Characterization of the pointing systems of the PoGOLite Pathfinder

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Cover page photo: A picture of the PoGOLite Pathfinder suspended from a purpose-built wooden frame designed for testing purposes. Credit: Miranda Jackson
Abstract

This thesis constitutes a performance study of the quality and accuracy of the pointing systems of the PoGOLite Pathfinder. The PoGOLite Pathfinder is a balloon-borne polarimeter set for launch during the summer of 2013. It will be carried by a one million cubic meter balloon to an altitude of $\sim 40$ km. During a 5 (possibly 20) day mission, it will measure the polarization degree and angle of the two main scientific targets, the Crab Pulsar and Nebula, and Cygnus X-1. The polarimeter design is based on phoswich type detector cells, with a plastic scintillator as the main detecting unit. This type of polarimeter measures polarization by use of Compton scattering and photoelectric absorption.

The polarimeter is pointed by use of an attitude control system (ACS), which by use of motors and encoders control the pointing of the polarimeter. Attitude feedback is based on GPS receivers and sensors. The ACS is supported by two star trackers which augment the pointing performance and enable tracking capabilities.

Based on data from a terminated 2011 maiden flight, Sun tracking tests in 2012 and indoor tests in 2013, the performance of the ACS and star trackers was evaluated to be $0.076^\circ$ and $0.016^\circ$ for azimuth and altitude respectively. Based on a performance target of the pointing which was set at $0.1^\circ$ and a minimum required accuracy of $0.3^\circ$, the accuracy of the pointing is determined to be within the margins set for this mission. Further studies of the pointing performance under controlled circumstances are desired, as these may have impact on future mission designs. A new study based on the results following the 2013 mission is suggested.
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Chapter 1

Introduction

The PoGOLite (Polarized Gamma-ray Observer Lite) experiment [1] is designed to study the polarization of 25-100 keV X-rays from astrophysical objects such as pulsars and accreting black holes. PoGOLite is a balloon-borne polarimeter and is scheduled to launch from Esrange in Kiruna, Sweden during the summer of 2013. It will be lifted by a one million cubic metre balloon to an operational altitude of approximately 40 km. Previous launch attempts were made in 2011 and 2012; the 2011 launch was cut short due to a balloon malfunction, and during the launch window of 2012, the weather conditions on the ground would not allow for a safe launch.

During this pathfinder mission, the two main targets of interest are the Crab Nebula (M1, NGC 1952) and Cygnus X-1 (HD 226868). Polarization measurements are made based on modulation factors from the distribution of the azimuthal scattering inside the polarimeter. The active part of the detector is made up of 61 detector cells of a phoswich type design employing plastic scintillators, crystals and PMTs.

The pointing of the polarimeter is controlled by the attitude control system (ACS) supported by two star tracker cameras. The ACS consists of motors, encoders and sensors to provide a pointing solution capable of pointing the polarimeter to within a fraction of a degree of any target.

This thesis will focus on the ACS and characterize the performance of the pointing, based on real data from the 2011 launch and pointing tests made during the summer of 2012 and start of 2013.

This chapter will serve as an introduction to the field of polarimetry in the X-ray and gamma-ray range. It contains a description of polarization, what it is and how it is created, how radiation interacts with matter and how these are combined to measure polarization, followed by a description of some of the astrophysical objects of interest for polarization measurements.

1.1 Polarimetry

Studying the different properties of radiation (light) has for a long time been the only window out into the Universe available to us on Earth. Following the huge advancements in science over the last hundred years, it was discovered that not only radiation came from the Universe, but subatomic particles such as electron, protons and neutrinos also
bombarded Earth. At the birth of astronomy, only the intensity of visible light was available to astronomers. This was used to classify stars and determine distances to nearby objects (by use of the parallax). As science progressed and the nature of light was determined, instruments were built to study light at other wavelengths, such as radio and infrared. Astronomers were met with a Universe with structures never before seen, structures that both answered questions and presented new ones. Through technological breakthroughs, this was expanded to include the X-ray and gamma-ray wavelengths. The picture of the Universe as it is known today consists of observations at a large range of wavelengths and for a large range of particles. All of these observations are important in order to try to understand the Universe.

A more recent branch of astronomy, known as polarimetry, deals with the polarization of light. While stars emit mainly unpolarized light\(^1\), there are celestial sources of polarized light. These include pulsars, active galactic nuclei (AGN), gamma-ray bursts (GRBs) and accreting black holes. Radiation (light) can interact with matter differently depending on the energy of the incident radiation, and these interactions provide the basis on which polarization measurements are made.

### 1.2 Polarization

Polarization is a property inherent in all waves and describes the plane of oscillation. It is always perpendicular to the direction of propagation. Light is an electromagnetic (EM) wave and as such possesses this property. The polarization of light is by convention described by specifying the orientation of the electric field at a point in space over one period. If the orientation does not vary with time, the polarization is linear. If it does vary in time, the polarization is circular or elliptical. As the PoGOLite polarimeter measures linear polarization, for the remainder of this thesis the term polarization will refer to linear polarization. Light is composed of photons, each of which has a polarization: a photon beam comprised solely of randomly polarized photons is per definition unpolarized. The fraction of identically polarized photons versus the fraction randomly polarized photons in beam is called the polarization degree, \( P\% \), defined as:

\[
P\% = \frac{N_P}{N_P + N_R}
\]

(1.2.1)

where \( N_P \) is the number of identically polarized photons and \( N_R \) the number of randomly polarized photons.

Another property of polarized light is the polarization angle, which is defined as the angle between the plane of polarization and a fixed reference frame. Polarized light may be produced indirectly by reflection or scattering of unpolarized light but also directly through bremsstrahlung, cyclotron and synchrotron radiation. A brief description of each of these production mechanisms will follow below.

#### 1.2.1 Reflection

Incident unpolarized light may be polarized by reflection from a surface (see Figure 1.2.1) as photons with electric field perpendicular to the plane of reflection are more likely to

\(^1\)Certain phenomena can lead to polarized light. Flares can for instance produce polarized light.
be refracted (transmitted), resulting in a polarized reflected beam. The polarization may be total or partial, depending on the angle of incidence. The angle corresponding to total polarization of incoming light is called Brewster’s angle, $\theta_B$. This angle depends on the index of refraction $n$ of the medium by the following formula:

$$\theta_B = \arctan \left( \frac{n_2}{n_1} \right),$$

This type of polarization production mechanism can happen when unpolarized light is reflected from an atmosphere.

Figure 1.2.1: Polarization by reflection. The incident unpolarized beam is reflected at the boundary of two media and the reflected beam is partially or totally polarized.

1.2.2 Scattering

Unpolarized light may undergo scattering with particles to produce polarized light. The type of particle (of the scatterer) determines the properties of the scattering and the resulting polarized light. If the particle is an electron (or positron), the scattering is called Compton scattering [2]. Such an event is shown in Figure 1.2.2. If instead the particle is a large atom or molecule, then this is called Rayleigh scattering [3]. Compton scattering will be discussed in Section 1.3. The scattering of light from the sun with the molecules in Earth’s atmosphere is responsible for the polarization of sunlight and is also the reason why the sky appears red at dusk [4].
Bremsstrahlung

Bremsstrahlung is the emission of photons due to the deceleration of a moving charged particle being deflected by another charged particle, as shown in Figure 1.2.3. By the conservation of energy, the kinetic energy lost by the charged particle as it is decelerated is converted to a photon. The emitted photon may be polarized in the presence of a magnetic field or due to a constant flow direction of a flux of photons. Bremsstrahlung occurs naturally in plasmas, which is why it can be seen in the spectra from H-II regions [5].

Cyclotron and Synchrotron Radiation

As charged particles traverse a magnetic field, they will be deflected, and as a result of the deflection, the particles will lose energy in the form of emitted photons. If the particle is going at relativistic speeds, then this emission of photons is called synchrotron radiation, and at sub-relativistic speeds it is called cyclotron radiation. These two types of emission will have a characteristic polarization. As a result, by measuring the polarization of astrophysical objects, it is possible to identify these types of radiation. Synchrotron
radiation is for instance seen from pulsars, the jets of active galactic nuclei and gamma-ray bursts. Cyclotron radiation can be observed from plasmas in interstellar space as well as around black holes.

![Diagram of an electron in a helical orbit around the magnetic field lines](image)

**Figure 1.2.4:** An electron in a helical orbit around the magnetic field lines will emit photons. If \( v \approx c \), it is called synchrotron radiation, or if \( v << c \), it is called cyclotron radiation.

## 1.3 Interaction of Radiation with Matter

Radiation interacts with matter through a variety of mechanisms. Depending on the energy of the radiation, it is dominated by either the photoelectric effect, Compton scattering or pair production (see 1.3.1). These interactions provide the basis for the designs of instruments capable of measuring properties of light coming from astrophysical objects. It is through the use of the equations that govern these interactions that it is possible to determine a property such as polarization. The PoGOLite polarimeter is based on Compton scattering. In the following sections, descriptions are given of each of these interactions. For all three interactions, it will also be mentioned what property is used to measure the polarization.

### 1.3.1 Compton Scattering

Compton scattering is defined as the process when an incident photon scatters inelastically on an electron at rest. The process is also known to occur in the opposite direction, that is, an electron scatters on a photon, which is called inverse Compton scattering. The Klein Nishina formula [7] describes the differential cross section of Compton scattering.

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

where \( r_0 \) is the electron radius, \( E \) and \( E' \) the initial and final photon energies, \( \theta \) is the polar scattering angle and \( \phi \) the azimuthal scattering angle.

As \( \phi \) depends on the polarization of the incident photon, measuring the distribution of azimuthal scattering angles provides the possibility to determine the polarization of
1.3.2 Photoelectric Effect

Photons interacting with matter may be absorbed by atoms in it. If the photon has an energy higher than the binding energy of the electrons in the atom, the atom will emit an electron. This process is shown in Figure 1.3.2 and is called the photoelectric effect.

The emitted electron, called a photoelectron, will have an energy of [8]:

\[ E_{pe} = h \nu - E_b \]  (1.3.2)

where \( h \) is Planck’s constant, \( \nu \) is the frequency of the incident photon and \( E_b \) is the binding energy of the electron.
In the differential cross section [9] governing the photoelectric effect, there is an angular dependence on $\theta$, where $\theta$ is the azimuthal emission angle. This can be used to measure the polarization of the photon by measuring the distribution of azimuthal electron emission angles.

### 1.3.3 Pair Production

The Coulomb field in the vicinity of a nucleus may interact with incident photons through the pair production mechanism. A photon interacting with the field may then be transformed into an electron-positron pair, as is shown in Figure 1.3.3. In order for this to be possible, the incident photon has to have an energy greater than twice the electron rest mass, 1.022 MeV.

The differential cross section [10] contains an angular dependence on $\Psi$, which is
the angle between the polarization vector of the incident photon and the plane of the electron-positron pair. Measuring the angular distribution of the electron-positron pair plane allows for determination of the polarization of the incident photons.

1.4 Polarization Measurement Techniques

The three interactions discussed in section 1.3 all share a common property: an angular dependence on the polarization. This provides an easy and straightforward technique for measuring polarization by simply measuring the angular distribution of many events.

As there is an angular dependence in the differential cross sections of the interactions, the angular distributions will be modulated by the polarization. It is from this modulation that the polarization angle and degree can be deduced. An example of such a modulation curve is shown in Figure 1.4.1. Fitting the modulation to a sinusoidal curve allows an amplitude, $A$ and a mean value $B$ to be calculated. The modulation factor, $M$, is defined as:

$$ M = \frac{A}{B} \quad (1.4.1) $$

from which the polarization degree is found as the ratio:

$$ P\% = \frac{M}{M_{100}} \quad (1.4.2) $$

where $M_{100}$ is the modulation factor of a 100% polarized beam, determined by experiments or simulation.

The polarization angle is found as the phase shift of the modulation curve relative to a fixed reference frame.

![Figure 1.4.1: An example of a polarization modulated angular distribution. The values A and B refer to the amplitude and the mean value respectively. Figure taken from [11]](image.png)

1.5 Scientific Targets

In astronomy, and all sciences, models are put forth to explain that which is observed. For a model to be validated it needs to be able to make accurate predictions that can
be tested. Often there are several models proposed that can explain some parts of the observations, which poses the question: which is the correct one? Often a specialized observation or measurement of the target or object in question may be needed to make a final decision. Such is the case with the high energy emissions from pulsars and GRBs, where polarization measurements may help provide insight into determining the correct model that describes the emission. Polarization measurements of X-ray binaries are of interest to determine the energy distribution as well as the geometry of the object. These types of objects (pulsars, GRBs and X-ray binaries) are presented in the following section.

1.5.1 Pulsars

A pulsar is a rapidly spinning, highly magnetized neutron star\(^2\) emitting beams of radiation from its two magnetic poles. Viewing this object from Earth means an observer will see a pulsating emission of radiation, hence the name. Pulsars were first discovered in 1967 by Jocelyn Bell [13] but were not identified as neutron stars until a year later by Thomas Gold [14] and Franco Pacini [15]. A neutron star is the collapsed core of a progenitor high mass (larger than 8 times the mass of the Sun) star that exploded in a supernova.

In the supernova process in which a neutron star is created, the star sheds its outer layers in a violent explosion, leaving only an iron and nickel rich core. As the inward pressure of gravitation is no longer balanced by the outward pressure of the radiation, the core starts collapsing in on itself and in the process turning protons into neutrons. The collapse is halted when the gravitational pressure is balanced by the neutron degeneracy pressure. What was once a large, slowly rotating star is suddenly transformed into a much smaller, dense ball of neutrons which, by the law of conservation of angular momentum, will spin rapidly. A typical neutron star has a radius in the order of 15 km, a mass in the order of 1.4 to 3 Solar masses, a density \(10^{14}\) times that of the Sun and a magnetic field \(10^{12}\) times stronger than that of the Sun. A newly formed neutron star can spin up to 600 times per minute, but a typical pulsar has a period in the order of 1 second.

The electromagnetic spectrum seen from pulsars spans all energies and displays characteristics of dipole radiation. There is, however, no model that can accurately predict the observed spectrum at all energies. For the high-energy X-ray and gamma-ray emission, there have been three competing models for the production of the observed radiation: the outer gap model [16], the caustic model [17] and the polar cap model\(^3\) [20] [21]. The models differ mainly in the region of the acceleration of the electrons (and positrons) that give rise to the observed radiation, as can be seen in Figure 1.5.1. The main ideas behind the three models are summarized below:

- **The Polar Cap Model:** This was the first model presented to explain the high energy emission. It was originally suggested by Sturrock in 1971 [22]. In this model, the acceleration takes place within the open field lines at the polar caps of the neutron star, shown in Figure 1.5.1. Curvature radiation is emitted by the particles as they spiral in the strong magnetic field. Photons in the magnetic field interact with the radiation through pair production, which results in an electromagnetic

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\(^2\)A star predominantly built up by neutrons with an extremely high density, proposed by W. Baade and Fritz Zwicky in 1934 [12]

\(^3\)Observations made with LAT instrument on the Fermi satellite [18] disfavors the polar cap model for the high energy emissions. The polar cap model is still viable for the radio emission [19].
cascade. Particles created from the cascade will in turn emit synchrotron radiation. This radiation will escape the star and produce the spectrum observed from Earth.

- **The Outer Gap Model:** This model assumes the acceleration takes place in the vacuum gaps between the open and closed field lines as seen in Figure 1.5.1. A combination of curvature and synchrotron radiation is emitted and similar to the polar cap model, the radiation interacts with photons to produce an electromagnetic cascade. The resulting emission from particles created in the cascade will be a combination of inverse Compton scattering and synchrotron radiation.

- **The Caustic Model:** This model suggests that the acceleration takes place at the edges of the open field regions as shown in Figure 1.5.1. This model is a combination of the previous two models in which the effects of special relativity are included. This leads to a caustic (piling up of photons) effect.

Both the outer gap and caustic model can, to some extent, describe the observed intensities at varying accuracies, but they both predict different results for the polarization. A summary of these predictions by all three models for the intensities, polarization angle (position angle) and the polarization degree in the case of the Crab Pulsar for the three models is shown in Figure 1.5.2.

The Crab, including the Pulsar and Nebula, is the main target of the PoGOLite Pathfinder mission. It is the remnant of a type II supernova that was seen on Earth in 1054. It could be seen with the naked eye, and astronomers at the time recorded the event. Due to its brightness, many mistook it to be a new star. In [23], the magnitude of SN 1054 is calculated based on historical documents to be in the range of -4.5 to -7 magnitude (Venus, for comparison is -6 at brightest). Figure 1.5.3 shows the Crab Pulsar and Nebula as seen by three different telescopes superimposed on top of each other. By contributing measurements for the polarization of the Crab, PoGOLite hopes to shine new light on which of the suggested models might be the correct one.

![Figure 1.5.1: Suggested emission regions for the three different models: the polar cap (yellow), the caustic (slot gap in the figure, magenta) and the outer gap (blue). Taken from [24].](image)
Figure 1.5.2: Model predictions of the intensity (top), polarization angle (middle) and polarization degree (bottom) for the three competing models, the polar cap model (left), the outer gap model (center) and the caustic mode in the case of the Crab Pulsar. Figure taken from [1].

Figure 1.5.3: The Crab Pulsar and Nebula, in a composite image showing a superposition of X-rays, infrared and optical wavelengths. The pulsar is seen as the small dot in the center of the blue field which looks to have rings around it. The nebula is the huge gas cloud surrounding it. Image courtesy of; X-Ray: NASA/CXC/J.Hester (ASU); Optical: NASA/ESA/J.Hester & A.Loll (ASU); Infrared: NASA/JPL-Caltech/R.Gehrz (Univ. Minn.) [25]
1.5.2 X-ray Binaries

In binary systems where one of the celestial objects is a compact object, such as a neutron star or a black hole, matter from the companion will flow onto the compact object and form a so-called accretion disc. The gravitational potential energy of the infalling matter will cause X-rays to be emitted. The archetypal X-ray binary is Cygnus X-1, which is the secondary target for the PoGOLite Pathfinder mission.

Cygnus X-1 is a black hole candidate in a binary system with HDE 226868, a blue super-giant variable star. It is one of the strongest known sources of X-rays and has been extensively studied. HDE226868 produces a strong solar wind that is funneled onto Cygnus X-1. The infalling matter spirals in on the black hole and causes an accretion disc to form. Part of the infalling matter will be expelled from the poles of the black hole in the form of two jets. Inside the disc and jets, the temperature reaches millions of degrees, causing X-rays to be emitted. An artist’s impression of this process is shown in Figure 1.5.4.

Cygnus X-1 has two distinct states, a hard and a soft state, referring to the energies of the X-rays. In the hard state, the accretion rate is lower and a hot corona surrounds the black hole. Emissions in the hard state are a combination of emission from the disc, the jets and the corona. This thermal emission is initially unpolarized. However, the emission from the corona can scatter on the accretion disc, giving it a distinct polarization. Observing the polarization in the hard state can help determine the geometry of the system.

In the soft state, the accretion rate is higher and there is no corona that surrounds the black hole. Instead, active regions of energetic electrons form above the accretion disc. Emissions from the disc can then Compton scatter on the electrons, thus becoming polarized.

Observations of Cygnus X-1 in the hard state can help determine the geometry of the system, whereas observations of Cygnus X-1 while in the soft state help determine the electron energy distribution in the active regions.

![Figure 1.5.4: An artist’s illustration of Cygnus X-1 and its binary blue super-giant star HDE 226868. Image courtesy of NASA/CXC/M.Weiss](image)
1.5.3 Gamma-ray bursts

Gamma-Ray Bursts (GRB) are brief, intense flashes of gamma-rays, thought to be associated with supernovae or neutron star mergers. They are the most luminous events known to occur and last for milliseconds to minutes. Following the initial flash, there is a much fainter afterglow, spanning all energies, that can last much longer.

GRBs are divided based on the duration of the initial flash into short and long. If it is longer than 2 seconds it is classified as long. Should it be less, then it is short. Supernova events are believed to be responsible for the short GRBs, whereas neutron star mergers have been suggested as being connected to the long GRBs.

Due to the nature of these events, in that they cannot be predicted and last for a very short time, little is known about the polarization of the radiation. Studies on the polarization may help limit the models that describe GRBs.
Chapter 2

The PoGOLite Pathfinder

The pathfinder mission for the PoGOLite project is scheduled for the summer of 2013 and is being launched from Esrange in Kiruna, Sweden. A gondola carrying the polarimeter will be lifted to an altitude of 40 km by a one million cubic meter balloon. The mission is intended for a $\sim 5$ day duration, though a possibility of an extension to a $\sim 20$ day circumpolar mission exists. The main instrument is a scaled down version of the originally suggested PoGOLite polarimeter [1] and it consists of 61 (instead of 217) phoswich detector cells based on Compton scattering and will operate in the 25-100 keV range. The main purposes of the pathfinder mission are to test the performance of the polarimeter and to measure the polarization of the two main targets, the Crab Nebula and Pulsar, and Cygnus X-1. A performance target of a minimum detectable polarization (MDP) of 10% from a 1 Crab (a unit of luminosity, defined by the luminosity of the Crab) source was set.

Originally, the PoGOLite Pathfinder was scheduled for a stratospheric turnaround flight during the summer of 2010. A failed balloon launch in Australia earlier that year caused all balloon missions to be grounded. On the 7th of July in 2011, PoGOLite had its first launch. A few hours into the flight it was discovered that the balloon was leaking and the flight was terminated. A new launch was scheduled for 2012. However, bad weather conditions during the flight window precluded any new launch. PoGOLite has been granted a new launch window for the summer of 2013. A drawing of the gondola and its flight train is shown in Figure 2.1.2.

The following chapter describes the polarimeter and auxiliary systems, the gondola carrying the payload, the control and data acquisition software and the flight plan for the 2013 launch.

2.1 Gondola

The gondola serves as the platform on which the polarimeter, attitude control system (ACS) and all the electronics are mounted. Figure 2.1.2 shows the gondola with all components mounted. The balloon will attach at the very top of the gondola, below which there is a collection of sensors and antennas. The two booms extending to the sides carry solar panels that charge the batteries seen at the bottom of the gondola, as well as GPS receivers on both ends of the boom.
The polarimeter sits at the center in a gimbal controlled by the ACS through motors and servos. A radiator, which is part of the cooling system to keep the polarimeter and electronics at optimal temperature, is mounted on the backside of the gondola, in a position as to minimize the Sun exposure [27]. Two star trackers are seen just below the polarimeter; these employ charge coupled device (CCD) cameras that are used to augment the pointing capabilities of the ACS. The auroral monitoring unit (AMU) is seen next to the star trackers. This separate unit was proposed in [28] and then designed and built by the Alfvén Laboratory [29]. It has its own scientific target, which is to study the auroral X-rays. These readings may, however, be useful for PoGOLite, as a strong aurora would significantly increase the background events in the polarimeter. It is predicted that strong auroral X-rays may happen for 5-10% of the flight [28]. They may help determine the X-ray background. The total payload weight is \(\sim 1750\) kg.

Figure 2.1.1: Left: The gondola on which the polarimeter, ACS and electronics are mounted. Right: The full flight train of the PoGOLite Pathfinder. The configuration, as it extends above the gondola, has been used in previous flights successfully. Figure taken from [30]
2.2 Polarimeter

The main instrument of the PoGOLite experiment is the polarimeter. Through the detection of Compton scattering and subsequent photoelectric absorption, it determines the polarization of X-rays in the 25-100 keV range. The polarimeter’s main components are 61 phoswich (a term coined from "phosphor sandwich") detector cells (PDC) surrounded by anti-coincidence shields, a polyethylene neutron shield and a pressure vessel. Figure 2.2.1 shows a schematic cross section of the polarimeter. The field of view of the instrument is $2^\circ \times 2^\circ$.

This section starts with a description of the main component of the polarimeter, the PDC, followed by details on background rejection, event selection and data processing.

2.2.1 Phoswich Detector Cell

Each of the phoswich detector cells (PDCs) is made up of two plastic scintillators and a bismuth germanate oxide (BGO) crystal, all read out by a single photomultiplier tube (PMT). A side view of a single PDC is shown in Figure 2.2.2. From the top, the first part of the PDC is a hollow slow plastic scintillator followed by a fast plastic scintillator, a BGO crystal and a photomultiplier tube. The purpose of the slow scintillator is to collimate incoming photons as well as veto events that are not fully contained. In the fast scintillator, which is the active detector, photons will interact with the scintillator through Compton scattering and subsequent photoelectric absorption. The BGO crystal acts as a veto for any events not fully contained in the fast scintillator as well as events caused by photons entering from the bottom.
Both of the plastic scintillators were manufactured by ELJEN Technology [31]. The slow scintillator has the designation EJ-240, with a scintillation decay time of 285 ns [32], while the fast is designated EJ-204, which has a decay time of 2 ns [33]. The difference in decay times allows for discrimination between events in the slow scintillator or BGO crystal and events in the fast scintillator. All components of the PDC are glued together using an optically transparent glue. A thin reflective material, VM2000 [34], is wrapped around both scintillators in order to decrease scintillation light loss. Two thin layers of tin and lead surround the slow scintillator. The tin stops the characteristic X-rays from lead, and the lead provides additional collimation of incident photons. The BGO crystal, manufactured by Nikolaev Institute of Inorganic Chemistry [35], is coated in a thin layer of barium sulphate, to enhance the internal reflectivity.

The PDCs are hexagonal in shape, to allow for a tight packing fraction, and are arranged in a honeycomb array, for an easily scalable design. This can be seen in Figure 2.2.3

![Figure 2.2.1: A schematic overview of the cross section of the PoGOLite Pathfinder polarimeter. Figure from [1]](image)
Figure 2.2.2: A side view cross section of a single PDC.

Figure 2.2.3: The geometry of the polarimeter array.
2.2.2 Background Rejection

While the PDC design offers some intrinsic background rejection, additional anti-coincidence BGO crystals and a polyethylene shield are employed to provide both active and passive shielding. The side anti coincidence shield (SAS) surrounds the polarimeter, as shown in Figure 2.2.3, and consists of 30 segmented BGO crystals read out by a PMT. These primarily prevent photons entering from the sides to register as valid events. The polyethylene shield is 15 cm thick and is designed to thermalize (decelerate) or stop incoming neutrons from entering the detector. It is predicted that non-thermal neutrons scattering between the fast scintillators is the predominant background [27]. To determine the amount of background caused by neutrons entering the detector, a small neutron scintillator of similar design as the PDC is employed. It consists of two BGO crystals with a layer of LiCaAlF$_6$ connected to a PMT.

2.2.3 Event Selection

Valid events are identified by a Compton scattering event in a fast scintillator followed by a photoelectric absorption in a neighboring fast scintillator, while none of the SAS, slow scintillators and bottom BGO crystal record a simultaneous event.

The distinction between hits in the scintillators is made possible by the difference in decay times. A waveform discrimination of the PMT signals, such as the one seen in Figure 2.2.4, shows a clear discrimination. Compton scattering and photoelectric absorption deposit different amounts of energy, and as the PMT signal from the scintillators is proportional to the energy deposited, there will be a difference between the two events. Figure 2.2.5 shows some possible events.

Figure 2.2.4: Fast and slow scintillator output in a single histogram. A clear distinction between the two can be seen. Taken from [11].
Figure 2.2.5: A few possible events that are expected to occur. Event 1 (a candidate event): a photon entering the slow scintillator perpendicularly and scattering in the fast scintillator followed by an absorption. Such an event would be stored. Event 2: a photon entering from outside the FoV of the instrument. Based only on the fast scintillator this would record as an event, but the slow scintillators will record a simultaneous event and this would be determined to be a false event. Event 3: a side entering photon, for which the SAS shield will record the hits and identify this as a false event. Event 4: a back entering photon recorded as a false event by the BGO crystal.

2.2.4 Data Processing

All of the electronics for signal readout are housed just beneath the PMTs. It consists of 12 Flash Digital-to-Analog (FADC) boards, a Digital Input-Output board (DIO), a SpaceCube (SpC) component and 2 router boards. Signal data from candidate events as recorded by the FADC boards are stored on a PC. The FADC boards have 8 channels each, for a total of 96 channels. The 61 PDC PMTs are read out by 8 FADC boards, and the remaining boards are connected to the SAS units and the neutron detector. Trigger logic is handled by the DIO board. It checks that all set trigger requirements are met and if so, signals the FADC boards to store the event data. The SpaceCube component
converts signals between a standard network interface (TCP/IP) and the SpaceWire [36] protocol. A connection scheme is shown in Figure 2.2.6.

![Diagram showing the electronic readout system for the polarimeter](image)

Figure 2.2.6: The electronic readout system for the polarimeter. The 12 FADC boards are connected to the PMTs, which in turn are connected through the 2 router boards to the DIO and SpaceCube. Candidate event data, as determined by the DIO board, are transferred through the router and SpaceCube (which converts the SpaceWire signal to a TCP/IP signal) to a PC for storage. Taken from [11]

### 2.3 Control and Data Acquisition

The PoGOLite Pathfinder will, due to restrictions in connection bandwidth, need to operate autonomously for the main portion of the flight. This is achieved by software installed on the devices comprising the payload control system (PCS). They are: two Linux based PC104 computers, each with a separate ground connection, a main processing board (MPB), also known as the payload control unit (PCU), and two interface utility boards (IUB). These are housed in the PCU box. As a failsafe, a third PC104 computer, nearly identical to the other two, is housed in a separate black box. The ACS, polarimeter and auxiliary systems are all subordinate to the PCS. It is the main control system, through which all communication with the ground is handled. The following section describes the main components of the PCS and their function.

#### 2.3.1 PC104 Computers

There are in total three PC104 computers, all of which contain nearly the same programming. During operation, one of the PC104 computers in the PCU box will serve as the main computer while the other serves as storage. In case the main computer fails, the other PC104 computer can perform the same function. An additional PC104 computer is housed in a separate black box. The main reason for the black box computer is as redundant storage, so that no scientific data are lost if the other PC104 computers are
It can additionally assume the functions of one, or both, of the other PC104 computers in case they should fail. However, it lacks its own ground connection, though it can use the ground connection in the ACS.

### 2.3.2 Payload Control Unit

The main component of the PCU is a MPB containing a 100 MHz AMD Elan SC520 processor. It is attached to the two IUBs and to the attitude control unit (ACU, described in section 3.4) through high speed RS422 connections. The PCU contains a real time operating system written by Miranda Jackson. It is designed to read off and gather all relevant information from the subordinate systems and store these as output signals, while also providing an interface through which input signals can be set. Based on the values and changes of these signals, it can also execute some functions.

### 2.3.3 Control Hierarchy

Control of the payload is ultimately performed by the main PC104 computer. This is where all the software and scripts for autonomous control are installed. All interaction by a user with the payload is handled by the main control software and scripts. The main computer is in turn connected to the PCU through which signals can be both read off and set. The full control hierarchy can be seen in Figure 2.4.1. The main control software accepts input from the user in the form of 3-character text commands corresponding to predefined operating modes for the polarimeter and the ACS. These include:

- **Polarimeter modes:**
  - Power Save/Startup - Default mode, switched off.
  - Initialize - Systems powered on and diagnosed.
  - Ready - Ready for data acquisition.
  - Acquisition - Acquiring data.

- **ACS modes:**
  - Startup - Default mode
  - Initialize - Systems powered on and calibrated.
  - Stow stabilized - Instrument locked at specified azimuth and 90° elevation angle.
  - Stow unstabilized - Instrument locked at 90° elevation angle.
  - Exercise - Runs systems to prevent ice buildup.
  - No control - Powered down.
  - Azimuth/Elevation pointing - Accepts input in the form of azimuth and elevation angles.
  - Right ascension/declination pointing - Accepts input in the form of right ascension and declination coordinates of a target.
During flight, this system can determine the optimum target based on predefined variables, point to it in a safe and controlled manor, detect the target once it is in view of the instrument and start data acquisition, without any user input. The control system and software are described in more detail in [37].

2.4 Launch

The PoGOLite Pathfinder will launch from Esrange in Kiruna, Sweden and has a launch window starting July 1st. A July launch was decided based on several criteria that needed to be fulfilled:

- That wind conditions in the upper stratosphere enable a long duration flight. During July, western winds will carry the gondola to Victoria Island after $\sim 5$ days, or if a full circumpolar flight is possible, back to Sweden after $\sim 20$ days.

- That the angular separation between the Crab and the Sun is larger than $15^\circ$. This condition is fulfilled after July 1st.

- Calm ground weather conditions, allowing for a safe launch. Summer launches are generally easier, as weather conditions are milder.

The main observation target of the pathfinder mission is the Crab. Should the Crab be unsuited for observation (too low in the sky or too close to the Sun), the secondary target is Cygnus X-1. Should neither of these two targets be possible to view, the polarimeter will resort mainly to background and performance studies. In case a target of opportunity appears, mainly gamma-ray bursts, this may take priority.

The projected flight path of the PoGOLite Pathfinder is shown in Figure 2.4.2

Figure 2.4.1: The control hierarchy of the PoGOLite Pathfinder. All systems are subordinate to the main PC104 computer, and connected as shown by the arrows. Taken from [37]
2.4.1 Ground Control

Communications with the instrument are handled through a Swedish Space Corporation (SSC) [38] developed system called E-Link [39], allowing for a data transfer rate of up to 2 Mb/s. It functions only while the instrument is in line of sight, which is expected to be $\sim 500$ km. For the remainder, and most part, of the mission, Iridium satellite communications will be used. They have a significantly lower data transfer rate, 1 kb/s. For redundancy, two Iridium data links are used. This low data transfer rate means that in planning the PoGOLite Pathfinder mission, the following criteria had to be met:

- The instrument will need to operate autonomously for most of the mission.
- All scientific data need to be stored locally on board the gondola.
- A minimal amount of information can be extracted during flight.
- To ensure that valuable scientific data are acquired, some pre-analysis of data needs to be performed and evaluated locally, and communicated back through the Iridium link.
Chapter 3

Attitude Control System

The attitude control system (ACS) controls the pointing of the PoGOLite polarimeter by means of actuators and motors. The ACS utilizes magnetometers, gyroscopes and a differential global positioning system (GPS) supported by two star trackers for absolute attitude information. The ACS, apart from the two star trackers, was built by DST Control [40]. Figure 3.0.1 shows a close up of the gondola, in which all parts of the ACS are marked.

Figure 3.0.1: A close up the PoGOLite Pathfinder with the components marked. Figure taken from [37].

Finding, locking onto and tracking an astrophysical object are the main purposes of the ACS. The purpose of this thesis is to determine how reliably and accurately it performs this function. This chapter describes the components of the ACS and its operation.
3.1 Physical Pointing

To provide the desired modes of rotation the polarimeter is controlled by three actuator units, the azimuth actuator unit (AAU), the elevation actuator unit (EAU) and the roll actuator unit (RAU). These constitute a three axis gimbal system providing a full range of motion for the polarimeter. The three units and their modes of rotation are shown in Figure 3.1.1. A description of each of these units is given below:

- **Azimuth Actuator Unit (AAU)**

  The AAU changes the azimuth angle (the angle between a reference vector (North) and the direction vector (Gondola)) of the gondola by means of a flywheel and two torque motors. It also serves as the physical connection between the flight train (balloon) and the gondola. During a rotation operation, the energy from the acceleration of the gondola is stored as angular momentum in a 50 kg counteracting flywheel. The flywheel reset motor (FRM) resets the angular momentum stored in the flywheel (by transferring it to the balloon). It is a direct drive torque motor of brush-less three phase type with an integrated digital temperature sensor. Azimuthal torque is created by the azimuth actuator motor (AAM). The AAM is a motor of the same type as the FRM. The flywheel reset encoder (FRE) is used to determine the speed of the flywheel with respect to the gondola and provide feedback to the FRM. It is an incremental encoder based on a magnetic read-head and a magnetic scale drum. A similar encoder, the azimuth actuator encoder (AAE), provides the same support to the AAU, measuring the speed of the gondola and the azimuth angle.

- **Elevation Actuator Unit (EAU)**
The EAU controls the elevation angle of the polarimeter. The elevation angle corresponds to the altitude angle (the angle between a star and the horizontal plane) of the instrument. The torque is produced by the elevation actuator motor (EAM). It is a motor of the same type as the FRM and AAM. As in the AAU, a magnetic incremental encoder, the elevation actuator encoder (EAE) measures the azimuth angle and provides commutation with the EAM.

- **Roll Actuator Unit (RAU)**

  The RAU controls the roll angle of the polarimeter by means of a brush-less geared servomotor, the roll actuator motor (RAM). The roll angle encoder (RAE) measures the roll angle and provides commutation to the RAM. It is an incremental magnetic encoder similar to the encoders in the AAU and the EAU; however, a flexible scale tape attached directly to the polarimeter tube serves as a magnetic drum.

The angular resolution of the AAE, EAE and RAE is 0.0044°.

### 3.2 Attitude Determination

A differential GPS solution together with gyroscopes and magnetometers provides absolute attitude information. Tracking feedback from one of two star trackers is used to increase the accuracy. Both star trackers will be described in detail in Section 3.3.

The two GPS receivers that make up the differential GPS are mounted on the boom approximately 10 meters apart. Positional (latitude, longitude and elevation) information is extracted from the GPS receivers. Heading information is acquired by tagging both signals and comparing them. This provides a means of measuring the heading by simple geometry. Heading and position information is determined at a rate of 10 Hz and an accuracy of at least 0.05°.

There are two gyroscopes, the main inertial sensor unit (ISUM), based on fibre optic gyros and high-performance micro-electro-mechanical (MEMS) accelerometers, and the backup inertial sensor unit (ISUB), based on lower performing MEMS gyros and accelerometers.

The magnetometer is a three axis magnetometer that provides less accurate, but reliable, gondola heading estimates as a redundancy in cases when the differential GPS malfunctions. The main reason for the differential GPS to give erroneous reading is reflections of the GPS signal off of the flight train.

### 3.3 Star Trackers

The pointing capabilities of the ACS are enhanced by the use of two star trackers mounted parallel to the polarimeter. Both are similar in design (Figure 3.4.1 shows the star tracker design), and are based on a CCD camera along with a custom made baffle system, optics tuned for optical light and a computer, but they have different Field Of View (FOV). The larger star tracker, the STM, as seen in Figure 3.0.1 has a smaller FOV, 2.6° x 1.9° and the smaller, the STR, has a larger FOV, 5° x 3.7°. Stars down tenth magnitude [41] can be detected by the star trackers.
The purpose of the star trackers is to detect, identify, lock onto and continuously track a star. Once a star tracker is locked onto a target, it will feed information back to the ACS to ensure that the polarimeter stays on target. This information comes as a 2-dimensional (x/y) tracking offset which describe the distance, as seen by the CCD camera, between the current pointing and the tracked star. If a target is not luminous enough to be tracked directly by one of the star trackers, which is the case for both main targets of the Pathfinder mission, a nearby star is chosen (before the mission) to be the object that is tracked. In these instances, the star tracker will not strive to center on the star, but rather on the point predefined to be the actual target. So the tracking offsets will by default be non-zero to account for the distance between the target and star. Both star trackers work independently of each other, and it is the user that determines which star tracker is used.

3.4 ACS Operation

The input and output of the EAU, AAU, RAU, differential GPS, magnetometers, gyros and one of the star trackers are monitored and controlled by the attitude control unit (ACU). The ACU is a MPB of similar design as the PCU and is connected to multiple IUBs. The ACU can additionally perform calculations to determine the position of the gondola, based on the GPS signals, as well as perform celestial coordinate transformations. It is connected through a high-speed RS422 link to the Payload Control Unit (PCU), which together with the main PC104 computer makes up the Payload Control System (PCS). Through the PCS, the user can both set and read the parameters of the ACU and control the mode of operation of the ACS.

The main mode of operation during acquisition of scientific data is right ascension (RA)/declination (Dec) pointing, in which the user provides input in the form of RA/Dec coordinates and the ACS transforms this to azimuth and elevation angles for the polarimeter. Once a target has been found and identified using the star tracker cameras, a command to track on that target using either of the star trackers is issued automatically. Once this mode has been initialized, feedback from the star tracker is prioritized by the ACS above all other signals and used to maintain a steady pointing.

During most of the flight, the PCS will operate in autonomous mode, issuing pre-programmed commands to the ACS (and all other subordinate systems). In autonomous operation for normal data acquisition, the instrument makes cycles of four five-minute measurements of a target and its background, chosen based on current position and a priority list. The purpose of the background readings is to provide a modulation curve of the unpolarized background to ensure a difference between it and the polarized source.

To determine the pointing accuracy of the ACS, the logged signals shared by the ACS, through the PCS, can be analyzed offline.
Figure 3.4.1: An image showing the design of one of the star trackers, the STM, without housing and baffle system. Taken from [41]
Chapter 4

ACS Performance

The performance of the ACS is evaluated based on four separate data sets, acquired on four separate occasions, and under disparate conditions. The first set of data comes from the terminated 2011 flight, the second comes from Sun tracking tests performed in July of 2012, and the third and fourth are based on indoor tracking tests performed during February and March, 2013. A testing procedure (a description of which is included in Appendix A) designed to specifically test the capabilities of the ACS was formulated and planned for the beginning of 2013. Due to unfortunate weather conditions and time constraints, it was not possible to fully perform these tests.

This chapter will specify when and under what conditions the data was acquired and the following analysis that was performed.

4.1 Data

4.1.1 Flight, 2011

During the summer of 2011, the PoGOLite Pathfinder had a launch window starting July 1st and ending on July 31st. On the 7th of July, after several days of inopportune weather conditions, the PoGOLite Pathfinder had its first successful launch. Several hours into the launch, after a seemingly normal climb to $\sim 35$ km, the balloon started to drop in altitude. It was suggested that the balloon was torn (later found to have happened during launch, due to sudden wind changes [27]), thus losing pressure and lift. The decision to terminate the PoGOLite Pathfinder mission was made soon thereafter. By means of a small explosive charge, the gondola was separated from the balloon. The gondola was later found crashed in the mountains near Nikkaluokta, Sweden. Most of the components were unharmed, even though the on-board g-shock sensors had picked up an impact in excess of 25g [27]. Figure 4.1.1 shows the launch of the balloon and the aftermath of the crash.

During the ascent, the ACS was put in exercise mode, in which it constantly runs all the motors to prevent freezing, as temperatures can reach well below $0^\circ$ C during the climb through the atmosphere. Once the balloon had reached a height of 30 km, the ACS was activated and calibration using previously chosen guide stars commenced. The calibration was not completed entirely, but was interrupted once it was discovered
that the balloon was leaking. Before cutting the balloon down, the final 30 minutes of the flight were spent pointing at Cygnus X-1. The data collected following the ACS activation constitute the basis for the analysis of the ACS performance during the 2011 flight. Together, these constitute \( \sim 2.5 \) hours of data, of which \( \sim 60 \) minutes are used for the analysis.

![Figure 4.1.1](image)

Figure 4.1.1: Top: A picture taken of the gondola configuration before the launch in 2011. Credit: Mark Pearce, KTH. Middle: A picture taken during the launch of the PoGOLite Pathfinder on the 7th of July. Credit: Swedish Space Corporation. Bottom: A picture of the gondola as it was found after the crash. Credit: Mark Pearce, KTH
4.1.2 Sun Tracking, 2012

After the 2011 launch was cut short due to a balloon malfunction, the majority of the payload was undamaged so a new launch window was set for July 2012. Prior to the 2012 launch, Sun tracking tests were performed, to test both the tracking capabilities of the ACS as well as functionality of the Sun shields. These shields are added to protect the star tracker cameras from a potentially harmful sudden increase of flux resulting from pointing them too close or at the Sun. The Sun shields have a small aperture covered by a thin mylar filter and are controlled by an independent light-meter which can deploy them automatically. Apart from adding another\(^1\) layer of protection for the star tracker cameras, they also provide the opportunity to track on the Sun. However, two difficulties arise when tracking on the Sun: firstly, the star tracking software looks for and locks onto a point source, not something with a large angular extent such as the Sun, and secondly, the Sun’s coordinates change over the course of a day so they often need to be reset.

The tests were performed on the 8th of July and the gondola was hung from a wooden frame at Esrange. Wood was chosen for the frame to reduce the chance of GPS signal reflections. The frame was originally designed by Stefan Rydström and then built by Esrange personnel. It can be seen in Figure 4.1.2

The data set chosen to perform analysis on was about \(\sim 60\) minutes of observation of the Sun.

![Figure 4.1.2: The wooden hang frame from which the gondola is hung for testing. Credit: Miranda Jackson](image)

4.1.3 Indoor Testing, 2013

Tests dedicated to specifically characterize the performance of the ACS were planned to be performed in the beginning of 2013 at Esrange. Originally, the tests were planned with the gondola hung from the wooden frame. Unfortunately, due to bad weather during the time alloted to perform these tests, this was not possible. However, two separate tests

\(^1\)The automation software goes to great lengths to avoid pointing at the Sun
were made with the gondola hanging inside the assembly building. This situation is less ideal, as the GPS signal and magnetometers do not work properly indoors.

In the first of these tests, performed on February 13th, an ordinary desk lamp was used to simulate a star. It was placed as far away as possible to minimize its angular extent as seen by the star tracker and for better focus. Once it had been placed, the instrument was pointed manually by inputting coordinates until the lamp was seen in the star tracker cameras (displayed at a terminal connected to the ACS). The star trackers locked on fairly well, even though the lamp was much larger in angular extent than a star would be, and emitted light isotropically. Due to having a stationary target, active tracking on a moving target could not be evaluated. Only the functionality of the system and its stability whilst locked onto a source could be determined. Due to a large amount of moving parts (motors, etc) the gondola will generate momentum and the ACS needs to counteract these movements to remain on target. These minute corrections will show up as an oscillation in the pointing measured over time.

In the second test, performed on March 15th, the instrument was pointed at stars through the large assembly building doorway. Through manually inputting coordinates, a suitably bright star was found through the star tracker cameras. A command was sent to the ACS to actively track on that star. The objective was to test the tracking capabilities of the ACS and determine the pointing accuracy.

Both of these tests suffered from problems with the GPS signal and with the tracking software, which reduced the amount of data recovered. From each of these occasions ∼ 20 minutes of data were used for analysis.

4.2 Analysis

For all the above-mentioned data sets, an analysis was performed to evaluate the pointing accuracy based on log-files of the ACS output and input. The log-files contain a multitude of information from all the various systems subordinate to the PCS. There are three types of log-files, one fast (FAST) that records values four times every second and two slow files (HOUS 1 and HOUS 2) that record values every ten seconds. They are all time tagged using the GPS, which is used to synchronize between the different files.

The parameters in the log-files pertinent to this analysis were:

- Reported four times every second:
  - GPS time - Time in seconds counted by the GPS from a reference date and time. Can be converted to a time and date.
  - Azimuth/Elevation - The current viewing angles of the polarimeter, as reported by the ACS.
  - Latitude/Longitude - The current position of the gondola, from the differential GPS.
  - Tracking offset x/y - The x/y offset between the star being tracked by one of the star trackers and the current target, from the star tracker that is being used.

- Reported every ten seconds:
– Target number - The current target number, which is compared to a target list with coordinates of the targets and the tracking offsets\(^2\), where for example 1 = The Crab and 2 = Cygnus X-1. (A complete list of targets and their corresponding numbers is included in Appendix B)

– Pointing status - A number describing which star tracker is being used, whether the GPS has a clear signal or not, and which star tracker, if any is being used.

A program written by the author using the cross platform programming language, Python [42], was developed specially for the analysis of the data. Due to some variations between the format of the log-files produced at different times, the originally developed program had to be slightly modified for each of the three (2011, 2012 and 2013) occasions to accommodate the differences.

The program is designed to first read the HOUS 2 file, in which it reads the pointing status and target number to determine if there is any active tracking. If there is, the corresponding FAST files are read, specifically the position of the gondola. Using the time and position as reported in the FAST file, the program calculates the current position of the target in azimuth and altitude (the right ascension and declination coordinates for the current target are extracted from the target list). Calculating the azimuth and altitude is done by standard formulae and the following algorithm [43]:

1. Get the Greenwich Mean Sidereal Time, \( GMST \) by:

\[
GMST = 18.697374558 + 24.06570982441908 * D
\]

where \( D \) is the days, and fraction of days since 12:00 (UT), January 1st, 2000.

2. Now the Local Sidereal Time, \( LST \):

\[
LST = GMST + \lambda
\]

where \( \lambda \) is the longitude.

3. Then the Hour Angle, \( HA \):

\[
HA = LST - \alpha
\]

where \( \alpha \) is the right ascension.

4. Now calculate the altitude, \( A \):

\[
\sin A = \sin \phi \sin \delta + \cos \phi \cos \delta \cos HA
\]

where \( A \) is the altitude, \( \phi \) is the latitude and \( \delta \) the declination.

5. And finally the azimuth, \( Az \):

\[
\cos Az = \frac{\sin \delta - \sin A \sin \phi}{\cos A \cos \phi}
\]

\(^2\)These are only \( \neq 0 \) if the star trackers cannot see this object, and instead tracks on a nearby star.
The following two quantities are then defined:

- \( D \), the difference between the calculated and reported values of the azimuth and altitude, the ACS offset:
  \[
  D_{Az/Alt} = Az/Alt_{Reported} - Az/Alt_{Calculated}
  \]  
  (4.2.6)

- \( DT \), the difference between the tracking offsets, \( T_{x/y} \), and \( D_{Az/Alt} \):
  \[
  DT_{Az/Alt} = D_{Az/Alt} - T_{x/y}
  \]  
  (4.2.7)

The interpretation of the quantity \( D \) is that it represents the offset between the point that the polarimeter is pointed at, based on ACS readings and the actual position of the point where the target actually is. Any deviation from 0 of the mean of this quantity might indicate that there is a problem in the calibration. In fact, this corresponds to the same quantity that is reported by the star trackers based on different measurements. The quantity \( DT \) could then be regarded as a measure of the calibration of the ACS and star trackers. It should at all times be 0 for a perfectly synchronized ACS and star tracker. It can also be used to determine the accuracy of the ACS readings of azimuth and altitude. The error used in \( D \) is based on the error of the ACS readings, as the error from the calculations in Equation 4.2.1 to 4.2.7 is much smaller. The error is approximately determined to be 0.01° and 0.005° for azimuth and altitude respectively. As for the tracking offsets, these have an error that is in the order of 0.00005° (based on how the tracking offset values change, as reported from the star trackers) and most likely even smaller.

The three quantities, \( D \), \( T \) and \( DT \) are presented in two graphs, one for azimuth and one for altitude (in the legend on the graph ACS offset corresponds to \( D \), tracking offset to \( T \) and difference to \( DT \)). The means and standard deviations of these three are also calculated and shown in a table. Additionally, the full width half maximum (FWHM) can be calculated as [44]:

\[
2\sqrt{2\ln 2}\sigma \approx 2.3548\sigma
\]  
(4.2.8)

where \( \sigma \) is the standard deviation. This formula is valid for normally distributed quantities, which is an assumption made for all three quantities, based on distribution plots.

The FWHM of the distribution of \( T \) will be used as a representation of the accuracy of the pointing.

It is important to note that for all tests, even though data were extracted for long periods of time, use is made of the data corresponding only to situations in which the instrument is actively tracking and is not suffering from signal loss (GPS or other) or is going through a coordinate (target) change.
Chapter 5

Results

In this section, all the results following the analysis of the four data sets are presented. For each of the data sets, the graphs produced according to Section 4.2 showing all three quantities for azimuth (top) and altitude (bottom) are shown in two figures, one of which is for a larger part of the data and the other of which is zoomed in on a small section. It is important to note that neither of the figures represents the full data sets, as nothing is discernible for such a figure, although the full data sets are used for calculations of the quantities. A third figure shows the distribution (for the full data set) of $T$ for both azimuth and altitude. Lastly, a table of the calculated means, standard deviations and the FWHM is presented.

5.1 Flight, 2011

The following results, following the analysis detailed in Section 4.2, pertain to the 2011 flight. Figure 5.1.1 shows the evolution of $D$ (the ACS offset: the difference between the calculated and reported values of azimuth and altitude), $T$ (the tracking offset: the offset between the target and the pointing direction as determined by the star trackers) and $DT$ (the difference between $D$ and $T$) over time for $\sim 150$ seconds of data while Figure 5.1.2 shows $\sim 20$ seconds of the same data. The distribution of $T$, based on the full $\sim 60$ minutes of data, is shown in Figure 5.1.3. The values for the mean, standard deviation and FWHM, shown in 5.1.1, are based on the full $\sim 60$ minutes of data.

Based on Figure 5.1.1, it is possible to see a periodic behavior in the offsets. This is due to the twist and torsions of the flight train and gondola from outer forces. This leads to continuous corrections in the pointing direction. The timescale for the corrections shown in Figure 5.1.1 are on average in the order of $\sim 6.5$ seconds.

By studying Figure 5.1.2, it is possible to see that both offsets intersect (or are within the error) at most points, which is to be expected for a calibrated instrument. Figure 5.1.3 shows the distribution of $T$. It is quite clear that the assumption of that these are normally distributed was warranted.

The FWHM derived are $0.07111^\circ$ and $0.02819^\circ$ for the azimuth and altitude respectively. These represent the mean pointing accuracies during the 2011 flight.

The mean of $DT$ is slightly offset from zero (by $0.00737^\circ$), which can suggest that the calibration is not optimal, leading to a slight difference between the point that the po-
larimeter is viewing and the actual point where the target is. As was previously mentioned in 4.1.1, the calibration was not entirely completed. This fact is most likely responsible for the tiny offset. Such a tiny offset would have only a small impact on the quality of the scientific data.

Figure 5.1.1: The evolution over time in seconds of $D$ (ACS offset, green), $T$ (Tracking offset, magenta) and $DT$ (Difference, cyan) in degrees. Based on data from the 2011 flight.

Figure 5.1.2: The same as Figure 5.1.1, but for a small section of data.
5.2 Sun Tracking, 2012

The following results, following the analysis detailed in Section 4.2, pertain to the Sun tracking tests performed in 2012. Figure 5.2.1 shows the evolution of $D$, $T$ and $DT$ over time for $\sim 60$ seconds of data while Figure 5.2.2 shows $\sim 5$ seconds of the same data. The distribution of $T$, based on the full $\sim 60$ minutes of data, is shown in Figure 5.2.3. The values for the mean, standard deviation and FWHM, shown in 5.2.1, are based on the full $\sim 60$ minutes of data.

From Figure 5.2.1, it is immediately evident that the periodic behavior in the offsets has a much shorter period, in the order of $\sim 1$ second. The difference is not unexpected, as the conditions at high altitudes are quite different from ground-based measurements, and this period depends strongly on the current weather conditions. A competing effect might be caused by the difference in length of the flight trains. In ground test situations, the flight train is just a few meters ($\sim 4$), whereas during flight, the flight train is 300 meters. For a simple pendulum, the ratio in the period for a 4 meter pendulum and a 300 meter pendulum is 10%. This is of a comparable order to the ratio of the two periods.
which is 6.5%. It is likely that the difference depends on a combination of both of these effects.

If both the offsets are studied in detail in Figure 5.2.2, there are quite a few points where the ACS offset and tracking offset do not intersect. As the Sun is such a large object in the view of the star trackers, it can be suggested that the star trackers have a hard time locking onto a specific point. Instead, the star trackers might periodically lock onto slightly different points. Such an effect could show up as these small differences between the points of the ACS offset and tracking offset. The effect seems larger in altitude than in azimuth. The reason for this can be attributed to the lower accuracy of azimuth readings (∼0.01) compared with altitude readings (∼0.005) in the ACS.

The distribution of $T$ is seen in Figure 5.2.3 and the FWHM of these distributions are 0.08472° and 0.00974°, these are the mean pointing accuracies based on the 2012 Sun tracking tests.

---

Figure 5.2.1: The evolution over time in seconds of $D$ (ACS offset, green), $T$ (Tracking offset, magenta) and $DT$ (Difference, cyan) in degrees. Based on data from the Sun tracking tests.
Figure 5.2.2: The same as Figure 5.2.1, but for a small section of the data. Based on data from Sun tracking tests.

Figure 5.2.3: The distribution of $T$, in degrees, for the full data set. Based on $\sim$60 minutes of data from the Sun tracking tests.
Table 5.2.1: Calculated values for the means ($\mu$), standard deviation ($\sigma$) and full width half maximum. Based on ~60 minutes of data from the Sun tracking tests

<table>
<thead>
<tr>
<th></th>
<th>$\mu$</th>
<th>$\sigma$</th>
<th>FWHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{Az}$</td>
<td>0.00332</td>
<td>0.03620</td>
<td>0.08535</td>
</tr>
<tr>
<td>$T_{Az}$</td>
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<td>0.03500</td>
<td>0.08472</td>
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<tr>
<td>$DT_{Az}$</td>
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<td>0.00243</td>
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<tr>
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<td>0.00974</td>
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<td>$DT_{Alt}$</td>
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<td>0.00181</td>
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</table>

5.3 Indoor, 2013

The following results, following the analysis detailed in Section 4.2, pertain to the indoor tests performed in 2013. Figures 5.3.1 and 5.3.4 shows the evolution of $D$, $T$ and $DT$ over time for ~90 and ~250 seconds of data respectively. Figures 5.3.2 and 5.3.5 show ~15 and ~10 seconds of the same data respectively. The distribution of $T$, based on ~20 minutes of data, for both tests, is shown in Figure 5.3.3 and 5.3.6. The values for the mean, standard deviation and FWHM, shown in 5.2.1, are based on the full ~60 minutes of data.

The plots shown in Figure 5.3.1 and Figure 5.3.4 are quite different to the previous plots, especially for the altitude. In an indoor setting, there are much less external influences, such as wind or pressure changes. Under such conditions, the gondola is much more stable. It can be inferred from the plots of the altitude that it is extremely stable in altitude. The corrections made to the altitude angle are on the lowest possible level, which is the resolution of the encoder (0.005°). The situation is quite different for the azimuth. The period of the offsets is much longer, owing to close to no wind; however, the accuracy is less than expected. This is a result of being indoors, where the azimuthal ACS readings based on the GPS signal are not reliable at all. These readings are then based on other, less accurate, readings.

The distributions in Figure 5.3.3 and Figure 5.3.6 look quite different as well, with the altitude distributions consisting simply of a few peaks. This is a consequence of what was discussed above, that the corrections by the ACS, in both angles, are discrete with the resolution of the encoders, which is 0.005°.

The pointing accuracies, based on the FWHM for the azimuth/altitude, are in these cases 0.07955°/0.00860° and 0.06625°/0.01872° for the indoor lamp tracking and indoor star tracking tests respectively.
Figure 5.3.1: The evolution over time in seconds of $D$ (ACS offset, green), $T$ (Tracking offset, magenta) and $DT$ (Difference, cyan) in degrees. Based on data from indoor tests with a stationary desk light as a target.

Figure 5.3.2: The same as Figure 5.3.1, but for a small section of data. Based on data from indoor tests with a stationary desk light as a target.
Figure 5.3.3: The distribution of $T$, in degrees, for the full data set. Based on ~20 minutes of data from indoor tests with a stationary desk light as a target.

Table 5.3.1: Calculated values for the means ($\mu$), standard deviation ($\sigma$) and full width half maximum. Based on ~20 minutes of data from indoor tests with a stationary desk light as a target.
Figure 5.3.4: The evolution over time in seconds of $D$ (ACS offset, green), $T$ (Tracking offset, magenta) and $DT$ (Difference, cyan) in degrees. Based on data from indoor tests with the instrument pointed at stars through the assembly hall doorway.

Figure 5.3.5: The same as Figure 5.3.4, but for a small section of data. Based on data from indoor tests with the instrument pointed at stars through the assembly hall doorway.
Figure 5.3.6: The distribution of $T$, in degrees, for the full data set. Based on ~20 minutes of data from indoor tests with the instrument pointed at stars through the assembly hall doorway.

Table 5.3.2: Calculated values for the means ($\mu$), standard deviation ($\sigma$) and full width half maximum. Based on ~20 minutes of data from indoor tests with the instrument pointed at stars through the assembly hall doorway.

<table>
<thead>
<tr>
<th></th>
<th>$\mu$</th>
<th>$\sigma$</th>
<th>FWHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{Az}$</td>
<td>0.00127</td>
<td>0.04259</td>
<td>0.10029</td>
</tr>
<tr>
<td>$T_{Az}$</td>
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<td>$T_{Alt}$</td>
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<tr>
<td>$DT_{Alt}$</td>
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<td>0.04489</td>
<td>0.10571</td>
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</table>

5.4 Summary

A summary of the results of the pointing accuracies (FWHM) is shown in table 5.4.1.

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<tr>
<th>Data set</th>
<th>Azimuth</th>
<th>Altitude</th>
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<tr>
<td>2011 flight</td>
<td>0.07111</td>
<td>0.02819</td>
</tr>
<tr>
<td>Sun tracking</td>
<td>0.08472</td>
<td>0.00974</td>
</tr>
<tr>
<td>Indoor (lamp)</td>
<td>0.07955</td>
<td>0.00860</td>
</tr>
<tr>
<td>Indoor (star)</td>
<td>0.06625</td>
<td>0.01872</td>
</tr>
<tr>
<td>Mean</td>
<td>0.0755</td>
<td>0.0163</td>
</tr>
</tbody>
</table>

Table 5.4.1: The FWHM for azimuth and altitude (in degrees) of $T$ from all data sets including a total mean FWHM.
Chapter 6

Discussion and Conclusions

The aim of this thesis consisted of evaluating the performance of the ACS, the system controlling the pointing of the polarimeter of the PoGOLite Pathfinder. Initially, several features and subsystems of the ACS were aimed to be tested and characterized. A test procedure was developed for this purpose and the tests were planned to be performed during February and March, 2013. To imitate the expected conditions during flight, the gondola was to be hung outside, from a specially designed wooden frame at night, with clear skies and no substantial wind. Due to unfortunate weather circumstances, these conditions did not arise during the time allotted for these tests.

Indoor testing methods were employed instead on two separate occasions, described in Section 4.1.3, from which data were acquired and analyzed. The results were presented in Section 5.3. This testing method has limitations which precluded the chance to perform all the tests specified in the procedure. The focus then shifted to determine the overall pointing accuracy of the ACS, as individual evaluation of the components of the ACS, such as the star trackers, was not possible due to lack of specific data.

To increase the statistics underlying the performance evaluation, old data, from the terminated 2011 flight and sun tracking tests performed in 2012, were also analyzed. The results presented in Chapter 5 indicate a mean pointing accuracy of 0.0755° and 0.0163° for azimuth and altitude respectively. It is possible to argue that only the results from the 2011 flight should be considered as a true indicator of the accuracy, and these were calculated to be 0.07111° and 0.02819°, for azimuth and altitude respectively. However, since 2011, there has been a change in the design of the gondola, in that the solar panels which were previously beneath the gondola now extend downwards from the boom. This configuration change could have a negative impact on the stability of the pointing, as it can possibly be more susceptible to wind. Based on the sun tracking tests which had the new configuration, there was a slight decline in the accuracy of the azimuth pointing (0.08472°), whereas there was a significant improvement in the altitude accuracy (0.00974°). These might not compare directly, as they were not acquired under the same circumstances, but they do hint that it can have a negative (positive) effect on the azimuth (altitude) accuracy.

This pointing accuracy, from both individual tests and as a whole, is well within the target accuracy, which was set at 0.1° and well within the required accuracy to measure a minimum detectable polarization of 10% for a 1 Crab source, which was determined to
be 0.3° [41]. Furthermore, the stated target accuracy of the ACS heading estimations of azimuth and altitude was 0.05°. By assuming that the star trackers yield more accurate results, this then corresponds to an evaluation of $DT_{Az/Alt}$. Based on the two outdoor tests (indoor tests omitted as ACS readings are severely hindered while indoors), the means of these are 0.0065° and 0.0041° for azimuth and altitude respectively. Thus, these readings seem to be significantly better than the stated accuracy.

There is still a reason to do further analysis based on strictly controlled tests for the planning and execution of future similar projects. An example of such a test is to determine STR vs STM performance, as they are significantly different in both size and weight. Reducing the weight is always a concern when it comes to high altitude balloon flights.

Another test would be to determine the stability of the pointing due to sudden bursts of wind, and how a strong constant wind would impact the performance. Such a test could influence the future design of similar projects. The results following such tests are, however, not crucial in the preparation for the upcoming launch of the PoGOLite Pathfinder.

It is, however, crucial to calibrate the system meticulously, to avoid any constant offsets which negatively impact the quality of the scientific data recovered. $DT$ can be used to check that ACS and star tracker readings are well calibrated to each other. During flight, the quality of the pointing should be monitored closely so that proper action can be taken quickly should the accuracy degrade. Post flight, a new analysis following the same procedure as presented in this paper should be made.

It is the opinion of the author that the ACS is performing up to the standard required and is ready for a launch.
Appendix A

Testing Procedure

This is the suggested testing procedure for the tracking tests during the start of 2013.

Star Tracker Alignment

• For this test a bright star should be chosen. Depending on time of day, one of target 17 (Capella), 49 (Procyon), 50 (Vega) or 48 (Arcturus) should be suitable.

• Point at chosen star and check both STM and STR output. Both should give the same position for star. Roll instrument and check if star maintains its position at the center.

Basic Tracking Tests

• Set ACS to track only on GPS, give RA and Dec of suitable bright star (choose from those given above).

• Check star tracker output and ensure star is in the center of FOV of both STM and STR.

• Enable STR tracking and ensure that star is in the center.

• Enable STM tracking and ensure that star is in the center.

Star Tracking Functionality

• This test checks how well the star trackers lock onto target. Based on stellarium, star fields with:
  – Multiple stars of similar magnitude, or
  – Two stars close together of similar magnitude

were chosen in order to ensure that the ACS locks onto the correct star.
• With full tracking enabled point to target 30 (12 Com). Identify stars in FOV and ensure ACS locks onto the correct star. Do the same for the following targets.
  • Point to target 31 (30 LMi).
  • Point to target 32 (Alcyone).
  • Point to target 36 (HIP 26054).
  • Point to target 37 (HIP 53377)

Elevation Dependence

• This test is to determine if there is a dependence on the tracking capabilities at different elevations. Some of the observations are made outside the 30°-60° range. Ten minute observations of the following stars should be sufficient. Should a target be unsuitable (obstructed, too low, too high), a new one can be chosen using Stellarium.
  • Track on target 38 (Mintaka)
  • Track on target 34 (Etamin)
  • Track on target 40 (Mirach)
  • Track on target 39 (ζ Cep)
  • Track on target 42 (ε Per)
  • Track on target 33 (ε Aur)

Magnitude Restriction

• This test is to find an upper limit on the magnitude (red magnitude, 680 nm) of a star while still having full tracking capabilities. The targets are listed in order of increasing magnitude. Point to each target and ensure a good lock with the ACS then move to next target.
  • Point to target 50 (κ Per, RMag = 3.2)
  • Point to target 51 (υ And, RMag = 3.8)
  • Point to target 52 (12 Per, RMag = 4.5)
  • Point to target 53 (41 And, RMag = 4.9)
  • Point to target 54 (HIP 35136, RMag = 5.2)
  • Point to target 55 (39 Aur, RMag = 5.7)
  • Point to target 56 (HIP 20800, RMag = 6.3)
- Point to target 57 (HIP 6943, RMag = 6.9)
- Point to target 58 (HIP11923, RMag = 7.4)
- Point to target 59 (HIP 18994, RMag = 7.9)
- Point to target 60 (HIP 15797, RMag = 8.4)
- Point to target 61 (HIP12579, RMag = 8.8)
- Point to target 62 (HIP 23688, RMag = 9.4)
- Point to target 63 (HIP 7452, RMag = 9.9)
Appendix B

List of Targets

The following tables contain the targets specified. The coordinates for the target corresponding to number 1-17 were calculated prior to the 2012 mission for July. Targets 18, 19 and 20 were added for testing purposes in 2012. The remaining targets, number 30-63, were calculated during the start of 2013 for the middle of February. Note that this target list is not the one that will exist during the 2013 launch. New values will need to be calculated to account for the (miniscule) change in right ascension and declination caused by the precession of Earth and the proper motion of the objects.
<table>
<thead>
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<th>RA</th>
<th>Dec</th>
</tr>
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<tbody>
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<tr>
<td>3</td>
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<td>Crab W1degr</td>
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Table B.0.1: List of targets with corresponding target number and RA/Dec coordinates (in degrees)
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<th>RA</th>
<th>Dec</th>
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</thead>
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<td>Epsilon Per</td>
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<td>Arcturus star</td>
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<td>Vega star</td>
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Table B.0.2: List of targets with corresponding target number and RA/Dec coordinates (in degrees)
Acknowledgments

I would first like to thank my supervisor, Miranda Jackson, for all the help, guidance and motivation throughout this project. An extra thanks to Miranda for the efforts involved in getting the tracking test data from March 2013, during which I was unable to be on location to help.

I would like to thank my girlfriend, Jessica, for motivation, encouragement and for taking care of our fantastic, although at times too much to handle alone, 7-month old son Theodor. A special thanks to Theodor for always knowing how to cheer me up, even after a 10 hour writing session. I would also like to thank the rest of my family for the understanding they have shown, with me missing a few birthdays and other festivities.

I would finally like to thank the entire Astroparticle and Particle Physics corridor for the opportunity to work alongside them.
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