Background Studies for the Balloon-Borne Hard X-ray Polarimeter PoGOLite

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Cover illustration: The PoGOLino launch on March 20th 2013 (left) and the PoGO-Lite launch on July 12th 2013 (right). Credit: Mark Pearce (left figure) and SSC (right figure).

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Abstract

The polarisation degree and angle of the X-ray flux emitted by astrophysical objects holds valuable information on the responsible emission mechanisms and on the emission environments. PoGOLite is a balloon-borne hard X-ray polarimeter designed to measure polarisation using a segmented plastic scintillator array. The instrument was launched for its first scientific, near-circumpolar, flight in July 2013 from the Esrange Space Centre in Northern Sweden. The primary observation target for this flight, the Crab, was observed during the first 2 days of flight.

One of the main challenges for PoGOLite is the relatively high measurement background, predicted to be induced by atmospheric neutrons. No measurement data on the neutron environment for the flight conditions of PoGOLite is however available, making exact predictions impossible. This environment was therefore studied in detail. A Monte Carlo based model of the atmospheric neutron flux was developed. This model is capable of providing differential neutron energy spectra for all altitudes, latitudes and solar activities. The predictions of this model were found to be in good agreement both with measurement data, measured by high altitude aircraft, and with predictions by location and time specific models. The results from the model were verified with data recorded by a purpose-build balloon-borne neutron detector, PoGOLino. The PoGOLino instrument uses novel neutron sensitive LiCAF scintillators sandwiched between BGO crystals which serve as an anti-coincidence system. PoGOLino was launched from the Esrange Space Centre to an altitude of 31 km on March 20th 2013 and performed the first successful measurements of the neutron flux for the PoGOLite flight conditions.

Using the developed model the background as measured by the PoGOLite mission in 2013 was studied. Monte Carlo simulations were used to confirm that the PoGOLite background during flight is dominated by neutrons. The simulated neutron induced signal rate and its variations with time were furthermore found to be in good agreement with measurements. Based on these results the implications of the background on the polarisation measurements of the Crab were studied. Lastly, based on the acquired knowledge of the background, changes to the instrument geometry for potential future flight of PoGOLite were studied along with the expected achievable improvement in performance for such flights.
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Preface

Outline

Polarimetry is a relatively unexplored field of high energy astrophysics. The polarisation degree and angle of photons with energies in the X-ray energy range, which extends from $\sim 1$ keV to 100’s of keV, hold information on the mechanisms responsible for the emission of the photon and the environments in which the photons were emitted. Polarimetry is therefore a powerful tool to study high energy astrophysical environments. Despite the wealth of information which can be extracted from polarimetry measurements few have been performed successfully thus far. A first reason for the lack of measurement data is the relatively low efficiency for polarimetry measurements with respect to, for example, spectral, spatial and flux measurements. The low signal rate in combination with the environment in which the measurements have to be performed forms a second reason for the current lack of data. Absorption of high energy photons by the atmosphere requires the measurements to be performed high up in the Earth’s atmosphere, on high altitude balloons, or above the atmosphere on satellites. This first of all results in a high cost for instrumentation and secondly in a relatively low signal-to-background ratio.

The work presented in this thesis focusses on the measurement background encountered by the X-ray polarimeter PoGOLite at stratospheric altitudes. This background, induced by atmospheric radiation, is one of the major challenges for balloon-borne X-ray polarimeters. The background environment was studied using data from the flight of PoGOLite and from data acquired using a purpose build experiment called PoGOLino. The data from these flights was compared to Monte Carlo based predictions of the atmospheric radiation environment. Lastly the implications of the background environment on the measurement capabilities of the PoGOLite instrument are discussed and future improvements are discussed.

The thesis will start with an overview of the field of X-ray polarisation. This includes an overview of the scientific goals of X-ray polarimetry along with the measurement techniques employed by different experiments. In chapter 2 a detailed description of the PoGOLite payload, as flown during the 2013 flight, will be presented together with an overview of that flight. Chapter 3 presents a Monte Carlo based model of the atmospheric neutron environment. Chapter 4 presents the
balloon-borne PoGOLino experiment, which during its flight in March 2013, provided data on the atmospheric neutron conditions at the flight latitude of PoGOLite. The results of chapter 3 and 4 were used to simulate the background encountered by the PoGOLite instrument during its 2013 campaign. This will be presented in chapter 5 along with a comparison with the flight results. Chapter 6 will provide simulation based suggestions to improve the signal-to-background ratio for future flights.

Author’s contribution

The work presented in this thesis was conducted as part of the PoGOLite Collaboration. In this section I detail my specific contributions. After starting my PhD on PoGOLite in May 2010, the first few months were spent on several hardware related tasks which included work on the PoGOLite cooling system, the polyethylene shield, one of the star trackers and sealing of the pressure vessels. Cancellation of the maiden flight of PoGOLite in the summer of 2010\(^1\) resulted in a shift of the work towards flight planning. Whereas the 2010 flight was foreseen to be a so called turn-around flight, which has a duration of \(\sim 24\) hours, there was a possibility to fly circumpolar in 2011. I investigated the scientific interest of such a flight by looking into interesting X-ray sources and writing a program which calculated the position of the sources and the Sun on the sky. Using this program the position on the gondola with the least solar radiation for the radiator of the cooling system was calculated and an observation plan for the 2011 flight was made. Besides this, work on the polarimeter hardware continued. The instrument was taken apart in order to implement improvements and the polyethylene shield was put into place. After finalisation of the instrument I contributed to setting up the on-board computers and to the physics tests of the polarimeter. I was furthermore involved in the tests of the attitude control system after the instrument was moved to DST Control in Linköping. Apart from tests of the attitude control system, my time during the period at DST Control was spent working on the mechanical integration of the polarimeter and the attitude control system. This work continued after moving the combined system to the Esrange Space Centre. Besides work on the hardware I expanded the before mentioned flight planning program to make it integrable within the PoGOLite software system. Lastly I was the main responsible for tests with the aim of determining the timing accuracy for X-ray interactions within the polarimeter during the summer of 2011. The results of this test are presented in this thesis.

Damage to the balloon sustained during launch on July 6th 2011 meant that the flight was terminated prematurely and that no scientific data was acquired. However, instrument functionality and background induced count rates could be extracted. I analysed the counting rates and started work on background simulations for comparison with the measured data and for the preparation for future

\(^1\)Due to a failed balloon launch in Australia all scheduled flights using NASA hardware were grounded.
flights. In order to make a better prediction more detailed information on the neutron background was required. For this purpose I started, together with a Bachelors student, to simulate the neutron flux as a function of altitude and latitude. I then compared the results from these simulations with the measured event rates from the 2011 flight. This work resulted in the conclusion that the high event rate measured during the 2011 flight was partly a result of an underestimation of the neutron flux in the polar regions. All the above mentioned work formed the basis for my licentiate thesis.

Work on the atmospheric background was continued through 2012 and 2013 and finally resulted in the results presented in chapter 3 of this thesis and in a paper accepted for publication in Astroparticle Physics. The maiden scientific flight was postponed for a third time during the summer of 2012 due to bad weather conditions. A spin-off experiment called PoGOLino was started after the cancelled flight and resulted in a balloon flight in March 2013. I was the main responsible for the PoGOLino project and was personally involved in every aspect of the instrument, ranging from mechanical design and construction to the flight analysis. The PoGOLino project is presented in chapter 4 of this thesis. The development and measurement results of PoGOLite are furthermore the subject of a paper accepted for publication in NIM A.

Aside from the PoGOLino project, work on PoGOLite continued. This included calibration measurements performed together with other members of the collaboration, and verification of these measurements using simulation software. An investigation into optical cross talk was performed. Optical cross talk has significant implications on the instrument performance and will therefore be discussed in chapter 2 of this thesis.

The maiden scientific flight of the PoGOLite experiment took place during the summer of 2013. As during all previous flight campaigns, I took part in the flight preparation. After the successful launch I was furthermore part of one of the 3 teams which performed data taking during the flight. After flight I chose to continue work on instrument calibration and background analysis instead of working on the flight analysis. The PoGOLite flight data presented in this thesis was therefore not a product of analysis by the author. The data, provided by other members of the collaboration, was compared with background simulations, the results of this are presented in chapter 5. It should be noted here that the simulation software and the software responsible for the analysis of the simulation data were partly developed by another member of the Collaboration. Lastly, the knowledge acquired during instrument calibration and flight simulations was used to provide design changes which would improve the signal to background of the instrument for future flights, these results are presented in chapter 6.

It should lastly be mentioned that I took part in the work for the proposal of a hard X-ray satellite-borne polarimeter called SPHiNX. This instrument is designed to measure the polarisation of Gamma Ray Bursts. For this proposal I was mainly involved in the estimation of the background for the instrument during its polar orbit and extrapolating the predictions of the background rates to the scientific
potential of such an instrument. The SPHiNX mission was not selected for the small Swedish satellite program by the Swedish National Space Board. The background studies, which can be of use for potential future proposals for similar polarimeters, will be part of a publication which is currently in preparation.

PoGOLite Collaboration

During my PhD studies the PoGOLite Collaboration has included significant contributions from the following persons:

- From KTH Royal Institute of Technology: Mark Pearce (PI), Maxime Chauvin, Miranda Jackson, Cecilia Marini Bettolo, Mózsi Kiss, Merlin Kole, Victor Mikhalev, Elena Moretti, Stefan Rydström
- From Hiroshima University: Takafumi Kawano, Tsunefumi Mizuno, Hiromitsu Takahashi
- From University of Tokyo: Tune Kamae
- From Stockholm University: Hans-Gustav Florén, Göran Olofsson
  David Shifrin (Central Aerological Observatory) and Anatoli Iyudin (Moscow State University) played an important role in the flight planning and recovery of PoGOLite in 2014.

Publications

- H. Takahashi et al., *Data acquisition system and ground calibration of polarized gamma-ray observer (PoGOLite)*, Conf. Proc. SPIE 2014,
Chapter 1

X-ray Polarimetry

For photons in the X- and gamma-ray energy range polarimetry is a relatively unexplored and upcoming field. Three of the measurable parameters of a photon flux, the spectrum, the intensity and the time of arrival, have been measured in great detail, both over wide energy ranges and from a large number of sources. The two remaining parameters of photon fluxes, the polarisation angle and degree, from most of these sources remain however unknown. Information can be extracted from the polarisation degree and angle on the emission mechanism and therefore on the environments in which the fluxes were emitted. These environments range from objects such as black hole binaries and pulsars, to gamma ray bursts and solar flares. This chapter provides a brief overview of the field of X- and gamma-ray polarimetry, starting with a description of the different mechanisms responsible for creating polarised X- and gamma-rays. This is followed by a description of different astronomical sources with an emphasis on the Crab pulsar, Cygnus-X1 and GRS-1915 the main observation targets of PoGOLite. Finally different detection mechanisms together with past, current and future polarimeters which make use of these techniques will be presented.

1.1 Polarisation Processes

The polarisation of a photon is defined as the orientation of the electric field vector within the plane perpendicular to the momentum vector. This orientation can be constant in time or it can rotate around the momentum axis. The former case is called linear polarisation, the latter circular or elliptical polarisation. The polarisation of a photon can be parametrised using the Stokes parameters, the four of which together form the Stokes vector [1]. The four parameters are defined as follows.
Chapter 1. X-ray Polarimetry

\[ S_0 = E_1^2 + E_2^2, \]  
\[ S_1 = E_1^2 - E_2^2, \]  
\[ S_2 = 2\sqrt{E_1 E_2} \cos \delta, \]  
\[ S_3 = 2\sqrt{E_1 E_2} \sin \delta. \]  

Here \( E_1 \) and \( E_2 \) are the two orthogonal components of the electric field vector and \( \delta \) is the phase difference between the two. For a 100% linearly polarised photon flux \( \delta = 0 \), the polarisation angle is then defined by the ratio between \( E_1 \) and \( E_2 \). When \( \sin \delta = 1 \) the flux is circularly polarised, for \( 0 < \sin \delta < 1 \) the polarisation is elliptical. Only linear polarisation can be measured using current X-ray polarimetry techniques. Therefore circular and elliptical polarisation will not be considered in this thesis and linear polarisation will from here on simply be referred to as polarisation.

Each individual photon is 100% polarised. Therefore the polarisation degree as discussed in this thesis refers to the polarisation of the photon flux, defined as the relative number of photons polarised in the same direction within a given photon flux. A non-polarised flux consists of a population of photons with a randomly distributed electric field vector orientation, whereas a 100% polarised photon flux refers to a population within which all photons have the same polarisation angle. In this section the most important physical processes involved in the production of polarised X-rays will be introduced.

1.1.1 Compton Scattering

In the Compton scattering process an incoming photon is scattered off an electron which can be considered to be at rest. The differential cross section for the process is given by the Klein-Nishina formula \([2]\) presented in equation 1.5.

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

Here \( r_0^2 \) is the classical electron radius, \( E \) is the initial photon energy, \( E' \) the final photon energy, \( \theta \) the polar scattering angle and \( \phi \) the azimuthal scattering angle with respect to the polarisation vector. This is visualised in figure 1.1. The \( \cos^2 \phi \) term in the Klein-Nishina formula results in a polarisation dependent cross section and a higher probability for scattering perpendicular to the polarisation vector. For a polarised photon flux Compton scattering on a target this results in a non-uniform distribution of the azimuthal scattering angles. However, the inverse is also true, a polarised flux can be created from an unpolarised beam scattering at large azimuthal angles. Compton scattering can thus increase the polarisation of an unpolarised beam and reduce that of a polarised beam. Since the \( \cos^2 \phi \) term is multiplied by \( \sin^2 \theta \) the modulating effect is strongest for large polar scattering angles \( \theta \). For example, as a result of the \( \theta \) dependence, a non-polarised beam can
1.1. Polarisation Processes

Figure 1.1: Schematic representation of the Compton scattering process. The incoming photon (blue; energy $E$, polarisation $\vec{p}$) scatters off an electron with a polar angle $\theta$ from its original trajectory. $\phi$ is the angle between the polarisation vector of the incoming photon and the azimuthal scattering angle $\eta$.

be made $\approx 100\%$ polarised by Compton scattering this beam and selecting the component scattered by a polar angle of $90^\circ$.

In the inverse Compton scattering process the photon is at low energy whilst the electron or positron is highly energetic. The dependencies of the scattering angles on the polarisation vector of the photons are the same as for normal Compton scattering.

1.1.2 Bremsstrahlung

Bremsstrahlung is the emission of photons from charged particles accelerated in the electric fields of ions. The emitted energy is inversely proportional to the mass of the particle, most radiation therefore originates from electrons or positrons. However for certain systems with high densities of protons, like the Sun, the bremsstrahlung component originating from protons can become significant.

The bremsstrahlung process occurs naturally in hot gases and in cosmic ray induced air showers in the Earth’s atmosphere. In the presence of a magnetic field or in case of a constant flow direction of the emitting particles the photon flux will be polarised. If the emitting medium is also optically thin at the photon energy of interest the radiation can be detected by an observer. Polarisation degrees as high as $80\%$ are predicted for this process [3].
1.1.3 Cyclotron Emission

Non-relativistic charged particles accelerated in a magnetic field emit cyclotron radiation [3]. As in the case of bremsstrahlung the emitted energy is inversely proportional to the mass of the emitting particle, therefore cyclotron radiation is most significant when emitted by electrons and positrons. The distribution of the photon emission has a dipole shape with a maximum pointed along the electron momentum vector, this is illustrated in figure 1.2. The majority of the photons are therefore emitted in the direction perpendicular to the electron acceleration vector. The polarisation vector of the emitted photons will be in the plane spanned by the acceleration and momentum vector of the electrons. The result is that the polarisation degree varies with the viewing angle of the observer. The maximum polarisation degree will be observed when looking at the source from a direction perpendicular to the magnetic field.

![Diagram showing the dipole profile emitted by an electron accelerated in the direction $\vec{a}$ for the case of cyclotron radiation. The emitted photons are polarised in a direction, $\vec{p}$ within the plane spanned by the momentum $\vec{v}$ and acceleration vector $\vec{a}$ of the electron.](image)

Figure 1.2: Diagram showing the dipole profile emitted by an electron accelerated in the direction $\vec{a}$ for the case of cyclotron radiation. The emitted photons are polarised in a direction, $\vec{p}$ within the plane spanned by the momentum $\vec{v}$ and acceleration vector $\vec{a}$ of the electron.

1.1.4 Synchrotron Radiation

Synchrotron emission is similar to cyclotron emission, however, for this mechanism the emitting particles are relativistic. Due to the relativistic velocities of the emitting particles the angular distribution of photon emission is beamed in the forward direction for this process, resulting in an emission profile as shown in figure 1.3. The energy of the photon emission here is higher than for cyclotron emission which generally does not exceed 100 keV. The energy spectrum is correlated to that of the electrons which, for many astrophysical sources, can be approximated by a power law, resulting in a power law function for the photons. The polarisation degree, $\Pi$ of the photons can then be correlated to the electron power law index $\alpha$ with [3]:

$$\Pi \propto \alpha$$
\[ \Pi = \frac{\alpha + 1}{\alpha + 7/3}. \] (1.6)

For electron power law spectra with \( \alpha = 4 \), \( \Pi \) can be as high as 80%.

Figure 1.3: Diagram showing the dipole profile emitted by an electron accelerated in the direction \( \mathbf{a} \) for the case of synchrotron radiation. Again the emitted photons are polarised in a direction within the plane spanned by the momentum and acceleration vector of the electron.

### 1.1.5 Curvature Radiation

Along with synchrotron radiation, curvature radiation is emitted when a particle moves within a strongly curved magnetic field. For magnetic systems where the curvature radius is comparable to the orbital radius of the particle around the magnetic field lines, the gyroradius, the fraction of the emission coming from curvature radiation will become significant. When the curvature and gyroradius are equal the intensity resulting from this process is higher than the intensity of the synchrotron radiation by a factor of \( \gamma \) (the Lorentz factor of the electron) [3]. Curvature radiation is therefore the dominant emission mechanism for strongly curved magnetic fields. The field orientation causes the photons to be polarised parallel to the magnetic field, this is illustrated in figure 1.4.

### 1.2 Sources

#### 1.2.1 Pulsars

After the gravitational force which keeps a star together exceeds the radiation pressure the star collapses. If the mass of the star exceeds \( \approx 20 \) solar masses, the
Figure 1.4: A schematic illustration of cyclotron/synchrotron radiation on the left and curvature radiation on the right. An electron moves along a magnetic field line, B. For cyclotron radiation the acceleration is perpendicular to both the magnetic field line and the momentum of the electron. The polarisation vector lies in the plane spanned by the momentum and the acceleration vector of the electron, this plane is shown in blue. For curvature radiation the momentum is parallel to the field while the acceleration is perpendicular to the field line, the polarisation again lies in the field spanned by these two vectors and is therefore parallel to the field line.

collapse results in a black hole. For lower masses, above \( \approx 8 \) solar masses, gravitational collapse into a black hole is stopped by the degenerate electron pressure governed by the Pauli Exclusion Principle; in this case the collapse results in a neutron star. The Crab system contains such a neutron star which is the primary observation target for PoGOLite. Neutron stars have a typical radius of \( \sim 10 \text{ km} \) and inherit angular momentum from their much larger progenitor, resulting in a very short rotation period, varying from several milliseconds to seconds. The neutron star in the Crab system has a rotational period of 33 ms. Neutron stars with a misalignment between the magnetic field axis and its rotational axis are called pulsars. The misalignment of the fields causes two beams of out-flowing matter from the magnetic poles, called jets, to orbit the rotation axis. Due to the neutron stars rotation this causes the star to appear pulsating for a distant observer.

Crab Nebula

The neutron star in the Crab system is a pulsar. The pulsar is surrounded by a an expanding gas cloud, called the nebula. An X-ray image of the system is shown, together with images taken in the optical and in the infrared, in figure 1.5. The nebula emits at wavelengths from the radio regime up to and including gamma-rays as shown in figure 1.7. The radiation from the nebula dominates the pulsar
1.2. Sources

<table>
<thead>
<tr>
<th>Energy band</th>
<th>Polarisation degree</th>
<th>Polarisation angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical</td>
<td>(19.0)%</td>
<td>(162)°</td>
</tr>
<tr>
<td>2.6 keV</td>
<td>(19.2 ± 1.0)%</td>
<td>(156.4 ± 1.4)°</td>
</tr>
<tr>
<td>5.2 keV</td>
<td>(19.5 ± 2.8)%</td>
<td>(152.6 ± 4.0)°</td>
</tr>
</tbody>
</table>

Table 1.1: The Measured polarisation angles of the Crab nebula for optical and X-ray energy ranges.

emission in the X-ray regime. For this reason measurements of the Crab pulsar in the X-ray regime with a low spatial resolution will have a significant background coming from the nebula. The X-ray emission from the nebula has been measured to be polarised in the optical [4] and soft X-ray energy bands [5]. A summary of the measurements is provided in table 1.1. It should be noted here that the nebula is significantly larger in optical than in the X-ray regime as can be seen in figure 1.5. The measurement from [4] quoted here is the polarisation of the central region (0’.486 radius) of the nebula coinciding with the X-ray emitting region of the nebula. In the X-ray regime a first polarimetric measurement of the Crab nebula was performed with a detector on a sounding rocket flight in 1972 [8]. A more significant measurement with the dedicated polarimeter OSO-8 (Orbital Solar Observatory 8) in 1976 resulted in measured polarisation degrees at 2.6 keV and 5.2 keV of (19.2 ± 1.0)% and (19.5 ± 2.8)% respectively [5] [9]. The polarisation angles at these two energies were measured to be (156.4 ± 1.4)° at 2.6 keV and (152.4 ± 4.0)° at 5.2 keV. For these measurements only the off-pulse fraction of the pulsar profile, as shown in figure 1.6, was used thereby removing the contribution from the pulsar. These measurements were performed using the Bragg scattering principle which uses the interference between scattered X-rays from different layers in a scattering crystal. As a result such measurements can only be performed at discrete energies. The OSO-8 results date from the 70’s, however, to date they are the only significant polarisation measurements of the Crab system in the soft X-ray regime. Based on these measurements, which show an energy independent polarisation up to the hard X-ray regime, and the emission spectrum the process responsible for the emission is thought to be synchrotron radiation [5].

Crab Pulsar

Due to the high magnetic fields, the relativistic rotation speed of the field lines and the strong gravitational fields, modelling the emission from pulsars is complex. Three classes of models for the emission of X-rays exist for pulsars, the polar cap model, the outer gap model and the caustic model. The predictions of these models on the X-ray intensity as a function of the pulsar phase do not vary significantly, the predictions on the X-ray polarisation degrees and angles are, however, very different for the three models. This makes a measurement of these parameters important for further development of these models.
Figure 1.5: On the left an overlay of the Crab system measured in optical by the Hubble space telescope with the X-ray image as measured by the Chandra telescope and the infrared image as measured by the Spitzer Space Telescope. The right shows the X-ray image alone as measured by the Chandra telescope. Reproduced from [11].

Figure 1.6: Illustration of the different time intervals of the pulsar profile. The period during which the nebula dominates is referred to as the off-pulse fraction, followed by the first emission peak, P1, the interpulse fraction and the second peak, P2.

In the polar cap model, electrons travelling near the poles emit curvature radiation in the presence of the strongly curved magnetic field. Interactions of the curvature radiation with the magnetic field results in an electromagnetic cascade. The particles created in this cascade produce synchrotron radiation which can be observed near Earth. For the Crab pulsar this model predicts a constant polarisation during the rotational period of around 80%. However, data from the Fermi Gamma-ray Telescope on the spectral shape [12] disfavours the polar cap model for the Crab pulsar based on the model prediction for high energy $\gamma$ emission. The
1.2. Sources

Figure 1.7: Spectrum of the radiation from Crab Nebula. The total spectrum is shown with the solid line, at high energies the emission from synchrotron and inverse-Compton emission are shown with dashed and dotted lines respectively. Measured data points from different detectors are shown with points. Reproduced from [10] with permission.

In the outer gap model, particles are accelerated in the gap between the closed and open field lines far away from the magnetic poles as illustrated in figure 1.8. Here they emit both curvature and inverse Compton radiation. Similar to the polar cap model, photon-photon interactions result in an electromagnetic cascade. However, the final state X-rays are a product of synchrotron emission and inverse Compton scattering. In this model the polarisation varies with time during the rotation period. The last model, the caustic emission model, is a combination of the first two models. Here the emission takes place around the last open field lines. The polarisation again varies with time, however, differently from the outer gap model. Figure 1.9 shows the predictions of the three different models for the Crab pulsar [13]. The predicted intensity of the flux can be seen to be very similar for the different models. However, the predictions on the polarisation differ greatly. Several
polarisation measurements of the Crab pulsar have been performed at different photon energies. An overview of these follows.

Figure 1.8: A schematic illustration of the three different pulsar acceleration models. The associated emission regions are shown: polar cap, outer gap and the slot gap which is associated to the caustic model. Reproduced from [14].

Optical Polarisation

The optical part of the emission from the pulsar was measured to be polarised [15]. These measurements in the optical region were performed using the OPTIMA (Optical TIMing Analyzer) instrument. The degree and angle of polarisation were found to vary with the pulsar rotation phase. The measured intensity, polarisation degree and polarisation angle are shown in figure 1.10. The rapidly changing polarisation angle around the peaks indicates that the emission is produced at different altitudes over the surface of the pulsar and appears to agree best with the predictions by the caustic model or the outer gap model shown in figure 1.9. However, none of the 3 models can fully explain the polarisation behaviour observed in the optical regime. The rapidly changing polarisation angle in the optical part of the spectrum illustrates a requirement not only for a precision in polarisation angle but also for a precise time tagging of the events. Using a poor timing resolution the
rapid rotation of the angle will be smeared out resulting in a false measurement of a low polarisation degree.

**High Energy Polarisation**

Two different detectors on the INTEGRAL mission have measured the polarisation of the Crab system in different energy ranges. Both detectors, however, are not dedicated polarimeters but could be used as such due to their segmented designs. The IBIS [6] instrument measured the Crab in the 200 – 800 keV range. A high polarisation degree of > 72% was observed for the off-pulse fraction. When including the inter-pulse fraction the degree was measured to be > 88%. During the peaks the degree was measured to be low, this could however be an effect of a rapid change in the polarisation angle. The polarisation angle in the off-peak fraction was found to be $(120.6 \pm 8.5)^\circ$ when adding the inter-pulse region the polarisation angle was found to be $(122 \pm 7.7)^\circ$.

The polarisation of photons with energies between 100 keV and 1 MeV was measured by the SPI instrument on board the INTEGRAL mission [16]. The polarisation degree in the off-pulse fraction in this energy range was found to be $(46 \pm 10)\%$ at an angle of $(123.0 \pm 11)^\circ$. This polarisation angle is consistent with the IBIS measurements. Later studies, which use an updated analysis method, resulted in pulsar phase averaged polarisation degrees of $28\% \pm 6\%$, $32\% \pm 7\%$ and $32\% \pm 8\%$ for the energy ranges $130 – 440$ keV, $130 – 650$ keV and $130 – 1000$ keV respectively. The polarisation angle was found to be at $(117 \pm 9)^\circ$ for all the energy ranges [17]. It should be noted here that, due to the computationally demanding analysis method applied here, only a small part of the available data was used to acquire these results. More precise measurements can therefore be expected to appear in the future [18].

The results presented here lack the high timing precision needed to distinguish between the emission models. For this reason several hard X-ray polarimeters are currently being prepared, most of these have the Crab as one of their primary targets. Two of these detectors, GRAPE and X-Calibur, will be presented in the following section. PoGOLite, which is the main subject of this thesis, will be described in detail in chapter 2. In the soft X-ray regime imaging of the pulsar furthermore becomes possible, the XIPE detectors, which is designed to have imagining capabilities will be described in the following section.
Chapter 1. X-ray Polarimetry

Figure 1.9: A schematic illustration of the theoretically predicted intensity in arbitrary units (top), polarisation angle (middle) and polarisation degree (bottom) of high energy emission (optical, X-rays, and gamma-rays) as a function of the rotation phase of the Crab pulsar as predicted for the caustic model (left), the polar cap model (middle) and the outer gap model (right). The term high energy emission here refers to optical, X-rays, and gamma-rays. The differences based on energy of the predicted parameters have been ignored. The X-axes of each figure is centred around the bridge area, which starts at a different phase for the different models. Reproduced from [13].
Figure 1.10: The intensity overlayed on the polarisation angle (top) and polarisation degree (bottom) as a function of the rotation phase as measured in the optical energy band. Reproduced from [15] with permission.
1.2.2 Black Hole Binaries

When a massive star is accompanied by a black hole, an emitting binary system can form when the black hole accretes matter from its heavy partner. These binary systems form some of the most luminous X-ray emitting objects in our galaxy. Examples are Cygnus-X1 and GRS 1915+105, which are secondary targets for the PoGOLite mission. Cygnus-X1 is formed by the super-giant 09-B0, with a mass between 20 and 30 solar masses and a black hole candidate measured to be $7 - 13$ solar masses. GRS 1015+105 consists of the combination of a star with around 1.2 solar masses [19] and a black hole with a mass between 10-18 solar masses, making it potentially the heaviest stellar type black hole candidate in the Galaxy [20]. The accreting matter forms a disk around the black hole where the gravitational energy of the particles is predicted to be transformed into electromagnetic radiation.

In the case of Cygnus-X1 one needs to distinguish between its two spectral states, the hard (low) and soft (high) state. The different states are thought to be connected to a difference in the accretion rate of the black hole candidate. Typical spectra of the two states are illustrated in figure 1.11. While in the hard state the system will be observable with PoGOLite, in the soft state the flux in the measurable energy range of PoGOLite is too low to make any significant measurements. The majority of the time is spent in the hard state, transitions to the soft state happen once every several years, after this the system typically stays in the soft state for several weeks or months. The intensity of the soft X-ray emission of Cygnus-X1 relative to the Crab is shown, together with the hardness as a function of time in figure 1.12. The hardness is defined here as the ratio of the number of photons measured in the $5 - 12$ keV energy band over those in measured in the $1.5 - 5$ keV energy band.

In the hard state a low accretion rate causes the disk around the accreting black hole to form of two components, a hot optically thin inner disk and a cold optically thick outer disk. Within the cold disk black body photons undergo inverse Compton scattering until they reach an energy, typically in the X-ray regime, for which the disk material is transparent. These photons form the first component of this state and are expected to be unpolarised. A second component is formed by hard X-ray photons from the hot inner disk that Compton scatter off the colder outer disk. This Compton scattering component is predicted to be polarised, the degree, however, depends on the optical thickness of the cold disk and the orientation of the system. This is a result of the dependence of the polarisation on the polar scattering angle as shown in equation 1.5. A polarisation measurement of this state would provide insight in the orientation and geometry of the system [23][24].

In the soft state the accretion rate is higher and the cold outer disks is thought to extend to the inner most stable orbits around the black hole. The hard X-ray emission is much lower and is thought to originate from inverse Compton scattering from electrons above the disk. A measurement in this state would provide information about the active regions above the disk [25].

A first polarimetric measurement of $\gamma$-rays from Cygnus-X1 was published in 2011 [26]. The measurements were performed by the IBIS instrument previously
1.2. Sources

used to measure the polarisation of the Crab emission. The results show a weak polarisation with an upper limit of 20% in the energy range from 250−400 keV. This is consistent with polarisation induced by photon scattering of thermal electrons. A strong polarisation of (67 ± 30)% for higher energies up to 2 MeV was furthermore observed. The higher level of polarisation is not consistent with emission from Compton scattering of the thermal electrons. It indicates that the high energy component is emitted through synchrotron or inverse Compton scattering from the jet [26].

Similar to Cygnus-X1 GRS 1915+105 exhibits state transitions between 2 soft states, referred to as state A and B and one hard state, referred to as C [27]. The transitions between states occur on a short time scale, of days or even hours, compared to the transitions by Cygnus-X1. Similar to the emission from Cygnus-X1 the emission during the soft states from GRS 1915+105 is dominated by soft X-ray photons, with energies typically below 10 keV. Based on predictions from [28] and [29] the polarisation degree and angle of the thermal X-rays emitted in the soft states are expected to have a large energy dependence due to general relativistic effects. Polarimetry measurements in the soft X-ray regime of GRS 1915+105 could therefore prove very valuable. During the C state of GRS 1915+105 the emission is expected to be dominated by inverse Compton scattering. The C state shows large similarities with the hard state of other black hole binaries like, for example, Cygnus-X1, however, it does not exhibit exactly the same behaviour [30], thereby leaving room for uncertainty on the emission processes involved during this state. To date no high energy polarisation measurements of GRS 1915+105 have been published.

1.2.3 Gamma Ray Bursts

Gamma Ray Bursts (GRBs) are the most powerful explosions in the Universe. They are believed to be connected to the formation of a black hole in a supernova-like event or a merger of two neutron stars. The length of the bursts vary, but a clear distinction between long and short bursts can be made. The first emission from the burst, called the prompt emission is followed by a longer lasting afterglow. The two different lengths of GRBs are thought to originate from different kinds of events. Longer bursts are connected to the death of massive stars whereas short bursts are thought to originate from neutron star mergers. Due to their high luminosity, it has been possible to detect bursts with a redshift as high as \( z = 9.4 \).

The origin of the observed X-ray and \( \gamma \)-rays from a GRB is still debated and several models exist. These models differ in the mechanism responsible for the radiation and in their prediction of the polarisation degree. Measurements of the polarisation of GRBs will give an insight in the GRB jet structure. For example, axisymmetric models which include a jet which is symmetric around its axis predict a polarisation parallel or perpendicular to the jet axis. This gives the measurable prediction of either having no change in the polarisation angle during a burst or a change of 90° [31]. Secondly polarisation measurements of GRBs can provide information on the level of magnetisation in the jets. Models which include a high
Chapter 1. X-ray Polarimetry

Figure 1.11: The energy spectra of Cygnus X-1 as measured by the Suzaku satellite when the system was in the hard state (red) and in the soft state (black). Reproduced from [21] with permission, © (2013) Oxford University Press.

level of magnetisation in the jet predict an average polarisation degree for GRBs of $\approx 40\%$ [32], whereas for models with low levels of magnetisation the expected polarisation degree peaks at 0%. Lastly, when measuring both the spectrum and the polarisation parameters of a GRB one can acquire information on the emission process, which has been predicted to be synchrotron emission [33] or photospheric emission [34].

Not only the mechanism behind the formation of the radiation changes the predicted polarisation but also geometrical factors, like the viewing angle, play an important role. For this reason and because of the large number of unknown parameters in the models, the polarisation of a large number of different GRBs needs to be measured before being able to distinguish between the models. Up to now several polarisation measurements have been performed on GRBs. The first of these was performed using the RHESSI experiment [35], which is not a dedicated polarimeter but, due to a segmented design, could be used as such. A high level of polarisation was reported ($80 \pm 20\%$). However, the data was reanalysed in [36] where it was concluded that no significant polarisation degree could be concluded. Also later measurements using the INTEGRAL instrument did not result in a generally accepted measurement conclusion [37]. The Gamma Ray Burst Polarimeter (GAP) [38], which will be discussed later in this chapter, has observed
1.2. Sources

Figure 1.12: The intensity of the emission from Cygnus X-1 in the 1.5–5 keV energy band as measured by the Rossi X-ray Timing Explorer (top) and the hardness of the emission (bottom). The hardness is defined here as the ratio of counts detected in a hard X-ray band (512 keV) to those detected in a soft (1.55 keV) band. Reproduced from [22] with permission, © (2011) AAS.

A total of 3 bursts. The first measurement showed a 30% polarisation degree. The polarisation angle was found to vary with time. The change in angle measured is compatible with an axisymmetric model, however the results are not significant enough to confirm such a model. Subsequently two more GRBs were measured by the same instrument. The measured polarisation degrees of these bursts were \(\approx (70\pm22)\%\) and \(\approx (84\pm28)\%\) [39]. The polarisation angle was found to be constant during these GRBs [39]. The measurements performed by GAP have not been able to exclude any model, showing the need for a larger number of measurements with a higher precision.

1.2.4 Solar Flares

Even within our solar system X-ray emitting processes exist which are not yet fully understood and for which X-ray polarimetry could provide important data. Solar flares are sudden increases of luminosity from the Sun with photon energies from radio to \(\gamma\)-rays. The bursts, caused by magnetic reconnection in the solar atmosphere, typically last from minutes up to several hours. The reconnection
occurs in the vicinity of Sun spots, the number of which varies during a 22 year solar cycle. The number of flares varies along with the solar activity, the maximum of which is expected around 2015. The majority of hard X-rays have been measured to be emitted from the foot points of the flare, as shown in figure 1.13. This region consists of a relatively high pressure plasma in which bremsstrahlung occurs. The predicted degree of polarisation depends on the level of order of the magnetic field and the thermal component of the radiation. A more ordered magnetic field and a non-thermal distribution leads to a more isotropic electron flow and therefore a higher polarisation. Moreover, the observed polarisation depends on the viewing angle of the observer. The maximum polarisation is expected for an observation perpendicular to the magnetic field.

Several polarisation measurements have been performed by different instruments. One of the most significant results comes from measurements performed by RHESSI which showed a relatively low level of polarisation [37]. Among other reasons the fact that this instrument was not designed as a polarimeter contributed to a relatively low certainty in the measurement results, leaving room for improvement using a dedicated polarimeter.

Figure 1.13: On the left an image of the Sun as taken by the Yohkoh Soft X-ray Telescope. On the right a more detailed image of the flare is shown as seen by the Hard X-ray Telescope (HXT). Reproduced from [40].

1.3 Polarimetry Techniques

When measuring X-/gamma-rays for polarimetry the interaction mechanism used for extracting the polarisation parameters depends on the energy range of interest. The three different mechanisms responsible for interactions between detector materials and photons in the X-/gamma-ray energy regime are the photoelectric effect, Compton scattering and pair production. For soft X-rays, up to $\approx 10$ keV
(depending on the detector material), the photoelectric effect dominates whereas in the high energy gamma-ray regime, at energies exceeding twice the electron mass, pair production is the main interaction mechanism. Compton scattering, which below \( \sim 10 \text{ keV} \) becomes Thomson scattering, dominates between these two regimes. This energy dependence for the different processes can be seen in figure 1.14 for two different materials. Figure 1.14 also illustrates the strong dependency of the cross sections of the different processes on the atomic number, \( Z \), of the detector material. The differential cross section of the photoelectric effect varies as \( Z^5 \), while for Compton scattering this dependency is \( Z \). The energy where Compton scattering becomes dominant therefore depends on \( Z \) and one can choose the detector material in such a way that the polarimeter is optimised for the desired energy range.

Only a limited number of successful polarisation measurements have been performed in the X-/gamma-ray energy regime. The main reason for this is a combination of the difficulty of both the measurement itself and the environment in which the measurements have to be performed. The absorption of X-rays by the atmosphere requires measurements to be made either at high altitudes using balloons, or above the atmosphere using satellites. These locations put constraints on the mechanics and mass of the payload which in combination with the high background and the low signal detection efficiency makes measurements challenging.

This section contains a description of the three processes involved in X-ray polarimetry and how these interactions are measured or planned to be measured in different polarimeters. First the figures of merit used in X-ray polarimetry will be introduced.

### 1.3.1 Figures of Merit

In this section it will be shown that the cross sections of the photoelectric effect, Compton scattering and pair production all show a dependency of the final state particle emission angles on the polarisation angle of the incoming photon. When plotting the differential cross section as a function of the azimuthal angle one acquires an harmonic function as shown in figure 1.15. From the function, called a modulation curve, one can extract both the polarisation angle and polarisation degree of the incoming flux.

The modulation curve can be fitted with an harmonic function of the kind:

\[
f(\eta) = T(1 + \mu(\cos(2\eta + 2\alpha))),
\]

here the parameter \( \eta \) is the azimuthal angle and \( \alpha \) is the polarisation angle. \( T \) is the average, and \( \mu \) the modulation factor, they are defined as:

\[
T = \frac{C_{\text{max}} + C_{\text{min}}}{2}, \\
\mu = \frac{C_{\text{max}} - C_{\text{min}}}{C_{\text{max}} + C_{\text{min}}}.
\]
Figure 1.14: The mass attenuation coefficient as a function of the photon energy for two different Z materials, bismuth (Z=83) and carbon (Z=6). The energy range where photoabsorption dominates is shown in blue, the range where Compton scattering dominates in red and the energy range where pair production dominates in green.

Figure 1.15: Example of a modulation curve.

The modulation factor acquired by a detector for a 100% polarised beam is called $\mu_{100}$, this value is detector specific and can be acquired by measurement or simulation. Using $\mu_{100}$ the polarisation degree $\Pi$ of a photon flux can be calculated.
1.3. Polarimetry Techniques

using:

\begin{equation}
\Pi = \frac{\mu}{\mu_{100}}.
\end{equation}

A second figure of merit which is widely used in polarimetry is the Minimum Detectable Polarisation (MDP) [41]. Its value represents the minimum degree of polarisation required in order to be able to confirm through measurement that the observed signal is polarised with a set amount of confidence. If for example, the MDP with 99% confidence level for a certain measurement is 10% and the polarisation of the target is 10% there is a 1% chance to measure a polarisation consistent with 0%. The level of confidence is usually set to 99%, for this choice the MDP is defined as:

\begin{equation}
MDP_{99\%} = \frac{4.29}{\mu_{100} R_s} \sqrt{\left(\frac{R_s + R_b}{T}\right)}.
\end{equation}

With \(R_s\) and \(R_b\) defined respectively as the signal and the background rate and \(T\) as the total observation time. For the remainder of this thesis we will refer to MDP\(_{99\%}\) simply as MDP. The MDP is a valuable figure of merit when designing an instrument since it shows the measurement capabilities of the instrument.

It should further be noted that the MDP is only valid when measurements are performed while the polarisation degree and angle of the background are perfectly known. This is important for measurements of the Crab pulsar during which the signal from the Crab nebula forms a background, if the polarisation degree and angle of the nebula are not known during the measurement the MDP as described here is not a valid figure of merit.

1.3.2 Photoelectric Effect

For soft X-rays the dominant interaction mechanism is the photoelectric effect. In this process the photon is absorbed by a bound electron which is subsequently emitted from the atom. The polar emission angle of the the photoelectron is preferentially perpendicular to the momentum of the X-ray. The azimuthal emission angle of this electron is non-isotropic. A dependency exists on the direction of the polarisation vector of the absorbed X-ray, as can be seen in equation 1.12,

\begin{equation}
\frac{d\sigma}{d\Omega} \propto \frac{Z^5 \sin^2 \theta \cos^2 \phi}{(1 - \beta \cos \theta)^4}.
\end{equation}

Here \(Z\) is the atomic number of the detector material, \(\theta\) is the polar angle between the incoming photon and the emitted electron and \(\phi\) is the azimuthal angle between the polarisation vector of the photon and the final state electron. It can be deduced from equation 1.12 that the preferred direction of the electron emission is in the direction of the polarisation vector. By measuring the azimuthal emission angle of the electrons one can determine the polarisation of the incoming flux.
Measuring the emission angle of the electron requires a measurement of the electron close to its emission point and at a subsequent point along its path. Doing this with high precision is non-trivial and to date, no astrophysical polarimetric measurements have been performed using the photoelectric effect. After being emitted the electron travels through the gas and loses energy through ionisation of the gas and by scattering off gas nuclei. Ionisation of the gas molecules leads to secondary free electrons which can be used to measure the path of the photoelectron. During each interaction the photoelectron changes direction, only the first part of the photoelectron track can therefore be used to reconstruct the emission angle. As the photoelectron travels through the gas it starts to lose more energy per unit distance travelled until it stops. The largest energy deposition is therefore at the end of the electron track. This characteristic can be used to distinguish between the emission point of the photoelectron and the point where it stops. Reconstruction of the emission angle is further complicated by the emission of Auger electrons. These electrons can be emitted together with the photoelectron by the atom using its excess energy after the position of the photoelectron is taken by an electron from a higher energy shell. The emission probability of an Auger electron increases with decreasing atomic number. The energy of the emitted Auger electron is however smaller for elements with low atomic numbers [42], making it easier to distinguish between the photoelectron and the Auger electron. Two different types of gas based polarimeters exist, one of each type will be discussed in this section.

GEMS

A proposed instrument able to to measure the electron path using a Time Projection Chamber (TPC) is the polarimeter of the GEMS mission [43]. A schematic representation of the detector principle is shown in figure 1.16. In the TPC the incoming photons first interact through the photoelectric effect with the gas molecules that fill the detector. Subsequently the emitted electron travels further through the detector chamber during which it undergoes secondary interactions with the gas molecules. With each interaction its direction will be altered as it frees a secondary low energy electron. As a result of an electric field, perpendicular to the incoming photon direction, these secondary electrons will drift towards the read-out strips. Close to these strips the electric field is greatly enhanced causing the drift electrons to gain enough energy within their mean free path to free further electrons. The result is an electron avalanche near the strips [44]. The charge of these avalanches is large enough to produce a measurable signal on the semiconductor read-out strips. By dividing the read-out strips into pixels with a size in the order of a 100 µm, one spatial direction of the electron path can be measured with a relatively high accuracy. The other spatial direction, that perpendicular to the incoming X-ray momentum, is measured using the the arrival time of the secondary electrons. To achieve a high resolution in the arrival time of the secondary charges a slow drift time of these particles is advantageous. In GEMS this is achieved by using dimethyl ether as a gas. Dimethyl ether has the slowest known electron drift speed of any gas [42].
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Figure 1.16: The detector principle for polarimeter on the GEMS mission, the detector layout is shown on the left. On the right the signal strength of the several channels is shown as a function of time. On the far right the measured energy as a function of position is shown, a larger blue circle indicates a higher energy deposition. Reproduced from [43].

Appropriate choices of a gas and its pressure have to be made in order to make good track reconstruction possible. A lower gas density will not only result in a lower interaction cross section with the incoming photons but also in a longer mean free path of the photoelectron. The result of this is less measurements along its path and therefore less information on its emission direction. However during each interaction of the photoelectron there will be an alteration of its original direction. These secondary interactions therefore make emission angle reconstruction non-trivial even in a low density environment. The position resolution also deteriorates as the secondary charges drift through the gas and interact with it. A compromise therefore has to be found when choosing the gas and gas pressure. For the GEMS mission fine tuning of the pressure and the gas mixture results in a relatively high $\mu_{100}$ value of $\approx 43\%$ measured during tests for photons of 4.5 keV [42]. The GEMS mission project was initially selected for a NASA small explorer launch in 2014 but the project was cancelled in 2012. The project is currently being re-proposed. The polarimeter on the mission is planned to measure the emission from point sources in the energy range of 2 – 10 keV.

XIPE

A second detector type which can be used to measure the emission angle of the photoelectron is the Gas Pixel Detector (GPD) as designed to be used in the XIPE mission [45]. In this type of detector the X-ray enters the detector through a thin (50 $\mu$m) beryllium window before interacting in a gas volume, see figure 1.17. As the emitted photoelectron travels through the gas it releases secondary charges as in the TPC detector. In this type of detector the electric field is however applied parallel to the momentum of the incoming X-ray, resulting in a relatively short drift length of the electrons before they are multiplied in Gas Electron Multipliers placed above
a pixellated grid with pixel sizes of 50 µm. Because of the electric field configuration both spatial directions of the photoelectron path can be measured using the pixel detectors, unlike in the TPC detector where one direction has to be derived from the arrival time. This feature in combination with the short drift length and the small pixel size results in a very precise position resolution. A further advantage of not relying on the arrival time of the secondary charges is that the instrument is symmetric around the momentum axis of the incoming X-ray. Unlike the detector type employed in GEMS the detector is therefore capable of imaging. A downside of this geometry is that the path length of the X-ray in the gas is proportional to the drift length of the secondary charges. One therefore has to make a trade off between the X-ray detection efficiency and the drift length and therefore the spatial resolution of the electron track. Using a gas consisting of 20% He and 80% dimethyl ether with a thickness of 1 cm and a density of 1 atmosphere GPD detectors have achieved a $\mu_{100}$ of 21% at 2.6 keV and 47% at 5.2 keV [42]. The XIPE project was not selected as a NASA mission, however a derivative is currently proposed for an joint mission between ESA and the Chinese National Space Agency.

Figure 1.17: The detector principle for the polarimeter on the XIPE mission. Reproduced from [45] with permission, © (2013) Springer.

1.3.3 Compton Scattering

For photons with energies between $\sim 10\text{ keV}$ and $\approx 1\text{ MeV}$, the dominating interaction process with matter is Compton scattering. In this process the incoming photon scatters off a semi-free electron in the detector material. As discussed in section 1.1.1 a polarisation dependent part is present in the differential cross section, see equation 1.5. For low photon energies in equation 1.5 $E' \approx E$, in this case Compton scattering is called Thomson scattering. Using the Thomson scattering technique energies as low as a few keV can be measured. This is the aim of the X-ray polarimeter proposed in [46]. Here the Thomson scattering takes place in a
1.3. Polarimetry Techniques

low Z crystal. The measurement of the photo-absorption of the final state photons will be performed using X-ray proportional counters which surround the scatterer. The general difficulty with the Thomson scattering measurements is the negligible amount of energy deposited through Thomson scattering, this makes coincidence triggers difficult, resulting in problems with background rejection.

In contrast, in Compton scattering a significant percentage of the energy is deposited in both interactions of the photon, the initial scattering and the photo-absorption. After requiring the two interactions to be within a set coincidence window, one can measure the positions of both of the interaction points to calculate the scattering angle. Typically the interaction points are measured using a scintillator connected to a photomultiplier. However since one cannot measure the interaction position within the scintillator, segmented scintillators are used to acquire information on the position. Additionally the scintillator segment can be read out by more than one photomultiplier tube (PMT) or avalanche photodiode (APD) to acquire information on where in the segment the interaction took place. The use of Cadmium Zinc Telluride detectors, which have a high spatial precision, for measuring the photoabsorption location has also been proposed. Four different detectors will be discussed in this chapter, POLAR, GRAPE, GAP and X-Calibur. The PoGOLite instrument also makes use of the Compton scattering effect and will be discussed in more detail in the next chapter.

POLAR

The POLAR detector consists of an array of 5 by 5 modules, each of which is made up of 8 by 8 scintillator bars as shown in figure 1.18. The scintillators have a relatively small cross section of 5 × 5 mm resulting in a good position resolution and therefore in a high $\mu_{100}$. Each module has one multi-anode photomultiplier (MAPMT) that reads out the 64 scintillators of its module. The scintillation material is an organic plastic. This choice is partly based on the low mass of this material which is advantageous for a satellite mission such as POLAR. Both the Compton scattering interaction of the photon and its secondary interaction, photo-absorption, are measured using the scintillator bars. This maximises the effective detector volume and therefore the signal rate and makes the instrument scalable. A drawback of this method is the poor energy resolution of the plastic. A second drawback is the lower photo-absorption cross section for photons with organic plastic with respect to for example BGO ($\text{Bi}_4\text{Ge}_3\text{O}_{12}$) or CsI scintillator crystals. Lastly the use of a MAPMT results in optical cross talk between different scintillator units. This can induce additional energy depositions in neighbouring channels, which can be wrongly identified as interaction locations. This problem can however be mitigated using an exact knowledge of the instrument response. The POLAR detector aims to measure the polarisation of the prompt emission from GRBs in the 50 – 500 keV energy range. Since GRBs appear at random positions on the sky it is important for such a detector to have a large field of view to maximize the number of observed GRBs. The uniform design that comes from the use of a single scintillator material makes it possible to measure events at large angles with the
zenith axis of the instrument. This is illustrated in figure 1.19 where the value of \( \mu_{100} \) is shown as a function of the incoming photon angle. The POLAR instrument is currently under construction and a possible installation on the Chinese space station is foreseen for 2015.

Figure 1.18: Detector principle of POLAR, a single detector unit is shown along with the complete proposed construction of the 5 by 5 array. Reproduced from [37] with permission.
1.3. Polarimetry Techniques

Figure 1.19: The simulated value of $\mu_{100}$ as a function of $\theta_\gamma$, the polar angle between the GRB and the zenith axis of the detector and $\phi_\gamma$, the azimuthal angle of the incoming GRB, for 100% polarised GRBs. Reproduced from [37] with permission.

GRAPE

The Gamma Ray Polarization Experiment (GRAPE), like POLAR, is designed to measure in the energy range of 50 – 500 keV. The major difference with the POLAR detector is that it uses different scintillator materials for measuring the first interaction (Compton scattering) and the second photon interaction (photoabsorption). This can be seen in figure 1.20. For its low mass and high Compton cross section an organic plastic scintillator is chosen to measure the Compton scattering events. Some of the scattered photons will be photo-absorbed in the CsI(Tl) scintillator blocks surrounding the plastic. Like in POLAR a group of 8 by 8 bars are connected to a single MAPMT. Here CsI(Tl) is chosen because of its higher stopping power, which increases the signal counting rate, but also for its high energy resolution compared to plastic scintillators. This last property gives GRAPE the possibility to measure the energy of the photons with a higher precision than POLAR. Secondly the use of CsI(Tl) reduces the neutron induced background significantly, as will be explained in chapter 3. The effective detection volume is, however, reduced by the use of this non-uniform detector geometry. The optical cross talk induced by the use of a MAPMT is mitigated by the use of pulse shape discrimination, the concept of which will be discussed in detail in chapter 2, to distinguish between interactions in the plastic and interactions in the CsI(Tl). The long scintillation decay time of CsI(Tl) with respect to CsI(Na) improves the ability to apply pulse shape discrimination.

A single MAPMT module was tested and measured to have a modulation factor of $(46 \pm 6)\%$ for a 97% polarised pencil beam at 69.5 keV and $(48 \pm 3)\%$ for a 97% polarised pencil beam at 129.5 keV [47]. The GRAPE detector has completed an
engineering flight as a balloon mission in 2007 and made its maiden science flight in the summer of 2011 using the full setup as shown in figure 1.20. It was planned to measure the Crab system and the Sun, however a low float altitude made precise measurements of the Crab impossible. The off-pulse region was measured to have a polarisation degree of \((55.3 \pm 35.6)\%\) with a polarisation angle of \((87.8 \pm 18.4)°\) [48]. A second flight with improved shielding is foreseen for autumn 2014 from Fort Sumner. The predicted MDP for the Crab nebula for a 4 hour observation for this flight is \(\approx 14\%\)[48]. Future flights in Antarctica to measure GRBs are furthermore planned. To measure these transient events an instrument version with a larger field of view than that of the previous missions is planned for these flights.

Figure 1.20: Detector principle of GRAPE, a single detector unit is shown on the left, for the 2011 science flight an array of 4 by 4 of these modules, as shown on the right, was used. Reproduced from [48] with permission, © (2010) IEEE.

GAP

The Gamma Ray Burst Polarimeter (GAP) consists of one large, 140 mm diameter, plastic scintillator dodecagon surrounded by 12 CsI(Tl) scintillators. As in GRAPE the Compton scattering takes place in the plastic scintillator and subsequent photo-absorption is measured in the CsI(Tl) scintillators. Contrary to GRAPE all scintillators are connected to their own PMT. The full detector setup can be seen in figure 1.21. The relatively small, 3.8 kg, instrument is optimised for measuring in the energy range of 50 – 300 keV with \(\mu_{100} \approx 0.3\). The instrument performed measurements on board the IKAROS solar sail driven spacecraft. GAP was the first dedicated instrument to measure the polarisation of a GRB on August 26th 2010. The measured polarisation is \(\approx 30\%\) with a significance of 3\(\sigma\). The polarisation angle was measured to change with time during the burst [38]. The changing polarisation angle implies that changes in either the magnetic field or
1.3. Polarimetry Techniques

the intensity of the outflow must take place within the observable part of the the GRB. Despite not being able to rule out any models this measurement does provide valuable data for the development of GRB emission theories. Subsequently two more GRBs were measured to have a high polarisation degree of $\approx (70 \pm 22)\%$ and $\approx (84 \pm 28)\%$. No change in the polarisation angle was measured for these GRBs [39]. The instrument has drifted out of the range for communication, however, the instrument is expected to return close enough to Earth again to make contact in the near future. If so, this will allow for several more months of observations.

![GAP detector layout](image)

Figure 1.21: The GAP detector layout as flown on the IKAROS mission. Reproduced from [49] with permission, © (2010) Oxford University Press.

### X-Calibur

The X-Calibur polarimeter [50] uses only a single plastic scintillator rod with a diameter of 1 cm for measuring the Compton scattering location of X-rays. The subsequent photoabsorption location is measured with a high precision using a high-Z Cadmium Zinc Telluride (CZT) detector which surrounds the scintillator rod. The polarimeter is novel in its use of a 40 cm diameter X-ray collecting mirror placed 8 meters in front of the detector. This design results in a large collecting...
area with a relatively small active detector area. This minimises the background contribution to measurements while maintaining a signal rate comparable to the previously discussed instruments. The technically demanding design further results in a high photon signal detection efficiency of 80%. This is a result of the use of a small, low-Z, detection volume which minimises the chance for multiple scattering within the volume. Furthermore the use of the CZT detector with a pitch of 2.5 mm provides a high precision in the position of the photoabsorption detection and therefore in a high angular resolution, finally resulting in a $\mu_{100}$ of approximately 50%. In order to further minimise the background contribution the polarimeter is placed in both active and passive shielding. A schematic overview of the instrument and the X-ray mirror are shown in figure 1.22.

The balloon-borne polarimeter is sensitive in the 20 – 75 keV energy range. The upper limit is a result of the dropping efficiency of the X-ray mirror with energy. At 75 keV its efficiency is less then 1% of its efficiency at 20 keV. The lower limit is a result of both the low detection efficiency of the low-Z scintillator for Compton scattering photons with energies below 20 keV and the absorption of photons in this energy range by the atmosphere.

The first balloon flight of the X-Calibur mission is currently foreseen to be a one day flight from Fort Sumner in autumn 2014. During this flight the Crab system is the primary observation target. A 5.6 hour observation is foreseen which is predicted to result in an MDP of 4.5% [50]. A potential next step in the X-Calibur project is a satellite mission where the low-Z scatter material will be replaced by a low Z passive material. This would make polarisation measurements in the Thomson scattering regime possible. Not measuring the Compton scattering of the incoming photons does however require an excellent understanding of the CZT response [50].

1.3.4 Pair Production

At photon energies exceeding twice the electron rest mass, pair production starts to dominate. For this process a dependency of the cross section on the angle between the incoming photon polarisation vector and the electron-positron plane exists, this is shown in equation 1.13.

$$\sigma \propto 1 + II R \cos(2\phi) \quad (1.13)$$

Here II is the polarisation degree, R is the quadrupole asymmetry for the pair production process [51] and $\phi$ is the angle between the photon polarisation vector and the plane defined by the electron-positron pair. The general detector concept of instruments measuring pair production is a set of parallel planes made up of both high density materials, which stimulate pair production, and silicon wafers which measure the electron and positron position with high precision. An instrument using this concept is the Large Area Telescope (LAT) on board the Fermi satellite. This instrument is designed to measure photons with energies above 20 MeV. It is not designed as a polarimeter but rather uses this technique to measure the intensity
1.3. Polarimetry Techniques

Figure 1.22: A schematic overview of the active detector volume of the X-calibur polarimeter showing the plastic scintillator in red and the CZT detector elements in blue. Reproduced from [50] with permission, © (2013) Elsevier.

and energy of the gamma-ray flux. Due to its design however the instrument could potentially be used as a polarimeter. The fact that to date it, nor any other detector, has been able to measure polarisation at these energies shows the difficulty involved with such a measurement.

A proposed dedicated polarimeter operating in the $5 - 200$ MeV energy range is the Advanced Energetic Pair Telescope (AdEPT) [52]. Unlike the LAT detector the instrument uses a homogeneous medium, both for pair production induction and for tracking. The medium used is gaseous argon. The use of a gaseous medium to induce pair production reduces the cross section for pair production with respect to instruments using high $Z$ planes, however, the omission of conversion planes greatly improves the tracking capabilities of the instrument. This improvement is achieved due to the removal of multiple scattering interactions of the electron and positron in the high $Z$ conversion planes which alters the electron positron paths. The TPC mechanism, which was briefly described before in the photoelectric effect section, is used to track the electron positron pair as it travels through the gaseous medium. The total geometric area of the instrument is foreseen to be $2 \times 2$ m, which in combination with the low background and the high intrinsic modulation for pair production is predicted to result in an MDP of less than 10% for a 10 mCrab source with an observation time of $10^6$ seconds. The instrument is in its early planning stages.
Chapter 2

PoGOLite

The Polarized Gamma-ray Observer (PoGOLite) is a balloon-borne X-ray polarimeter developed by an international collaboration from Sweden, Japan and the USA [25]. The instrument is sensitive in the energy range of 20 – 100 keV and is optimised for observing point sources with a Field of View (FoV) of 2.0° by 2.0°. The requirement for performing the observations at stratospheric altitudes results in a high flux of particles with an atmospheric and cosmic origin. The instrument is therefore equipped with a set of dedicated background rejection systems which are optimised for these conditions.

PoGOLite was originally designed to contain a total of 217 detector cells. The current instrument is a Pathfinder version, containing 61 detector cells. The Pathfinder made its maiden flight in July 2011 during the time of year where the stratospheric winds blow westward and make a long duration flight to Canada possible. This flight was, however, terminated after approximately 5 hours due to a tear in the balloon sustained during the launch. The leak caused the balloon to reach a maximum altitude of 35 km and therefore made scientific measurements impossible, however the functionality of the instrument was studied. A second flight was foreseen for the summer of 2012, however due to bad weather conditions there were no launch opportunities during this period. The second launch of the instrument took place on July 12th 2013. The instrument performed a near circumpolar flight with a duration of 14 days before landing near the city of Norilsk in Russia.

This chapter contains a description of the PoGOLite Pathfinder instrument, the attitude control system and the flight gondola. The combination of these three systems will be referred to as the payload. A picture of the full payload as flown in

---

1 The Royal Institute of Technology (KTH) and Stockholm University (SU) from Sweden. Tokyo Institute of Technology, Tokyo University, Hiroshima University, Waseda University, Nagoya University, Japan Aerospace Exploration Agency (JAXA) from Japan. Stanford Linear Accelerator Center (SLAC), Kavli Institute for Particle Astrophysics and Cosmology (KIPAC) and the University of Hawaii from the USA. Moscow State University (MSU) and Central Aerological Observatory (CAO) from Russia.
2013 can be seen in figure 2.1. The payload description is followed by an overview of the 2013 flight.

Figure 2.1: The PoGOLite payload during the 2013 campaign. Courtesy of the PoGOLite Collaboration.

2.1 Polarimeter Design

2.1.1 Polarimeter

A schematic cross section of the polarimeter showing the different components can be seen in figure 2.2. This section will start with a description of the plastic scintillators, used for the signal detection, followed by an overview of the different active and passive background reduction systems. It will end with an overview of the electronic read-out system.

2.1.2 Signal Detection

The PoGOLite polarimeter is designed to measure both the photo-absorption and Compton scattering interactions of incoming hard X-ray photons using a segmented detector volume. The azimuthal scattering angle can be determined when an incoming X-ray is scattered in one segment and subsequently interacts in a different segment of the detector array. The detection material chosen for this purpose is a plastic scintillator material, type EJ-204 [53]. The use of a homogeneous plastic scintillator material results in a low mass, scalable detection volume. A specific property of the plastic scintillator material used is its short decay time of 2 ns.
2.1. Polarimeter Design

Figure 2.2: A schematic view of the PoGOLite pathfinder containing the fast scintillators responsible for signal detection, the slow scintillators and the BGO used for active background reduction and the polyethylene shield used for passive background reduction.

These scintillators will therefore be referred to as ‘fast scintillators’. For a polarimetric measurement a photon needs to be measured to interact in at least two of the fast scintillators. The first interaction is required to be a Compton scattering event. The second interaction can be either a photo-absorption or a second Compton scattering event. The azimuthal scattering angle is taken as the angle between the centre of the scintillator with the lowest energy deposition to the centre of the scintillator with the highest energy deposition. The distribution of these angles makes up the modulation curve.

For plastic scintillators Compton scattering is the dominant process throughout the energy range of PoGOLite as shown in figure 2.3. The detection efficiency is therefore smaller than for detectors which use different materials for Compton scattering and photo-absorption detection, such as the GRAPE and X-Calibur polarimeters described in chapter 1. This is however compensated by the relatively...
larger detection areas achievable with polarimeters making use of a homogeneous detector volume.

The polarimeter is sensitive to energy depositions above \( \approx 1\) keV. This corresponds to the energy deposited in a Compton scattering interaction of a 20 keV photon. This sensitivity therefore defines the lower energy limit of the instrument at 20 keV. The upper energy threshold is not strictly defined before flight. The maximum energy deposition in a single scintillator recorded by the instrument is set relatively high to 120 keV. However due to the decreasing detection efficiency at high energies, a result of the decreasing photo-absorption cross section with energy, and the decreasing flux of the observed targets the observed signal rate at 120 keV is already negligible. The exact upper energy threshold used for flight data will be optimised based on the signal and background data, setting the upper threshold relatively high allows for a higher flexibility in the post-flight analysis.

The detector volume consists of a total of 61 fast scintillators. The fast scintillators have a hexagonal shape with a side length of 13.9 mm and a height of 200 mm and are packed close together in a honeycomb structure. The scintillator array is rotated around its centre during measurements to remove systematic effects induced by, for example asymmetries in the detector geometry, from the modulation curve.

![Figure 2.3: Calculated cross sections for EJ204 for photo-absorption (red) and Compton scattering (blue) as a function of energy. The vertical black line indicates the lower energy limit of the instrument.](image)

**Background Rejection**

The PoGOLite polarimeter is designed to operate in the high radiation environment encountered at the top of the atmosphere. At these altitudes the instrument will be irradiated by a wide variety of particles with atmospheric, galactic, magnetospheric and solar origins. Depending on their charge and energy many of these particles
are capable of inducing an event in the polarimeter similar to a signal event. In order to optimise the signal-background-ratio in the high radiation environment PoGOLite employs a variety of active and passive background reduction systems which will be explained here.

To limit the charged particle and gamma flux entering the polarimeter, the instrument makes use of an active collimator system which reduces its field of view to $\sim 2.0^\circ$ by $\sim 2.0^\circ$ (due to the hexagonal shape of the scintillators the exact value depends on the direction). Active collimation is accomplished using hollow plastic scintillator tubes constructed out of EJ-240 [54] glued to the top of the fast scintillators. The tubes have the same hexagonal shape as the fast scintillator and are attached to these using an optically transparent glue. EJ-204 and EJ-240 differ in their scintillation decay time, for the EJ-240 this is 285 ns. These hollow scintillators are therefore referred to as the ‘slow scintillators’. The fast and slow scintillator are wrapped in a highly reflective material, VM2000 [55], to improve the light yield of the set up. The slow scintillator is additionally wrapped in foils of lead and tin of thickness 50 $\mu$m. The lead acts as a passive collimator while the tin stops fluorescence X-rays produced in the lead from reaching the scintillator.

**Anti-coincidence**

In order to reduce background induced by charged particles and photons entering the instrument from out of the field of view PoGOLite employs both a bottom and a side anti-coincidence system. The anti-coincidence systems are active detection materials with a high cross section for photon and charged particle interactions. When an interaction is registered in this system a veto is issued, causing events taking place in the fast scintillators at that moment not to be stored. Events in the fast scintillator induced by particles coming from the side and bottom of the instrument are therefore greatly reduced.

The bottom anti-coincidence system consists of BGO scintillators with a height of 4 cm glued to the bottom of the fast scintillators. BGO, which has a scintillation decay time of 300 ns, was chosen here for its high absorption cross section, see figure 2.4, resulting from its high effective atomic number ($Z = 75$) and its high density ($\rho = 7.13 \text{ g/cm}^3$). These properties result in a high interaction probability for high energy gammas entering from the bottom of the instrument. Furthermore charged particles traversing the BGO crystals will deposit large amounts of energy in the crystal and will therefore be stopped within a relatively short distance. A detailed description of the BGO crystals used in PoGOLite and callibration tests of the units can be found in [56].

The BGO, fast scintillator and slow scintillator together form a Phoswich Detector Cell (PDC). The 61 PDCs used in PoGOLite are surrounded by a 60 cm high segmented Side Anti-coincidence Shield (SAS); each segment is constructed from three 20 cm high BGO crystals. The shield consists of a total of 30 segments each connected to a PMT. The SAS system issues a veto whenever an energy deposition occurs inside this detector volume above a set trigger threshold. This trigger threshold is set as low as possible, meaning just above the electronic noise level. The
efficiency of the bottom and side-anti-coincidence systems to reject events induced by atmospheric gammas will be discussed in chapter 5.

Figure 2.4: Calculated cross sections for BGO for photo-absorption (red) and Compton scattering (blue) as a function of energy while ignoring atomic shell effects. The vertical black lines indicates the lower and upper energy limit of the instrument.

Figure 2.5: Schematic representation of a Phoswich Detector Cell (PDC) together with a PMT, together with pictures of the three individual components.
Waveform Discrimination

Each PDC is read out by a single Photo Multiplier Tube (Hamamatsu R7899EGKNP). Figure 2.5 shows the dimensions of each individual component and those of a full PDC. Determining in which material an interaction took place within a PDC is accomplished using waveform discrimination. This method makes use of the differences in scintillation decay time of the different components of the PDC. Interactions taking place in the slow scintillator and the BGO produce a relatively long signal in the PMT with similar waveforms due to their similar scintillator decay time. The fast scintillator has a much shorter decay time and therefore a different signal shape. The differently shaped output signals from a PMT reach a charge-sensitive preamplifier after which the signal is digitised with a sampling rate of 37.5 MHz by a (Field Programmable Gate Array) FPGA. Due to the relatively slow response of the preamplifier the signals resulting from the fast scintillator have a recorded rise time of $\approx 0.1 \mu s$, whereas for signals from the slow scintillators and the BGO this is $\approx 0.3 \mu s$. An example of a fast signal is presented in figure 2.6. A signal from a slow scintillator can be seen in figure 2.7. A BGO induced signal has an almost identical shape. For each sampled signal two points are selected, the first called the fast output and the second the slow output. These points are separated by 15 clock cycles as shown in figures 2.6 and 2.7. Online analysis on the signals is performed using FPGAs in which threshold and trigger levels can be set. On the FPGA the ratio between the fast and slow output of the waveform are used to distinguish between signal and background events. A histogram with the slow versus the fast output can be seen in figure 2.8. In this figure a clear distinction between events occurring in the fast scintillator and events occurring in one of the two other scintillator materials can be observed for high energy depositions. For high energy depositions the online veto system is therefore relatively efficient. At lower energies the number of optical photons responsible for inducing the signal decreases, causing the difference between signal shapes induced by the different scintillators to reduce. For lower energies the online veto system is therefore less efficient. At these low energies where the separation between the fast and slow output becomes negligible, the online vetoes are set lenient enough to prevent the loss of any signal events. A schematic representation of the operation of the active background rejection systems can be seen in figure 2.9.

Trigger levels

Further background reduction is accomplished using the trigger system of the polarimeter. Firstly lower and upper energy thresholds are applied for event selection. The upper threshold serves to reject charged particles, which due to their ionizing behaviour, typically deposit large amounts of energy in a single detector unit. Two different lower energy thresholds are used. The first, referred to as the hit threshold, is set to be just above the electronic noise level. The second lower energy threshold is referred to as the trigger threshold and is set to a level corresponding to $\approx 17.5 \text{keV}$. A 2-hit event is registered in the instrument when at least one
energy deposition in the instrument is above the trigger threshold and a second deposition above the hit threshold. As a result only 2-hit events are registered where one of the energy depositions corresponds to a photo-absorption event, typically corresponding to a high energy deposition, and the second can correspond to a Compton scattering event. The total minimum recorded energy deposition is therefore the sum of the two lower energy thresholds, $\approx 20 \text{ keV}$.
2.1. Polarimeter Design

Figure 2.8: A typical 2d histogram, resulting from irradiation of the instrument with a $^{241}$Am source, showing the fast output of a signal on the x-axis and the slow output on the y-axis. A clear distinction between the different events becomes visible. Events between the two branches are a result of photons scattering from one material to another. Reproduced from [57] with permission.

Polyethylene Shielding

Passive shielding is used mainly for the reduction of the neutron background. A 15 cm thick polyethylene plate placed below the PMT array acts as a shield for neutrons coming from below while a cylindrical shell covers most of the PMTs and PDCs. The cylindrical shield consists of 3 different layers. At the height of the PMTs the cylinder has a thickness of 15 cm, whereas below and above this the cylinder has a thickness of 10 cm. A schematic representation of the polyethylene shield and its position with respect to the different scintillator components is shown in figure 2.10. The mass distribution and configuration of the shield were initially optimised using Monte Carlo simulations in [58], subsequently the thickness was optimised for the achievable MDP in [59]. The effects of the polyethylene shield on the incoming neutron flux will be discussed in more detail in the following chapters.

Despite the use of the different background rejection systems, both active and passive, a non-negligible background rate is expected at float altitudes. In chapter 5 it will be shown that the major components responsible for this background are the neutron and gamma component of the atmospheric radiation. Both of these components will be discussed in detail in the remainder of this thesis. Furthermore an improvement of the background rejection system will be the focus of chapter 6.
2.1.3 Neutron Scintillator

Neutrons scattering between the fast scintillators are predicted to cause the dominant background at float altitudes [60]. Although reduced by the previously men-
tioned active and passive shielding mechanisms the induced background rate is expected to be significant. Detailed predictions on the induced rate will be presented in chapter 5. Due to the significance of the neutron induced background rate and in order to study the relatively unknown neutron environment at this high altitude/high latitude environment, PoGOLite contains a small neutron detector developed by the Collaboration [61].

The neutron detector is based, like the PoGOLite polarimeter, on the Phoswich Detector principle. The scintillator material used for neutron detection is LiCaAlF$_6$ doped with Europium [62] developed at Tokuyama corporation, Japan [63]. $^6$Li which is embedded in the crystal structure has a high cross section, 940 barn, for thermal neutron capture. Neutron capture by $^6$Li proceeds as follows:

$$n + ^6\text{Li} \rightarrow ^4\text{He} (2.73\,\text{MeV}) + ^3\text{H} (2.05\,\text{MeV})$$

The decay products will deposit all their energies in the scintillator material within several microns through ionization, thereby producing a characteristic detection signal.

The 5 mm thick layer of LiCaAlF$_6$ is placed between two BGO crystals. The crystals are of the same type as the bottom anti-coincidence crystals used in the polarimeter. The different scintillator materials can be seen in figure 2.11. The BGO crystals serve as an anti-coincidence system in order to reduce charged particle and gamma induced background. The signals originating from these crystals have a rise time of 300 ns and can therefore be distinguished from the LiCaAlF$_6$ signals which have a rise time of 1.6 $\mu$s using waveform discrimination. The results of a measurement of both a $^{137}$Cs gamma-ray source, serving as the background source, and a $^{252}$Cf neutron and gamma-ray source is presented in figure 2.12.

This neutron detector was flown on the PoGOLite pathfinder flights and was positioned next to the PMTs. The position of the neutron detector causes the incoming spectrum to differ from the spectrum in the atmosphere since the neutrons need to traverse the polyethylene shield before reaching the scintillator, resulting in a spectrum with a lower energy with respect to the spectrum impinging on the instrument. This effect makes the measurement dependent on Monte Carlo simulations of the shield performance. Two similar detectors were flown on the PoGOLino flight, described in chapter 4, to study the high altitude, high latitude neutron spectrum which is expected to form the major background component for PoGOLite. The detectors flown on PoGOLino, the full instrument and the flight results will be the subject of chapter 4.

### 2.1.4 Electronic Read Out System

The electronic read out system of the instrument is placed below the bottom polyethylene shield. The 91 PMTs are read out by 12 Flash-ADC (FADC) boards with a sampling rate of 37.5 MHz. Each FADC can handle a total of 8 PMT input signals. The FPGAs on the FADCs are connected to a Digital Input-Output (DIO) board through 2 routers. The FADCs handle the trigger logic for a single board,
such as the hit threshold and the trigger threshold. The DIO handles the global trigger logic, it checks if all event trigger requirements are met and if so sends a data acquisition request to the FADC boards. Two different connections exist between the DIO and the FADC boards. The first is a Low-voltage Differential Signalling (LVDS) connection, used to send the data storage command to 12 boards simultaneously through a Fan-In/Fan-Out Board. The second is a SpaceWire connection [65], used for settings on the FADC boards and to communicate the trigger requirements. A SpaceWire connection is further used for communication between the FPGAs and an on-board PC104 computer [66] which handles the data taking and final data storage to RAID’ed solid state disk arrays. The FADC boards were developed for the PoGOLite instrument [67]. Each FADC board has 8 channels available for input signals. For this reason the PoGOLite Pathfinder needs a total of 12 FADCs (61 PDC signals + 30 SAS signals + 1 neutron scintillator). The SAS units are read out using 4 boards. The 8 remaining boards are connected to the PDCs. A flow chart of the instrument read out electronics is shown in figure 2.13. The PC104 computer is placed, together with electronics responsible for power distribution and ground communication, in a pressurised aluminium container, referred to as the Polarimeter Control Unit Box or PCU Box. For the 2013 flight the PCU Box was placed the side of the polarimeter.

Figure 2.11: An assembled LiCAF PDC in front of the three individual crystals. Reproduced from [64] with permission, © (2014) Elsevier.
2.2. Payload Components

2.2.1 Pressure Vessel Assembly

Due to the low atmospheric pressure at the planned float altitude of 38.5 km both the flight electronics, the PMTs and the scintillators are mounted inside pressurised containers. This ensures both a safe operating pressure for the electronics and the PMTs, both of which have the potential to fail at low pressures. A second reason for the pressurised system is the internal cooling of the system. Due to the presence of air inside the polarimeter convection induced cooling of the electronics and PMTs becomes possible.

The PDC and SAS units are contained in the 'top pressure vessel'. This aluminium cylinder is connected to a second PMT pressure vessel, containing the PMTs, the PMT cooling system and the lower polyethylene shield. An air tight connection between the two cylinders is ensured by a silicone O-ring which maintains its sealing properties down to temperatures as low as $-40^\circ$C. The electronics

Figure 2.12: The output from a sampled waveform of the LiCAF detector irradiated by $^{137}$Cs and $^{252}$Cf. The fast and slow channel are the signal heights measured at sampling points separated by 15 clock cycles of the waveform sampler. A clear difference between events occurring in the BGO crystals and those occurring in the LiCaAlF$_6$ scintillator becomes visible. Events selection is based on the ratio between the fast and the slow channel number. Reproduced from [61] with permission, © (2010) IEEE.
Figure 2.13: Flow chart of the PoGOLite read out electronics. Solid lines show the SpaceWire communication cables to set operational modes and read stored data from each board. Dashed ones show LVDS signal lines used to send signals among the 12 FADC, Fan-In/Fan-Out and the DIO boards to store waveforms. Reproduced from [68] with permission.

is contained in the lowest of the three pressure vessels which is connected, again using an O-ring at its top to the PMT pressure vessel. The bottom is sealed using the an aluminium plate, containing air tight feed-throughs for signal and power cables and an input and output tube for the cooling system which is described later in this section.

The top pressure vessel, containing the scintillators, is sealed using a thin window. This window consists of two layers, one ensuring light tightness of the instrument while the other provides the necessary mechanical strength to sustain the pressure difference of \( \approx 1 \text{ bar} \). The light tight material is TEDLAR [69] from Du Pont, with a thickness of 0.12 mm. The material responsible for providing the mechanical strength is a layer of polyether ether ketone (PEEK) with a thickness of 0.19 mm. A test at Innventia in Kista, Sweden, was performed where it was shown to sustain an over-pressure of 1.2 bar with temperatures cycling between \(-40^\circ \text{C}\) and \(60^\circ \text{C}\). Above the window a thin layer of 0.2 \(\mu\)m thick metallised mylar is added to prevent solar radiation from heating the (black) window and therefore the instrument. The combination of the three thin layers of material ensures a light and air tight instrument at balloon altitudes while stopping less than 1.5\% of the incoming X-ray at 25 keV and less then 0.2\% at 60 keV.

The PVA is mounted inside the Rotation Frame Assembly (RFA), in which it can be rotated around its pointing axis using a motor and a bearing system. Rotating the detector within the RFA while observing a source will allow counting rate asymmetries resulting from asymmetries in the geometry or detector response to be smeared out. The RFA contains segmented shelves on the outside in which the polyethylene neutron shield can be placed. A picture showing the polarimeter, the pressure vessels and the RFA is presented in figure 2.14.
2.2.2 Cooling System

Both the electronics and the PMTs are connected to a cooling system. The electronics uses $\approx 100\, \text{W}$ while each PMT consumes $\approx 1\, \text{W}$. The cooling system consists of a pump and an expansion tank, both placed outside the instrument in their own pressurised container. From this container a paraffin-based liquid (Paratherm LR [70]) is pumped to a radiator placed outside the gondola from which the liquid is transported into the instrument. After this the fluid flows in the pump box again. The radiator [71] is placed in such a way that the radiation it receives from the Sun is minimal during an observation of the different observation targets. A schematic representation of the cooling system is shown in figure 2.15.

Inside the instrument the fluid is led through a cooling plate, which is thermally coupled with copper braids to each PMT. The cooling plate is described in more detail in [71]. Apart from the cooling plate the fluid is led through a copper structure thermally coupled to the electronics. The crate ensures maximum thermal coupling between the electronic boards and the cooling fluid. The crate can be seen in figure 2.16.

2.2.3 Attitude Control System

In order to point the instrument at observation targets and keep the pointing solution of the instrument stable, the polarimeter is mounted in an Attitude Control
Chapter 2. PoGOLite

Figure 2.15: A schematic representation of the cooling system with the different component. From the pump the cooling fluid is led through the gondola wall into the radiator where it is cooled. From the radiator it flows back into the gondola in the instrument to both the electronics and the cooling plate. From the polarimeter the fluid is led to an expansion tank after which it goes back to the pump.

System (ACS) described in detail in [72]. The communication of the ACS with the polarimeter electronics, placed in the PCU box, is discussed in [73]. The ACS consists of a differential GPS, encoders, a magnetometer, an inclinometer, a gyroscope, an accelerometer and two different star trackers. These sensors are used to calculate the location, pitch and rotation of the gondola and the elevation angle of the instrument. This information is then used to calculate the needed adjustments to the pointing. The adjustments are made possible by an elevation motor and a second motor connected to a flywheel. A schematic representation of the ACS is shown in figure 2.17.

The ACS, with exception of the star trackers, was designed and built for the Pathfinder by the Swedish company DST Control [75]. Information from the different sensors is combined to acquire both an accurate location of the payload and the pointing position on the sky of the polarimeter with an accuracy better than 0.1°[56]. The elevation of the instrument can be varied between the horizon and zenith using a torque motor which acts directly on the elevation axis of the instrument. At an elevation above 60° the field of view (FoV) of the instrument is however blocked by the gondola structure. For azimuthal movement of the instrument a motor connected to a 60 kg flywheel is used. The pointing accuracy was evaluated during the flights of 2011 and 2013.

Two independent star trackers are mounted on the RFA of the instrument. The two systems are identical in their use of a CCD camera operating in the optical
2.2. Payload Components

Figure 2.16: The crate containing the PoGOLite electronics. The copper plates on the side contain channels through which the cooling fluid is circulated. Courtesy of the PoGOLite Collaboration.

range but differ in their FoV. For one this is $5.0^\circ \times 3.7^\circ$ for the other it is $2.6^\circ \times 1.9^\circ$ [56]. Custom made baffles ensure a sensitivity high enough to operate at an angular separation larger than $10^\circ$ away from the Sun. This provides the ability to use the star trackers for Crab observations during July when the angular separation between the Sun and the Crab is small.

2.2.4 Ground Communication

Communication with the instrument and the ACS can proceed through two independent systems. The fastest of the two communication systems is E-link, a real time WLAN communication system operating in the 2.45 GHz band. This system is developed by SSC [76]. E-link has the advantage of its speed which can be as high as 1 Mbit/s, however its range is limited to within the line of sight of the antenna. For the PoGOLite flight this range is up to several hundred kilometres from the launch site plus a possible additional similar distance from a second ground station at the Andoya Rocket Range in Norway. After losing contact through E-link, communication proceeds through Iridium [77], which has a full coverage over the Earth. However bandwidth is limited to about 1 kb/s, limiting the command and download capability. During the Iridium communication phase of the flight downloading the data is impossible, as a result safe data storage on the payload is required. Data storage takes place on three separate RAID’ed disk systems, six
Figure 2.17: The ACS containing the PoGOLite polarimeter and the star trackers. The PCU Box is not present in this picture, during flight this was placed on top of the polarimeter below the flywheel. Reproduced [74] with permission, © (2012) IEEE.

copies of the data should therefore exist. Two of the RAID’ed storage systems are connected to PC104 units placed in the PCU box, the third is placed in a separate pressure vessel dedicated to safe data storage, referred to as the black box.

2.2.5 AMU

An Auroral Monitoring Unit (AMU) is mounted next to the two star trackers. This instrument was proposed to be added to the payload in order to observe potential auroral activity during flight. The auroral X-ray emission is generated by
bremsstrahlung radiation emitted by electrons high in the atmosphere and is predicted to be polarised [78]. By monitoring the auroral activity it will be possible to exclude periods in which this extra background source was present. The AMU has been developed at the Alfvén Laboratory, part of the Royal Institute of Technology in Stockholm.

### 2.2.6 Gondola

The ACS and polarimeter are mounted inside a gondola structure. This mechanical structure is designed to protect the instrument during flight from solar radiation and the heavy impacts sustained during landing. The structure is presented in figure 2.18. The two booms at the top provide the necessary distance for two GPS antennas to create a differential GPS signal for the attitude control system. Apart from these GPS antennas several communication antennas are placed on the booms where the interference from the structure is minimal. The booms further form part of the support structure for the solar cells, the position of which is optimised for producing a maximum amount of power during observations of the Crab system and Cygnus-X1. The position of the solar cells was changed with respect to the 2011 flight when they we placed beneath the gondola in a skirt formation.

Several hundred kg’s of ballast hang from the bottom of the gondola and can be released in controlled amounts during the flight. The ballast consists of small iron grains and therefore cause no danger when being dropped. The ballast can be released during the ascent in order to accelerate the ascent rate if necessary, for example during a period where the balloon stalls in the coldest regions of the atmosphere. Ballast drops can also be used to place the balloon at altitudes where the wind is in the preferred direction. The bottom of the gondola is furthermore equipped with several crashpads which serve to absorb the impact during landing. The full payload as in 2012, without the ballast and crashpads, can be seen in figure 2.18.

### 2.2.7 Flight Train

The gondola is attached to the balloon by a flight train which can be seen in figure 2.19. The thickness of the balloon material is $20\mu m$ and at float altitude the total balloon diameter is $\approx 140\,m$. The flight train contains a receiver to which the commands to disconnect the payload or to operate a valve at the balloon apex are sent. The separation of the gondola from the balloon is performed by a device which contains an explosive to cut the cable connecting the balloon to the gondola, see figure 2.19. After being separated from the balloon the gondola free falls, however when the atmospheric pressure is high enough a parachute will open to slow down the payload before impact. During its descent by parachute a strobe light will ensure visibility and a radar reflector will cause the falling payload to be visible to radar. The truck plate is positioned right above the payload and is used during launch to connect the instrument to the launch vehicle.
2.3 Calibration Measurements

2.3.1 Time tagging test

Measuring the time of arrival of each photon is required to measure the potentially phase dependent polarisation degree and angle. The phase dependent X-ray flux, or light curve, of the Crab pulsar will need to be measured in order to time resolve the polarisation. In order to measure the light curve the instrument must be capable of time tagging each event with a precision significantly lower than the pulsar period. For the Crab pulsar, which has a period of 33 ms, a precision in the order of millisecond is sufficient to see a phase dependent polarisation. A higher time resolution is possible, however, the relatively small amount of data of the pulsar will most likely limit the time resolved polarisation capabilities of PoGOLite beyond this precision. The timing information is acquired using a GPS pulse received and forwarded by the GPS antennas on the booms of the instrument. The pulse is sent to the read-out electronics every second. Using an internal oscillator and the information from the GPS pulse each event can be assigned a time stamp with the required precision. A pre-flight test of this system was performed using the flight ready instrument.

To test the time tagging capability of the instrument a second independent read-out system was designed to measure cosmic-ray muons. These muons were detected both with this external setup and the polarimeter. The detector part of this external setup consisted of two scintillators which were placed on top of the horizontally pointing polarimeter. By comparing the acquired data from both set-ups, coincidences can be found in cases where a muon traversed and caused a
trigger in both the external scintillator setup and the polarimeter. By registering
the absolute trigger time in both set-ups and comparing them, the time resolution
of the instrument can be estimated.

The instrument itself was read out using its flight electronics in order to test the
behaviour of the full flight configuration. Only a selected number of PDC channels
was used to reduce the trigger rate. The lower energy thresholds of these channels
was set to its maximum value in order to reduce chance coincidence events.

The two scintillators of the external setup were placed directly on top of each
other in order to create a coincidence detector for cosmic muons. The number of
coincidences was further minimized by wrapping the scintillators in a lead foil of
several mm thick with the purpose of stopping low energy photons and electrons.
The external detectors were placed on top of the instrument and aligned with the
central PDC.

The read-out system of the 2 external PMTs consisted of a NIM setup of which
a schematic representation can be seen in figure 2.20. The signals from the PMTs
were first individually sent to a discriminator. The signals from the discrimina-
tor channels were sent to a coincidence unit. The coincidence window of this unit was set to 100 ns. The number of coincidences was \( \approx 4/\text{minute} \) compatible with the expected muon flux and surface area of the two scintillators of \( \approx 5 \text{ cm}^2 \). The coincidence signal was sent as an input to a programmable FPGA board [79] programmed to create event lists. This FPGA board received the events coming from the coincidence unit after being converted from NIM to TTL. On another input the FPGA received a GPS pulse per second (PPS). A 100 MHz internal oscillator on the FPGA board in combination with the PPS signal was used to assign a time stamp to the events coming from the coincidence unit.

![Diagram](image)

Figure 2.20: Schematic representation of the external read out setup used in the time tagging test.

A set of measurements was performed where the 8 SAS units closest to the external scintillator setup were read out. A total of 4 measurements were performed, one of 5 minutes duration and three of 15 minutes. A histogram of the event time registered by PoGOLite subtracted by that of the external readout was produced containing the combined data of all 4 measurements. The results can be seen in figure 2.21.

In the histogram a clear surplus of coincidences exists for \( \Delta T \) close to zero, this shows that these events are indeed events resulting from cosmic muons and not random coincidences. The total number of events within the measurement time also supports this. In both histograms the peak is shifted in the positive direction by \( 1 - 2 \mu s \). This implies that PoGOLite is \( \approx 1 \mu s \) slower in registering an event than the external setup. In previous tests the time between event and registration in the DIO was measured to be within 100 ns. The reason must therefore lie outside of the PoGOLite DAQ system. It is believed that the delay results from the ACS electronics responsible for forwarding the GPS time signal from the GPS unit. It is however not the absolute timing which is of importance for the measurement but rather the relative timing between events. The width of the peak, which shows
2.3. Calibration Measurements

2.3.2 Optical Cross Talk

For detectors with a segmented scintillator array it is important that different scintillator units remain optically isolated from each other. The loss of photons from the scintillator will reduce the signal height and therefore result in a loss of detection efficiency. For polarimeters additional problems arise when coincident signals are induced by photons lost to neighbouring scintillators. This last process is referred to as optical cross talk. Optical cross talk can result in fake double-hit event indistinguishable from polarisation events, ultimately resulting in a reduction of $\mu_{100}$. Furthermore valid polarisation events can be lost by changing a double-hit event into a triple-hit event (an event where energy is deposited in three different PDCs). In the case of PoGOLite optical cross talk from a PDC to a SAS unit can furthermore result in vetoing of valid polarisation events. In order to achieve optical isolation while maximising the light yield for the scintillators the slow and fast scintillator are wrapped in a layer of high reflective VM2000 [55], produced by 3M. The layer of VM2000 is surrounded by the passive tin and lead collimators and a layer of 250 $\mu$m thick heat shrink. These three layers absorb any photons which penetrated the VM2000. Due to the shape of the bottom BGO scintillator, which varies from cylindrical near the bottom to hexagonal near the top, wrapping this scintillator with VM2000 and heat shrink is non-trivial. Instead it was decided
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to coat the BGO pieces with a 100 \( \mu \text{m} \) thick layer of the highly reflective material BaSO\(_4\) as used in the Suzaku hard X-ray detector [80].

During calibration measurements in 2013 a discrepancy of the observed polarisation fraction of a \(^{241}\text{Am}\) source was found between calibration data, measured with the fully assembled instrument, and simulation data. Additionally minor discrepancies in the measured spectra were found indicating potential optical cross talk. The measurements showed double-hit events consisting of a 59.5 keV absorption in one PDC and an energy deposition of several keV in a second PDC which can be induced by a single photo-electron. The total deposited energy therefore appears to exceed the initial X-ray energy of 59.5 keV. The magnitude of the optical cross talk, defined as the fraction of optical photons escaping to a neighbouring PDC, was estimated to be \(<1\%\). The level of optical cross talk therefore has a relatively small effect on the measured spectra. However it has a relatively large effect on the \(\mu_{100}\) of the polarimeter. Mitigation of the problem requires the instrument to be fully disassembled and was therefore not possible prior to the 2013 flight. It was therefore decided to study the effect and implement the optical cross talk in the simulations, thereby making it possible to study the influence of the effect on the \(\mu_{100}\) for flight conditions. Dedicated measurements were therefore performed to study the magnitude of the optical cross talk and the variation of the magnitude between PDCs.

Measurements were performed using a pulsed LED with a pulse length of several ns to simulate scintillation pulses. Initial measurements were performed with the LED and two spare PDCs placed on a test bench. The PDCs were placed directly adjacent to each other to represent two neighbouring PDCs in the polarimeter. After making the test environment light tight the LED was placed at different locations within the slow scintillator of one PDC. This was done to study the dependency of the optical cross talk on the LED position. The positions varied from the top of the slow scintillator (outside the layer of VM2000 which closes off the top of the slow scintillator) to the bottom of the slow scintillator (corresponding to the top of the fast scintillator). The level of optical cross talk, defined as the relative average pulse height measured in the neighbouring PDC with respect to the pulse height measured in the illuminated PDC, can be seen as a function of the LED location in figure 2.23. The results presented in figure 2.23 indicate that the level of measured cross talk does not depend on the LED position in the slow scintillator. Based on these results it was decided to measure the optical cross talk for each PDC in the flight polarimeter by placing the LED at the top of the PDC, thereby eliminating the need for opening the layer of VM2000 at the top of the slow scintillators. It should however be noted that the level of optical cross talk measured using the LED can be different from optical cross talk induced by light produced in the fast or BGO scintillator, this can however not be measured. The measurements presented here are therefore a best approximation.

Using the setup with the external PDCs, the location where the optical cross talk occurs was also investigated. A layer of light absorbing material was placed between the PDCs at different locations. When placing the absorbing material
between the bottom BGO pieces of the PDCs it was found that the level of optical cross talk dropped to a negligible level ($\ll 0.1\%$). Indicating that optical cross talk occurs in the polarimeter as a result of photons escaping through the layer of BaSO$_4$. It should be noted here that the layer of BaSO$_4$ of the PDCs used for this measurement showed some signs of damage. The level of optical cross talk is therefore expected to be higher for these PDCs. Similar damage can however not be excluded to be present in the instrument. The location of the optical cross talk is indicated in figure 2.22.

In order to accurately measure the level of optical cross talk the voltage of the PMT connected to the illuminated PDC was reduced. This made it possible to increase the brightness of the LED significantly, thereby inducing a relatively high pulse height in neighbouring PDCs without saturating the PMT of the illuminated PDC. The gain lost due to lowering the PMT voltage was measured separately and corrected for in the analysis phase. An example of the relative pulse height for each PDC when illuminating the central PDC can be seen on the right side in figure 2.24. The position of the different PDC units is shown in on the left side of this figure. The optical cross talk to the 6 direct neighbours can be seen to be of the order of 0.15%. This means that $\approx 0.15\%$ of the optical photons induces a signal in the one of the directly neighbouring PDC. The cross talk to second neighbours is an additional factor of $\sim 100$ smaller. Figure 2.24 furthermore shows that the level of optical cross talk varies significantly between PDCs. For example the largest level of cross talk from the central PDC can be seen to be 0.21% to PDC unit 6, whereas the smallest level to a direct neighbour was measured to be 0.11% to PDC unit 3. Similar measurements were performed for all PDCs. The amount of optical cross talk was measured for each PDC not only to all other PDCs but also to the SAS units.

In the simulations the effect of optical cross talk is taken into account as follows. Whenever energy is deposited in a PDC, the energy is distributed among all PDCs according to the measured optical cross talk levels. For example when 60 keV
Figure 2.23: The level of optical cross talk as measured with two external PDCs as a function of the LED position within the slow scintillator, where 1.0 indicates the top of the slow scintillator and 0.0 the bottom.

Figure 2.24: The level of optical cross talk as measured when irradiating the central PDC with and LED as a function of the PDC number. The position of the different PDC units is indicated on the right side of the figure which additionally shows the level of optical cross talk for this measurement. Courtesy of the PoGOLite Collaboration.
is deposited in the central PDC, 0.15% of this energy is placed in PDC unit 1, 0.11% in PDC, 0.19% in PDC unit 2 etc. This way energy is deposited in all the other 60 PDCs and in the 30 SAS units. The total amount of energy distributed among the other units is then subtracted from the initial energy deposited in the central PDC. In the specific case of the central PDC the remaining energy is 98.8% of the initially deposited energy. This is followed by calculating the chance for creating photo-electrons in each of the PMTs as in the normal analysis which is described in appendix A of this thesis. As a result the chance of inducing a signal in the neighbouring units is correctly taken into account in the simulation analysis software. The effect of the optical cross talk on the instrument performance is discussed in section 6.1.

2.4 PoGOLite Flights

2.4.1 Launch Window

The three past launch windows of PoGOLite have taken place in the summer during the period where the high altitude winds are foreseen to cause the balloon to drift westwards. Every year this period starts in mid-May and ends around mid-August. A second constraint on the flight period comes from the angular distance between the Sun and the Crab. The Crab moves behind the Sun on the 15th of June. Before and after this date the angular separation changes by approximately 1° per day. When the angle between the Crab and the Sun is below ≈ 10° reflections from inside the star tracker baffle systems make star tracking and therefore stable Crab observations impossible. A secondary issue could be damaging the star trackers or overheating the instrument when pointing it close to the Sun. The flight window was therefore defined to start from the day the angular separation was larger than 15° which is around the 1st of July. The end of the launch window is defined by the stability of the westward winds. For a circumpolar flight stable winds throughout the whole flight, which can last up to 3 weeks, can be guaranteed up to the middle to the end of July. The exact end of the launch window is highly dependent on the stratospheric weather conditions and therefore differs from year to year.

2.4.2 Observation Targets

The primary observation target of the polarimeter is the Crab system, the brightest continuous point source in the hard X-ray energy range. Secondary targets are Cygnus-X1 and GRS 1915+105. Cygnus-X1 can only be observed when it is in the hard state as explained in chapter 1. Like Cygnus-X1 the flux of GRS 1915+105 varies as the system changes state, when in the highest state the flux can be as high as half that of the Crab. Due to the lower elevation of GRS 1915+105 above the horizon the observed flux will however be significantly lower. Assuming an average signal rate of 20% with respect to that from the Crab and a background rate as
discussed in chapter 5 of this thesis a measurement with an MDP below 40% is still possible with a full circumpolar flight.

Throughout the launch window all targets will be separated by more than $15^\circ$ from the Sun. The choice of target is therefore only dictated by its priority and its elevation, or airmass. The airmass is a variable accounting for the relative amount of atmosphere between the target and the observer at a certain elevation compared to the atmosphere between the observer and the target at zenith. An approximation of the airmass valid for elevation angles above $5^\circ$ is:

\[
\text{Airmass} = \frac{1}{\cos(z)},
\]  

(2.1)

with $z$ the angle of the target from zenith. For elevations below $30^\circ$, equivalent to an airmass of 2.0, the airmass increases rapidly with time and the observed flux from the target quickly becomes negligible. An example of these variables calculated for the Crab for the first of July 2013, is shown in figure 2.25, for Cygnus-X1 in figure 2.26 and for GRS 1915+105 in figure 2.27.

As a result of having the highest priority the Crab would be observed whenever its airmass would be below 2.0, resulting in a total observation time equivalent to $\sim 9$ hours. The observable periods of GRS 1915+105 and Cygnus-X1 overlap and therefore a choice has to be made between the targets. During the 2013 flight Cygnus-X1 was in an intermediate state with a flux significantly lower than in the hard state, whereas GRS 1915+105 was in its hard state during the flight. As a result of the generally lower airmass of GRS 1915+105 with respect to Cygnus-X1 the expected signal rate of the two targets was calculated to be similar. GRS 1915+105 was finally prioritised over Cygnus-X1 because it was in a more stable state, making a potential interpretation of the measurement results more straightforward. During the periods where both the Crab and GRS 1915+105 were below $30^\circ$ elevation Cygnus-X1 would be observed. The remaining time would be used to measure blank sky regions in order to be able to study the background. It was furthermore foreseen to observe blank sky regions 25% of the target observation time to study potential changes in the background with time.
Figure 2.25: The observability predictions for the Crab system as calculated for the 1st of July 2013 at Kiruna for an instrument with a longitudinal velocity of zero. In the left upper corner the azimuthal difference between the target and the Sun is shown, in the right upper corner the elevation angle between the two is shown. Left down the total angular difference between the two is presented and in the lower right corner the airmass as a function of time is presented, the airmass of 2 is indicated by the vertical black line. The angle between the radiator and the Sun is calculated from the azimuthal difference with the Sun by adding a 120° to this value.
Chapter 2. PoGOLite

Figure 2.26: The observability predictions for Cygnus-X1 as calculated for the 1st of July 2013 at Kiruna for an instrument with a longitudinal velocity of zero. The angle between the target and the Sun is calculated from the azimuthal difference indicated by the vertical black line. The angle between the target and the Sun is calculated by adding a 120° to this value.
Figure 2.27: The observability predictions for GRS 1915+105 as calculated for the 1st of July 2013 at Kiruna for an instrument with a longitudinal velocity of zero. In the left upper corner the azimuthal difference between the target and the Sun is shown, in the right upper corner the elevation angle between the two is shown. Left down the total angular difference between the two is presented and in the lower right corner the airmass as a function of time is presented, the airmass of 2 is indicated by the vertical black line. The angle between the radiator and the Sun is calculated from the azimuthal difference with the Sun by adding a 120° to this value.
2.4.3 Flight Time lines

The launch of the maiden flight of the PoGOLite Pathfinder took place on July 6, 2011 at 23:57 (UTC). The balloon was damaged during launch resulting in a helium leak. The payload reached a maximum altitude of approximately 35 km and was cut from the balloon about 4 hours after launch. Due to the leak from the balloon the planned float altitude was not reached and no scientific measurements of the targets were performed. Background measurements at near float altitudes were conducted and flight tests of the operation of the instrument and the ACS have provided valuable information for future flights. For a more complete description of the 2011 flight and a study of the performance of the ACS and the polarimeter throughout the flight the reader is referred to [60].

The second flight opportunity of PoGOLite was during the summer of 2012. Bad weather conditions with unfavourable winds for launch made a launch impossible during the period in which westward winds were guaranteed for the full duration of the flight.

The second launch of the PoGOLite instrument took place on July 12, 2013. The instrument was launched for the start of its near circumpolar flight at 8:18 (UTC) and reached its float altitude at approximately 12:00 UTC. As a result of the relatively late launch time and the long ascension time, caused by a relatively cold atmosphere, the elevation of the Crab was starting to drop below 30° while the ACS was being commissioned. Only a limited amount of time was therefore spent to observe the Crab during the launch day. The commission of the ACS continued after the limited Crab observation and resulted in a performance of the ACS well within the required 0.1° pointing precision [81].

On the second and third day of operation observations of the Crab, Cygnus-X1 and GRS 1915+105 were performed. The small separation between the Crab and Sun resulted in high temperatures in the PCU box, and to a lesser extent in the polarimeter electronics, during the Crab observations. As a result the instrument was turned off for several hours after the Crab observation on the 13th of July. Communication was lost with the payload for several hours after the polarimeter was powered off. As a result no measurements were performed for several hours. The small angular separation between the Crab and the Sun furthermore made stable pointing challenging. This, in combination with the loss of communication during the Iridium phase of the flight, resulted in several pointing excursion off the Crab, finally resulting in a loss of observation time. The Cygnus-X1 and GRS 1915+105 observations were performed without any significant issues.

Towards the end of the Crab observation on July 14th an unexpected issue occurred with the power control system of the polarimeter hardware. A post-flight investigation showed that the FPGA on the board responsible for power control no longer booted correctly, making powering of the polarimeter hardware impossible. Potential causes of the board failure are overheating of the board, located in the PCU Box, or radiation induced damage. The power failure made it impossible to perform further measurements for the duration of the flight. It was however decided
to continue the flight to study the performance of the ACS and the circumpolar balloon path.

The flight was terminated 13 days after launch on the 25th of July at 23:24 UTC. The payload landed near the city of Norilsk in northern Russia 15 minutes after midnight on the 26th of July. The reason for termination of the flight was a drift of the trajectory of the balloon in a northern direction. As a result a landing in Scandinavia could not be guaranteed and stability in the stratospheric winds could not be guaranteed for a potential flight towards Greenland. The full flight path of PoGOLite during the 2013 flight can be seen in figure 2.28. A time line of the flight can be seen in figure 2.29. A total of $\approx 14$ hours was spent observing the Crab during this flight. The time spent on the other 2 targets was insufficient to perform any polarisation measurements given the lower fluxes of these two targets.

Figure 2.28: The path of PoGOLite during its 2013 flight. The flight track during which communication over E-link was possible is shown in purple while the part where communication was performed using Iridium is shown in brown. The crosses for the 26th, 27th and 28th of July indicate the predicted flight trajectory for these dates. Courtesy of SSC Esrange.

Due to the unforeseen landing in Russia recovery of the instrument took longer then expected. As a result the instrument and the full flight data, stored on the solid state disks in the payload, could not be studied until January 2014. Post-flight studies of the polarimeter performed in Stockholm showed that no significant damage to the instrument was sustained during the landing.
Sky and calibration targets are shown with red, green, blue and black.

Figure 2.29: The timeline of the 2013 flight of PoGOLite. Observations of the Crab, Cygnus-X1, GRS 1915-105 and blank sky.
Chapter 3

Atmospheric Neutron Environment

Due to the flight altitude and magnetic latitude of PoGOLite, a relatively high background rate is expected. This high rate, of both primary and secondary cosmic rays, was indeed measured during the short 2011 flight [60]. The instrument is optimised to minimise the number of triggers induced by cosmic rays and atmospheric radiation. The passive shielding of the system stops most particles while events induced by the remaining cosmic rays, like minimum ionizing particles, will be rejected by the active shielding. Two remaining particle species are able to produce a signal in the polarimeter indistinguishable from a signal event. These are neutrons and X- and gamma-rays. Previous Monte Carlo studies of the PoGOLite instrument have shown that the main source of background is induced by the neutron component, see for example [60] and [56] and references therein. Atmospheric neutrons were shown to be capable of producing double-hit events, indistinguishable from valid signal events, after entering the polarimeter. In both studies the induced double hit rate was shown to be of the same order of magnitude or larger than the signal rate expected during Crab observations. Due to its expected magnitude it is important to understand the exact rate and its variations during the PoGOLite flights. For this purpose two different approaches were employed. The first approach makes use of a dedicated neutron detector. One version of this detector was flown on the PoGOLite payload as discussed in section 2.1.3. The neutron detector was furthermore flown on a dedicated mission which is the topic of chapter 4. The second approach makes use of detailed Monte Carlo simulations aimed at providing the expected neutron induced counting rate during the PoGOLite flight. These simulations are the topic of this chapter.

The Monte Carlo based studies were started in [56]. The simulations of the induced rate made use of neutron spectra for an altitude corresponding to 5 g/cm² at Palestine, Texas. These spectra, which were originally presented in [82], were multiplied by a factor of 2 to account for the difference in magnetic latitude between
Palestine, Texas and the flight location of PoGOLite. Subsequent studies in [60], which made use of dedicated Monte Carlo simulations to find a more exact factor required for accounting for the difference in flight location, showed that, for solar minimum conditions, the factor of 2 previously employed was an underestimation. Instead a factor of 10 was found. The results presented in [60] were, however, only applicable for conditions encountered during an extreme solar minimum. For all other conditions this factor will be significantly less than 10. The work as started in [60] was expanded in order to find the correct neutron energy spectrum for all locations on Earth, all solar activities and all stratospheric altitudes. This chapter will start with a description of the process responsible for the neutron induced background in PoGOLite. This is followed by a description of the production processes of atmospheric neutrons and dependencies of their flux on altitude, magnetic latitude and solar activity. The performed Monte Carlo simulations will be described in detail in section 3. The results of these simulations are compared with previously published spectra in section 4. Finally the directional dependence of the neutron flux as predicted by the simulations will be presented in section 5.

3.1 Atmospheric Neutron Background

Three main processes exist through which a neutron can interact with matter: elastic scattering, inelastic scattering and absorption. These three processes are illustrated in figure 3.1. Both inelastic scattering and neutron absorption interactions result in an excited nucleus. The de-excitation of the nucleus after one of these reactions results in a number of particles with energies which typically exceed 1 MeV. For PoGOLite inelastic scattering and absorption will therefore not form a significant contribution to the background. However within the polyethylene shield atmospheric neutrons are expected to loose a significant amount of energy through these processes.

Elastic scattering of the neutrons in the fast scintillators is expected to be responsible for the most significant part of the PoGOLite background. The energy lost by a neutron through an elastic scattering process can be parametrized as:

\[
\frac{E}{E_0} = e^{-\xi}, \xi = \frac{4A}{(A+1)^2}.
\] (3.1)

With \(E_0\) the energy of the incoming neutron, \(E\) the energy after the elastic scattering and \(A\) the atomic number of the material with which the neutron scatters[83]. The energy loss through this process can be seen to be inversely proportional to \(A\). The energy loss is therefore maximum for scattering interactions with hydrogen. This is the primary reason for the choice of polyethylene, which has a hydrogen to carbon ration of 1 to 1 and a high density, as the passive shielding material of the instrument.

Neutrons scattering between the fast scintillator bars can produce background in the PoGOLite energy range both by scattering from hydrogen and carbon. To calculate the measured energy for one of these events, quenching effects become
3.1. Atmospheric Neutron Background

Figure 3.1: An illustration of the three major neutron interactions. Elastic scattering is shown at the top. Inelastic scattering followed by gamma emission in the middle and neutron absorption, followed by gamma/α/β/neutron emission is shown at the bottom.

Important. Quenching effects, which are discussed in detail in chapter 5 are a result of the lower efficiency for heavy ionising particles to create scintillation photons compared to electrons. For neutron scattering events, it is not the neutron itself which produced scintillation photons in the scintillator, but rather the recoil nucleus which is considerably heavier than an electron. The scintillation light yield for a recoil nucleus is significantly lower than that from an electron. For a hydrogen atom the relative light yield, or quenching factor, is of the order of 0.1, for heavier nuclei the quenching factor becomes even smaller. Neutrons capable of inducing a signal in PoGOLite must therefore have energies exceeding several hundred keV. Before depositing energy in the plastic scintillators however, the neutrons will most likely have lost a significant amount of energy in the polyethylene shield, their
Chapter 3. Atmospheric Neutron Environment

initial energy can therefore be significantly higher. For the background study of PoGOLite it is therefore neutrons in the energy range exceeding $\sim 100\text{keV}$ which are of interest.

3.2 Atmospheric Neutrons

Neutrons are produced as secondary particles in cosmic ray induced air showers. The majority are produced in hadronic air showers, induced by cosmic ray protons or helium nuclei. In electromagnetic air showers, induced either by cosmic gamma rays or electrons, a small hadronic component can be formed in which neutrons are also produced. This hadronic component is, however, small and as a result only a few percent of the shower consists of hadrons. At low altitudes a second source of neutrons is radioactivity in the Earth’s crust. The high density of the atmosphere at ground level results in a short mean free path for these neutrons. As a result these neutrons lose their energy in a relatively short distance and the neutron component resulting from radioactivity is therefore only relevant near the Earth’s surface. Lastly a negligible contribution from neutrons with a solar origin exists. For the remainder of this chapter only the contribution coming from hadronic air showers, which dominates the other components at the relevant altitudes, will be considered.

Within the hadronic shower neutrons can be produced through three different processes. Charge-exchange interactions between incoming protons and atmospheric nuclei result in the highest energy neutrons. In such a reaction a proton with a cosmic origin interacts weakly with an atmospheric nucleus resulting in a high energy neutron and a charged excited nucleus. The resulting neutron will carry approximately the momentum of the original proton. Neutrons produced through this process will therefore preferentially have a momentum in the direction of the Earth’s surface. Since the interaction takes place through the exchange of $W^\pm$, the cross section is relatively small at sub-GeV energies and only becomes relevant for high energies, resulting in neutrons with typical kinetic energies exceeding 1 GeV.

The second process responsible for atmospheric neutron production is commonly referred to as the intranuclear cascade. In this process the incoming cosmic hadron collides head on with a nucleus. Since the typical wavelength of the incoming particle is shorter than the radius of the nucleus, the cosmic hadron interacts with a nucleon inside the atmospheric nucleus rather than the nucleus itself. The nucleon gains significant momentum in the interaction. Subsequently it travels through the nucleus interacting with the other nuclei and produces hadrons along the way. A cascade is formed inside the nucleus, hence the name for this production mechanism [84]. The nucleus can be considered as a fully degenerate Fermi gas, meaning that all the lowest energy levels in the nucleus are occupied. As a result newly created hadrons in the cascade are required, by the Pauli Exclusion principle, to have an energy exceeding that of the highest occupied state in the nucleus. Typically this is of the order of a few MeV [84]. Neutrons produced in the intranuclear cascade
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therefore have typical energies of 10's to 100's of MeV with a momentum in the direction of the Earth’s surface.

The final products of the intranuclear cascade are a range of newly created hadrons and the left over nucleus which, due to the cascade, is left in an excited state. After the cascade the nucleus returns to its ground state by emitting its excess energy in the form of particles. While its excitation energy exceeds the binding energies of its nucleons, these can be expelled from the nucleus. This process is commonly referred to as evaporation. In this process protons and neutrons are emitted from the nucleus isotropically in the rest frame of the nucleus. The momentum of neutrons produced through this process is therefore more isotropic in nature than those produced through the two previously described processes. The typical production energy of these neutrons is around 1 MeV. When the excitation energy of the nucleus drops below a few hundred keV, hadrons can no longer be emitted and the remaining energy is therefore emitted in the form of photons. A schematic representation of atmospheric neutron production in a hadronic shower is shown in figure 3.2.
Subsequent to production neutrons can interact with the atmosphere through the three interaction mechanisms described before, elastic scattering, inelastic scattering and absorption. High energy neutrons can interact through inelastic scattering with atmospheric nuclei resulting potentially in additional lower energy neutrons. The majority of neutrons with energies in the MeV range and below will lose most of their energy through elastic scattering interactions with atmospheric nuclei. With each scattering interaction the direction of the neutron is altered. The momentum distribution of a neutron population therefore becomes more isotropic as the neutrons undergo more elastic scattering interactions. Neutrons continue to lose energy to the atmospheric nuclei through this process until their kinetic energy is equal to that of the atmosphere surrounding them, which is typically of the order of a few eV. At this point the neutrons are said to be thermalised, while the process of multiple elastic scattering interactions is referred to as thermalisation. At thermal energies the absorption cross sections for neutrons by different atmospheric nuclei furthermore becomes relevant. An example of such a reaction is neutron absorption by $^{14}$N resulting in $^{14}$C and a free proton.

Whereas the momentum of high energy neutrons is typically directed towards the Earth’s surface the majority of neutrons move upward at stratospheric altitudes. This is a result of the density gradient of the atmosphere which results in a shorter mean free path for neutrons in the direction of the Earth’s surface than in the upward direction. A significant number of neutrons will therefore leave the atmosphere before decaying as: $n \rightarrow p^+ + e^- + \bar{\nu}_e$. This process is partly responsible for the charged particles in the Earth’s radiation belts. The rest of the neutrons either decay in the atmosphere or are absorbed by atmospheric nuclei.

Due to the three different production mechanisms and the subsequent thermalisation the energy range in which atmospheric neutrons are found spans many orders of magnitude. Thermalised neutrons have typical energies in the sub-eV range while neutrons produced through charge-exchange reactions can have energies of hundreds of GeV. A typical energy spectrum of atmospheric neutrons multiplied by the neutron energy can be seen in figure 3.3. Two clear peaks can be observed in this spectrum, one centred around 1 MeV and one around 100 MeV. The first peak is caused by neutrons produced through evaporation while the second by neutrons produced in the intranuclear cascade. The area between the peaks is populated by neutrons produced either by the intranuclear cascade or charge-exchange interactions which have already undergone elastic scattering interactions. The low energy region is populated by thermalising neutrons.

When dividing the spectrum, shown in figure 3.3, by the energy one recovers the differential neutron energy spectrum. In the 8 keV – 1 GeV region this spectrum can be approximated well using 4 power laws. An example of such a differential energy spectrum is shown in figure 3.4. The first power law extends from 8 keV up to 900 keV. This region is populated by thermalising neutrons and neutrons produced through the evaporation process. The lower energy limit of 8 keV is dictated by a change in slope below this energy, neutrons populating the region below 8 keV are furthermore not relevant for the background studies of PoGOLite. The second
3.2. Atmospheric Neutrons

Figure 3.3: A differential neutron energy spectrum multiplied by the neutron energy measured at an altitude of $\approx 20$ km and a magnetic latitude of $58^\circ$. The data points were taken from [86]. Reproduced from [101] with permission, © (2014) Elsevier.

Figure 3.4: The black markers show the spectrum from figure 3.3 divided by the energy. The data points are fitted with 4 power laws in the regions $8 - 900$ keV (blue), $0.9 - 15$ MeV (green), $15 - 70$ MeV (red) and $70 - 1000$ MeV (purple).
Chapter 3. Atmospheric Neutron Environment

power law starts at 900 keV around which the first peak in figure 3.3 can be found, which in the differential neutron spectrum is seen as a kink in the spectrum. This region extends up to 15 MeV at which the minimum in figure 3.3 can be seen. The third power law starts at this energy and extends up to the maximum of the intranuclear cascade peak found at 70 MeV. Above this energy the spectrum can be approximated well by a power law up to 1 GeV.

The average interaction altitude of cosmic protons in the atmosphere lies around 100 g/cm$^2$ which corresponds to an altitude between 15 and 20 km, depending on the atmospheric conditions. The maximum neutron flux is therefore encountered around these altitudes. After production the majority of the neutrons will have a momentum in the direction of the Earth’s surface, however, due to the atmospheric pressure gradient, after several scattering interactions most neutrons will have their momentum directed away from the Earth’s surface. The flux encountered in the lower part of the troposphere is therefore low. At ground level the flux is approximately three orders of magnitude smaller than that found around 100 g/cm$^2$ [86]. Above the maximum the flux drops off due to the loss of neutrons through inelastic interactions, decay and absorption. Furthermore, both above and below the maximum the spectrum shifts towards lower energies. Both the normalisation and the slopes of the power laws which describe the differential neutron spectrum are therefore expected to vary with altitude.

The neutron spectra are furthermore expected to vary with magnetic latitude. This dependency is correlated to the dependency of the incoming charged cosmic ray flux on the magnetic latitude, a result of the dipole nature of the Earth’s magnetic field. At the equator the Earth’s magnetic field shields the Earth from charged cosmic rays with rigidities below $\sim 15$ GV whereas at the magnetic poles only charged cosmic rays with rigidities below a few hundred MV are unable to enter the atmosphere. The cosmic ray rigidities for which the magnetic field provides shielding, referred to as the cut-off rigidity, is shown as a function of the location on Earth in figure 3.5. The cosmic ray proton and alpha flux impinging on the Earth’s magnetic field drops of steeply with energy in the GeV region. The difference in cut-off rigidity therefore results in a significantly higher incoming charged cosmic ray flux at the poles with respect to the equator. The neutron flux is therefore also significantly higher near the poles.

The observed neutron flux is furthermore affected by the magnetic field frozen in the solar wind. The solar wind affects the Local Interstellar Spectrum (LIS) similar to the Earth’s magnetic field. The strength of the field varies along with the solar activity, resulting in a lower incoming cosmic ray flux during a solar maximum than during a solar minimum. As an example the cosmic ray proton energy spectrum as measured by the PAMELA experiment during different periods of low solar activity is shown in figure 3.6. The figure shows the increased flux at the end of 2009, which coincides with a solar minimum, with respect to the other periods. The increase is most prominent at the lower energy part of the spectrum. The dependency on the solar activity can be expressed using the force-field approximation [88]. The amount of modulation of the LIS by the magnetic field is expressed using a potential term.
3.2. Atmospheric Neutrons

Figure 3.5: The calculated geomagnetic cut-off (in GV) in the cosmic ray spectrum as calculated for 450 km altitude as a function of longitude and latitude [87]. For protons the presented values are equal to the cut-off energy in GeV. The latitude of the PoGOLite flight is shown indicated using the red line, the latitude of one of the balloon launch sites of CSBF/NASA, Palestine Texas, is shown in blue. Reproduced from [87] with permission, © (2005) Elsevier.

\( \phi \). For periods with a low solar activity typical values of \( \phi \) are around 350 MV, whereas for periods with a high solar activity this is \( \approx 1250 \) MV [89]. It should be noted here that the exact value of \( \phi \) depends on the used approximation of the spectral shape of the LIS [90]. For the work presented here we assume the proton LIS from [91].

The dependencies of the neutron flux on magnetic latitude and solar activity are both a result of magnetic fields which modulate the incoming cosmic ray spectrum. Both effects affect the same part of the incoming spectrum, as a result the two dependencies are correlated. The solar modulation of the neutron flux is most pronounced near the poles whereas at the equator solar modulation of the neutron flux is negligible. The neutron production cross section as a function of proton energy can furthermore be considered to be constant for proton energies above 1 GeV. Below 1 GeV the cross section decreases rapidly. As a result the modulation of the incoming proton spectrum only affects to the total number of neutrons produced whereas the spectral shape is relatively unaffected below for neutron energies below 1 GeV [86]. The spectral shape above 1 GeV does depend on both parameters as can be seen in figure 3.3.
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3.3 Simulations Procedure

The atmospheric neutron environment was simulated using the PLANETOCOSMICS simulation package [93]. PLANETOCOSMICS contains models of the magnetic field, surface and atmosphere of different planets including the Earth. The user can setup the required geometry of the planet, in this case the Earth, together with a source emitting particles with the desired energy spectrum. The Geant4 simulation toolkit [94] is used by PLANETOCOSMICS to handle the particle interactions. For the simulations performed here an unreleased version of PLANETOCOSMICS, compatible with Geant4.9.5.p02, was used. The Geant4 physics model used for handling particle interactions was the QGSP_BIC_HP [95] physics list. Which treats protons and neutrons with energies between 20 MeV and 10 GeV using the Binary Cascade Model. For scattering interactions of neutrons with energies below 20 MeV the G4NDL4.0 data set [96] is used. The Earth was modelled using a spherical model with a radius of 6371 km with the surface consisting fully of SiO$_2$. The composition and density of the atmosphere was modelled according to the NRLMSISE00 model [97] for 0 degrees latitude and longitude and was set to extend up to 100 km. The internal magnetic field was modelled using the IGRF model [98] using the reference date of the 1st of January 2000. The outer magnetic field and the magnetopause were modelled according to the TSY2001 model [99].

The cosmic ray hadrons were emitted isotropically from a sphere centred around the Earth with a radius of $2 \times 10^6$ km. The incoming hadronic cosmic ray component was modelled as consisting of both protons, contributing 90% of the total number of particles and $\alpha$ particles which made of the remaining 10%. The sec-

Figure 3.6: Cosmic ray proton spectra for different periods of solar activity as measured by the PAMELA experiment. The spectrum as measured during December 2009 can be considered to be a spectrum for a solar minimum. Reproduced from [92] with permission, © (2013) AAS.
ondary particles created in the atmosphere were sampled at altitudes corresponding to 550 hPa (\(\approx 5 \text{ km}\)), 234 hPa (\(\approx 11.3 \text{ km}\)), 100 hPa (\(\approx 16 \text{ km}\)), 55 hPa (\(\approx 20 \text{ km}\)), 25 hPa (\(\approx 25 \text{ km}\)), 12 hPa (\(\approx 30 \text{ km}\)), 6 hPa (\(\approx 35 \text{ km}\)), 3 hPa (\(\approx 40 \text{ km}\)), 0.225 hPa (\(\approx 60 \text{ km}\)), 0.00025 hPa (\(\approx 99 \text{ km}\)) and 0 hPa. Thereby making it possible to produce neutron energy spectra for these altitudes for all magnetic latitudes.

Solar modulation effects on the incoming cosmic ray spectra were taken into account by dividing the incoming proton and alpha spectra into separate energy ranges. The incoming spectra for each primary particle species was divided in a total of 11 mono-energetic emission energies ranging between 1 GeV and 15 GeV. The energy range between 20 GeV and 1000 GeV was represented as a power law with a slope of \(\approx -2.7\) which represents the LIS at these energies. Simulations were performed for each energy range individually. The different simulation results could then be combined such that the incoming proton and alpha spectra represented those measured at different periods of solar activity. The spectrum representing that of solar minimum conditions was recreated using normalisation constants based on the spectrum measured by the PAMELA experiment during December 2009 [92]. For a high solar activity, with \(\phi = 1109 \text{ MV}\), the spectra measured by BESS during the Summer of 2002 [100] were used. By combining the simulation results according to the incoming hadronic spectra for a certain solar activity the neutron energy spectra can be created for that solar activity without having to redo the simulations. The combination of the simulation results therefore contains all the information required to produce neutron energy spectra for the above mentioned altitudes, all magnetic latitudes and all solar activities.

### 3.4 Results

#### 3.4.1 Parametrisation

**Altitude Dependence**

Neutron energy spectra acquired from the simulations were fitted in the range of 8 keV and 1 GeV using 4 power laws as described before. The lower energy limit here is dictated by a change in slope at this energy, while the neutrons populating the region below 8 keV are not relevant for the background study of PoGOLite. The upper energy limit of 1 GeV is determined by the limited amount of simulation statistics. The neutron population above this energy can furthermore be neglected in the PoGOLite background studies due to its low flux. The influence of the Earth’s surface furthermore becomes important at low altitudes, the neutron flux below 550 hPa (\(\approx 5 \text{ km}\)) was therefore not studied.

The normalisation of the different power laws which were found to best fit the simulation results are referred to as \(A, B, C\) and \(D\) for the ranges 8 – 900 keV, 0.9 – 15 MeV, 15 – 70 MeV, 70 – 1000 MeV respectively. For the same regions the slopes will be referred to as \(\alpha, \beta, \gamma\) and \(\delta\), respectively. The correlation between the fit parameter \(A\) and the altitude was investigated first. When the altitude is
Figure 3.7: The altitude dependence of the normalisation (8-900 keV) for power law parametrisation of simulated neutron differential energy spectra for 4 different magnetic latitudes (30° in blue, 40° in red, 50° in green and 60° in black) together with the fitted functions of the form $A = [ah + b]e^{-h/c} + d$ for a solar minimum. The presented error bars are the fitting errors of the power law fits. Reproduced from [101] with permission, © (2014) Elsevier.

expressed in atmospheric pressure, $h$ (hPa), the following relation was found to best describe parameter $A$:

$$A = [ah + b]e^{-h/c} + d \quad (3.2)$$

This can be seen in figure 3.7 where the values of $A$, acquired by fitting the simulation results for the different altitudes for the magnetic latitudes 30°, 40°, 50° and 60° are plotted. The simulation results are for solar minimum conditions. The values of $A$ were fitted using a function of the form $A = [ah + b]e^{-h/c} + d$. The reduced $\chi^2$ values, with 7 degrees of freedom, for all performed fits was found to be in the range of 0.4 to 1.8 with a mean value of 0.9. It can therefore be concluded that this function describes the altitude dependence of $A$ well for all magnetic latitudes. Similar results were found for solar maximum conditions. The altitude dependence shows an exponential decay, dictated by the (positive) parameter $b$, for high atmospheric pressures and an exponential increase, dictated by the (positive) parameter $a$ for low pressures, starting from a plateau level defined by the parameter $d$. The altitude where the exponential decay starts, which coincides with the altitude where the maximum neutron flux is found, is dictated by the parameter $c$. The minimum number of parameters required to describe the altitude dependence is therefore four.
3.4. Results

Figure 3.8: Parameters $a, b, c$ and $d$ plotted as a function of magnetic latitude for a solar minimum fitted with functions of the form $p_0 + p_1(1 - \tanh(p_2\lambda))$. The presented error bars are the fitting errors. Reproduced from [101] with permission, © (2014) Elsevier.

Magnetic Latitude and Solar Dependence

The parameters describing the altitude dependence of $A$ vary with magnetic latitude, as can be seen in figure 3.7. They can furthermore be found to vary with solar activity. The values of the four parameters were extracted from fits of parameter $A$ as shown in figure 3.9. The resulting values from these fits together with the fitting errors are shown in figure 3.8 as a function of magnetic latitude. The dependency on magnetic latitude can be described using a $p_0 + p_1(1 - \tanh(p_2\lambda))$ relationship for $a, b, c$ and $d$. A minimum of 3 parameters is therefore required to describe the magnetic latitude dependence.

Using the same procedure as that used to find the altitude dependence of $A$ the parameters $a, b, c$ and $d$ were found to be best described as a function of magnetic latitude and solar activity using:

\[
a = 6.0 \times 10^{-4} + (1.85 - 1.35 S) \times 10^{-2} \left[1 - \tanh(180 - 3.5\lambda)\right], \quad (3.3)
\]

\[
b = 1.1 \times 10^{-2} + (1.2 - 0.8 S) \times 10^{-1} \left[1 - \tanh(180 - 3.5\lambda)\right], \quad (3.4)
\]

\[
c = 150 - 33 \left[1 - \tanh(180 - 5.5\lambda)\right], \quad \text{and,} \quad (3.5)
\]

\[
d = -4 \times 10^{-3} + (2.4 - 1.0 S) \times 10^{-2} \left[1 - \tanh(180 - 4.4\lambda)\right] \quad (3.6)
\]
Where \( \lambda \) is the magnetic latitude, measured in degrees, and \( S \) is a parameter expressing the solar activity. The reduced \( \chi^2 \) values for the performed fits with 12 degrees of freedom were in the range of 0.5 to 1.9 with a mean of 1.1. The parameter \( S \) is zero for extreme solar minimum conditions with \( \phi = 250 \text{MV} \) and equal to unity for conditions where \( \phi = 1109 \text{MV} \). The value of \( S \) varies linearly with \( \phi \) between these two extremes. It should be noted here that the incoming cosmic ray spectrum for a given magnetic latitude varies additionally with geomagnetic conditions. The parametrisation is presented here is therefore only valid for standard geomagnetic conditions similar to those on January 1st 2000.

The resulting value of \( A \) can now be plotted as a function of altitude and magnetic latitude for different solar activities. In figure 3.9 the result can be seen for solar minimum conditions. The figure shows the large increase of \( A \) with magnetic latitude at locations corresponding to cut-off rigidities above 1 GV. For lower cut-off rigidities the value of \( A \) can be seen to become stable. This is a result of the decreasing neutron production cross section for protons with energies below 1 GeV.

In order to visualise the error on parameter \( A \) from this model the deviations of the model from the original Monte Carlo data is shown in figure 3.10 and 3.11 for solar minimum and solar maximum conditions respectively. The figures show the ratio between the value of \( A \) from the model and the value from the Monte Carlo data. The largest deviations between the model and the fitted Monte Carlo data is observed in the regions where the neutron flux is low. As a result the Monte Carlo data is statistically limited in these regions. The deviation between the data and the model can therefore be assumed to be mainly a results of statistical fluctuations in the data. The values presented in the figures are distributed as a Gaussian around 1 and have a standard deviation of 9% and 13% for solar minimum and solar maximum respectively.

**Slopes**

After having parametrised the normalisation parameter \( A \), a similar procedure was used to find the dependency of the slope parameters \( \alpha, \beta, \gamma \) and \( \delta \) on altitude. The slope parameters \( \alpha, \beta \) and \( \delta \) were plotted as a function of altitude and were found to be best approximated using exponentials reaching a plateau at high atmospheric pressures. A minimum of three parameters is therefore required to describe these slope parameters. The parameter of \( \gamma \) was additionally found to decrease exponentially at high atmospheric pressures, an extra parameter was therefore required to best represent its dependency on altitude. As the slope parameters are not expected to depend on magnetic latitude and solar activity the amount of Monte Carlo data available to constrain the functions is relatively high, resulting in small errors on the functions describing the dependency on altitude. The parameters were found to be best approximated by:

\[
\alpha = -(0.281 \pm 0.003) e^{-h/(4.6\pm0.1)} + (0.732 \pm 0.002),
\] (3.7)
Figure 3.9: The normalisation parameter $A$ as a function of altitude and magnetic latitude for a solar minimum. Reproduced from [101] with permission, © (2014) Elsevier.

$$
\beta = -(0.186 \pm 0.005) e^{-h/(13.2\pm1.2)} + (1.308 \pm 0.003), \quad (3.8)
$$

$$
\gamma = [(0.011 \pm 0.001) h + (0.30 \pm 0.03)] e^{-h/(68.0\pm9.7)} + (0.26 \pm 0.03), \quad \text{and}, \quad (3.9)
$$

$$
\delta = (0.66 \pm 0.03) e^{-h/(8.5\pm0.6)} + (1.40 \pm 0.02) \quad (3.10)
$$

The dependency of the slope parameters on altitude is shown in figure 3.12. No dependency on magnetic latitude and solar activity was found for these parameters. Using the following relations the values of $B$, $C$ and $D$ can now be calculated as:

$$
B = A 0.9^{-\alpha+\beta}, \quad (3.11)
$$

$$
C = B 15^{-\beta+\gamma}, \quad \text{and}, \quad \quad (3.12)
$$

$$
D = C 70^{-\gamma+\delta} \quad (3.13)
$$

With the four normalisation parameters $A$, $B$, $C$ and $D$ and the corresponding slope parameters the neutron energy spectra in the energy range $8 \text{keV} - 1 \text{GeV}$ can now be calculated for all atmospheric pressures below 550 hPa, all magnetic latitudes and all solar activities.
3.4.2 Comparisons with Other Work

Spectra resulting from these parametrisations can be compared with simulation results from [82]. These simulation results were previously used in the first PoGOLite background studies presented in [102] and [56]. The spectra presented in [82] are for a magnetic latitude of 42 degrees and solar minimum conditions. Spectra are presented for different altitudes. Furthermore comparison can be made with simulation results presented in [103]. In [103] it was shown that Geant4 based Monte Carlo simulations can be used to reproduce the atmospheric neutron environment well for specific, mainly low, altitudes, all cut-off rigidities and all solar activities by comparing results to available measurement data. Using the model presented in this thesis neutron energy spectra were calculated for three different altitudes 0 hPa, 5 hPa and 100 hPa for which spectra are presented in [82]. In [103] data is only presented for altitudes corresponding to 5 hPa and 105 hPa. Data for these altitudes are therefore also used for comparison for a cut-off rigidity of 3.8 GV and a solar activity of 250 MV. The results from the parametrisation simulations can be seen in figure 3.13 to agree well for the different altitudes with both studies.

Predictions from the parametrisation model can furthermore be tested with spectra measured on high altitude aircraft flights. First the model predictions are tested against measurements presented in [86]. The data presented in [86] was taken at an altitude of 20 km or 56 hPa, a magnetic latitude of 60.2° during a solar
3.5 Directional Dependence

The presented parametrisation model considers a $4\pi$ integrated atmospheric neutron flux. For balloon-borne instruments, like PoGOLite, the directional dependence of the neutrons is of additional importance. Among other effects an anisotropic flux could potentially lead to an uneven interaction distribution in PoGOLite which may be interpreted as a polarisation signal. The level of anisotropy is expected to

Figure 3.11: The ratio of parameter $A$ as resulting from the model and the Monte Carlo data. Both the values of the model and the Monte Carlo data are for solar maximum conditions. The ratio values are distributed as a Gaussian around unity and have a standard deviation of 9%. Reproduced from [101] with permission, © (2014) Elsevier.

activity corresponding to $\phi = 405$ MV. The spectrum as predicted by the model is plotted together with the data from [86] in figure 3.14. A second comparison with data from [104] is also shown in the figure. The data presented in [104] was taken at an altitude of 11.28 km, a magnetic latitude of 26° during a solar activity corresponding to $\phi = 660$ MV. It can be seen that the spectra as calculated with the parametrisation model agree well with both sets of measurement data. Small discrepancies can be seen around the evaporation peak. This is a result of large fluctuations in the measurement data observed at these energies whereas the spectrum resulting from the model is simplified to be a broken power law. From the comparisons it can be concluded that the model predictions agree well with measurement data recorded at different magnetic latitudes.
depend strongly on the altitude. The directional dependence of the neutron flux therefore needs to be studied including altitude dependence.

The neutron flux resulting from the simulations was divided into an upward and a downward component where the upward flux is defined as the flux consisting of all neutrons with momentum directed away from the Earth’s surface. The simulation data was analysed in the same way as presented previously for the omnidirectional data.

### 3.5.1 Upward component

Parameter $A$ of the upward moving component was found to be best described using the following parametrisation:

$$A = [ah + b] e^{-h/c} + d. \quad (3.14)$$

Parameters $a, b, c$ and $d$ were found to vary with magnetic latitude $\lambda$ and solar activity $S$ according to:

$$a = 3.0 \times 10^{-4} + (7.0 - 5.0 S) \times 10^{-3} [1 - \tanh(180 - 4.0\lambda)], \quad (3.15)$$

$$b = 1.4 \times 10^{-2} + (1.4 - 0.9 S) \times 10^{-1} [1 - \tanh(180 - 3.5\lambda)], \quad (3.16)$$
3.5. Directional Dependence

Figure 3.13: Simulation results of the differential neutron flux for three different altitudes as extracted from [82] (stars), [103] (circles) and as predicted by the model presented here (solid lines). The uncertainties from the model presented here are indicated by the dashed lines. The atmospheric overburden of 0 g/cm$^2$ is shown in red. The atmospheric overburden of 5 g/cm$^2$ is shown in blue. The atmospheric overburden of 100 gr/cm$^2$ is shown in black. For the results from [82] the incoming cosmic ray spectrum was assumed to be a perfect power law, results from the model presented here are calculated using $\phi = 250$ MV, a magnetic latitude of 42$^\circ$. For the simulation results from Nesterenok a cut-off rigidity of 3.8 GV is used. Reproduced from [101] with permission, © (2014) Elsevier.

\[ c = 180 - 42 [1 - \tanh(180 - 5.5\lambda)] , \text{ and,} \]
\[ d = -8.0 \times 10^{-3} + (6.0 - 1.0 S) \times 10^{-3} [1 - \tanh(180 - 4.4\lambda)] \] (3.17) (3.18)

The slope parameters $\alpha$, $\beta$, $\gamma$ and $\delta$ were found to depend on altitude as:

\[ \alpha = -(0.290 \pm 0.005)e^{-h/(7.5\pm0.4)} + (0.735 \pm 0.004), \] (3.19)
\[ \beta = -(0.247 \pm 0.008)e^{-h/(36.5\pm5)} + (1.4 \pm 0.0), \] (3.20)
\[ \gamma = -(0.40 \pm 0.05)e^{-h/(40\pm10)} + (0.90 \pm 0.05), \text{ and,} \] (3.21)
Figure 3.14: The differential neutron flux multiplied by the energy from measurement data extracted from [86] (blue) and from measurement data extracted from [104] (black). The data from [86] was taken on an aircraft at an altitude of 20 km at 54° N, 117° W, during the summer of 1997. The data from [104] was taken on an aircraft at an altitude of 11.28 km, a magnetic latitude of 26° on February 27, 1985. The data from [86] is compared to spectra as predicted by the presented model (red) for an altitude of 20 km (pressure of 56 g/cm²), magnetic latitude of 60.2° and $\phi = 405$ MV. The data from [104] is compared to spectra as predicted by the presented model (red) for an altitude of 11.28 km (pressure of 218 g/cm²), magnetic latitude of 26.0° and $\phi = 660$ MV. Data points were presented without errors in [86] and [104]. Reproduced from [101] with permission, © (2014) Elsevier.

$$\delta = -(0.46 \pm 0.03)e^{-h/(100\pm11)} + (2.53 \pm 0.03)$$  \hspace{1cm} (3.22)

The dependence on altitude, magnetic latitude and solar activity of the normalisation and slope parameters were found to be similar to the omnidirectional flux.

3.5.2 Downward component

The dependency of parameter $A$ on the altitude was found to be well described for the downward flux using:
3.5. **Directional Dependence**

\[ A = [ah - b]e^{-h/c} + b. \] (3.23)

Parameter \( d \), as used previously to describe the dependency of \( A \) on altitude, is found to be equal to \( b \) for the downward component. From this relation it can be observed that, as expected, the flux of the downward component approaches 0 at high altitudes. The dependency of parameters \( a, b \) and \( c \) were found to vary with magnetic latitude and solar activity according to:

\[ a = 3.0 \times 10^{-4} + (1.1 - 0.8 S) \times 10^{-2} [1 - \tanh(180 - 3.5\lambda)], \] (3.24)

\[ b = 1 \times 10^{-3} + (1.5 - 0.75 S) \times 10^{-2} [1 - \tanh(180 - 4.0\lambda)], \text{ and,} \] (3.25)

\[ c = 1.40 \times 10^{-2} - 33 [1.0 - \tanh(180 - 5.0\lambda)] \] (3.26)

The slope parameters \( \alpha \) and \( \beta \) were found to be constant for the downward component, whereas the parameters \( \gamma \) and \( \delta \) were found to behave in a way similar to those in the description of the omnidirectional and upward flux. The following relationships on altitude were found for the downward components:

\[ \alpha = (0.738 \pm 0.003), \] (3.27)

\[ \beta = (1.270 \pm 0.003), \] (3.28)

\[ \gamma = [(0.007 \pm 0.001)h + (0.84 \pm 0.02)]e^{-h/(52\pm5)} + (0.110 \pm 0.005), \text{ and,} \] (3.29)

\[ \delta = (-0.27 \pm 0.03)e^{-h/(230\pm40)} + (1.45 \pm 0.02), \] (3.30)

The parameter \( A \) is shown both for the upward and downward component in figures 3.15a and 3.15b respectively. The parameters \( B, C \) and \( D \) can again be calculated using the combination of \( A \) and the slope parameters. As for the the omnidirectional flux the standard deviations of the relative differences between the value of parameters \( A \) resulting from the model and this value directly from the Monte Carlo data was calculated for both the upwards and downward component. For the upward component the deviation is 14%, for the downward component 16%. The larger values of these standard deviations are a result of lower statistics in the simulation data. This is a result of the division of the Monte Carlo data in an upward and downward component thereby reducing the statistics. The parametrisations of the upward and downward component of the neutron flux will be validated against flight data of the PoGOLino experiment in chapter 4. It will furthermore be used to simulate the neutron induced background rate in PoGOLite as a function of time during its 2013 flight in chapter 5.
(a) Normalisation parameter $A$ for the upward moving spectrum as a function atmospheric pressure and magnetic latitude for a solar minimum ($\phi = 250$ MV). Reproduced from [101] with permission, © (2014) Elsevier.

(b) Normalisation parameter $A$ for the downward moving spectrum as a function atmospheric pressure and magnetic latitude for a solar minimum ($\phi = 250$ MV). Reproduced from [101] with permission, © (2014) Elsevier.

Figure 3.15
Chapter 4

The PoGOLino Detector

A dedicated balloon-borne neutron detector, called PoGOLino, was developed by the PoGOLite Collaboration. The instrument provided data on the high latitude neutron environment after being launched to an altitude of 31 km from the Esrange Space Centre (ESC) on the March 20th 2013. This data was used to validate the atmospheric neutron energy spectra calculated using the direction dependent parametrisation model developed in the previous chapter. PoGOLino makes use of a LiCAF-based neutron detector unit of the type flown on the PoGOLite instrument as described in chapter 2. The PoGOLino instrument thereby serves the secondary purpose of flight testing this novel type of neutron detector.

The first section of this chapter will provide a detailed description of the PoGOLino instrument. This is followed by a description of the on-ground calibration performed on the instrument prior to flight. Finally the PoGOLino flight is described together with the flight results in section 4.3 where a comparison with simulations, based on spectra calculated using the model presented in chapter 3, is also presented.

4.1 Instrument Design

4.1.1 PDC Design

PoGOLino makes use of LiCAF scintillators for neutron detection. Scintillator based detection has advantages over other neutron detection techniques, such as gas based $^3$He detection, since it provides the possibility to produce a light weight and mechanically simple instrument. These features are especially advantageous for balloon-borne detectors. LiCAF is a novel type of scintillator developed at the Tokuyama Corporation, Japan [63]. The scintillator contains $^6$Li which has a high cross section, 940 barn for capturing sub-eV, or thermal, neutrons. Neutron capture by $^6$Li proceeds as follows:
\[ ^6\text{Li} + n \rightarrow ^4\text{He} \ (2.73 \text{ MeV}) + ^3\text{T} \ (2.05 \text{ MeV}) \]

The two high energy charged decay products will lose their energy through ionisation and thereby produce scintillation light within several microns. All their energy will therefore be deposited within the scintillator, resulting in a characteristic mono-energetic energy deposition for each neutron capture reaction. Pulse height discrimination can therefore be applied to distinguish neutron capture events from, for example, photon or charged particle induced energy depositions in the scintillator material. The type of LiCAF used, both in PoGOLino and PoGOLite, is europium doped LiCAF, the characteristic energy deposition corresponds to $3 \times 10^4$ photons/neutron capture \[62\]. The high number of scintillation photons produced per neutron capture reaction makes pulse height discrimination more efficient than for the other variant of LiCAF, cerium doped LiCAF. For cerium doped LiCAF the light yield for a neutron capture reaction is $3.5 \times 10^3$ photons/neutron capture \[105\]. Cerium doped LiCAF has a significantly shorter signal rise time of 40 ns than europium doped LiCAF, 1600 ns, however due to the low count rate expected during flight a long rise time is not problematic. The LiCAF crystals used on PoGOLino are of a newer type than that integrated in the PoGOLite polarimeter. The \( ^{6}\text{Li} \) content in the crystals used in PoGOLino is enriched to 95%, while for PoGOLite this is 50%, resulting in a higher detection efficiency for the PoGOLino crystals.

The neutron capturing material, \( ^{6}\text{Li} \), is incorporated in the scintillator structure resulting in a relatively high density of the this material and therefore a high detection efficiency for thermal neutrons. The scintillator material furthermore has a relatively low effective atomic number, resulting in a lower photon and charged particle induced background during flight. In order to further reduce the charged particle and photon induced background experienced during flight, the hexagonal LiCAF scintillator used on PoGOLino, which has a thickness of 5 mm and a side length of 16 mm, is sandwiched between two BGO crystals to form a PDC unit. The BGO crystals placed on either side of the LiCAF scintillator provide an anti-coincidence system for high energy photons and charged particles. BGO is transparent for the emission wavelength of europium doped LiCAF of 370 nm, the two materials are therefore compatible to form a PDC unit. The BGO crystals used in the PDC unit are of the same type as those used in the bottom anti-coincidence shield of PoGOLite. The BGO crystals have a hexagonal shape with a side length of 16 mm, similar to the LiCAF crystals, and have a height of 40 mm.

The combination of the three crystals is read out using a single PMT of the same type as those used on PoGOLite. The PDC unit is wrapped in several layers of teflon tape which serves mainly to prevent external light leaking into the scintillator. It furthermore has a relatively high reflectivity an therefore reduces the loss of scintillation photons by the scintillators. Figure 2.11 shows the three scintillator components which form a PDC together with an assembled unit.

The neutron capture cross section as a function of neutron energy of the PDC units is similar to that of pure \( ^{6}\text{Li} \). It has a high cross section, of 940 barn, for
thermal neutrons which quickly drops-off with increasing neutron energy. By sur-
rounding the PDC with a thermalising material, such as polyethylene, the energy
range to which the PDC is sensitive can be altered. The thermalising material will
absorb or deflect low energy neutrons, thereby reducing the sensitivity of the de-
tector to these neutron energies. Whereas non-thermal neutrons will lose energy in
the material through elastic scattering interactions. The energy of these neutrons
thereby decreases towards energies where the absorption cross section of $^6$Li be-
comes higher. The combination of the thermalising material and LiCAF therefore
has a higher sensitivity to high energy neutrons with respect to bare LiCAF. The
PoGOLino instrument makes use of this technique for one of its two PDC units
which is embedded in an 8.5 cm thick polyethylene shield. The second PDC unit
in the PoGOLino instrument remains unshielded and therefore sensitive to thermal
neutrons. PoGOLino will therefore not only measure the flux of thermal and non-
thermal neutrons but will also be able to provide information on the spectral shape
of the neutron flux using the ratio between the measured rates of the two detectors.

Figure 4.1 shows the simulated detection efficiencies of a PDC with and with-
out the polyethylene shield as a function of neutron energy. The simulations were
performed using Geant4.9.6 with the QGSP_BIC_HP physics list, described earlier
in chapter 3, together with the high precision thermal scattering data library [96]
which provides a high precision for the cross section of low energy neutrons scatter-
ing in the polyethylene shield. The figure shows the detection efficiency for thermal
neutrons to be almost 100% for the unshielded detector despite the use of a scin-
tillator of only 5 mm thickness. For the shielded detector this efficiency is lower.
For increasing neutron energies the detection efficiency of the unshielded detector
can be seen to drop off sharply, whereas for the shielded detector the detection effi-
ciency as a function of energy can be seen to remain stable up to MeV energies. For
neutron energies above 1 MeV the polyethylene shield starts to become transparent
resulting in a decreasing detection efficiency.

The PoGOLino instrument contains a third PDC in which the LiCAF scintil-
lator is replaced by a EJ-204 scintillator of the same shape. Interpretation of the
measurement results of this PDC require a separate study which is not part of this
thesis.

4.1.2 Read Out Electronics

The three PMTs of the PoGOLino instrument are read out using a single FADC
board. This FADC is of the same type as that used on the PoGOLite instrument.
As in PoGOLite, the PMT output is sampled with a clock speed of 37.5 MHz. The
FPGA on the FADC is programmed to store the output from all three channels
whenever the output of one channel exceeds the set trigger threshold. The number
of stored sample points per channel for a trigger is 50, 10 of which occurred before
the trigger was issued and 40 after. The time corresponding to the 50 clock cycles is,
however, not equal for all three channels. For the plastic scintillator PDC, which
contains scintillating components with a relatively fast rise time, a high timing
resolution is required to distinguish between signals originating from the BGO and
the plastic scintillator. For this channel the maximum sample speed of 37.5 MHz is therefore employed. This results in a time between stored sample points of 27 ns. The total time between the first and the last stored sample point is therefore 1.3 µs for this channel. For the LiCAF PDCs a high timing resolution is not required because of the long rise time (1600 ns) of signals originating from europium doped LiCAF. Only every third sampled point is therefore stored, resulting in an effective read out speed of 12.5 MHz. The total time between the first and the last sample point stored for these channels is therefore 4 µs. The full rise time of a signal originating from LiCAF is therefore contained within the stored waveform, while the timing resolution remains high enough to perform accurate waveform discrimination between signals originating from LiCAF and BGO.

During the storage of an event the instrument is unable to record other events. Event storage thus results in measurement dead-time. It is therefore important to minimise the number of stored background events. Online, pulse shape-based vetoes can be issued by the FPGA. For the LiCAF channels this veto is based on the ratio between the amplitude of the waveforms measured during the 4th and the 19th stored sample point. Here the 4th sample point corresponds to the maximum in a BGO induced signal, whereas the 19th clock cycle corresponds to the maximum in a LiCAF induced signal. Figure 4.2 illustrates this. As will be shown

![Image of neutron capture efficiency graph](image-url)

Figure 4.1: The neutron capture efficiency as a function of energy for the shielded (red) and unshielded (blue) LiCAF-BGO PDC as simulated using Geant4. Reproduced from [64] with permission, © (2014) Elsevier.
in the following section, the ratio required for issuing a veto was set low enough to ensure that no signal events would be discarded. To minimise measurement dead-time during flight most measurements were performed with the application of online vetoes, however, several measurements were also performed without veto application. The data from these measurements was used to verify the efficiency of the online veto system after flight. Apart from the storage of waveforms, the ADC values measured during the 4th and 19th stored sample point after the issue of a trigger are stored separately, independent from the application of online vetoes. The dead-time induced by the storage of these two values is minimal and storage of this data continues during waveform storage. This data, referred to as the histogram data, therefore effectively provides a dead-time free measurement of the BGO and LiCAF rates which can be used to verify the dead-time corrected rate measured using the waveform data.

A PC104 computer controls and reads-out the FADC board through a SpaceWire to Gigabit Ethernet bridge. On ground the PC104 can be operated through an Ethernet connection on the instrument. During flight it is connected to the Ethernet over radio E-link system provided by the Esrange Space Centre [76]. This connection is fast enough to control the instrument during flight, while simultaneously being able to download all the data. In case of a loss of communication the data is also stored on a solid state disk connected to the PC104. The PC104 is furthermore programmed to start automatic data taking in case of a loss of communication. For this purpose the functionality of the FADC is checked every 10 minutes by reading out a set of pedestal values of the FADC board. The pedestal values are an

![Figure 4.2: The waveforms resulting from an interaction in a BGO scintillator together with one originating from the LiCAF scintillator. The electronics used to produce this figure are equal to that used on the instrument.](image-url)
indication of the board’s functionality. When these values are outside a predefined range the PC104 cycles a switch through its General-Purpose Input/Output (GPIO) which results in a power cycle of the FADC board. This procedure continues until the pedestal values are in the predefined range. Lastly the PC104 reads out a set of temperature and pressure sensors placed in the instrument. Read out of these sensors proceeds through the serial port of the PC104 connected to a second FPGA. In order to ensure a stable temperature during the flight and the electronics to stay within their safe operating temperatures the instrument contains an autonomous heating system. The system contains its own temperature sensor and is set to provide $\sim 30\text{ W}$ of heating when temperatures inside the instrument drop below $0^\circ\text{C}$.

Eight batteries, type SAFT LSH20, are capable of providing at least 6 hours of power to the instrument. The power of the batteries is divided between a 12 V and a 5 V circuit through DC/DC converters. The internal DC/DC converters in the three PMTs are also supplied with 12 V from the battery system. The control voltage, which can be set to 0-5 V, required for the PMTs is provided through, and controlled by, the FADC board. In order to handle spikes in the current drawn by the FADC and the PC104, which can be experienced during booting, 2 capacitors are charged before power is supplied to these components. The power stored in the capacitors can be used by the components during booting in case the power supplied directly by the batteries is not sufficient. Using this solution the FADC boots successfully at every attempt, something which is not the case for PoGOLite where occasionally the FADC boards have to be power cycled several times before operating nominally. A schematic representation of the read out and power supply systems of the instrument can be seen in figure 4.3.

4.1.3 Mechanical Design

All the PoGOLino components are placed in a cylindrical aluminium pressure vessel with a height of 670 mm, a radius of 165 mm and wall thickness of 3 mm, as shown in figure 4.4. A pressurised environment results in a more easily controllable temperature environment. PoGOLino was flown on a test flight of the Esrange Space Centre which took place during March. During a balloon flight in March from Northern Sweden, outside temperatures as low as $-80^\circ\text{C}$ can be encountered during the ascent phase [106]. In order to ensure stable operation of the flight electronics the temperature in the instrument therefore needs to be managed during the flight. A stable temperature environment is furthermore necessary due to the strong dependency of the light yield and rise time of BGO signals [107]. Large variations in the temperature could potentially result in a varying efficiency in the veto system. In order to monitor the temperature two temperature sensors are placed directly on top of the two LiCAF PDCs, while a third is placed near the hottest part of the electronics. The two pressure sensors are placed on opposite sides of the pressure vessel in order to provide information on a possible temperature gradient inside the pressure vessel.
4.2 Instrument Calibration

The shielded and unshielded PDC units are placed at opposite sides of the pressure vessel to ensure a minimal thermalising effect from the polyethylene shield on the neutron flux reaching the unshielded detector. The electronics are placed in between the PDC units in the middle of the instrument. All components are mounted using printed plastic connectors to 4 steel rods connected to the bottom plate of the pressure vessel. The signals to and from the pressure vessel are supplied through an air tight connector placed on the bottom plate. This connector is furthermore used to provide the instrument with external power during ground tests. The total mass of the PoGOLino instrument is 13 kg, making it light enough to fly as a piggy-back experiment with other balloon experiments. Several different components of the PoGOLino instrument are shown in figure 4.5.

4.2 Instrument Calibration

This section provides a description of the various calibration tests which have been performed on the PoGOLino instrument prior to launch. The instrument is designed to perform its measurements in a high radiation environment without the guarantee of radio communications with the payload during flight. It can therefore not be guaranteed that the settings of, for example, the veto system can be...
altered during flight. The veto system was therefore tested extensively prior to flight to ensure proper operation in flight conditions. The performed tests and the results are described first. Interpretation of the flight data is heavily reliant on Geant4 simulations. Benchmarking of these simulations against measurement data is therefore described. Details on long duration measurements performed to test the autonomy and mechanical stability of the instrument in varying temperature and pressure environments are provided in the final part of this section.

4.2.1 Phoswich System

PoGOLino is designed to accurately measure the neutron flux in a high radiation environment. The radiation consisting of low energy photons and charged particles will mostly be absorbed by passive materials surrounding the PDCs. High energy charged particles which penetrate the passive materials can be vetoed based on their high energy deposition in the detector. The most important source of background is therefore expected to come from hard X-rays and gamma rays. The photon/neutron discrimination capability of PoGOLino was therefore tested extensively.

Figure 4.4: A schematic overview of the PoGOLino instrument. Reproduced from [64] with permission, © (2014) Elsevier.
4.2. Instrument Calibration

The photon/neutron discrimination capability of the instrument was tested by irradiating the unshielded PDC both with a $^{252}\text{Cf}$ source and a variety of different gamma sources. $^{252}\text{Cf}$ emits neutrons and photons as a result of spontaneous fission. The used source had an activity of 2.3 MBq. This corresponds to a neutron emission rate of $2.58 \times 10^5$ neutrons/s. The neutron energy spectrum from $^{252}\text{Cf}$ peaks at $\sim 1\text{MeV}$. The number of photons emitted by the fission reaction is a factor $\approx 2.7$ higher than the number of neutrons. Per reaction a total of $8.2\text{MeV}$ [108] is distributed between the emitted photons, resulting in a broad photon emission spectrum in the MeV energy range. The unshielded detector was used here because of its lower efficiency to high energy neutrons, thereby minimising the expected signal to background.

One measurement was performed where the $^{252}\text{Cf}$ was placed at a distance of 16.5 cm from the unshielded detector resulting in a signal rate of the same order of magnitude as that expected for flight. To further increase the photon flux entering the detector two additional measurements were performed with different gamma sources placed on top of the $^{252}\text{Cf}$ source. In one measurement the added

Figure 4.5: The mounting scheme of the different components of PoGOLino.
source was a $^{137}$Cs source, which has a strong emission line at 662 keV. During the other measurement the added source was $^{22}$Na, which has a strong emission line at 511 keV and a weaker one at 1274 keV. The sources were positioned such to maximise the unshielded LiCAF area irradiated by the sources.

The spectrum resulting from interactions in either the BGO or LiCAF is shown in red in figure 4.6 while the signal as recognised by the online veto system as originating from the LiCAF is shown in blue for the different measurements. Additionally an enlarged image of the neutron capture peak from the $^{22}$Na measurement, fitted using an exponential function plus a Gaussian, is shown in the bottom right corner of the figure. The presented errors in the figure are statistical. The measured rates can be seen to increase significantly over the whole energy range with the addition of the extra gamma sources. For the measurement with the additional $^{22}$Na source the neutron absorption peak becomes less pronounced. This is most likely a result of the 1274 keV emission line from $^{22}$Na which results in an energy deposition similar to that resulting from neutron capture.

The dead time corrected neutron capture rates were determined from the waveform data by fitting the neutron absorption peak with the combination of an exponential, to fit the background component, and a Gaussian function, to fit the neutron absorption peak. The neutron capture rate determined from the measurement with irradiation using $^{252}$Cf only, was $4.38 \pm 0.26$ neutrons/s. The measurements with the additional $^{22}$Na and $^{137}$Cs sources resulted in a measured neutron capture rate of $3.98 \pm 0.21$ neutrons/s and $4.79 \pm 0.29$ neutrons/s respectively.

The signal-to-background ratio of the performed measurement is expected to be 1 to 2 orders of magnitude lower than that encountered during flight. Measurements were additionally complicated by adding strong photon emission lines to be setup, which, with the exception of the 511 keV line, are not present at float altitudes [109]. The count rates as measured with the different setups are statistically compatible with one another. We can therefore conclude that, using the online veto system, the neutron count rate can be measured accurately independent from the background environment.

### 4.2.2 Absolute counting rate

To benchmark the Geant4 simulations both the shielded and the unshielded PDC were irradiated from a distance of 20 cm by the $^{252}$Cf source. The dead-time corrected neutron capture rates of both detectors were measured with different amounts of additional polyethylene blocks placed between the source and the detector. The setups were simulated using Geant4. All simulations were performed using Geant4.9.6 with the QGSP_BERT_HP physics list, together with the high precision thermal neutron scattering data libraries.

The measured neutron capture rate, acquired using the method described in the previous subsection, is plotted against the thickness of the additional polyethylene together with the rates resulting from simulations in figure 4.7. The errors plotted for the measurement points are the errors resulting from the fitting errors of the neutron absorption peak. The error plotted for the simulation error is the
4.2. Instrument Calibration

Figure 4.6: The spectra as measured using the LiCAF+BGO PDC. All events from either BGO or LiCAF (in red) and only those recognised by the online veto system as coming from LiCAF (in blue) are shown for only $^{252}$Cf (top left), $^{252}$Cf with $^{137}$Cs (top right) and $^{252}$Cf with $^{22}$Na (bottom left). A zoom-in of the area within the black dotted line in the bottom left figure can be seen in the bottom right. Reproduced from [64] with permission, © (2014) Elsevier.

systematic error resulting from uncertainties in the simulated measurement setup. This error was found to be 10% by varying the unknown components in the simulations within their uncertainty and recording the resulting difference in simulated counting rate. Examples of such uncertainties are the thickness of the walls of the laboratory and the position of the measurement electronics with respect to the setup. It should be noted that for neutron experiments not only the source and the detector but also the materials surrounding the measurement setup can have a significant influence on the measured counting rate.

The simulated and measured rates as presented in figure 4.7 can be seen to be statistically compatible with one another. We can therefore conclude that the used Geant4 physics lists can accurately simulate the thermalisation process in polyethylene and the neutron capture process in LiCAF.

4.2.3 Instrument Performance Stability

Depending on atmospheric conditions, the temperature experienced during a balloon flight from Northern Sweden during March can vary between $-10^\circ$C and $-80^\circ$ C [106]. Both the light yield and the rise time of BGO induced signals have a large dependency on temperature [107]. Temperature variations during the flight can therefore influence the veto efficiency of the instrument.
Figure 4.7: The neutron count rate as measured (blue) and simulated (red) as a function of the thickness of the polyethylene moderator placed between the source and the detector both for the unshielded LiCAF PDC (top) and for the LiCAF PDC placed within an additional 7.5 cm cylindrical polyethylene shield (bottom). Reproduced from [64] with permission, © (2014) Elsevier.

The efficiency of the veto system with varying temperature conditions was tested by placing the full, flight ready, instrument in a climate chamber at atmospheric pressure for a duration of 3 days. The instrument was powered using an external power supply and the on-ground neutron background flux was measured continuously throughout this period. The temperature during the three days was varied between room temperature and $-40^\circ$ C. Although temperatures during the flight of the instrument can drop significantly below $-40^\circ$ C the heat loss of the instrument can be considered higher during the climate chamber tests. During this test heat is lost through convection and conduction. While, due to the low pressures encountered during flight, heat loss through these 2 mechanisms can be considered to be negligible during flight.
4.3. Flight Results

The results of the test showed an increase in the decay time of BGO signals consistent with previously published results. Additionally a correlation in the neutron absorption rate with the activity of the air circulation system in the building was found. However no correlation between the measured neutron absorption rate and the temperature was found. From these results it can be concluded that the online veto system settings were chosen correctly, as these result in a veto system which remains efficient down to outside temperatures of at least $-40^\circ\text{C}$.

The test further showed that the instrument can operate autonomously for a duration of 3 days without the need for outside intervention. The temperatures as measured inside the instrument were furthermore found to stabilise around $0^\circ\text{C}$ at climate chamber temperatures of $-40^\circ\text{C}$. The stable temperature is well above the critical minimum temperatures of any of the components used in the instrument. Lastly no significant dependency of the scintillation properties of LiCAF on temperature was observed.

A second thermal test was performed on the instrument by placing it into a thermal vacuum facility at SSC, Solna, Sweden. The pressure in the climate chamber was set to 5 hPa, equal to conditions encountered at $\approx 35\text{ km}$. The temperature was set to the minimum achievable temperature of $-20^\circ\text{C}$. The pressure variation in the instrument indicate that the instrument is airtight down to low outside temperatures. The instrument temperature stabilised at room temperature for these pressure and temperature settings.

4.3 Flight Results

4.3.1 Flight and Gondola Description

The PoGOLino instrument was launched as a piggy-back experiment on a test flight mission of the Esrange Space Centre as shown in figure 4.8. The main goal of the ESC mission was flight qualification of several payload components. The launch site was the same as the PoGOLite launch site. By flying from the same location a few months prior to the PoGOLite launch, data on the neutron environment was acquired for the same location and approximately the same solar activity. Thereby the model, as described in chapter 3, can be verified using the PoGOLino data for conditions relevant for the PoGOLite flight.

To minimise thermalisation effects by the equipment from the Esrange Space Centre in the gondola, PoGOLino was placed as far away from all the other payload equipment as possible. The gondola is shown in figure 4.9 and the position of PoGOLino inside the gondola is indicated as red dotted lines. The launch took place on March 20th 2013 at 17:27 LT. The payload reached a float altitude of 30.9 km after an ascent phase of approximately 2 hours. After ascent the altitude of the payload remained stable for approximately one hour. Subsequently the gondola was separated from the balloon with the use of an explosive charge. The gondola returned safely to ground near Muonio, Finland by parachute. The altitude, pressure, outside temperature and the temperature as measured in the instrument are
Chapter 4. The PoGOLino Detector

Figure 4.8: The launch of the PoGOLino instrument from the Esrange Space Centre on March 20th 2013.

shown as a function of time in figure 4.10. The figure shows that temperature inside the instrument stabilises just above 0°C as was predicted based on calibration measurements.

PoGOLino was powered approximately half an hour before launch and performed 5 minute data taking measurements from this moment up to the moment it was powered off, several minutes before the gondola was disconnected from the balloon. All equipment on the PoGOLino instrument behaved as expected for the duration of the measurements. The instrument was recovered and fully functional after landing.

4.3.2 Flight Spectra

Figure 4.11 shows several examples of spectra as measured throughout the duration of the PoGOLino flight. The top figures show the spectra as measured by the BGO in red, and the that measured by LiCAF in blue as recorded during a 5 minute measurement on ground by both detectors. The BGO spectra both show a clear peak in the spectrum resulting from $^{40}$K emission mainly coming from the soil. The
peak is measured at different ADC values which is a result of the different gain of the two PMTs. The neutron induced counting rate can be seen to be negligible on ground. The middle figures show the spectra as recorded during a 5 minute measurement by the shielded and the unshielded detector when the instrument was at an altitude of 15 km. The $^{40}$K can be seen to have disappeared, while a 511 keV peak resulting from electron-positron annihilation becomes prominent in the BGO spectra. The neutron absorption peak in the LiCAF can furthermore be observed in both detectors. As a result of its efficiency over a larger energy range the neutron absorption rate in the shielded detector is significantly higher than in the unshielded detector. It can furthermore be observed that the exponential background spectrum in the LiCAF channels decreases to a negligible level near the neutron absorption peaks. It can therefore be concluded that the background contamination of the signal is negligible. The bottom figure shows the BGO and LiCAF spectra as recorded at float altitudes. The neutron absorption rate can be seen to have decreased with respect to the measurements performed at 15 km. Due to the relatively stable altitude of the payload during the last hour of the flight the incoming neutron flux can be considered to be relatively stable during this period. Measurements could therefore be performed with and without veto application to verify the veto efficiency. The reconstructed neutron absorption rate should be consistent between measurements performed with and without veto application for this period. Two sets of data were recorded without veto application, the measured rates were found to be equal to the rates measured with online veto application. It can therefore be concluded that the veto system behaved as expected during flight.
4.3.3 Simulations

The count rate as measured by both detectors during the flight was simulated using Geant4.9.6. The interactions were modelled using the physics list as used for the benchmarking tests described in the calibration section. The energy spectra between 8 keV and 1 GeV of the upward and downward moving neutron components used for simulation were calculated using the parametrisation presented in chapter 3. For lower energies the spectra was approximated as a single power law with a slope of $-0.85$ extending down to 1 eV. For the calculation of the spectra the altitude and location as measured and provided by the Esrange Space Centre were used. For all the spectra $\phi$ was set to be 800 MV. This value was estimated using the combination of the neutron count rate data as measured on ground by the Oulu station [110] and the solar activity parameters presented in [90]. The latter presents the average value of $\phi$ for periods of one month, while the former presents the average neutron count rate per hour. The on-ground count rate as measured during the hours of flight was found to match those measured during past periods where the value of $\phi$, reported by [90], was $\approx 800$ MV. The relatively high value of $\phi$ during these hours was a result of a large Coronal Mass Ejection (CME) which occurred several days before the flight. Large CMEs can result in a significant decrease of the incoming cosmic ray flux for a duration of several days. This effect is called a Forbush decrease [111].
Figure 4.11: Spectra as measured by the unshielded (left) and shielded PDC (right) for three different altitudes, on ground (top), 15 km (middle) and 30 km (bottom). The spectra, taken from the histogram data, as measured by BGO is shown in red and that from LiCAF in blue. On ground the BGO can be seen to measure emission for $^{40}$K decay, during flight this emission peak disappears, instead the 511 keV peak can be observed. Reproduced from [64] with permission, © (2014) Elsevier.

For the simulations, neutrons were emitted from two halves of an instrument centred sphere with a radius of 2 m. The upward moving neutron flux was emitted from the bottom sphere while the downward moving component was emitted from the upper hemisphere. The neutrons were emitted with an angular distribution resulting in an isotropic flux within the sphere. The simulated measured rates are therefore independent on the location of the gondola within the sphere.
Chapter 4. The PoGOLino Detector

full gondola geometry was simulated including components present in the gondola during flight. Unknown parameters, such as the thickness of certain gondola components, were varied within their uncertainty. These variations resulted in variations on the simulated count rate of the order of only a few percent. The temperatures as measured in the PoGOLino instrument during flight were used to set the temperatures of the polyethylene in the simulations. These temperatures only have a minor influence on thermalisation properties of the polyethylene but were taken into consideration. The gondola geometry as used in the simulations is shown in figure 4.12

Figure 4.12: The gondola geometry containing the PoGOLino instrument as used in the Geant4 simulations. The full gondola structure is present along with the crashpads below the gondola and the two major components flown by the Esrange Space Centre (ESC).

The measured and simulated counting rates from both detectors can be seen in figure 4.13. The count rate as a function of altitude can be seen to match the profile as described in chapter 3. At low altitudes, or high atmospheric pressures, the neutron flux is low as a result of the high atmospheric density which deflects the incoming neutrons. A maximum is found around $50 - 100 \text{ hPa} \ (15 - 20 \text{ km})$, the average interaction altitude for incoming cosmic ray hadrons. At higher altitudes the neutron flux decreases slowly as a result of a loss of neutrons due to absorption and decay.

The measured count rates can be seen to be in relatively good agreement with the simulation results, especially for the shielded detector. A small overestimation of the order of 10% by the simulations can be observed around the maximum. This discrepancy is most likely a result of the lack of precision in the directional dependence in the simulated spectra. Approximating the total flux to only comprise of an
upward and a downward moving component is correct far away from the production
location where most neutrons have scattered already several times with the atmo-
sphere. A significant part of the flux can therefore be assumed to move horizontally
at these altitudes. Near the neutron production altitudes more neutrons will enter
the instrument directly without interacting with the atmosphere first, the horizon-
tal component is therefore relatively small at these altitudes. In the simulations the
angular distribution of the neutrons is however treated equal for all altitudes. As
a result, the horizontal moving component around the maximum is overestimated,
while the directly downward moving component is underestimated. This finally
results in an overestimation of the the measured rate. For these altitudes a higher
level of precision for the angular dependency is required in the model to produce a
better agreement. For higher altitudes, relevant for the PoGOLite flight conditions,
the agreement between simulations and measurements is better. The current level
of angular precision can therefore be considered to be sufficient for the PoGOLite
flight altitudes.

For the unshielded detector a higher level of discrepancy between measurement
and simulation is found. This is expected to be a result of the oversimplification
of the neutron energy spectra in the $1\,\text{eV} - 8\,\text{keV}$ range. The model presented in
chapter 3 is only valid for higher neutron energies. The unshielded detector is more
sensitive to neutrons in the low energy range than the shielded detector.

The PoGOLino flight produced valuable data required for validating the model
as presented in chapter 3 as well as other existing atmospheric neutron models. The
results show that, especially at higher altitudes, the model describes the measured
rates well. It thereby validates the model for use for simulations of the neutron
induced rate in PoGOLite at float altitudes. The PoGOLino flight furthermore
showed the potential for the LiCAF based detectors to be used in balloon-borne
detectors. The light weight and mechanically simple novel technology was shown
to be able to provide accurate neutron flux measurements within a relatively short
integration time free of background contamination.
Figure 4.13: The count rate as measured in the shielded (red crosses) and unshielded (black crosses) PDC compared to the count rates as simulated using spectra coming from chapter 3, for the shielded detector (blue dots) and the unshielded detector (green dots) as a function of altitude (top axis) and atmospheric pressure (bottom axis).
Chapter 5

PoGOLite Background Simulations

One of the main challenges for X-ray polarimeters measuring through Compton scattering is the low signal-to-background ratio of the measurements. This is partly a result of the relatively low efficiency for signal detection, caused by the requirement that only photons undergoing both a Compton scattering and photoabsorption within the detector can be used. A second reason is the high radiation environments in which the measurements have to be performed which can result in a high background induced rate. PoGOLite performs measurements at an altitude of \( \approx 40 \text{ km} \) and at high latitudes, resulting in a high incoming neutron flux as discussed in chapter 3. A secondary potential source of background is high energy photons both with cosmic and atmospheric origins.

The background induced double-hit rate in a polarimeter can deteriorate the polarisation measurement in two ways. Firstly, the background will induce additional statistical fluctuations in the modulation curve. These statistical fluctuations remain after subtracting the background, as shown in the upper part of figure 5.1. When the background is significantly higher than the signal, and the observation time is limited, the statistical fluctuations can have the same magnitude as the signal modulation. Secondly, the background can induce events with a preferred reconstructed scattering angle. The effects of a background which has a 360° period can be seen in the bottom of figure 5.1. A background with such a 360° period can, for example, result from an unpolarised photon flux entering the polarimeter from the side. A background induced signal in the modulation curve can either fake a polarisation, for example when inducing a modulation with a 180° period, or distort the signal induced modulation. To be able to correctly measure the polarisation of the signal, it is therefore essential to understand the magnitude of the background and the distribution it induces in the modulation curve. Uncertainties on the signal-to-background ratio will induce an error in the reconstructed polarisation degree. The first part of this chapter will therefore focus on simulations of the
signal-to-background ratio as a function of time encountered during the 2013 flight of PoGOLite. These simulations are required to be able to properly reconstruct the measured signal-to-background ratio. For this purpose both the double-hit rate induced by atmospheric neutron and by atmospheric photons will be studied in detail. Since subtraction of the wrong background shape, as in the bottom of figure 5.1, leads to additional errors in the measured polarisation degree and angle. The last part of this chapter will therefore focus on the potential modulation induced by the atmospheric neutron and photon fluxes encountered by the polarimeter during its flight.

Figure 5.1: Schematic representation of the effects of the background on the modulation curve. The top row the effect of a background without a preferred reconstructed scattering angle, while the bottom shows the effect induced by a background with a preferred scattering angle. The original modulated signal is shown on the left. The middle panel shows the background (blue) and the signal and background together (red). The distorted reconstructed signal after subtracting a scattering angle independent background is shown on the right.

### 5.1 Neutron Induced Background Component

The high neutron flux found in the high altitude/high latitude region has been shown to induce a significant background rate in PoGOLite in previous studies [60]. In order to understand this neutron induced double-hit rate during the PoGOLite flight the instrument response needs to be understood first. This section will therefore start with a brief description of the quenching effects which have to be taken into account when studying neutron interactions in plastic scintillators. This is followed by a discussion of the study of the effects of passive materials in the
5.1. Neutron Induced Background Component

Instrument geometry on the neutron induced rate, the importance of which was shown in the PoGOLino calibration study. In chapter 3 it was shown that the neutron induced rate depends on the altitude and magnetic latitude of the payload and on the solar activity persisting during the flight. However the neutron induced rate can potentially also have a dependency on the elevation of the instrument. In order to accurately predict the neutron induced double-hit rate such a dependency therefore needs to be understood. After understanding the effects of the instrument response on the incoming neutron flux and the potential dependency on the elevation of the instrument, the simulated neutron induced double-hit rate as a function of time during flight is studied.

5.1.1 Quenching

Neutrons can induce a signal in the polarimeter when scattering twice in the polarimeter and when the energy depositions of the two scattering interactions is reconstructed to be in the keV energy range. For an elastic neutron scattering event in plastic energy is transmitted from the neutron to either a proton or a carbon nucleus. For high energy interactions the carbon nucleus can furthermore break up and produce helium nuclei. Both the proton, helium and the carbon nucleus will deposit their energy in the scintillator through ionisation resulting in scintillation photons. The efficiency for nuclei to produce scintillation light is significantly lower than for electrons as previously mentioned in chapter 3. For nuclei a larger fraction of energy is converted into vibrations in the crystal structure instead. For EJ-204, the plastic scintillator material used in PoGOLite, the number of optical photons produced by a 1 MeV electron is $10.4 \times 10^3$, each of which has an energy of $\approx 2\text{ eV}$. The total energy converted into scintillation photons is therefore $\approx 20\text{ keV}$, or 2% of the total deposited energy by the electrons (which in turn has been emitted by a photon). For heavy nuclei the relative light yield with respect to electrons, called the quenching factor [112], is less than unity. In order to correctly simulate the neutron induced event rates the quenching factor needs to be accounted for in the simulations. The quenching factors used in the analysis of the simulations are equal to those used in previous PoGOLite publications, for example [56] and are based on data presented in [112]. In PoGOLite only energy depositions below 120 keV are registered. Protons with energies above 1 MeV will deposit energies above this upper discriminator threshold. It is therefore mainly the quenching factors for particles with an energy below 1 MeV which are relevant for the studies presented here. The quenching factors below 1 MeV as used for the work presented here were found to be in good agreement with more recent results presented in for example, [113]. The quenching factors for protons, helium and carbon nuclei are the following:

- For protons:
  
  For: $E_{\text{dep}} \leq 1\text{ MeV} \rightarrow E_{\text{scint}} = 5.64 \times 10^{-2} E_{\text{dep}} + 1.19 \times 10^{-1} E_{\text{dep}}^2$

- For helium nuclei:
  
  For: $E_{\text{dep}} \leq 4\text{ MeV} \rightarrow E_{\text{scint}} = 1.45 \times 10^{-2} E_{\text{dep}} + 8.78 \times 10^{-3} E_{\text{dep}}^2$
Else: $E_{\text{scint}} = 4.95 \times 10^{-2} E_{\text{dep}}$

- For carbon nuclei: $E_{\text{scint}} = 6.2 \times 10^{-3} E_{\text{dep}}$

Here $E_{\text{dep}}$ is the energy deposited by the nucleus (in MeV) and $E_{\text{scint}}$ is the relative amount of scintillation light with respect to that produced by an electron with equal energy. The quenching factors can be seen as a function of energy in figure 5.2. The quenching effect is taken into account in the simulations by multiplying the deposited energy in a plastic scintillator by the quenching factor of the appropriate particle. This step is performed directly in the Geant4 simulations and therefore before the simulation analysis which is described in Appendix A.

When combining the quenching effect with equation 3.1, one can calculate that neutrons capable of producing a signal-like-event in the plastic scintillator need to have an energy in the $1-1000$ MeV range. Before scattering in the plastic scintillator the neutrons traverse the polyethylene shield and so their primary energy can be significantly higher than this.

![Figure 5.2: The ratio of $E_{\text{scint}}$ over $E_{\text{dep}}$ for protons (red), helium nuclei (blue) and carbon nuclei (green) as a function of energy.](image)

### 5.1.2 Geometrical Effects

For simulations of the polarimeter response to the photon induced signal rate only the PDCs and the SAS units need to be considered. Materials such as the polarimeter mechanics do not significantly influence the instrument response to the signal induced rate. For background studies also passive materials surrounding the detector units need to be implemented. As described in chapter 3 the neutron flux impinging on the PoGOLite instrument during flight has an atmospheric origin. As a result neutrons enter the instrument from all directions and are thereby likely
to interact with the passive materials surrounding the instrument. Producing an exact replica of the full flight payload, including the ACS and the gondola, in the simulations would however slow down simulation time significantly. Both addition of material and complication of the material shapes will result in an increased simulation time. Creating a full replica of the flight model is furthermore not necessary as the effect of certain materials will not influence the instrument response. For this reason the effects of leaving out parts of the payload in the simulation geometry were studied systematically. The procedure consists of adding or changing payload components, starting with those which are expected to have the largest influence, and studying the resulting changes in the instrument response. For neutrons changes to the geometry which include materials close to the detector units, materials with a high hydrogen fraction and materials with isotopes which can be activated through neutron interactions are considered to have the largest influence on the instrument response. Changes which include such materials were made to the payload up to the point where no significant effects on the instrument response were found.

A total of 6 steps was performed. The starting geometry of the payload can be seen in figure 5.5a. This geometry contains the PDCs in detail, including the fast, slow and BGO scintillator, the passive tin and lead shielding and a small plastic cap at the top which is used to stabilise the position of the PDCs. The implemented geometry furthermore contains the PMTs, represented as a hollow aluminium cylinder with a wall thickness of 1 mm, the SAS units, the bottom polyethylene shield, the rotation frame, consisting of aluminium (alloy 6061) and the side polyethylene shield including small gaps in between the different pieces of the shield.

Using the described geometry, neutrons were emitted separately from both the top and the bottom half of an instrument centred sphere. The instrument was positioned with an elevation of 90°, which is defined as pointing to zenith. A total of 35 simulations were performed, each with a different neutron energy, for each geometry. For these simulations neutrons were emitted isotropically from the two hemispheres. The simulated neutron energies ranged from 100 keV to 800 MeV, the number of emitted neutrons for each energy was equal. The number of single-hit and double-hit events induced in the polarimeter were stored.

The following changes were made to the geometry: In step 2, shown in figure 5.5b, the bottom electronic pressure vessel (aluminium alloy 6061) was added to the setup. The pressure vessel was set to contain 16 electronic boards, 12 representing the FADCs, 1 the DIO, 1 the SpaceWire-to-Ethernet-Bridge and 2 representing the router boards. Each board has the dimensions of an FADC board as used in PoGOLite (65 × 85 × 7.5 mm) and consists of the material FR4. In step 3, shown in figure 5.5c, one of the star trackers (the STM) was added to the setup. The STM includes the baffle system, the pressure vessel, the glass window and the electronics which are represented as a solid cylinder consisting of the material FR4. In step 4,

\footnote{FR4 is a flame resistant composite material composed of woven fiberglass cloth with an epoxy resin.}
shown in figure 5.5d, the second star tracker (STR) and the auroral monitor unit were added, both are represented in a similar way to the STM. In the next step, step 5, shown in figure 5.5e, the heat shrink material is added to the PDCs. This material is placed around each PDC from the top down to the bottom of the fast scintillator, the thickness of the material is 0.25 mm. In the last step, step 6, the two pressure vessels containing the PMTs and the PDCs were added to the setup. These pressure vessels consist of aluminium (Alloy 6061) and are shown in 5.5f in black. The number of induced double-hit events as a function of the neutron energy, for each step, is shown in figure 5.3 for neutrons emitted from the bottom half and in figure 5.4 for neutrons emitted from the top half of the sphere.

![Figure 5.3: The simulated number of neutron induced double-hit events as a function of incoming neutron energy for the different geometries for neutron coming from below the instrument.](image)

From the results it can be observed that the changes had only minor effects on the neutron detection efficiency. For the upward moving flux the changes do not have a significant influence on the detection efficiency. For the downward moving flux only minor changes to the neutron detection efficiency can be observed for high energy neutrons. For the upward moving flux the effect is expected to be smaller as a result of the bottom polyethylene shield. The expected high energy incoming downward flux is relatively low and therefore these geometry changes will have a negligible effect on the final result. Additional materials which could be added either consist of materials with a relatively high Z-value, like the aluminium attitude control system, or have a small mass and are placed relatively far away from the
5.1. Neutron Induced Background Component

Figure 5.4: The simulated of neutron induced double-hit events as a function of incoming neutron energy for the different geometries for neutron coming from above the instrument.

active detector volume, like the gondola structure. It can therefore be concluded that additional changes to materials, both outside and inside the polarimeter, will only have a negligible effect on the neutron induced double-hit rate. The results for the single-hit detection efficiencies were found to be similar. For all simulation results presented in the later part of this thesis the instrument geometry of step 6 will be used.

5.1.3 Elevation Dependence

Knowing the dependency of the instrument geometry on the neutron induced rate, the dependency of the pointing position needs to be studied. The anisotropy of the incoming neutron flux can potentially result in a pointing elevation dependency on the neutron induced double hit rate. Such a dependency would result in a variation of the measured double hit rate throughout an observation of a target. For example, the neutron induced double-hit rate observed when the Crab is at maximum elevation could result in a lower neutron induced rate than when it is at an elevation of 30°. Such a dependency can, when not understood properly, result in an underestimation of the signal induced rate. In order to understand the count rates as measured during flight it is therefore essential to know the elevation dependency. A dependency on the azimuthal pointing angle of the instrument can
(a) Geometry as used for simulations of step 1. For providing a better view the instrument is cut in half along the z-axis for this figure and the bottom part, including the bottom of the PMT is removed.

(b) Geometry as used for simulations of step 2. For providing a better view the instrument is cut in half along the z-axis for this figure.

(c) Geometry as used for simulations of step 3.

(d) Geometry as used for simulations of step 4.

(e) Geometry as used for simulations of step 5. For providing a better view the instrument is cut in half along the z-axis for this figure.

(f) Geometry as used for simulations of step 6. For providing a better view the instrument is cut in half along the z-axis for this figure.

Figure 5.5: The different geometries of the instrument as used to study the effects of passive material on measured count rates.
only be the result from a dependency of the incoming neutron flux on azimuth. Such a dependency is not present in the atmospheric neutron model, the relation between the azimuthal pointing angle and the neutron induced rate can therefore not be studied here. However such a dependency cannot induce an error on the reconstructed signal induced rate and is therefore not as important as the elevation dependence.

Previous studies of the elevation dependence for PoGOLite showed no such dependency [56] [60]. However, due to the recent updates of the instrument geometry and the model of the incoming neutron flux a new set of simulations was performed to check for compatibility with previous results.

Simulations were performed with an incoming neutron energy spectrum as expected for the PoGOLite flight. The spectra for the upward and downward moving flux were acquired using the model presented in chapter 3 with the following parameters: atmospheric pressure = 3 g/cm$^2$, magnetic latitude = 64.5° and $\phi$ = 715 MV. These conditions are similar to those experienced by the instrument during flight at noon of July 13th 2013. The low atmospheric pressure (high altitude) situation was chosen intentionally to maximise the anisotropy of the incoming flux.

Neutrons in the 100 keV and 1 GeV energy range were considered in the simulations. Consistent with the used spectra, 85.3% of the neutrons was emitted from the bottom sphere and 14.7% emitted from the top hemisphere. The simulated number of photons corresponds to a 5 minutes, which is the length of a measurement during the PoGOLite flight. The measured double-hit rates are plotted as a function of the elevation angle and are well described by a straight line, as shown in figure 5.6.

![Figure 5.6: The simulated detection rate of double-hit events as a function of the elevation angle of the instrument for a neutron flux corresponding to an atmospheric pressure of 2.8 g/cm$^2$, a magnetic latitude of 64.5° and $\phi$ = 715 MV.](image-url)
The results of the fit indicate that for a 5 minute measurement the neutron induced double-hit rate does not show a significant dependence on the elevation angle of the instrument. Similar results were found for the single-hit event rate. The reason for the lack of dependency despite the non-isotropy of the incoming flux is the high scattering probability of neutrons with the polyethylene shield. From the simulation results it was found that ∼ 90% of the neutrons responsible for double-hit events have scattered at least once in the polyethylene shield before depositing energy in the fast scintillators. These scattering interactions increase the isotropy of the neutron flux responsible for depositing energy in the fast scintillators, resulting in a measured rate with no significant dependence on the instrument elevation. The interaction probability of neutrons with the polyethylene shield will be further discussed in chapter 6.

5.1.4 Neutron Induced Rate

To understand the measurements performed during the PoGOLite flight of 2013 it is important to understand the variations of neutron induced double-hit rate with time. After excluding the dependency on elevation the neutron induced double-hit rate is only expected to vary with altitude, magnetic latitude and solar activity. Using the measured altitude and location of the payload during flight and the solar activity persisting during the flight the variation of the neutron induced double-hit rate can now be calculated with the model as described in chapter 3 and Geant4 simulations making use of the most complex instrument geometry described in section 5.1.2.

First a high statistics simulation run was performed using the neutron energy spectra for an atmospheric pressure of 3.0 g/cm² a magnetic latitude of 64.5° and \( \phi = 715 \text{ MV} \). The simulated double-hit event rate resulting from the spectrum for these conditions, which will later be referred to as the reference spectrum, was 5.2 ± 0.1 Hz.

Subsequently the neutron energy spectra in the 100 keV – 1 GeV energy range were calculated for the altitude, magnetic latitude and solar activity conditions corresponding to each measurement during the PoGOLite flight of 2013 using the model from chapter 3. For the altitude and position the values as measured during the flight were used. An approximation of the solar activity parameter \( \phi \) was acquired through data from the Oulu station [110], an on ground neutron monitor which operates continuously. The neutron count rate from this station is correlated to the solar activity parameters as reported in [90]. The values of \( \phi \) reported in [90] can be plotted against the monthly mean of the time averaged neutron detection rate of this station. The result, shown in figure 5.7, can be fitted with a second order polynomial function:

\[
\phi = 9911.0 - 2.35 R_{\text{Oulu}} + 1.38 \times 10^{-4} R_{\text{Oulu}}^2
\]  

Using this relation an approximation of \( \phi \) can be acquired with a one hour timing precision for periods during which the geomagnetic conditions are stable, as they
5.1. Neutron Induced Background Component

Figure 5.7: The Solar modulation parameter as reported in [90] as a function of the monthly averaged neutron counting rate measured at the Oulu station [110] fitted with a second order polynomial.

were during the PoGOLite flight. The K-index is a parameter which quantifies the level of disturbances in the Earth’s magnetic field with 0 meaning no disturbances and a value of 5 or more indicating a geomagnetic storm. During all the performed measurements it was \( \leq 3 \) [114].

Energy spectra coming from the model were folded with the energy response of the instrument as calculated in section 5.1.2. This was first done for the reference spectrum for which the resulting double-hit rate was shown to be 5.2 Hz, subsequently this was done for all spectra corresponding to the conditions persisting during each flight measurement. The ratio between the folded spectrum for each measurement and the folded reference spectrum was multiplied with the previously simulated rate for these conditions, 5.2 Hz, to acquire the neutron induced rate as a function of time. The resulting neutron induced double-hit rate, measured pressure and magnetic latitude and the solar activity parameter are plotted as a function of time for the PoGOLite flight are shown in figure 5.9. From the results we can conclude that the neutron induced rate is of order \( \approx 5 \text{ Hz} \) throughout the flight and therefore significantly higher than the expected signal rate of \( \approx 1 \text{ Hz} \). This signal-to-background is however higher than that predicted previously in [60] of 1:10, for which solar minimum conditions were considered. The rate can be seen to decrease on the morning of the 13th of July which coincides with the start of the Crab observation of that day. On the 14th of July the neutron induced rate is relatively stable. A similar pattern is observed in the counting rates recorded by the neutron detector flown with the polarimeter. The neutron absorption rates of this scintillator are shown as a function of time in figure 5.8.

The neutron rate can be seen to decrease at the time predicted by the model. However the statistics on the neutron induced rate of this detector are limited and a quantitative comparison is therefore not possible. For future flights of PoGOLite it is therefore suggested to optimise the position of the neutron scintillator in the
Figure 5.8: The neutron absorption rate measured in the neutron detector flown on the PoGOLite payload as a function of time. The polarimeter was turned off for several hours after the first Crab observation (between $\approx 1.6$ and $\approx 1.9$ days after launch), causing the lack of data in this period.

Polarimeter in order to increase the neutron induced rate. Placing the detector in a position where the neutron flux is less moderated by the polyethylene shield, for example below the bottom polyethylene shield, will likely increase the counting rate. The optimum position will have to be found through a Geant4 based study. The currently used LiCAF scintillator can furthermore be replaced by a LiCAF scintillator with a 95% $^6$Li doping level as used in PoGOLino. Both these changes result in a higher count rate thereby improving the statistics and making a comparison with model possible. The model predictions for the neutron induced double-hit rate in the PDCs can however be compared to polarimeter data, this will be the subject of section 3 of this chapter.
Figure 5.9: The double-hit event rate (in Hz) shown in blue, the pressure as measured on the payload (in g/cm$^2$) in black, the magnetic latitude divided by 10 (in degrees) in green and the solar activity parameter divided by 100 (in MV) in red, as a function of time shown in days since midnight of the 12th of July 2013 (UT). The start and end of the Crab observations on both days are indicated using the red dashed lines. The polarimeter was turned off for several hours after the first Crab observation (between $\approx 1.6$ and $\approx 1.9$ days after launch), causing the lack of data in this period.

5.2 Photon Induced Background Component

In previous background studies for PoGOLite it was shown that a major background component results from gamma radiation [25]. The gamma radiation impinging on the PoGOLite instrument comprises both a cosmic and an atmospheric component. The cosmic component consists of photons emitted by different X-ray sources such as active galactic nuclei and type 1a supernovae [115]. The secondary component is formed in the atmosphere both in hadronic and electromagnetic air showers through several different processes. The most important of which are $\pi^0$-decay, bremsstrahlung by electrons, electron-positron annihilation and lastly through inelastic and capture reactions by atmospheric neutrons [116]. The photon flux and angular dependence is highly dependent on the magnetic latitude as shown in figure.
This figure shows the photon flux in the $40 - 500 \text{ keV}$ energy range measured at an altitude of 750 km at different latitudes as a function of the zenith angle. At this altitude all the atmosphere is below the detector, therefore all photons coming from zenith can be assumed to have an cosmic origin. At low latitudes one can see that the majority of the flux has a cosmic origin, whereas at high latitudes the majority comes from below and therefore originates from the atmosphere. The figure furthermore indicates that, similar to neutrons, the flux produced in the atmosphere is highly dependent on latitude indicating that photons are produced in showers induced by charged cosmic rays.

As a result of the active and passive shielding and the collimator system of PoGOLite the background rate induced by photons in the $20 - 100 \text{ keV}$ is reduced \cite{25}. Due to their longer mean free path, higher energy photons are capable of penetrating the passive and active materials surrounding the fast scintillator array. A significant part of the induced events is therefore expected to come from high energy photons with energies exceeding $\sim 100 \text{ keV}$. At these photon energies the atmospheric photon spectrum dominates the primary cosmic gamma ray spectrum, especially at high magnetic latitudes.

The energy spectra of the upward and downward moving component of the secondary cosmic gamma-ray component differ significantly both in spectral shape and magnitude. For the simulation results as presented in \cite{25} the upward moving spectrum for an altitude of $4 \text{ g/cm}^2$ and a magnetic latitude of $42^\circ$ was approximated as follows:

- For photon energies $E$ between $45 \text{ keV}$ and $20 \text{ MeV}$: $1010 \ E^{-1.34} (1/(\text{s m}^2 \text{ sr MeV}))$
- for $E$ between $20 \text{ MeV}$ and $1 \text{ GeV}$: $7290 \ E^{-2.0} (1/(\text{s m}^2 \text{ sr MeV}))$
- and a $511 \text{ keV}$ line with intensity $470/(\text{s m}^2 \text{ sr})$

The downward component was approximated using:

- For $E$ between $45 \text{ keV}$ and $150 \text{ keV}$: $629 \ E^{-1.2} (1/(\text{s m}^2 \text{ sr MeV}))$
- for $E$ between $150 \text{ keV}$ and $1 \text{ MeV}$: $250 \ E^{-1.7} (1/(\text{s m}^2 \text{ sr MeV}))$
- for $E$ between $1 \text{ MeV}$ and $1 \text{ GeV}$: $250 \ E^{-1.7} + 1.145 \times 10^5 E^{-2.5} e^{-E/120} (1/(\text{s m}^2 \text{ sr MeV}))$
- and a $511 \text{ keV}$ line with intensity $78.33/(\text{s m}^2 \text{ sr})$

The spectra for energies above $1 \text{ MeV}$ are based on \cite{118}, whereas the approximations for the lower energies are based \cite{117} for the $511 \text{ keV}$ lines and the upward moving spectrum. The downward spectra are based on \cite{116}. The altitude dependence for the upward moving part can furthermore be assumed to be negligible for photon energies above $100 \text{ keV}$ \cite{118} whereas the the downward moving part is proportional to the atmospheric overburden.

The photon induced double-hit rate was studied using the updated instrument geometry, the updated simulation analysis and using a spectrum corrected for the
5.2. Photon Induced Background Component

Figure 5.10: The photon flux measured at an altitude of 750 km in the energy range 40 – 500 keV as a function of the incoming photon angle with respect to zenith for two different magnetic latitudes. The circular data points are for the flux as measured in the polar region, the square points are from measurements in the equatorial region. Reproduced from [117] with permission, © (1976) American Geophysical Union.

difference in magnetic latitude (the study presented in [25] used background spectra for a PoGOLite flight from Fort Sumner, New Mexico). As the spectra provided in [118] are for a cut-off rigidity of 4.5 GV, a factor of \((R_C/3.0)^{-1.13}\), from [119], is used to correct for the cut-off dependence of the magnitude of the spectra. In this correction factor \(R_C\) is the cut-off rigidity for the location for which the spectrum is
required. Using these spectra the photon induced count rate as expected for flight was simulated and the effect of the instrument elevation on the count rate was studied. Due to a lack of knowledge on the exact evolution of the spectral shape and angular dependence with altitude, latitude and solar activity only an average count rate as expected at float altitudes could be calculated.

Similar to the neutron induced double-hit rate, the photon induced rate can potentially vary with instrument elevation. As the photon induced rate is expected to be non-negligible such a dependency needs to be understood. Using the described spectra, simulations were performed where the elevation of the instrument was varied. In the simulations the spectra were emitted from 2 hemispheres centred around the instrument, equal the the setup described for the neutron induced event rate studies. The elevation of the instrument, defined as the angle of the instrument with respect to the horizon, was varied in steps of 15° from 0° to 90°. Each simulation corresponded to 10 minutes of observation. The resulting counting rates are shown in figure 5.11. The data was fitted with a flat line, resulting in a reduced $\chi^2$ of 1.6. The elevation dependence on the photon induced double-hit event rate can therefore be assumed to be negligible. The average double-hit rate induced by photons for these conditions is found to be 1.92 Hz, the contribution to the background rate from photons is therefore found to be non-negligible but lower than that induced by neutrons. Furthermore, by excluding a dependence of the double-hit rates induced by both major background components on the instrument elevation it can now be concluded that variations of the measured double-hit rate with elevation must be induced by the photons from the target. The rate is therefore expected to increase as the observed target rises in elevation and decrease again after the target has reached its highest position on the sky.

Figure 5.11: The simulated double-hit event rate as a function of the elevation angle of the instrument. The elevation angle is defined with respect to the horizon, 90° therefore corresponds to pointing to zenith.
5.3 Comparison With Flight Data

The count rates as simulated in the previous two sections can be compared to data recorded during the 2013 flight of PoGOLite. First flight data will be used to verify the simulated neutron/photon induced double-hit rate ratio. For this purpose the difference between the distribution of interaction locations induced by neutrons and photons within the polarimeter will be used. After this principle component analysis (PCA) will be used to confirm that the temporal variations in the double-hit counting rate are a result of variation of the neutron flux with time. PCA furthermore provides a second independent proof that the PoGOLite background is neutron dominated. After confirming through the position distribution and PCA study that the background is dominated by neutrons and that the ratio between photon and neutron induced double-hit events can be simulated well the double-hit rate as measured during flight is directly compared to the simulated double-hit rates.

5.3.1 Position Distribution

The simulations presented in the previous two sections predict a neutron and photon induced double-hit rate of $\approx 5$ Hz and $\approx 1.9$ Hz respectively. In order to investigate the relative double-hit rates induced by these two particles during the 2013 flight one can look at the positional distribution of the induced events in the polarimeter. The distribution induced by neutrons is expected to be very different from that induced by photons. The positional distribution induced by photons will be discussed first. This is followed by a discussion of the neutron induced positional distribution. Lastly the distribution measured during the PoGOLite flight of 2013 will be compared to simulations to verify the neutron and photon induced background rates predicted in the previous two sections.

For double-hit events originating from photons the position of the two energy depositions in the scintillator array is dominated by geometrical effects. A photon scattering in the central PDC can be absorbed with equal chance in any of the other PDCs, independent of the scattering angle. A photon scattering initially in one of the outer PDCs can only be absorbed when it scatters away from the SAS units. The chance of having a double-hit event, with at least one interaction in the central PDC, is therefore a factor of $\sim 2$ higher than a double-hit event with one interaction in one of the outer PDCs. Simulations were performed with a Crab-like photon spectrum entering the instrument aperture. Secondly a simulation was performed with the secondary cosmic ray gamma spectrum used in the previous section. Both simulations resulted in the same position distribution per ring for the double-hit events. A histogram resulting from the Crab simulation, of the positions of the interaction location of photons for double-hit events is shown in figure 5.12. This histogram shows the number of hits per PDC for each PDC ring, where ring 0 corresponds to the central PDC and ring 4 corresponds to the PDCs in the outer ring. The histogram is further normalised to unit area. The figure confirms that the chance of having an interaction in a PDC in the outer ring is
approximately half of having an interaction in the central PDC. The same result is found when simulating the instrument response to an atmospheric photon flux as described in section 5.2. Photons originating from the Crab will therefore result in a distribution similar to that from secondary cosmic ray gammas.

![Figure 5.12](image)

Figure 5.12: Normalised histogram of the number of energy depositions per PDC for each PDC for double-hit events originating from photons. Ring 0 corresponds to the central PDC and ring 4 the outer ring.

While for double-hit events originating from photons it is geometrical effects which dictate the position distribution per PDC ring, for neutrons it is effects originating from the high elastic cross section with the plastic scintillators. Neutrons entering the scintillator array have a high chance to interact with the first encountered scintillator. For a large fraction of the neutrons this will be a PDC in the outer ring. A relatively small number of neutrons will penetrate down to the central PDC, resulting in a relatively small number of neutron induced interactions in this PDC. After scattering, the same geometrical effects are valid as for photon. The effects induced by the high scattering cross section can however be shown to dominate. This results in a larger number of interactions in an outer PDC with respect to the inner PDC.

Simulations were performed with the setup as described in section 5.1 of this chapter for a typical neutron background encountered during flight. The same distribution histogram as in figure 5.12 was produced for neutrons and is shown in figure 5.13. The distribution shows a trend opposite to that induced by photons.

These distributions can be used to investigate the background percentage induced by neutrons and by photons respectively during flight and to study the signal-to-background ratio during a Crab observation. For this purpose similar distribution plots were produced using the data recorded during the PoGOLite flight. One such distribution histogram was produced using data recorded while observing
5.3. Comparison With Flight Data

Figure 5.13: Normalised histogram of the number of energy depositions per PDC for each PDC for double-hit events originating from neutrons. Ring 0 corresponds to the central PDC and ring 4 the outer ring.

The flight data was compared to simulation results. The normalised distributions resulting from simulations of the neutron and photon flux were combined with different ratios and compared the measured distributions. The best agreement, with the lowest reduced $\chi^2$ value, with the blank sky observations data was found when combining the photon and neutron flux with respective ratios of 0.32 and 0.68. The comparison between the combination of the simulation results and the flight data can be seen in figure 5.15. The same was done for the data acquired during Crab observations, the results can be seen in figure 5.16. Here the best agreement was found when combining the histograms resulting from photon and neutron simulations with the ratio of 0.4 and 0.6 respectively.

The flight data was compared to simulation results. The normalised distributions resulting from simulations of the neutron and photon flux were combined with different ratios and compared the measured distributions. The best agreement, with the lowest reduced $\chi^2$ value, with the blank sky observations data was found when combining the photon and neutron flux with respective ratios of 0.32 and 0.68. The comparison between the combination of the simulation results and the flight data can be seen in figure 5.15. The same was done for the data acquired during Crab observations, the results can be seen in figure 5.16. Here the best agreement was found when combining the histograms resulting from photon and neutron simulations with the ratio of 0.4 and 0.6 respectively.

The method thereby shows, independent from the neutron and photon flux models, that the neutron-to-photon ratio observed during flight is of order 1:2, compatible with the rates simulated in the first two sections of this chapter. The photon induced double-hit rate fraction was furthermore found to increase significantly during an observation of the Crab, thereby showing that the Crab was observed. Extracting the exact signal-to-background ratio from these distributions is not possible due to the varying neutron flux during the Crab observations and
the limited statistics. The signal rate can however be seen to be almost one order of magnitude smaller than the background rate, indicating that the measurements are background dominated.

5.3.2 Principle Component Analysis

The double-hit event rate as measured during flight can be seen as a function of time in figure 5.17. In this figure each data point corresponds to the average double-hit rate as observed during a 5 minute measurement. The figure shows an initial decrease of the count rate as the instrument reaches its float altitude around midday on the 12th of July. A small increase is observed at 1.2 days which coincides with the start of a Crab observation. On the July 14th, at 2.3 days, the increase can be seen to be much more pronounced. The rate does show strong fluctuations during this observations which are a result of the polarimeter moving off-source several times as was described in chapter 2. In section 5.1 it was discussed that a significant drop in the neutron induced background is expected from simulations approximately at the time when the first full Crab observation started. Such a decrease was furthermore observed using the neutron detector flown on the payload. This could explain why the increase during in count rate on the July 14th is more pronounced than that on July 13th. Principle Component Analysis (PCA) will be used to study if this is correct, secondly PCA will be used to study the signal-to-background of the Crab observations independent from Geant4 simulations. The results can thereby be used to independently verify the signal-to-background ratio predicted from simulation, which will be the subject of the next chapter. This section will
5.3. Comparison With Flight Data

Figure 5.15: Normalised histogram of the number of energy depositions per PDC for each PDC for double-hit events for flight data acquired during observations of blank sky regions (red) compared to the histogram acquired by combining the histograms resulting from photon and neutron simulations (blue) with respective ratios of 0.32 and 0.68.

Figure 5.16: Normalised histogram of the number of energy depositions per PDC for each PDC for double-hit events for flight data acquired during observations of the Crab (red) compared to the histogram acquired by combining the histograms resulting from photon and neutron simulations (blue) with respective ratios of 0.40 and 0.60.
start with a brief description of the idea behind principle component analysis, for more detailed information on the method the reader is referred to [120].

![Graph showing double-hit event rate as a function of time]

Figure 5.17: The double-hit event rate as a function of time as measured during the flight of PoGOLite. The time on the x-axis is given in days since midnight of the 12th of July 2013 (UT). The decreases in count rate as observed around 2.5 days coincide with periods during which the polarimeter was pointing off target.

PCA is most commonly used to find a correlation between different variables in data and to use this correlation to reduce the data size. A typical example could be a data set containing several measurement variables on a human body, including the size of different parts of the body. Generally the length of several body parts are correlated, e.g. people with longer arms generally have longer legs. One can use PCA to find such a correlation and subsequently use it to combine several length variables, like leg and arm length, into a single variable, and see how the other variables such a body mass vary with respect to this new variable.

For the work presented here PCA will be used in a different way. This type of analysis will be used to find correlations between the measured double-hit event rate and different variables, such as the incoming neutron flux, and to subsequently remove the dependency of these parameters on the measured double-hit event rate. The goal is to acquire a double-hit event rate from which all dependencies have been removed and which therefore only contains the change in rate induced by target observations. PCA was used previously in this way in for example [121].

One of the parameters which is expected to influence the measured signal rate is the incoming neutron flux which has been simulated in section 5.1 of this chapter. PCA is most efficient when the parameters of which the dependencies are removed
from the count rates are orthogonal to each other. This effectively means that these parameters show no correlation in the data. A parameter which is expected to potentially influence the double-hit event rate while having no correlation with the incoming neutron flux is the instrument elevation angle. The lack of correlation between the neutron induced rate and the instrument elevation angle was demonstrated in section 5.1.

PCA was performed on the PoGOLite flight data of 2013 as follows. First a measurement period has to be defined during which the Crab does not influence the event rate. This period will be referred to as the sample period. The data from this period is used to calculate the correlations between the different parameters. This is done by first calculating the mean and standard deviation of each parameter for the sample period. Subsequently the mean is subtracted from each data point, before dividing it by the standard deviation. This last step makes the parameter unitless which makes the use of PCA more reliable [120]. After this step all parameters have a mean of zero and a variance of unity. Subsequently the covariance between each parameter can be calculated (the covariance is acquired instead of the correlation because of the division by the standard deviation). The covariance matrix has the form

\[
\begin{bmatrix}
    \text{Var}(A) & \text{Cov}(A, B) & \text{Cov}(A, C) \\
    \text{Cov}(A, B) & \text{Var}(B) & \text{Cov}(B, C) \\
    \text{Cov}(A, C) & \text{Cov}(B, C) & \text{Var}(C)
\end{bmatrix}
\]

The variances here are equal to unity as a result of the division by the standard deviation. The covariances lie between -1 and 1. A covariance of unity implies a strong correlation between the two parameters while a covariance with a value of zero implies none. A covariance of -1 implies a maximal negative correlation. The eigenvalues and eigenvectors of this matrix can now be calculated. For the method for which PCA is employed here, the eigenvector with the smallest eigenvalue is selected. The full data, including the Crab observations, can now be transformed. First by again removing the mean of each parameter and dividing it by its standard deviation and subsequently by multiplying it by the eigenvector. This removes the dependencies of parameters B and C from parameter A. Lastly the acquired parameter is multiplied again by its standard deviation in order to give it the original unit. The final result is a parameter, in this case the count rate without dependencies on the neutron rate and instrument elevation, which has a value of zero in the sample region and a non-zero value corresponding to the Crab induced signal rate.

This method can be applied using the periods when the Crab was not observed as the sample region, for example the periods of 0-0.48 and 0.56-1.15 days since midnight July 12th 2013. Observations of Cygnus-X1 and GRS 1915-105 did occur during this period. The source rate during this period is therefore small but cannot be excluded to be non-zero and will therefore potentially induce an error. However, the the time spent observing blank sky, areas where no observable X-ray source is
present, is limited. Using only the blank sky data will result in a small number
of data points for the sample region which will increase the error on the final
result. The size of the errors induced by either of these two situations needs to be
understood in order to choose the sample region and to understand the error on
the final results. A toy Monte Carlo was therefore setup to investigate the effects of
source contamination of the sample region and a limited number of sample points.

In the toy Monte Carlo 4 parameters were used. One represents the instru-
ment count rate rate which had dependencies on the 3 other parameters. These
parameters are here called the signal rate, the temperature and the neutron rate.
For this toy Monte Carlo we assume that the signal rate is not known by the ob-
server whereas the total instrument count rate, the neutron rate and temperature
are known and can therefore be used as parameters in the PCA. The signal was
set to zero for the first 1000 data points and was set to be unity during the last
10 data points. This is shown in figure 5.19. The temperature and neutron rate
were set to vary throughout the observation. The dependency of the instrument
counting rate on the other parameters was set such that no increase in rate was
observed in these last 10 points. The effect of the signal rate on the instrument
recorded rate is therefore not visible. The PCA method was used to reconstruct
the signal rate using the neutron rate, the temperature and the instrument count
rate as parameters. The signal rate was reconstructed several time using the PCA
method while changing the used sample region in between runs. Furthermore the
PCA method was run several times while the source rate was changed to be non-
zero in the sample region, thereby testing the effect of source contamination in the
sample region on the final result.

An example of the output of a particular PCA run which makes use of a rela-
tively large sample region without source contamination can be seen in figure 5.19.
The source rate can be seen to be reconstructed to \( \approx 1 \) for the last data points while
it fluctuates around zero for the remainder. The original signal rate is therefore
retrieved albeit with an error. This error was, as expected, found to increase when
using a smaller sample region or when introducing contamination to the sample
region. For all the tested configurations the error on the reconstructed count rate
in the signal region was found to be equal to that found in the reconstructed sam-
ple region. For example, in figure 5.19, the error in the last 10 data points, where
the signal rate fluctuates around \( \approx 1 \) is equal to the error on the sample region,
the region where the reconstructed rate is \( \approx 0 \). In order to find the error on the
reconstructed signal rate during the target observation, which is normally unknown
to the observer, the standard deviation from zero in the sample region can be used,
as for this period the observer knows the signal rate should be zero. In the case of
PoGOLite this means that in order to estimate the error of the PCA reconstructed
Crab signal rate, the deviation from zero in the signal rate for periods where the
Crab is not observed can be used. The ideal sample region to be used for recon-
structing the signal rate is the sample region which results in the smallest standard
deviation from zero in the reconstructed sample region.
5.3. Comparison With Flight Data

Figure 5.18: The different parameters as used in the Toy Monte Carlo to study the PCA method. The total rate (blue) is a combination of the 3 other parameters, the neutron rate (green), the temperature (black) and the signal rate (red).

Figure 5.19: An example of the signal count rate given as an input to the toy MC (red) and that recovered using the PCA (blue).

Using the knowledge acquired using the toy Monte Carlo, the regions of 0.4-0.48 and 0.56-1.15 days since midnight July 12th 2013 were identified as the best sample region as they resulted in the smallest mean deviation from zero of the reconstructed counting rate in the sample region. The selected input variables were the neutron induced rate, as calculated in section 5.1, and the elevation angle of the instrument as measured during the observations. The covariance between the simulated neutron induced rate and the measured signal rate was found to be 0.93, while the covariance with the elevation was found to be 0.2. This implies a large correlation between the neutron induced rate and the signal rate while
the dependency on the elevation angle of the instrument is small. Similarly the
correlation between the neutron induced rate and the elevation of the instrument
was found to be 0.15 for this period which shows that the components are almost
orthogonal and therefore suitable for the PCA. This furthermore verifies the lack
of dependency of these two variables found in section 5.1. Similarly the PCA
was tested with the SAS count rate instead of the elevation angle, however, here
a covariance of 0.3 was found between the simulated neutron induced rate and
the SAS rate, while the covariance between the SAS rate and the signal rate was
found to be 0.2. The elevation angle of the instrument was therefore found to be
more suitable for use. The final reconstructed signal rate for the 2 days of flight
measurements are shown in figure 5.20, the error on the sample region is shown to
be $\sim 0.3$ Hz in figure 5.21.

![signal count rate as derived using principle component analysis](image)

**Figure 5.20:** The signal count rate as derived using principle component analysis.
The periods between the red dotted lines indicate the periods during which the
instrument was observing the Crab. The decreases in count rate as observed around
2.5 days coincide with periods during which the polarimeter was pointing off target.

The figures show that the double-hit induced signal rate from the Crab reaches
a maximum of $\approx 1.5 \pm 0.3$ Hz during both of the Crab observations. It should
however be noted that during the second day of observations the signal rate becomes
negative during the period without Crab observations. This implies a dependency
on another, unknown, variable which changes significantly during the first and sec-
ond day. We can conclude that, as expected, the observed double-hit rate cannot be
fully described using the neutron flux, the instrument elevation and the source rate.
5.3. Comparison With Flight Data

Figure 5.21: Histogram of the count rates of the sample region. The width of this histogram is representative for the error on the count rate in the ‘on-source’ sample.

The double-hit rate has further dependencies, a candidate for this is the photon induced rate, the fluctuations of which during flight are not understood. The results however confirm that the measured double-hit rate shows a large dependency on the incoming neutron rate, thereby verifying independently from simulations that the background induced rate is dominated by neutrons. The PCA method furthermore confirms that the lower observed increase in double-hit event rate during the first day of observations with respect to the second day can be explained by the drop in neutron rate. Lastly, the results imply a background rate of \(\approx 7\) Hz.

5.3.3 Total Simulated Count Rate

Using the positional distribution study it was confirmed that the ratio between the simulated neutron and photon induced double-hit rates agrees with that measured during flight. Furthermore the PCA method confirmed that the double-hit rate as measured during flight is strongly correlated to the incoming neutron rate predicted using the model from chapter 3. These two tests have therefore shown that the response of the polarimeter to the background can be accurately simulated. The simulated double-hit rate as measured during the PoGOLite flight of 2013 can therefore be compared with the combination of the simulated counting rate induced by neutrons, photons and by the Crab. For this purpose the neutron induced count rate as simulated in section 5.1.4 was combined with the simulated photon induced double-hit rate from section 5.2. In order to calculate the double-hit rate induced by the Crab as a function of time a set of simulations was performed to first find the
relation between the Crab induced double-hit rate and the atmospheric overburden. For these simulations the Crab spectrum was assumed to be \( F(E) = 9.7 \cdot E^{-2.1} \), where \( F(E) \) is the flux in units of photons/(cm\(^2\) s keV) and \( E \) is the energy in keV. This spectrum was previously used for PoGOLite simulations of the instrument response to the Crab \[56\] \[60\], and was taken from \[122\]. The photons were emitted towards the polarimeter from a disk with a radius of 30 cm. A 1 cm thick cylinder of air with a radius of 50 cm, representing the atmosphere, was placed in between the photon emitting disk and the polarimeter. The density of the disk of air was varied between 0 g/cm\(^3\) and 10 g/cm\(^3\) in steps of 0.5 g/cm\(^3\) to simulate the response of the instrument to a Crab spectrum attenuated by an atmospheric overburden in the \( 0 - 10 \) g/cm\(^2\) range. The resulting simulated double-hit counting rate as a function of atmospheric overburden can be seen in figure 5.22.

\[
\chi^2 / \text{ndf} \quad 21.86 / 18 \\
p_0 \quad 0.34 \pm 0.02802 \\
p_1 \quad 6.734 \pm 0.05718 \\
p_2 \quad -0.3221 \pm 0.006153
\]

![Graph](image)

Figure 5.22: The simulated Crab induced double-hit rate as a function of atmospheric overburden fitted with a function of the form \( R = p_0 + p_1 e^{p_2O} \).

The data points in figure 5.22 were fitted with a function of the form \( R = p_0 + p_1 e^{p_2O} \). Where \( R \) is the double-hit rate in Hz and \( O \) is the atmospheric overburden in g/cm\(^2\). The double-hit rate from a Crab-like spectrum was thereby found to depend on the atmospheric overburden as follows:

\[
R = 0.34 + 6.7e^{-0.32O} \quad (5.2)
\]

Using this relationship and the instrument altitude and elevation as measured during flight, the simulated double-hit rate induced by the Crab can be calculated as a function of time for the 2013 flight. The results can be seen in purple in figure
5.3. Comparison With Flight Data

5.23 together with the simulated double-hit rates induced by neutrons, in green, by photons, in brown, the combination of these two background components in blue and the combination of the signal and background in red. The measured rate is shown in black. For this figure the simulated Crab rate was set to zero whenever the instrument was not actively observing the Crab, either because it was pointing off-source or because data taking was stopped.

Figure 5.23: The double-hit rate as a function of time from the PoGOLite flight. The measured rate is shown in black. The simulated neutron induced rate is shown in green, the photon induced background rate is shown in brown, the total background rate (neutron plus photon) is shown in blue, the Crab induced rate is shown in purple and the combination of the simulated signal and background rate is shown in red.

The difference between the measured total count rate and the neutron induced rate from figure 5.23 is plotted as a function of atmospheric overburden together with the relationship from equation 5.2, derived from simulations in figure 5.24. The simulated and measured counting rates can be seen to agree well. Some small discrepancies can be seen throughout the considered period, these discrepancies are most prominent during the start of the second Crab observation period. During this Crab observation pointing of the instrument was lost several times due to sporadic loss of communication with the payload over Iridium. The average measured double-hit rate is therefore lower in several points than simulated. Further improvement between measured and simulated counting rates can be acquired by taking the altitude, magnetic latitude and solar activity dependence on the photon
induced counting rate into account. Assuming relative variations of the photon induced rate similar to that of the neutron induced rate variations of order of 0.2 Hz can be expected. In order to be able to find the exact variation of the photon flux with time a detailed study is required similar to that performed for the neutron induced rate in this thesis.

Figure 5.24: The measured signal rate, acquired by subtracting the simulated neutron induced double-hit rate from the measured double-hit, as a function of atmospheric overburden (black points) compared to the simulated relationship between the double-hit rate and the atmospheric overburden: \( R = 0.34 + 6.7e^{-0.32 \cdot O} \) (red line).

### 5.4 Modulation

The results presented in the previous section show that the absolute rate induced by the atmospheric neutron and photon flux and can be reconstructed well. It was furthermore shown that the signal-to-background ratio during a Crab observation is of the order of 1:7. When using this signal-to-background ratio, assuming the Crab flux to be polarised by 30% and assuming the \( \mu_{100} \) of the instrument to be \( \approx 0.25 \) for the Crab flux (this value will be discussed later in chapter 6), the contribution of the polarised signal on the total modulation curve will have a small amplitude, corresponding to \( \approx 1\% \) of the mean of the modulation curve. As discussed in the beginning of this chapter and shown in figure 5.1, the background
can distort the signal polarisation when inducing a polarisation like signal in the modulation curve with an amplitude of the the same order as the signal induced modulation. For PoGOLite a background induced modulation with an amplitude of the order of 1% can distort the signal induced modulation significantly. It is therefore important to study the potential for the atmospheric neutron and photon flux to induce modulation.

Due to the lack of models of the incoming neutron and photon flux with sufficient precision the modulation induced by the background cannot be acquired through simulations with the required accuracy (order of 1%). However, simulations can be used to give an indication of the form the modulation induced and the order of magnitude of the effect, thereby indicating whether the background is capable of distorting the signal induced polarisation. Using Geant4 simulations the modulation induced by neutrons and photons will be discussed separately in this section. The modulation induced by photons was additionally studied on ground using a $^{137}$Cs source, the results of this study will additionally be compared with simulations.

### 5.4.1 Neutrons

In order to study the effects of the neutron flux on the modulation curve simulation data was produced using the same setup as that described in section 5.1.3 for two different instrument angles set to be 45° and 60° with respect to zenith. These angles are representative of the instrument elevation during a Crab observation. Furthermore the polarimeter was set to rotate during the simulations from 0 to 359 degrees to remove effects induced by asymmetries in the polarimeter, e.g. induced by optical cross talk, on the modulation curve. The modulation curve was fitted with a function of type:

$$f(\eta) = T(1 + \mu \cos(2\eta - 2\alpha) + \mu_{360} \cos(\eta - \alpha_{360}))$$  \hspace{1cm} (5.3)$$

where $T$, $\mu$, $\alpha$ and $\eta$ are equal to the definitions for equation 1.7 and $\mu_{360}$ and $\alpha_{360}$ are the modulation and the angle of a potential component with a 360° period respectively. For the analysis of the polarisation of the signal the azimuthal scattering angle is calculated using the angle between the lowest energy deposition, which for a photon interaction coincides with the Compton scattering location, to the highest energy deposition which coincides with the photoabsorption location. The phase of the azimuthal scattering angle is defined such that, for an instrument pointing horizontally, 0° corresponds to scattering towards zenith while 180° corresponds to a photon scattering towards the Earth’s surface.

The modulation curves resulting from the simulations, for 45° and 60° instrument elevation, including the fit results can be seen in figures 5.25 and 5.26 respectively. From the fit results it can be concluded that, independent from the instrument elevation, the neutron flux induces a significant modulation with a 360° period. The phase of the modulation corresponds to photons scattering in the direction of the Earth’s surface. This is a result of a combination the kinematics of a
Chapter 5. *PoGOLite Background Simulations*

neutron scattering event and the anisotropy of the incoming flux after traversing the neutron shield. Before interacting in the shield 85.7% of the neutrons comes from below the instrument. The polyethylene shield reduces this anisotropy, however, the incoming neutron flux retains a level of anisotropy. This is visible in figure 5.27 where a significant asymmetry around the x-axis can be observed, indicating that the majority of the neutrons interact in the bottom of the instrument. The phase of the induced modulation is a result of the kinematics of neutron interactions. Neutrons deposit a percentage of their energy in each scattering interaction. The average energy deposited in the first scattering interaction therefore exceeds that deposited in the second. Since the majority of the neutrons comes from the direction of the Earth’s surface the largest energy deposition is therefore in the bottom of the instrument while the second, smaller energy deposition takes place higher up in the instrument. This corresponds to the signal from a photon scattering in the instrument in the direction of the Earth’s surface.

Figure 5.25: The simulated azimuthal angular distribution for double hit events induced by a neutron flux corresponding to an atmospheric pressure of 2.8 g/cm². The elevation angle of the instrument (with respect to zenith) was set to be 45°.

The neutron induced modulation is increased by the optical cross talk effect discussed in chapter 2. The PDCs in the outer ring can only induce cross talk towards the centre of the instrument. Neutrons scattering only once in the outer ring therefore induce double-hit events resulting in a reconstructed angle away from the centre of the instrument. When not taking optical cross talk into account in the analysis the 360° modulation was found to be reduced by 25%. The different modulation inducing effects are illustrated in figure 5.28.
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Figure 5.26: The simulated azimuthal angular distribution for double hit events induced by a neutron flux corresponding to an atmospheric pressure of \(2.8 \text{ g/cm}^2\). The elevation angle (with respect to zenith) of the instrument was set to be 60°.

It should be noted here that the angular distribution of the neutrons in the simulations is simplified as the omnidirectional neutron flux is only divided into an upward and downward component. From the simulated modulation induced by atmospheric neutrons we can therefore only derive that a 360° modulation, with 180° phase, and an amplitude of the same size as that resulting from a polarised Crab flux (~1%) induced by neutrons cannot be excluded. The exact amplitude of this effect has to be measured during flight.

5.4.2 Photons

On Ground

Similar to the neutron flux, the photon flux entering the polarimeter is anisotropic. The effect of an anisotropic high energy photon flux on the modulation curve was studied before flight using a \(^{137}\text{Cs}\) source placed on the outside of the polyethylene shield. Analysis of the measurement data shows a polarisation signal induced in the instrument figure 5.29, these results were subsequently confirmed using simulations, figure 5.30. Both the simulated and measured modulation curve show a 180° and 360° component with equal phase. The simulated amplitudes of the two components are within the error of the measured amplitudes.
Figure 5.27: A cross section of the polarimeter showing the scattering locations of neutrons inside the instrument. The negative z-axis points in the direction of the Earth’s surface. The bottom of the outer ring can be seen to be more populated. The lower counting rate observed on the edge of the outer right (radius of 135 mm) is caused by the combination of the rotating instrument and the geometry of the instrument which is not perfectly circular.

The combination of a 180° modulation and a 360° modulation can be explained using the kinematics of high energy photon interactions in the polarimeter. Due to the high energy of the photons the photoabsorption cross section remains small even after scattering, as can be seen in figure 2.3, a double scattering event is therefore more probably than an event consisting of both a scattering and a photoabsorption interaction. In a double scattering event both energy depositions will be similar, which, in combination with the low energy resolution of the instrument, leads to an event for which the initial and secondary interaction cannot be distinguished. Since the scattering angle is calculated from the lowest to the highest energy deposition, not being able to distinguish between the two depositions results in a 180° modulation. Events for which the first and second interaction can be distinguished based on energy induce a 360° modulation. Further double-hit events can be induced by optical cross talk, this can induce an additional 360° component as discussed for the neutron induced modulation. For the neutron flux the optical cross talk induced a signal with a phase equal to the neutron induced modulation. For a photon flux the modulation induced by optical cross talk will have a phase shifted by 180° with respect to the modulation induced by the photon induced flux.
5.4. Modulation

Figure 5.28: Illustration of the reconstructed azimuthal scattering angle from neutron and photon induced events. In red the interaction of a photon entering the polarimeter through the aperture (represented by the X) is illustrated, the photon Compton scatters at E2 (lowest energy deposition) and gets absorbed at E1 (highest energy deposition). The reconstructed angle would be 180°. In blue a neutron entering the instrument from below is illustrated, its first interaction results in the highest energy deposition E1, the second energy deposition is smaller. The reconstructed angle would be 190°. Lastly a neutron induced optical cross talk event is illustrated in green. The neutron scatters once, depositing the highest energy, E1, subsequently optical photons leak to a neighbouring PDC and induce a second hit in the polarimeter. The reconstructed scattering angle from such an event would be 180°.

Flight Background

The angular distribution of the atmospheric photon flux encountered by PoGOLite is important when studying the modulation it induces in the instrument. Unlike the angular distribution of the neutron flux encountered at high altitudes, which peaks at the nadir (180° with respect to zenith), the photon flux peaks around 120° [123]. This is a result of the relatively complex origin of the photons at these altitudes. At the float altitude of PoGOLite the contribution from photons emitted by bremsstrahlung dominates. The electrons responsible for emitting the photons can have a cosmic or an atmospheric origin. Electrons with a cosmic origin have an average momentum directed towards the Earth’s surface whereas atmospheric electrons can come from all directions. Especially electrons produced through muon decay can move upwards in the atmosphere. When these electrons leave the atmosphere and have a rigidity below the cut-off rigidity they will follow the Earth’s magnetic field lines and re-enter the atmosphere on the other hemisphere. It can be shown
Figure 5.29: The modulation curve induced by the photon induced background as measured on ground using a $^{137}$Cs source placed on the side of the instrument.

that due to the angular distribution of the electrons the majority of the photons produced at high altitudes through bremsstrahlung are emitted horizontally [123]. While travelling through the atmosphere towards the instrument, however, the photons can Compton scatter with the atmosphere. For photons in the $1-3\text{ MeV}$ energy range, measured at an altitude corresponding to an atmospheric overburden of $2.5\text{ g/cm}^2$, this finally results in an angular distribution which peaks at $120^\circ$ from zenith, as shown in figure 5.31. The position of this peak changes both with photon energy and with altitude [123], the anisotropy increases with increasing energy and altitude. The angular distributions of photons responsible for inducing double-hit events in PoGOLite during flight will therefore vary both with energy and altitude.

The anisotropy of the photon flux at float altitudes is modelled in [124] for different photon energies. Angular distributions as calculated using the analytical equation presented in [124] were used to simulate the induced modulation for photon fluxes with several different photon energies. The studied energies were $40, 60, 100, 200, 300, 500$ and $750\text{ keV}$. The modulation curves induced by photons with these energies for an instrument with an elevation angle of $30^\circ$ ($60^\circ$ away from zenith) can be seen in figure 5.32.

Figure 5.32 shows that different photon energies induce different kinds of modulation with different amplitudes. The fit parameters acquired for the different energies are summarised in table 5.1.

For energies below $80\text{ keV}$ no significant modulation is induced. In the energy
5.4. Modulation

Figure 5.30: The modulation curve induced by the photon induced background as simulated for a $^{137}$Cs placed on the side of the instrument.

$\chi^2 / \text{ndf} = 15.31 / 7$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prob</td>
<td>0.0322</td>
</tr>
<tr>
<td>$T$</td>
<td>$206.6 \pm 4.1$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$0.2171 \pm 0.0282$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$-37.37 \pm 3.69$</td>
</tr>
<tr>
<td>$\mu_{900}$</td>
<td>$0.09155 \pm 0.02968$</td>
</tr>
<tr>
<td>$\alpha_{900}$</td>
<td>$-36.02 \pm 16.70$</td>
</tr>
</tbody>
</table>

Figure 5.31: The simulated angular distribution of photons in the $1 - 3$ MeV energy range at an altitude of $2.5\,\text{g/cm}^2$. The flux can be seen to peak around $120^\circ$. Reproduced from [123] with permission, © (1977) American Geophysical Union.

range of $80\,\text{keV}$ to $300\,\text{keV}$ a significant $360^\circ$ modulation component becomes visible. The phase of this component is, as expected from the difference in photon and
Figure 5.32: The modulation curves induced by gamma induced background components with energies of the 40, 60, 80, 100, 200, 500 keV and 750 keV with the instrument at an elevation of 30°.

neutron kinematics, shifted by 180° with respect to the neutron induced component. The amplitude is highest for photons with energies of 100 keV. For photon energies above 500 keV no significant 360° modulation component is observed. However for
5.4. Modulation

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>$\mu$ (%)</th>
<th>$\alpha$</th>
<th>$\mu_{360}$ (%)</th>
<th>$\alpha_{360}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>$-0.54 \pm 0.82$</td>
<td>$4.8 \pm 43$</td>
<td>$-0.80 \pm 0.82$</td>
<td>$-29.9 \pm 59.3$</td>
</tr>
<tr>
<td>60</td>
<td>$-0.45 \pm 0.52$</td>
<td>$-33.7 \pm 32.9$</td>
<td>$-0.29 \pm 0.53$</td>
<td>$65.6 \pm 102.4$</td>
</tr>
<tr>
<td>80</td>
<td>$1.19 \pm 0.40$</td>
<td>$-17.1 \pm 9.7$</td>
<td>$1.9 \pm 0.4$</td>
<td>$0.1 \pm 11.8$</td>
</tr>
<tr>
<td>100</td>
<td>$0.42 \pm 0.30$</td>
<td>$-11.8 \pm 21.7$</td>
<td>$3.2 \pm 0.3$</td>
<td>$5.3 \pm 5.7$</td>
</tr>
<tr>
<td>200</td>
<td>$0.27 \pm 0.19$</td>
<td>$-51.1 \pm 20.3$</td>
<td>$2.1 \pm 0.2$</td>
<td>$3.7 \pm 5.1$</td>
</tr>
<tr>
<td>300</td>
<td>$0.25 \pm 0.17$</td>
<td>$-26.8 \pm 19.5$</td>
<td>$1.6 \pm 0.17$</td>
<td>$-6.0 \pm 5.9$</td>
</tr>
<tr>
<td>500</td>
<td>$-0.27 \pm 0.18$</td>
<td>$-21.8 \pm 18.8$</td>
<td>$-0.14 \pm 0.18$</td>
<td>$-25.6 \pm 72.1$</td>
</tr>
<tr>
<td>750</td>
<td>$-0.58 \pm 0.18$</td>
<td>$-28.0 \pm 8.81$</td>
<td>$-0.0 \pm 0.18$</td>
<td>$-74.7 \pm 304.1$</td>
</tr>
</tbody>
</table>

Table 5.1: The fit parameters for modulation curves induced by mono-energetic photon background fluxes.

these high energies, where double scattering interactions dominate over scattering plus absorption events, a small 180° modulation component appears. For photon energies of 750 keV the amplitude of this component is 0.6%.

Based on the results presented in table 5.1 and the incoming photon spectra presented in section 5.2, the modulation induced by the energy integrated gamma background can be expected to have mainly a 360° component and an amplitude of the order of several percent. The phase of the photon induced 360° modulation is shifted by 180° with respect to the neutron induced modulation. The neutron and photon backgrounds therefore partly cancel out each others effects on the modulation curve. Since neutrons dominate the background the two will not cancel each other out completely and the remaining 360° component is expected to have a phase of 180°, corresponding to the upward direction.

The modulation induced by both background components has a relatively small amplitude. However, when assuming the Crab flux to be polarised by, for example, 30%, the $\mu_{100}$ of the instrument to be $\approx 0.25$ for the Crab flux, and a signal-to-background ratio of $\approx 1:7$ as presented in in section 5.3, the amplitude induced by a polarised signal on the total modulation curve will have an amplitude of $\approx 1%$. This shows that, although the modulation induced by the background is small, it will be of the same order of magnitude as the expected modulation induced by the signal. This is a result of the low signal-to-background ratio. The simulations thereby show the necessity to measure the background induced modulation curves during flight. Such measurements were performed during the PoGOLite flight of 2013 and the resulting modulation curves are currently under investigation. The results presented in this chapter furthermore show the necessity for improving the signal-to-background ratio of the PoGOLite polarimeter for potential future flights. This will be the subject of the following chapter.
Chapter 6

Outlook

The results presented in chapter 5 indicate that during the 2013 flight PoGOLite experienced a signal-to-background ratio of \( \approx 1:7 \) when measuring the Crab. In order to investigate whether this signal-to-background ratio can be improved for a potential re-flight, several design optimisations were studied. Using a combination of the knowledge acquired through the background studies, calibration measurements and a set of Monte Carlo simulations the effect of different potential instrument improvements were investigated. This chapter starts with a brief discussion of the effect of optical cross talk on the instrument performance. This is followed by a study of the optimal length of the fast scintillators. In the third section the potential of an active neutron shield is discussed. Lastly the effect of adding a layer of boron carbide to the polyethylene shield is discussed. The effects of the discussed design improvements on the MDP for a future flight of the PoGOLite instrument is presented in the final section.

6.1 Optical Cross Talk

The effect of the optical cross talk on the instrument performance was investigated by simulating the polarimeter response when observing a 100% polarised Crab-like spectrum with an atmospheric overburden of 5 g/cm\(^2\). For these simulations the Crab spectrum was simulated as described in section 5.3. The modulation curves acquired when observing the target for a duration of \( \sim 5 \) hours were studied both with and without taking optical cross talk effects into account. The double-hit rate was found to increase by 20% when including optical cross talk. This corresponds to an increase from 1.43 Hz, without optical cross talk, to 1.71 Hz with optical cross talk. The increase in counting rate has however a negative effect on the MDP of the instrument as the extra events do not contain any information on the polarisation and are therefore effectively background events. As a result of the additional signal events the modulation factor was found to decrease from \( (33.2 \pm 0.8)\% \) to \( (23.4 \pm 0.8)\% \). The neutron and photon induced background
rates were additionally both found, through simulations, to decrease by 15% when removing the effect of optical cross talk from the simulation analysis.

These results illustrate that when removing the optical cross talk the performance of the instrument will improve. The effects on the achievable MDP will be discussed at the end of this chapter. Removing the optical cross talk effect requires the instrument to be fully taken apart. This was not possible in the preparation of the 2013 campaign as this procedure takes several months. When the individual PDCs are accessible an additional layer of optically absorbent material needs to be added to the bottom BGO pieces, from which the scintillation photons were shown to escape in chapter 2.

6.2 Scintillator Length

The length of the fast scintillators in the PoGOLite instrument was defined when the instrument was foreseen to be launched from a mid-latitude location where the atmospheric neutron flux is significantly smaller as was shown in chapter 3. At polar latitudes the atmospheric neutron and photon flux were shown in chapter 5 to exceed the signal induced count rate. The interaction position of these particles within the fast scintillators is expected to be more uniform than the interaction positions of X-rays contributing to the signal. Whereas atmospheric neutrons and gammas enter the instrument from all sides, X-rays from the observed source all enter through the aperture and therefore interact primarily at the top of the fast scintillator. Shortening the scintillators can therefore result in a larger signal-to-background ratio. Furthermore, shorter scintillators can potentially improve the $\mu_{100}$. Shortening the scintillators results in removal of scattering interactions with polar angles close to 0° and 180° for which the modulation is small compared to that for photons scattering at 90°. Shortening of the scintillators furthermore reduces the chance of multiple scattering interactions in the scintillators. Overall the loss in signal rate is therefore partly compensated by a higher modulation factor.

Using the atmospheric neutron model presented in chapter 3 the fast scintillator length can be optimised for the polar flight path of PoGOLite. For this purpose four different sets of simulations were performed. First the expected signal rate for a typical Crab observation was studied as a function of the fast scintillator length.Secondly, the double hit rates induced by neutrons and gammas were studied as a function of the fast scintillator length. Lastly, the effect of the scintillator length on $\mu_{100}$ was studied. Using the combination of these four dependencies the optimum fast scintillator length for a minimal MDP can be found.

Geant4 simulations were performed with a Crab-like flux, as presented in chapter 5, entering the instrument through the aperture. The flux was set to be 100% polarised. A layer of atmosphere with a thickness of 1 cm and a density of 5 g/cm$^3$ was placed between the emitting surface and the instrument to represent an atmospheric overburden of 5 g/cm$^2$, which is representative of an observation of the Crab at its maximum elevation at a float altitude of 40 km. The simulation was performed with different lengths of fast scintillator and assuming no optical cross
talk, as it is expected that this problem will be mitigated for future flights. The same set of simulations was performed with the typical neutron irradiation environment encountered at float altitude and the typical gamma background encountered at these altitudes, as discussed in chapter 5.

Contrary to the X-rays contributing to the signal, the atmospheric neutrons and photons enter the instrument from all directions. A large fraction therefore enters the fast scintillator array from the bottom or from the side, resulting in a larger reduction of the background rate with respect to the signal rate when reducing the scintillator length. The interaction locations for both a Crab-like signal and the neutron induced background in the scintillator array can be seen in figure 6.1. The figure shows that a negligible number of signal interactions takes place at the bottom of the scintillators. This is a result of the mean free path for X-rays in the PoGOLite energy range in plastic which can be calculated to be 2.2 cm for 20 keV and 5.9 cm for a photon of 100 keV. The distribution of the interaction locations of atmospheric photons in the scintillator array was found to be similar to that of atmospheric neutrons.

The Crab induced double-hit rate as a function of scintillator length is shown in figure 6.2 together with the background induced double-hit rate. The signal rate decreases significantly less than the background rate when reducing the scintillator length from 20 cm to 10 cm. Figure 6.3 shows the signal-to-background ratio as a function of the fast scintillator length. The figure shows that the largest signal to background ratio is found for a fast scintillator length of 10 cm.

The modulation factor observed for a 100% polarised Crab flux was simulated for a range of scintillator lengths. The results can be seen in figure 6.4. The value of $\mu_{100}$ increases significantly when reducing the scintillator length. For short (<10 cm) scintillator lengths the signal-to-background ratio deteriorates.

Using the values of the signal rates, the background rates and $\mu_{100}$ as a function of scintillator length the MDP was calculated for a one hour Crab observation with an atmospheric overburden of 5 g/cm$^2$, assuming 25% instrument deadtime, for different length configurations. The results can be seen in figure 6.5. The optimum length of the fast scintillator is therefore found to be 10 cm.

6.3 Active Shielding

Using simulations the current polyethylene shield of PoGOLite, which has a mass of $\approx 300$ kg was found to reduce the double-hit rate induced by neutrons by a factor of $\approx 9$. The induced rate remains however higher than the signal rate expected during an observation of the Crab. A further reduction of the neutron induced rate is therefore desirable, preferably without the need to increase the mass of the polyethylene shield. The effect of replacing the current polyethylene shield by an active shield consisting of plastic scintillators was therefore studied.

Simulations were performed with the typical neutron flux for flight. The spectrum for this flux was calculated using the model presented in chapter 3 with parameters: atmospheric pressure = 3 g/cm$^2$, magnetic latitude = 64.5° and $\phi = 715$ MV.
Figure 6.1: A cross section along the radius of the fast scintillator array showing the interaction locations in the array for a typical Crab spectrum in the top figure and from the neutron induced background in the bottom figure. X-rays from a Crab-like signal are seen to interact mostly in the top of the scintillator array whereas the neutron interaction locations are more isotropically distributed. The gaps between different PDC units are not visible in the figures as the scintillator array was rotating for these simulations.

The flux was emitted, as in chapter 5, from two hemispheres to account for the anisotropy of the incoming neutron flux. The polyethylene shield as flown during the 2013 flight was completely replaced by a shield with the same shape consisting of plastic scintillator material. For the simulations performed here the energy depositions in the shield were stored. Quenching effects for neutron induced energy depositions in the shield were taken into account.

In figure 6.6 the energy as deposited (after correcting for quenching) by all
6.3. Active Shielding

![Graph](image)

Figure 6.2: The simulated Crab induced double-hit event rate (red) together with the background induced rate (black) as a function of the fast scintillator length.

![Graph](image)

Figure 6.3: The double-hit event rate induced by the Crab divided by that induced by atmospheric neutrons as a function of the fast scintillator length (black).

When replacing the polyethylene shield by a plastic scintillator material, signals from the scintillator can be used to veto double-hit events observed in the fast scintillator array. The efficiency of the active shield veto will depend strongly on the minimum measurable energy deposition in the shield. For the PDCs the minimum energy which can be recorded is of the order of 1 keV. The large scintillator volumes of the active shield will most likely have to be read out using several optical fibres connected to a single PMT. The collection of the scintillation light will therefore be significantly less efficient than for the PDCs in the polarimeter. The effect of the active shield vetoing on the observed double-hit rate induced by neutrons was therefore simulated with different veto thresholds ranging from 1 eV to 1 MeV. The neutrons in the shield is shown. The peak observed around 2.1 MeV results from neutron absorption by hydrogen which results in the emission of a 2.1 MeV photon.
results are shown in table 6.1.

These results indicate that the neutron induced background can be reduced significantly by the use of an active shield. It can furthermore be observed that 90% of the neutrons which induce a double-hit event in the polarimeter deposit at least 1 eV in the shield. A large fraction of the neutrons can therefore be assumed to scatter in the shield before depositing energy in the plastic scintillators. This explains the lack of elevation dependence on the neutron induced rate discussed in chapter 5.

The event rate induced by neutrons in the shield is $\approx 13 \text{ kHz}$. Applying a realistic lower energy limit of 500 keV reduces this to 6.4 kHz. When assuming a deadtime of the order of 1 $\mu$s per veto event in the shield the deadtime induced by neutrons alone therefore remains of the order of 1% and therefore manageable. It
should however be considered that apart from neutrons, the shield will be irradiated by both charged particles and photons at float altitudes. The total count rate in the shield can therefore be considered to be significantly higher than the 6.4 kHz coming from neutrons alone.

6.4 Boron Carbide Shielding

Changing the material of the passive neutron shield can also reduce the neutron induced double-hit rate in the polarimeter. The current polyethylene shield reduces the rate by moderating the incoming neutron flux. Polyethylene was chosen as the shield material because of its high hydrogen content and relatively high density.

<table>
<thead>
<tr>
<th>Lower veto threshold (keV)</th>
<th>Neutron induced double-hit event rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 \times 10^{-3}$</td>
<td>0.57</td>
</tr>
<tr>
<td>1</td>
<td>0.69</td>
</tr>
<tr>
<td>10</td>
<td>0.85</td>
</tr>
<tr>
<td>100</td>
<td>1.06</td>
</tr>
<tr>
<td>500</td>
<td>1.75</td>
</tr>
<tr>
<td>1000</td>
<td>2.20</td>
</tr>
<tr>
<td>No veto</td>
<td>5.2</td>
</tr>
</tbody>
</table>

Table 6.1: The simulated neutron induced double-hit rate for different veto thresholds in the active shield.
By adding a second, neutron absorbing, material to the shield the induced rate can be further reduced. Most neutron absorbers, such as \( ^6\text{Li} \), have a high cross section for capturing thermal neutrons but have a negligible capturing cross section for neutrons in the keV and MeV energy ranges. \( ^{10}\text{B} \) has a relatively high capture cross section for fast neutrons, as shown in figure 6.7, and can furthermore be incorporated in mechanical constructions in the form of boron carbide (\( \text{BC}_4 \)). Neutron capture by \( ^{10}\text{B} \) results in the reaction \( ^{11}\text{B} \rightarrow ^4\text{He} + ^7\text{He} \), in 94% of the reactions an additional 478 keV photon is emitted. As such photons have a small, but non-negligible probability, to penetrate the SAS such photons could induce a signal. The emission of such photons can reduce the effect of the boron carbide layer on the double-hit rate.

![Figure 6.7: The neutron capture cross section as a function of the neutron energy.](image)

Boron carbide can be produced using enriched boron with up to 99% \( ^{10}\text{B} \), see for example [125], to form rigid parts which can be constructed in the desired shapes [126]. Since the cross section for neutron capture decreases with increasing neutron energy placing the boron carbide behind a layer of moderating material will result in a larger decrease in flux. Simulations were performed to study the effect replacing the inner layer of the polyethylene shield by a layer of high density (2.52 g/cm\(^2\)) boron carbide. The effect on the neutron induced double-hit rate was studied for layers with a thickness of 5, 10, 20, 30, 40, 50 and 60 mm using the neutron spectrum as used in the study of the active shield. An example of the instrument geometry with a layer thickness of 50 mm can be seen in figure 6.8. The resulting double-hit rates, induced either by neutron or secondary particles formed in the instrument geometry, can be seen in figure 6.9. When replacing less than 10 mm of polyethylene by boron carbide the double-hit rate can be seen to decrease. When further increasing the thickness of the boron carbide shield, the moderating effect of the polyethylene is further reduced, as a result fewer neutrons are moderated towards energies where the capture cross section of boron carbide is high. The double-hit event rate therefore increases again when increasing the thickness of the boron carbide layer beyond 10 mm. The results indicate that the
neutron induced rate can be reduced by $\sim 15\%$ when adding a layer of boron carbide with a thickness of 10 mm behind the moderating polyethylene shield.

![Cross section of the instrument geometry after implementation of a 50 mm thick BC$_4$ layer as used in the Geant4 simulations. The layer of BC$_4$ is shown in grey below the yellow polyethylene shield.](image)

**Figure 6.8:** Cross section of the instrument geometry after implementation of a 50 mm thick BC$_4$ layer as used in the Geant4 simulations. The layer of BC$_4$ is shown in grey below the yellow polyethylene shield.

### 6.5 MDP Predictions

The effect of the discussed improvements on the MDP for a future flight of the PoGOLite instrument was studied. In order to study the improvement with respect to the instrument as flown in 2013, the MDP for the 2013 flight is calculated for the first three days of flight using simulated counting rates which were previously tested against measurement data in chapter 5. Using the data on the altitude, magnetic latitude and solar activity for the full flight path of 2013 the MDP can furthermore be calculated for the case where the instrument would have been operational for the full flight. The Crab flux was simulated for the atmospheric overburden present at each moment during the flight, while the neutron background was simulated based on the model presented in chapter 3. The atmospheric gamma background was assumed to be constant. The observation efficiency, defined as the time spent observing the target when it was observable, was taken to be 58% based on the
efficiency achieved during the 2013 flight. This efficiency can be taken as a worst case scenario since difficulties with keeping the instrument pointing at the Crab, which were one of the main reasons for the low efficiency, would have most likely been resolved as the flight progressed. The measurement deadtime was furthermore taken to be 25%. Figure 6.10 shows the simulated double-hit rates coming from the Crab and from background for the entire flight based on the altitude and location of the instrument and the solar activity as a function of time. Using the signal and background rates the MDP was calculated as a function of time. This was done for the following scenarios:

- Instrument performance as flown during 2013
- Instrument without optical cross talk
- Instrument without optical cross talk and optimum fast scintillator length
- Instrument without optical cross talk, optimum fast scintillator length and active shielding with veto threshold of 500 keV

The implementation of the boron carbide shield was found to result in a small relative improvement of the MDP of $\approx 7\%$ and is therefore not shown in the figures. For the instrument configuration with an active shield the instrument deadtime was increased to 35% to account for the potential increase in deadtime. The MDPs as a function of time for these scenarios are shown together in figure 6.11. The figure shows that for the scenario of a flight to Canada of 6 days, the MDP can be reduced from the current 19% to 12% by implementing the, relatively simple, improvement of mitigation of the optical cross talk. When shortening the fast scintillator an
implementing an active shield, which are more severe interventions, the MDP can be reduced to 7.5% for such a flight. For a circumpolar flight these numbers would decrease to 12%, 7% and 4.5% respectively. Figure 6.12 shows the MDP for the off-pulse period of the Crab for these configurations.

Figure 6.10: The simulated double-hit rates induced by the Crab flux (black) and atmospheric neutrons and gammas (red) based on the altitude and location of the instrument and the solar activity as a function of time. The presented count rates assume an instrument configuration as flown during 2013.
Figure 6.11: The simulated MDP for the full Crab for the different instrument configurations as a function of days since the launch date. The MDP for an instrument as flown in 2013 is shown in green diamonds, the MDP for an instrument without optical cross talk is shown in blue triangles, with additional optimisation of the fast scintillator length in red squares and with an active neutron shield with a veto (threshold at 500 keV) in black circles.
Figure 6.12: The simulated MDP for the full off-pulse period of the Crab for the different instrument configurations as a function of days since the launch date. The MDP for an instrument as flown in 2013 is shown in green diamonds, the MDP for an instrument without optical cross talk is shown in blue triangles, with additional optimisation of the fast scintillator length in red squares and with an active neutron shield with a veto (threshold at 500 keV) in black circles.
Chapter 7

Conclusions

Polarimetry is a relatively new and unexplored field within X-/gamma-ray astrophysics. The polarisation of the X-ray flux of a wide variety of astrophysical sources holds information on the emission mechanisms and on the emission regions. Such measurements are however challenging. This is partly due to the relatively low detection efficiency of polarimeters, caused for example in the case of polarimeters working in the hard X-ray energy regime, by selecting only events which undergo Compton scattering followed by photoabsorption. A second reason is the high radiation environment in which the measurements need to be performed. As a result few measurements have been performed in the X-ray energy range. However a large number of newly proposed polarimeters are currently being developed. PoGOLite is one such instrument. The balloon-borne PoGOLite polarimeter uses a segmented plastic scintillator array to measure the azimuthal Compton scattering angle of incoming X-rays. It furthermore employs a variety of background rejection systems, include both active and passive collimators, an anti-coincidence system and a passive polyethylene shield which reduces the neutron induced rate.

The instrument was launched successfully on July 12th 2013 from the Esrange Space Centre in Northern Sweden. It performed a near circumpolar flight of 15 days before landing close to the city of Norilsk in Russia. Due to an issue with power distribution the polarimeter was only able to operate during the first two and a half days of the flight. During this period two Crab observations were performed. The background was furthermore measured and was found to vary throughout the flight, thereby providing valuable information for future flights.

Previous studies, such as [60], have already shown that the neutron induced rate in the instrument would exceed the signal rate. Due to the expected dependency of the neutron flux on the altitude, magnetic latitude and solar activity the exact neutron induced rate for the particular conditions persisting during the PoGOLite flight of 2013 could not be predicted in previous studies. For this purpose a Monte Carlo based model was developed. Monte Carlo simulations were performed using the PLANETOCOSMICS toolkit to reproduce the neutron environment in the Earth’s atmosphere for different solar activities. The data resulting from the simulations
was used to find the variations of the neutron flux and spectral shape with altitude, magnetic latitude and solar activity. These variations were parametrised to develop a model capable of providing the neutron energy spectrum in the 8 keV – 1 GeV energy range for all altitudes, magnetic latitudes and solar activities. The predictions from the model were found to match data measured on high altitudes aircraft. The spectra provided by the model were furthermore found to agree well with predictions available from other Monte Carlo based models which are only valid for specific locations and solar activities.

The developed model could however not be tested with measurement data for the conditions relevant for PoGOLite, as no such data existed. For this purpose a dedicated balloon-borne neutron detector was developed called PoGOLino. PoGOLino uses the novel type of scintillator, LiCAF, developed at the Tokuyama corporation in Japan. The LiCAF scintillator, which is sensitive for neutron detection, is sandwiched between BGO crystals which form an anti-coincidence system. The PoGOLino instrument was extensively calibrated on ground. In the calibration measurements it was shown that using the BGO anti-coincidence system the instrument is capable of accurately measuring the neutron flux in two different energy ranges in a high radiation environment. It was furthermore shown that the instrument is capable of measuring in the harsh environmental conditions encountered during a balloon flight in late winter in Northern Sweden. The instrument was launched from the Esrange Space Centre on March 20th 2013 to an altitude of 31 km. It successfully performed measurements of the neutron flux throughout the 3 hour flight. The measured neutron flux was found to be in good agreement with predictions from the previously mentioned model. This model was therefore validated for conditions relevant for PoGOLite and showed the potential of the novel detection technique to be used for measuring the neutron flux in high radiation environments.

Predictions from the verified model could now be compared to the neutron environment measured by PoGOLite during its circumpolar flight. First the distribution of interactions in the polarimeter induced by neutrons and photons was simulated and subsequently compared to flight data. The comparison confirmed that the distribution distribution of hits in the polarimeter as measured during flight is compatible with a neutron dominated background. Subsequently the PCA method was used to prove that variations in the event rate as measured during flight are compatible with variations in the neutron flux in flight as predicted by the parametrisation model. It was thereby shown that the changes in the event rate observed in the flight data are induced by variations in the neutron flux impinging on the instrument which in turn result from variations of the balloon position and the solar activity. The PCA method furthermore showed the signal-to-background ratio measured during flight to be 1:7. Lastly the absolute event rate as a function of time as measured during the 2013 flight was found to agree well with a combination of the simulated neutron, photon and Crab induced rate. It was thereby shown that the background induced event rate in PoGOLite can be reproduced well using simulations.
Using simulations both the neutron and photon induced background were shown to induce a modulation in the azimuthal scattering angle. The amplitude of the background induced modulation is small, of the order of 1%. However, due to the low signal-to-background rate such an amplitude is of the same order of magnitude as the expected amplitude induced by the Crab signal. The background induced modulation therefore needs to be taken into account when deducing the Crab polarisation from the flight data. This work is currently in progress.

After it was confirmed that the background as measured during the 2013 flight of PoGOLite can be reproduced well, simulations were used to study potential improvements to the instrument design for potential future flights. It was shown that the MDP achievable for future PoGOLite flights can be decreased by mitigating the optical cross talk in the polarimeter, shortening the scattering scintillators and by replacing the passive polyethylene shield by an active scintillator shield. Using the altitude profile of the instrument the MDP of the off-pulse period of the Crab was calculated to be $\approx 18\%$ for a situation where the polarimeter functioned throughout the entire flight of 2013. When mitigating the optical cross talk, subsequently shortening the fast scintillators and additionally using a realistic active shield, this MDP was shown to be reduced to 11%, 10% and 7% respectively. The achievable MDP would therefore be significantly lower than the degree of polarisation previously measured by other instruments at lower photon energies.
Appendix A

The simulation results for PoGOLite presented in this thesis were acquired using Geant4. The PoGOLite simulations are set up to output the coordinates of each interaction which occurs in an active detection material together with the name of the active detector volume (e.g. SAS unit number 1) and the deposited energy (in keV). When the energy is deposited by a proton, helium nucleus or carbon nucleus the deposited energy is multiplied by the quenching factors discussed in chapter 5 of this thesis. The output file from a Geant4 simulation therefore contains only the energy deposited in each interaction (corrected for quenching) and the coordinates of the interaction location. This output from the simulation is subsequently processed with ROOT [128] based software which takes the instrument response into account. The analysis proceeds as follows:

1. For energy depositions in a plastic scintillator (the fast or slow scintillator) the non linear response of the plastic scintillators with energy is taken into account. For high energy depositions ($\gtrsim 50$ keV) the light output of a plastic scintillator is proportional to the deposited energy. For lower energy depositions the response is non-linear and therefore a correction factor has to be applied. For the scintillators used in PoGOLite the response at low energies was measured during calibration [127]. Based on these measurements the following correction factor is applied to account for the non-linearity: $E_{cor} = E_i (1.001 - 0.486 e^{-0.0902 E_i})$, where $E_i$ is the uncorrected deposited energy and $E_{cor}$ is the corrected energy.

2. The number of optical photons leaving the fast scintillator depends on the interaction location in the scintillator. All energy depositions in the fast scintillator are therefore corrected using the following factor based on results presented in [127]: $E_{cor} = E_i (1.0 - (z - 132)0.0008)$. Where $E_{cor}$ is the energy after correction, $E_i$ is the energy after the non-linearity correction and $z$ is the position along the rotation axis in mm of the polarimeter, with $z = 0$ corresponding to the interface of the fast scintillator with the bottom BGO.

3. For events with several energy depositions in the same PDC, for example from a photon scattering twice in the same fast scintillator, the deposited energies are summed.
4. The optical cross talk is taken into account as described in chapter 2 of this thesis.

5. The deposited energy is converted into photoelectrons by picking a random number from a Poisson distribution with a mean of $E \times Q$ where $E$ is the energy after the position correction and $Q$ is the number of photoelectrons per keV, which was measured for each PMT individually.

6. The effect of PMT gain fluctuation is taken into account by picking a random number from a Gaussian distribution with a mean of $N_{pe}$, the number of photoelectrons calculated from the previous step and a width of $0.35 N_{pe}$. The factor of 0.35 is based on calibration measurements presented in [127].

7. The number of photoelectrons is converted in an ADC level by multiplying the output of the previous step by the ADC/photoelectron ratio which was measured for each PMT individually by measuring the position in ADC channels of the single-photoelectron peak.

8. The energy, now in ADC channels, is compared to the thresholds set on the instrument. First all PDCs in which the measured energy is below the hit threshold of 10 ADC are discarded.

9. To take the trigger threshold into account all events in which none of the PDCs contains a measured energy exceeding 300 ADC are discarded.

10. The event is discarded if the measured energy in one of the PDCs exceeds the upper discrimination threshold of 2500 ADC.

11. The event is discarded if there is an energy deposition in one of the SAS units.

12. To take the online trigger of the instrument into account the event is discarded if: $E_v E_{fast} + O$. Where $E_v$ is the energy measured in the BGO or slow scintillator. $E_{fast}$ is the measured energy in the fast scintillator and $O \sim 15$ ADC. The exact value of $O$ depends on the PMT gain and ADC/photoelectron ratio of the PMT.

13. Finally only events with measured energies in 2 different PDCs are kept.
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