PoGOLite - The Polarised Gamma-ray Observer

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Cover illustration: Image of the Crab Nebula at X-ray wavelengths taken by Chandra X-ray Observatory.
Abstract

PoGOLite [1] [2] is a balloon-borne experiment which will study polarised soft gamma-ray emission from astrophysical targets in the 25 keV - 80 keV energy range by applying well-type phoswich detector technology. Polarised gamma-rays are expected from a wide variety of sources including rotation-powered pulsars, accreting black holes and neutron stars, and jet-dominated active galaxies. Polarisation measurements provide a powerful probe of the gamma-ray emission mechanism and the distribution of magnetic and radiation fields around the source. The polarisation is determined using Compton scattering and photoelectric absorption in an array of 217 plastic scintillators. The sensitive detector is surrounded by a segmented Bismuth Germanium Oxide (BGO) anticoincidence shield. The function of this shield is to reduce backgrounds from charged cosmic rays, primary and atmospheric gamma-rays, and atmospheric and instrumental neutrons. The anticoincidence shield consists of 427 BGO crystals with three different geometries. The characteristics of the BGO crystals of the bottom anticoincidence shield have been studied with particular focus on the light yield.

The PoGOLite polarimeter has a field of view of 2.4° × 2.4° and must be kept aligned to objects of interest on the sky. A star tracker forms part of the attitude control system. The star tracker system comprises a CCD camera, lens, and a baffle system. Preliminary studies have been made concerning optimization of the focus, flat field correction, map of hot pixel and CCD response. An estimate of the star magnitude limit is also derived and found to be compatible with the environment around the Crab, which is the first observational target. These studies pave the way toward an autonomous star tracking device which together with the other attitude control devices will reconstruct the pointing solution.
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Preface

Outline of the thesis

This thesis describes two diverse elements of the Polarized Gamma-ray Observer (PoGOLite). The first study concerns the performance of BGO crystals used for the bottom anticoincidence shield. The second study addresses a preliminary calibration of the star tracker used for the pointing reconstruction.

Chapter 1 provides an overview of developments in gamma-ray polarimetry, and describes possible scientific targets especially the ones of interest to PoGOLite. The physics of the detection of polarization is also briefly described emphasizing the interaction processes on which the experiment relies.

The experiment is described in chapter 2, with the polarimeter, anticoincidence shield, electronics and pointing system described in detail.

Chapter 3 presents the laboratory set-ups used for testing the scintillator crystals and the results of the performance studies.

Chapter 4 describes more in detail the star tracker system and presents preliminary tests made on the CCD camera.

The author’s contribution

I started my PhD position in the Particle and Astroparticle group at KTH in 2005. My position forms part of the AlbaNova High Energy Astrophysics and Cosmology (HEAC) Centre, funded as a centre of excellence by the Swedish Research Council. Already from the first year I started working on the balloon experiment PoGOLite. During the first months I was involved mainly in testing the light yield of BGO samples. I made the final CAD drawings of the crystals and of the prototype of the mechanical support for the anticoincidence shield. Considering the large number of crystals that we would have received I setup a MySQL database in order to keep track of the crystals results. The second year I have been testing all the bottom BGO crystals and also started to work on the star tracker system.

Beside PoGOLite I have been involved also in the SEASA (Stockholm Educational Air Shower Array) project, especially in building together with the school students the scintillator detectors and later in installing the detectors in the schools.
The work presented here is partially described in the following publications, of which I am author or co-author:


- M. Axelsson et al., "Measuring energy dependent polarisation in soft gamma-rays using Compton scattering in PoGOLite". astro-ph/07041603. Accepted for publication by Astroparticle Physics.

Chapter 1

Introduction

1.1 Gamma-ray Polarimetry

Since the early 1960’s the study of celestial X-ray and gamma-ray sources has dealt with their spectrum, time variability and projected image on the sky. This information can probe the nature of different emission mechanisms for sources but in many cases is not enough to model the distribution of magnetic and radiation fields. Sources expected to exhibit strong polarisation include rotation-powered pulsars, accreting black holes, neutron stars and gamma-ray bursts (GRB). Polarisation measurements add two parameters to the conventional measurements: polarisation degree and polarization angle, which restrict the parameter space and can test competing models.

In astrophysical environments, polarisation arises under a variety of conditions. For synchrotron radiation, polarisation is due to electrons gyrating in ordered magnetic fields, in this case the study of polarisation provides information on the characteristic of the magnetic fields around the source. Since the interaction cross-section of the photons propagating through the magnetic field is energy and polarisation dependent, it is possible to investigate directly the field close to the source, for example a neutron star or a GRB. Polarisation can also be observed in Compton scattering of photons in the accretion disks around compact stars and active galactic nuclei. In both cases the orientation of the polarisation plane depends on the geometry of the sources, including the orientation of the magnetic field and accretion disk. All this makes polarisation a powerful diagnostic tool. Polarisation measurements from radio to UV wavelengths have already been performed in order to study the plasma and magnetic phenomena on the sun, magnetic field in the interstellar medium and accretion onto magnetic compact stars [3]. However, to date, few experiments have measured polarisation at hard X-ray/soft gamma-ray energies.

The first attempt to measure polarisation at X-ray energies was made in 1967 with an instrument based on Thomson scattering in lithium [4]. The apparatus
flew several times on balloons and sounding rockets to measure the polarisation of X-ray sources in Sco X-1 and Tau X-1 (Crab Nebula). The first prototype was flown on a balloon in 1967 and was dedicated to the study of backgrounds. The first rocket-borne experiment was performed in 1968 and established a polarisation of less than 18% for the X-ray flux from Sco X-1 between 5 keV and 16.8 keV with a probability of 99%. The Crab Nebula was observed with a second sounding rocket experiment in 1969 with an observation time of 4 minutes. The results stated that X-ray flux from the Crab nebula was 27% polarised between 5 keV and 22 keV with a confidence level of 99%. In 1971 a larger version of the Thomson scattering polarimeter with an additional Bragg reflection polarimeter were launched on a sounding rocket \[5\] to observe the Crab Nebula. A polarisation degree (angle) of \((14.7\pm7.9)\% \ ((155\pm14)\degree)\) was measured for photon energies in the range of 7.0-17.0 keV. At an energy in the range of 2.0-3.2 keV, the measurements yielded \((24.1\pm10.2)\% \ ((155\pm11)\degree)\) respectively.

In 1975 polarisation measurements were made by the two X-ray polarimeters on the Orbiting Solar Observatory 8 (OSO-8). The Crab nebula was viewed at energies of 2.6 keV and 5.2 keV since Bragg reflection technique was used (see figure 1.1) \[6\]. The measured polarisation degree was \((19.2\pm1.0)\%\) for the nebula.

Most recently, in 2006 the PHENEX hard X-ray Compton scattering polarimeter attempted to observe the Crab system in the energy range 40-300 keV from a balloon-borne platform. The reported degree of polarisation \[7\] \((33\pm26)\%\) is inconclusive. A failure of the attitude control system was reported during the flight.

Many new polarimetric instruments have been proposed to investigate the X/γ region. POLAR (10-300 keV) will study polarisation arising in gamma-ray bursts through Compton scattering and photoelectric absorption in a plastic scintillator array \[8\]. GRAPE (50-300 keV), also based on Compton scattering with a very precise geometry reconstruction, will focus on polarisation produced in solar flares as well as in GRB \[9\]. CIPHER is a hard X- and soft gamma-ray spectroscopic and polarimetric coded mask telescope and will study the Crab pulsar over the energy range 10 keV-1 MeV \[10\]. POLARIX (1.5-10 keV) will be a pathfinder for a new technique, the Micropattern Gas Chamber. This method is a good imager and performs simultaneously timing and spectra \[11\].

In this thesis the PoGOLite \(^1\) balloon-borne polarimeter is presented. PoGOLite is designed to study polarised emission from point-like sources in the energy band 25-80 keV. The primary targets are the Crab system (pulsar and nebula) and an accreting black hole, Cygnus X-1. The detection of polarisation is based on Compton scattering and photo-absorption in a close packed array of plastic scintillator elements. The full version of PoGOLite comprises 217 such elements. A 'pathfinder' flight of 61 element instrument expected to last between 6 and 24 hours is foreseen for 2010 from the Esrange facility in the North of Sweden. The primary aim of this flight will be to test PoGOLite systems, evaluate backgrounds, and observe the Crab system. This will be followed by longer duration flights, and

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\(^1\) Polarised Gamma-ray Observer - Light weight version.
1.1. Gamma-ray Polarimetry

the instrument volume will be enlarged. Long duration flights of several days from Esrange to Western Canada are a long term goal.

![Figure 1.1](image.png)

**Figure 1.1.** The polarization vectors for the Crab Nebula at (left) 2.6 keV and (right) 5.2 keV. Surrounding the vectors in order of increasing size are the 67% and 99% confidence contours. The radial scale is the polarization in percent [12].

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>Technique</th>
<th>Result</th>
<th>Status</th>
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<tbody>
<tr>
<td>OSO-8</td>
<td>2.6, 5.2 keV</td>
<td>Bragg reflection</td>
<td>(19.2 ± 1.0)%</td>
</tr>
<tr>
<td>PHENEX</td>
<td>40-300 keV</td>
<td>Compton scattering</td>
<td>(33 ± 26)%</td>
</tr>
<tr>
<td>POLAR</td>
<td>10-300 keV</td>
<td>Compton scattering</td>
<td>photoelectric absorption</td>
</tr>
<tr>
<td>GRAPE</td>
<td>50-300 keV</td>
<td>Compton scattering</td>
<td>photoelectric absorption</td>
</tr>
<tr>
<td>CIPHER</td>
<td>10 keV-1 MeV</td>
<td>Coded mask</td>
<td>proposed</td>
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<tr>
<td>POLARIX</td>
<td>1.5-10 keV</td>
<td>Micropatter Gas Chamber</td>
<td>proposed</td>
</tr>
<tr>
<td>PoGOLite</td>
<td>25-80 keV</td>
<td>Compton scattering</td>
<td>photoelectric absorption</td>
</tr>
</tbody>
</table>

**Table 1.1.** List of some experiments aimed to study X-ray polarization.
1.2 Scientific Objectives

X-ray astronomy is a relatively new science since X-rays cannot penetrate the Earth’s atmosphere. It is impossible to observe X-rays of astronomical sources with ground-based instruments and so instruments must be deployed above the atmosphere. The specific altitude depends on the energy of the X-rays, for example in order to detect radiation in the range of 0.5-5 keV one has to reach 80 km, whereas for 30 keV photons 35 km is sufficient. Until the middle of 20th century there was the technological obstacle to escape the atmosphere, but at the same time there was no strong will to overcome it since no astronomical X-ray sources had been predicted. A X-ray quantum has an energy of 1000 times larger than an optical photon, thus if produced in a thermal process the temperature of the X-ray source has also to be 1000 times greater than the one of optical source, usually at a typical temperature of \(\sim 3000 \text{ K}\). Until the discovery of the first astronomical X-ray emitter, sources with temperatures of millions of degrees had not been hypothesized.

The first extra-solar X-ray source was detected in 1962 by Giacconi using a rocket [13]. The target of the mission was the study the X-ray radiation of the sun reflected from the moon. Unexpectedly besides the two peaks coming from the sun and the moon a much brighter source was observed coming from the constellation of Scorpius and was called Sco X-1, the optical counterpart is hundred times fainter than the faintest star that can be seen by naked eye. This discovery opened a new field in astronomy and revealed the presence of high energy phenomena and sources (see figure 1.2).

To date thousands of sources has been classified and the challenge is to understand the mechanism of their emission, one tool is studying the polarisation which some objects are expected to emit. This can be either intrinsic, if the radiation produced is polarised, or extrinsic, if polarization is induced after emission.

1.2.1 Pulsars

Pulsars, rapidly rotating neutron stars, are one of the primary targets for PoGOLite observations. Pulsars were discovered in 1968 by Jocelyn Bell and Anthony Hewish using a radio telescope meant to study scintillation observed when radio waves from quasars pass through the solar wind [15]. The data showed the presence of a source once every sidereal day (\(\sim 23 \text{ hours and 56 minutes}\)) indicating that the source was outside the solar system. Investigating more in detail this signal, it revealed a series of regularly spaced radio pulses 1.337 seconds apart. Several more were quickly found by other radio observatories. Today about 550 pulsars are known, each is designed by “PSR” (Pulsating Source for Radio) followed by the ascension (\(\alpha\)) and declination (\(\delta\)). The pulsar discovered by Bell is for example PSR 1919+21, identifying the position as \(\alpha=19^h 19^m\) and \(\delta=+21^\circ\). One of the properties of pulsars is that the frequency mean profile is (in most cases) extremely stable. The phase of this profile is very predictable.

Another characteristic of pulsar emission is that it is generally highly polarised, with linear polarisation dominating over circular. The polarisation is determined...
1.2. Scientific Objectives

Figure 1.2. The HEAO-1 sky survey in galactic coordinates showing 842 X-ray sources. The sizes of the dots are proportional to the log of the intensity, the energy band is 0.25-25 keV [14].

by magnetic fields in or above the emission region. The profile of the polarization degree and polarization phase is very stable within a source.

There are three main models that describe the high-energy emission: polar cap model, caustic model and outer gap model (figure 1.3).

In the polar cap model electrons and positrons are accelerated in the open field line region near the magnetic polar cap of a rotating neutron star. The curvature radiation (radiation emitted from particles that have an acceleration because they are forced to follow the lines of the magnetic field) they emit, interacts with the strong magnetic field of the pulsar and produces $e^\pm$ pairs. These pairs in turn emit synchrotron radiation which also interacts with the strong magnetic field. An electromagnetic cascade results, and the gamma-ray flux seen from the Earth consists of the escaping curvature and synchrotron radiation.

The outer gap model describes the emission of particles accelerated in the vacuum gaps formed in the outer regions of the pulsar magnetosphere along the boundary between the “closed” and “open” field line zones. In these gaps a high potential drop is formed which accelerates electrons and positrons to high energies. Curvature radiation and inverse Compton photons emitted by these particles interact with low-energy particles to produce secondary pairs of electrons and positrons responsible for the synchrotron and inverse Compton radiation we observe.

Finally, the 2-pole caustic model, a combination of the other two models, predicts that the emission takes place in a region confined to the surface of last open
magnetic field lines but extending between the polar cap and the light cylinder (the radial distance at which the rotational velocity of co-rotating particles equals velocity of light).

All three predict similar emission features, whereas the polarisation profiles simulated for the first peak are different (see figure 1.4). The primary target of PoGOLite will be the Crab, pulsar and nebula, since it is one of the brightest astronomical objects in X-rays.

Figure 1.3. Schematic illustration of pulsar acceleration models. The pulsar in the middle rotates with velocity $\Omega$ around the vertical axis. The magnetic field $B$ forms an angle $\alpha$ with the rotation axis [16].
Figure 1.4. Model predictions for pulsars versus phase: intensity (top panels), polarisation position angle (middle panels) and polarisation degree (bottom panels) for (left) the polar cap model ([17]), (center) the outer gap model ([18]) and (right) the caustic model ([19]). The areas between a pair of vertical lines in the figure correspond to the first pulse (P1) and the second pulse (P2). The numerical data are provided by Alice Harding.
1.2.2 Accreting Black Holes

Another type of object of great interest for PoGOLite are accreting compact sources. The best object among these is Cygnus X-1 which is a black hole candidate. It is the brightest accreting compact source of X-rays above 20 keV, is part of a X-ray binary (XRB) system consisting of a super-giant 09-B0 (20-30 $M_{\odot}$) and a compact object (7-13 $M_{\odot}$). Since the mass of a neutron star cannot exceed 3 $M_{\odot}$ it is believed that the compact object is a black hole. The material flowing from the super giant to the black hole is predicted to gather in a hot, rapidly rotating accretion disk, hot enough to emit X-rays. The source shows a spectrum which consists of two distinct spectral states (see figure 1.5), the so called hard (low) state and soft (high) state (see figure 1.5, 1.6). Transitions from the hard state to the soft state take place every few years and the source stays in the soft state only for weeks or months.

The hard state is primarily due to multiple scattering of blackbody photons from a cold disk by thermal electrons in a hot inner flow. The contribution of non-thermal synchrotron emission is small. Some hard X-rays are Compton reflected on the cold disk, which is truncated and does not reach the most inner stable orbit but overlaps the inner flow. The signature of this secondary component are the 6.4 keV K fluorescence line, proof of cold material in the disk, and a broad "hump" at 10-200 keV, an indication of Compton reflection by the cool material. The second component is believed to be intrinsically polarised (>50%), depending on the inclination relative to the observer, but since albedo particles contribute with a 30% polarisation the resulting polarisation is about 15%. Polarisation measurements in the energy range of the "hump" (10-200 keV) can provide constraints on the geometry of the emission.

In the soft state X-ray emission arises from Compton up-scattering of non-thermal electrons in active regions above the disk surface. In this case polarisation could give information about the anisotropy of the non-thermal distribution of electrons.
1.2.3 Accreting Magnetic Neutron Stars

The accreting source of a XRB can also be a neutron star with a strong magnetic field, $10^{13}$ Gauss, on the surface. The X-ray and gamma ray radiation originates from the accreting material which is flowing along the lines of the magnetic field onto the poles of the neutron star.

In the strong magnetic field near the poles the plasma electrons will gyrate in the plane perpendicular to the magnetic field and interact with higher probability with photons that are polarised in the plane orthogonal to the magnetic field. The resulting radiation will also have a net polarisation. Since the neutron star is rotating the polarisation and degree of linear polarisation will be modulated in time. Time resolved polarisation measurements can provide information about orientation and magnitude of magnetic field relative to the observer. In a long duration flight PoGOLite will be able to confirm the underlying mechanism responsible for the reflection component, most probably Compton scattering.

The first target among these objects will be Hercules X-1, and in addition the two bright transient objects, 4U0115+63 and V0332+53, which have been observed to have an outburst of several months.
Figure 1.6. Schematic representation of the two different geometries of Cygnus X-1. Hard spectral state (top): hot inner accretion flow surrounded by optically thick accretion disk. The disk does not reach the minimum stable orbit but overlaps the hot flow. The soft photons emitted by the disk are Compton up-scattered in the hot flow, and the emission from the hot flow is partly Compton-reflected from the disk.

In the soft state (bottom) a flares/active region extends on an optically thick accretion disk close to the minimum stable orbit. The soft photons are up-scattered in the flares, and emission from flares is partly Compton-reflected from the disk [21].

1.3 Interaction of Gamma rays

When a monoenergetic photon beam of intensity $I_0$ passes through a material of thickness $x$, and of mass thickness $X = \rho x$, the intensity of the beam decreases as

$$I(x) = I_0 e^{-\mu x} = I_0 e^{-(\mu/\rho)X}$$

(1.1)

where $\mu$ is the linear mass absorption coefficient and $\mu/\rho$ the mass absorption coefficient. This coefficient is related to the cross-section $\sigma$ by $\mu = \sigma N_0 \rho / A$, where $A$ is the mole mass of the material and $N_0$ is the Avogadro number. The dominant contributions to the cross-section for photon energies above 10 keV are (see figure 1.7): photoelectric effect at energies below 100 keV, the Compton effect around energies of 1 MeV and pair production the photon above energies of 2 MeV.
1.3. Interaction of Gamma rays

The PoGOLite determination of polarisation is based on the first two interactions. In photoelectric absorption a photon is absorbed by an atom, and a photoelectron from an atomic shell (usually the K-shell) is ejected with an energy

\[ E_e = h\nu - E_b \]  

(1.2)

where \( E_b \) represents the binding energy of the photo-electron in its original shell, \( \nu \) its frequency and \( h \) is the Planck constant. The vacancy in the ionized absorber atom is filled through capture of a free electron from the medium and/or a rearrangement of electrons from the other shells of the atom. The photoelectric effect dominates for gamma and X-rays of relatively low energy, and the probability increases with increasing atomic number \( Z \). No analytical equation for the differential cross-section exists, but an approximation is given by:

\[ \frac{d\sigma}{d\Omega} = K \times \frac{Z^n}{E_\gamma^{3.5}} \]  

(1.3)

for photon energy, \( E_\gamma \), below 0.5 MeV, \( K \) is a constant and \( n \) varies between 4 and 5 [22]. For higher energies the differential cross-section becomes

\[ \frac{d\sigma}{d\Omega} = K' \times \frac{Z^n}{E_\gamma} \]  

(1.4)
where $n$ is defined as before and $K'$ is a new constant. In Compton scattering the gamma-ray photon is deflected from the original direction. Part of the energy is transferred to an electron. All angles of scattering are possible and the energy of the electron can vary from zero to a large fraction of the photon energy. The probability of Compton scattering depends on the number of electrons available as scattering targets and therefore increases linearly with $Z$ (see equation 1.7). Since PoGOLite detector relies on this process, a detailed description is given in section 1.4.

Figure 1.8. Schematic view of Compton scattering, the incident photon has initial wavelength $\lambda_0$, after scattering on the electron the wavelength changes to $\lambda$. $\theta$ is the angle between incident and scattered direction.

Pair production is possible if the energy of the gamma-ray photon exceeds twice the rest-mass of an electron (1.02 MeV). The probability remains very low until the gamma-ray energy approaches several MeV. The gamma-ray photon interacts in the Coulomb field of a nucleus and it is absorbed, at its place a electron-positron pair appears. The differential cross-section is described by

$$\frac{d\sigma}{d\Omega} = AZ^2 (\ln E_{\gamma} - B)$$

(1.5)

for photon energies such as $2 \text{ MeV} \ll E_{\gamma} < \frac{137}{Z^{1/3}}$, $A$ and $B$ are constant, $Z$ is the atomic number. For photon energies $E_{\gamma} \gg \frac{137}{Z^{1/3}}$ the differential cross-section becomes

$$\frac{d\sigma}{d\Omega} = CZ^2 \left( \ln \left( \frac{183}{Z^{1/3}} \right) - D \right)$$

(1.6)

where $C$ and $D$ are new constants.
1.4 Polarisation Measurement Principle

The PoGOLite polarimeter relies on the “simultaneous” measurement of Compton scattering and photo-absorption of gamma-rays in an array of plastic scintillators. The differential polarimetric Compton cross-section is described by the equation as

\[
\frac{d\sigma}{d\Omega} = \frac{1}{4} Z r_e^2 \left( \frac{1}{\epsilon} + \epsilon + 4 \cos \Theta \right)
\]  

(1.7)

where \(\epsilon = E' / E = 1 / (1 + \alpha (1 - \cos \theta))\), \(\alpha = E / m_e c^2\), \(r_0\) is the classical electron radius, \(m_e\) the mass of the electron and \(\theta\) is the angle between the incident photon direction and the scattered photon direction. The electric vector \(\xi'\) of the scattered photon is so polarised to form an angle \(\Theta\) with the electric field \(\xi\) of the incident photon (see figure 1.9), however this information is not needed to determine the polarisation of the incident photon. Averaging over the electric vector of the scattered photon the formula reduces to

\[
\frac{d\sigma}{d\Omega} = \frac{1}{2} Z r_e^2 \epsilon^2 \left[ \frac{1}{\epsilon} + \epsilon - 2 \sin^2 \theta \cos^2 \eta \right],
\]  

(1.8)

where \(\eta\) is the azimuthal scattering angle relative to the plane of polarisation. When projected on the plane, the angle of scattering will thus be modulated as \(\cos^2 \eta\) and the resulting scattering angle depends on the polarisation of the photon.

![Figure 1.9. A schematic illustration of Compton scattering. An incoming photon with energy E and electric vector \(\xi\) scatters off an electron. The incident and scattered photon form an angle \(\theta\) and \(\eta\) is the azimuthal angle of the scattered photon with respect to the electric vector of the incident photon [23].](image)

If the incoming beam has a net linear polarisation and the detector is rotating the distribution of the scattered photons should reveal a \(\cos^2 \eta\) shape. This modulation contains the information about the polarization of the source. Photons scattered directly forward (\(\theta = 0^\circ\)) or directly backward (\(\theta = 180^\circ\)) carry no information.
about polarisation of the incident photon beam. To extract the polarisation information of the source the modulation factor $M$ and the average value $T$ are used, defined as

$$M = \frac{C_{\text{max}} - C_{\text{min}}}{C_{\text{max}} + C_{\text{min}}}$$

(1.9)

and

$$T = \frac{C_{\text{max}} + C_{\text{min}}}{2}.$$  \hspace{1cm} (1.10)

It can be shown [23] that the modulation can be parametrized as

$$f(\eta) = T(1 + M(cos(2\eta + 2\alpha)))$$

(1.11)

where $\eta$ is the azimuthal angle (see figure 1.10), and $\alpha$ is the polarisation angle of the source.

![Figure 1.10. Distribution of scattering angles used to determine the modulation factor [24].](image)

The modulation factor is connected to the polarisation degree through the equation

$$P = \frac{M}{M_{100}}$$

(1.12)

where $M_{100}$ is the modulation factor for a 100% polarised source. The determination of the modulation factor is done through simulations or beam test measurements.
Chapter 2

PoGOLite Polarimeter

2.1 Instrument Overview

The PoGOLite payload, shown in figure 2.1, consists mainly of a polarimeter telescope, a data acquisition system and an attitude control system (ACS). These systems are mounted on a gondola frame which connects to a stratospheric balloon which lifts the apparatus to an altitude of 40 km. The polarimeter and data acquisition electronics are placed in a pressure vessel which is mounted on an offset pivot to allow the full sky to be observed. The polarimeter is able to rotate around its longitudinal axis to allow systematic effects to be studied during observations. The ACS controls the position of the telescope relative to the gondola platform, and the orientation of the gondola in space.

2.1.1 Polarimeter Telescope

The polarimeter consists of a hexagonal close-packed array of 217 phoswich detector cells (PDC), made from plastic scintillators, surrounded on the side and bottom by an anti-coincidence shield made from bismuth germanate oxide (Bi$_4$Ge$_3$O$_{12}$, BGO) crystals (see figure 2.3). The assembly is housed in a cylindrical structure (the inner cylinder) which can rotate. The inner cylinder is placed in a second cylinder (the outer cylinder) filled with polyethylene for neutron background reduction[25].

Each PDC unit is composed of a thin-walled tube of slow plastic scintillator (fluorescence decay time $\sim$ 230 ns), a solid rod of fast plastic scintillator (decay time $\sim$ 2 ns) and a short BGO crystal (decay time $\sim$ 300 ns), all read out by a single photomultiplier (PMT). The wells serve as active collimators, the fast scintillator rod is where photon detection and scattering takes place, and the bottom BGO acts as lower anticoincidence. More details about the configuration and working operations of the detector are given in section 2.3.

The anticoincidence system comprises an array of BGO crystals which covers the side and bottom of PoGOLite polarimeter as shown in figure 2.3. The bottom
Figure 2.1. Schematic view of PoGOLite payload. The dimensions of the platform will be 2.5 m × 2.5 m and height about 3.5 m.

shield consists of an interlocking assembly of crystals with hexagonal cross-section. Each crystal forms part of a PDC unit, and interfaces the PMT to the solid fast scintillator. The side shield is made of 54 elements which in turn consist of 3 crystals of pentagonal cross-section.

Signals from the 217 PDC units and from the 54 SAS elements are read out by PMTs and fed to individual ADCs and digitized to 12 bit accuracy at 24 MHz. Field programmable gate arrays (FPGA) check for transient signal compatible with energy deposits in the fast scintillator between 15 keV and 200 keV. If the FPGAs detect a signal above the discrimination level or with a slow rise-time due to the slow plastic scintillator or to the BGO a veto signal is produced, whereas if the signal is clean a trigger is issued and the digitized waveforms of all PMTs are stored. The trigger rate is expected to be about 0.5 kHz and the data-rate about 100kB/s. The waveforms are recorded by a microprocessor on flash memory banks. For a complete description of the data acquisition and data processing see [26].
2.2. Scintillators

There exist two types of scintillators, organic (liquid and plastic) and inorganic (crystals, ceramics, glasses and noble gases). In inorganic scintillators the production of scintillation light relies on the process of fluorescence which is the transition in the energy level structure of the single organic molecule and thus does not depend on the physical state. Many organic scintillators are based on molecules with a $\pi$-electron structure (the structure is illustrated in figure 2.4). Energy absorption can excite the electron to a number of excited singlet states: $S_0$, $S_1$, $S_2$,… (spin 0) or $T_1$, $T_2$, $T_3$… (spin 1). The singlets are subdivided in different vibrational states, $S_{00}$ represents the lowest vibrational state of the electronic state. A charged particle passing nearby can excite the electron to a higher energy singlet which then deexcites to the $S_{10}$ singlet. The principal scintillation light (prompt fluorescence) is emitted in transitions between $S_{10}$ and $S_{0}$ states.

The intensity of fluorescence at a time $t$ is described by

$$I = I_0 \exp(-t/\tau)$$  \hspace{1cm} (2.1)
where $I_0$ is the initial intensity and $\tau$ the fluorescence decay time. Since the fluorescence energy is less than the total absorbed energy (see figure 2.4) the organic scintillators can be transparent to their own fluorescence emission. The organic scintillators PoGOLite uses are plastic, Eljen Technology EJ-204 and Eljen Technology EJ-240 [28].

The scintillation mechanism in inorganic scintillators depends on the energy states determined by the crystal lattice. Absorption of energy results from the elevation of an electron from its normal position in the valence band to the conduction band (figure 2.5).

The gap is such that the released energy would be too high to lie in the visible band, to increase the probability of emission of visible photons, impurity, activators, are added. In PoGOLite the inorganic scintillator used is BGO. The total cross section for gamma absorption is dominated by the Compton effect and the photoelectric effect is negligible. Plastic scintillators are not ideal as absorber but have good performances for Compton scattering. The performances of the plastic scintillators have been tested and showed that polarisation signal is still possible to be detected (see section 2.5).

The anticoincidence shield is made of BGO, an inorganic scintillation material. Its major advantage is the high density (7.13 g/cm$^3$) and the large atomic number (83) of the bismuth component, which result in very high probability per unit volume for the photoelectric absorption of gamma rays. It is also easy to handle since it is not hygroscopic in comparison to other inorganic scintillator materials. BGO presents a large shift between optical absorption and emission spectra, thus
2.2. Scintillators

The crystal remains transparent to its own emission over dimensions of many centimeters.

The disadvantages are the low light yield, the high refractive index (2.15) which makes light collection difficult due to internal reflections, the light output which depends on temperature, and the large weight and the cost.

The BGO crystals are grown through the Czochralski process, in which a small seed crystal is used to produce a bigger boule [30]. Later the crystals are shaped in
the desired shape into (some limitations exist). This process does not permit, so far, to grow easily big volumes of BGO, in fact in the case of the side anticoincidence shield of 600 mm a unit is made of three different sections of 200 mm each. A typical boule from which the PoGOLite crystals are cut is shown in figure 2.7.

Figure 2.6. Linear attenuation factor for plastic scintillator (left) and BGO (right) [29].

Figure 2.7. Example of BGO boule, this crystal is later cut in the required shape, the size is about 60 cm.
2.3 Phoswich Detector

The PDC cells combine collimation, detection and anticoincidence functions in a single unit (see figure 2.8), thus they can be packed close together to avoid gaps. The dimensions and characteristics of these units are dictated by the physics of photon interactions. The lowest photon energy to which PoGOLite is sensitive puts a limit on the width of the PDC fast scintillator (EJ-204). At 20 keV a significant fraction of the scattered photons are photo absorbed and stopped within a few cm after the scattering point. Since Compton scattering and photoabsorption have to take place in two different PDCs a width of 2.75 cm has been chosen, a lower width would require a much higher pixellization and thus more complex mechanics and electronics. The depth of the detection unit has to fulfill two requirements: the volume has to be deep enough for a Compton scattering to take place and shallow enough to limit the photons that remain in it to polar scattering angles about $(90 \pm 30)\degree$. A length of 20 cm ensures that 95% of photons will Compton scatter. To improve light collection, the plastic scintillators will be wrapped in highly-reflective 3M VM2000 reflector film [31].

The slow plastic scintillator (EJ-240) serves as a collimator. The efficiency in detecting and vetoing charged particles depends on the thickness of the walls, 2 mm. Each well is sheathed in a thin layers of tin and lead foils to provide passive collimation. The length of 60 cm and its associated passive collimator shell determines the field of view (FOV) of $2.5\degree \times 2.5\degree$. The BGO crystals at the end of the PDC unit are part of the anticoincidence shield and will thus described in the following section. All three sections are joined together with a UV transparent epoxy glue (Hartel). At the end of each PDC a PMT (Hamamatsu R7899EGKNP) converts the scintillation light to an electrical pulse which is sampled by a flash ADC. The photomultiplier is choosen since it has a low noise, which is very important since the energy deposited during Compton scattering is very small, moreover the PMT matches the characteristics of all three scintillators, its spectral response goes from 300 nm to 650 nm with the peak at 420 nm.

2.4 The Anticoincidence Shield

The polarimeter detector is surrounded by a BGO crystal anticoincidence shield. Three different crystal geometries are used (figure 2.10), giving an overall mass of about 250 kg. The BGO crystals are provided by the Nikolaev Institute of Inorganic Chemistry, Novosibirsk, Russia.

The shield consists of a side and a bottom shield, both main function is to reduce background from charged cosmic rays, primary and atmospheric gamma-rays, and atmospheric and instrumental neutrons, operating in two different ways. Signals produced in the SAS BGO crystals will be used to veto background signals in the off-line analysis, whereas the signals from the PDC BGO crystals are used in the trigger which selects Compton scattering/photoabsorption events.
2.4.1 Bottom Shield

The bottom BGO shield consists of 217 identical crystals, of length 4 cm and maximum width of 3 cm, as shown in figure 2.10. Each crystal has a mass of 160 g. The complex geometry, a hexagonal section which goes to a cylindrical one, arises from the its function as waveguide: it has to couple the hexagonal detector section to the round aperture of the PMT. The length is a compromise for having a high light transmission, a low weight and cost and at the same time an efficient anticoincidence shield. The width is 0.5 mm wider than the plastic well and detector, in order to form a nearly continuous layer with rest of the PDC unit (the 0.5 mm gap in the upper part is filled by reflection material and passive shield). To improve the light yield and to provide optical isolation between the adjacent units the crystals are coated with a 100 µm thick BaSO$_4$ loaded resin. The entire PDC stack is read out by a single PMT, and the different decay times of the scintillation...
2.4. The Anticoincidence Shield

![Figure 2.10](image1.png)

**Figure 2.10.** Picture of the side and bottom crystals: left the bottom crystal, in the middle the corner unit and right the edge unit. The SAS units are seen from the end that will be connected to the PMT; it is made of three 20 cm long crystals, the height of the bottom BGO is 4 cm.

Light (slow plastic: $\sim 285$ ns, fast plastic: $\sim 1.8$ ns, and BGO: $\sim 300$ ns), allow the signal to be separated and thus to trigger the data acquisition. The crystals have to be transparent to their own scintillation light (480 nm) and to the light produced in the slow (435 nm) and fast (408 nm) plastic scintillators. The transparency has been studied with an UV spectrometer. The crystals are seated in an aluminum base plate, the hexagonal end is joined to the detector scintillator with the epoxy glue, the cylindrical part fits in to the PMT aperture and is attached to the PMTs window through optical grease and a silicon pad.

![Figure 2.11](image2.png)

**Figure 2.11.** Picture of PMT Hamamatsu R7899EGKNP. The aperture is visible where the cylindrical protrusion of the BGO bottom crystal is seated, the total length is 20 cm.
2.4.2 Side Anticoincidence Shield, SAS

The SAS shield is segmented into 54 units, each of them has a BGO mass of \( \sim 4.5 \text{kg} \), is 600 mm long and is built of three crystals, since it is difficult and uneconomical to grow crystals to full length. The SAS units together with the PDC hexagonal array form a bigger hexagonal assembly (see figure 2.12), the resulting geometry for the BGO crystals is of two types (see figure 2.10). This configuration is scalable and in a future bigger version of detector the crystals can be reused.

![Figure 2.12. Cross section of 217 PDC cells (red) and 54 SAS units (green). The dimensions of the crystals are: \( W_1 = 29.3 \text{ mm} \), \( W_2 = 16.9 \text{ mm} \), \( W_3 = 17.3 \text{ mm} \), \( T_1 = 30.0 \text{ mm} \), \( T_2 = 38.5 \text{ mm} \), \( V = 28.5 \text{ mm} \), \( S = 16.45 \text{ mm} \), \( D = 32.9 \text{ mm} \), \( A = 1.5 \text{ mm} \).](image)

The SAS shield covers two thirds of the length of the PDC elements. Each unit of a given type is built of two upper crystals with flat ends and one piece which has on one end a cylindrical protrusion, 23 mm in diameter, which interfaces to a PMT (the same type that is used for the PDC units). The three crystals within a unit are joined together with UV-transparent epoxy glue (EpoTek 301-2). All BGO surfaces, except optical interfaces, are coated with the same \( \text{BaSO}_4 \)-loaded resin layer as the bottom crystals to improve light yield and to optically separate adjacent crystals. The SAS crystals are located around the PDC array with a mechanical support system. The design of this must allow for the significant acceleration at the end of the flight (parachute opening, landing). The segmentation of the SAS shield makes it possible to correlate SAS and PDC events thus reducing the risk of rejecting valid
events: the estimated SAS rate at float altitude is about 100 kHz and a simple SAS veto would reject 6% of the valid events.

2.4.3 Attitude Control System

The PoGOLite field of view (FOV) needs to be accurately aligned to observation targets during balloon flight. Simulations ([32]) that to secure a minimum detectable polarization MDP = 10% for a 200 mCrab source, alignment is needed to within 5% of the FOV of $2.5^\circ \times 2.5^\circ$. The ACS needs to account for target sources moving on the sky and "random" gondola movements. The orientation of the gondola is surveyed by attitude sensors. The exact composition of the sensor system is under review, but is likely to contain a DGPS (Differential Global Positioning System), two star trackers, gyroscopes, magnetometers, and accelerometers. Only DGPs and star trackers give absolute attitude information. Sensor outputs are processed by a dedicated ACS computer and control signals generated for polarimeter elevation motor, and azimuthal fly wheel (see figure 2.1). Since the latter saturates for a certain number of revolutions per seconds, a momentum dump system is needed to transfer the angular momentum of the flywheel to the balloon. The ACS control loop requires sensor inputs at about 100 Hz, this can achieved with the DGPS but its antenna would require a large separation for the required attitude (pitch and roll) resolution. Moreover, GPS signals maybe unreliable for periods of time. The most accurate sensor is potentially the star tracker (see chapter 4) but it needs a stable gondola for observations and has a limited FOV. Gyroscopes are very accurate but are liable to drift, and must periodically be calibrated with the absolute pointing information from DGPS and star tracker. Magnetometers provide useful redundant measurement of gyro outputs, but easily perturbed by magnetic environments. Development of the ACS system is in progress; in this thesis, particular attention is placed on the star tracker system. The challenge in building the star tracker lies in the fact that it must work during day and night.

2.5 Performance Study

In the last years, some units of PoGOLite have been tested at different polarised beam tests and studied using simulations. The expected polarisation signal from possible sources has been studied in these simulations.

The modulation for the Crab has been simulated for a 6 hour observation with an atmospheric overburden of 4 g/cm$^2$ at $\sim$40 km. The polarisation degree and angle has been assumed to be the ones measured by OSO-8 [33] for the nebula. In figure 2.13 the modulation for three different models using the first peak of the pulse period is shown.

Background rates have been calculated using Geant4 simulations [34], the total background rate is shown in figure 2.14. The expected total background is equivalent to a 40-100 mCrab source between 30 and 50 keV. Of the total background,
60-70\% is produced by albedo neutrons, the rest by albedo gamma-rays. Furthermore, segmentation allows us to study possible asymmetries in the background and to make corrections for it. The anticoincidence threshold for the SAS BGO crystals is 75 keV.

Values for $M_{100}$ depending on the detector characteristics are shown in table 2.1. They are calculated for a 10\% minimum detectable polarisation for a 200 mCrab source in a 6-hour flight, the field of view of the instrument is of $2.5^\circ \times 2.5^\circ$ and the effective area is about $93 \text{ cm}^2$ at 4 g/cm$^2$ overburden.

<table>
<thead>
<tr>
<th>Energy</th>
<th>25 keV</th>
<th>30 keV</th>
<th>50 keV</th>
<th>80 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective area for pol. meas. [cm$^2$]</td>
<td>112</td>
<td>185</td>
<td>244</td>
<td>143</td>
</tr>
<tr>
<td>Signal rate for a 100mCrab source at [$s^{-1}keV^{-1}$]</td>
<td>0.039</td>
<td>0.044</td>
<td>0.025</td>
<td>0.0056</td>
</tr>
<tr>
<td>Background [$s^{-1}keV^{-1}$]</td>
<td>0.029</td>
<td>0.026</td>
<td>0.021</td>
<td>0.015</td>
</tr>
<tr>
<td>Modulation for 100% polarised beam with Crab spectrum</td>
<td>26%</td>
<td>25%</td>
<td>22%</td>
<td>34%</td>
</tr>
</tbody>
</table>

Table 2.1. Instrument performance characteristics for 6 hour flight at 4 g/cm$^2$ overburden for a 10\% minimum detectable polarisation for a 200 mCrab source.
2.5. Performance Study

Figure 2.14. Expected background rates at an atmospheric overburden of 4 g/cm² compared to expected signal rates expected for a Crab source (thick solid histogram) and 100 mCrab source (thin solid histogram). Filled circles denote the total background; open circles the neutron background; and filled squares gamma-ray background.

In order to measure the scattering angles, it is necessary to detect both the scattering and the photoabsorption sites. The detector has to be segmented to provide spatial resolution in order to detect the positions of the signals. The PoGOLite detector is segmented into 217 pixels. A clean event travels through the slow plastic scintillator without hitting the walls, reaches the fast scintillator where it Compton scatters, is photo-absorbed or manages to escape from the active detector (see figure 2.16). If it is photo-absorbed, we get a signal from the two pixels where the scattering and photoabsorption take place, and knowing the position of the pixels the modulation curve can be plotted and the two parameters of interest can be fitted. If more than two scattering sites are identified, the relative energy depositions can discriminate between Compton scattering and photoelectric absorption sites.

The selection of the PDC where the photoabsorption takes place is done by choosing the highest energy compatible with being a clean fast signal in the fast scintillator. Figure 2.15 shows how clean fast signal of gamma-rays from $^{241}$Am (59.6 keV) which are selected in the fast scintillator, embedded in a background environment created by $^{90}$Sr (546 keV) electrons in the slow scintillator. The diagonal concentration of dots between the two dashed lines corresponds to clean fast signals in the fast scintillator. A strong concentration of recorded events can be found around the dominant line of 60 keV and around several weaker line. The site with the highest clean fast signal pulse-height is selected as the photoabsorption site.
Figure 2.15. Selection of clean gamma-ray hits from $^{241}$Am on the fast scintillator while the slow scintillator is irradiated with $^{90}$Sr electrons. Each dot corresponds to one triggered event. The horizontal and vertical coordinates are the charges integrated over the fast ($\sim$120 ns) and slow ($\sim$1$\mu$s) component of the pulse. A crude energy scale for gamma-rays detected in the fast scintillator has been added [27].

For complete valid events the distribution of the sum of the energy depositions, at the photoabsorption site and at the Compton scattering site, is plotted versus the distribution of the energy deposition at the Compton scattering site. Such a distribution, obtained at the test beam at KEK Photon Factory in 2007, is shown in figure 2.17. The bound region identifies the selected the events for which both events took place, for these the azimuthal angle is then calculated and it is possible to plot the modulation curve shown in figure 2.18, the polarisation of the beam was correctly reconstructed.
2.5. Performance Study

Figure 2.16. Schematic cross section of PoGOLite detector (not to scale) showing valid and background photon interactions. Also possible background events are shown [35].
Figure 2.17. Selection of Compton scattered events for data taken in a 25 keV polarised beam at KEK. The dashed box shows valid Compton scattering events [27].
Figure 2.18. Modulation measured in a polarized 25 keV pencil beam at KEK (top)[27], (bottom) arrangement of 7 PDCs, the polarized beam hits the center of the PDC 0, photoabsorption is recorded in the 6 peripherals units. The setup is rotated in azimuth by 15° steps.
Chapter 2. PoGOLite Polarimeter

2.6 Balloon Flights

The maiden flight will be with a reduced volume instrument (61 PDCs) and is planned for August 2010 from Esrange Space Center in Sweden. The total scientific payload weight will be around 1 tonne and will be carried by a $1.11 \times 10^6 m^3$ balloon to an altitude of $\sim 41\text{-}42 \text{ km}$ where the residual atmosphere is $\sim 4g/cm^2$. The primary goal is a system test, background evaluation, and observations of the Crab system. This fight is expected to be followed by other 6-24 hour long flights from Esrange, and also NASA ballooning facilities in Texas. A full volume polarimeter will be developed with which will be possible to study many more targets (see table 2.2). A long term goal is a long duration balloon flight from Sweden to Canada (about 5 days) and maybe a complete circumnavigations of the Northern pole.

<table>
<thead>
<tr>
<th>Object</th>
<th>Counting Rate</th>
<th>MDP</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 hour flight</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crab (total)</td>
<td>13.7/s</td>
<td>3%</td>
</tr>
<tr>
<td>Cyg X-1 (Hard state)</td>
<td>13.3/s</td>
<td>3%</td>
</tr>
<tr>
<td>Cyg X-1 (Soft state)</td>
<td>4.6/s</td>
<td>5%</td>
</tr>
<tr>
<td>long duration flight</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hercules X-1</td>
<td>2.5/s</td>
<td>8%</td>
</tr>
<tr>
<td>Mkn 501 (Flare)</td>
<td>0.65/s</td>
<td>14%</td>
</tr>
<tr>
<td>V0332+53 (burst)</td>
<td>$\sim 4/s$</td>
<td>5%</td>
</tr>
<tr>
<td>4U0115+63 (burst)</td>
<td>$\sim 4/s$</td>
<td>5%</td>
</tr>
<tr>
<td>GRS 1915 (burst)</td>
<td>$\sim 4/s$</td>
<td>5%</td>
</tr>
</tbody>
</table>

Table 2.2. Expected northern-sky PoGOLite targets in priority order, with respective counting rate and minimum detectable polarisation MDP.
Chapter 3

Tests of BGO Scintillators

3.1 Introduction

In this chapter the tests performed on the BGO crystals are described. The procedure starts from the small samples used to determine the characteristics of the BGO crystals available on the market. Tests were then performed on prototypes from two suppliers, that after the first screening, presented the best characteristics. After having refined the performances a tendering procedure was established and the final crystals ordered. The final crystals have been tested to check if they matched the requirements listed in the procurement contract, also further tests have been performed to fully characterize them.

3.2 Market Survey

In 2003 the evaluation of 4 potential suppliers for BGO crystals started. Both technical and commercial aspects had to be evaluated. To establish the quality of the crystals the absolute light yield and light transmission of cubic samples of side 10 mm was studied.

Light yield is an absolute measurement and allows to identify the quality of BGO, light transmission is measured to check if the crystal is transparent to its own scintillation light (480 nm) and to the scintillation light of the plastic scintillators (408 nm and 425 nm).

For the light yield measurement a $^{137}\text{Cs}$ source is used. $^{137}\text{Cs}$ $\beta^-$-decays to an excited state of $^{137}\text{Ba}$. Upon its deexcitation, a gamma-photon of an energy of 661.2 keV is emitted. The corresponding photo-peak will be used to determine the energy resolution. The spectrum is recorded using a multichannel analyzer (MCA), the channel number on the x-axis is proportional to energy, and on the y-axis the number of counts is shown.
The absolute light yield is defined as

\[ N_{ph}[\text{photons/MeV}] = \frac{1}{E^{(137\text{Cs})}} \frac{1}{\text{q.e.}} \frac{N_{\text{peak}} G_2}{N_{\text{sph}} G_1} \]  \hspace{1cm} (3.1)

where \( E^{(137\text{Cs})} \) is the energy of the photopeak of 0.661 MeV (see figure 3.1), \( \text{q.e.} \) is the quantum efficiency of the PMT, \( N_{\text{peak}} \) is the channel number of the photopeak position, \( N_{\text{sph}} \) is the channel number of position of the single photoelectron peak, \( G_1 \) and \( G_2 \) the gain used to measure \( N_{\text{peak}} \) and \( N_{\text{sph}} \) respectively. In the setup at KTH, \( G_1 \) is set equal to 10 and \( G_2 \) equal to 500. The value of \( G_2 \) is 50 times higher in order to be able to distinguish the single photoelectron peak from the background level. A threshold is set around channel number 400 in order to reduce the dead time, the threshold is set to zero when measuring the single photoelectron peak.

The single photoelectron peak is due to the spontaneous electron emission from the photocathode of the PMT and is a characteristic that depends only on the PMT. It is needed in order to calibrate the measurement. The measurement of this peak is performed without source and choosing a high gain \( G_2 \) since the signal is weak (see figure 3.2).

**Figure 3.1.** Typical energy spectrum of \(^{137}\text{Cs}\) acquired with the Tukan-8k MCA. The x-axis shows the channel number which is proportional to the energy, on the y-axis the counts are shown. The photopeak at about channel number 1300 is due to photoeffect of the emitted \(^{137}\text{Cs}\) \(\gamma\)-line.
Figure 3.2. *Single photoelectron peak.*
All BGO crystal surfaces, except the one that will be connected to the PMT, are covered with Teflon tape and black tape to maximize reflectivity and shield from light respectively. The crystal is then connected with the free surface, which is also polished, through optical grease to a Philips XP2020/Q PMT. The whole assembly is covered in black paper and irradiated with a 370 kBq $^{137}$Cs radioactive source. The results of the first samples are listed in table 3.1, and were found to agree with other published values [36].

The light transmission is measured with an UV-spectrometer and the value of transmission at 425 nm is given, which is the wavelength of the emission of BGO. This measurement is not absolute since many effects are not considered: reflections from crystal surfaces and the instrument is not calibrated.

<table>
<thead>
<tr>
<th>id</th>
<th>Sample Size</th>
<th>Light yield ($^{137}$Cs)</th>
<th>Transmission (at 425 nm)</th>
<th>Cost for 1 bottom BGO (2004)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10x10x10 mm (3) (polished)</td>
<td>3650 photons/MeV</td>
<td>48%</td>
<td>460 USD</td>
</tr>
<tr>
<td>2</td>
<td>10x10x10 mm (ground-polished)</td>
<td>5900 photons/MeV</td>
<td>72%</td>
<td>450 USD</td>
</tr>
<tr>
<td>3</td>
<td>10x10x10 mm (2) (ground-polished)</td>
<td>6300 photons/MeV</td>
<td>73 %</td>
<td>200 USD</td>
</tr>
<tr>
<td>4</td>
<td>10x10x10 mm (ground-polished)</td>
<td>5160 photons/MeV</td>
<td>74 %</td>
<td>550 USD</td>
</tr>
</tbody>
</table>

Table 3.1. Results of 10x10x10 mm samples for 4 different suppliers. Some of them had 4 ground and 2 opposite polished surfaces and others presented a polished surfaces on all 6 sides. First column indicates contains the id of the supplier, the second the size and number of crystals tested, third the light yield value and the fourth the transmission in percent evaluated at 425 nm which is the wavelength of maximum emission for the fast plastic scintillator. The transmission is not absolute, only relative.

From the results of these measurements it has been concluded to acquire 10 bottom crystals of the required shape, shown in figure 3.3, for the PDC cells each from supplier 2 and supplier 3, since the two suppliers show good quality and have a good price. At this point the ability to make a proper surface treatment want to be studied.

### 3.3 Tests of Selected Candidates

The candidate PDC crystals were tested in 2005 with the same setup except for the PMT, this time a Photonis XP5202/B PMT. The crystal is coupled to the PMT through optical grease applied to the cylindrical end. The results are plotted in figure 3.4. The two suppliers are almost equivalent regarding quality. These prototypes were subsequently used in the PDC units constructed for test beams.
3.4 Acceptance Tests

After these tests the final geometry of the BGO crystals was decided, and drawings of both the bottom BGO and the side anticoincidence shield final were produced. The final version of PoGOLite needs 217 bottom BGO crystals and 54 SAS units.

When purchasing for high cost a tender has to be issued to which different suppliers can reply. The specifications of the tender have to be unambiguous and easy to check. The tender was issued in June 2006, the winner was the Nikolaev Institute of Inorganic Chemistry, Novosibirsk, Russia. The tender requirements were: dimensions and tolerances must be met, the crystals have to be transparent with no visible grain boundaries when viewed under strong lightning, surfaces have to be fine mirror-like polish, the light yield must exceed a certain level, and there should be no dramatic degradation in the light yield due to radiation damage.

3.4 Acceptance Tests

The final crystals were delivered in a series of shipments during 2007. Each shipment contained alternately PDC BGO crystals or SAS crystals. The testing of the SAS crystals is described elsewhere [37]. Before assembling the anticoincidence system, each crystal undergoes acceptance testing. This consists of visual inspection.
and measurement of energy resolution using a 661 keV photopeak from a $^{137}$Cs radioactive source. This measurement is used as a measure of the light yield as explained in next section. The crystals are produced in large rods, boules as shown in figure 2.7, a number of samples are cut out of one rod and then machined. One rod is not enough to provide all the crystals needed for the detector, thus the crystals originate from different boules. Small cylindrical samples are also archived from each boule, to allow boule parameters to be monitored independently from the cut crystals. The characteristics of the crystal depends on the crystalline structure that can vary from boule to boule and also within the same boule.

For each shipment the relative transmission is also tested for 5 PDC BGO crystals, a typical plot of the transmission is shown in figure 3.5.

### 3.4.1 Energy Resolution

For the measurement setup for the relative energy resolution of the bottom BGO crystals an energy spectrum is sampled and the 661 keV line of $^{137}$Cs is used to determine the relative energy resolution. The parameter that more accurately characterizes the crystal is the absolute light yield but it is difficult to isolate contributions coming from the PMT and electronics and thus it is not easy to compare
values obtained with two different setup, the KTH setup and the setup of the manufacturer in Novosibirsk. Moreover in this case we are interested in tracking the relative changes within the different crystal coming from the same source. The relative energy resolution is defined as:

$$R = \frac{\Delta E}{E}$$ \hspace{1cm} (3.2)

where $E$ is the position of the peak and $\Delta E$ is the corresponding full width at half maximum value (see figure 3.8).

The energy resolution measured with a scintillator coupled to a photodetector can be written as

$$\left( \frac{\Delta E}{E} \right)^2 = (\delta_{sc})^2 + (\delta_{st})^2 + (\delta_n)^2$$ \hspace{1cm} (3.3)

where $\delta_{sc}$ is the intrinsic resolution of the crystal, $\delta_{st}$ is the statistical contribution, and $\delta_n$ is the dark noise contribution to the resolution [38].

The intrinsic resolution is associated to the non-proportional response of the scintillator, inhomogeneities in the scintillator and non uniform reflectivity of the
crystal covering, and it depends on the energy. In our measurement the energy is constant, thus this term will be constant. The dark noise contribution in the case of measurements with PMTs is negligible.

The statistical uncertainty is described as

\[
(\delta_{st})^2 = (1 + \epsilon) \left( \frac{2.35\sigma}{N} \right)^2
\]

and since it is a Poisson distribution and \(\sigma = \sqrt{N}\)

\[
(\delta_{st})^2 = (1 + \epsilon) \left( \frac{2.35\sqrt{N}}{N} \right)^2 = (1 + \epsilon) \left( \frac{2.35}{\sqrt{N}} \right)^2
\]

where \(N\) is the number of photoelectrons and \(\epsilon\) is the variance of the electron multiplier gain (\(\sim 0.1\) from data-sheet). \(N\) is a measure of the light yield, so by measuring the energy resolution we evaluate indirectly the light yield. The resolution is enhanced if the light yield is high, good resolution is defined by small values of \(R\).

### 3.4.2 Energy Resolution Setup for PDC Crystals

The setup for the measurement of the energy resolution is similar to the one used in section 3.2, but has been redesigned so that the measurement can be reproducible. For the energy resolution measurement the BGO crystal is placed in a 5 mm thick reflective Teflon “cup” to maximize light collection and the cylindrical portion of the crystal is connected to the PMT (Photonis XP5202/B) with a thin layer of optical grease. The spectral range of this PMT goes from 270 nm to 650 nm with a peak at 420 nm, this range is identical to the one of the PMT Hamamatsu R7899 that will be used in the flight configuration. The entire assembly is made light-tight with a black PVC cup that covers the Teflon and PMT window. A collimated \(^{137}\text{Cs}\) source is directed toward the hexagonal face of the crystal directly opposite the PMT 3.6. The PMT is connected to high voltage of -1500 V, the output of the PMT is connected to a preamplifier and a shaping amplifier with a time constant set to 2 \(\mu\)s, this is connected to a multichannel analyzer, Tukan 8k USB, connected to a PC (figure 3.7). An energy spectrum is acquired for 5 minutes, at constant temperature of 23°C, for each crystal.

### 3.4.3 The Fitting Method

With each measurement of 8192 channels a histogram with 1024 bins is filled. The peak position is determined which corresponds to the \(^{137}\text{Cs}\) photopeak. The data are fitted with a Gaussian peak (see eq 3.6) on a symmetrical range of about 200 channels around the peak. The background is not fitted since only the peak is fitted to avoid the ”bump” on the right side of the peak which will be discussed later.
3.4. Acceptance Tests

![Figure 3.6. Setup for energy resolution measurement: a collimated source (1+2), (2) is a block of lead with a hole in the center, irradiates a BGO crystal covered in a Teflon and PVC (3), and attached to a PMT (4). The PMT signal is amplified and read out by a multichannel analyzer.](image)

\[ f(x) = Ae^{-\frac{(x-m)^2}{2\sigma^2}} \]  \hspace{1cm} (3.6)

The parameters A, m and \( \sigma \) are determined by \( \chi^2 \) fitting. A is the number of counts in the bin of the fitted peak, m is the position of the peak and \( \sigma \), the standard deviation, is proportional to the full width at half maximum (FWHM) of the Gaussian peak. The parameters that determine the energy resolution are m and \( \sigma \).

\[ R = \frac{\Delta E}{E} = \frac{\text{FWHM}}{m} = 2.35\sigma \]  \hspace{1cm} (3.7)
Chapter 3. Tests of BGO Scintillators

Figure 3.7. Schematic diagram of the data acquisition chain. The preamplifier has a time constant of $t = 2\mu$s, and the gain $G$ of the amplifier is set to 10.

Figure 3.8. A typical energy spectrum of a $^{137}$Cs source reconstructed using a bottom BGO crystal. The vertical line indicates the peak position $E$, and the horizontal line indicates the FWHM. The spike at channel number 500 is due to binning effects and the "bump" on the right side of the peak is due to the geometry of the crystal (see section 3.5).
This procedure is done for each crystal and at the end it is possible to fill a histogram with the 240 energy resolution values as shown in figure 3.10.

The energy resolution values obtained have a mean value of $(12.75 \pm 0.20)\%$, whereas the value obtained at the Nikolaev Institute of Inorganic Chemistry have a mean value of $(11.83 \pm 0.86)\%$. The two measurements are compatible within standard deviation. The KTH results are more reproducible, possibly because a more sophisticated fitting technique is used. The value obtained is lower than 16%, which is the value stated in the tender requirement.

Also the other acceptance tests were positive, and the crystals respect all the requirements mentioned in the tendering documentation. The results of the tests are uploaded to a MySQL database (see figure 3.9). Each row contains information about one crystal, the first column identifies in a univoque way the crystal, the second column contains the name assigned during production. Comments are listed in the third column. The result of transmission, energy resolution and dimensions are reported respectively in fourth, fifth and sixth column. The last column shows the date of last modification.

In order to study if the energy resolution depends on the boule of origin the results have been grouped for each boule. The mean value of the energy resolution value from each crystal belonging to one boule has been calculated and the respective standard deviation. This has been performed for all 23 different boules and plotted in figure 3.11. The boules do not show any particular features, they are almost equivalent.
### Table 3.9

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*Figure 3.9. Screen shot of the database of the PDC BGO crystals. The first column identifies each crystal with an unique id, the second column contains the name of the crystal, in the third column comments can be reported, the fourth column contains the dimensions and last shows the last time of update.*
Figure 3.10. Distribution of energy resolution values for 240 bottom BGO crystals, the dotted histogram represents the values measured by Novosibirsk and has a mean value of $(11.83\pm0.86)\%$; the histogram with diagonal lines represents the value measured at KTH and has a mean value of $(12.75\pm0.20)\%$. 
Figure 3.11. The mean value of the energy resolution of the crystals belonging to one boule are plotted versus the boule id.
3.5 Further Studies

3.5.1 Spectrum Anomaly

After accepting the crystals further studies take place. As can be seen from the spectrum, next to the photo emission peak, at higher energies, a "bump" is visible which is possible to fit with a second Gaussian peak (figure 3.12).

Different hypothesis were made on the origin of this "bump": contribution of background, effect of electronics and multichannel analyzer, geometry of the crystal. The first two were rejected, the "bump" is obtained also by changing PMT, MCA and electronics, and the background due to intrinsic radioactivity (measured in a low backgroud laboratory with a Germanium detector) is not significant. Testing a cylindrical BGO boule sample (see figure 3.15) the bump is not observed (see figure 3.13) thus indications that the origin of it could be the crystal geometry has been studied in more detail.

![Energy spectrum of BGO PDC crystal](image)

**Figure 3.12.** Energy spectrum of BGO PDC crystal, the first peak is the photo emission peak that is used to calculate the relative energy resolution, the second peak is fitting the "bump".

The crystal has been irradiated from the side in two different positions with a more collimated source. A spectrum (the peak on the left in figure 3.14) with the source closer to the hexagonal upper part of the crystal has been recorded, the bump is visible as before. A second spectrum (the peak on the right in figure 3.14) is taken when the source is placed closer to the cylindrical end of the BGO, the
bump is more pronounced. In both cases the PMT is attached to the cylindrical protrusion.

We conclude that the bottom BGO crystal consisting of two different parts contributes with them in different ways to the light yield. The hexagonal part is bigger so the probability to have photoabsorption is high which gives a higher peak but the light gets partly reflected and trapped when passing through the cylindrical protrusion resulting in a lower light yield (peak at lower channel number). The cylindrical part has low counting rate but the light that is produced inside it can travel undisturbed to the PMT resulting in a high light yield.
3.5. Further Studies

Figure 3.14. Energy spectra of $^{137}$Cs for PDC BGO crystal for two different positions: (green left) close to the hexagonal part and (black right) close to the cylindrical part.

Figure 3.15. PDC BGO crystal and sample BGO crystal. The PDC crystal is 4 cm tall, and the cylindrical sample is 1 cm tall.
Chapter 3. Tests of BGO Scintillators

3.5.2 Temperature Dependence of BGO

As in many scintillation materials the light yield is a function of temperature. The reason for this is that the probability for radiative transitions is temperature dependent. The radiative transitions are responsible for the production of scintillation light and they dominate at low temperatures. The light output as a function of temperature for BGO and other inorganic scintillators is shown in figure 3.16. Contrary to other scintillators, BGO has the disadvantage of a strong and negative-slope temperature dependence. The temperature characteristics of the PoGOLite flight have not yet been fully studied. The temperature can vary depending on the float altitude, position of the sun, and pointing direction. A study of the light yield over a wide temperature range -20° to 60° has been performed. The temperature has an influence on the counting rate of the the SAS crystals, and on the veto efficiency of the PDC, whereas for the PDC the counting rate will remain the same since here the BGO is only a waveguide.

![Figure 3.16. Temperature response of various inorganic scintillation materials [22].](image)

The temperature affects both scintillation decay time and light output. The decay time increases whereas the light output decreases with increasing temperature. The scintillation decay time can be described with the function \( f(t) \) which consists of several components

\[
f(t) = r_1 e^{-t/\tau_1} + r_2 e^{-t/\tau_2} + r_3 e^{-t/\tau_3}
\] (3.8)
where $t$ is the time, $r_{1,2,3}$ are constants of the order unity, and $\tau_{1,2,3}$ are decay time constants. The contribution of each exponential term depends on the temperature [39]. The decay time can be studied by means of delayed coincidence method. As can be seen in [39] the scintillation decay time also above room temperature will remain higher than the typical decay time of the fast scintillators, thus the pulse shape discrimination described in section 2.5 is not affected.

The light output has been measured for one sample crystal for different values of temperature from (-20 - 60)$^\circ$C. The temperature values below 0$^\circ$C have been obtained with dry ice while the values above room temperature with a programmable oven. In figure 3.17 the energy spectra for some temperature values shown ((20,40,50)$^\circ$C). The position of the energy peak moves to higher energies with decreasing temperature as expected. The peak are fitted with the same procedure as for the relative energy resolution. For each temperature the single photoelectron peak has been measured, the position of this does not vary with temperature, thus the absolute light yield is proportional to the energy of the photopeak. The peak positions are plotted as a function of the respective temperature in figure 3.18, and fitted with a linear function. For comparison and completeness also the light yield values obtained in a second setup, the measurement described in [39], have been plotted after a calibration with the data obtained at KTH. The calibration has been performed by calculating the ratio between the light yield values at 20$^\circ$C obtained by both setups:

$$E_{KTH}(20^\circ C)/E_2(20^\circ C) = K \quad (3.9)$$

$E_{KTH}(20^\circ C)$ is the light yield value obtained at KTH, whereas $E_2(20^\circ C)$ the value obtained by the second setup, $K$ is the calibration constant.

By multiplying the data obtained in the other setup it is possible to compare the data and fit with the same function. The data are fitted with a linear function, $a+bx$, the value of the fitted parameters relating to channel number are

$$a = (2456.25 \pm 12.15) \quad (3.10)$$
$$b = (-27.21 \pm 0.51)^\circ C^{-1} \quad (3.11)$$

The BGO behaves as expected and it will be possible to correct the polarimeter data once more information about the temperature in flight will be available.
Figure 3.17. *Energy spectrum of $^{137}$Cs depending on temperature: the peak position moves to higher energies with decreasing temperature.*

Figure 3.18. *Peak position versus temperature: data1 (green square) are the KTH data, data2 (blue dots) are the data taken from [39]. All points are fitted linearly (continuous line).*
4.1 Introduction

The star tracking system of PoGOLite consists of 2 independent star trackers which provide together with the differential GPS absolute attitude information which calibrates the other attitude sensors. To guarantee PoGOLite performances, the pointing accuracy has to be better than 5% of the FOV, which means about 0.12°.

PoGOLite will fly during day and night, thus the star tracker which operates in the optical wavelength has to fulfill special requirements. PoGOLite will adopt a solution, used by BLAST (Balloon-borne Large Aperture Sub-millimeter Telescope) and HEFT (High Energy Focusing Telescope), which consists of two identical star tracker cameras attached to the polarimeter. One of them is mounted parallel to the X-ray instrument and the second with an offset of ∼ 30° to ensure that at least one camera is never obscured by the balloon. The possibility to operate also during day-time is guaranteed by long baffles which reduce the sunlight scattered by the balloon and the residual atmosphere still present at an altitude of ∼40 km. Since PoGOLite does not require the high pointing accuracy of HEFT, the second star tracker could be replaced by a sun sensor. The combination of a night-time star sensor and a day-time sun sensor has been used by several experiments, but the sun sensor cannot be used when the Sun is obscured by the balloon and when the sun rises above ∼ 65° elevation. The task of the star tracker system is the localization of stars and identification of them. It acquires pictures of the sky, extracts information about relative positions and magnitudes of the stars and determines the coordinates of the centre of the image by comparing the star pattern with a star catalog, e.g Tycho [40]. A star tracker prototype has been constructed and first performance tests are reported in this chapter.
4.2 Instrument Design

The star tracker consists of a Retiga-EXi CCD camera from Qimaging [41] which is read out by a PC104 computer system (MSMT3SEG) from Digital-Logic [42]. On the camera is mounted a 200 mm f/2 Nikon Nikkor IF-ED lens (see figure 4.2). These components are housed in a pressure vessel connected through a fused silica window (not present during the tests) to the baffle system (see figures 4.1, 4.8).

![Figure 4.1. Mechanical drawing of star camera assembly. The CCD camera is coupled to a 200 mm f/2 lens, the entire system together with the PC104 computer system is kept in a pressured vessel which has a length of ~0.56 m and a radius of ~0.40 m. This design of the star tracker has been used both in HEFT and BLAST experiments [43], [44].](image)

4.2.1 CCD Camera

The digital camera Retiga-EXi from Qimaging [41] is equipped with a Sony ICX285 progressive-scan interline monochrome CCD with an array of 1392 $\times$ 1040 6.45 µm-square pixels with a 100% fill factor (see figure 4.3). The camera has an electronic shutter which can expose from 40 µs to 17.9 min in 1 µs increments. The well capacity, i.e. the maximum number of electrons that can be stored by single pixel before saturation, is 18,000 $e^-$. The digital output is 12 bit which gives a maximum value of $2^{12} = 4096$. The CCD is connected through an IEEE 1394 Firewire interface to a PC104 computer system, and the digital output is translated to a 16 bit output in order to store the image on the computer. The data are transferred from the CCD to the computer at a speed of 400 Mbps, thus the transfer of a complete picture takes about 1 ms. The quantum efficiency (plotted in figure 4.4) is maximal at 600 nm. The IR cut-off filter which is usually supplied with the camera is not used.
4.2. Instrument Design

Figure 4.2. Picture of the CCD camera EXi with a 200 mm f/2 Nikon Nikkor IF-ED photo lens. These elements will be kept in a pressure vessel during flight. The CCD camera is 20 cm long and lens is 25 cm long. The two stepper motors, for focal position and for aperture respectively, are visible.

Figure 4.3. Sony ICX285 CCD chip schematic view. 3D-view of the chip (left), plan view of the chip (right), the height and length are in pixels[45].
4.2.2 Optics

The camera CCD is equipped with a lens whose choice is a compromise between having a large field of view but at the same time having the flux of one star distributed on more than one pixel. These are determined by the signal-to-noise ratio, the diffraction limited spot size, the field of view and the use of filters. The requirements are fulfilled by a 100 mm diameter Nikon Nikkor IF-ED lens, which has a focal length of f=200 mm. The focus ranges from 2.5 m up to infinity, the aperture goes from a maximum of f/2 to a minimum value of f/16.

The CCD size and the focal length of the lens determine the FOV through the formula [46]:

$$\text{FOV} = 57.3^\circ \frac{A}{\text{focal length}}.$$  \hspace{1cm} (4.1)

The FOV is in one dimension, A is the width of the imaging area, 8.98 mm and 6.71 mm for the whole CCD chip, and 6.45 \(\mu\)m for a single pixel in both directions. Inserting the values the formula gives a FOV of 2.57°×1.92° for entire chip, and a FOV of 0.11’×0.11’ for the single pixel.
4.2. Instrument Design

The size of the aperture is chosen as large as possible, i.e. \( f/2 \) or \( f/2.8 \), to collect as much light as possible. The aperture choice affects the size of diffraction spot, \( \delta \), described by the formula [46]:

\[
\delta = 2.44 \lambda f/\# \tag{4.2}
\]

where \( \lambda \) is the wavelength, \( f/\# \) the f-number and 2.44 an integration constant. In the red band \( \lambda=650 \text{ nm} \). The size of the diffraction spot for \( f/2 \) (f/2.8) is 3.172 \( \mu \text{m} \) (4.4 \( \mu \text{m} \)) which is smaller than 1 pixel. So the light of a point source placed at infinity will be concentrated on one pixel or 4 depending were the photon hits the pixel (see figure 4.13), in practice this will be not the case due to chromatic aberration [47]. The star has to cover more than one pixel in order to distinguish from cosmic rays, but has not to cover too many pixels since that will decrease the signal-to-noise ratio.

The lens has a Nikon R60 filter which cuts out the light below 600 nm (see figure 4.5). This helps in reducing the sky background, but also rejects some light of stars. The properties of the CCD and the lens are sum up in table 4.1.

![Figure 4.5. Transmission curve of two typical red filter used in astronomy. PoGO-Lite star tracker uses the R60 filter, which attenuates out all wavelengths below 650 nm.](image)

Additional background can be caused by reflection of direct sun light entering the camera opening, this can be reduced by the baffle system attached to the front of each camera. By means of the baffle system it is possible to point 60° close to the sun. It prevents a source that is placed at an angle greater than 7° from the optical axis from illuminating directly the CCD and eliminates primary reflections from sources placed at an angle greater than 10° from the optical axis [43]. The baffle design has been taken from BLAST and adapted to PoGOLite. The design,
calculated with ray tracing techniques [48], is just scaled to a shorter length (see figure 4.8). The shield consists of a 91.32 cm long tube of FR4 (Flame Retardant 4) with diameter 15.6 cm. Inside 10 knife-edged aluminum rings are placed (see figure 4.7). The distance at which they are placed and their radius has been calculated through simulations. The inside of the baffle is coated with Aeroglaze Z306 which is an absorptive polyurethane coating which prevents internal reflections.

During flight the temperature and atmospheric conditions can vary, thus an adjustment of aperture and focus could be necessary. For this purpose the aperture and focus rings are driven through gearwheels by two stepping motors from Lin Engineering [49]. The motors are controlled by a controlling board EZ Stepper EZ17 from Allmotion [50] which is connected through a serial port to the PC104 computer system. The motor full step is 0.9° which can be subdivided into 8 micro steps. In figure 4.6 a block diagram of the setup is shown.

The maximum exposure time should be set lower than 1 second to ensure that the stars do not show any trail. The maximum speed of a star (on the ecliptic and observed from the equator) is about:

\[
\frac{180^\circ}{12h} = \frac{180 \times 3600''}{12 \times 3600s} = \frac{180''}{12s} = \frac{15''}{s}
\]

(4.3)

and since a pixel is about 6.8” if the exposure time is less than 450 ms even the fastest star should move less than 1 pixel.

**Figure 4.6.** Block diagram of the electronics of the star tracker. The computer controls the camera through a fire-wire IEEE 1394 cable and stepper motors through a RS 232 port.
4.2. Instrument Design

| CCD Sensor QImaging EXi | | |
|------------------------|------------------|
| Light Sensitive Pixels | 1360×1036         |
| Exposure Time          | 40 μs to 17.9 min in 1 μs increments |
| Pixel Size             | 6.45 μm × 6.45 μm |
| Linear Full Well       | 18,000e⁻         |
| Read noise             | 8e⁻              |
| Dark Current           | 0.15e⁻/pix/s cooled |
| Digital Output         | 12-bit           |

<table>
<thead>
<tr>
<th>Nikon Lens</th>
</tr>
</thead>
<tbody>
<tr>
<td>focal length</td>
</tr>
<tr>
<td>lens diameter</td>
</tr>
<tr>
<td>max. aperture</td>
</tr>
<tr>
<td>min. aperture</td>
</tr>
</tbody>
</table>

Table 4.1. Summarized properties of CCD Sensor QImaging EXi and Nikon Lens.

Figure 4.7. Picture of the baffle system before the Aeroglaze paint is applied to the collimator rings.
Figure 4.8. Drawing of PoGOLite baffle system, the position and the radius of the knife-edged rings are shown.
4.3 Tests

4.3.1 Setup

The star tracker requires several tests and calibrations before starting to deal with the star matching software. Regarding the CCD, the efficiency of each pixel has to be measured, and eventually noisy or dead pixels have to be masked away. Regarding the optics, the best value for aperture and focal distance has to be set, and a calibration performed using the measured intensity of known sources. In order to test and calibrate the star tracker on ground a special setup has been constructed. It consists of a tripod equipped with two motors that can move the star tracker in elevation and azimuthal direction. The motors are connected to a PC through a USB port. An electromagnet, when switched on, can lock the star tracker in the required elevation position (see figure 4.9).

![Figure 4.9. Star tracker system during calibration on ground. The long baffle system is visible and the CCD camera with the lens. The whole system is mounted on a tripod which permits to move in azimuth and elevation. The metal semicircular plate permits to block through an electromagnet the star tracker in position.](image)
4.3.2 Hot Pixels

Every CCD has hot pixels, which are pixels with a higher rate of charge leakage than neighboring elements. The number of hot pixels and the value of the brightness of these can increase with temperature and exposure time. The final goal of the PoGOLite CCD is to take pictures of stars that on the CCD will have a size comparable to that of a pixel, so it is very important to identify hot pixels which could be misinterpreted as possible point sources. Once identified it is possible to mask them or assign to them the mean value of the surrounding pixels. To map out the hot pixels different pictures with closed shutter have been taken. By looking at pixel intensities in the pictures (see figure 4.10) one can find pixels which have a much higher intensity than the background. The background in this case is due to dark noise normally present in every pixel. After removing the background, and by plotting the H-direction versus V-direction (see figure 4.3) of the filtered data, a map of the hot pixel results. This procedure is done at room temperature for an exposure time of 100 ms for different pictures, and each hot-pixel map is plotted in the same graph 4.11. It can be seen that the hot pixels of different acquisitions match.
4.3. Tests

Figure 4.10. Intensity profile of one picture: (top) intensity profile in V direction, (bottom) intensity profile in H direction.

4.3.3 Flat Field (Pixel Calibration)

The flat field correction reduces the artifacts in the CCD image due to difference in the pixel sensitivity. The pixel calibration is done by illuminating evenly the CCD with a bright source, which was fulfilled using the bright sky. The exposure time has been set to 0.2 ms in order to guarantee that none of the pixels saturate. To build a flat field from the sky images the value of each pixel was divided by
the image mean and a number of such flat fields were then averaged to reduce the Poisson noise. The resulting flat-field image is shown in figure 4.12. The pixels in the center are more illuminated than the region at the border, this is due to the fact that lens and baffle system are optimised for the radiation that travels in the center of the field of view. Especially when the flux of stars is sought, the flat-field correction has to be taken into account and the image of interest has to be divided by the flat-field image.

When doing these observations the efficiency of the baffle system was also tested. This was done by pointing the camera approximately 80° and 60° from the direction of the sun and comparing the mean value of the measured flux when the baffle entrance was shielded and unshielded from the direct sunlight. The difference is about 0.5% and 0.7% for the two different angles respectively, which is an order of magnitude less than the Poisson noise. This means that the baffle system operates as expected.
4.3.4 Determination of Focal Position

Periodically during the flight an auto focusing procedure is performed. In order to do this, the characteristics that determine the optimum focus have to be established. The infinity focus position marked on the lens is not a reliable indicator since the CCD could be placed not exactly at the focal plane, and the infinity position is temperature dependent.

Because of bad weather conditions it was not possible to study the focusing properties of the lens by taking images of stars. A source at infinity has been created in the laboratory by collimating the light of an LED of wavelength 700 nm. The collimation setup consists in a Schmidt-Cassegrain telescope, with a red LED placed behind a 20 µm pinhole in its focal plane. The focal length of the collimator is 3556 mm, and that of the CCD lens is 200 mm. Thus the image of the pinhole will occupy about 1 µm on the focal plane which is less than the resolution of the CCD. Assuming that the nominal position of the focus of the CCD is correct the focal length of the collimator has been adjusted so that the image of the source is well focused on the CCD. Once the collimator characteristics are fixed, the focal length variation of the star tracker can be studied.

One way to study the focusing is to investigate the intensity profile of a source. The profile of the source has a big systematic error since the intensity of a pixel on the sky could be shared between between 2 or 4 pixels in the CCD if it misses a the center of the pixel as shown in figure 4.13.

A more accurate way to calculate the FWHM (full width half maximum) of the source is to use IRAF software [51], which uses a PSF (point spread function) fit. It uses a Gaussian profile and fits the flux profile by weighting each individual pixel. The fit gives the flux value, the pixel of maximum intensity and FWHM which can be compared with value obtained with the other method. Both methods agree on the choice of focusing position. The FWHM calculated with IRAF versus focusing position has been plotted in figure 4.18 and also the values of FWHM of defocused images are shown, FWHM $>2$. The positions are given in motor steps counting from the mechanical stop of the lens, each step is about 0.1°. Images of the source for different focal positions are shown in figures 4.14, 4.15, 4.16, 4.17 for the region around the source. From the plot it can be seen that the image is well focused in a range of 7 steps around the best focusing position.
Figure 4.12. Flat field correction, the gray scale represents the normalized fluctuations around the mean value of 3 flat-field images. The bottom of the image is darker on the bottom because the CCD is read out from the top.
Figure 4.13. Three different cases how the intensity can fall on the CCD pixels. The first is the optimal case for a good signal to noise ratio, in the second the intensity is shared by two pixels, and in last four pixels the intensity falls in the middle of 4 pixels.

Figure 4.14. Image of the LED placed at infinity position 133 steps after end position. The PSF fitting gives a FWHM = 2.51 and a flux F= 276606.
Figure 4.15. Image of the LED placed at infinity position 136 motor steps after end position. The PSF fitting gives a FWHM = 1.22 and a flux $F = 256829$. This is the best focused image.

Figure 4.16. Image of the LED placed at infinity position 139 motor steps after end position. The PSF fitting gives a FWHM = 1.11 and a flux $F = 249850$. 
4.3. Tests

Figure 4.17. Image of the LED placed at infinity position 142 motor steps after end position. The PSF fitting gives a FWHM = 1.34 and a flux $F = 232343$.

Figure 4.18. Plot of FWHM versus focusing position. The minimum represents the position of best focusing.
### 4.3.5 Magnitude Calibration

To calibrate the CCD response a series of images with stars of known magnitude and color have been taken (see figure 4.20). The focus has been tuned before observations. The intensity is calculated, as before, by integrating the intensity of the pixels in a circle around the pixel of maximum intensity. Since the CCD camera is sensitive to wavelengths greater than 600 nm the emission of the stars will be mostly in the red wavelength band (see figure 4.19).

![Figure 4.19. Photometer transmission curves for UBVRI (ultraviolet blue violet red infrared) filters used in astronomy [52].](image)

<table>
<thead>
<tr>
<th>id</th>
<th>RA (h m s)</th>
<th>DEC (° m ″)</th>
<th>flux</th>
<th>FWHM</th>
<th>red magnitude</th>
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<td>2.83</td>
<td>6.149</td>
<td>F5III</td>
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**Table 4.2. List of stars used for the calibration (see figure 4.20).** The first column contains the label of the stars, the second and third column are the coordinates of the stars in right ascension and declination, fourth and fifth column show the flux and FWHM computed with IRAF, and the last two columns contain the red magnitude and spectral type, the flat field correction has been applied.

The region of observation is approximately known, and with the help of a star map and star catalogue the exact coordinates have been calculated. The image has been corrected with the flat-field image, and hot pixels have been taken into
account. The flux and the FWHM of the stars has been calculated with IRAF PSF routine, the FWHM values are greater than the value obtained for the source in the lab, since the aperture chosen for these acquisitions is bigger, f/2 in this case, whereas f/5.6 was used during laboratory tests. The red magnitude is taken from a star database, in this case Sky2000 [53]. The efficiency of the CCD is linear in photon flux so one can write:
Chapter 4. Star Tracker

\[ m = -2.5 \times \log\left(\frac{N}{k}\right) \]  

(4.4)

or equivalently

\[ N = k \times 10^{-0.4m} \]  

(4.5)

thus

\[ k = N \times 10^{0.4m} \]  

(4.6)

where \( k \) is the calibration constant, \( N \) is the number of counts/sec and \( m \) the magnitude of the star, in this case the red magnitude.

For the stars for which the red magnitude is available we can compute the calibration constant as shown in table 4.3.

<table>
<thead>
<tr>
<th>id</th>
<th>( N )</th>
<th>( m )</th>
<th>( k \times 10^7 )</th>
</tr>
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<tr>
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<td>288622</td>
<td>5.877</td>
<td>6.71</td>
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<tr>
<td>7</td>
<td>219106</td>
<td>6.149</td>
<td>6.31</td>
</tr>
</tbody>
</table>

Table 4.3. Table containing the values of calibration constant for the efficiency of the CCD. The first column identifies the star, the second column contains the counting rate \( N \), the third repeats the value of the red magnitude and the last column contains the value of the calibration constant.

By taking the mean value of the calibration constants (see table 4.3) one obtains \(<k> = 6.41 \times 10^7\). For any star with known red magnitude one can predict the counting rate \( N \):

\[ N = 6.41 \times 10^7 \times 10^{-0.4m}. \]  

(4.7)

One can also compute the value of magnitude to which the counting rate of background corresponds. Taking a typical value, \( N_{sky} = 6.32 \times 10^3 / \text{s/pixel} \) of the background at 40 km at wavelength of 650 nm [47] one can calculate to which magnitude this corresponds:

\[ N_{sky} \times a = 6.41 \times 10^7 \times 10^{-0.4m}. \]  

(4.8)

The variable \( a \) is the area in pixels on which the flux of the source has been calculated, a FWHM of 2.5 gives \( a = \pi \left(\frac{\text{FWHM}}{2}\right)^2 = 4.9 \) pixels. Inserting the values one obtains a value for the magnitude of \( m=10 \).
4.3.6 Star Field around Crab and Cygnus X-1

In order to perform the star recognition one need a sufficient number of detectable stars in the wavelength band in which the star tracker operates. In figure 4.21 and 4.22 a region of $3^\circ \times 3^\circ$ around the Crab and Cygnus X-1 is shown. These are stars in the V-band (see figure 4.19).

**Figure 4.21.** Star field around the Crab, stars of different optical magnitudes $m_v$ are shown $2 < m_v < 8$.

In these preliminary tests it was possible to define parameters for the determination of the focal position, the FWHM was found to be a good indicator of the focusing, and the number of motor steps should be of the order of 3 to be able to find the best focused image. The baffle system needs a more accurate study, in order to know the star magnitude limit of the star tracker in flight. The fact that the magnitude of the estimated background in flight corresponds to a star of magnitude 10 is a promising result since in the field around the Crab and Cygnus-X1 there are enough stars of magnitude less than 8. The development of the work on the star tracker will concentrate in the following months on star pattern recognition software.
Figure 4.22. Star field around the Cygnus X-1, stars of different optical magnitudes $m_v$ are shown $4 < m_v < 8$. 
Acknowledgments

I would like to thank Prof. Mark Pearce for giving me the opportunity to work on the PoGOLite project, and for the help with this thesis. I want to thank all people of the PoGOLite collaboration, especially Stefan Larsson for the help in the last months, Göran Olofsson and Hans Gustav Florèn for helping me with the last measurements, Włodek Klamra for helping me getting started with the crystal testing and for replying my neverending questions about scintillators. A special thank goes to Stefan Rydström for helping me with everything and for showing me what tape can do. I would like to thank also Prof. Bengt Lund-Jensen for insisting on speaking with me in Swedish. I would like also to thank Jan Conrad for letting me know about the existence of SExtractor and for the moral support. The time at KTH has been pleasant thanks to all my colleagues both from KTH and SU, especially Anders for the breaks in the afternoon. I would like to thank Mözsi and Petter for helping with the printing of the thesis. My warmest thanks go to Silvio, Simonetta and Clementina for having given me the feeling of family in my first year in Stockholm. A big thank goes to my family for always being there.

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Bibliography


[37] M. Kiss. Licenciate Thesis, Department of Physics, KTH-Royal Institute of Technology, date to agree.


