite electronics and event selection logic can be found in \cite{68, 69}.

\section{2.2 Photon beam tests of a PoGOLite prototype}

The design of the PoGOLite Pathfinder, which will be the subject of the next section, has been optimized based on photon beam tests of a prototype instrument. To date, three accelerator-based tests of the PoGOLite prototype have been conducted at the KEK “Photon factory” \cite{70} in Tsukuba, Japan. This is a synchrotron facility capable of producing a beam with a polarization degree of about 90\% \cite{65} in the PoGOLite energy range. The tests will only be briefly summarized here. Additional information can be found in \cite{71} and references therein.

The first KEK test \cite{67, 72} was in December 2005 and featured one full PDC surrounded by six “peripheral” units comprising fast scintillators only. The central unit was irradiated with a pencil beam of synchrotron photons and count rates in the peripheral units were studied. Between each measurement, the detector array was rotated in 15\textdegree steps, until a full revolution had been completed. Through this rotation, systematic bias could be eliminated, and the flight-version of the instrument will also be rotated for this purpose. The detector array is shown in Figure 2.10.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure2_10.png}
\caption{Sketch of the seven-unit prototype detector array. Rotation direction and polarization vector of the incident beam are also indicated.}
\end{figure}

\textsuperscript{11} Regions outside that defined by the thresholds need not be completely empty. For instance, a signal may appear below the trigger threshold of a channel if a read-out is initiated by a signal exceeding the trigger threshold in another channel.
A higher count rate is here expected in units 2, 3, 5 and 6, since photons are more likely to scatter perpendicularly to the polarization vector. As the detector array is rotated relative to the fixed polarization of the incident beam, the count rate in each peripheral unit is modulated, following a sinusoidal modulation curve. Several beam energies were studied in these measurements: 25 keV, 30 keV, 50 keV and 70 keV. At 50 keV, the observed modulation factor was found to be (35.8 ± 1.2)\%, in agreement with simulations within about 10\% (relative). The modulation of this measurement is shown in Figure 2.11. Similar results were seen at all these energies, demonstrating that the instrument is performing well in the stated energy range.

![Graph showing modulation](image)

**Figure 2.11.** Relative count rates in the peripheral units as a function of the rotation angle, measured at a 50 keV beam energy [72]. Numbers have been averaged for co-planar pairs of detector units. The average modulation is (35.8 ± 1.2)\%.

The second beam test was in March 2007 and involved a prototype with seven full PDCs and one segment of the anticoincidence shield. The purpose of this test was to measure modulation with an array of full phoswich detector cells and to evaluate the event rejection capability of the anticoincidence system. As in the previous beam test, the central unit was irradiated with photons from the beaml ine and count rates in the surrounding units were studied. Between measurements, the detector array was rotated in 15° or 30° steps. Most of the tests were carried out with a beam energy of 50 keV. The modulation was measured both with and without the SAS unit in place, in order to investigate any differences caused by photons scattering back from the SAS unit into the PDCs. A radioactive source, $^{137}$Cs, was also attached to the back of the SAS segment. The detector array was thus irradiated with 662 keV photons through the SAS. This configuration mimics in-flight conditions, with a gamma-ray background incident on the side anticoincidence shield.
With the SAS unit installed, the modulation factors of the three co-planar pairs were \((26.1 \pm 2.1)\%\), \((32.0 \pm 2.1)\%\) and \((31.2 \pm 1.9)\%\), producing an average modulation factor of \((29.8 \pm 1.1)\%\). One pair has a considerably lower modulation factor, possibly caused by an incorrect calibration or a problem with the photomultiplier tube voltage setting, which deteriorates the overall value. Excluding this pair yields an average modulation factor of \((31.6 \pm 1.4)\%\), which agrees with previous values within less than 15\% (relative). The modulation curves of this measurement are shown in Figure 2.12. Additional details can be found in [71].

Figure 2.12. Modulation measured at 50 keV with the SAS unit installed. The three modulation factors are \((26.1 \pm 2.1)\%\), \((32.0 \pm 2.1)\%\) and \((31.2 \pm 1.9)\%\).

For the third photon beam test, conducted in February 2008, the prototype instrument had been upgraded to 19 full phoswich detector cells, one central unit and two additional rings, along with one section of the side anticoincidence shield. A sketch of this detector array is shown in Figure 2.13, where units have been color-coded based on their distance from the central unit.

Figure 2.13. Sketch of the 19-unit prototype detector array. Cells are divided into three groups based on their distance to the center. The SAS unit (not shown) was used for testing the electronics only and was not integrated into the detector array.
The central unit was again irradiated with 50 keV photons from the beam-line, and count rates in the surrounding units were studied. Between measurements, the array was rotated relative to the fixed polarization of the beam. This prototype allowed several key aspects of the instrument to be tested for the first time, e.g. the effect of multiple-site events (where a photon deposits energy in three or more PDCs), as well as changes in the modulation obtained when a Compton scattering and a subsequent photoelectric absorption take place in spatially separated cells instead of in neighboring ones. From this 19-unit array, the instrument is scalable and its behavior and characteristics do not change significantly with the inclusion of additional detector rings, making this beam test an important milestone.

The modulation arising as the detector array is rotated is different for these three groups of units (red, green and blue in Figure 2.13), due to the different “angular resolution” of the detectors: cells at large distance subtend a small solid angle as seen from the central unit and therefore provide a high angular resolution, whereas cells that are closer have a larger solid angle and thus yield a somewhat worse angular resolution. On the other hand, closer units have a higher count rate, which reduces the statistical uncertainty.

For each group of PDCs, the modulation can be calculated using the “decoupled ring technique” [73] based on the distance from the scattering site (the central unit in this case) to the absorption site, and on the movement of individual units around the center of the detector array as the instrument is rotated. The resulting modulation, shown in Figure 2.14, was determined using a weighted average of the modulation factors of the individual groups as discussed in [71], and yielded a (34.1 ± 0.3)% overall modulation [69], which agrees with simulations and previous beam tests within about 5% (relative).

![Figure 2.14. Modulation obtained at 50 keV with a 19-unit instrument [69]. Three different modulation curves can be seen, corresponding to the three groups of detector units in Figure 2.13.](image)
2.3 The PoGOLite Pathfinder

Following the assembly of a large number of PDCs and SAS units in 2008 [56, 74], construction of the 61-unit Pathfinder instrument commenced around mid-2009. The first target of the Pathfinder will be the Crab system. Since the 217-unit instrument should be able to detect 10% polarization from a 200 mCrab source, a 61-unit detector array, which has about 30% of the same effective area, is expected to be sufficient for detecting the same polarization degree from a 1 Crab source. This section describes the polarimeter and its various subsystems.

2.3.1 Polarimeter assembly and electronics

The polarimeter is the main component of the PoGOLite instrument. This assembly consists of two cylinders – an inner one, which contains the detector array (phoswich detector cells, side anticoincidence shield, photomultiplier tubes, a neutron scintillator and associated electronics), and an outer cylinder, which houses a polyethylene neutron shield. The components are shown in Figure 2.15.

![Figure 2.15](image_url)  
*Figure 2.15.* The polarimeter, pressure vessel and rotation frame. Individual detector cells can be seen at the top of the polarimeter, surrounded by the segmented anticoincidence shield. The pressure vessel is sectioned into three parts for the polarimeter, photomultiplier tubes and electronics, respectively. The rotation frame has slots where blocks comprising the polyethylene neutron shield will be inserted.
To remove systematic bias, the inner cylinder is rotated around the line of sight of the instrument. The telescope can also turn with respect to a pivot axis for elevation pointing. An axial cross-section of the assembly is shown in Figure 2.16.

![Schematic axial cross-section of the polarimeter telescope assembly.](image)

**Figure 2.16.** Schematic axial cross-section of the polarimeter telescope assembly.

The SAS units are held in compression to make them more impact resistant. This is achieved by using screws from a rigid structure which press down on the crystals from the top via an elastic interface. The concept is shown in Figure 2.17. Similarly, the phoswich detector cells are individually pre-tensioned using two steel wires running along the length of the cells. By stretching the wires, the units are compressed, which is shown in Figure 2.18. Each wire is terminated by a conical “lug” which steers into a faceplate situated at the top of the instrument to ensure that the detector cells are parallel. This faceplate, shown in Figure 2.19, can be positioned using eccentric screws\(^\text{12}\). The photomultiplier tubes, which can be seen in Figure 2.20, have an independent support mechanism where the optical contact pressure is assured through the use of spring plates and soft transparent silicone wafers.

\(^\text{12}\)The implicit assumption made here is that the geometric center of the faceplace is aligned with the viewing axis of the instrument. This will be investigated in pointing tests once the instrument is fully integrated and can be compensated for if there is a discrepancy caused e.g. by the rotation of the instrument.
Chapter 2. The PoGOLite experiment

Figure 2.17. Picture of the SAS tensioning mechanism. The top is held in place with multiple fastening screws. Individual tensioning screws interface to an elastic material (not seen) which holds the SAS units in compression. Eccentric screws are used to align the anticoincidence shield relative to the outer mechanical structure. Part of the rotation frame can be seen in the background (upper left corner).

Figure 2.18. PDCs being inserted into the detector array. Each unit has two steel wires running along its sides. By stretching these wires, the PDC is held in tension. The wires are terminated by conical “lugs” which steer into holes on a faceplate to keep the PDCs aligned. Reflective VM2000 can be seen on the end of each detector cell. Bubble wrap is temporarily covering the pressure vessel to protect it from damage.
2.3. The PoGOLite Pathfinder

Figure 2.19. Front of the instrument. The precision-machined faceplate has holes at each vertex where the lugs at the top of the PDCs are steered in, ensuring that all detector cells are parallel. Eccentric screws are then used to align the units with the rotation axis (viewing axis) of the instrument.

Figure 2.20. Bottom of the instrument and photomultiplier tubes. Two rods hold each PMT in place and the optical coupling is assured by the use of spring plates pushing the tube against the bottom BGO piece. Aluminum rods screwed into the base of the PMTs transfer heat to a cooling system.
The photomultiplier tubes have built-in DC-DC converters [65] and are tightly packed in the detector array. To prevent them from overheating with prolonged use, each unit is thermally coupled to a cooling plate through a copper braid attached to an aluminum rod which screws directly into the base of the PMT. The cooling plate is a sandwich of two aluminum pieces and has a milled groove spiraling from the center and outwards. Cooling fluid\textsuperscript{13} is circulated from radiators mounted on the gondola to the cooling plate using a pump system which regulates the flow rate based on temperature readings. The inlet of the cooling fluid is close to the center of the plate (see Figure 2.21), where the operating temperature is expected to be highest. Thermal properties of the instrument are further discussed in Chapter 6.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{pmt_cooling_plate.png}
\caption{Picture of the PMT cooling plate and heat-conducting copper braids. One end of the braid is fastened on the cooling plate, while the other end attaches to the cooling rod screwed into the base of each individual photomultiplier tube. Thermal paste is used to maximize the heat transfer from the tube. Cold fluid from the radiators enters through the inlet in the center of the plate, spirals outwards within the plate and exits through the outlet near the edge.}
\end{figure}

The volume below the PMT cold plate contains polyethylene with a thickness of about 15 cm. Directly beneath this polyethylene is a crate which houses the polarimeter electronics. To prevent the system from overheating in the confined volume,\textsuperscript{13}Paratherm LR\textsuperscript{TM} Heat Transfer Fluid [75], a non-toxic paraffinic hydrocarbon solution usable down to around \(-60 \, ^\circ\text{C}\).
volume of the pressure vessel, the electronics crate, shown in Figure 2.22, is also connected to the cooling loop. It has a construction similar to that of the cold plate, with fluid from the cooling system flowing through the walls, transporting heat produced by the electronics boards to the radiators.

Figure 2.22. Picture of the cooling crate housing the electronics boards. The walls are aluminum-copper sandwiches, through which cooling fluid can be circulated. Slots can be seen in the far wall, which is where the electronics boards slide in.

The polarimeter electronics, which consist of 12 FADC boards (Flash-Analog-to-Digital Converter boards), one DIO board (Digital Input-Output board) and one “SpaceCube” component, are interconnected by two router boards and communicate using a “SpaceWire” protocol [76]. The FADC boards are used for digitizing and sampling waveforms from the 92 PMTs (61 PDCs, 30 SAS units, 1 neutron scintillator), while the trigger logic is handled by the DIO board, which issues a data acquisition request to the FADC boards if the trigger criteria are met. The “SpaceCube” component is used to convert signals to a standard network interface (TCP/IP).

The “SpaceCube” is a SpaceWire interface jointly developed by Shimafuji Electric Inc. and ISAS/JAXA, the Institute of Space and Astronautical Science and Japan Aerospace Exploration Agency. It can either be a small on-board computer [77] or a converter for communicating with SpaceWire components using an external computer.
Each router board has eight SpaceWire ports. One port of each router board is occupied by the bridge connection between the two. Six FADC boards are connected to each router board, and the final two ports are used for the SpaceCube and DIO board, respectively. A schematic overview of the system is presented in Figure 2.23. More detailed descriptions of the electronics are given in [68, 69].

![Figure 2.23. SpaceWire interconnections between the electronics boards. A SpaceCube (“SpC”) converts signals to and from TCP/IP, allowing connection to an outside computer, which controls the data acquisition. Trigger signals and data acquisition requests are sent between boards using LVDS (low-voltage differential signaling). (For clarity, these connections are not shown here.)](image)

The FADC boards can accommodate up to eight channels each, thus eight boards are required for the 61 PDCs (8 x 8 = 64, three unused channels) and four for the 30 SAS units and the neutron scintillator (4 x 8 = 32, one unused channel). The pairing of PMTs to FADC boards has been optimized to maintain maximum functionality in the event of an FADC board failure. The functionality was evaluated based on how much of the 360° possible azimuthal scattering angle can be detected for each PDC. Generally, one PDC has six neighbors, so if one neighbor fails, about 60° of scattering sensitivity is lost for that particular unit. Several configurations were compared [78]: “symmetric placement” (PMTs are connected to FADCs forming groups with as high symmetry as possible), “scattered placement” (no two adjacent units are coupled to the same FADC board), “asymmetric cluster placement” (no two groups of units have identical geometry) and “petal placement” (see Figure 2.24), which was chosen. For the petal configuration, about 80–90% of the scattering sensitivity is maintained if one random FADC board fails.
For the SAS units, background rejection is equally important on all sides, thus no favored connection to the remaining four FADC boards exists. Even if one SAS FADC board fails in flight\textsuperscript{15}, passive shielding from neutrons and cosmic rays is still provided by the polyethylene and the high stopping power of the SAS BGO crystals, respectively. Also, since the detector array is rotated in flight, the asymmetry in the background will be minimized.

Simulations show that the minimum detectable polarization\textsuperscript{16} of the instrument for a measurement of the Crab increases from $(8.52 \pm 0.19)\%$ to $(9.49 \pm 0.22)\%$ if an FADC board fails. For the failure of a single photomultiplier tube, the increase is less, and the minimum detectable polarization in that case becomes $(8.67 \pm 0.20)\%$ \textsuperscript{[79]}, with a slight dependence of the location of the failing unit within the detector array, i.e. the failure of a tube with six neighbors (close to the center of the instrument) is more severe than if a unit with three or four neighbors fails (in the outer-most ring of PDCs, numbers 37–60 in Figure 2.24).

\textsuperscript{15}SAS FADC boards are identical to PDC FADC boards, except for their trigger and threshold settings. For example, the SAS units should be read out if there is a valid event, but they should not issue triggers themselves.

\textsuperscript{16}Minimum detectable polarization (MDP) is the lowest source polarization degree that the instrument can detect at a given significance level for a given source rate, background rate and observation time (see [41] for a discussion on the PoGOLite MDP).
2.3.2 Attitude control system and instrument pointing

In order to meet the observational goals (10% polarization from a 200 mCrab source in a single six-hour flight for PoGOLite-217 and 10% from a 1 Crab source for the PoGOLite Pathfinder), the pointing accuracy of the instrument must be better than 5% of its field of view ($2.0^{\circ} \times 2.0^{\circ}$) [41]. This is achieved using an attitude control system (ACS) combining information from differential GPS systems, magnetometers, gyroscopes, accelerometers, and a pair of optical star trackers. The attitude control system allows individual photons to be time-tagged to an expected absolute temporal resolution of about 1 $\mu$s.

A custom-made integrated solution for the attitude control system has been developed and implemented by DST Control [80], a company based in Linköping in Sweden, which specializes gyro-stabilized platforms and pointing systems. The system will provide pointing reconstruction to better than 0.1$^{\circ}$ based on relative attitude information from accelerometers and gyroscopes, which is combined with absolute attitude data from the differential GPS in order to calibrate against bias and drift in the relative pointing. The attitude control system feeds back information to motors controlling the orientation of the instrument. For the azimuthal pointing, a flywheel is used, which is about 60 cm in diameter and weighs around 50 kg. By changing the rotation speed of the flywheel, the instrument is forced to rotate in the opposite direction to conserve angular momentum, allowing the polarimeter to slew as needed. If the flywheel is rotating at maximum speed and the instrument needs to slew additionally, a momentum dump system is used to transfer angular momentum to the flight train.

Two star tracker cameras are used [41], each one consisting of a CCD camera, optics and a custom-made baffle system, which enables stars down to magnitude 8 to be tracked even in daylight. Both cameras are co-aligned with the polarimeter. One has a small field of view (FoV), $2.57^{\circ} \times 1.92^{\circ}$, while the other one is larger: $5.0^{\circ} \times 3.7^{\circ}$. Depending on their programming, the star trackers can either be used in a “fast” mode where they track the brightest star visible at any given time and feed back information to the attitude control system, or in a “slow” mode, which performs a pattern matching based on a star catalog [41] and provides an independent pointing solution for redundancy.

An auroral monitoring unit (AMU) has been developed by the Alfvén Laboratory [81], a department of the Royal Institute of Technology devoted to space and plasma physics. Although a source of background for astrophysical polarimetry of distant objects, the polarization of the aurora itself has not been studied to detail in the X-ray band. Since the first flight of PoGOLite will occur during a period of relatively high solar activity, the AMU is piggy-backing the payload, allowing auroral X-ray polarization to be studied.

Final integration of the polarimeter, pointing system, star trackers and auroral monitoring unit is currently ongoing. A computer model of the assembled system is shown in Figure 2.25.
2.3. The PoGOLite Pathfinder

Figure 2.25. CAD image of the polarimeter and attitude control system. Transparent cylinders indicate the apertures of the detector array and various subsystems. The height of the assembly is close to three meters.

2.3.3 Gondola and supplementary systems

The gondola is designed to be light-weight but strong and stable to maintain a good pointing accuracy. A preliminary gondola configuration is shown in Figure 2.26.

Figure 2.26. Preliminary gondola configuration during a hang-test in October 2010, where the pointing performance of the attitude control system was tested. In the background, the 47-tonne launch vehicle “Hercules” can be seen.
To enhance the resolution of the differential GPS, the separation between the two antennas should be maximized, which is done by mounting them on a 10 m long boom made of fiber glass. For the flight, a “skirt” with solar panels, crash pads and ballast will be hung from the bottom of the gondola. The skirt is expected to be crushed in the landing, absorbing some of the shock in order to protect the polarimeter so it can be reused for subsequent flights. The gondola, polarimeter and subsystems are designed to be able to withstand a shock of at least 10 G (~100 m/s² acceleration) from the three expected impacts: parachute deployment, landing and (possibly) tipping over. The intended flight-configuration is shown in Figure 2.27.

![Figure 2.27. Foreseen flight-configuration of the PoGOLite Pathfinder gondola.](image)

### 2.3.4 Balloon and flight train

The balloon has a volume of around one million cubic meters and is filled with helium. At float altitude (up to about 40 km) it expands to a diameter of more than 100 m due to the low ambient pressure. The position of the balloon and the payload is constantly tracked using GPS. When a decision is made to cut the balloon and disengage the payload at the end of the campaign, command is sent to the cut-down device, which separates the payload by detonating a cable cutter on the cable connecting to the balloon. The instrument then starts a free-fall, whereupon the parachute is automatically deployed due to the atmospheric drag. A strobe light is used to enhance the visibility of the payload during its descent,
along with a reflector system to provide the payload with a radar signature. The truck plate, finally, is a robust metallic piece with a hole in its center. It provides an interface where the flight train is hung from the launch vehicle (see Figure 2.26), from which the payload can be released once the balloon is filled. A sketch of the flight-train and its various components is presented in Figure 2.28.

Figure 2.28. Sketch of the flight-train and its various components (not to scale), adapted from [82]. Parts above the gondola and flywheel are standardized and have been used previously for flying similar payloads.

The maiden voyage of the PoGOLite Pathfinder, scheduled for mid-2011, is foreseen to be a circumnavigation with the Crab as the main observation target. The instrument will be launched from the Esrange ballooning facility in Northern Sweden and travel westwards over Greenland, Northern Canada and Russia, even-
Eventually returning for a landing in Sweden after a period of about 20 days. A possible trajectory of the flight is shown in Figure 2.29.

**Figure 2.29.** Possible trajectory for a circumnavigation flight. The instrument is launched from northern Sweden (located at a longitude of about 20°, close to the “three o’clock” direction in this figure) and moves westwards (clockwise). The solid red line indicates a flight from Sweden terminating over western Canada and the dashed segment is an extrapolation showing a circumnavigation.
Chapter 3

SAS BGO tests

3.1 Background

The BGO crystals used for the PoGOLite instrument were supplied by the Nikolaev Institute of Inorganic Chemistry [61] in Novosibirsk, Russia. As these crystals form the main part of the anticoincidence system (the other part being the slow scintillator collimator tubes), the quality of the crystals strongly influences the performance of the instrument and its background rejection capabilities.

Since the crystals needed for the instrument have a substantial monetary value, a tendering procedure was carried out during the second half of 2006. A number of requirements were specified regarding the quality, performance and dimensions of the crystals. These specifications were outlined based on light yield evaluation tests of prototype crystals. The Nikolaev Institute of Inorganic Chemistry could provide crystals compatible with the specified requirements at the lowest price and was therefore contracted.

3.2 Crystal specifications

Five differently shaped BGO crystals are used in the PoGOLite instrument. Four of these, namely the type 1A and 1B “edge” crystals and the type 2A and 2B “corner” crystals, are shown in Figure 3.1. The fifth type is the bottom BGO crystal of the PDCs. This type is only mentioned here for completeness and a detailed description of these crystals and their characteristics is given in [41]. The “edge” and the “corner” crystals comprise the side anticoincidence shield (see Figure 3.2), and the only difference between the “A” and “B” type crystals is the cylindrical protrusion on the B-type crystals, which is where the photomultiplier tube is attached. Two A-type crystals and one B-type crystal are glued together [74] using Epo-Tek® 301–2 epoxy [83], forming a 60 cm long SAS unit (see Figure 3.3).
Chapter 3. SAS BGO tests

(a) Type 1A “edge” crystal.  
(b) Type 1B “edge” crystal.

(c) Type 2A “corner” crystal.  
(d) Type 2B “corner” crystal.

**Figure 3.1.** The four types of BGO crystals used in the side anticoincidence shield. The length of each crystal is 20 cm (excluding the protrusion of the B-type crystals). Detailed drawings and dimensions can be found in [71].

**Figure 3.2.** Computer-generated top view of the 61-unit detector array of the PoGOLite Pathfinder [58]. The segmented side anticoincidence shield, comprising 24 “edge” segments and 6 “corner” segments, can be seen along the circumference of the array. The 217-unit PoGOLite instrument will feature 48 “edge” units and 6 “corner” units.
3.2. Crystal specifications

Figure 3.3. Four glued SAS units (right), each one with a total length of 60 cm. The glued crystals are attached to an aluminum “backbone” using shrink-tube, with a shock-absorbing layer of silicone between the crystal and the aluminum (left).

In total, 427 BGO crystals were received in seven separate shipments. Table 3.1 shows the number of received crystals of each type, along with the number needed to assemble the 61-unit Pathfinder as well as the full 217-unit instrument.

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<th>Type 1B</th>
<th>Type 2A</th>
<th>Type 2B</th>
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<td>12</td>
<td>6</td>
<td>61</td>
</tr>
</tbody>
</table>

Table 3.1. BGO crystals received from Novosibirsk, along with the quantities required for the Pathfinder and the full instrument.

More than 10% spares are available of each crystal type. Small cylindrical boule samples\(^1\) (1 cm in diameter) were also provided, and act as reference crystals which have not been altered.

\(^1\)The crystals are grown in large pieces (boules) weighing tens of kilos, and are then cut to size.
The following requirements were stated for the SAS BGO crystals:

- The specified dimensions and tolerances [71] (at 20 °C) must be met.
- The crystal material must be transparent and without visible grain boundaries when viewed under strong lighting.
- All crystal surfaces must have a mirror-like polish and be free from visible scratches, cracks or dents.
- The energy resolution, observed when the crystal is irradiated by a well-collimated beam of 662 keV photons from $^{137}$Cs in the points shown in Figure 3.4, should be better than 20% (16% for the bottom BGO crystals).
- There should be no dramatic degradation of the light output from the crystals due to ionization radiation damage.
- The end-surfaces of the crystals must be parallel to ensure that the crystals are properly aligned when they are glued together.
- The edges of the crystals should be beveled or slightly rounded to reduce the risk of chipping.
- The light yield of the crystal should not decrease by more than 5% when the crystal is irradiated 1 cm from any end of the crystal compared to when the crystal is irradiated in the central position, i.e. 10 cm from one end (see Figure 3.4). The irradiating source should be a well-collimated beam of 662 keV photons from $^{137}$Cs.

![Figure 3.4. Irradiation points specified for the tests of the SAS BGO crystals.](image)
3.3 Crystal inspection

The procured crystals were carefully examined upon delivery. Overall, the surface polish and transparency were extremely good and most of the crystals were completely flawless. A limited number, about ten crystals, had conspicuous imperfections, such as scratches or dents, an example of which can be seen in Figure 3.5. In each of these cases, however, the size of the flawed area has been negligible compared to the total size of the crystal. Thus, the deterioration in light yield from the crystal, if any, will be insignificant, and these have been accepted as well.

![Figure 3.5. Chipped-off corner of a BGO crystal. The defect is about 5 mm wide. The worst example is shown here and remaining crystals have smaller or no flaws.](image)

The dimensions of the crystals were measured using two sliding gauges, each with a resolution of 0.01 mm. Histograms showing the distributions of all measured dimensions can be found in [71]. Two examples are shown in Figure 3.6.

![Figure 3.6. A good distribution (left) with a mean value close to the specified value (thick dashed line) and a poor distribution (right) with a mean value that is shifted from the specified value. The thin dashed lines show the allowed tolerance.](image)

(a) Example of a good distribution.  
(b) Example of a poor distribution.
Only a few of the measured dimensions were found to be outside the tolerance. The greatest deviation from the specified value was found in the total “height” of the 1A- and 1B-type crystals, which should be (38.45 ± 0.15) mm. As can be seen from the distribution in Figure 3.6(b), the mean is slightly shifted to a value below the specified number. However, as this part of the crystal is facing inwards in the detector array, a small deviation in this dimension will not matter, because it does not affect the gaps between the anticoincidence shield segments. As a result, no crystals have been rejected based on the measured dimensions.

3.4 Light yield tests

The relative light yield of each crystal was measured with equipment previously used for testing the CsI(Tl) crystals of the GLAST (now Fermi) instrument [84]. This equipment consists of a light-tight black box, shown in Figure 3.7, fitted with a PMT and a radioactive source housed inside a motor-driven lead collimator.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{black_box.png}
\caption{The light-tight black box. Top: external view. The width of the box is about 1.5 m. Bottom: internal view. One 20 cm long crystal is ready to be tested.}
\end{figure}
The box was originally equipped with a PMT optimized for use with CsI(Tl) crystals and was therefore retrofitted with one which has a sensitivity better matching the emission of BGO crystals: Photonis model XP5202/B, shown in Figure 3.8(a). For consistency with subsequent measurements (see e.g. [56, 74]), the photomultiplier tube used should have been the flight-version PoGOLite PMT manufactured by Hamamatsu, R7899 [64], which has been chosen to perform well both with plastic scintillators and with BGO crystals [55]. The reason why this PMT was not used in the measurements described below is twofold. First of all, since the R7899 is housed inside a metal tube, shown in Figure 3.8(b), and connects to the cylindrical protrusion found on the B-type crystals, it cannot be directly used with the A-type crystals which lack this feature, and a light-guide must then be used. This complicates the measurements by adding another source of uncertainties. Secondly, flight-version PMTs were not readily available at the time of these measurements, since the specifications for the tube were still being finalized. The spectral response of the two PMTs is, however, very similar, peaking at 420 nm for the tube from Hamamatsu [64] and at 400 nm for the one by Photonis [85].

Crystals were wrapped with Tyvek [86], a white high-reflectivity paper-like material manufactured by DuPont, and coupled to the PMT using optical grease. Signals were sent via a pre-amplifier (Ortec Model 113 [87]) and an amplifier (Canberra Model 2026 [88]) to a multi-channel analyzer (Tukan 8k USB [89]). A radioactive source, $^{137}$Cs (662 keV photons), was placed inside a lead collimator, restricting the beam to an angle of less than $10^\circ$. Using a stepper motor, the collimator could be moved along the length of the crystal. Thus, the irradiation point could be changed without having to turn off the PMT and open the black box in order to move the source, giving the PMT voltage time to settle to stable operating conditions.
Each crystal was irradiated at five equidistant points (Figure 3.9) and an energy spectrum was recorded for each one. Data was collected for ten minutes for each point and changes in the relative light yield depending on the distance between the irradiation point and the photomultiplier tube were studied. Background spectra, obtained without irradiation from the source, were also saved for comparison.

Figure 3.9. The five irradiation points used in the light yield measurements.

3.5 Analysis and results

An example of a recorded spectrum can be seen in Figure 3.10.

Figure 3.10. Spectra with and without irradiation by 662 keV photons from $^{137}$Cs ("signal" and "background", respectively). The photoabsorption peak has been fitted and its channel number (position) corresponds to the deposited energy.
Three peaks can be seen in the recorded spectrum. The first one is the signal: 662 keV photons from $^{137}$Cs. The second and the third are from the background: 1461 keV photons and 2614 keV photons from $^{40}$K and $^{208}$Tl, respectively. Small radioactive impurities may be present during the measurements, e.g. in the glass window of the photomultiplier tube. The isotope $^{40}$K is naturally occurring and can be found both in building materials and in small amounts in the human body, while $^{208}$Tl arises from a decay chain starting with $^{212}$Po. This isotope undergoes alpha decay to $^{208}$Tl, which decays via $\beta^-$ into an excited state of $^{208}$Pb, which subsequently de-excites into the ground state, whereupon a 2614 keV photon is emitted [90]. Figure 3.11 shows the expected background spectrum for a measurement with BGO. The features in this spectrum are very similar to the background seen in Figure 3.10 and the spectral shape is therefore believed to be well-understood.

![Figure 3.11](image)

**Figure 3.11.** Expected background in a measurement with a BGO crystal [90]. Two peaks, 1.461 MeV and 2.614 MeV from $^{40}$K and $^{208}$Tl, respectively, are naturally present in the background spectrum.

The figure of merit in these measurements is the peak channel number, i.e. the position of the photoabsorption peak of the 662 keV photons. The channel number is proportional to the amplitude of the pulse from the amplifier, which is proportional to the number of photons detected by the photomultiplier tube, which, in turn, is proportional to the energy deposited in the scintillator. Since events in the photoabsorption peak arise from mono-energetic photons from the $^{137}$Cs source, the peak channel number becomes a measure of the number of detected photons in the photomultiplier tube, i.e. the light yield [91, 92].
To obtain a precise value for the peak channel number, the peak region was fitted with the following equation, which gives the number of counts in the fitted region as a function of the channel number and has two components, a Gaussian curve for the signal and a linear polynomial for the background:

\[ p_0 e^{-\frac{1}{2} \left( \frac{x-p_1}{p_2} \right)^2} + p_3 + p_4 x \]  

(3.1)

where \( x \) is the channel number and \( p_0, p_1, p_2, p_3 \) and \( p_4 \) are fitting parameters corresponding to the amplitude, mean value and standard deviation of the Gaussian term, and the constant offset and linear coefficient of the background term, respectively. The background, onto which the photoabsorption peak is superimposed, is expected to decrease exponentially with increasing energy, but since the fitting range is limited to a small region around the peak, a linear approximation to the background was found to work equally well. In Figure 3.12, the two components of the fitting curve are shown with dashed lines, while the solid line indicates the sum. The peak channel number corresponds to the parameter \( p_1 \), which is obtained from the fit, along with its statistical uncertainty.

![Figure 3.12. Photoabsorption peak of 662 keV photons from \(^{137}\text{Cs}\). Dashed lines are the signal and background curves, while the solid line is the sum of the two.](image)

The energy resolution of the peak [93] was calculated as

\[ \frac{\Delta E}{E} = \frac{2.35 p_2}{p_1} \]  

(3.2)

where \( p_1 \) and \( p_2 \) are the mean value (peak channel number) and standard deviation of the Gaussian, respectively. Peak channel numbers were plotted as a function of the distance between the irradiation point on the crystal and the photomultiplier tube to allowed changes in the relative light yield to be studied. An example of such a plot is shown in Figure 3.13. The absolute light yield was not considered.
3.5. Analysis and results

Figure 3.13. Results from a five-point light yield test. Error bars are shown but barely visible due to their small size. A similar behavior is seen in all crystals.

The light yield first decreases with increasing distance between the irradiation point and the photomultiplier tube, towards a minimum close to the center of the crystal, and then increases again as the irradiation point gets closer to the far end of the crystal. The specified requirement was that the light yield should not decrease by more than 5% when the crystal is irradiated 1 cm from one end compared to when irradiated in the central position. This is a conservative requirement – as can be seen from the plot, the light yield is in fact higher when the irradiation point is close to one of the ends of the crystal, thus no crystals were rejected based on this test. However, if the quality of the crystals is poor, no increase is expected towards the far end of the crystal [94]. The fact that this U-shaped behavior is seen in all units demonstrates the high quality of the crystals. After all 187 crystals had been tested, the results for measurement point 3 (center) on each crystal were databased and visualized in histograms. An example of these results, for type 1A crystals, can be seen in Figure 3.14. Results from all light yield tests are presented in [71].

Similarly, the energy resolution was calculated for the five measurement points of each crystal and databased. The number that has been compared is the energy resolution for the third point, i.e. when the crystal is irradiated at its center. This is a conservative test, since the light yield reaches a minimum for this point, as shown in Figure 3.13. In the specifications, the required energy resolution was 20% for the SAS BGO crystals and 16% for the bottom BGO crystals\(^2\), and each crystal met this requirement. Subsequently, no crystals were rejected based on this test. An example of the results for the type 1A crystals is shown in Figure 3.15. All results are collected in [71].

\(^2\)The reason why the requirement on the energy resolution is more strict for the bottom BGO than for the SAS BGO is because the aforementioned pieces are smaller. They should therefore suffer less from light attenuation due to self-absorption inside the crystal and light-loss at its surfaces, which may deteriorate the measured energy resolution.
Chapter 3. SAS BGO tests

(a) Light yield and crystal number (in the order of testing).

(b) Histograms with light yield data.

Figure 3.14. Example of results from the light yield tests of the type 1A crystals. Top: light yield (peak channel number) obtained in the order the crystals were tested. Bottom: histograms with all obtained light yield results.
3.5. Analysis and results

(a) Energy resolution and crystal number (in the order of testing).

(b) Histograms with energy resolution data.

Figure 3.15. Example of results from the energy resolution tests of the type 1A crystals. Top: energy resolution obtained in the order the crystals were tested. Bottom: histograms with all obtained energy resolution results.
3.6 Discussion

The quality of the BGO crystals from the Nikolaev Institute of Inorganic Chemistry has consistently been very high. All crystals have a high transparency and well-polished surfaces with few or no flaws. Measured dimensions are within specified tolerances with only a few acceptable exceptions. These are mostly for dimensions where a small mismatch does not cause any problems, neither in the efficiency of the shield, nor when assembling the detector array. Each crystal has a good energy resolution, significantly better than the required 20% for the SAS BGO crystals, even better than the 16% limit set for the smaller bottom BGO crystals. The conservative limits are motivated by the fact that the crystals are not intended for calorimetry, only for background vetoing. The light output degradation caused by radiation damage has not been explicitly tested, but as it is quoted to be between 15% and 30% after a gamma-radiation dose of $10^4$–$10^5$ Gy [95], it is expected to be negligible for the purpose of the PoGOLite instrument. Furthermore, all crystals meet the requirement on the relative light yield, i.e. that the value should not decrease by more than 5% when the crystal is irradiated 1 cm from one end of the crystal compared to when irradiated in the central position. There are some differences between the crystals from the three different shipments. Particularly, those from shipment 1 seem to have a somewhat higher absolute light yield. However, since there were no explicit requirements on the absolute light yield of the crystals in the specifications, no further inquiry has been made regarding this difference.

The fact that the light yield of the crystals is first decreasing with increasing distance between the irradiation point and the photomultiplier tube, but then increasing when the irradiation point is close to the far end of the crystal, is counter-intuitive. Figure 3.16 shows an example of results from light yield tests performed in Novosibirsk, in conjunction with the crystal production.

![Figure 3.16. Light yield results from Novosibirsk for 11 tested crystals [96].](image-url)
The U-shaped behavior is thus seen in test results from Novosibirsk as well, which confirms that this effect is not caused by the measurements described here, but rather due to the properties of the crystals themselves. It is noted that this behavior is not seen in similar tests of CsI(Tl) crystals [84], which have a significantly lower index of refraction, about 1.8. BGO has a high refractive index, 2.15 [95], so the critical angle for total internal reflection will be small, only about 28°. Thus, photons can only escape from the crystal if the angle of incidence relative to the surface normal is less than 28°. If the angle is greater than this, the photon will be reflected at an angle of reflection equal to the angle of incidence, since the surface of the crystal has a polished finish [92]. While this has the advantage of reducing the loss of photons through the surface of the crystal, it also reduces the number of photons that can reach the photomultiplier tube, since this similarly requires the photons to traverse the boundary of the crystal. Due to the optical grease at this boundary, which has an index of refraction between that of BGO and that of the PMT glass window, the critical angle is greater than 28°, thus photons have a higher probability to escape towards the photomultiplier tube than through any other surface on the crystal. Since scintillation photons are generated isotropically [92], some photons will be emitted at angles for which they cannot escape the crystal, neither at the surfaces, nor towards the PMT. Even though the self-absorption of the crystal is low, such photons will eventually be absorbed. However, if there are impurities in the crystal, or defects on the surface of the crystal, the photons can scatter off these and attain scattering angles that are essentially random, which may allow these photons to leave the crystal. The defects therefore serve to randomize the scattering angles of photons that would otherwise be trapped within the BGO. When the irradiation point is moved closer to the far end of the crystal, the solid angle subtended by the end surface increases. If impurities or defects where the photons can scatter at favorable angles exist at this surface, the light yield may increase as the irradiation point is moved closer to the far end. Although the solid angle towards the photomultiplier tube decreases as well, the decrease in light yield caused by this is less than the increase in light yield from the far end of the crystal, since the photons have a greater probability to escape towards the PMT than through any other side due to the optical grease. As a result, the light yield is increasing towards both ends of the crystal, i.e. the light yield as a function of the distance between the irradiation point and the photomultiplier tube exhibits a U-shaped behavior. This also demonstrates the high quality of the crystals, since for crystals with many defects, the light yield is expected to be strictly decreasing [94].

To further investigate the U-shaped behavior, tests were also carried out on a complete SAS segment, covered with BaSO$_4$ (see Figure 3.17) and attached to an aluminum "backbone". The unit was irradiated at several different points with a collimated beam of 662 keV photons from $^{137}$Cs and the light yield (peak channel number) as a function of the distance between the irradiation point and the photomultiplier was studied using the procedure described in previous sections. Results are shown in Figure 3.18.
The U-shaped behavior can be seen in each of the three crystals even when they are glued together: since the adhesive has a lower index of refraction than the crystals, about 1.53 [83] compared to 2.15 [95], scintillation photons emitted in the opposite direction relative to the photomultiplier can undergo total reflection at the boundary between the crystals instead of traversing the entire length of the glued crystal before being reflected. The increase in light yield towards the far end of the crystal (the last data point in Figure 3.18) is small, which is thought to be due to a thinner layer of reflective BaSO$_4$ on this edge. These results also show that the approach with glued crystals is feasible, i.e. that the light loss is low, only about 10% in this measurement, even over the total length of three connected crystals.
Chapter 4

Neutron irradiation tests

4.1 Background

A six-hour observation of the Crab system with the 217-unit PoGOLite instrument was previously simulated with realistic atmospheric conditions [21]. This simulation included background not only from cosmic rays and atmospheric as well as cosmic X-rays [97], but also from atmospheric neutrons incident on the instrument and from “structure-induced” neutrons and other secondary particles arising from cosmic-rays interacting with passive materials, e.g. the gondola structure. The structure-induced background, caused by processes such as (p, n), (p, 2n) and (p, α), was found to be negligible both in the simulations [21] and in numerical calculations [16] based on empirical formulas [98]. However, atmospheric neutrons, which are created by interactions of cosmic rays in the atmosphere, can fake polarization events by scattering multiple times in the detector array. The inclusion of neutrons in this simulation was therefore crucial.

Few measurements of the atmospheric neutron flux have been published, and the situation is further complicated by the fact that the neutron flux is anisotropic at the float altitude of the balloon due to a significant contribution from albedo neutrons scattering back from the atmosphere [99]. Figure 4.1 shows neutron spectra at different atmospheric depths, whereas Figure 4.2 presents several measured and calculated neutron spectra as reported in various publications. Based on these figures, the neutron flux in the simulation was modeled as a broken power law spectrum divided into four intervals [21]:

\[
f(E) = \begin{cases} 
0.104E^{-0.884} & \text{for } 1 \text{ keV} < E < 1 \text{ MeV} \\
0.100E^{-1.189} & \text{for } 1 \text{ MeV} < E < 15 \text{ MeV} \\
0.0135E^{-0.450} & \text{for } 15 \text{ MeV} < E < 70 \text{ MeV} \\
3.135E^{-1.732} & \text{for } 70 \text{ MeV} < E < 1 \text{ GeV} 
\end{cases} \quad (4.1)
\]

The simulated neutron spectrum is shown in Figure 4.3.
Figure 4.1. Calculated neutron spectra at different atmospheric depths [100].
Figure 4.2. Calculated and measured neutron spectra near the top of the atmosphere [100].
Chapter 4. Neutron irradiation tests

The result from the simulation, given in Figure 4.4, contains several curves: “Detected neutron background before vetoing” is the expected flux in the instrument if all signals are recorded, independent of any activity in the anticoincidence system. “Detected neutron background after vetoing” shows the flux if events are discarded when there is a simultaneous signal in the anticoincidence system. “Detected neutron background, veto & Compton kinematics” means that events are rejected not only by activity in the anticoincidence system, but also if the relation between an observed scattering angle in the detector array and the energy deposition is not consistent with the Compton process. “Total gamma ray background” is the combined flux from atmospheric and cosmic gamma-rays. The flux from a 100 mCrab source with a Crab spectrum is shown for comparison. These simulations show that in the PoGOLite energy range, the background from atmospheric neutrons exceeds the gamma-ray background by more than an order of magnitude, even with vetoing and event selection based on Compton kinematics. In response to this, the PoGOLite design was modified: a polyethylene neutron shield surrounding the instrument was introduced, which would either prevent neutrons from entering the detector array entirely, or slow them to energies where their probability of causing fake polarization events would be minimized. As the addition of a polyethylene shield increases the total mass of the payload, thus potentially limiting the flight altitude, detailed simulations were carried out to determine the optimum shield thickness. These demonstrated that a polyethylene shield, 10 cm on the sides of the instrument and 15 cm in the bottom, would reduce the background from atmospheric neutrons to less than a 100 mCrab level in the PoGOLite energy range [21] (Figure 4.5). As a result, new observation goals were presented: 10% polarization from a 200 mCrab in the energy range 25–80 keV (previously quoted values [20] were 25–100 keV and 100 mCrab).
4.1. Background

Figure 4.4. Simulated background without the polyethylene shield [21]. The neutron flux is assumed to be anisotropic with 80% and 20% flux in the upwards and downwards direction, respectively. The background from neutrons exceeds the gamma-ray background by more than an order of magnitude over most of the range.

Figure 4.5. Simulated background with the polyethylene shield included [21]. The neutron flux is assumed to be anisotropic with 80% and 20% flux in the upwards and downwards direction, respectively. The neutron background is reduced to less than the 100 mCrab level over most of the range.
The simulations were carried out using Geant4 (GEometry ANd Tracking version 4) \cite{101, 102}, a framework developed at CERN, which uses the Monte Carlo technique \cite{103} to simulate particle interactions in matter. In the simulation, a detector geometry is first defined as consisting of different materials. This geometry is then irradiated with particles which have energies chosen from a pre-defined spectrum. The particles are individually tracked and can interact in different ways within the materials. In Geant4, all possible processes – ionization, radioactive decay, elastic and inelastic scattering, etc. – are defined in “physics lists”. The probability each interaction is dictated by cross-section tables depending on the material, the interacting particle and its energy.

For simulating neutron interactions in the PoGOLite instrument, the physics list “QGSP\_BERT\_HP” (Quark-Gluon String Precompound – BERTini – High Precision) \cite{104} was used. To validate simulations of the in-flight neutron background, several experimental studies were carried out. The purpose of these tests was to measure the response of plastic scintillators and BGO crystals irradiated with neutrons, as well as to study the shielding effects of polyethylene.

The first tests took place in Japan with $^{252}$Cf. This isotope can undergo spontaneous fission, whereupon neutrons and photons in the MeV range are generated isotropically, with a continuum spectrum peaking between 0.5 MeV and 1 MeV \cite{7}. In these tests, such neutrons and 59.5 keV photons from $^{241}$Am were incident on a fast plastic scintillator and the spectral response was measured with a photomultiplier tube coupled to flight-version front-end electronics. The waveforms generated by elastic neutron-proton scatterings in the scintillator were compared to those caused by the interactions of gamma-rays. Particularly, the ratio of the “fast” and the “slow” outputs, as defined in Equation 2.3 and Equation 2.4, was studied. The distribution of this ratio will be bimodal with one peak corresponding to each interaction type. These results demonstrated that it is possible to reduce the number of neutron-induced events by about a factor of two while sacrificing less than a third of the gamma-ray events by applying a threshold based on this ratio \cite{105}.

Tests were also carried out in Stockholm with an americium-beryllium source. This source contains a mixture of $^{241}$Am and $^9$Be. The $^{241}$Am radioisotope is an alpha-emitter, which decays to an excited state of $^{237}$Np and subsequently de-excites through photon emission, mainly at 59.5 keV. An alpha particle can interact with beryllium, forming carbon and a neutron: $\alpha + ^9\text{Be} \Rightarrow ^{12}\text{C} + n$. The resulting emission from this source will therefore contain both photons and neutrons, which complicates its use. Spectra were recorded with plastic scintillators and BGO crystals, but the continuum of neutron energies and the features introduced in the spectra by interactions of high-energy de-excitation photons from $^{12}$C made the isolation of spectral features caused by neutrons extremely difficult. Thus, due to the nature of the source, the results from this test were inconclusive.
4.2 Tests with 14 MeV neutrons

A neutron test facility is available at the Nuclear Engineering Department [106] at the Chalmers University of Technology in Gothenburg, Sweden. The laboratory features a SODERN 16C neutron generator [107], shown in Figure 4.6.

![Figure 4.6. The SODERN 16C neutron generator [106].](image)

This generator is based on the D–T reaction, and therefore does not suffer from problems associated with AmBe sources, i.e. a continuum of neutron energies and strong gamma-ray background. Deuterium particles are accelerated towards a tritium target, triggering the reaction \( ^2\text{H} + ^3\text{H} \rightarrow ^4\text{He} + \text{n} \). The neutrons are generated isotropically and are mono-energetic at 14 MeV [7]. Simulations [58, 108] show that neutrons with energies around 10 MeV have the highest probability to induce events that may be misinterpreted as a polarization signal in the PoGOLite detector array (“fake polarization events”). Neutrons from this reaction are therefore highly suited for studying how well the PoGOLite instrument is able to reject atmospheric neutrons.

The generator was shielded on all sides by thick layers of polyethylene and lead, and only a small opening remained on one side. Neutrons passing through this opening were incident on a simple detector array, consisting of four units comprising fast plastic scintillators and bottom BGO crystals, and three SAS BGO crystals, as shown in Figure 4.7(a). The shielding properties of polyethylene could then be tested. Simply placing polyethylene between the neutron generator and the detector would not have been sufficient, since neutrons could scatter from the walls in the laboratory and reach the detector anyway. Instead, a polyethylene box, shown in Figure 4.7(b), was used, shielding the detector from all directions, including the top and the bottom.
Chapter 4. Neutron irradiation tests

Figure 4.7. The detector array used in the neutron irradiation tests.

In the first set of measurements, no polyethylene was placed towards the neutron generator. This setup, shown in Figure 4.8(a), corresponds to the original design of PoGOLite, which did not have a designated neutron shield. In subsequent measurements, the detector array was shielded from all directions as shown in Figure 4.8(b). This mimics the current detector construction of the PoGOLite instrument, i.e. a passive outer layer of polyethylene and an active inner layer of BGO crystals shielding the plastic scintillators in the detector array.

Figure 4.8. Detector configurations used in the neutron irradiation tests. The polyethylene box has a “lid” as well, which was removed for taking these pictures.
Waveforms from all detectors were sampled using flight-version front-end electronics. Fast and slow signals from each unit were calculated as described in Section 2.1.2. The resulting values were plotted in two-dimensional histograms, from which signals corresponding to events in the fast scintillator could be identified. An example of such a histogram for the central detector unit, “Fast0” in Figure 4.7(a), can be seen in Figure 4.9.

![Figure 4.9](image)

**Figure 4.9.** Fast and slow signals from the central unit, calculated as detailed in Section 2.1.2. The narrow region indicated by parallel lines and the wide region shown with oblique lines correspond to signals in the fast scintillator and the bottom BGO crystal, respectively. Events from neutrons interacting in both components appear between these branches. The horizontal line with a slow output channel number around 2800 is due to saturation in the slow output of the electronics. Similarly, a saturation in the fast output can be seen as a vertical line around fast output channel number 3300.

Events from the fast branch were selected using Equation 2.5 and histogrammed. A linear calibration of the units was performed using 59.5 keV photons from $^{241}$Am. For energies above 25 keV the response of the fast scintillator is very close to linear. Between about 20 keV and 25 keV, this assumption may over-estimate the detected energies by about 10% [109]. However, since this measurement focused on neutron count rates and not on calorimetry, a small discrepancy at low energies should not affect the final results notably. The calibration spectrum can be seen in Figure 4.10.
Chapter 4. Neutron irradiation tests

Figure 4.10. Events from the fast branch were selected for a calibration with $^{241}$Am. The absorption peak of 59.5 keV photons from the source was fitted with a Gaussian curve. The peak position of this curve gives a conversion factor from the channel number to the corresponding energy.

After calibrating the detectors, the neutron count rate in the central plastic scintillator, “Fast0”, was measured both with and without active vetoing in the surrounding detector units. Three different selection criteria were considered in the off-line analysis:

**No vetoing (passive BGOs):** All signals in the central plastic scintillator are counted, regardless of any signals in the other detectors.

**Active vetoing, BGOs only:** Events in the central unit are only counted if there is no coincident signal in any of the BGO crystals within the 50 sample points recorded for each trigger. This corresponds to the normal operation mode of PoGOLite, i.e. events are rejected if there is a coincident signal in the BGO shield.

**Full active vetoing:** The three surrounding fast plastic scintillators and the BGO crystals all act as anticoincidence units and events in the central unit are only counted if there are no coincident signals in any of the other units. This corresponds to a mode of operation where not only the BGO shield acts as an active anticoincidence system, but where also events in the outer-most ring of PDC units are rejected. Such an operation mode that can be used if the in-flight background turns out to be higher than expected.
Since the live time\(^1\) was recorded for each measurement, the count rate (number of counts per second of live time) obtained with the different selection criteria could be compared. The relative change in the neutron rate gives an indication of how well active vetoing in the anticoincidence system can be used to reject neutron events.

The result from the measurement with no polyethylene between the neutron generator and the detector can be seen in Figure 4.11. Background spectra, recorded for the three selection criteria but with the neutron generator inactive, were also recorded. All data is shown background-subtracted.

![Figure 4.11](image)  
*Figure 4.11. Spectra for different selection criteria with no polyethylene between the neutron generator and the detector. The energy scale is based on a linear calibration with \(^{241}\)Am. The two peaks in the spectrum around 185 keV and 215 keV are caused by saturation in the slow and fast outputs (see Figure 4.9) and are thus features caused by the electronics, not by neutron interactions.*

The measurements were repeated with 5 cm and 10 cm polyethylene between the neutron generator and the detector array in order to separately test the shielding effect of polyethylene. Results for these different configurations are shown in Figure 4.12.

---

\(^1\)The time during which the data acquisition system is sensitive to signals is called “live time”. Once a trigger is issued, the system will be busy for a short time while processing the signal. This is “dead time”. The sum of the two is the total time or “real time”.

---
Figure 4.12. Spectra for different selection criteria with 5 cm polyethylene (top) and with 10 cm polyethylene (bottom) between the neutron generator and the detector. The energy scale is based on a linear calibration with $^{241}\text{Am}$. The peaks around 185 keV and 215 keV in the spectrum are caused by saturation in the slow and fast outputs (see Figure 4.9).
In each measurement, the shield thickness was held constant (0 cm, 5 cm or 10 cm polyethylene, respectively), while the selection criteria were changed (no vetoing \(\Rightarrow\) active vetoing \(\Rightarrow\) full active vetoing). A quantitative comparison is given by the relative neutron count rates with the three different selection criteria. These results, for the PoGOLite energy range (25–80 keV), are collected in Table 4.1. For each measurement (0 cm, 5 cm and 10 cm polyethylene), the count rate was normalized to the spectrum with no vetoing recorded in that configuration.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Rel. neutron count rate (25–80 keV)</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 cm – no vetoing</td>
<td>1 (138 cts/s live time)</td>
<td>4.11</td>
</tr>
<tr>
<td>0 cm – active vetoing</td>
<td>0.59 ± 0.08</td>
<td></td>
</tr>
<tr>
<td>0 cm – full active vetoing</td>
<td>0.41 ± 0.06</td>
<td></td>
</tr>
<tr>
<td>5 cm – no vetoing</td>
<td>1 (111 cts/s live time)</td>
<td>4.12(a)</td>
</tr>
<tr>
<td>5 cm – active vetoing</td>
<td>0.57 ± 0.09</td>
<td></td>
</tr>
<tr>
<td>5 cm – full active vetoing</td>
<td>0.39 ± 0.07</td>
<td></td>
</tr>
<tr>
<td>10 cm – no vetoing</td>
<td>1 (83 cts/s live time)</td>
<td>4.12(b)</td>
</tr>
<tr>
<td>10 cm – active vetoing</td>
<td>0.56 ± 0.10</td>
<td></td>
</tr>
<tr>
<td>10 cm – full active vetoing</td>
<td>0.38 ± 0.08</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1. Relative neutron count rates obtained with different selection criteria for the measurements with 0 cm, 5 cm and 10 cm polyethylene, respectively.

To evaluate the effect of the polyethylene on the neutron rate, the spectra above were compared for different shield thicknesses, instead of for different selection criteria. Figure 4.13 shows the result for 0 cm, 5 cm and 10 cm with no vetoing.

Figure 4.13. Neutron spectra for different thicknesses of the polyethylene shield, obtained with no vetoing in the peripheral detectors. The two peaks in the spectrum around 185 keV and 215 keV are caused by saturation in the slow and fast outputs.
Results for active vetoing and full active vetoing are given in Figure 4.14.

![Graph of neutron irradiation tests](image)

(a) Spectra for different shield thicknesses – active vetoing.

![Graph of neutron irradiation tests](image)

(b) Spectra for different shield thicknesses – full active vetoing.

**Figure 4.14.** Spectra for different shield thicknesses, obtained with active vetoing (top) and full active vetoing selection criteria (bottom). The energy scale is based on a linear calibration with $^{241}$Am. The peaks around 185 keV and 215 keV in the spectrum are caused by saturation in the slow output (see Figure 4.9).
In the spectra presented above, the selection criteria have been held constant while the shield thickness has been varied. This enables the effect of the shield thickness to be separated from that of the selection criteria. The results of this study, for the energy range 25–80 keV, have been collected in Table 4.2. For each set of selection criteria (no vetoing, active vetoing and full active vetoing), the count rate is normalized to the spectrum with no polyethylene recorded for that selection.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Rel. neutron count rate (25–80 keV)</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 cm – no vetoing</td>
<td>1 (138 cts/s live time)</td>
<td>4.13</td>
</tr>
<tr>
<td>5 cm – no vetoing</td>
<td>0.80 ± 0.10</td>
<td></td>
</tr>
<tr>
<td>10 cm – no vetoing</td>
<td>0.60 ± 0.08</td>
<td></td>
</tr>
<tr>
<td>0 cm – active vetoing</td>
<td>1 (82 cts/s live time)</td>
<td>4.14(a)</td>
</tr>
<tr>
<td>5 cm – active vetoing</td>
<td>0.77 ± 0.13</td>
<td></td>
</tr>
<tr>
<td>10 cm – active vetoing</td>
<td>0.57 ± 0.10</td>
<td></td>
</tr>
<tr>
<td>0 cm – full active vetoing</td>
<td>1 (55 cts/s live time)</td>
<td>4.14(b)</td>
</tr>
<tr>
<td>5 cm – full active vetoing</td>
<td>0.77 ± 0.15</td>
<td></td>
</tr>
<tr>
<td>10 cm – full active vetoing</td>
<td>0.57 ± 0.13</td>
<td></td>
</tr>
</tbody>
</table>

*Table 4.2. Relative neutron count rates obtained with different shield thicknesses for the selection criteria “no vetoing”, “active vetoing” and “full active vetoing”.*

Since the PoGOLite detector geometry is different from the simple detector array used here, and since atmospheric neutrons are not mono-energetic as the ones from this neutron generator, the above results cannot directly be used to evaluate the neutron background rejection capabilities of the flight-version of the instrument. Instead, the most important test is to compare these results with simulated data from Geant4. If the two are consistent, it would show that the treatment of neutron interactions in Geant4 is reliable, thus validating the simulation of the full-size PoGOLite instrument. This study is the subject of the next section.

### 4.3 Monte Carlo simulations

The simulation was run with Geant 4.9.1.p01 using the “QGSP\_BERT\_HP” physics list and with the latest available cross-section tables, G4NDL3.12 (Geant4 Neutron Data Library). These libraries are maintained by the Cross Section Evaluation Working Group (CSEWG) [110] and include both thermal and non-thermal cross-sections for neutrons.

The first step in the simulation was to recreate the detector geometry. First, the materials were defined: BGO consisting of bismuth, germanium and oxygen in appropriate quantities, polyethylene containing carbon and hydrogen, etc. Geometric shapes were then created from these materials to resemble the detector array and the polyethylene shields as precisely as possible. Mono-energetic 14 MeV neutrons
were generated from a point source placed at the same distance in the simulation as the measured separation between the neutron generator and the detector in the laboratory. From this point source, neutrons were emitted within a cone with an opening angle wide enough to ensure that all parts of the detector, as well as the surrounding polyethylene shield, can be hit (see Figure 4.15). The materials surrounding the neutron generator itself were not included in the simulation as the rate of neutrons escaping through this thick lead and polyethylene shielding is expected to be negligible compared to the rate of direct neutrons.

![Simulated detector geometry and several neutron tracks. The tracks originate from a point-source towards the right-hand side but outside the picture. This particular setup shows the measurement with no polyethylene between the neutron generator and the detector, i.e. the setup shown in Figure 4.8(a).](image)

Neutrons were generated and tracked one by one. When a simulated neutron enters a material, different interactions can take place, with probabilities based on the cross-section tables in Geant4. If secondary particles are produced in the interactions, these are individually tracked until they either lose all their energy or escape from the laboratory\(^2\). The simulated volumes corresponding to the detector units are defined to be “sensitive”, and energy deposited in these volumes is stored by the program and output to a file. The software also keeps track of the particle species causing the energy deposition. Thus, each particle type can be treated individually, e.g. to take quenching effects\(^3\) [111, 112] into account.

\(^2\)In Geant4, the “laboratory” is represented by a “world volume” with dimensions that are sufficiently large to contain the simulated detector geometry.

\(^3\)Quenching is a process causing protons or heavier particles to generate less scintillation light than a photon or an electron, even if the deposited energy is the same. In these cases, some of the energy is converted to heat instead. The amount of detected energy is measured in MeVee, electron-equivalent energy, i.e. by definition, electrons have a quenching factor equal to unity.
One million neutrons were generated for each of the three simulation setups, 0 cm, 5 cm and 10 cm polyethylene between the neutron generator and the detector array. The simulation is based on pseudo-random numbers generated using the Ranecu algorithm [113], a random number engine initiated using two integers. This input to the random number engine, called the random “seed”, can be used to exactly recreate the same series of pseudo-random numbers. Thus, by storing the initial random seed from the simulation, the simulation can be exactly reproduced. Furthermore, by keeping the last random seed from a simulation and setting it as the initial seed for the next run, the simulations can be extended to improve statistics, while ensuring that the same series of random numbers is not repeated.

The output of the simulation is a text file with 43 columns. The first column is the event number. Data is only stored if energy is deposited in one or more detector cells and the number in this column is used to keep track of the neutron causing the energy deposition. The remaining 42 = 7 × 6 columns correspond to the seven detector units (four plastic scintillators and three BGO crystals), with six outputs for each unit. These are for six different groups of particles that were considered: “EM”, “Proton”, “Neutron”, “Alpha”, “C12” and “Others”. Quenching factors could then be individually applied in the subsequent analysis, not only for the different particle types but also separately for the plastic scintillators and BGO crystals.

4.4 Analysis and results

For the analysis, all 42 energy depositions, the majority of which are zero, were read for one event at a time, whereupon each of the six groups of particles was treated individually according to the following procedure:

**EM:** This group contains electromagnetic shower particles, i.e. photons, electrons and positrons. A photon has three main interactions in matter, as described in Section 1.1: photoelectric effect, Compton scattering and pair production. The result of each of these interactions is that the photon energy is transferred to electrons and positrons. As a result, these particles will deposit the same amount of energy in the detector if they have the same initial energy (provided that the interactions are fully contained in the detector volume). The quenching factor these particles is therefore, by definition, equal to unity.

**Proton:** Protons have a quenching, which, in plastic scintillators, is given by [114]

\[ E_{\text{Quenched, proton}} = 0.119 \cdot E_{\text{Proton}}^2 + 0.0564 \cdot E_{\text{Proton}} \]  \hspace{1cm} (4.2)

where \( E_{\text{Proton}} \) is the energy deposited in the plastic scintillator by the incident proton and \( E_{\text{Quenched, proton}} \) is the detected (electron-equivalent) energy.

**Neutrons:** The quenching for neutrons is assumed to be the same as for protons. Since neutrons are uncharged, they lose energy through elastic and inelastic
scatterings [7], mostly with protons. The energy in the detector will thus be deposited by protons, which is why the same quenching factor is used here.

**Alphas:** Since alpha particles are charged, they deposit energy by exciting and ionizing atoms as they traverse the detector material. In this case, the quenching factor for plastic scintillators is given by the quadratic relation [114]

$$E_{\text{Quenched, alpha}} = 0.00878 \cdot E_{\text{Alpha}}^2 + 0.0145 \cdot E_{\text{Alpha}}$$  (4.3)

where $E_{\text{Alpha}}$ is the energy deposited in the plastic scintillator by the alpha particle and $E_{\text{Quenched, alpha}}$ is the detected (electron-equivalent) energy.

**C12:** For carbon atoms, $^{12}$C, the quenching in a plastic scintillator material is given by [114]

$$E_{\text{Quenched, } ^{12}\text{C}} = 0.0062 \cdot E_{^{12}\text{C}}$$  (4.4)

where $E_{^{12}\text{C}}$ is the energy deposited in the plastic scintillator by the particle and $E_{\text{Quenched, } ^{12}\text{C}}$ is the electron-equivalent energy measured in the detector.

**Others:** This group contains all other particles that can cause energy deposition in the simulation. In this analysis, the quenching for these particles has been assumed to be the same as for carbon [108].

Equations 4.2, 4.3 and 4.4 are based on empirical results for liquid organic scintillators, tabulated up to 40 MeV in [112]. Figure 4.16 shows a plot recreated from this data. A difference of 10% is assumed in between the quenching factor of a solid plastic scintillator and a liquid scintillator [114], which gives the relations above.

![Figure 4.16](image)

**Figure 4.16.** Electron-equivalent energy for different particles in a liquid organic scintillator, recreated from data given in [112]. Due to quenching effects, whereupon some energy is converted to heat instead of scintillation light, the detected energy (ordinate) is less than the deposited energy (abscissa). Values for a plastic scintillator are assumed to be 10% less than these numbers [114].
For the BGO crystals, which are only used for vetoing and not for calorimetry, a constant quenching factor of 0.1 [108] was assumed for all of these particle types except photons, electrons and positrons, which have a quenching factor equal to unity.

Once the quenched energies had been determined, the total energy deposition was calculated for each of the seven detector units by adding the contributions from all six groups of particles. In accordance with previous simulations of the PoGOLite instrument [108], a detection threshold of 2 keV and 30 keV was assumed for the plastic scintillators and for the BGO crystals, respectively.

Events in the central detector were plotted with one histogram for each of the three selection criteria, “no vetoing”, “active vetoing” and “full active vetoing”, respectively. The number of counts below 300 keV was studied for each of the three cases.

The simulation was repeated for the three different detector configurations used during the beam test: 0 cm, 5 cm and 10 cm polyethylene located between the neutron generator and the detector array. Results can be seen in Figure 4.17 and Figure 4.18.

![Figure 4.17](image.png)

**Figure 4.17.** Simulated neutron spectra for different selection criteria with 0 cm polyethylene between the neutron generator and the detector.
Figure 4.18. Simulated neutron spectra for different selection criteria: 5 cm (top) and 10 cm (bottom) polyethylene between the neutron generator and the detector.
4.4 Analysis and results

Figure 4.19 shows the simulated and measured spectra for the setup with 10 cm polyethylene between the neutron generator and the detector array and with “full active vetoing”. The two spectra have been normalized to the value at 10 keV.

![Figure 4.19](image)

Figure 4.19. Simulated (thick solid line) and measured (thin solid line) neutron spectra for the setup with 10 cm polyethylene and full active vetoing. The peaks in the measured spectrum are caused by saturation in the electronics (see Figure 4.9).

Apart from the two peaks in the measured spectrum, which are not caused by neutron interactions but by saturation effects in the electronics (see Figure 4.9), the agreement between the measured and the simulated data is good, all the way up to about 250 keV, which is the range of the electronics. Plots from the other measurements, 0 cm and 5 cm polyethylene between the neutron generator and the detector, as well as the other two selection criteria, “no vetoing” and “active vetoing”, show similar likeness when compared.

A quantitative comparison is given in Table 4.3 and in Table 4.4. The first of these contains the relative neutron count rates for events in the PoGOLite energy range, i.e. 25–80 keV, whereas the latter shows the relative count rates in the energy range up to 300 keV and acts as a more general test of the simulated neutron interactions over a wider energy range. The agreement between both the spectra and the relative neutron count rates demonstrates that the treatment of neutron interactions in Geant4 with the “QGST_BERT_HP” physics list is reliable, which validates the simulations of in-flight background from atmospheric neutrons described in [21].
### Table 4.3.
Measured (center column) and simulated (right column) relative neutron count rates in the PoGOLite energy range (25–80 keV) for different shield thicknesses and event selection criteria.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0 cm – no vetoing</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0 cm – active vetoing</td>
<td>0.59 ± 0.08</td>
<td>0.63 ± 0.03</td>
</tr>
<tr>
<td>0 cm – full active vetoing</td>
<td>0.41 ± 0.06</td>
<td>0.38 ± 0.02</td>
</tr>
<tr>
<td>5 cm – no vetoing</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>5 cm – active vetoing</td>
<td>0.57 ± 0.09</td>
<td>0.61 ± 0.03</td>
</tr>
<tr>
<td>5 cm – full active vetoing</td>
<td>0.39 ± 0.07</td>
<td>0.38 ± 0.02</td>
</tr>
<tr>
<td>10 cm – no vetoing</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>10 cm – active vetoing</td>
<td>0.56 ± 0.10</td>
<td>0.60 ± 0.03</td>
</tr>
<tr>
<td>10 cm – full active vetoing</td>
<td>0.38 ± 0.08</td>
<td>0.38 ± 0.03</td>
</tr>
</tbody>
</table>

### Table 4.4.
Measured (center column) and simulated (right column) relative neutron count rates in the energy range up to 300 keV for different shield thicknesses and event selection criteria.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0 cm – no vetoing</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0 cm – active vetoing</td>
<td>0.62 ± 0.04</td>
<td>0.68 ± 0.02</td>
</tr>
<tr>
<td>0 cm – full active vetoing</td>
<td>0.43 ± 0.03</td>
<td>0.44 ± 0.01</td>
</tr>
<tr>
<td>5 cm – no vetoing</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>5 cm – active vetoing</td>
<td>0.59 ± 0.04</td>
<td>0.66 ± 0.02</td>
</tr>
<tr>
<td>5 cm – full active vetoing</td>
<td>0.41 ± 0.03</td>
<td>0.44 ± 0.01</td>
</tr>
<tr>
<td>10 cm – no vetoing</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>10 cm – active vetoing</td>
<td>0.60 ± 0.05</td>
<td>0.65 ± 0.02</td>
</tr>
<tr>
<td>10 cm – full active vetoing</td>
<td>0.42 ± 0.04</td>
<td>0.43 ± 0.01</td>
</tr>
</tbody>
</table>
4.5 The PoGOLite neutron scintillator

To monitor the in-flight neutron background of the PoGOLite instrument, a neutron detector has been added to the detector array. This detector consists of a LiCaAlF$_6$ crystal with a 2% europium-doping (“LiCAF (Eu)” provided by the Tokuyama Corporation in Japan, sandwiched between two bottom BGO crystals, identical to those used for the PDCs. The constituents are shown in Figure 4.20 and the location of the unit within the detector array can be seen in Figure 4.21.

![Figure 4.20. The BGO pieces (left, right) and LiCAF crystal (middle) used for the neutron scintillator. The crystal were covered with BaSO$_4$ and the entire assembly was wrapped with several layers of teflon tape to maximize the reflectivity.](image)

![Figure 4.21. Location of the neutron scintillator within the detector array, adjacent to the PMTs connected to “SAS21” and “SAS20” in Figure 5.17. Vulcanizing tape is used to provide mechanical stability and assure light-tightness.](image)
Neutrons incident on the PoGOLite instrument are thermalized in the polyethylene shield. The cross-section for thermal neutron capture in $^6\text{Li}$ (which is present in the LiCAF with a 50% concentration) is 940 barn, and the 5 mm thick LiCAF piece is expected to be able to capture such neutrons with an efficiency of about 90% [115]. Charged particles and photons incident on the detector assembly can be rejected in the BGO pieces, which shield the LiCAF from most directions.

The scintillator assembly was tested in Japan [115] with neutrons from a $^{252}\text{Cf}$ source. An additional gamma-ray background, 662 keV photons from $^{137}\text{Cs}$, was present during the measurements. The different configurations used for the testing are illustrated in Figure 4.22.

![Figure 4.22. Measurement setups used for testing the neutron scintillator [115]. Top: reference measurement with BGO pieces only, irradiated by neutrons from $^{252}\text{Cf}$ and 662 keV photons from $^{137}\text{Cs}$. Middle: flight configuration with the LiCAF sandwiched between the two BGO pieces. Bottom: as previous, but with an 2.5 mm thick cadmium shield absorbing some of the incident radiation, mostly neutrons. A flight-version Hamamatsu PMT (model R7899) was used for the read-out.](image)

The scintillation decay time of europium-doped LiCaAlF$_6$ is about 1600 ns [116], compared to 300 ns for BGO. In order to study such pulses, the sampling rate of the electronics was changed to 6.25 MHz, i.e. each clock corresponds to 160 ns, instead of the otherwise used rate, 37.5 MHz (~30 ns per clock, see Section 2.1.2). An example of waveforms from the BGO and from the LiCAF pieces at this sampling rate is shown in Figure 4.23.
4.5. The PoGOLite neutron scintillator

Figure 4.23. Examples of waveforms from BGO (green points marked by 'x') and europium-doped LiCAF (red points indicated with '+' [115]. The relation between the two is similar to that of the fast and slow scintillator waveforms (see Figure 2.6), which, however, are recorded at a different sampling rate.

Events from the two components become clearly separated when plotted in a two-dimensional histogram with the fast and slow outputs using the procedure described in Section 2.1.2. An example of the result is presented in Figure 4.24.

Figure 4.24. Separation of events from BGO and LiCAF in the neutron scintillator [115]. Fast and slow output are calculated as described in Section 2.1.2. Two "branches" appear due to the difference in scintillation decay times of the materials. The "blob" in the LiCAF branch is from neutron capture events, while the continuum in the BGO branch is caused by photons from $^{252}$Cf.
Events from the LiCAF crystal are separated by selecting only events from the upper branch in Figure 4.24. Results with and without such a selection are shown in Figure 4.25. This plot is obtained by projecting the events onto the ordinate (slow output\(^4\)) of the two-dimensional histogram, with or without a selection of events from the neutron scintillator only. In the spectrum which includes events from both the BGO crystals and from the LiCAF piece (configuration b in Figure 4.22), several of the features described in Section 3.5 can be seen: absorption peaks of 662 keV and 1461 keV photons from \(^{137}\text{Cs}\) and \(^{40}\text{K}\), respectively, along with the neutron capture signal from the LiCAF piece. When selecting events corresponding to the LiCAF scintillator only, the photoabsorption peaks disappear and the continuum level is reduced by more than an order of magnitude, while the neutron capture signal remains. Finally, when introducing the cadmium-shield between the source and the detector (configuration c), the neutron capture feature is further reduced, while the continuum remains almost unchanged. The difference between the three curves demonstrates that this feature indeed arises from neutrons interacting in the LiCAF scintillator. Additional details on this measurement are given in [115].

\(4\) Projection onto the fast branch, as is done for events in the fast scintillator, is also possible. However, for waveforms from the LiCAF crystal, the slow output is typically greater than the fast output (see Figure 4.24) and this projection therefore produces a better separation between features in the spectrum.

Figure 4.25. Neutron scintillator spectra from BGO and LiCAF [115]. Top curve (black): events from BGO and LiCAF are both included. Middle curve (red): events from the LiCAF are selected. Bottom curve (black): as previous, but with a cadmium absorber between the source and the detector, further reducing the neutron rate.
4.6 Discussion

Although a simple detector geometry cannot directly be used to evaluate the background rejection capability of the full-size PoGOLite instrument, the neutron beam test has been extremely useful for validating the neutron interaction processes in Geant4. Despite the good agreement between measured and simulated data, there are a number of known weaknesses and simplifications in the simulations presented here. These are discussed in some detail below.

**Infinite energy resolution:** The simulated energy resolution of the detector is infinite, i.e. the amount of energy that is deposited a detector unit (after suitable quenching) is assumed to be exactly equal to the energy that is measured. However, in a real measurement, finite energy resolution and statistical processes governing the photoelectron emission and amplification in the photomultiplier tube will fluctuate the measured energy to some extent. Since there are no sharp features in the simulated spectra, this simplification should have only a limited effect on the results.

**Constant BGO quenching:** In this analysis, the quenching factors for the BGO crystals have been assumed to be not only constant with energy, but also independent of the particle causing the energy deposition (except for photons, electrons and positrons). This assumption is a consequence of the lack of published material about quenching effects of different particles interacting in BGO. However, since the BGO crystals are only used for vetoing purposes and not for calorimetry, this simplification should not change the outcome of the simulation significantly.

**Mono-energetic neutrons:** Currently, all simulated neutrons incident on the detector array (and the surrounding polyethylene shield) are mono-energetic with an energy of 14 MeV and originate from a point-source. A more realistic simulation should include the full geometry of the neutron generator, i.e. the shielding material surrounding the equipment (mostly lead and polyethylene blocks), since some neutrons, although few compared to the rate of the direct beam, can scatter in this material and reach the detector with an energy lower than 14 MeV.

Due to the good agreement between measured and simulated data, the simulations of the neutron beam test, as well as those of the in-flight neutron background, are considered to be reliable and the polyethylene neutron shield has been implemented in the PoGOLite Pathfinder.

Additional simulations of the neutron shield performance showed that neutrons which are most likely to cause fake polarization events mainly enter the instrument in the region around the fast scintillators. By moving some of the shielding from the upper part of the instrument to this particular region, it was found that the neutron background could be reduced by 23.1% with only a 1.4% increase in total...
mass [58]. In this new configuration, the thickness varies between 5 cm and 15 cm in the sides of the instrument, with a bottom thickness of about 15 cm beneath the photomultiplier tubes. The shield structure resulting from this optimization process will be used for the flight of the Pathfinder instrument and is shown in Figure 4.26.

![Figure 4.26](image)

Figure 4.26. The assembled polyethylene neutron shield, integrated into the rotation frame of the PoGOLite instrument (shown in Figure 2.15). The shield weighs around 200 kg and consists of about 250 pieces. These are distributed as to provide maximal shielding around the fast scintillator region. Thicknesses in different parts have been indicated.

Finally, the added LiCAF neutron scintillator has been tested and is expected to have a high efficiency for detecting thermal neutrons penetrating the polyethylene shield. It will allow the in-flight neutron background to be studied and the impact on the polarimetric capabilities of the instrument by neutrons causing fake polarization events to be evaluated. Furthermore, since few measurements of the atmospheric flux have been published, this detector can strongly contribute to the scientific potential of the PoGOLite instrument.
Chapter 5
Detector performance optimization

The sensitivity of the PoGOLite instrument strongly depends on the individual scintillators and photomultiplier tubes. Many factors affect the performance of the detector: the quality and purity of the materials (fast scintillator, slow scintillator, BGO crystal), the glue joints between these components, the wrapping layers (VM2000 to maximize internal reflection, lead and tin foils to improve background rejection and passive collimation), the BaSO$_4$ coating of the BGO parts, the intrinsic gain of the coupled photomultiplier tubes, etc. Since each detector element is assembled by hand from the raw materials, the light yield can be expected to vary somewhat from unit to unit. Although the instrument will be rotated in flight to eliminate contributions from such systematic effects, a significant effort has been made to arrange the detector units in a way that maximizes the uniformity of the instrument and its detection sensitivity. This procedure will be described here.

5.1 PDC arrangement

A total of 61 phoswich detector cells (PDCs) are used in the PoGOLite Pathfinder. These must provide good collimation and high sensitivity for detecting X-ray photons, and should be arranged to produce a response that is as close to uniform as possible over the detector area. After initial qualification tests described in [56], the three scintillating components of each assembled unit were individually tested as outlined below.

The fast scintillators were irradiated with 59.5 keV photons from $^{241}$Am at a point located 4 cm from the top of the fast scintillator$^1$, as shown in Figure 5.1.

$^1$This position was chosen for consistency with tests carried out in preparation for the beam tests carried out at the KEK “Photon Factory” in Tsukuba, Japan.
The slow scintillators were tested with electrons from $^{90}$Sr irradiating the unit from the side at five equidistant points as shown in Figure 5.2. Electrons from this source are minimum ionizing particles and deposit $\sim$2 MeV/cm as they traverse the scintillator material. As the source was attached to the side of the scintillator, the emitted electrons always passed through the same amount of material, thus depositing approximately the same amount of energy every time. The walls of the slow scintillator are 2 mm thick and two walls are traversed by each electron, thus the energy deposition is expected to be $\sim$800 keV.

The bottom BGO crystals were tested with 662 keV photons from $^{137}$Cs as shown in Figure 5.3.

In these measurements, the figure of merit is the light yield (peak channel number) of the corresponding spectral feature (see e.g. [91, 92]). By fitting the peak region of each recorded spectrum with a Gaussian curve, the quality of the PDCs can be quantized as the position (mean value) of the Gaussian. Results as exemplified in Figure 5.4 were collected and databased for a total of 80 assembled PDC units.
5.1. PDC arrangement

Figure 5.4. Example of test results for an assembled PDC unit. Upper left: spectra of electrons from $^{90}$Sr irradiating the slow scintillator at five different points. Upper right: peak channel numbers for these five irradiation points, obtained by fitting each of the peaks with a Gaussian curve. The light yield is decreasing with increasing distance between the irradiation point and the photomultiplier tube, in accordance with expectations. Error bars are small compared to the data point size and have been omitted. Lower left: Compton continuum and photoabsorption peak of 59.5 keV photons from $^{241}$Am. Lower right: photoabsorption peak of 662 keV photons from $^{137}$Cs. The “shoulder” on the right-hand side of this spectrum arises from the geometry of the bottom BGO crystal, as demonstrated in [41].
Peak positions obtained by fitting each spectral feature with a Gaussian curve have been histogrammed. These results for all 80 PDC units are given in Figure 5.5.

<table>
<thead>
<tr>
<th>Position</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position 1</td>
<td>80</td>
<td>1702</td>
<td>227.5</td>
</tr>
<tr>
<td>Position 2</td>
<td>80</td>
<td>1073</td>
<td>150.3</td>
</tr>
<tr>
<td>Position 3</td>
<td>80</td>
<td>736.3</td>
<td>136.4</td>
</tr>
<tr>
<td>Position 4</td>
<td>80</td>
<td>579</td>
<td>119</td>
</tr>
<tr>
<td>Position 5</td>
<td>80</td>
<td>508.1</td>
<td>122.4</td>
</tr>
</tbody>
</table>

(a) Histogrammed results for the five irradiation points on the slow scintillators of the 80 assembled and tested PDC units. Values in the statistics boxes along the top show how the mean value of each distribution (and therefore the light yield) is decreasing with increasing distance between the irradiation point and the photomultiplier tube.

<table>
<thead>
<tr>
<th>Peak channel number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position 1</td>
</tr>
<tr>
<td>Position 2</td>
</tr>
<tr>
<td>Position 3</td>
</tr>
<tr>
<td>Position 4</td>
</tr>
<tr>
<td>Position 5</td>
</tr>
</tbody>
</table>

(b) Collected results: fast scintillator tests.  
(c) Collected results: bottom BGO tests.

**Figure 5.5.** Collected results from the tests of all 80 assembled PDC units.
From these results, the PDCs were ranked in four different categories:

- Slow scintillator light yield (sum of the peak channel numbers obtained for the five irradiation points using Gaussian fits)
- Fast scintillator light yield (peak channel number from the Gaussian fit)
- Bottom BGO crystal light yield (peak channel number from the Gaussian fit)
- Total light yield (sum of the above three)

Four lists, each with 80 entries, were created, ranking the PDCs according to their light yield in the above categories. The placement of each unit within the detector array was then determined using the following procedure:

1. From the list with PDCs sorted according to their total light yield, the top 61 units were selected for use in the instrument, while the remaining 19 were kept as spares.

2. For each of the selected PDCs, the individual lists were checked to determine if the particular unit had higher ranking in terms of light yield from the fast scintillator or from the slow scintillator. Units with higher slow scintillator ranking were added to an “outside” list, and conversely to an “inside” list if the fast scintillator ranking was higher. The two lists correspond to PDCs in the outer-most detector ring (24 units) and inner rings (37 units).

3. When one list was full (the “inside” list filled up first), remaining PDCs were added to the other list.

4. The “inside” list was sorted according to the fast scintillator ranking. Units were then “spiraled” from the center of the detector array and outwards, i.e. the PDC with the highest fast scintillator light yield was placed in the middle of the instrument, and then decreasing outwards.

5. Step 4 was not required for the “outside” list, since all sides of the instrument should be equally well protected from background events. Here, the order was instead “pseudo-randomized” by sorting the PDCs according to their production dates.

By following these steps, the detector cells are arranged in a way that takes all aspects of the PDCs into account, and also optimizes the performance of the instrument in terms of sensitivity, uniformity and background rejection capabilities. The resulting placement is shown in Figure 5.6, where PDCs have been listed according to their “names”.

---

2 The philosophy behind optimizing the outer-most ring with respect to the slow scintillator performance is that this ring can be used as an additional anticoincidence layer if the in-flight background turns out to be more severe than expected.

3 When the PDC mass-production first started in 2006 [117], units were labeled with names in alphabetical order. This tradition has since then been maintained, with detector names inspired by colleagues, movie stars and video game characters...
5.2 SAS arrangement

A total of 34 SAS (Side Anticoincidence System) units have been assembled and covered with BaSO$_4$ [74]: 27 “edge” type (24 are needed for the Pathfinder instrument, leaving three spares) and seven “corner” segments (six needed, one spare). These are shown in Figure 5.7.
Figure 5.7. Assembled SAS units with BaSO$_4$ coating. Blue pieces of shrink tube, used to attach the BGO crystals to an aluminum backbone, can be seen. A silicone layer between the BGO and the aluminum provides shock-absorption. Shrink tube pieces are staggered on adjacent segments, allowing them to be packed as closely together as possible to minimize gaps in the anticoincidence shield (see Figure 2.15).

Testing each assembled unit is crucial for ensuring the quality of the glue joints and the reflective BaSO$_4$ coating, as well as for determining its position in the detector array. Since the individual crystals had already been tested, three irradiation points for each unit, shown in Figure 5.8, were deemed sufficient.

Figure 5.8. Measurement setup used for testing the assembled SAS units. Since these have a cylindrical protrusion on one end, optical coupling to a PoGOLite PMT (Hamamatsu model R7899, see Section 3.4) is straight-forward, and such a PMT was therefore used here, instead of the previously employed Photonis PMT (XP5202/B).
When irradiating with 662 keV photons from $^{137}$Cs, spectra such as the ones in Figure 5.9(a) were obtained. The behavior shown in Figure 5.9(b) was observed for all assembled SAS units.

(a) Example of spectra obtained when irradiating an assembled SAS unit with 662 keV photons in three different points. A background spectrum, recorded with no irradiating source, is shown for comparison.

(b) Light yield for the three different irradiation points along the length of one of the SAS units. Error bars are small compared to the size of the data points and have therefore been omitted.

Figure 5.9. Example of test results for one of the assembled SAS units.
The described procedure was repeated for all 34 assembled SAS units. Results are collected in Figure 5.10 and in Figure 5.11 for the “edge” and “corner” type crystals, respectively.

(a) Light yield and SAS unit number (“edge” type, in order tested).

(b) Histograms with the light yield data.

Figure 5.10. Light yield results for the assembled SAS “edge” units. Positions 1, 2 and 3 refer to the irradiation points shown in Figure 5.8.
(a) Light yield and SAS unit number (“corner” type, in order tested).

(b) Histograms with the light yield data.

Figure 5.11. Light yield results for the assembled SAS “corner” units. Positions 1, 2 and 3 refer to the irradiation points shown in Figure 5.8.
A strong correlation is seen between the light yield of the three irradiation points for each assembled SAS unit: variations between these points are less than that from unit to unit, i.e. if an element has high light yield for one position, it is expected to remain high for other positions as well. There are no major deviations from the average light yield in any unit, which demonstrates that the gluing and BaSO₄ coating procedure [74] is well standardized and reproducible.

The SAS units were ranked according to their total light yield, obtained by summing the peak channel numbers of the three measurement points. The top 30 units (24 “edge” type and six “corner” type) were selected for flight, while the four remaining ones (three “edge” and one “corner” type) were kept as spares. Since the detector array should be equally well shielded from all sides, the best unit was placed next to the worst one, second best next to second worst, etc. The light yield, when averaged over two adjacent elements, should therefore be close to constant around the circumference of the array. This concept is illustrated in Figure 5.12, where the SAS units are numbered based on their total light yield.

Figure 5.12. The 30 SAS units and their placement around the circumference of the detector array (as seen from the top). Numbers correspond to the “rank” of the SAS elements in terms of the total light yield (red: “edge” type, blue: “corner” type). Units have been arranged such that the “average rank” of each pair is constant.
Chapter 5. Detector performance optimization

5.3 PMT arrangement and voltage settings

A total of 107 photomultiplier tubes were delivered in three separate shipments from Hamamatsu in Japan. These have previously undergone extensive qualification tests [65] and the measurements described here were therefore instead aimed at determining the placement of the tubes within the detector array and a suitable operating voltage\(^4\) for each unit. The tubes were characterized by measuring the position (channel number) of the spontaneous electron emission peak (“single photoelectron peak”) at a given voltage. This signal arises from individual electrons that are thermally emitted from the photo-cathode and go through the amplification chain of the photomultiplier tube, producing an electric pulse [7]. It is the lowest possible “true” signal from a photomultiplier tube (only noise is lower) and it gives rise to the “dark-current” of a tube, i.e. the current that is given off even if the tube is operated in a completely dark environment (typically a few nA [64]). The amplitude of the produced pulse is characteristic of the PMT itself (the electronic gain at a certain supplied voltage) and it can therefore be used to quantify the performance of the tube in a way that is independent of the connected scintillator.

The spectrum of each PMT was recorded with the tube housed in a dark environment without coupling to any scintillator piece. An example of such a spectrum, recorded with a “bare” photomultiplier tube, is presented in Figure 5.13.

![Figure 5.13. Example of a spectrum recorded with a photomultiplier tube only. The broad bump around channel number 20 is the single photoelectron peak (spontaneous electron emission peak), whereas the spike at lower channel numbers is noise.](image)

\(^4\text{The PMTs are powered with }+12 \text{ V and a control voltage of up to }+5 \text{ V. In the DC-DC converter of the tube, this control voltage is amplified by a factor 250. The PMT is thus operated in the range 0–1250 V.}\)
The single photoelectron peak was fitted with a Gaussian curve and the peak position (and thus the gain) as a function of the applied voltage was databased for each photomultiplier tube. Due to the amplification process of the PMT, where multiple dynode stages are used to increase the number of electrons producing the output signal, the PMT gain is expected to follow a power-law with an index of about 7.63 [7, 65]. An example is shown in Figure 5.14.

![Figure 5.14. Single photoelectron peak position (gain) as a function of the applied control voltage for one tested PMT. The data has been fitted with a power-law and the obtained index, ~7.66, is in good agreement with expectations (~7.63) [65]. Error bars are small compared to the point size and have been omitted. A similar behavior is observed for all tested PMTs.](image)

PMTs were sorted based on the control voltage required to produce a single photoelectron peak centered on channel number 25. This number was chosen in accordance with calibration tests carried out in Japan in preparation for the KEK beam tests: a lower required voltage corresponds to a better PMT, i.e. one with a higher intrinsic gain. The following procedure was employed for testing the tubes:

1. The control voltage was initially set to +4.6 V (i.e. +1150 V after DC-DC conversion) and a spectrum of the “bare” PMT was recorded.

2. The position (channel number) of the single photoelectron peak was determined using a Gaussian fit.

3. The voltage was adjusted as needed (increased if position was less than channel 25, otherwise decreased) and the measurement was repeated.

4. Steps 2 & 3 were repeated until a suitable voltage had been found.

5. Steps 1 – 4 were repeated for each photomultiplier tube.
Not all tubes had gain sufficient for the peak to reach channel number 25. These have been listed after the channel number produced when operated at (close to) the maximum allowed control voltage (+5 V). Results are collected in Figure 5.15.

<table>
<thead>
<tr>
<th>Shipment</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21</td>
<td>4.763</td>
<td>0.1198</td>
</tr>
<tr>
<td>2</td>
<td>65</td>
<td>4.499</td>
<td>0.1957</td>
</tr>
<tr>
<td>3</td>
<td>19</td>
<td>4.572</td>
<td>0.1669</td>
</tr>
</tbody>
</table>

Figure 5.15. PMT voltages required for producing peak channel number 25. Several tubes are operated at (close to) the maximum voltage (+5 V).

The peak can also be distinguished when the tube is coupled to a scintillator, as shown in Figure 5.16. PMT performance can thus be monitored in flight, allowing the analysis to be corrected for drifts in gain e.g. due to temperature variations.

(a) Full spectrum with features.  
(b) Zoom-in on the photoelectron peak.

Figure 5.16. Single photoelectron peak for a PMT coupled to a PDC. The peak can be distinguished even when the PDC is irradiated (here with 59.5 keV photons).

\[^5\text{At the time of measurements, the voltages were limited to somewhat lower values due to resistance in the cables feeding the voltage control electronics with +5 V.}\]
In order to produce a uniform sensitivity over the detector array, PMTs were paired to the PDCs and SAS units based on the following procedure:

1. The best 91 PMTs were selected from the 107 available units.

2. The “worst” 30 PMTs were used for the SAS units, pairing the “best” tube with the worst detector, second best with second worst, etc.

3. The best 37 PMTs were used for the inner-most 37 PDC units, pairing the best tube to the worst unit, etc.

4. For the remaining 24 PDCs in the outer detector ring, the pairing procedure was the same, but here based on the light yield of the slow scintillators instead of that from the fast scintillators.

The resulting detector arrangement is shown in Figure 5.17.

Figure 5.17. Optimized arrangement of the PoGOLite detector array (top view).
With the PMTs paired to their respective detector cell, the operating voltages were defined. For the PDCs, the main component is the fast scintillator, which has an energy resolution of about 50\% \cite{55}. The electronics saturate at a fast output channel number of about 2800, as seen e.g. in Figure 5.16(a). Since the PoGO-Lite energy range is specified to extend up to 80 keV \cite{16}, the saturation region should correspond to an energy of about 120 keV, i.e. 80 keV photons recorded with a 50\% energy resolution should produce a signal within the dynamic range of the electronics (1.50 \times 80 \text{keV} = 120 \text{keV}, 120 \text{keV} \Rightarrow \text{channel 2800}). For PMTs coupled to PDC units, the operating voltages were thus chosen such that channel number 2800 corresponds to a 120 keV energy deposition, assuming a linear calibration with 59.5 keV photons. With these settings, photons with energies well above 80 keV may cause a saturation if absorbed. However, as shown in Figure 2.4, such photons are more likely to scatter than to be absorbed, thus causing a trigger. Voltages can also be changed in flight if the amplification is too high or low.

In the SAS units, 511 keV signals from electron-positron annihilations should be visible within the range of the electronics to allow in-flight calibration. For simplicity and aesthetic appeal, SAS PMT voltages were chosen such that 662 keV photons yield a peak close to channel number 662. With a linear calibration, this gives a one-to-one relation between the channel number and the deposited energy. With the current saturation limit (around channel number 2800), this gives an energy range up to almost 3 MeV. This allows cosmic ray muons (minimum ionizing particles, deposit $\sim$2 MeV/cm traversed) to be studied for ascent diagnostics.

The neutron scintillator will be operated at a control voltage of about 3.2 V, which, based on measurements carried out in out in Japan, will ensure that the 5 MeV neutron capture line will clearly be seen in the spectrum (see Chapter 4).

\section{5.4 Threshold levels}

The final step in optimizing the performance of the detector array is fine-tuning the threshold levels. At least two operation modes are foreseen for flight: one “restrictive” and one “permissive”. The restrictive mode has the following properties:

- PDCs only trigger on energy depositions of at least $\sim$15 keV (conservatively chosen such that 25 keV photons which scatter in the detector before being absorbed will cause a trigger).
- SAS units never issue triggers.
- The upper discrimination threshold is set to exclude saturated events.
- The waveform discrimination threshold of the PDC units is set to exclude events from the slow scintillator or bottom BGO crystal.

These settings are expected to maximize the quality of the recorded data by reducing the number of triggers from background events and saturation, thus minimizing the dead-time of the system. In the permissive mode, the following applies:
5.5 Discussion

- SAS units can also issue triggers.
- The upper discrimination threshold is sufficiently high to allow the saturation peak to be recorded in the spectra.
- The waveform discrimination threshold is set to accept all events, i.e. from the PDC slow scintillators and BGO crystals as well.

With these settings, the trigger rate is expected to be significantly higher, producing a larger data volume and increasing the dead-time of the system. However, since the SAS units can trigger the data acquisition as well, this setting can be used to study e.g. anisotropies in the background on different sides of the instrument. Studies of such data is important for ensuring that events included in the analysis are not biased by running in the “restrictive” mode.

5.5 Discussion

The uniformity of the detector array count rate (number of counts in individual cells over a given time interval) is visualized in Figure 5.18, which shows the number of hits in each unit as a function of the detector number in “pseudo-arbitrary units”. These are “arbitrary” in the sense that the actual number itself is not relevant, but “non-arbitrary” because the numbering follows the order the units are connected to the electronics, thus each number can be linked to the corresponding detector element. Gaps in the plot are introduced at numbers 62 and 93 to separate between the PDC units (#1–61), SAS units (#63–92) and the neutron scintillator (#94).

![Figure 5.18. Detector array count rate for a background measurement. Detector number 46, which has a lower number of counts, was here accidentally operated at a slightly lower voltage. For the SAS units, the trigger rate is not equally uniform, since these had not yet been properly calibrated at the time of the test.](image)
A list of PMT voltages and thresholds (trigger, hit, upper discrimination, waveform discrimination and histogram, as described in Section 2.1.3) has been created, which the data acquisition system will read upon initialization. Additional lists could be read to quickly change the mode of operation, e.g. from measuring polarization to studying background. Other operation modes with different threshold settings can be imagined as well. For instance, there could be a “PMT monitoring mode” where the trigger threshold and upper discrimination threshold are set to encompass only a small interval around the expected position of the single photo-electron peak. The peak could then be recorded even in a very short measurement, whereby the gain of the PMTs can be monitored.

Since the time of the original PMT installation (October 2009), four tubes have failed and been replaced. Their locations are indicated in Figure 5.19.

Figure 5.19. Locations of previously faulty PMTs within the detector array. These have subsequently been replaced, restoring full functionality to the array.
Two of these tubes had broken PMT windows and were possibly damaged either when the instrument was transported or as a result of a rapid change in temperature during thermal testing. The remaining two tubes have a failure mode that is currently unknown. One tube of each failure mode has been returned to Hamamatsu in Japan for an investigation which is currently pending.

The broken tubes have subsequently been replaced with four of the spare PMTs with rank 98, 99, 100 and 101. This means that for these units, the pairing no longer matches the original scheme (best PDC coupled to worst PMT, etc.). Although the pairing is different, this can be compensated for by adjusting the corresponding PMT voltages and threshold levels. Figure 5.18, which was obtained with the new photomultiplier tubes already in place, demonstrates that the concept is feasible.

\[ \frac{dT}{dt} < 0.5 \degree C/\text{minute} \]

\[ \text{The temperature gradient } \left| \frac{dT}{dt} \right| < 0.5 \degree C/\text{minute has been confirmed to be safe in the range between } \pm 30 \degree C \text{ [65].} \]
Chapter 6

Characterization of the PoGOLite Pathfinder

The most important pre-flight test of the PoGOLite instrument is of its polarimetric capabilities. To this end, the assembled detector array of the Pathfinder was characterized through measurements with both unpolarized and polarized photon beams.

6.1 Setting up unpolarized and polarized beams

An unpolarized beam (photons with random polarization directions) in the PoGOLite energy range (25–80 keV) is readily available from radioactive sources such as $^{241}$Am, which has a 59.5 keV emission line. To produce a polarized beam, photons from the aforementioned source scattering at a polar angle of 90° can be used, e.g. with a small piece of low atomic number material contained inside a lead block. The unpolarized beam can enter through one hole and exit through another one, which is offset from the first by 90°. If the holes are small, only photons scattering at close to right angles can escape from the block, whereas the remaining ones are absorbed. The assembly thus essentially “selects” photons with a certain scattering angle, which, according to Equation 1.4, corresponds to “selecting” photons with a certain polarization.

For the laboratory measurements, the scatterer used was a piece of plastic scintillator, 5 mm × 5 mm × 5 mm, made of the same material as the fast scintillators in the PDCs. The concept is shown in Figure 6.1, and further detailed in [55, 71]. From this setup, a polarization degree of almost 100% is expected, as demonstrated by Figure 6.2, with a photon energy of about 53.3 keV (see Equation 1.3). Measuring the polarization in this case is therefore in principle equivalent to measuring $M_{100}$ for this setup.
Figure 6.1. Scattering assembly used to create a polarized beam. Photons can enter on one side, scatter at 90° and then exit on another side. The blocks of lead housing the radioactive source and the scatterer have the same dimensions, so if the block with the source is placed in the position of the scatterer (and turned so the opening is facing downwards), an unpolarized beam in the same position is obtained.

Figure 6.2. Polarization degree (modulation factor) as a function of scattering angle for different photon energies [118]. The top curve is applicable for 59.5 keV photons from $^{241}$Am, since such photons deposit about 6.2 keV for a 90° scattering, whereupon the remaining photon energy will be 53.3 keV.
The laboratory measurements were thus based on a mono-energetic beam of 53.3 keV photons with a polarization degree of close to 100%. Emission from an astronomical object is neither mono-energetic, nor likely to be completely polarized. Instead, it follows a spectrum dictated by the nature of the source, e.g., the Crab system. Simulations and beam tests [67] have shown, however, that the modulation for a fully polarized beam, \( M_{100} \), does not vary strongly with energy within the specified range of the instrument, validating the use of mono-energetic photons for this measurement. Furthermore, once the instrument response to fully polarized and fully unpolarized beams is known from measurements or simulations, a data set with an arbitrary polarization degree can be constructed as the sum of these two components, following the procedure described in [41].

6.2 Monte Carlo simulations

Measurements with unpolarized and polarized beams were simulated using a simplified Geant4 model of the detector array, developed from the geometry described in Chapter 4 and utilizing physics lists with photon interactions validated through beam tests\(^1\). The three BGO pieces of the neutron simulation were replaced with fast plastic scintillators, creating a seven-unit detector array (one central scintillator surrounded by a ring of six peripheral units) as shown in Figure 6.3.

\[ \text{Figure 6.3. Wire-frame image of the simulated detector array.} \]

\(^1\)Following the analysis of data from a beam test conducted at the Advanced Photon Source Facility of the Argonne National Laboratory in 2003, members of the PoGOLite collaboration discovered an incorrect implementation of Compton/Rayleigh processes within the Geant4 framework, producing an unphysical polarization (over 100%) [8]. The implementation was corrected, yielding results consistent with measured data, and reported to the Geant4 team.
For simplicity, the slow scintillators and bottom BGO crystals were omitted, since events interacting in these components are discarded during data analysis. Surrounding passive materials were also omitted: due to the symmetry of the array, the relative count rate in the detectors is not expected to change if a passive material of uniform thickness (such as the aluminum cylinder of the pressure vessel) is symmetrically introduced around the geometry.

For simulating the unpolarized case, photons were emitted from a point-source 60 cm from the top of the fast scintillators, aligned above the central unit. This distance corresponds to the length of the slow scintillators, i.e. having the radioactive source placed directly on the face of the detector, as intended for the laboratory measurements. The simulated beam had a cone shape with an opening angle as foreseen from the geometry of the lead shielding of the radioactive source, and was sufficiently large to enclose the entire seven-unit detector array, as shown in Figure 6.4(a). A polarized beam was obtained in the simulation by placing a “scattering scintillator” in the same position above the central unit and irradiating it from the side with initially unpolarized 59.5 keV photons emanating from a point 5 cm from the center of the scatterer. In accordance with the laboratory tests, the scatterer was of the same material as the fast plastic scintillators, and with dimensions 5 mm \times 5 mm \times 5 mm. This situation is shown in Figure 6.4(b). The lead block surrounding the scatterer was omitted, since photons interacting in lead have a high cross-section for absorption and will not reach the detector array.

(a) Simulated unpolarized beam.  
(b) Simulated polarized beam.

Figure 6.4. Simulated geometries for unpolarized (left) and polarized (right) beams. Only one track is shown in the latter case (which, however, misses the geometry), since the tracks otherwise obscure the scattering scintillator.
To double-check the validity of the simulation, the energy deposition in the scattering scintillator was scrutinized. Due to its limited size, only a small fraction of the incident photons interact within the material, whereby they can be either scattered or absorbed. The maximum energy deposition of a 59.5 keV photon is either about 11 keV (when scattering at 180°), or 59.5 keV (in the case of an absorption). For photons to reach the detector array, they must scatter at a polar angle close to 90° in the scatterer. Thus, when requiring a coincidence between a hit in the scattering scintillator and one in the central unit of the detector array, the energy deposition in the scatter is expected to be about 6.2 keV. Simulated spectra shown in Figure 6.5 confirm this behavior.

**Figure 6.5.** Simulated spectra of the scattering scintillator. Top: photons can deposit a maximum energy of about 11 keV (when scattering at 180°) or 59.5 keV (upon absorption). Features are sharp due to the infinite energy resolution of the simulation. Bottom: for photons scattering into the central unit (polar angle around 90°), the energy deposition in the scatterer is close to 6.2 keV. The width of the peak is defined by the solid angle of the detector array as seen from the scattering scintillator (photons scattering at polar angles ~(90 ± 3)° can reach the detector).
For events with exactly two hits in the detector array, the total energy deposition (obtained by summing the values of the two involved detectors) was studied. If the second interaction is a photoelectric absorption, the total deposited energy should amount to the energy of the incident beam: 59.5 keV for the direct photons, or around 53.3 keV for photons scattering at ~90° before reaching the detector array. On the other hand, if the second interaction is also a scattering, the photon has escaped the detector array. For two consecutive scatterings, the maximum energy deposition of a 59.5 keV photon is about 18.9 keV, as can be seen by invoking Equation 1.3 twice (for the initial and for the scattered photon) with a scattering angle of 180°.

A two-dimensional histogram with the energy deposition in the central unit and the total energy deposition for events with exactly two hits in the detector array is shown in Figure 6.6.

![Figure 6.6. Simulated central and total energy deposition of two-hit events for an unpolarized (direct) beam. Due to the infinite energy resolution of the simulation, absorbed photons always deposit exactly 59.5 keV. For clarity, only a fraction of the events included in the analysis are shown. The plot is similar for the simulation with polarized photons, but with the total energy deposition shifted to around 53.3 keV, since some energy is lost in the scattering scintillator.](image)

The total energy deposition of photons interacting in two detector cells, obtained by projecting events in Figure 6.6 onto the ordinate, is presented in Figure 6.7. This plot allows the Compton region and the photoabsorption peak to be clearly distinguished.
6.2. Monte Carlo simulations

Figure 6.7. Simulated total energy deposition of two-hit events for an unpolarized (direct) beam. Two bumps can be seen below 20 keV, from photons scattering once or twice at angles close to 180°. The peak at the far end is from events where the second interaction is an absorption. For the simulation with polarized photons, the plot is similar, but with the total energy deposition shifted to around 53.3 keV, since some energy is lost in the scattering scintillator.

Polarization events were selected by requiring a low energy deposition in the central unit (scattering) and a high in one of the six peripheral units (absorption). For such events, hits in each of the peripheral units from photons that are first scattered in the central unit were counted. Since spatial resolution within a detector cell is not achievable in an actual measurement, center-to-center scatterings were assumed for the simulation. The possible scattering angles were thus restricted to 0°, 60°, 120°, 180°, 240° and 300°, as shown in Figure 6.8.

Figure 6.8. Definition of scattering angles in the simulation. Photons are assumed to scatter center-to-center, thus limiting the possible angles to six discrete cases.
Results with the number of counts as a function of the scattering angle can be seen in Figure 6.9 and Figure 6.10 for the unpolarized and polarized simulations, respectively. In the latter, data points have been fitted with a sinusoidal curve

\[ p_0 \left\{ 1 + p_1 \cos \left[ \frac{\pi}{180} (2x + 2p_2) \right] \right\} \]  

where \( x \) is the scattering angle and \( p_0, p_1 \) and \( p_2 \) are fitting parameters. A factor two has been included due to the \( 180^\circ \) symmetry of the Compton scattering.

**Figure 6.9.** Simulated modulation for the setup with an unpolarized beam. The ordinate has been truncated to show error bars more clearly. Data points show no significant deviation from the mean value (dashed line), as expected.

**Figure 6.10.** Simulated modulation for the setup with a polarized beam. Data points have been fitted with a sinusoidal curve. Anisotropy in the scattering angles is clearly seen, as expected for a polarized beam.
For the unpolarized setup, no overall modulation is seen in the simulation. This is expected, since all scattering angles within the detector array should be equally probable if the incident photons have random polarization.

For the polarized case, modulation factor of \((23.5 \pm 2.2)\%\) was observed. Assuming a 100% polarization, this also corresponds to \(M_{100}\) for the setup. The polarization angle (phase of the sinusoidal fit, parameter \(p_2\) in Equation 6.1) consistent with \(0^\circ\) (towards unit 1 in Figure 6.8). This is in accordance with expectations, since photons have a higher probability of scattering in directions perpendicular to the polarization of the incident radiation, which will be in the “east-west” direction in Figure 6.8. In comparison, simulations of \(M_{100}\) for a Crab spectrum have yielded the value \((27.8 \pm 0.5)\%\) [41]. It is noted, however, that this value was obtained with parallel beams irradiating the entire detector array instead of with the configuration used here, with a cone of beams incident over a seven-unit detector array.

6.3 Laboratory measurements

For the measurement of an unpolarized beam, the instrument was irradiated with direct 59.5 keV photons from \(^{241}\text{Am}\). Ideally, the entire face of the detector should be exposed to a uniform flux of photons, mimicking an in-flight observation of a distant unpolarized source with parallel beams incident on the detector cells. With only one radioactive source, such a configuration is not achievable, since a source placed at a sufficient distance to produce “parallel” beams would give a very low count rate in the detector array. Instead, a single detector cell was irradiated with a collimated beam from the source. In this case, most of the remaining units will only record background. Thus, in order to increase the signal-to-noise ratio, only one group of seven PMTs was powered: a “central” unit and the six surrounding ones. For simplicity, a region of the detector with seven units connected to one single FADC board was chosen, namely the group labeled as “FADC 2” in Figure 2.24, with the beam irradiating PDC number 26.

Voltages and thresholds were chosen as defined in Chapter 5. Since the photons from the source have a known energy, the detector cells could be properly calibrated\(^2\), which was done by fitting the 59.5 keV photoabsorption peak with a Gaussian curve in order to determine its position. Assuming a linear calibration, the peak channel number gives a conversion factor between the channel number (pulse amplitude) of the electronics and the energy deposited in the scintillator material.

Once all seven detectors had been calibrated, the central unit was irradiated. Examples of calibrated spectra from this measurement are shown in Figure 6.11.

\(^2\)Since in-flight calibration is impossible, the energy reconstruction for flight is based on ground calibrations. Ultimately, however, the limiting factor is the poor energy resolution of the plastic scintillators, not the calibration, which has a small uncertainty in comparison.
(a) The central detector is directly irradiated by the beam and a photoabsorption peak around 59.5 keV can be seen.

(b) For the peripheral cells, photons scattering from the central unit are seen and the peak is shifted to lower values.

Figure 6.11. Calibrated spectra for the central unit (top) and one peripheral unit (bottom). The “step” below 20 keV is caused by the trigger threshold. Entries below this level result from read-outs being triggered by a different detector than the one plotted. The feature above 120 keV is from saturation in the electronics.
Events where exactly two detector cells had been triggered by fast scintillator hits were extracted using Equation 2.5. In order to validate the calibration, the sum of the two energy depositions was plotted. If the detectors are properly calibrated, this sum should amount to 59.5 keV for photons interactions that are fully contained within the detector array. The resulting spectrum was fitted with a Gaussian curve for the signal and a linear plus an exponential curve for the background:

\[
p_0 \cdot e^{-\frac{1}{2} \left( \frac{x-p_4}{p_2} \right)^2} + p_3 + p_4x + p_5e^{-\frac{x-p_6}{p_7}}
\]  

(6.2)

where \( x \) is the energy and \( p_0 \) through \( p_7 \) indicate fitting parameters. The spectrum and the fit, which peaks at an energy of (59.1 ± 0.2) keV, are presented in Figure 6.12. Since events from all powered detectors are included in this plot, the result is a strong test of the calibration of each individual detector: if a unit is incorrectly calibrated, the peak would be shifted from the expected value, 59.5 keV.

**Figure 6.12.** Measured total energy deposition spectrum for two-hit events. Dashed lines indicate the “Signal” and “Background” components of Equation 6.2, whereas the solid line is the sum of the two. The bump around 20 keV is part of the Compton continuum, truncated by the trigger threshold, which causes the “step” in the low-energy end of the spectrum.

For two-hit events, the lowest energy deposition was selected as the scattering site and the highest was assumed to be due to a photoabsorption. Plotting a two-dimensional histogram with the energy deposition in the central unit and the total energy deposition produced a result as shown in Figure 6.13.
Several regions of interest can be seen here:

1. These events have a low energy deposition in the central detector cell as well as a low total energy deposition and thus correspond to photons that scatter once within the instrument array, but subsequently escape instead of being absorbed.

2. This region contains events from cosmic rays hitting the peripheral scintillators and from background present in the lab (low energy deposition in the central unit but high total energy deposition).

3. Photons scattering in the central unit (low energy deposition) and undergoing absorption in one of the peripheral units (total energy deposition consistent with the energy of the incident photon beam) produce an event within this region. These are the events of interest.

The analysis is complicated by the fact that the regions are partially overlapping. Events with a low energy deposition in the scattering unit may be difficult to distinguish from the noise region and to ensure that the event in the central unit is indeed a scattering and not just noise, region #2 was excluded from the analysis by requiring an energy deposition of at least 3.5 keV in the central unit. An upper limit of 20 keV was also used for the the central detector cell to exclude events from photons are absorbed in that unit.
For the total energy deposition of the two-hit events, the position of the photoabsorption peak, hereafter referred to as the “centroid”, was at $(59.1 \pm 0.2)$ keV (as obtained from the Gaussian fit presented in Figure 6.12). Due to the limited energy resolution of the plastic scintillators, events within $\pm 15$ keV of the centroid were included in the analysis.

In order to select events from region #3, two additional selection criteria were introduced:

\[
\text{“Total”} > [1.5 \times \text{“Central”} + \text{“Centroid”} - 30\text{keV}] \quad (6.3)
\]

and

\[
\text{“Total”} < [-1.5 \times \text{“Central”} + \text{“Centroid”} + 30\text{keV}] \quad (6.4)
\]

where “Central” and “Total” are the central and total energy deposition, respectively, and “Centroid” is the position of the photoabsorption peak in the total energy deposition spectrum.

The selection region derived from the above criteria is shown in Figure 6.14. The size of the region is conservatively chosen to be sufficiently large to ensure that polarization events are included even with the poor energy resolution of the plastic scintillators. Since the individual detector cells had been successfully calibrated, the exact shape of the region has limited effect on the selected events and will thus not bias the data.

![Figure 6.14.](image)

**Figure 6.14.** Selection region used for identifying polarization events. Points within the acceptance are from photons that scatter in the central unit and undergo absorption in one of the peripheral units.

Results from the measurement with an unpolarized beam, along with the chosen selection region, are shown in Figure 6.15.
Figure 6.15. Energy deposition in the scattering unit and total energy deposition for the measurement with an unpolarized beam. Entries within the marked region are identified as “polarization events”, i.e. photons that scatter in the central unit and are absorbed in one of the peripheral units. For clarity, only a fraction of the events included in the analysis are shown.

Scattering angles were determined for events within the selection region, producing the results presented in Figure 6.16.

Figure 6.16. Measured modulation for the setup with an unpolarized beam. The mean value has been indicated by a dashed line.
The result shows significant differences between the count rates of the six peripheral units. Since the beam from the source is unpolarized, the observed anisotropy, which is not seen in the simulation, implies that the behavior of the detector array is not entirely uniform, despite the calibration procedure. An anisotropy can arise if detector cells are slightly offset from their position in the detector array. Even small offsets within the mechanical tolerances of the components may be sufficient. To study this, simulations with the seven-unit detector array irradiated by unpolarized photons were repeated, but with the central unit translated by 1 mm from the geometric center of the array. The anisotropy obtained for the simulation with the central unit shifted by 1 mm in the $0^\circ$ direction (see Figure 6.8) is shown in Figure 6.17. Results for shifts in other directions are summarized in Appendix A.

![Graph](image)

**Figure 6.17.** Simulated anisotropy obtained with the central unit shifted by 1 mm. The dashed horizontal line indicates the mean number of counts.

The anisotropy is assumed to be rectified by rotating the instrument (or, equivalently, the radioactive source), whereby systematic effects such as detector offsets are averaged out. To confirm this, the source was rotated one full revolution in $15^\circ$ steps, and the above measurement was repeated for each step.

For each rotation angle, the number of scatterings from the central unit into one peripheral detector was counted. Instead of plotting the number of counts in different detectors cells as a function of the scattering angles, this number can be presented as a function of the rotation angle of the instrument (or the radioactive source). If the instrument is rotated relative to a fixed polarization direction (or vice versa), a modulation is expected in the count rate of the peripheral detectors. Since the modulation has a $180^\circ$ symmetry, count rates in two opposing detectors can be
pairwise averaged, further reducing systematic differences between the units. Results from the 24 measurements (0° ⇒ 345° in 15° steps) can be seen in Figure 6.18. The average modulation is found to be as low as (0.6 ± 0.3)%, demonstrating how the systematic effects are effectively reduced through this rotation.

![Figure 6.18](image-url)

**Figure 6.18.** Counts as a function of rotation angle for the measurement with an unpolarized beam. Results have been averaged for opposing detectors due to the 180° symmetry of the Compton scattering process. The uncertainty in the angles is estimated to about ±5°. Data points have been fitted with curves as given by Equation 6.1. Some points have a conspicuous grouping (particularly those at 45° and 240°), which could be due to a slight misalignment for those measurements.

During these measurements, the instrument was in a vertical position (pointing to zenith) and thus, rotating the source is expected to be equivalent to rotating the detector array itself. For a configuration where the instrument is instead horizontal or at some intermediate angle, these two situations need not be the same, since the flux of cosmic rays is higher from zenith than from directions close to the horizon, in which case the background rejection efficiency on different sides of the instrument may cause an anisotropy in the measurement. In flight, the instrument will not be vertical, but rather change its elevation as it tracks an object moving across the sky. Furthermore, if the instrument is not perfectly aligned mechanically, the rotation may cause a “precession” of the viewing axis around the axis of rotation. A properly configured rotation is therefore crucial for flight, whereas rotating the radioactive source is sufficient for the laboratory measurements described here.

For the tests with a polarized beam, the previously mentioned group of seven detector cells was used again. In this case, the analysis procedure described above produced a modulation curve as shown in Figure 6.19.
Figure 6.19. Measured modulation for the setup with a polarized beam. Data points have been fitted with a sinusoidal curve. Taking the pairwise average of entries offset by 180° improves the fit (without affecting the modulation) but removes information about individual differences between the detectors.

The observed modulation factor, \( (22.8 \pm 1.3)\% \), is consistent with that obtained in the simulation, \( (23.5 \pm 2.2)\% \). It is also in good agreement with similar tests previously carried out at the Stanford Linear Accelerator Center (SLAC) [55], which exhibited a modulation factors of \( (24.5 \pm 3.9)\% \).

This result shows how polarization can be measured in a laboratory environment using a photon beam with known energy. Assuming, in accordance with Figure 6.2, that the beam has a polarization degree of close to 100%, the obtained modulation factor is approximately equal to \( M_{100} \). Once the parameter \( M_{100} \) is known, the polarization of an observed source can be evaluated, even if the beam energy is not precisely known, as will be described next.

6.4 “Flight-like” analysis

While the simulations and laboratory measurements described here are useful for testing the polarimetric capabilities of the detector array, they are strongly simplified compared to the situation in flight: a beam with a known energy has been used, only one detector cell has been directly irradiated, only a small fraction of the detector cells have been powered, etc. For flight data, a selection such as the one

\[ \chi^2 \text{/ ndf} = 28.38 / 3 \]
\[ p_0 = 2066 \pm 18.56 \]
\[ p_1 = 0.2282 \pm 0.0318 \]
\[ p_2 = -4.307 \pm 1.511 \]

\[^3\]These tests were carried out with a prototype detector consisting of one full PDC surrounded by six units with fast scintillators only. Although the present measurement was with the full 61-unit instrument, only seven units were powered, making these two configurations very similar.
demonstrated in Figure 6.15 is not possible, since the energy of the incident photons is not known a priori. A “general” analysis procedure has therefore been developed, which does not require any prior information about the observed photons, nor does it make any assumptions regarding the positions of different interactions: any detector cell can act both as a scatterer and as an absorber.

The analysis program developed for this purpose reads all waveforms belonging to one trigger at the time. If any of the waveforms are from a SAS unit or from a PDC unit but with a pulse shape inconsistent with a clean hit in a fast scintillator, a “veto flag” is issued. For the polarization analysis, only events without veto flags and with exactly two valid detector hits are considered. The procedure is repeated until the end of the data file is reached. A plot is produced, showing the coordinates of the triggered events, i.e. how the events are distributed over the detector array. Since there is no spatial resolution within a detector element, hits are randomly distributed over the area corresponding to the size of one cell. An example of such a plot can be seen in Figure 6.20.

![Detector Coordinates](image.png)

**Figure 6.20.** Plot showing coordinates of detector hits for a measurement with an unpolarized beam irradiating the central unit. A higher concentration of events can be seen close to the center of the detector array than compared to the background level near the edges. Points in the lower left corner of the figure are from the neutron scintillator. While not physically located at those coordinates, these events are displayed here, so they can be visualized in the same plot. For programming reasons, SAS units are shown as hexagonal, although they are in reality pentagonal.

---

4 A majority of the events interact in one or two detector cells. Simulations have shown that modulation can reliably be reconstructed when including three-hit events as well (the lowest energy deposition is assumed to be a photon scattering at a small angle and thus not changing its direction notably). Less than 20% of the events interact in more than three detector cells [119].
6.4. “Flight-like” analysis

To identify units with unusually high or low activity, caused e.g. by an incorrectly set trigger threshold or photomultiplier tube control voltage, a plot is produced showing the number of hits in the different detector cells in “pseudo-arbitrary units”, as discussed in Chapter 5 and exemplified in Figure 5.18.

The program can either consider coincidences between any two detectors (SAS units and neutron scintillator excluded) or only between adjacent cells. Each PDC has three, four or six “neighbors”, depending on its location in the array. The program uses look-up tables to identify the neighbors of a triggered unit and determine if the second interaction is within one of those neighbors.

Once a valid polarization event is found (two hits in two fast scintillators, within neighboring units if requested), the program calculates the scattering angle, based on the randomized coordinates within the triggered detector cells. The angle is counted in the clockwise direction (as seen from the top), with 0° towards PDC “Hirotaka”, which corresponds to the “three o’clock” position in these plots. If desired, the scatterings can be indicated in the plot showing the detector hit coordinates and an example of this is given in Figure 6.21.

![Figure 6.21. Scattering events in the detector array. Photons are incident on the central unit and scatter into adjacent cells. Some chance coincidence events are visible outside the irradiated region. With an excessive number of events included, these plots become cluttered with black lines, losing their usefulness, and the user can therefore choose to suppress the drawing of these lines if needed.](image)

The program also produces a data output with the calculated azimuthal angles of all valid scattering events, along with the rotation angle of the instrument at the time of the trigger.\(^5\) A separate program then reads the calculated (relative)

\(^5\)Since the attitude control system and rotation encoder which provide the position angle of the instrument at any given time were not present when these measurements were first carried out, the program has an option where the user can input the angle to be written to the output file (the current rotation of the source).
scattering angle as well as the current rotation angle of the instrument, and plots the absolute scattering angle, with respect to to some fixed direction, which could be taken as the line of the horizon, the zenith direction or any other suitable reference. This concludes the polarization analysis of “flight-like” data, apart from the timing analysis (e.g. checking if a recorded event is “on-pulse” or “off-pulse” relative to the Crab rotation) and the pointing analysis (i.e. if the instrument is really pointing at the intended source at the time an event was recorded). Such analyses are beyond the scope of this discussion and will be presented elsewhere.

In flight, the bandwidth available for downloading scientific data will vary significantly depending on the location of the payload at a given moment. As long as the instrument has line-of-sight to the Esrange ballooning facility in Kiruna in northern Sweden, the high-bandwidth “E-Link” communications system\(^6\) can be utilized. When the payload moves far away from Esrange and the antenna on the ground drops below the horizon, communications will be constrained to systems providing much more limited bandwidth, such as the satellite-based Iridium network\(^7\).

In flight, scientific data is expected to be recorded at a rate which is on the order of 1 gigabyte per hour. The analyses described up to now are suitable for laboratory measurements (where the data is immediately accessible upon completion of a measurement) and for flight-circumstances where a high bandwidth connection is available (in which case most of the data can be downloaded with little delay). For situations when the bandwidth is limited, a “quick-look” study has been developed. Instead of downloading complete waveforms of all photomultiplier tubes (50 waveform sample points plus event headers, multiplied by the number of triggered channels in each event, multiplied by the number of events in a measurement), data containing only waveform peak values can be downloaded. For each recorded waveform, the peak value (highest channel number within the sampled range) is separately histogrammed. Since the peak values are not sampled but only counted in the histogram, the data size is independent of the number of stored events and the length of the data acquisition run. The histogram entries only constitutes a few kilobytes of data and can easily be downloaded even with a limited bandwidth.

Histograms are stored every few seconds. Once this data has been downloaded, a program reads the values and produces a $12 \times 8$ plot with the recorded spectra. Such a plot, an example of which is shown in Figure 6.22, can be used e.g. to quickly identify units with unusually high or low activity. For a laboratory measurement where one cell is irradiated by photons from a radioactive source, the corresponding plot should have characteristic spectral features (photoabsorption peak, Compton continuum), whereas in flight, all detectors should behave similarly, since the flux is expected to be uniform over the face of the detector if the instrument is directly aimed at the source of interest.

\(^6\)The Esrange Airborne Data-Link (E-Link) \([120]\) is a long-range (up to 400 km) radio-based Ethernet system with a high bandwidth (2 Mbit/s in full duplex).

\(^7\)Using a network of satellites, the Iridium system can provide about 1–2 kbit/s bandwidth (depending on the signal strength, data compression, etc.) through a dedicated transceiver \([121]\).
Figure 6.22. Example of a $12 \times 8$ plot with histogram data. The sharp features are from saturation, as shown in Figure 4.9. Four spectra are empty since only 92 channels are used (61 PDCs, 30 SAS units, 1 neutron scintillator). The four bottom rows are spectra from the SAS units and therefore have a somewhat different shape. Finally, the neutron scintillator spectrum is seen in the bottom right corner.
The data acquisition software also separately stores “rate files”, which are simple text outputs where each line shows the current measurement time as well as the number of written events, triggers, upper discrimination signals and waveform discrimination signals. There is one rate file where such lines are continuously appended and one “quick-look” rate file, which is overwritten and only contains the most recent line of information. As an even more bandwidth-conserving approach, these files can be downloaded instead of the full waveforms, or even the histogram data. The quick-look rate file is only a few tens of bytes and can be downloaded frequently to provide “pseudo-real-time” information to show, for instance, if the instrument is pointing on or off-source. The complete rate files can be used to trace back what was happening in the measurement at a given time, e.g. how the background rate varies as the instrument is changing its elevation or rotation.

6.5 Strong background

In order to test the background rejection capabilities of the instrument, the detector array was simultaneously irradiated from the top with 59.5 keV photons from $^{241}$Am (“signal”) and from the side by 662 keV photons from $^{137}$Cs (“background”) as shown in Figure 6.23. Photons from the side were incident at the height of the fast scintillators, which is where the instrument is most “vulnerable”, since photons hitting any other part (slow scintillator or bottom BGO crystal) are vetoed.

Figure 6.23. Irradiation points for the “signal” (59.5 keV photons from the top) and “background” (662 keV photons from the side).
Scattering directions as calculated by the program for this measurement are presented in Figure 6.24. As can be seen, the contamination from the strong background is immediately reduced by requiring the two interaction sites to be in adjacent detector cells.

Figure 6.24. Scattering events recorded in a strong gamma-ray background. When all two-hit interactions are included, many coincidences appear between photons from the top (“signal”) and from the side (“background”). By selecting only interactions with hits in adjacent cells, background-induced scatterings are suppressed and true polarization events of photons irradiating from the top can be distinguished.
The trigger rate (number of accepted events per second) of this measurement was about \(6.5 \text{ s}^{-1}\), approximately twice as high as that expected in flight, which is estimated from simulations to around \(3.29 \text{ s}^{-1}\) (1.52 s\(^{-1}\) from source and 1.77 s\(^{-1}\) due to background) \([41]\) for an observation of the Crab system – the strongest persistent source on the sky in the energy range of the PoGOLite instrument. Even in this enhanced rate, the absorption peak of 59.5 keV photons can still be clearly distinguished, as shown in Figure 6.25, thus demonstrating that the anticoincidence system and event selection procedure are efficient in reducing the background to manageable levels.

![Figure 6.25. Photoabsorption peak in a measurement with strong background. The “step” around channel number 300 is caused by the trigger threshold, which truncates the Compton continuum region.](#)

### 6.6 Thermal characterization

Operating the instrument at float altitude (\(\sim40\) km) is vastly different from running in a controlled laboratory environment. Flight conditions are also much more dynamic than measurements on the ground, and the temperature of the instrument can drastically change, for example depending on how the polarimeter is oriented relative to the sun or how long the instrument spends in different atmospheric layers with varying temperatures during the ascent (see Figure 6.26).
6.6. Thermal characterization

Although the temperature of the photomultiplier tubes is monitored and can be actively reduced through the cooling loop, there is no way to heat or cool the PDCs and SAS elements themselves. Since the detector array has been calibrated at room temperature, it is important to evaluate how the light yield will change as the detector array cools down in flight so this can be compensated for if needed. This topic will briefly be expanded upon here.

The detector array can be thought of as consisting of four different parts: the fast scintillators, slow scintillators, BGO crystals (in the PDCs as well as in the SAS segments) and the photomultiplier tubes. Each of these can have characteristics with a different dependence of the temperature. To study these effects, the performance of the components was compared when operating at room temperature and at $-35 \, ^\circ C$. At flight altitude, an ambient temperature of around $0 \, ^\circ C$ is
testing at $-35 \, ^\circ C$ thus corresponds to a “worst case scenario”, e.g. if the ascent through the colder atmospheric layers takes longer than expected, whereby the instrument can cool down to low temperatures.

For testing the temperature dependence of the photomultiplier tube gain, the single photoelectron peak position was used. The procedure used for determining the position was the same as described in Section 5.3, and changes in gain were quantized as the ratio between the peak position (channel number) at low temperature and that at room temperature. An example of these results is presented in Figure 6.27.

![Figure 6.27](image)

**Figure 6.27.** Example of PMT cooling test results. The single photoelectron peak is here shifted from $14.6 \pm 0.1$ to $17.4 \pm 0.1$ when exposed to a low temperature (around $-35 \, ^\circ C$) in a freezer, corresponding to an increase of about 19%. The noise rate (counts in the lowest channel numbers) is also found to decrease significantly.

On average, for the PMTs studied during a thermal test where the entire instrument was cooled to around $-35 \, ^\circ C$, the gain increased by about 20% at the lower temperature, with a somewhat greater increase towards the edge of the detector array. This is thought to be due to the lower temperature expected further out from the center. Results are summarized in Table 6.1. It is again noted that the single photoelectron peak (and thus the gain) is characteristic of the photomultiplier tube only, and therefore independent of the scintillator coupled to the tube.
6.6. Thermal characterization

<table>
<thead>
<tr>
<th>Detector section</th>
<th>Relative change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring 1</td>
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</tr>
<tr>
<td>Ring 2</td>
<td>+19.6%</td>
</tr>
<tr>
<td>Ring 3</td>
<td>+22.9%</td>
</tr>
<tr>
<td>Ring 4</td>
<td>+22.3%</td>
</tr>
<tr>
<td>Overall</td>
<td>+21.3%</td>
</tr>
</tbody>
</table>

**Table 6.1.** Relative change in PMT amplification at around −35 °C compared to room temperature for different regions of the detector array.

The phoswich detector cell components were studied using a spare PDC and PMT at room temperature and at about −35 °C. In accordance with the previously described characterization tests, different radioactive sources were used here: $^{241}$Am, $^{90}$Sr and $^{137}$Cs for the fast scintillator, slow scintillator and BGO crystal, respectively.

Figure 6.28 shows spectra of the fast scintillator for the two different temperatures, obtained by selecting events from the fast branch only. Plots showing the original two-dimensional histograms where this selection was applied are presented in Appendix B, Figure B.1.

![Figure 6.28](image-url)

**Figure 6.28.** Fast scintillator spectra of $^{241}$Am at two different temperatures. The feature around channel number 300 is caused by 59.5 keV photons from the source.
Although the spectral feature is subtle (a weak and uncollimated source was used for testing and the PDC was a spare, i.e. with a somewhat lower light yield than the ones in the detector array), its position is seen to remain unshifted between the measurements (the two spectra in the plot are overlapping), thus demonstrating that the light yield of the fast scintillator does not change significantly from room temperature to $-35$ °C, in agreement with specifications for the scintillating material in question$^8$.

Spectra for the test with electrons from $^{90}$Sr irradiating the slow scintillator, obtained when selecting events from the slow branch only by using Equation 2.6, are presented in Figure 6.29. Corresponding two-dimensional histograms can be found in Appendix B, Figure B.2.

![Figure 6.29. Slow scintillator spectra of $^{90}$Sr at two different temperatures. One bump is seen, caused by electrons from the source.](image)

The bump is here shifted from $769.8 \pm 1.8$ (Gaussian fit) to $564.2 \pm 2.1$ at low temperatures, implying a decrease in slow scintillator light yield of about 27%. This does not agree with expectations$^9$, but is not believed to reduce the vetoing capability of the detector array considerably, since charged particles will deposit enough energy to be detected even with a lower light yield, and photons will be stopped by the passive collimation of the lead and tin foils surrounding the PDCs.

Finally, irradiating the bottom BGO crystal with 662 keV photons from $^{137}$Cs produced the two-dimensional histograms shown in Figure 6.30.

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$^8$The product data sheet claims “No change [in light output] from +20 °C to -60 °C” [60].

$^9$The product data sheet of this scintillating material also claims “No change [in light output] from +20 °C to -60 °C” [59].
6.6. Thermal characterization

Figure 6.30. Thermal test spectra with $^{137}$Cs irradiating a bottom BGO crystal. 
Top: room temperature. Bottom: $-35$ °C. The slope of the slow branch steepens at low temperatures, and the events extend to higher channel numbers.

The steeper slow branch at low temperatures implies that the scintillation decay time increases as the temperature decreases. This behavior is expected [123] and favorable, since it enhances the separation between the fast and the slow branch, allowing events from the fast scintillator to be more clearly distinguished. The absolute light yield also increases as the BGO is cooled, which can clearly be seen by selecting events from the slow branch$^{10}$ and projecting them onto the slow output (ordinate of Figure 6.30). This result is presented in Figure 6.31.

$^{10}$Due to the steepening, the selection has here been modified to include all events above the lower blue line of Figure 6.30, instead of only accepting events between the two oblique lines.
Using a Gaussian fit, the first peak was found to be shifted from $540.5 \pm 0.7$ to $774.8 \pm 1.3$, i.e. an increase in light yield of about 43%, while the position of the second peak changed from $1203.6 \pm 1.0$ to $2053.2 \pm 3.0$, corresponding to a 71% increase. A detailed study regarding the light yield of the PoGOLite bottom BGO crystals and their temperature dependence can be found in [41].

Effects of the electronics temperature on the recorded data have also been studied. Comparing results from tests where the entire instrument (detectors as well as electronics) was cooled and a setup where only the detector (PDC and PMT) were held at low temperature ($-35 ^\circ C$) demonstrated that the shift in the single photoelectron peak position was the same in both cases, about 20%, thus confirming that the change arises from the PMT temperature only. The temperature of the electronics boards themselves is thus not expected to change the amplitude of the recorded PMT pulses notably.

The measurements discussed here show that most aspects of the detector array performance improve when the instrument is in a low temperature environment. The light yield of the fast scintillator does not change significantly, which means that calibrations and voltage settings used for laboratory measurements are equally well-suited for flight conditions.

![Bottom BGO spectra of $^{137}$Cs at two different temperatures. The first peak is 662 keV photons from the source, while the second one is caused by 1461 keV photons from $^{40}$K (see Section 3.5). Both peaks are shifted considerably as the scintillator is cooled down.](image-url)
6.7 Discussion

The assembled detector array of the PoGOLite Pathfinder has been tested in the laboratory using unpolarized and polarized beams and results have been compared with Geant4 Monte Carlo simulations based on a simplified detector geometry.

For the setup with unpolarized photons irradiating the detector, no anisotropy in the azimuthal scattering angles is expected, as was confirmed through simulations. This is not what was seen in the measurements, and additional simulations with the central unit shifted by 1 mm from the geometric center of the detector demonstrated that the observed anisotropy could be due to offsets in the positions of the detector cells within the mechanical tolerances. However, by rotating the detector array, as will be done in flight, systematic effects can be averaged out, and in this case, a modulation as low as $(0.6 \pm 0.3)\%$ could be recovered.

In the measurement with a polarized beam, a modulation factor of $(22.8 \pm 1.3)\%$ was observed, consistent with the value from the simulation, $(23.5 \pm 2.2)\%$, demonstrating the polarimetric capabilities of the instrument. Since the polarization degree in the measurement is expected to be close to 100\%, this result also corresponds to $M_{100}$ of the setup.

Software for analyzing flight data has been developed. The program identifies valid polarization events and determines their scattering angles. It is also suitable for visualizing the distribution of detector hits, as well as for evaluating the detector performance. Currently, the only feature known to be missing from this software is the timing analysis. In flight, triggered events will be tagged with a time-stamp from the attitude control system (ACS). Since the instrument was not integrated to the ACS at the time of testing, this feature has not yet been implemented.

Since the instrument has been tested and calibrated mostly at room temperature, its behavior has been carefully studied to temperatures down to about $-35$ °C, with findings as briefly summarized below.

**Photomultiplier tube:** an increase in the single photoelectron peak channel of about 20\% is noted, along with a decrease in the noise level. This should make low-energy Compton scattering events easier to distinguish, which is important for maintaining the lower bound on the PoGOLite energy range.

**Fast scintillator:** essentially no change in light yield is observed at low temperatures.

**Slow scintillator:** a decrease of about 27\% is observed in the one case studied here, even though no change is expected based on data from the manufacturer. Tests could be carried out with an isolated slow scintillator (not integrated into a PDC, i.e. read out directly, not through a fast scintillator and BGO piece) to fully characterize the effect, which, however, is not expected to impede the performance of the instrument notably, since the slow scintillator is only used for event rejection and not for calorimetry. Charged particles can still be detected due to their high energy deposition and photons within the
energy range of the instrument can still be absorbed in the passive collimation lead and tin foils of the individual detector cells.

**BGO crystal:** exhibits, as expected, a significant enhancement both in the scintillation decay time and in the absolute light yield, which improves the performance of the pulse shape discrimination technique since the separation between the fast and the slow branch is increased, and also allows lower energy depositions to be detected. These results are assumed to apply to the BGO crystals both in the phoswich detector cells and the side anticoincidence shield units.

**Electronics boards:** show little or no effect on the recorded PMT signals when at low temperature.

In conclusion, every aspect of the detector array improves to some extent at low temperatures, with the sole exception of the slow scintillator light yield, which was found to decrease in this measurement. The behavior of a PDC coupled to a PMT is essentially unchanged in terms of the performance of the fast scintillator. For the slow scintillator, the light yield may be somewhat reduced, but not enough to change the background rejection capabilities. Finally, although the BGO changes its behavior when cooled, it does so in a favorable way. Therefore, the calibration tests and performance evaluation studies presented here are assumed to maintain their validity even at the low ambient temperatures the payload will be subjected to in flight. The temperatures of the detector units and photomultiplier tubes will be monitored and logged in-flight, allowing corrections to be applied in the off-line analysis if needed.

Apart from the scientific capabilities of the instrument, the mechanical integrity at low temperatures has also been studied. In a two-day thermal vacuum test carried out at the SAAB Aerospace facility in Linköping, Sweden, in June-July 2010, the complete polarimeter assembly and associated electronics were exposed to low pressure (~20 mbar) and temperatures as low as −50 °C. The climate chamber with the various hardware components of the PoGOLite Pathfinder inside is shown in Figure 6.32. During this test, a number of mechanical shortcomings were identified, such as a leak in the pressure vessel at very low temperatures and problems with the instrument rotation caused by the bearing assembly grease becoming highly viscous when cooled. These issues were addressed and subsequently confirmed as resolved during a second thermal test, carried out at Innventia in Kista, Sweden, in December 2010. The hardware configuration in this test is shown in Figure 6.33.
Figure 6.32. Thermal vacuum test of the polarimeter and associated electronics.

Figure 6.33. Polarimeter configuration during the second thermal test.
Chapter 7

Summary and outlook

The 61-unit PoGOLite Pathfinder is currently being prepared for its maiden voyage. Integration with the attitude control system and pointing tests will be carried out during the first quarter of 2011. The assembled system will then be shipped to Esrange to be integrated with the gondola structure and outer frame. The launch window is currently end-June to mid-July 2011, defined by wind conditions at the float altitude and by the angular separation on the sky between the sun and objects of interest.

As discussed in Chapter 1, numerous types of astronomical objects are of interest for polarimetric studies in the X-ray and gamma-ray band. On the northern hemisphere, the most prominent ones are the Crab (a pulsar and nebula system) and Cygnus X-1 (an X-ray binary system). Both of these will be studied during the maiden-flight of PoGOLite.

Based on observations with the Chandra X-Ray Observatory, the position angle of the Crab system spin axis (measured north through east) has been calculated to be about 124°–126° [39]. Models of the nebula predict synchrotron emission in the X-ray band from high-energy electrons trapped in a magnetic torus around the pulsar [124]. If this model is valid, the polarization angle of the X-ray emission is expected to be parallel to the spin axis of the Crab system [16]. However, an instrument on-board the OSO-8 satellite measured the polarization angle to be (156.36 ± 1.44)% at 2.6 keV and (152.59 ± 4.04)% at 5.2 keV with a polarization degree of about 19% [33], i.e. the polarization angle was found to be shifted by about 30° from the spin axis predicted from the Chandra observations.

Assuming, in accordance with the OSO-8 measurements, a 19% polarization in the PoGOLite energy range (25–80 keV), the Pathfinder instrument is expected to be able to measure the polarization degree from the Crab nebula with a 7σ significance and the polarization angle with a precision of about 5° even in a six-hour flight. Results from a simulated observation of the Crab nebula with the PoGOLite Pathfinder are shown in Figure 7.1.
Chapter 7. Summary and outlook

Figure 7.1. Simulated six-hour observation of the Crab nebula with the PoGOLite Pathfinder [108]. A 19% polarization degree has been assumed and the P1 and P2 pulses of the Crab pulsar (see Figure 1.7) have been excluded. The atmospheric overburden is assumed to be 5 g/cm², which is consistent with a six-hour observation during a flight from the North of Sweden.

Such a measurement will not only test whether the polarization degree remains constant with energy, but also determine if the polarization angle aligns with the spin axis of the system at higher energies, thus testing the paradigm that the observed X-ray emission from the Crab system is caused by synchrotron radiation from high-energy electrons trapped in toroidal magnetic structures around the Crab pulsar.

For Cygnus X–1 in the hard spectral state, the PoGOLite Pathfinder instrument is expected to be able to measure as low as 10% polarization, which enables the predicted energy dependence of the polarization to be tested against measurements [20].

Several different flight configurations are possible for the instrument:

**Short-duration flight:** launched in a “turnaround” period when there is almost no wind at the expected float altitude. This permits a short (~24–48 h) flight where the instrument can be recovered in close proximity to the launch site. Such a mission would focus mainly on observing the Crab and Cygnus X–1, as well as to study the in-flight background.

**Long-duration flight:** can be carried out when the winds at float altitude are in the westward direction, whereby a balloon launched from northern Sweden can travel over Greenland and land in western Canada. Such a flight provides about five full days of measurement time, which would give better statistics and also allow temporal variations in the observed sources to be studied.
Circumnavigation: a possibility where, instead of terminating the flight over Canada, the payload is allowed to return over Russia for a landing back in Sweden. These flights are expected to take about 20 days and would allow several sources of interest to be studied, including possible “targets of opportunity” such as transient events detected by the Fermi Gamma-ray Space Telescope [17] or Swift [125, 126].

The flight in mid-2011 is foreseen to be a circumnavigation. Since the instrument is designed to withstand the landing impact, it can be re-used. Flights on the southern hemisphere are also possible, where other sources are visible, such as Scorpius X-1, a low-mass X-ray binary system in the Scorpius constellation [41], which is the strongest low-energy X-ray source in the sky apart from the sun.

Once the Pathfinder project has come to a conclusion, focus will be shifted to this full-scale instrument, PoGOLite-217 (see Figure 7.2), which will be able to observe polarization from more sources than the Pathfinder, and obtain results with improved statistical significance.

![Figure 7.2. Sketch of the 217-unit PoGOLite detector array. For clarity, only part of the side anticoincidence system is shown.](image)

To achieve the required performance, the PoGOLite instrument must have good background rejection capabilities, both active (side and bottom anticoincidence, active collimation) and passive (polyethylene neutron shield, passive collimation from lead and tin foils). A total of 187 BGO crystals for the side anticoincidence shield have been received, which is sufficient for the (217-unit) full-size instrument. The testing of these has been a crucial step to assure the performance of the anticoincidence system. All crystals meet the requirements, both in terms of energy resolution, linear dimensions and relative light yield.
Photon-based beam tests are important for understanding the performance of the instrument and to calibrate simulation models. Several of these tests have been carried out to date, each one probing new aspects of the instrument, such as new hardware, active vetoing with a segment of the side anticoincidence shield and multiple site events. The successful tests have clearly demonstrated how the Compton scattering technique can be used to measure polarization. They are also useful for developing data analysis algorithms for the eventual analysis of flight data.

In-flight background from atmospheric neutrons can be an issue in ballooning missions and the development of a suitable neutron shield is a design challenge due to the trade-off between weight and shielding efficiency [58]. Geant4 simulations demonstrated that the neutron background can be reduced to a manageable level using a polyethylene shield with a thickness of 10 cm on the sides of the instrument and 15 cm in the bottom. To validate these results, a neutron-based beam test was carried out, and the simulations thereof have been an important step towards realizing a flight-ready instrument. The agreement between measurements and simulations shows that the treatment of neutron-based interactions in Geant4 is reliable, which demonstrates that the neutron background levels will become manageable with the introduction of this shield. The flux of atmospheric neutrons is poorly known and will be measured in flight using a dedicated detector.

For a segmented detector such as PoGOLite, where individual cells have been assembled by hand, intrinsic differences between detector elements are always present to some extent. Optimizing the detector arrangement in terms of the placement of individual units as well as their operational parameters (voltages and threshold levels) is therefore important for maximizing the detector performance.

Laboratory measurements with radioactive sources and Geant4 Monte Carlo simulations have been used to evaluate the capabilities of the instrument. A clear modulation has been observed for polarized beams. For an unpolarized beam, it is shown that the instrument rotation is successful in reducing the residual modulation essentially to the zero level, allowing even low source polarization degrees to be measured.

Software for analyzing flight data has been developed and tested with data recorded in laboratory tests. Thermal characterization tests have also been conducted and indicate that the instrument should behave similarly at float altitude as compared to in the laboratory environment. Where low-temperature effects exist, they are mostly favorable, e.g. the change in BGO light yield and the separation between events in the fast and slow branch, which both improve at low temperatures.

The characterization of the PoGOLite instrument on both component-level (detector cells and photomultiplier tubes) and in the assembled detector (laboratory tests and photon beam tests) along with simulations should provide a good understanding of the system and allow the design goals to be reached, hopefully already during the maiden-flight, expected to take place in mid-2011.
Appendix A

Detector-offset anisotropies

Figure A.1. Simulation with the central unit unshifted. Top: direction of shift and relative changes in count rates. Bottom: counts as a function of the scattering angle. The dashed horizontal line indicates the mean number of counts.
Figure A.2. Simulated anisotropy for an unpolarized beam arising from a shift in the central unit by 1 mm in the $0^\circ$ direction (a realistic value within the mechanical tolerances of the components). Top: direction of shift and relative changes in count rates. Bottom: counts as a function of the scattering angle. The dashed horizontal line indicates the mean number of counts.
Figure A.3. Simulated anisotropy for an unpolarized beam arising from a shift in the central unit by 1 mm in the $180^\circ$ direction (a realistic value within the mechanical tolerances of the components). Top: direction of shift and relative changes in count rates. Bottom: counts as a function of the scattering angle. The dashed horizontal line indicates the mean number of counts.
Figure A.4. Simulated anisotropy for an unpolarized beam arising from a shift in the central unit by 1 mm in the 90° direction (a realistic value within the mechanical tolerances of the components). Top: direction of shift and relative changes in count rates. Bottom: counts as a function of the scattering angle. The dashed horizontal line indicates the mean number of counts.
Figure A.5. Simulated anisotropy for an unpolarized beam arising from a shift in the central unit by 1 mm in the $270^\circ$ direction (a realistic value within the mechanical tolerances of the components). Top: direction of shift and relative changes in count rates. Bottom: counts as a function of the scattering angle. The dashed horizontal line indicates the mean number of counts.
Appendix B

Thermal test spectra

Figure B.1. Thermal test spectra with $^{241}$Am irradiating a PDC fast scintillator. Top: room temperature. Bottom: $-35 \, ^\circ C$. Events in the fast branch (red lines) remain unaffected while the slow branch, populated by background events, steepens.
Figure B.2. Thermal test spectra with $^{90}$Sr irradiating a PDC slow scintillator. Top: room temperature. Bottom: $-35$ $^\circ$C. A large contamination (events outside the two branch regions) is seen from the high event rate, but the slope of the slow branch (events from the slow scintillator, indicated by blue lines) remains unaffected.
Figure B.3. Thermal test spectra with $^{137}$Cs irradiating a bottom BGO crystal. Top: room temperature. Bottom: $-35$ °C. The slope of the slow branch steepens at low temperatures, and the events extend to higher channel numbers, reflecting the increase in light yield.
Figure B.4. Thermal test spectra showing a SAS unit background measurement. Top: room temperature. Bottom: −35 °C. The slope of the slow branch (blue lines) steepens at low temperatures, i.e. the scintillation decay time increases. The fast branch is unpopulated, since the SAS unit comprises BGO crystals only.
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Working together with everyone at DST Control and SSC Esrange and following the development of the PoGOLite hardware has been very rewarding. I look forward to returning to Esrange in a few months for enjoying the launch. And the lunch! (The best lunch in Sweden is conveniently served 100 m from the balloon launch pad...)

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