

**Quality Control of Mirror Alignment Components for
the Cherenkov Telescope Array Observatory
and
Pulsar Analysis with the 28 m Telescope of the
High Energy Stereoscopic System**

Dissertation

der Mathematisch-Naturwissenschaftlichen Fakultät
der Eberhard Karls Universität Tübingen
zur Erlangung des Grades eines
Doktors der Naturwissenschaften
(Dr. rer. nat.)

vorgelegt von
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aus Laichingen

Tübingen
2024

Gedruckt mit Genehmigung der Mathematisch-Naturwissenschaftlichen Fakultät der
Eberhard Karls Universität Tübingen.

Tag der mündlichen Qualifikation:

24.10.2024

Dekan:

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Dedicated to everyone who has inspired and supported me on my journey.
Thank you.

Abstract

Imaging Atmospheric Cherenkov Telescopes (IACTs) detect Cherenkov light from secondary particle showers initiated by γ -rays with photon energies of $\sim 10^{-2}$ TeV – 10^2 TeV. The Cherenkov light is focused by reflectors with a tessellated mirror consisting of up to several hundred individual mirror facets into a camera located in the focal plane of the telescope. This thesis deals with the quality control of Mirror Alignment Components (MACs) for the Large-Sized Telescope (LST) and Medium-Sized Telescope (MST) of the future ground-based Cherenkov Telescope Array Observatory (CTAO) and the observational data analysis of two pulsars using a novel camera trigger setting of the 28 m telescope of the High Energy Stereoscopic System (H.E.S.S.).

Each mirror facet of the tessellated reflector is mounted with a fix point fixed in length and two actuators with adjustable length to the mirror support structure. This constitutes a set of MACs. Image resolution and pointing accuracy constraints impose limits on the non-reproducible positioning uncertainties of the MACs under various weight and wind loads, which makes quality control a necessary tool to ensure the scientific performance of the telescope. A meanwhile patented test stand developed by the Institut für Astronomie und Astrophysik Tübingen measures the force-displacement characteristics and quantifies the mechanical properties of the MACs with the latter being mechanical play and (visco-)elastic deformation. This thesis contributes key insights into the measurement theory, and the qualitative and quantitative assessment of the systematic and statistical errors influencing the measurement accuracy of the test stand. The statistical error introduced by repeated mountings of an exemplary actuator with a two Degree of Freedom gimbal was empirically determined to be $\pm 5 \mu\text{m}$ on the absolute displacement measured for a given tensile and compressive load resembling observation conditions.

The force-displacement characteristics of mirror-sided and telescope-sided interface solutions of the MACs were evaluated with the test stand. Suitable solutions offering satisfactory performance to fulfill the scientific requirements of the LST and MST were identified. Furthermore, the viscoelastic behavior of the mirror-sided interface solutions was identified to complicate, compared to only elastic deformation and mechanical play, the quantification of the non-reproducible positioning uncertainties of the MACs. Consequently, the absolute displacement is identified as the figure of merit for the quality control.

The test stand is ready for the performance evaluation and large-scale quality control of MACs produced for the MSTs and LSTs.

Pulsars are rapidly rotating neutron stars with strong magnetic fields that accelerate charged particles leading to the emission of pulsed electromagnetic radiation. The 28 m telescope of H.E.S.S. (CT5) offers the possibility to study the spectral-cutoff region of pulsars in the energy range of ~ 10 GeV with high statistics. A FlashCam, a

camera planned for the MST, was installed into CT5 in October 2019. Observations of the Vela pulsar verified the timing system of the camera in 2020 and motivated observations of the Vela pulsar and the pulsar B1706-44, two pulsars already detected with CT5, using a novel camera trigger setting, which is reduced by 15 % compared to the nominal one.

End-to-end Monte Carlo (MC) simulations of the Cherenkov light emitted by the particle shower and the instrument response are necessary for the analysis of data acquired with IACTs. The MC simulations of the H.E.S.S. Analysis Program (HAP) were adapted to the reduced trigger setting, and the Night Sky Background (NSB) and atmospheric transparency conditions present during the pulsar observations. From the MC simulations, the Instrument Response Functions (IRFs) are derived. A significant increase of the effective area for simulated energies of $\lesssim 80$ GeV is observed for the reduced camera trigger setting compared to the nominal one, while a reduction of the safe energy threshold relevant for the spectral analysis requires future optimization work within HAP.

With the 2021 observations, the P2 peak of the Vela pulsar is observed with a statistical significance of 27.3σ , and the P1 and P3 peak with 2.96σ and 3.95σ , respectively. The pulsed emission of B1706-44 is observed with 5.7σ . A comparison of the excess and event rates as function of the zenith angle using observations of the Vela pulsar taken with the reduced and the nominal trigger setting revealed a gain in sensitivity with the reduced trigger setting. The proper working principle of the IRFs was verified by reconstructing the spectra of the two pulsars, which were in accordance with previous results published by H.E.S.S. In conclusion, the reduced trigger setting is a good observational strategy for astronomical sources with a steep spectrum such as pulsars and potentially Gamma-Ray Bursts.

Zusammenfassung

Abbildende Cherenkov Teleskope (IACTs) detektieren Cherenkov-Licht von sekundären Teilchenschauern, die durch γ -Strahlung mit Photonenenergien von $\sim 10^{-2}$ TeV – 10^2 TeV ausgelöst werden. Das Cherenkov-Licht wird durch Reflektoren mit einem segmentierten Spiegel, der aus bis zu mehreren hundert einzelnen Spiegelfacetten besteht, in eine Kamera fokussiert, welche sich in der Brennebene des Teleskops befindet. Diese Dissertation befasst sich mit der Qualitätskontrolle von mechanischen Komponenten zur Spiegelausrichtung für das große Teleskop (LST) und das mittelgroße Teleskop (MST) des zukünftigen bodengebundenen Cherenkov Telescope Array Observatory (CTAO) und der Datenanalyse von zwei Pulsaren unter Verwendung einer neuartigen Kamera-Auslöseeinstellung des 28 m Teleskops des High Energy Stereoscopic System (H.E.S.S.).

Jede einzelne Spiegelfacetten des Reflektors ist mit einem Fixierpunkt und zwei längenverstellbaren Aktuatoren an der Spiegelträgerstruktur befestigt. Dies ist ein Satz von Spiegelausrichtungskomponenten. Die Bildauflösung und Genauigkeit der Teleskopausrichtung setzen den nicht reproduzierbaren Positionsunsicherheiten der Spiegelausrichtungskomponenten unter verschiedenen Gewichts- und Windbelastungen Grenzen. Die Qualitätskontrolle der Spiegelausrichtungskomponenten ist somit ein notwendiger Kontrollprozess, um die wissenschaftliche Leistung des Teleskops zu gewährleisten. Ein inzwischen patentierter Prüfstand, der vom Institut für Astronomie und Astrophysik Tübingen (IAAT) entwickelt wurde, misst die Kraft-Weg-Kennlinie und quantifiziert die mechanischen Eigenschaften der Spiegelausrichtungskomponenten, wobei letztere das mechanische Spiel und die (visko-)elastische Verformung sind. Diese Dissertation liefert wesentliche Erkenntnisse zur Messtheorie, sowie zur qualitativen und quantitativen Bewertung der systematischen und statistischen Fehler, die die Messgenauigkeit des Prüfstands beeinflussen. Der statistische Fehler, der durch die wiederholte Montage eines beispielhaften Aktuators mit einem Kardanring mit zwei Freiheitsgraden verursacht wird, wurde empirisch auf $\pm 5 \mu\text{m}$ der gemessenen absoluten Auslenkung bei einer gegebenen Zug- und Druckbelastung ermittelt, die den Beobachtungsbedingungen entspricht.

Die Kraft-Weg-Eigenschaften von spiegel- und teleskopseitigen Schnittstellenlösungen der Spiegelausrichtungskomponenten wurden mit dem Prüfstand bewertet. Es wurden geeignete Schnittstellenlösungen identifiziert, die eine zufriedenstellende Leistung bieten, um die wissenschaftlichen Anforderungen der LST und MST zu erfüllen. Darüber hinaus wurde festgestellt, dass das viskoelastische Verhalten der spiegelseitigen Schnittstellenlösung die Quantifizierung der nicht reproduzierbaren Positionsunsicherheiten der Spiegelausrichtungskomponenten, im Vergleich zu ausschließlich elastischer Verformung und mechanischem Spiel, erschwert. Infolgedessen wird die absolute Auslenkung als Leistungsmerkmal für die Qualitätskontrolle festgelegt.

Der Prüfstand ist somit bereit für die Leistungsbewertung und die großangelegte Qualitätskontrolle, der für die MSTs und LSTs hergestellten Spiegelausrichtungskom-

ponenten.

Pulsare sind schnell rotierende Neutronensterne mit starken Magnetfeldern, die geladene Teilchen beschleunigen. Dies führt zur Emission gepulster elektromagnetischer Strahlung. Das 28 m Teleskop von H.E.S.S. (CT5) bietet die Möglichkeit, den spektralen Grenzbereich von Pulsaren im Energiebereich von ~ 10 GeV mit hoher Statistik zu untersuchen. Im Oktober 2019, wurde eine FlashCam – eine für das MST geplante Kamera – in CT5 installiert. Beobachtungen des Vela-Pulsars verifizierten das Timing-System der Kamera im Jahr 2020 und motivierten Beobachtungen des Vela-Pulsars und des Pulsars B1706-44, zwei bereits mit CT5 entdeckte Pulsare, unter Verwendung einer neuartigen Kamera-Auslöseeinstellung. Diese Auslöseeinstellung ist um 15 % im Vergleich zur nominalen Einstellung reduziert.

Ganzheitliche Monte-Carlo (MC) Simulationen des von dem sekundären Teilchenschauen emittierten Cherenkov-Lichts und der Instrumentenantwort sind für die Analyse der mit IACTs gewonnenen Daten unerlässlich. Die MC-Simulationen des H.E.S.S. Analysis Program (HAP) wurden an die reduzierte Kamera-Auslöseeinstellung, den Nachthimmelhintergrund und die atmosphärischen Bedingungen, welche während den Pulsarbeobachtungen herrschten, angepasst. Aus den MC-Simulationen wurden die Instrumentenantwortfunktionen bestimmt. Eine signifikante Erhöhung der effektiven Fläche für simulierte Energien von $\lesssim 80$ GeV wird für die reduzierte, im Vergleich zu der nominellen, Kamera-Auslöseeinstellung festgestellt. Dagegen erfordert eine Verringerung des für die Spektralanalyse relevanten sicheren Energieschwellenwertes weitere Optimierungsarbeit innerhalb von HAP.

Mit den Beobachtungen von 2021 wird der P2-Peak des Vela-Pulsars mit einer statistischen Signifikanz von 27.3σ beobachtet, und der P1- und P3-Peak mit 2.96σ beziehungsweise 3.95σ . Die gepulste Emission von B1706-44 wird mit einer statistischen Signifikanz von 5.7σ beobachtet. Ein Vergleich der Exzess- und Signifikanzraten als Funktion des Zenitwinkels anhand von Beobachtungen des Vela-Pulsars mit der reduzierten und der nominalen Kamera-Auslöseeinstellung ergab einen Empfindlichkeitsgewinn mit der reduzierten Kamera-Auslöseeinstellung. Die korrekte Funktionsweise der Instrumentenantwortfunktionen wurde durch die Rekonstruktion der Spektren der beiden Pulsare verifiziert, die mit früheren, von H.E.S.S. veröffentlichten Ergebnissen übereinstimmten. Zusammenfassend lässt sich sagen, dass die reduzierte Kamera-Auslöseeinstellung eine gute Beobachtungsstrategie für astronomische Quellen mit einem steil abfallenden Spektrum, wie Pulsaren und möglicherweise Gammastrahlenausbrüchen, ist.

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Glossary

ACT	Atmospheric Cherenkov Technique
ACU	Actuator Control Unit
ADC	Analogue-to-Digital Converter
AERONET	Aerosol Robotic Network
AGN	Active Galactic Nuclei
AMC	Active Mirror Control
AOD	Aerosol Optical Depth
ARGO-YBJ	Astrophysical Radiation with Ground-based Observatory at Yang-Ba-Jing
BDT	Boosted Decision Tree
CCD	Charged-Coupled Device
CMB	Cosmic Microwave Background
CMOS	Complementary Metal-Oxide-Semiconductor
COG	Center of Gravity
CTAO	Cherenkov Telescope Array Observatory
CTC	Cherenkov Transparency Coefficient
DAQ	Data Acquisition
DC	Davies-Cotton
DESY	Deutsches Elektronen-Synchrotron
DL	Data Level
DOF	Degree of Freedom
DST	Data Summary Table
EAS	Extensive Air Shower
EBL	Extragalactic Background Light
FADC	Flash Analogue-to-Digital Converter
FEM	Finite Element Method
FITS	Flexible Image Transport System
FOV	Field of View
FPGA	Field Programmable Gate Array
GRB	Gamma-Ray Burst
H.E.S.S.	High Energy Stereoscopic System
HAP	H.E.S.S. Analysis Program
HAWC	High Altitude Water Cherenkov

HEGRA	High Energy Gamma Ray Astronomy
IAAT	Institut für Astronomie und Astrophysik Tübingen
IACT	Imaging Atmospheric Cherenkov Telescope
IC	Inverse Compton
IRF	Instrument Response Function
LAT	Large Area Telescope
LED	Light-Emitting Diode
LHAASO	Large High Altitude Air Shower Observatory
LSB	Least Significant Bit
LST	Large-Sized Telescope
MAC	Mirror Alignment Component
MAGIC	Major Atmospheric Gamma Imaging Cherenkov
MC	Monte Carlo
MILAGRO	Multiple Institution Los Alamos Gamma Ray Ob- servatory
MPIK	Max-Planck-Institut für Kernphysik
MPP	Max-Planck-Institut für Physik
MST	Medium-Sized Telescope
MSU	Mirror Support Unit
NSB	Night Sky Background
PDP	Photon Detector Plane
PMT	Photomultiplier Tube
PSF	Point Spread Function
PTFE	Polytetrafluoroethylene
PWN	Pulsar Wind Nebula
RMS	Root Mean Square
ROI	Region of Interest
ROS	Readout Electronics
SC	Schwarzschild-Couder
SCT	Schwarzschild-Couder Telescope
SiPM	Silicon Photomultiplier
SNR	Supernova Remnant
SSC	Synchrotron Self Compton
SST	Small-Sized Telescope
STACEE	Solar Tower Atmospheric Cherenkov Effect Experi- ment
SWGO	Southern Wide-field Gamma-ray Observatory
UCSC	University of California, Santa Cruz
UZH	Universität Zürich

VERITAS	Very Energetic Radiation Imaging Telescope Array System
VHE	Very High Energy
WIMP	Weakly Interacting Massive Particle

Introduction

While astronomy is historically associated with the observation and recording of the properties of astronomical objects, the discipline of astrophysics can be understood as the application of physical models to explain the temporal and spatial variation of these properties. At least since the discovery of the Fraunhofer lines in the solar spectrum in 1817, the boundary between astronomy and astrophysics has become more and more transparent, and today there is no clear distinction. The main objective of astronomy and astrophysics can therefore be summarized as the observation and understanding of the astronomical sources and phenomena present in our Universe. To accomplish this, a wide variety of messengers have become accessible in recent years serving as information carriers of the astrophysical processes active at or in the vicinity of astronomical sources. These messengers include not only electromagnetic radiation, but also non-electromagnetic ones such as cosmic-rays, neutrinos, gravitational waves, and possible dark matter candidates. Combining the information from all these messengers provides an unprecedented view and more complete understanding of our Universe and the astrophysical processes within it.

Electromagnetic radiation is one of the most fundamental carrier of information and is characterized by its energy, polarization, and temporal and spatial coherence. Nowadays, the electromagnetic spectrum is accessible from the radio waveband with photon energies of 10^{-8} eV to the γ -ray waveband with photon energies of 10^{15} eV and beyond. These energies correlate with a wide range of densities, temperatures, and gravitational and magnetic field strengths of the observed astronomical sources. For example, the density of a cluster of galaxies is $\sim 10^{-24}$ kg m $^{-3}$, while neutron stars have densities of $\sim 10^{17}$ kg m $^{-3}$. Therefore, the discipline of astrophysics is a science of the extremes and the Universe provides laboratory conditions that cannot be replicated on Earth.

The part of the γ -ray waveband dealing with energies of $\sim 10^{-2}$ TeV – 10^2 TeV constitutes the subdiscipline of TeV astronomy. TeV astronomy exploits the fact that γ -rays with these energies interact with the Earth's atmosphere and produce showers of secondary particles that can be observed either directly or indirectly from the Earth's surface. An indirect detection method, the imaging atmospheric Cherenkov technique, images the Cherenkov light emitted by the secondary particles as they move through the Earth's atmosphere at superluminal velocities.

The Imaging Atmospheric Cherenkov Telescopes (IACTs), ground-based telescopes using the imaging atmospheric Cherenkov technique, are essentially optical telescopes and consist of two main subsystems. First, an optical system that collects, directs and focuses the Cherenkov light into the focal plane and forms an image of it. Second, a photosensitive detector, located in the focal plane, records and processes the image and converts the detected Cherenkov light into a physical quantity such as a voltage or a current. This physical quantity is digitized and stored to allow a consequent

analysis of the images. From the images of the observed Cherenkov light, the energy and direction of the initial γ -ray entering the Earth's atmosphere can be determined. This facilitates the calculation of the spatial and spectral properties of the observed astronomical source. A wide range of astronomical sources emit electromagnetic radiation in the range of TeV energies, including Active Galactic Nuclei (AGN), Pulsar Wind Nebulae (PWNe), Supernova Remnants (SNRs), and pulsars.

The latter are rapidly rotating neutron stars that emit pulsed electromagnetic radiation up to the high energy part of the γ -ray waveband due to their rotation and the misalignment between the rotational and magnetic field axes. To study the pulsar spectrum in the range of ~ 10 GeV and beyond, IACTs complement space-based telescopes such as the Fermi Gamma-Ray Space Telescope to improve the understanding of the underlying astrophysical processes.

This thesis deals with both subsystems of the imaging atmospheric Cherenkov technique. The information collecting one, the optical system, and the information recording one, the detector, as well as the analysis of observational data acquired on two pulsars. This thesis is divided into three parts. Part I conveys the necessary astrophysical background as well as the description of the ground-based TeV astronomy facilities relevant for this work. This includes the fundamental scientific questions as well as the detection methods of ground-based TeV astronomy in Chapter 2, and the description of the currently operating High Energy Stereoscopic System (H.E.S.S.) and the future Cherenkov Telescope Array Observatory (CTAO) in Chapter 3.

The optical system of an IACT usually consists of a reflector with a diameter of ~ 10 m, resulting in collection areas of several 100 m^2 . To produce such mirrors cost-efficiently, the reflector follows a tessellated mirror design with up to several hundred individual mirror facets. Exact alignment of the individual mirror facets so that the incident light from a point source is reflected to a single point is essential for good imaging quality of the telescope. One of the factors influencing the precise alignment of the mirror facets is the intrinsic positioning accuracy of the mechanical Mirror Alignment Components (MACs) of the mirror alignment system. Therefore, the quality control of the MACs is of great importance for the optical performance of the telescope. This is the main topic of Part II with a focus on the quality control of the MACs of the mirror alignment system of a telescope type planned for the future CTAO. A more specific introduction into quality control is given in Chapter 4 and the telescope type of the CTAO is described in Chapter 5. In Chapter 6, a test stand designed and developed at the Institut für Astronomie und Astrophysik Tübingen (IAAT) for verifying the mechanical design specifications of the MACs is described. Furthermore, this chapter discusses the qualitative and quantitative assessment of the error sources impacting the measured mechanical properties of the MACs. The performance evaluation of various parts of mechanical components are summarized in Chapter 7.

Part III of this thesis deals with the observations of two pulsars, the pulsar B0833-45 (the Vela pulsar) and the pulsar B1706-44, with a novel trigger setting of the focal plane instrument installed in the 28 m telescope of H.E.S.S. For the analysis of the astrophysical data, detailed MC simulations of the Cherenkov light emitted by the secondary particle shower and the instrument response are a necessity. The MC simulations serve as input to the algorithms that reconstruct the energy and direction of the γ -ray, as well as differentiate the γ -rays from hadronic background events. The motivation for the observation of pulsars using the 28 m telescope of

H.E.S.S. and the novel trigger setting, which is reduced compared to the nominal trigger setting, of the focal plane instrument is given in Chapter 8. The analysis methods for the observational data analysis are described in Chapter 9. Furthermore, this chapter covers the adaptation of the MC simulations to the novel trigger setting and the environmental observation conditions present during the pulsar observations. In Chapter 10, the observational data analysis of the Vela pulsar and B1706-44 is described. A summary and conclusion of the work is given in Part IV.

Part I

Astrophysical Context and Ground-based Facilities

I was born not knowing and have had only a little
time to change that here and there.

RICHARD P. FEYNMAN

TeV Gamma-Ray Astronomy

γ -ray astronomy is concerned with photon energies > 100 keV. Up to ~ 300 GeV, the direct observation with space-based observatories such as the Fermi Gamma-Ray Space Telescope is favorable due to the absorption of γ -rays at such energies in the Earth's atmosphere, as shown in Figure 2.1. However, direct detection of γ -rays from space is constrained by the construction-limited collection areas of approximately 1 m^2 and the decreasing flux of incoming γ -rays as a function of energy. Starting at photon energies of ~ 10 GeV, γ -rays interacting with the Earth's atmosphere initiate showers of secondary particles that reach the Earth's surface and can thus be detected by ground-based experiments. This facilitates the field of TeV astronomy dealing with the very high energy part of the γ -ray waveband (De Angelis et al. 2018a)¹.

TeV astronomy provides insight into some of the most fundamental questions in astrophysics. As explained in more detail in Section 2.1, the production of γ -rays is linked to the interaction of cosmic-rays with ambient matter, magnetic fields and photon fields, as well as the decay of potential dark matter candidates. Therefore, the observation of γ -rays provides information about the acceleration sites of cosmic-rays as well as potentially the nature and distribution of dark matter in our Universe (e.g., Hinton et al. 2009).

The astrophysical sources of interest for TeV astronomy can be broadly divided into galactic and extragalactic origin. The former includes the identification of sources contributing to the diffuse emission in the Galactic plane as well as the identification of the astrophysical source located at the Galactic Center (e.g. H.E.S.S. Collaboration 2016; H.E.S.S. Collaboration et al. 2018b). Typical examples of galactic TeV sources are objects associated with the final stages of stellar evolution (e.g., pulsars, PWNe, SNRs), star-forming regions (e.g., by stellar wind interactions in stellar clusters) and binary systems consisting of a compact object and a companion star (e.g., Gamma-Ray Loud Binaries, microquasars, recurrent novae). More details can be found in Holder (2012) and Bose et al. (2022). In addition, the search for PeVatrons, astronomical sources that accelerate γ -rays to PeV energies, has found a new foundation with the detection of γ -rays with energies up to 1.4 PeV from galactic sources by the Large High Altitude Air Shower Observatory (LHAASO), as reported in Cao et al. (2021). This extends the window of TeV astronomy to an even higher energy range.

Extragalactic sources of TeV astronomy include, among others, AGN and starburst galaxies (Holder 2012). Furthermore, the first detection of Very High Energy (VHE) γ -rays from Gamma-Ray Bursts (GRBs) reported in 2019 by the H.E.S.S. and Major Atmospheric Gamma Imaging Cherenkov (MAGIC) collaborations added this new source class to the emitters of γ -rays (H.E.S.S. Collaboration et al. 2019; MAGIC

¹Unless otherwise stated, the term γ -rays will henceforth refer to γ -rays in the very high energy range.

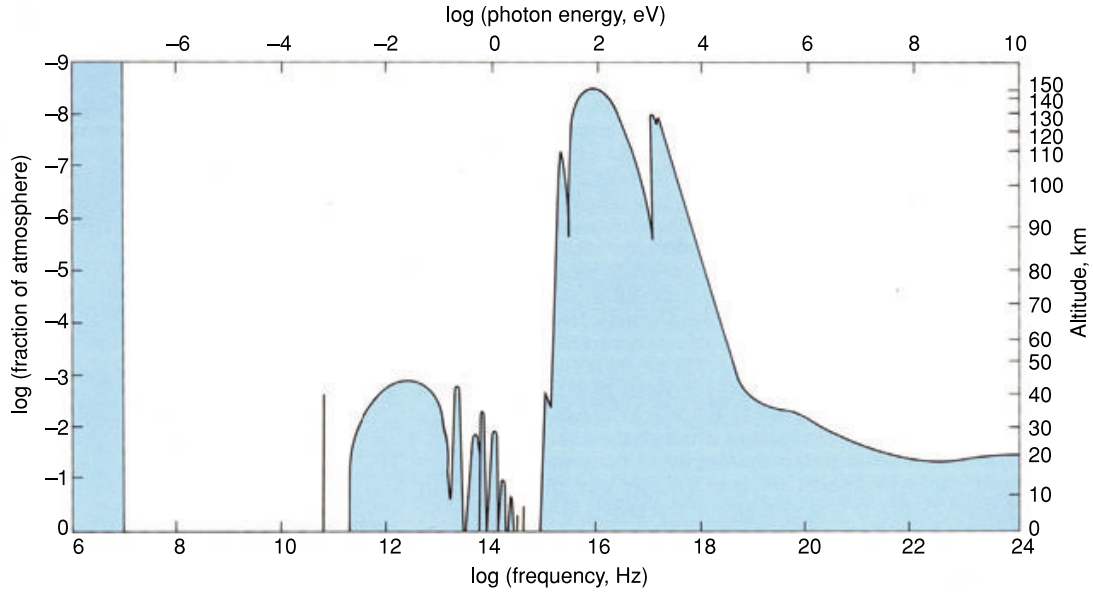


Figure 2.1. Transparency of the Earth's atmosphere to electromagnetic radiation. The black line indicates the altitude above sea level at which the atmosphere becomes transparent to electromagnetic waves of the corresponding energy. Taken from Longair (2011), which is an adapted version of the image by Giacconi et al. (1968).

Collaboration 2019). Furthermore, the investigation of extragalactic sources provides insight into the properties of the Extragalactic Background Light (EBL) due to its interaction with γ -rays traveling through the interstellar medium (Bose et al. 2022).

The production and propagation of γ -rays are described in Section 2.1, while the interaction with the Earth's atmosphere and the detection with ground-based facilities are explained in Sections 2.2 and 2.3, respectively.

2.1. Production and Propagation of γ -rays

The production of γ -rays is closely linked to the production and acceleration sites of cosmic-rays, which are charged particles consisting of 98% protons and heavier nuclei and 2% electrons² (Longair 2011). Cosmic-rays were first discovered in 1912 by Victor Hess, who measured the ionization levels of air as a function of altitude using balloons (Hess 1912). Today, the differential energy spectrum of cosmic-rays is well measured by various ground- and space-based experiments and spans several orders of magnitude in intensity and energy, as shown in Figure 2.2. For energies above several TeV, it can be approximated by a power law according to

$$\frac{dN}{dE} \propto E^{-\Gamma} \quad (2.1)$$

where E is the energy of the particle and Γ is the spectral index. There are two special regions shown in Figure 2.2 – the knee region at $\sim 10^5$ GeV – 10^6 GeV and the ankle region at $\sim 10^9$ GeV – 10^{10} GeV. While the sources below the knee region are assumed to be within our Galaxy, the ankle region is assumed to be dominated by

²Electrons in this context include positrons.

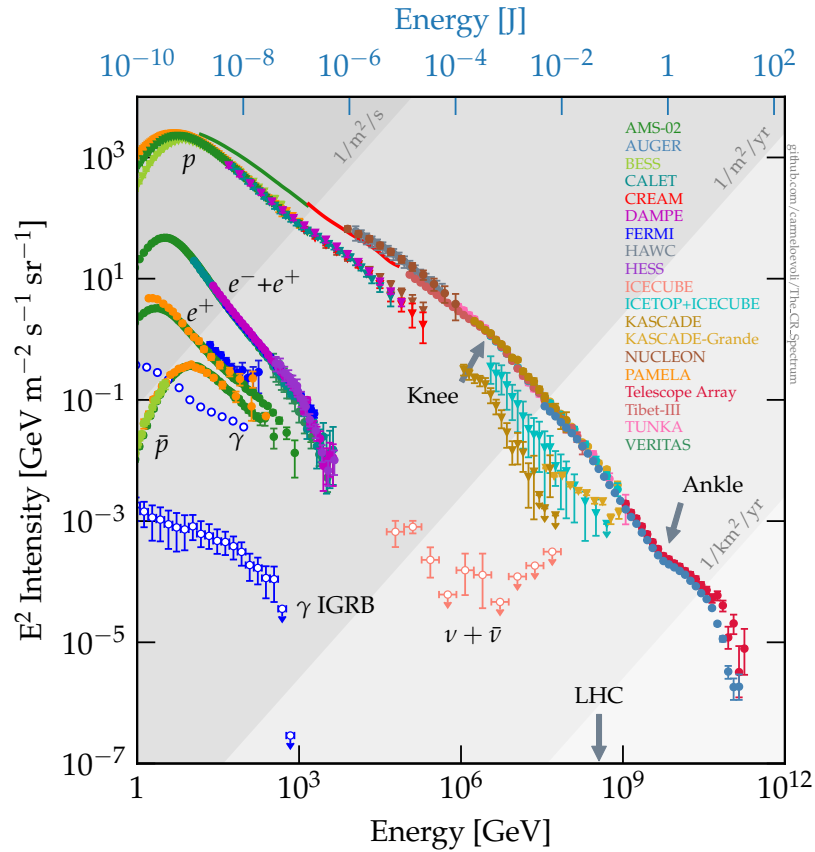


Figure 2.2. Cosmic-ray spectrum as a function of energy, as measured by various ground- and space-based facilities. The spectra are shown for γ -rays, neutrinos, electrons, protons, and heavier nuclei. The knee and ankle regions and the maximum acceleration energy of particles with the Large Hadron Collider are indicated by gray arrows. The gray shaded bands indicate the order of expected particles per area and time. Taken from Evoli (2020).

extragalactic sources, since the cosmic-rays with these energies have a Larmor radius larger than the size of our Galaxy (Bell 2013). The cutoff starting at approximately 10^{11} GeV can be attributed either to a lack of sources accelerating cosmic-rays to these energies (Hillas 1984) or to energy losses during the propagation of cosmic-rays through the interstellar medium (Greisen 1966; Zatsepin et al. 1966).

While cosmic-rays are deflected by magnetic fields as they propagate through the galactic and intergalactic medium, and are therefore isotropically distributed across the sky, this is not the case for γ -rays. This, and the fact that the Universe is transparent to γ -rays up to energies of ~ 100 GeV, offers the possibility to study the sites of cosmic-ray acceleration by observing γ -rays and to give insight into the nature of the cosmic-ray spectrum (De Angelis et al. 2018a). In addition, γ -rays can originate from the annihilation or the decay of exotic particles. Depending on their origin, the production of γ -rays can be divided into two basic scenarios – the bottom-up scenario and the top-down scenario – which are explained below.

2.1.1. Bottom-up Scenario

The starting point for the production of γ -rays in the bottom-up scenario is a population of charged particles. This population of charged particles can then be accelerated by various mechanisms. The two main mechanisms are the Fermi mechanism for, e.g., SNRs and PWNe and the acceleration by strong magnetic fields as for, e.g., pulsars (De Angelis et al. 2018a). The focus here is on the former acceleration mechanism.

The two requirements for the Fermi mechanism are a strong shock wave and particles in front of and behind the shock front with random velocity vectors. The maximum energy that can be achieved by the Fermi mechanism is

$$E_{\text{CR,max}} = ZeBUL \quad (2.2)$$

where Z is the charge number, e the elementary charge, U the velocity of the shock wave, B the magnetic flux density of the interstellar magnetic field, and L the size of the accelerating region. Inserting typical values for a young SNR³ in Equation 2.2 yields maximum cosmic-ray energies of 10^{14} eV per nucleon. The acceleration of particles beyond 10^{14} eV can be explained by effects leading to an amplification of the interstellar magnetic field near the shock front (Longair 2011).

The production of γ -rays from the accelerated particles can then be separated according to their leptonic or hadronic nature. A population of relativistic electrons and a strong magnetic field are the two basic ingredients for the leptonic emission of γ -rays. The production of γ -rays can then happen by the Inverse Compton (IC) process, where infrared and optical photons as well as photons of the Cosmic Microwave Background (CMB) are up-scattered by relativistic electrons (Hinton et al. 2009). Another possibility is the Synchrotron Self Compton (SSC) process, a combination of the synchrotron and the IC processes. In this scenario, the relativistic electrons produce photons due to the synchrotron process and these photons are up-scattered by the IC process to X-ray and γ -ray energies (Longair 2011). Consequently, a strong indication for the SSC process in an astronomical source is the simultaneous observation of flares in the radio/X-ray and the γ -ray parts of the source spectrum. This further emphasizes the importance of multi-wavelength observations of sources, such as, e.g., AGN (De Angelis et al. 2018b).

The hadronic emission of γ -rays is caused either by hadron-nucleon collisions (pp interaction) or by photoproduction. In the former case, an accelerated hadron collides with a target of nucleons, producing charged (π^+ , π^-) and neutral pions (π^0). The π^0 decays into two γ -rays, each of which has half the energy of the π^0 . In the latter case, an accelerated proton interacts with a target field of photons and produces γ -rays via the Δ^+ resonance

$$\begin{aligned} p + \gamma &\rightarrow \Delta^+ \rightarrow \pi^+ + n \\ p + \gamma &\rightarrow \Delta^+ \rightarrow \pi^0 + p \end{aligned} \quad (2.3)$$

In this case, the π^0 also decays into two γ -rays. An important feature of the hadronic emission of γ -rays is the production of neutrinos for the hadron-nucleon interaction as well as for the photoproduction by the decay of the generated charged pions.

³Typical values for a SNR for magnetic flux density, shock wave velocity, and age are $B = 10^{-10}$ T, $U = 10^4$ km s⁻¹, and $t \approx 10^3$ years, respectively.

Therefore, the simultaneous observation of γ -rays and neutrinos is a strong indication for hadronic emission (De Angelis et al. 2018a).

2.1.2. Top-down Scenario

γ -rays can also be produced by the annihilation or decay of exotic particles, such as Weakly Interacting Massive Particles (WIMPs), one of the most promising dark matter candidates. When two WIMPs annihilate, the resulting γ -rays are produced either directly or indirectly. In the latter case, the γ -rays are produced by the resulting decay processes of the generated hadrons or by the IC scattering of the electrons produced in the process. The expected γ -ray flux following the annihilation of WIMPs with mass M and annihilation rate $\langle \sigma v \rangle$ is

$$\Phi_\gamma = \left(\frac{\langle \sigma v \rangle}{M^2} D_\gamma(E) \right) \left(\frac{1}{4\pi} \int_{LOS} \rho^2 dl \right) \quad (2.4)$$

where $D_\gamma(E)$ is the spectral yield per annihilation and ρ is the dark matter particle density. According to Equation 2.4, the expected flux of γ -rays is proportional to the integral of the density squared along the line of sight. Consequently, an increased γ -ray flux is expected from sources with high dark matter density, such as the galactic center or dwarf spheroidal galaxies. So far no dark matter induced signal has been found in γ -rays (Hinton et al. 2009). For both production scenarios, the γ -rays are subject to absorption as they propagate from the astronomical source to the observer. This is described in the following section.

2.1.3. Propagation

When a γ -ray travels from the astronomical source to the observer, the dominant absorption process is pair production with the cosmic background

$$\gamma + \gamma_{\text{bkg}} \rightarrow e^+ + e^- \quad (2.5)$$

whenever the mean free path of the photon is smaller than the distance to the source. The pair production process is allowed for a γ -ray with energy E_γ and a background photon with energy E_{bkg}

$$E_\gamma E_{\text{bkg}} = m_e^2 c^4, \quad (2.6)$$

where m_e is the mass of the electron and c is the speed of light in vacuum. According to De Angelis et al. (2018b), the cross section of the pair production process in Equation 2.5 is maximized for a background photon energy of

$$E_{\text{bkg}} = \left(\frac{900 \text{ GeV}}{E_\gamma} \right) \text{ eV} \quad (2.7)$$

assuming an isotropic background photon distribution. The cosmic background as a function of frequency is shown in Figure 2.3. There are three dominant peaks visible, which are the CMB, the cosmic infrared background, and the cosmic optical background. The latter two are labeled EBL according to the convention of, e.g., Dwek et al. (2013). The EBL includes most of the radiation during the star formation phase. According to Equation 2.7, for γ -rays with energies between $10 \text{ GeV} - 10^5 \text{ GeV}$

the EBL plays the dominant role in the absorption. For even higher γ -ray energies in the $10^5 \text{ GeV} - 10^{10} \text{ GeV}$ energy range, the CMB becomes dominant (De Angelis et al. 2018b). Therefore, the interaction between γ -rays and the cosmic background affects the spectra of extragalactic sources. On the one side, a good knowledge of the spectrum and the intensity of the EBL allows a better determination of the intrinsic source spectra. On the other side, the detection of extragalactic sources at increasing distances and a good knowledge of their intrinsic spectra allow to derive limits on the EBL. The reader is referred to Dwek et al. (2013) for a more detailed review of the determination of the EBL.

As the γ -rays travel from the astronomical source to Earth, they interact with the Earth's atmosphere. This is described below.

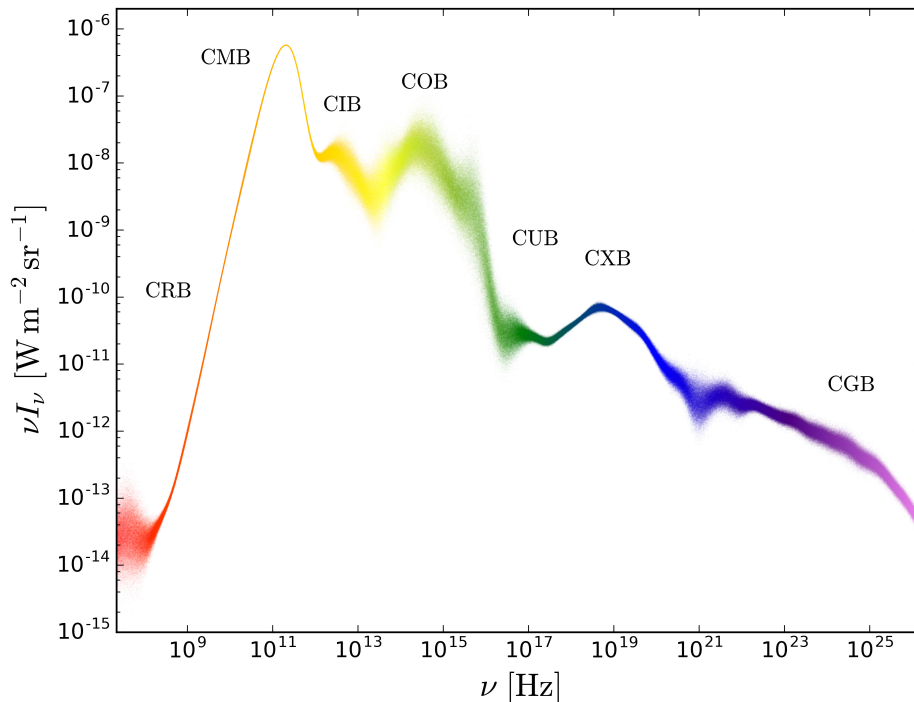


Figure 2.3. Cosmic background in the Universe as a function of frequency. The most dominant background radiation is the Cosmic Microwave Background, the Cosmic Infrared Background and the Cosmic Optical Background. The magnitude of the smearing indicates the uncertainties of the corresponding measurements. Taken from Hill et al. (2018).

2.2. Interaction with the Earth's Atmosphere

After propagating from the astronomical source to the Earth, the primary particle interacts with Earth's atmosphere, producing a shower of secondary particles. The resulting shower of secondary particles is called an Extensive Air Shower (EAS). The EASs are divided into hadronic and electromagnetic showers, depending on whether the primary particle is a hadron or a γ -ray⁴. A proper understanding of the interaction between the primary particle and the atmosphere is a crucial aspect for

⁴Electrons also generate electromagnetic showers. However, the following description focuses on γ -rays as the primary particles of electromagnetic showers.

the accurate determination of the properties of the primary particle, which are mainly its energy, direction and type. The main focus of this section is on the development of electromagnetic showers in the Earth's atmosphere and the related Cherenkov effect, before briefly highlighting the differences to hadronic showers. For a detailed description of EASs, the reader is referred to Gaisser et al. (2016).

2.2.1. Development of Electromagnetic Showers

The main physical processes governing the development of an electromagnetic shower are pair production, bremsstrahlung, and ionization losses. A simple analytical description of electromagnetic showers is the Heitler model, which explains the main characteristics of electromagnetic showers and is described after Matthews (2005).

The schematic diagram of an electromagnetic shower according to the Heitler model is shown in Figure 2.4. Upon interaction with the Earth's atmosphere, a γ -ray with initial energy E_0 produces an electron-positron pair by pair production in the presence of the Coulomb field of an atomic nucleus. The electron and the positron each receive on average half of the initial energy E_0 . As a result, the electron and positron interact with the surrounding medium via bremsstrahlung and, after one splitting length d , emit a γ -ray with half the energy of the electron or positron, respectively. The splitting length d is given by

$$d = X_0 \ln 2 \quad (2.8)$$

where X_0 is the radiation length of electrons in the surrounding medium. The radiation length corresponds to the amount of matter an electron traverses along its path to lose all but $1/e$ of its energy⁵. The resulting bremsstrahlung γ -ray then undergoes pair production, repeating the process. The development of the electromagnetic shower stops when the shower particles reach the critical energy $E_c = 85 \text{ MeV}$, after which the ionization losses dominate over the energy losses by bremsstrahlung and pair production. The maximum number of particles N_{max} in a shower is reached when the condition

$$E_0 = N_{\text{max}} E_c \quad (2.9)$$

is satisfied. To calculate the maximum shower depth X_{max} in the atmosphere, the number of particles after n splitting lengths must be determined. One of the assumptions of the Heitler model is that the radiation length of electrons and the mean free path of pair production are equal⁶. Therefore, the number of shower particles after n splitting lengths is given by

$$N = 2^n. \quad (2.10)$$

The maximum shower depth X_{max} can be calculated with Equations 2.8 and 2.9, assuming a maximum number of splitting lengths n_{max} in Equation 2.10, to

$$X_{\text{max}} = X_0 \ln \left(\frac{E_0}{E_c} \right). \quad (2.11)$$

⁵In dry air at a pressure of 1013 hPa, X_0 corresponds to 36.6 g cm^{-2} (Errando et al. 2024).

⁶This approximation holds true for ultra-relativistic electrons as, e.g., shown in Longair (2011).

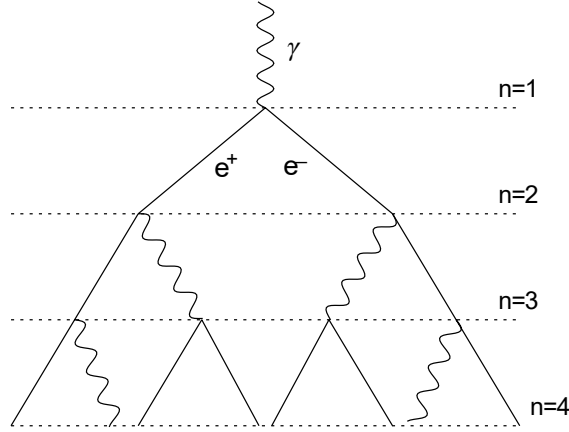


Figure 2.4. Schematic diagram of an electromagnetic shower according to the Heitler model. Cut-out from Matthews (2005).

There are two important conclusions that can be drawn from the Heitler model, which are

- the shower size is proportional to the initial particle's energy E_0 (see Equation 2.9), and
- the maximum shower depth increases logarithmically with the initial particle's energy and scales with the radiation length X_0 (see Equation 2.11).

However, the Heitler model is not accurate enough to describe the shower development near and beyond the maximum shower depth. For example, it does not take into consideration the fact that during the bremsstrahlung process several γ -rays are usually emitted over one radiation length.

An improved, semi-empirical description of the longitudinal shower development is given by Greisen (1956), according to which the number of secondary electrons at the atmospheric depth X is given by

$$N(X) = \frac{0.31}{\sqrt{\ln(E_0/E_c)}} \exp\left(\frac{X}{X_0}(1 - 1.5 \ln(s))\right). \quad (2.12)$$

The atmospheric depth X is the amount of matter the secondary particles pass through on their trajectory through the atmosphere⁷. The parameter s in Equation 2.12 is the age of the shower and is given by

$$s = 3 \cdot \left(1 + 2 \cdot \frac{\ln(E_0/E_c)}{X/X_0}\right)^{-1}. \quad (2.13)$$

It is defined such that

- $s = 0$: is the start of the shower,

⁷The vertical height z corresponding to the shower depth can be calculated as $X = \int_z^\infty \rho(z') dz'$, where $\rho(z')$ is the atmospheric density profile. One of the simplest assumptions is that of an isothermal density profile according to $\rho(z') = \rho_0 \exp(-z'/z_0)$ with the atmospheric density at sea level ρ_0 and the scale height z_0 (Errando et al. 2024).

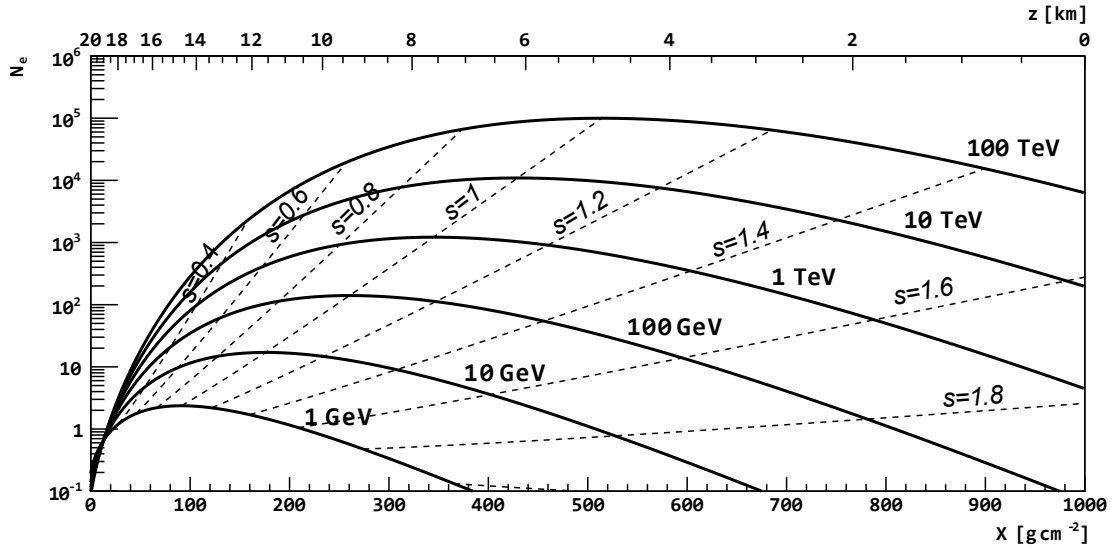


Figure 2.5. Longitudinal development of an electromagnetic shower described according to the Greisen formula (Equation 2.12). The solid line indicates the number of secondary electrons for different simulated primary particle energies as a function of atmospheric depth X (lower axis) and vertical altitude z (upper axis). An isothermal density profile is assumed for the atmosphere. Taken from Naurois et al. (2015).

- $s = 1$: is the maximum of the shower ($N(X_{\max})$), and
- $s > 1$: is the development of the shower after the maximum.

The longitudinal development of the shower according to Equation 2.12 is shown in Figure 2.5 for an isothermal atmospheric density profile (Naurois et al. 2015).

The lateral extension of an electromagnetic shower can be characterized by the Molière radius, which is given by

$$R_M = 0.24 \frac{X_0}{\rho}. \quad (2.14)$$

The Molière radius is the radius of a cylinder containing 90 % of the electromagnetic shower for a medium with density ρ . It increases with increasing altitude as the density of the atmosphere decreases and plays an important role in the detection of electromagnetic showers with the EAS technique described in Section 2.3. In addition, the Earth's geomagnetic field extends the lateral distribution of the secondary shower particles (Errando et al. 2024).

When the electrons travel through the atmosphere at a speed greater than the speed of light in the medium they emit light due to the Cherenkov effect, which can be observed in order to detect electromagnetic and hadronic showers. The Cherenkov effect is explained below.

2.2.2. Cherenkov Effect

The experimental and theoretical study of the Cherenkov effect is largely due to the work of the three Russian scientists Cherenkov, Frank, and Tamm in the 1930s, for which they were awarded the Nobel Prize in 1958. Cherenkov light is observed when

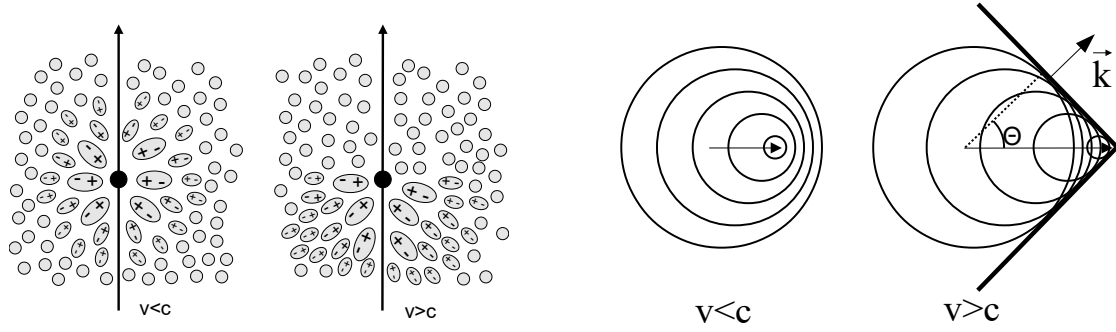


Figure 2.6. Cherenkov light generation in a dielectric medium. Left: The polarization of the medium along the path of the charged particle is shown for particle velocities $v < c/n$ and $v > c/n$. Right: The emission and interference of the electromagnetic waves according to the Huygens principle are displayed for the same cases of particle velocities, as well as the resulting wavefront of the Cherenkov light with the wave vector $\vec{k}$. Taken from Naurois et al. (2015).

a charged particle passing through a transparent dielectric medium has a velocity v that is faster than the speed of light c in the medium of refractive index n , i.e., when

$$v > \frac{c}{n} \quad (2.15)$$

is satisfied (Jelley 1961). The Cherenkov effect is explained according to Jelley (1961), where for simplicity an electron is considered as the charged particle. However, the same considerations apply to other charged particles such as protons or muons.

As the electron passes through the dielectric medium, it causes a local polarization of the medium by distorting the electrons in the atoms and molecules of the surrounding medium. This is shown on the left side of Figure 2.6. The following two cases are distinguished.

- $v < c/n$: In this case, the local polarization of the medium is symmetric around the electron moving along its path. Since the polarization is symmetric, the electromagnetic waves emitted by each dipole interfere destructively according to the Huygens principle, and therefore no resulting light is emitted.
- $v > c/n$: In this case, the local polarization is not symmetric along the path of the electron. The electromagnetic waves emitted by the individual dipole fields of the surrounding atoms and molecules add up coherently along the direction of the electron path, resulting in the emission of Cherenkov light.

In the second case, the electromagnetic waves of the individual dipoles add up coherently only if the Cherenkov relation

$$\cos \theta = \frac{1}{\beta n} \quad (2.16)$$

holds. Here $\beta = v/c$ and the Cherenkov angle θ is the angle between the wave vector $\vec{k}$ of the resulting Cherenkov light and the direction of motion of the electron, as shown on the right side of Figure 2.6. In the three-dimensional case, the resulting Cherenkov light is emitted along the surface of a cone.

Two important constraints can be derived from Equation 2.16. First, Cherenkov light is emitted only when the Cherenkov angle θ is greater than 0. This leads to a threshold velocity of

$$\beta_{\text{thres}} = \frac{1}{n} \quad (2.17)$$

Second, in the case $\beta \rightarrow 1$, the maximum Cherenkov angle is given by

$$\theta_{\text{max}} = \cos^{-1} \left(\frac{1}{n} \right) \quad (2.18)$$

and is therefore independent of the electron's velocity. Both of these constraints emphasize that the refractive index of the surrounding medium has an important effect on the generation and development of Cherenkov light⁸.

To calculate the number of Cherenkov photons N_γ produced by an electron per unit path length dx and wavelength $d\lambda$, the Frank-Tamm relation

$$\frac{d^2 N_\gamma}{dx d\lambda} = \frac{2\pi\alpha}{\lambda^2} \sin^2(\theta), \quad (2.19)$$

with the fine structure constant α , applies (Frank et al. 1937). The example of a Cherenkov spectrum is shown in Figure 2.7. A distinct peak is visible in the UV wavelength range between 300 nm – 350 nm. The attenuation of the Cherenkov light at wavelengths smaller and larger than the peak wavelength range is caused by absorption in the atmosphere due to Rayleigh and Mie scattering, respectively (Errando et al. 2024).

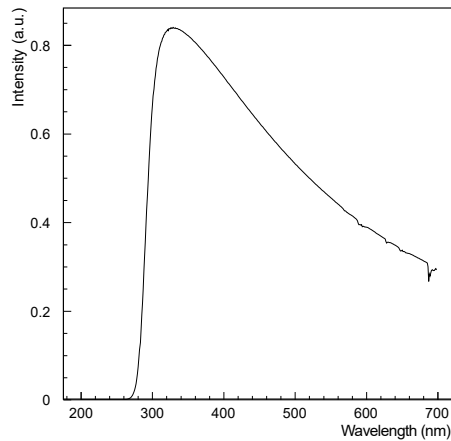


Figure 2.7. Spectral distribution of Cherenkov light at an altitude of 2200 m above sea level. A distinct peak is visible in the UV wavelength range of 300 nm – 350 nm. Adapted from Doering et al. (2001).

One of the many practical applications of the Cherenkov effect is the emission of Cherenkov light by the secondary electrons of an electromagnetic shower traveling at superluminal velocities through the Earth's atmosphere. The Cherenkov angle for an electron at an altitude of 30 km is $\sim 0.2^\circ$. As it travels through the atmosphere, the Cherenkov angle increases due to the change in refractive index caused by the atmospheric density profile, resulting in $\sim 1.5^\circ$ at sea level. This is illustrated on the left side of Figure 2.8. The intrinsic development of an electromagnetic shower and the change of the Cherenkov angle with decreasing altitude leads to a characteristic ring of Cherenkov light with a radius of ~ 150 m from the impact of the shower core on the Earth's surface. This is shown on the right side of Figure 2.8 for showers with different simulated primary energies E_0 ⁹. The fact that the Cherenkov light is mostly contained at and inside this ring is an important

⁸It should be added that the velocity of the particle can be translated into a kinetic energy, and thus the threshold velocity is also an indirect function of the mass of the particle. In air, the threshold kinetic energy is ~ 21 MeV for an electron and ~ 38 GeV for a proton.

⁹The interested reader is referred to Arbeletche et al. (2021) for a more detailed description of the angular distribution of Cherenkov light.

design feature for ground-based experiments attempting to image the Cherenkov light of an EAS (Naurois et al. 2015).

To determine the Cherenkov light yield from the secondary particles of an electromagnetic shower, Equation 2.19 applies. In the case of a vertically incident particle and assuming an isothermal density profile, e.g., Naurois et al. (2015) shows that

$$\frac{dN_\gamma}{d\lambda} \propto \frac{E_0}{E_c}. \quad (2.20)$$

Therefore, the Cherenkov light emitted by an electromagnetic shower is proportional to the energy of the primary particle. Furthermore, measuring the Cherenkov light emitted by an electromagnetic shower allows to determine the properties of the primary particle, which is explained in more detail in Section 2.3. Hadronic showers and their differences to electromagnetic showers are briefly explained in the following.

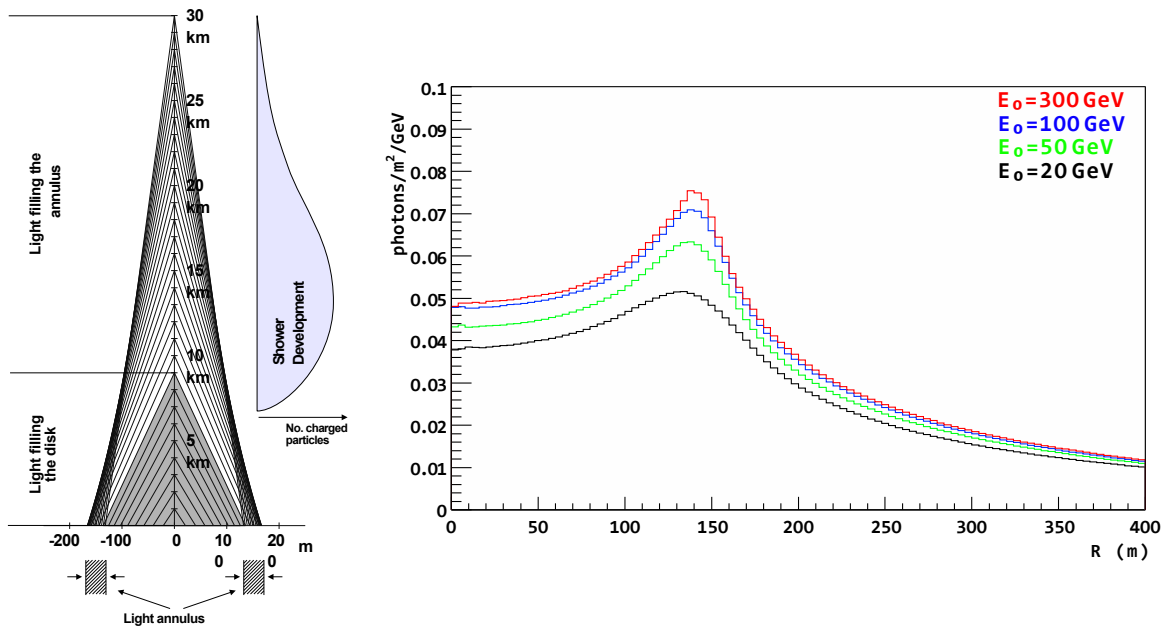


Figure 2.8. Longitudinal development of an electromagnetic shower (left) and lateral distribution of the emitted Cherenkov light for different initial energies E_0 of the primary γ -ray (right). A distinct peak in the Cherenkov light distribution is visible at approximately 150 m from the shower core on the ground. Adapted from Naurois et al. (2015).

2.2.3. Hadronic Showers

A hadronic shower is initiated when a hadronic cosmic-ray enters the Earth's atmosphere and interacts with the nuclei therein. The development of a hadronic shower is shown on the right side of Figure 2.9 and is qualitatively explained according to Longair (2011).

The interaction of a proton with a target nucleus is illustrated on the left side of Figure 2.9. The principal particles produced are pions (π^+ , π^- , π^0) due to the strong interaction between the proton and the target nucleus. In addition, strange particles as well as light nuclei and single nucleons (protons, neutrons) are produced due to

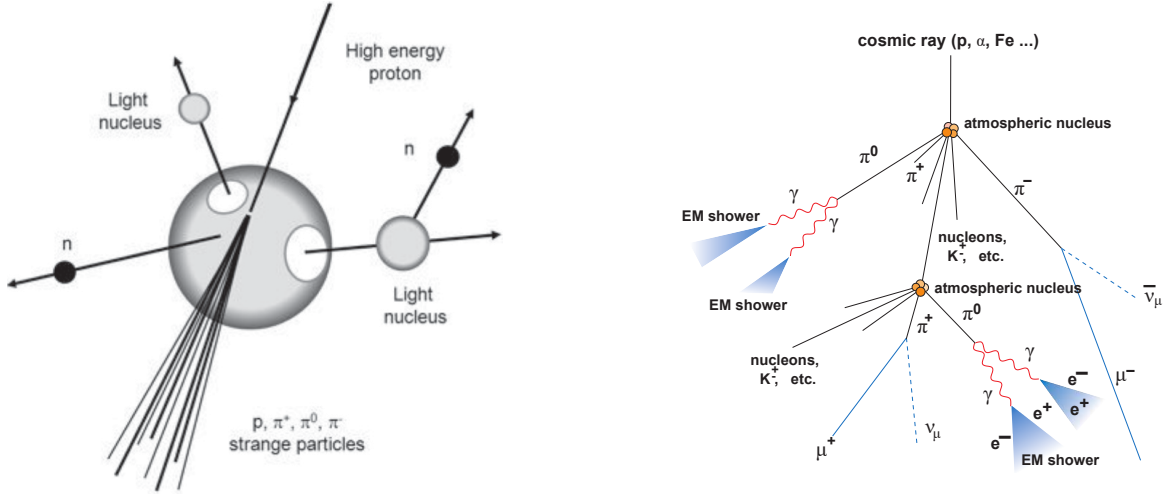


Figure 2.9. Interaction of a proton with a nucleus (left) and development of a hadronic shower in the Earth's atmosphere (right). Taken from Longair (2011) and Otte (2007), respectively.

the spallation of the target nucleus caused by the interaction between the proton and the single nucleons inside the target nucleus. The single nucleons and light nuclei continue to interact with other nuclei in the atmosphere, causing a nucleonic cascade until the energy per nucleon falls below 1 GeV, which is the energy required to produce pions. The neutral pions π^0 , with a short lifetime of $\sim 10^{-16}$ s, decay according to

$$\pi^0 \rightarrow \gamma + \gamma \quad (2.21)$$

and give rise to an electromagnetic shower. The charged pions have a slightly longer lifetime of $\sim 10^{-8}$ s, but many of them decay according to

$$\begin{aligned} \pi^+ &\rightarrow \mu^+ + \nu_\mu \\ \pi^- &\rightarrow \mu^- + \bar{\nu}_\mu. \end{aligned}$$

as they travel through the atmosphere. Most of the generated muons reach the Earth's surface because they have little interaction with other nuclei. Additionally, they have rather large relativistic Lorentz factors of $\gamma \geq 20$ and consequently only a minority of muons decays according to

$$\begin{aligned} \mu^+ &\rightarrow e^+ + \nu_e + \bar{\nu}_\mu \\ \mu^- &\rightarrow e^- + \bar{\nu}_e + \nu_\mu \end{aligned}$$

due to relativistic time dilation. In conclusion, hadronic showers can be understood as a superposition of electromagnetic subshowers in combination with muons and charged pions.

Hadronic showers differ from electromagnetic ones mainly by the different shower particles involved, which leads to a more irregular development of the shower, since a hadronic shower can contain several electromagnetic subshowers. The simulated Cherenkov light distributions at the Earth's surface for a 300 GeV γ -ray and a 1 TeV proton as the primary particle are shown on the left and right side of Figure 2.10, respectively. The distribution of Cherenkov light is more uniform for the electro-

magnetic shower than for the hadronic shower. Furthermore, the distribution of the hadronic shower shows characteristic rings of Cherenkov light, caused by the muons of the shower. Therefore, hadronic and electromagnetic showers can be distinguished by their secondary shower particles as well as by the lateral distribution of the emitted Cherenkov light. The two main techniques to detect electromagnetic showers are described in the following section.

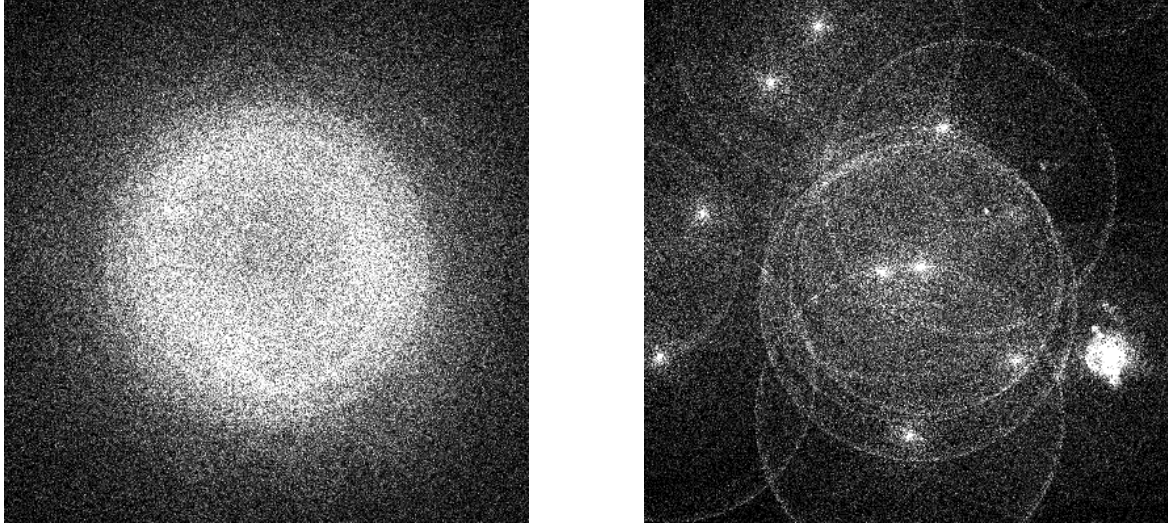


Figure 2.10. Simulated lateral Cherenkov light distribution for a 300 GeV γ -ray (left) and a 1 TeV proton (right) as the primary particle. The images are centered on the shower core. In the hadronic shower, the Cherenkov light rings are characteristic of muons. Taken from Bernlöhr (2024).

2.3. Detection of Extensive Air Showers

One cannot detect electromagnetic showers without detecting hadronic showers. In the following section, however, the focus will be on the detection of electromagnetic showers and the consequent treatment of hadronic showers as background. Nevertheless, it should be mentioned that there are dedicated facilities that are optimized for the detection of cosmic-rays. One example is the Pierre Auger Observatory in Argentina (The Pierre Auger Collaboration 2015).

There are two main techniques for detecting electromagnetic showers with ground-based facilities. The EAS arrays detect the secondary shower particles directly, while the Atmospheric Cherenkov Technique (ACT) detects them indirectly through their emitted Cherenkov light. The latter can be further divided into sampling arrays using the ACTs and the imaging ACT. The working principle of sampling arrays is the measurement of the lateral Cherenkov light distribution by placing mirrors over an area corresponding to the size of a Cherenkov light pool on the ground and reflecting the light into photosensitive devices such as, e.g., Photomultiplier Tubes (PMTs) (Aharonian et al. 2008). An example of such a facility is the Solar Tower Atmospheric Cherenkov Effect Experiment (STACEE), described in Gingrich et al. (2005). The imaging ACT measures the longitudinal and lateral distribution of the Cherenkov light emitted by the secondary shower particles. The following is a brief explanation of the working principle of an EAS array and a more detailed explanation

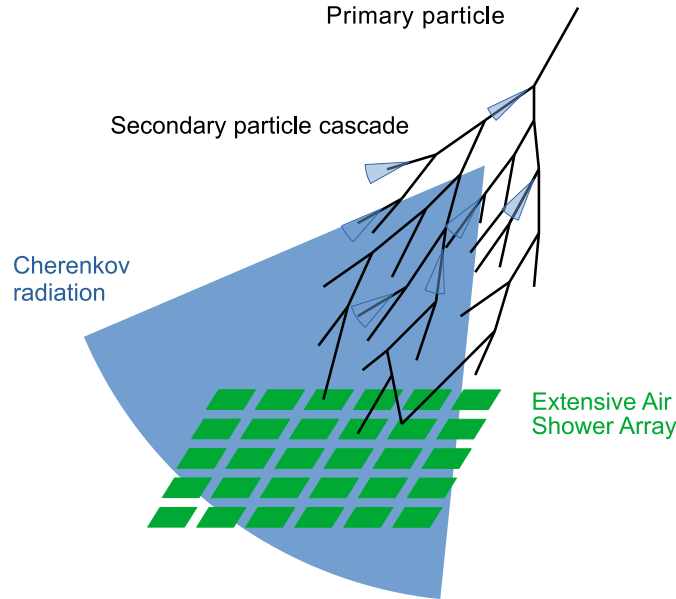


Figure 2.11. Schematic diagram of an EAS array. Adapted cut-out from Sitarek (2022).

of the imaging ACT. The emphasis is on the three main instrument properties – the energy threshold, the angular resolution and the ability to differentiate between electromagnetic and hadronic showers.

2.3.1. Extensive Air Shower Arrays

The lateral distribution of the secondary particles of an EAS can be measured with two different approaches. The first approach is a counting measurement using either scintillators or resistive plate chambers as detectors. With this approach, the measured signal is proportional to the amount of secondary particles counted. Two examples of EAS arrays using this principle are Tibet AS-gamma and ARGO-YBJ¹⁰. The second approach is a calorimetric measurement using water Cherenkov detectors, where the measured signal is proportional to the incident energy of the secondary shower particles. This is measured by the Cherenkov light of the secondary particles generated in water tanks. Ground-based facilities using this approach are in the past MILAGRO¹¹ and currently HAWC¹² (DuVernois et al. 2024). For both approaches, the tracks of the secondary particles passing the EAS array are measured, as shown in Figure 2.11. The design choices of an EAS array, which affect the energy threshold, the angular resolution, and the ability to discriminate between electromagnetic and hadronic showers, are briefly discussed.

The energy threshold depends mainly on the altitude of the EAS array and the density of detectors in the area enclosed by the array. To detect the secondary particles of a shower produced by a lower energy primary, the array must be located at higher altitudes to be closer to the shower maximum (see Figure 2.5). The effect of the altitude on the energy threshold of an EAS array is illustrated in Figure 2.12.

¹⁰Astrophysical Radiation with Ground-based Observatory at Yang-Ba-Jing

¹¹Multiple Institution Los Alamos Gamma Ray Observatory

¹²High Altitude Water Cherenkov

It is clearly visible that with increasing altitude, the fraction of primary particles producing an EAS with at least 100 particles each with energies above 100 MeV increases. The density of detectors within the enclosed area of the array determines the fraction of secondary particles that are detected. Therefore, a lower density of detectors leads to a higher energy threshold, and a higher density leads to a lower energy threshold.

Furthermore, the energy threshold of an EAS array depends on the shower development itself and mainly on the fluctuation of the depth of the first interaction of the primary particle in the atmosphere as well as the development of the shower after the maximum shower depth. Therefore, the energy threshold of an EAS array is usually given as the median energy of the detected primary γ -rays for a Crab-like spectrum with $E^{-2.6}$ (Aharonian et al. 2008).

The arrival times of the secondary shower particles as a function of the radial distance from the shower core are shown in Figure 2.13 for a high probability γ -ray event detected with the HAWC facility. The direction of the primary particle is determined by fitting this shower front. Therefore, the angular resolution depends on several factors. First, the shower core must be within the area enclosed by the detectors to determine the lateral extent of the shower. Second, the temporal resolution of the array must be high enough to resolve the temporal distribution of incoming secondary particles. Third, enough secondary particles must be detected to have good enough statistics to fit the shower front with sufficient accuracy (Aharonian et al. 2008; DuVernois et al. 2024).

The distinction between electromagnetic and hadronic showers is made by measuring the muon content of an EAS and taking into account the shower morphology. Hadronic showers have a higher muon content and a more irregular shower front than electromagnetic ones, as shown in Figure 2.14. Therefore, the time-incident detection of muons of an EAS allows the identification and consequent rejection of hadronic showers in the analysis. The interested reader is referred, e.g., to DuVernois et al. (2024) for more details on EAS arrays.

2.3.2. Imaging Atmospheric Cherenkov Telescopes

As explained in Section 2.2, the secondary particles of an electromagnetic shower emit Cherenkov light leading to a light pool at the Earth's surface around the shower core, i.e., the intersection between the extrapolated trajectory of the primary γ -ray and the Earth's surface (see Figure 2.10). The main characteristics of this light pool are a radius of ~ 150 m, a spectral peak in the UV wavelength range, and a duration of several nanoseconds. The Cherenkov photons are almost uniformly distributed within the light pool with a density of ~ 100 photons m^{-2} for an initial γ -ray energy of 1 TeV. Above the radius of ~ 150 m, the density of Cherenkov photons slowly decreases (see Figure 2.8). These shower characteristics drive the design of IACTs, which are telescopes using the imaging ACT. The design of the IACTs and their effect on the instrument characteristics is explained below.

The schematic diagram of an IACT and the imaging of an EAS are shown in Figure 2.15. Unlike EAS arrays, IACTs are usually designed with an altitude-azimuth mount and allow pointed observations of dedicated sources. This is a necessity due to their smaller FOV in comparison to EAS arrays. An IACT consists mainly of an optical system that collects the Cherenkov photons and a camera that takes an

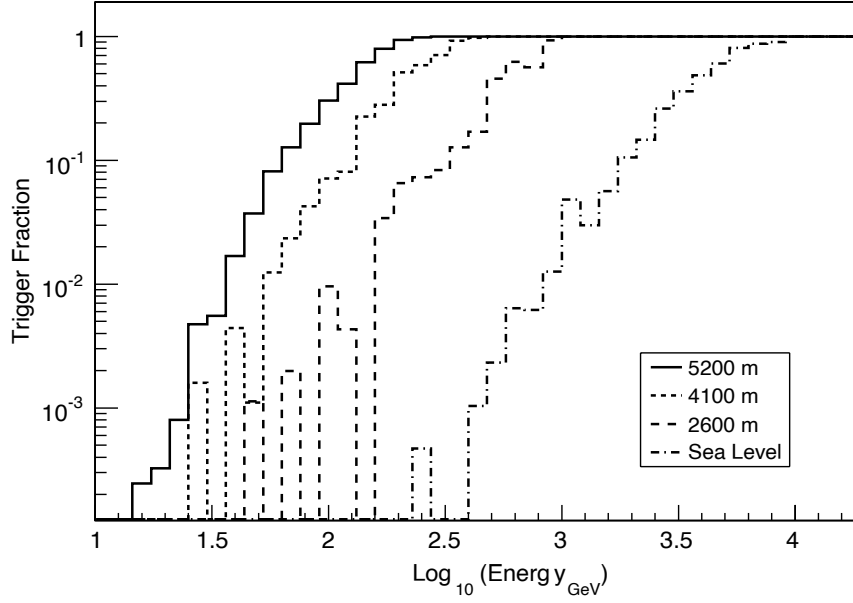


Figure 2.12. Fraction of primary particles as a function of primary particle energy for different observing altitudes above sea level. The primary particles give rise to an EAS with ≥ 100 secondary particles each with an energy of ≥ 10 MeV. Taken from Aharonian et al. (2008).

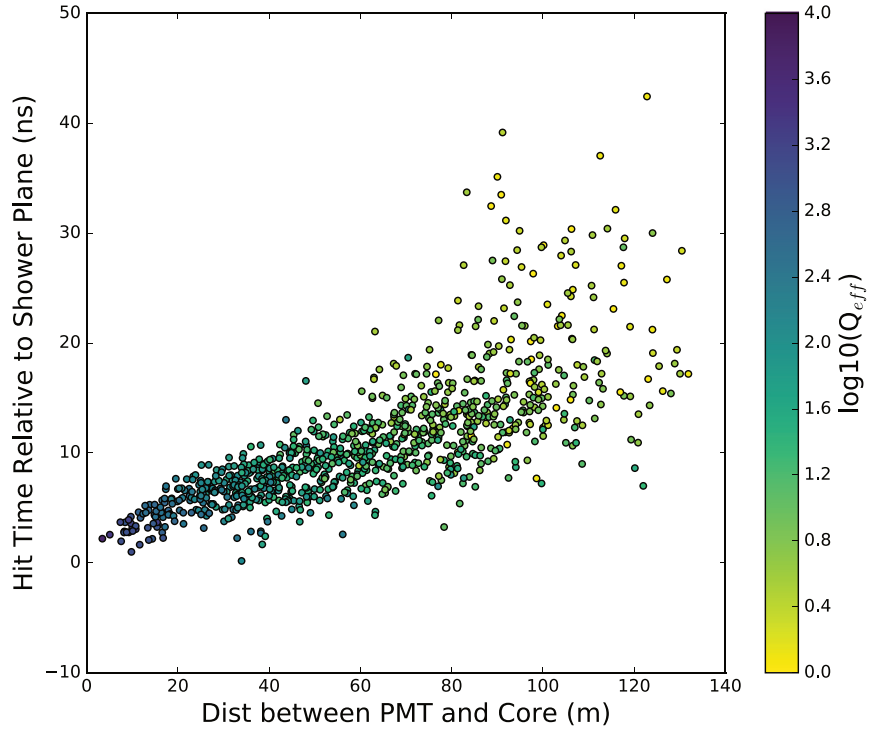


Figure 2.13. Detected shower wavefront of a high probability γ -ray event from the Crab Nebula as observed with HAWC. The timing of the individual detector elements relative to a plane shower front is shown as a function of the distance between the individual detector element and the shower core. A distinct curvature of the order of ~ 10 ns is visible. The color bar indicates the charge deposited in the individual detector elements. Taken from Abeysekara et al. (2017).

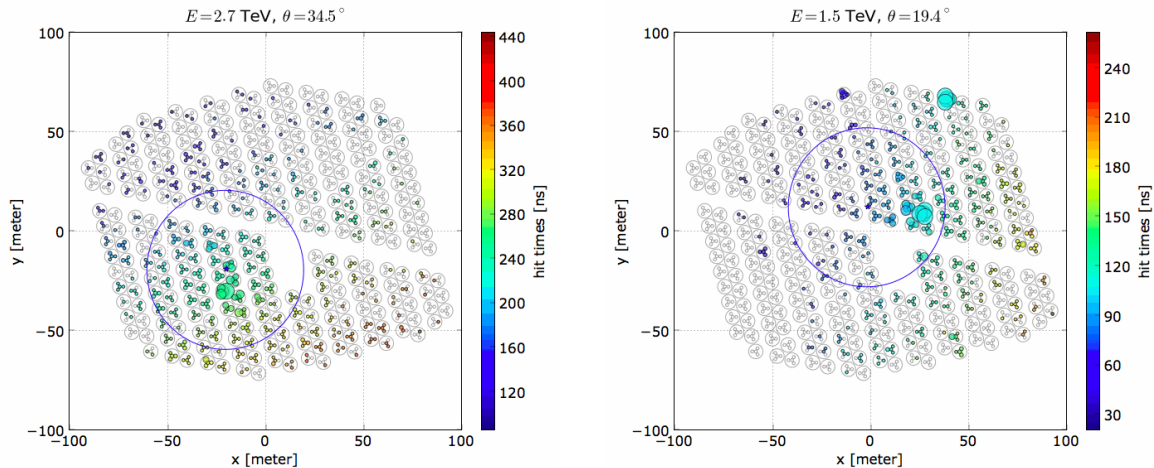


Figure 2.14. Distribution of arrival times for a shower simulated for a primary γ -ray (left) and a primary proton (right) for the HAWC detector. The blue star indicates the center of the shower core, and the markers are proportional to the corresponding signal. A more irregular morphology for hadronic showers is visible. Taken from HAWC Collaboration (2024).

image of the angular distribution of the Cherenkov light emitted by the EAS. The main parameters of the optical system and the camera are summarized in Table 2.1 and are described in the following. The characteristics of an IACT, the operation in an array and a brief comparison to EAS arrays is given afterwards.

Optical System

The optical system consists of a reflector with a focal length f to diameter D ratio in the order of $0.7 - 1.5$ and total mirror areas ranging from $\sim 10 \text{ m}^2$ to $\sim 600 \text{ m}^2$ to collect enough Cherenkov photons for image formation. The reflector has a tessellated mirror design consisting of ~ 10 to ~ 800 individual mirror facets¹³. The layout of the reflector usually follows a Davies-Cotton (DC) design for telescopes with reflector diameters of up to $\approx 13 \text{ m}$ to provide a good angular resolution over the entire Field of View (FOV) of the telescope. However, the DC design introduces a spread of the photon arrival times in the focal plane. Therefore, telescopes with larger diameters follow a parabolic design that is isochronous but has a slightly worse off-axis optical performance. More details on the DC design are given in Section 5.2.2. Additionally, the optical system should provide a $\text{FOV} \geq 3.5^\circ$ to observe the Cherenkov light of secondary particle showers with a large impact parameter, which is the distance between the shower core and the telescope. Due to the indirect detection of the EAS, the collection area of an IACT corresponds to $\sim 10^5 \text{ m}^2$ when located within the Cherenkov light pool (Aharonian et al. 2008). The optical system reflects the Cherenkov light into the focal plane, where a camera records the shower as a two-

¹³Production of monolithic mirrors with a size larger than $\sim 8 \text{ m}$ is limited by the transportation by road and the available facilities for the production of monolithic mirrors. Therefore, the tessellated mirror designs is more cost-efficient for reflectors exceeding that size (Bely 2003). This is the case for optical astronomy, where the mirrors need a higher optical quality than the mirrors of IACTs. It should be noted that the given threshold on the mirror size with cost might be different for IACTs.

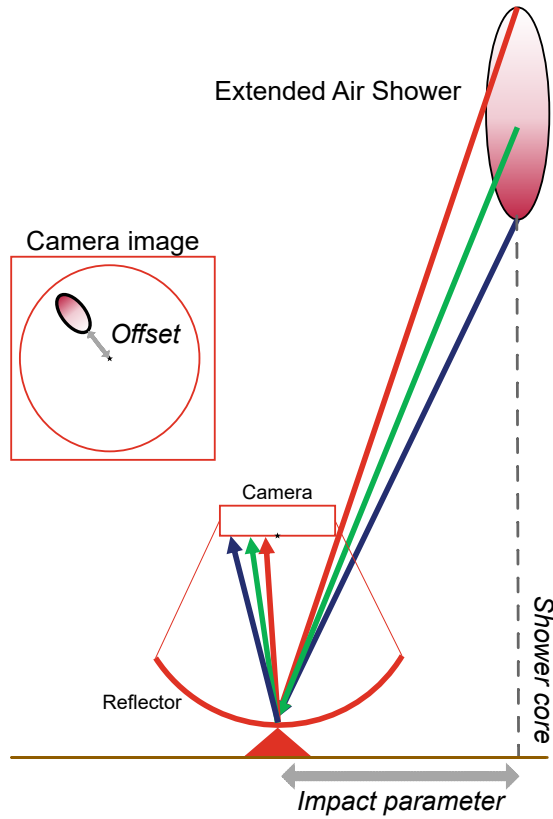


Figure 2.15. Schematic diagram of the imaging of an EAS with an IACT. The color gradient in the shower roughly represents the number of secondary particles in the shower. Adapted from Errando et al. (2024).

dimensional image.

Camera

The camera consists of photosensitive devices as individual pixels and converts the Cherenkov light into a measurable physical quantity such as an electric current or voltage. The operation of IACTs is limited to clear nights with moderate moonlight. The number of pixels is on the order of $\sim 10^3$ for PMTs or $\sim 10^4$ for Silicon Photomultipliers (SiPMs)¹⁴. To detect the Cherenkov light emitted by the EAS, short camera exposures of ≤ 30 ns are required to distinguish the Cherenkov light from the ever-present Night Sky Background (NSB). Therefore, the camera pixels must have the necessary time resolution and the connected camera readout electronics need high sampling rates of ~ 100 MHz – 1000 MHz to resolve the intrinsic duration of the Cherenkov light cone.

There are additional measures to keep the accidental trigger rate caused by the NSB low by applying a set of trigger criteria. These include having multiple pixels above a defined signal threshold within a short time coincidence window, as well as requiring that the corresponding pixels be adjacent. Common trigger criteria are a pixel multiplicity of ~ 4 and time coincidence windows of 3 ns – 25 ns (Aharonian et al. 2008). In Section 3.1.2, more details are given about the working principle of a

¹⁴While PMTs are still commonly used, there are already cameras that use SiPMs, as reported in, e.g., Pantaleo (2023).

Table 2.1. Typical parameters of the optical system and the camera of an Imaging Atmospheric Cherenkov Telescope. Information taken from Aharonian et al. (2008), Cortina et al. (2024), and Pantaleo (2023).

Optical System		Camera	
f/D	0.7 – 1.5	No. of pixels	$10^3 - 10^4$
No. mirror facets	$\sim 10 - 800$	Pixel type	PMT or SiPM
Mirror area	$10 \text{ m}^2 - 600 \text{ m}^2$	Pixel angular $\varnothing$	$\leq 0.1^\circ$
Field of View	$3.5^\circ - 10^\circ$	Time resolution	$\sim \text{ns}$

specific Cherenkov camera and the camera trigger that is associated with it. The design of the optical system and the camera affect the instrument characteristics of an IACT. This is further described below.

Instrument Characteristics

According to Aharonian et al. (2008), the signal-to-noise ratio of any telescope is given by

$$\frac{S}{N} \propto \left(\frac{\epsilon A_m}{\tau \Omega_{\text{pix}}} \right)^{1/2}. \quad (2.22)$$

It can be roughly divided into the main properties of an IACT, where the numerator resembles the light collection capability of the telescope and the denominator is the temporal and spatial resolution of the shower image. The photon collection capability is given by the mirror area A_m and a convolution of the reflectivity of the optical system and the quantum efficiency of the camera pixels ϵ . The temporal and spatial resolution of the shower image is given by the signal integration time τ and the angular pixel size Ω_{pix} .

Some important conclusions can be drawn from Equation 2.22 on the instrument characteristics of an IACT. A large mirror area A_m and a high photon collection capability lead to an increase of the signal-to-noise ratio. It also decreases the energy threshold, which is inversely proportional to the signal-to-noise ratio. Additionally, the signal integration timescale should be reduced to the intrinsic duration of the Cherenkov light emitted by the secondary particles to reduce the accidental trigger rate. To resolve the shower morphology, the angular diameter of the pixels Ω_{pix} should remain below the minimum lateral extent of the secondary particle shower core, which is on the order of 0.1° (Aharonian et al. 2008).

Good spatial resolution of the shower image is important for distinguishing between electromagnetic and hadronic showers. For the former, the angular distribution of the emitted Cherenkov light looks like a compact ellipse in the camera image, where the major and minor axes represent the longitudinal and lateral extent of the particle shower. Consequently, the major axis points in the direction of the primary particle. For a hadronic shower, the camera image is more diffuse and shows an irregular pattern caused by the electromagnetic subshowers. The Cherenkov light cone of a representative electromagnetic and a hadronic shower and the corresponding camera images are shown in Figure 2.16. The intrinsic morphology of the shower is used as a separation parameter by performing, e.g., a moment analysis of the shower image as proposed by Hillas (1985). Here, the length and width of the ellipse serve as indicators of the compactness of the ellipse, and thresholds on these parameters

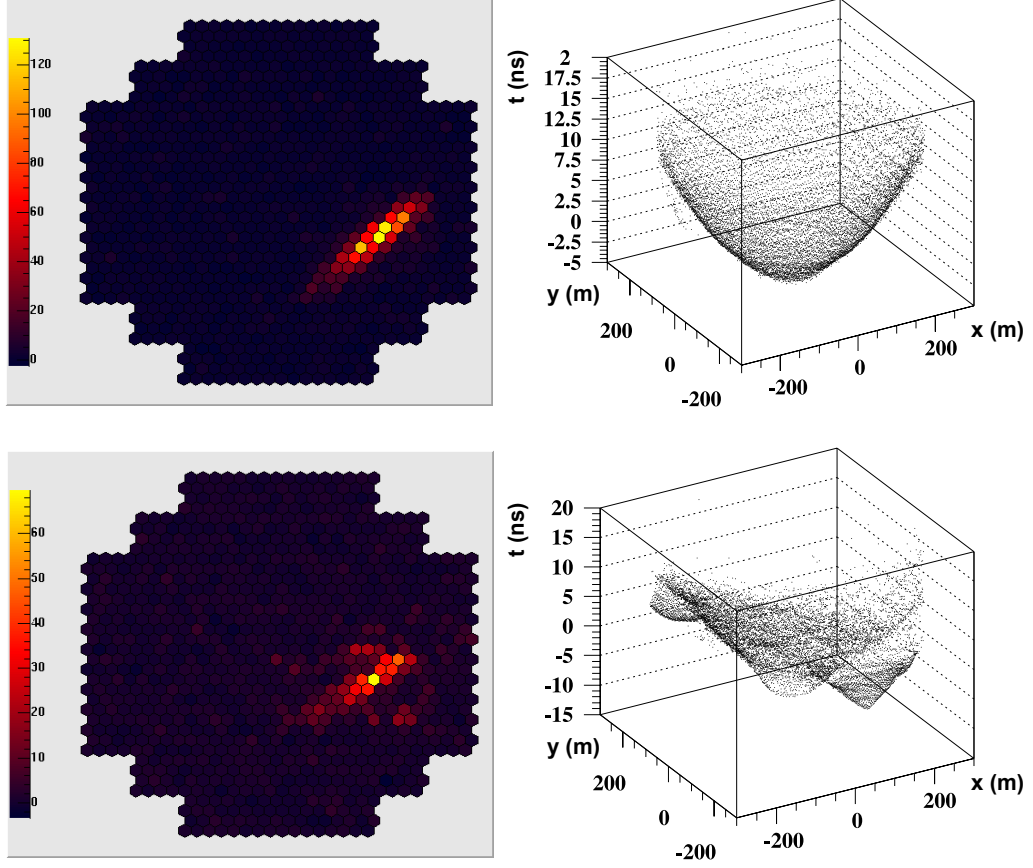


Figure 2.16. Cherenkov light wavefront (right) and corresponding camera image (left) for an electromagnetic shower (top) and a hadronic shower (bottom). The Cherenkov wavefront is from simulated showers, while the shower images are from real data. The camera images are taken from Hofmann (2012) and the Cherenkov wavefront is adapted from Oser et al. (2001).

allow the discrimination between electromagnetic and hadronic showers. In addition, the integrated intensity of the shower image serves as an estimate of the energy of the primary particle as a function of the impact parameter (Aharonian et al. 2008). This is discussed further in Chapter 9. For a more accurate determination of the properties of the primary particle and a substantial reduction of triggers by muons, several IACTs are operated as an array.

Stereoscopic Observations

Extending a single IACT to an array of several IACTs allows stereoscopic observation and imaging of the Cherenkov light emitted by the particle shower in three dimensions. This improves the angular and energy resolution by resolving the degeneracy of observing the same angular distribution of Cherenkov light emitted by particle showers with different primary particle energies for different impact parameters with a single IACT. Furthermore, this helps to reduce the hadronic background by introducing an array trigger and suppressing muon-induced subshowers, which are the dominant background (on the triggered events) for single IACTs (Aharonian et al. 2008). The stereoscopic approach is used for most modern IACT facilities such as H.E.S.S., MAGIC or the Very Energetic Radiation Imaging Telescope Array System (VERITAS).

Comparison: EAS and IACT Arrays

In summary, EAS and IACT arrays are suitable for different use cases. The former, with their high uptime of $> 90\%$ and their large FOV, are ideal for all-sky surveys. On the other hand, the operation of IACTs is limited to clear nights with moderate moonlight resulting in an uptime of approximately 15% . However, IACTs are well suited for follow-up observations of transient phenomena or for observing sources that require good angular and energy resolution. In addition, IACTs have a higher sensitivity per unit of observation time for point sources and have a lower energy threshold (Aharonian et al. 2008). A combination of both approaches in a single facility is done, e.g., by the LHAASO collaboration as described in Cao et al. (2019). In the following chapter, the current IACT array H.E.S.S. and the future CTAO are described, as they are crucial for this work.

Ground-Based Facilities

The field of ground-based TeV astronomy began in the second half of the twentieth century. In 1968, one of the first IACTs was built at the Whipple Observatory on Mount Hopkins in Arizona, USA. The Whipple 10 m reflector consisted out of 248 single mirror facets and a single PMT was installed in the focal plane of the telescope (Fazio et al. 1968). An upgrade of the focal plane instrumentation with the installation of a 37 pixel camera in 1983 allowed imaging of the Cherenkov light emitted by the secondary particle showers. This, and the suggestion of Hillas (1985) to use a second-order moment analysis of the recorded images to distinguish between electromagnetic and hadronic showers, laid the groundwork for the unambiguous detection of the Crab Nebula above energies of 700 GeV in 1989 (Weekes et al. 1989). The detection of the first extragalactic source Markarian 421 followed shortly after in 1992 (Punch et al. 1992). The Whipple 10 m reflector provided the proof of concept for the imaging ACT and achieved several milestones in the development of ground-based TeV astronomy.

Building on this success, the High Energy Gamma Ray Astronomy (HEGRA) collaboration started in 1991 to build an array of six IACTs at the El Roque de los Muchachos Observatory on La Palma, Spain. With the HEGRA array, stereoscopic observations were performed for the first time and showed to improve the reconstruction of the image parameters of the recorded Cherenkov light distribution (Mirzoyan 2024; Kohnle et al. 1996). For a more extensive history of the field, the reader is referred to Mirzoyan (2024).

The stereoscopic approach is also followed by the three major IACT facilities currently in operation, H.E.S.S., MAGIC, and VERITAS, built in the first decade of this century and located in the Khomas Highlands (Namibia), La Palma (Spain), and Arizona (USA), respectively. Besides increasing the sensitivity in the core energy range, one of the main goals of these IACT arrays was also to lower the energy threshold into the ~ 20 GeV region. In Section 3.1, H.E.S.S. is explained in more detail. The interested reader is referred to Blanch et al. (2024) and Hanna et al. (2024) for more information on MAGIC and VERITAS, respectively.

A unification of the worldwide ground-based TeV astronomy community led to the formation of the Cherenkov Telescope Array Observatory (CTAO), which was originally proposed in 2005. The goal is to build a ground-based TeV astronomy facility of IACTs with unprecedented sensitivity with one site in the northern hemisphere and one site in the southern hemisphere (Hofmann et al. 2024). The CTAO is described further in Section 3.2.



Figure 3.1. The H.E.S.S. array in the Khomas highlands, Namibia. The four small telescopes CT1-4 and the large telescope CT5 in the center of the array are visible. Image credit belongs to F. van Greunen (H.E.S.S. Collaboration).

3.1. High Energy Stereoscopic System

The High Energy Stereoscopic System is a ground-based TeV astronomy facility that is located in the Khomas highlands in Namibia at an altitude of 1800 m and is depicted in Figure 3.1. The first phase of the experiment involved the deployment of four telescopes, designated CT1-4, arranged in a square with side lengths of 120 m. The design of the telescopes and array arrangement aimed for an energy threshold of ~ 100 GeV. The first of the four telescopes commenced operation in June 2002, followed by the other three by the end of 2003 (Aharonian et al. 2006). The initial proposal to extend the array with 12 additional telescopes of the same design as CT1-4 was abandoned in 2005, and a new plan was formulated to install a single telescope with a larger mirror area in the center of the array. The primary objective of this extension was to reduce the energy threshold of the array to ~ 20 GeV, thereby increasing the overlap with space-based telescopes such as the Fermi Gamma-Ray Space Telescope (Punch 2005). Consequently, the H.E.S.S. array entered its second phase in 2012 with the installation of CT5. The addition of CT5 to the array led to a decrease in the energy threshold down to ~ 80 GeV for the analysis of the AGN PKS2155-304, as described by Zaborov et al. (2016). The energy threshold can be reduced even further, e.g., for pulsar observations, where the systematic uncertainties are smaller, as discussed in H.E.S.S. Collaboration et al. (2018a). Further discussion of the observation of pulsars with CT5 will be presented in Part III.

Since H.E.S.S. started operating it produced numerous scientific achievements in the field of TeV astronomy, ranking among the top ten most influential observatories

in 2009 (Madrid et al. 2009). Two recent major scientific highlights of H.E.S.S. comprise the first time detection of VHE emission of a GRB in 2019 as well as of a recurrent nova in 2021. These observations verified previous assumptions and established both source classes as emitters of VHE γ -rays (H.E.S.S. Collaboration et al. 2019, 2022). For a recent overview of the scientific highlights of H.E.S.S. the interested reader is referred to Pühlhofer et al. (2024).

H.E.S.S. was initially planned to operate until 2019. However, given that H.E.S.S. is currently the only operational IACT facility in the southern hemisphere, operations have been extended until 2024. A further extension up to 2028 is currently under review. This section focuses on the technical systems of H.E.S.S. that are relevant to this thesis. This encompasses the optical system described in Section 3.1.1, the cameras discussed in Section 3.1.2, and the central trigger system and event timing, as detailed in Section 3.1.3. A comprehensive overview of H.E.S.S. is given in Pühlhofer et al. (2024).

3.1.1. Optical Systems

The optical system of an IACT collects and reflects the Cherenkov light emitted by the EAS to the detector located in the focal plane of the telescope. Its main objective is to provide an image of the angular distribution of the Cherenkov light as free of optical aberrations as possible¹. However, the actual design is always a tradeoff between cost, collection area and imaging quality. The optical system is characterized by the optical Point Spread Function (PSF) and the pointing accuracy. The former quantifies the size of the reflected light spot in the focal plane of the telescope for a point source located at infinity as a function of the position in the telescope FOV. The latter quantifies how accurately the optical axis coincides with the tracking position in the focal plane. Both of these quantities need to be good and well understood in order to provide high quality observational data.

The optical system can be divided into several subsystems and consists of

- the telescope structure and drive system,
- the mirror system, and
- the mirror alignment system.

In addition, CT5 is equipped with a camera focusing system. This allows the camera to be moved in the focal plane along the direction of the optical axis. The main parameters of the optical system of the H.E.S.S. telescopes are listed in Table 3.1 and the subsystems are described below. The section concludes with a description of the optical PSF and the pointing accuracy of the telescopes and the corresponding monitoring procedure.

Telescope Structures and Drive Systems

The three main characteristics of the telescope structure and drive system are the stiffness of the structure, the tracking accuracy and the slew rate of the drive system. The former affects the bending behavior of the telescope over different positions in

¹The three most important optical aberrations are spherical aberration, coma, and astigmatism. For a detailed description of these, the interested reader is referred to, e.g., Sasián (2012).

Table 3.1. Main parameters of the optical system of the H.E.S.S. telescopes. Information taken from Bernlöhr et al. (2003), Bolz (2004), Cornils et al. (2005), Hofverberg et al. (2013), and Gottschall et al. (2015).

System	Parameter		CT1-4	CT5
Structure	Mounting		Altitude-azimuth	
	Material		Steel	
	Weight		~ 60 t	~ 600 t
Drive System	Elevation	slew rate	100 ° min ⁻¹	100 ° min ⁻¹
		tracking RMS	0.9"	2.1"
		range	−35° to 90°	−32° to 175°
	Azimuth	slew rate	100 ° min ⁻¹	100 ° min ⁻¹
		tracking RMS	1.9"	3.0"
		range	≥ 385°	560°
Mirror System	f/D		~ 1.2	~ 1.3
	No. mirror facets		380	876
	Mirror area		107 m ²	614 m ²
	Reflector design		Davies-Cotton	Parabolic

the sky and thus the imaging capability of the telescope. The latter two describes how accurate a sky position can be tracked and how fast the telescope reaches the desired observation position. The speed to reach a desired observation position is especially important for transient phenomena like GRBs where a small time on target is critical. The ideal case would be a very stiff structure with a high tracking accuracy and a high slew rate. In a realistic scenario, there is always a trade-off between the slew rate and the stiffness of the structure. This is due to the fact that a very stiff structure comes with an increased weight and consequently the slew rate is limited by the achievable power of the installed drive system motors. Another limitation is imposed by the flexibility of the telescope structure and braking power of the drive system. Therefore, different scientific cases warrant different designs of the telescope structure.

In the case of the five H.E.S.S. telescopes, the structure is made out of steel in order to minimize the bending of the reflector shape and therefore provide stable imaging over a wide range of elevation angles (Bernlöhr et al. 2003; Cornils et al. 2005). This eliminates the need to adjust the alignment of the mirrors as a function of the elevation angle. The telescopes have an altitude-azimuth mount and the elevation axis ends in a pair of towers. These towers are placed on circular rails with a diameter of 13.6 m and 36 m for CT1-4 and CT5, respectively (Bernlöhr et al. 2003; Hofverberg et al. 2013).

To move CT1-4 along the azimuth axis, the drive system of CT1-4 consists of six wheels with friction drives on which the ~ 60 t telescope structure is placed. The same drive system is used for the elevation axis, resulting in a slew rate of $100^\circ \text{ min}^{-1}$ in both axes. The range of motion for the azimuth axis is $\geq 385^\circ$ and for the elevation axis is -35° to 90° with respect to the horizontal axis (Bolz 2004).

The ~ 600 t structure of CT5 is placed on twelve wheels in azimuth and the twelve wheels are driven by four servo motors. The total range of motion in azimuth is 560° and the slew rate is $100^\circ \text{ min}^{-1}$. The same drive system is used for the elevation axis. This results in the same slew rate and allows a range of motion of -35° to 175° with

respect to the horizontal axis. In principle, the design of the elevation drive system of CT5 allows the observation of sources in reverse mode by moving the detector to elevation angles of $> 90^\circ$. This allows a shorter time on target and is relevant for transient phenomena like a GRB where time is a critical factor (Hofverberg et al. 2013). The impact of the reverse pointing on the optical PSF and reconstruction of the Cherenkov air shower parameters has been investigated by Gottschall (2018). However, this mode is not been used in regular observations so far. The tracking accuracy in elevation and azimuth is $0.9''$ and $1.9''$ for CT1-4, respectively (Bolz 2004). For CT5, the corresponding value is $2.1''$ in elevation and $3.0''$ in azimuth (Hofverberg et al. 2013). The task of the drive system is to provide stable tracking within the given accuracy and to position the reflector such that the mirrors can collect the Cherenkov light emitted by the particle shower. The mirror systems are described below.

Mirror Systems

IACTs require a large telescope FOV and a small f/D ratio, as described in Section 2.3.2. Therefore, in order to save costs, the currently operating IACT arrays use telescopes with a tessellated mirror design².

The reflectors follow two basic layouts – the Davies-Cotton and the parabolic layout as described in Section 2.3.2. While the former provides good imaging capabilities even for off-axis light³, it introduces a time dispersion of the photon arrival times in the focal plane that grows linearly with the reflector diameter for a fixed f/D ratio. In contrast, the latter layout is isochronous, but offers reduced imaging capability for off-axis light compared to the Davies-Cotton layout. The final choice of layout therefore depends on the dimensions of the reflector. A mixture of both designs is also a possibility. In both cases, the individual mirror facets usually follow a spherical design for cost reasons.

The layout of the mirror system of the CT1-4 telescopes is shown on the left side of Figure 3.2. It is divided into twelve sectors and consists of 380 round mirror facets with a diameter of 60 cm each. This results in a mirror area of 107 m^2 , which is reduced by shadowing to an effective mirror area of $\sim 94 \text{ m}^2$. The layout of the reflector follows a Davies-Cotton design with a diameter of $\sim 12 \text{ m}$ and a focal length of 15 m resulting in a f/D ratio of $f/D \approx 1.2$. For the given f/D ratio, the Davies-Cotton design introduces a dispersion in the photon arrival times of $\sim 1.4 \text{ ns}$ in the focal plane. For the scientific performance of the telescope, this is still unproblematic since this time spread is in the same order of magnitude as the intrinsic time spread of the Cherenkov wavefront (Bernlöhr et al. 2003).

The CT5 reflector is shown on the right side of Figure 3.2. It has a rectangular shape with dimensions of $24 \text{ m} \times 32 \text{ m}$ (width x height), which corresponds to a circular reflector with a diameter of 28 m. The tessellated mirror system consists of 876 mirror facets with a hexagonal shape to minimize light collection losses between the individual mirror facets. The mirror facets have a flat-to-flat diameter of 90 cm, resulting in a total mirror area of 614 m^2 . The reflector has a focal length of 36 m and this results in a $f/D \approx 1.3$ for the given reflector diameter (Cornils et al. 2005;

²In addition, one of the commonly used telescope designs, the DC design, requires a tessellated mirror design.

³Off-axis light refers to incoming light that has an angle of incidence with respect to the optical axis of the telescope.

Gottschall et al. 2015). For a reflector with the dimensions of CT5, the Davies-Cotton layout would have led to an increased energy threshold, since only more energetic γ -rays would have triggered the telescope. Therefore, a parabolic layout was chosen (Cornils et al. 2005). For an ideal parabolic layout, the focal length of each mirror facet would vary with its position in the reflector. However, simulations by Cornils et al. (2005) showed that the effect of different focal lengths on the optical imaging qualities of the telescope is negligible, while the manufacturing costs increase significantly. Therefore, a single focal length for all mirror facets was chosen.

In order to reflect the light of each mirror facet in a single point in the focal plane, the mirrors need to be aligned precisely. The alignment systems responsible for this are explained below.

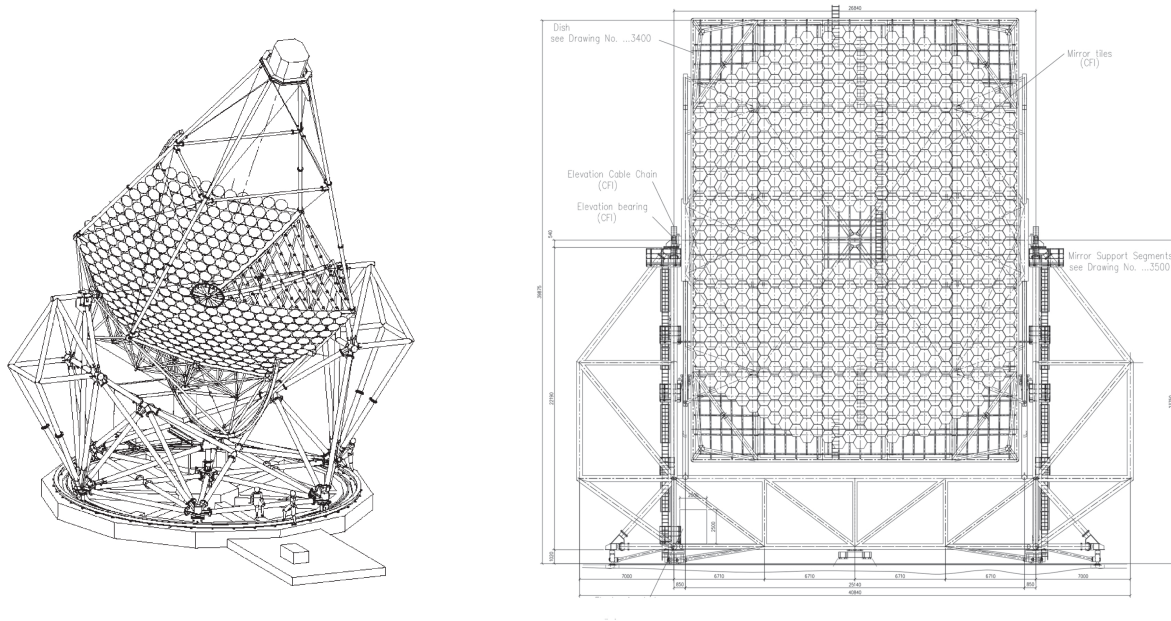


Figure 3.2. Reflector layout of the H.E.S.S. telescopes for CT1-4 (left) and CT5 (right). Taken from Bernlöhner et al. (2003) and Benkhali (2017), respectively.

Mirror Alignment Systems and Alignment Procedure

The purpose of the mirror alignment system is to precisely align each of the mirror facets so that their reflected light from a point source is focused into a single light spot in the focal plane. To accomplish this, the mirror facets are typically mounted at three points on the mirror support structure, and the tilt of the mirror facets can then be adjusted either manually or using a motorized system. An optical feedback system can be used to determine the correlation between the movement of the light spot in the focal plane and the amount of movement required to tilt the mirror by a given amount. Once this correlation is known, the mirror facets are oriented such that their light is reflected in the same spot. However, the optical performance of the telescope is affected by, among other things, the gravitational bending of the telescope structure and the bending of the mirror mounting as a function of the elevation of the observed sky position. Consequently, the stiffness of the telescope structure is a key factor in the design of the mirror alignment system.

There are two design concepts for a mirror alignment system. While the initial alignment system design concept is suitable for both manual and motorized alignment systems, active alignment is only possible when a motorized system is used. With the initial alignment system, the mirror facets of the telescope are aligned once and the alignment is optimized for a wide range of elevation angles. This alignment is appropriate when the telescope structure is rigid enough to provide adequate imaging capability over the range of elevation angles used for observations. The active alignment system adjusts the alignment as a function of the elevation angle of the observation. This is accomplished either by using an active feedback system of the alignment status or by using lookup tables that store the optimal mirror positions as a function of elevation angle. The latter approach only works if the deformation of the telescope structure is mainly elastic. The active alignment is used when the telescope structure is not rigid enough to provide adequate imaging capabilities over the range of elevation angles, which is the case for large carbon fiber structures. The active alignment system is used for the MAGIC telescopes or the Large-Sized Telescopes (LSTs) of the CTAO, as described in Biland et al. (2007) and Hayashida et al. (2015), respectively. Since the steel structure of the five H.E.S.S. telescopes is rigid enough to provide adequate imaging over the range of observation elevation angles, they use an initial alignment procedure described in more detail here.

The mirror alignment systems of CT1-4 and CT5 follow the same basic design and operating principle, but differ slightly in their technical properties and associated control electronics. The mechanical components and the mirror alignment procedure are explained according to Bernlöhr et al. (2003) and Cornils et al. (2003) for CT1-4 and Gottschall et al. (2015) for CT5. For a more detailed explanation of the control electronics and software, the reader is referred to Cornils (2006) and Schwarzburg (2012) for CT1-4 and CT5, respectively.

The mechanical components of the mirror alignment system and the interface to the mirror support structure are shown in Figure 3.3. Two motorized actuators and a fix point are screwed to metal plates that are glued to the back of each mirror facet and form the interface between the mirror facet and the mirror support structure⁴. The fix point is fixed in length and has only rotational degrees of freedom. The tilt of the mirror facets is adjusted by the motorized actuators, which are adjustable in length and the spindle of the actuator is driven by a motor unit. The movement of the motor unit is detected by Hall sensors that detect the rotation of the motor. To determine the step resolution of the actuator spindle, it is necessary to know the number of Hall counts per motor revolution, the pitch of the actuator spindle, and the ratio of the worm gear between the spindle and the motor unit. Combining this information results in a step resolution of $3.4\text{ }\mu\text{m}$ and $2.4\text{ }\mu\text{m}$, which corresponds to a mirror tilt of 0.013 mrad and 0.005 mrad ⁵ for CT1-4 and CT5, respectively. The technical parameters of the mirror alignment system components are summarized in Table 3.2. Here, one of the actuators provides tilt in two directions and the other actuator provides tilt in one direction in the plane of the mirror. This, together with

⁴The main difference in the interface between the mirror facet and the mirror support structure between CT1-4 and CT5 is the mounting of the actuators and the fix point to the mirror support structure. For CT1-4, the mechanical components are mounted to a support triangle that is mounted to the mirror support structure. For CT5, the actuators and the fix point are mounted directly to the mirror support structure.

⁵These mirror tilts correspond to $\sim \frac{1}{250}$ and $\frac{1}{100}$ of a camera pixel FOV for CT1-4 and CT5, respectively.

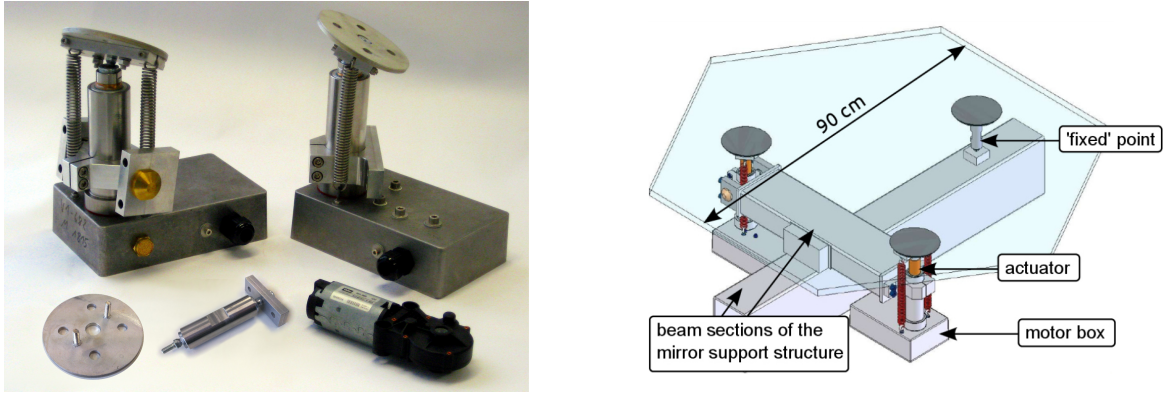


Figure 3.3. Mechanical components (left) and the mounting of the mirror alignment system to the mirror support structure of CT5 (right). Taken from Schwarzburg (2012).

Table 3.2. Technical parameters of the mirror alignment system for CT1-4 and CT5. Information taken from Bernlöhr et al. (2003) and Gottschall et al. (2015) for CT1-4 and CT5, respectively.

	CT1-4	CT5
Actuator movement range	30 mm	40 mm
Lift per motor turn	0.75 mm	1.00 mm
Hall sensor edges per motor turn	220	420
Lift per hall sensor edge	3.4 μm	2.4 μm
Mirror tilt per hall sensor edge	0.013 mrad	0.005 mrad

the fix point, fully constrains the position and tilt of the mirror facet and avoids stressing the mirror facet during movement of the actuators.

To align the individual mirror facets so that they reflect their light in a single spot in the focal plane, one can either use an artificial light source located at a certain distance from the telescope, or one can use a star. The second approach is used in H.E.S.S. The basic mirror alignment procedure is shown in Figure 3.4. A star between an elevation of $60^\circ - 70^\circ$ is tracked in order to achieve an optimal PSF around an elevation angle of 65° , the main observing range of the telescopes. The light from the star is reflected by each mirror facet onto an optical target⁶, which is placed in front of the camera. The optical feedback is provided by a Charged-Coupled Device (CCD) camera located in the center of the reflector, which observes the lid of the camera and is therefore named LidCCD. If all the mirror facets of a telescope are not aligned, one light spot per mirror facet is visible in the image of the LidCCD. By taking an image with the LidCCD before and after the tilting of a mirror facet by a certain amount of actuator steps, one can calculate the difference image and determine the correlation between the amount of actuator steps and the movement of the light spot in the focal plane. Once this correlation is known the mirror facet can be moved to the desired position. By repeating this procedure for each of the mirror facets, all of the individual mirror facets can be tilted so that their light is reflected into the same spot. Most of the steps of the alignment procedure are automated.

⁶The optical target is essentially a diffuse reflective surface. For CT1-4, the optical target is the camera lid, while for the FlashCam camera in CT5 a dedicated circular target with a diameter of

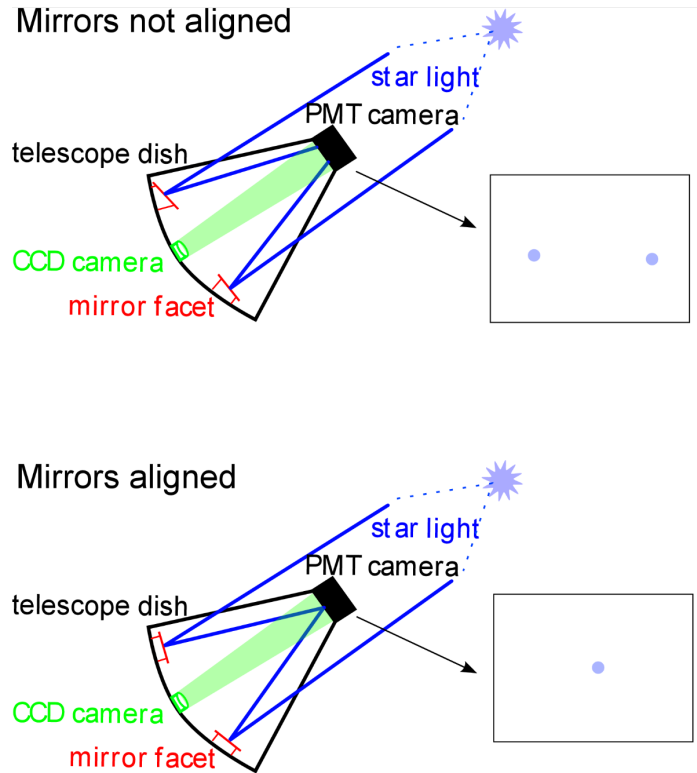


Figure 3.4. Schematic diagram of the mirror alignment procedure. In the top case, the mirrors are not aligned and the resulting image of the optical target is shown on the right side for two mirrors exemplary. On the bottom, all the mirrors are aligned. Cut-out from Schwarzburg (2012).

Mirror alignment has an important influence on the optical performance of the telescope. The long-term quality of the mirror alignment can be quantified by monitoring the optical PSF. In addition, the mirror alignment determines the pointing of the telescope, which is the position of the optical axis in the focal plane. After a brief description how the H.E.S.S. telescopes are focused, both of these quantities and their measurement are explained.

Focusing of the H.E.S.S. Telescopes

When it comes to focusing an IACT, there are two approaches as described in Hofmann (2001). The first approach is to focus the telescope in the direction of the Cherenkov photons at infinity, as would be the case in optical astronomy. This is a valid approach because the direction of the primary particle and thus the direction of the Cherenkov photons is important and not necessarily their exact position. In contrast, the second approach focuses the telescope on the height of the EAS at an altitude of the order of 10 km – 30 km. This approach allows a better imaging of the Cherenkov light emitted by the EAS and a more precise determination of the properties of the shower, which are used to derive the properties of the primary particle. For this reason, this is the main approach taken for the design of IACTs.

175 mm is used.

As a consequence, the detector has to be placed at a distance of

$$f_{\text{opt}} = \frac{f}{1 - f/S} \quad (3.1)$$

from the reflector, where f is the nominal focal length of the reflector and S is the distance between the telescope and the typical maximum of the particle shower. For the H.E.S.S. telescopes, this is accomplished in different ways for CT1-4 and CT5.

The smaller telescopes CT1-4 are focused to an height of the EAS of ~ 8 km. This is achieved by locating the photon detection plane⁷ approximately 30 mm behind the camera lid. The position of the camera lid corresponds to the nominal focal plane of 15 m at which the individual mirror facets are aligned when observing a star located at infinity (Cornils et al. 2003).

Because the distance between the telescope and the EAS depends on the elevation of the observed astronomical source, as well as the energy of the primary particle, CT5 is equipped with a focusing system. In principle, this focusing system allows the camera to be moved in the focal plane along the direction of the optical axis, providing optimal imaging capabilities for different elevation angles (Bolmont et al. 2014). A schematic diagram of the focusing system is shown in Figure 3.5 and its technical parameters are summarized in Table 3.3. Currently, two fixed settings of the focusing system are used. One for regular observing runs and one for aligning the mirrors and measuring the optical PSF of the telescope. The former focuses the telescope to a height of 15 km at zenith on the photon detection plane of the camera. The latter focuses the telescope to infinity on the camera lid, which is located at the nominal focal length of $f = 36$ m from the center of the reflector. The effect of adjusting the focus of CT5 on the height of the EAS using Monte Carlo simulations is shown in Trichard et al. (2015) and described in detail in Trichard (2015). The calibration runs to measure the optical PSF and the pointing of the telescope are described below.

Table 3.3. Technical parameters of the focusing system of CT5. The negative zenith angles indicate that CT5 is capable of reverse observations by moving the camera through zenith. The initial values are taken from Bolmont et al. (2014) and the values denoted with $\dagger$ were updated according to Salzmann (2020) after the installation of a new focal plane instrument in 2019.

Parameter	Value
Focus range	230 mm
Distance reflector center $\leftrightarrow$ camera lid †	35.97 mm – 36.20 mm
Depth of field †	5.8 km to ∞
Position accuracy	0.35 mm
Moving speed	0.015 m s^{-1}
Zenith angle	125° to -90°
Temperature range	0°C to 50°C

⁷The photon detection plane is defined by the entrance plane of the Winston cones. Winston cones are non-imaging light collectors in front of the photosensitive devices of the camera. Their task is to reduce light losses by minimizing the non-photosensitive area between the photosensitive devices.

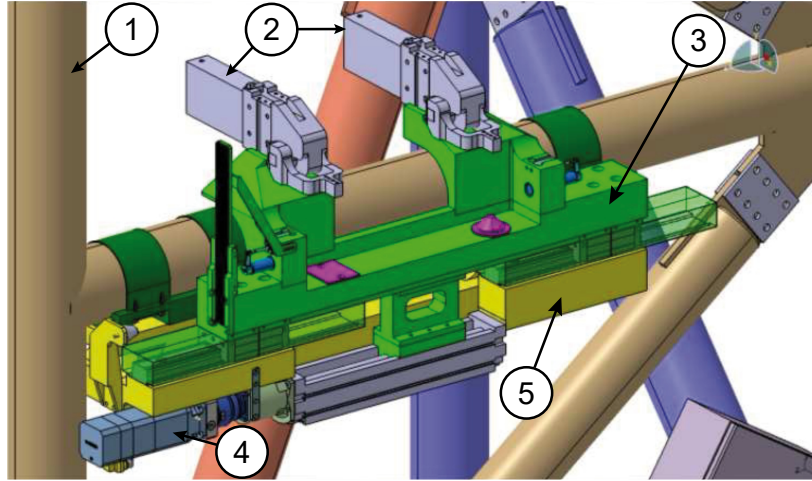


Figure 3.5. Schematic diagram of the focusing system of CT5. The various components are: 1) Telescope structure. 2) Locks to fixate the camera to the structure. 3) Moving part of the focusing system. 4) Motor. 5) Static part of the focusing system, attached to the telescope structure. Adapted from Bolmont et al. (2014).

Optical Point Spread Function and Monitoring

The optical PSF of a telescope describes how well a point source located at infinity is imaged in the focal plane of the telescope. It serves as a figure of merit of the air shower imaging capabilities of the telescope and is an important quantity of the optical system of a telescope. The shape and size of the optical PSF depends on several parameters. For incoming light parallel to the optical axis (on-axis light), it is dominated by the optical quality of the individual mirror facets, which includes the reflectivity and the optical PSF of the individual mirror facet. For incoming light with an incident angle towards the optical axis (off-axis light), it is dominated by the overall reflector layout and the effect of the individual mirror facets becomes negligible above a certain incidence angle. In both cases, on-axis and off-axis light, the optical PSF is affected by the quality of the mirror alignment. One parameter that affects the quality of the mirror alignment is the positioning uncertainty of the components that constitute the mirror alignment system described above⁸ (Pühlhofer et al. 2024). A more detailed discussion of the optical aberrations for on-axis and off-axis light and the imaging capability of a Davies-Cotton reflector layout is part of Section 5.2.2. In H.E.S.S., only the on-axis PSF is monitored regularly. This monitoring approach is sufficient, because a deterioration of the off-axis performance without a deterioration of the on-axis performance is very unlikely. For measurements and simulations of the off-axis PSF, the reader is referred to Cornils et al. (2003, 2005) for CT1-4 and CT5, respectively. In the following, the measurement procedure and the monitoring of the optical PSF of the H.E.S.S. telescopes are described according to Cornils et al. (2003). Additionally, a new algorithm to determine the PSF of CT5 with the installed FlashCam was developed by Arroyo Salas (2023) and is described at the end of the section.

⁸The determination of the positioning uncertainty of the mechanical components of an optical alignment system is an important aspect of this thesis. The main focus of Part II is the quality control of mirror alignment components.

The measurement procedure of the optical PSF is the same for all five H.E.S.S. telescopes. The PSF is measured as a function of elevation angle to quantify the gravitational deformations of the mirror support structure. To properly describe the elevation-dependent deformation, 30 – 40 stars are tracked within elevation angles of $20^\circ - 90^\circ$ in a given night at arbitrary azimuth angles. The LidCCD, a CCD camera installed in the center of the reflector, takes images of the optical target of the camera. From the images of the LidCCD, the radius $r_{80\%}$ of the spot containing 80 % of the reflected light intensity is calculated, which serves as the figure of merit of the optical PSF. For CT1-4, the change of the $r_{80\%}$ as a function of the elevation angle θ is described by

$$r_{80\%}(\theta) = \sqrt{R_{\min}^2 + d_0^2 \cdot (\sin \theta - \sin \theta_0)^2} \quad , \quad (3.2)$$

where $R_{\min}$ is the minimum $r_{80\%}$ at the elevation angle θ_0 . The parameter d_0 describes the change of the $r_{80\%}$ per 90° in elevation angle and quantifies the bending of the mirror support structure, including the actuator system, with gravity. For CT5, an additional parameter d_1 has been introduced to describe the larger and heavier mirror support structure. Consequently, Equation 3.2 has been extended by Gottschall et al. (2015) to

$$r_{80\%}(\theta) = \sqrt{R_{\min}^2 + d_0^2 \cdot (\sin \theta - \sin \theta_0)^2 + d_1^2 \cdot (\cos \theta - \cos \theta_0)^2} \quad . \quad (3.3)$$

A fit of the $r_{80\%}$ as function of the elevation for CT5 is shown in, e.g., Gottschall et al. (2015). From the fitted model for a given set of PSF measurements, the $r_{80\%}$ at an elevation angle of 65° is extracted and monitored as a function of time⁹. The results as of May 2024 are shown in Figure A.1 and Figure A.2 for CT1-4 and CT5, respectively. The optical PSF shows a constant deterioration between $(1.47 \pm 0.13) \% \text{ year}^{-1}$ (CT5) and $(2.92 \pm 0.12) \% \text{ year}^{-1}$ (CT3). Except for dedicated cases where the mirrors have been exchanged, no realignment of the mirrors has been deemed necessary so far. This seems to be the case over the remaining lifetime of H.E.S.S. with the moderate increase of the PSF observed so far.

One of the main differences between the previous camera and FlashCam regarding the monitoring of the optical PSF is the optical target. The previous camera, like the CT1-4 cameras, uses the camera lid as an optical target, while FlashCam uses a diffusely reflecting circular surface with a diameter of 175 mm. This so-called lollipop is deployed 25.5 mm in front of the PDP during PSF and pointing calibration runs, as shown in Figure 3.6. The verification of the optical response after the installation of FlashCam in CT5 is described in Salzmann (2020). In order to calculate the size of the optical PSF from the LidCCD images, a good and reliable determination of the background of the light intensity from the images is necessary. The algorithm used to calculate the PSF for CT1-4 and the previous camera of CT5 is the SpotExtraction algorithm developed by Cornils (2006). It essentially performs several image segmentation steps to identify the region of the image that

⁹The PSF of CT1-4 is determined at the beginning and end of each observation period as part of the pointing calibration. The observation period is determined by the lunar cycle. CT5 requires dedicated calibration runs to measure the PSF because the focusing system settings during pointing calibration runs are the same as the one for observations. The PSF of CT5 is measured approximately every six months.

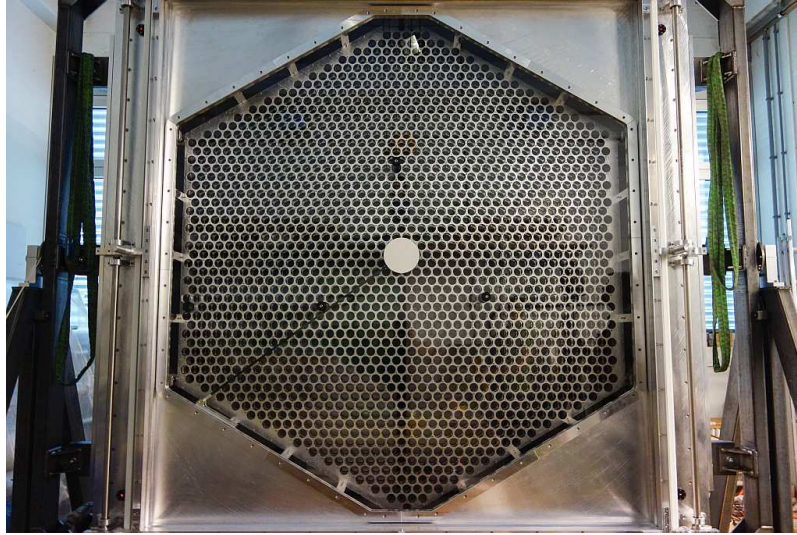


Figure 3.6. FlashCam with the deployed optical target. Image credit belongs to A. Vollhardt (University of Zürich).

contains the signal, which, in this case, would be the reflected star spot. As noted by Salzmann (2020), the SpotExtraction algorithm struggled to reliably determine the signal and background regions for the FlashCam at CT5 because the geometry of the lollipop was not considered. This problem was especially present for PSF calibration runs under moonlight conditions, where there was a large difference in the level of background intensity between the lollipop and the surrounding PDP. This problem is shown in Figure 3.7. As a result, it was necessary to:

- (a) either adapt the SpotExtraction algorithm to take into account the geometry of the new optical target,
- (b) or develop a new algorithm that takes into account the geometry of the lollipop.

After a brief evaluation phase, option (b) was determined to be the more promising option as the code of the SpotExtraction algorithm does not provide an easy way to define a Region of Interest (ROI) in the LidCCD image. An additional consideration was the change of the programming language from Objective C to the, nowadays, more widely used Python programming language to facilitate a potential usage within the context of the PSF monitoring of FlashCam during operation in the CTAO. The newly developed radial profile algorithm is programmed in Python and was developed as part of his master's thesis by Arroyo Salas (2023) under the day-to-day supervision of the author of this thesis. The main approach of the radial profile algorithm is briefly summarized here according to Arroyo Salas (2023).

The first step is to identify the lollipop in the LidCCD image and define it as the Region of Interest (ROI) (see Figure 3.8a). From the defined ROI, the intensity frequency distribution is fitted with a one-dimensional Gaussian (see Figure 3.8b). The resulting mean and width of the distribution are the mean and error of the background intensity level, respectively. The Center of Gravity (COG) of the light spot is then calculated by fitting an asymmetric two-dimensional Gaussian to the ROI (see Figure 3.8c). After subtracting the background level from the ROI containing the raw pixel intensities, the corrected light intensity is integrated in radial direction

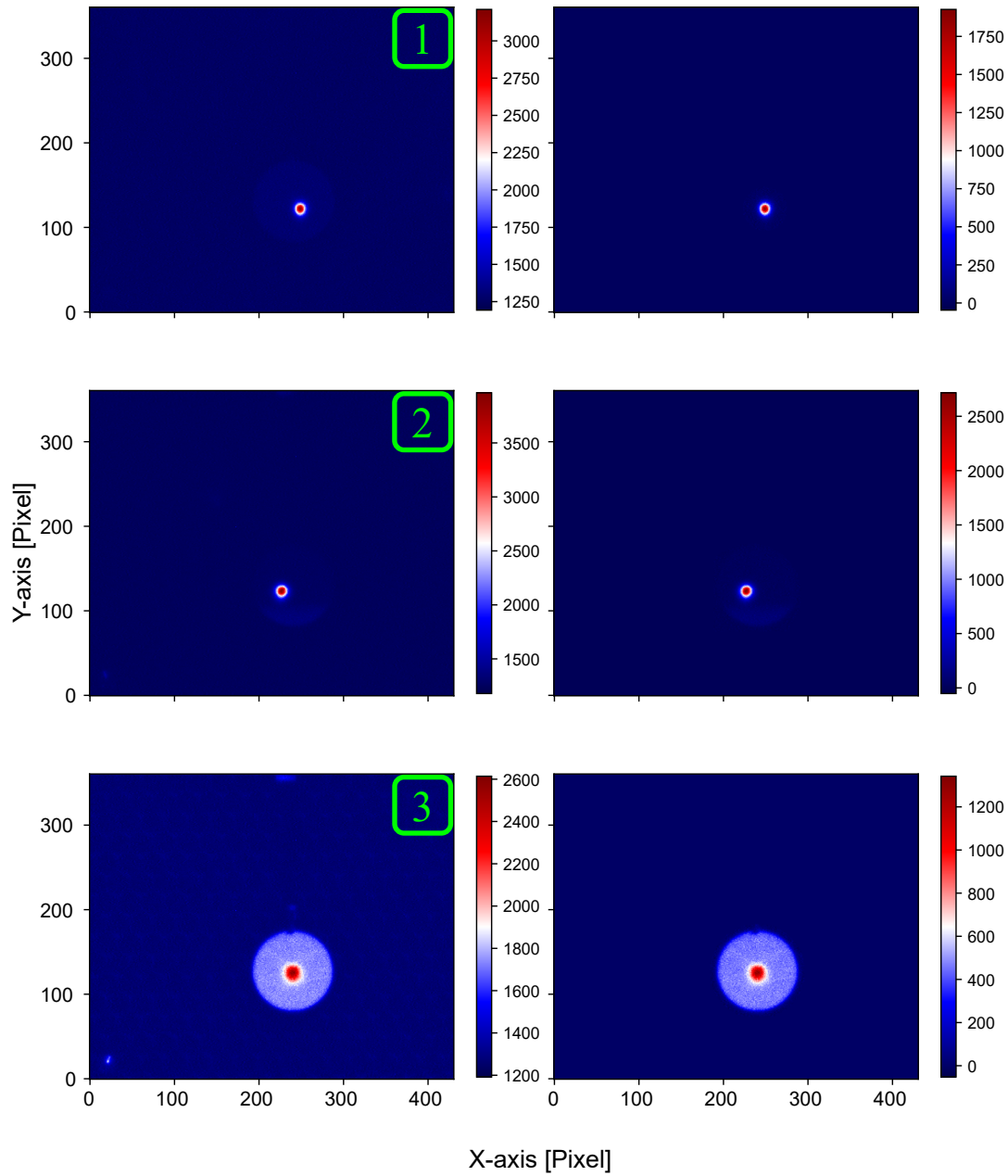


Figure 3.7. Three exemplary LidCCD images (left) and the derived signal regions (right) from the SpotExtraction algorithm derived for PSF calibration runs taken with FlashCam at CT5. The optical target of FlashCam is visible in each of the three images to a varying degree. While the signal region is derived properly in the upper image, the background induced by the lollipop is rejected insufficiently in the middle and bottom images leading to a too large signal region. The calculated $r_{80\%}$ thus is not a proper estimation of the actual size of the reflected light spot. Taken from Salzmann (2020).

starting from the COG of the light spot. A fit to the identified region where the accumulated intensity I saturates determines the level of $I_{100\%}$ (see Figure 3.8d). From this $I_{100\%}$, the intensity level containing 80 % and the corresponding $r_{80\%}$ and its error are derived. In addition, before fitting the resulting elevation-dependent $r_{80\%}$ distribution for a given set of PSF measurements with Equation 3.3, the radial profile algorithm implemented some preliminary quality selection cuts to identify LidCCD images for which a reliable determination of the $r_{80\%}$ is difficult. These problematic images could have been contaminated by artifacts such as a secondary star or shadows from the telescope structure on the optical target.

Although the PMT camera surface and the surface of the optical target are vastly different, the SpotExtraction algorithm delivered reasonable results for dark time conditions even though it is not aware of the geometrical properties of the optical target. This stems from the fact that during dark time conditions, there is no significant difference in the measured background level in the LidCCD image between the optical target and the PMT camera surface. However, during moonlight conditions, the background in the LidCCD images is nonhomogeneous due to the different reflectivity of the PMT camera surface and the optical target (see Figure 3.7). As described by Arroyo Salas (2023), a comparison between the SpotExtraction and the radial profile algorithm showed a comparable performance for PSF calibration runs during dark time conditions. Under moonlight conditions, the radial profile algorithm had a better performance than the SpotExtraction algorithm, which resulted in more PSF measurements considered in the fit of the elevation-dependent $r_{80\%}$ distribution. In conclusion, it can be stated that the radial profile algorithm is a valid solution to determine the PSF for FlashCam cameras installed in the Medium-Sized Telescopes (MSTs) of the CTAO. The procedure of the pointing calibration and the determination of the pointing accuracy is described below.

Pointing Calibration and Accuracy

The pointing accuracy describes how well the position of the telescope optical axis corresponds to the tracked position in the focal plane. It is a critical quantity for determining the direction of the EAS and thus the position of the astrophysical source. While the typical accuracy to locate the direction of the particle shower is $\sim 0.1^\circ$, the localization of γ -ray sources with high enough photon statistics is possible in the order of $\sim 10''$, as described, e.g., by Pühlhofer et al. (1997). The pointing accuracy of a telescope depends on two parameters. The first is the tracking accuracy of the drive system. The tracking accuracy of CT1-5 is well below the size of the optical PSF and therefore does not lead to blurring of the image of a γ -ray point source (see Table 3.1). Second, the bending of the telescope structure as a function of the telescope position under different gravitational loads. The latter is determined by the bending of the masts holding the camera and the mirror support structure including the mechanical components of the mirror alignment system (Pühlhofer et al. 2024).

The effects that affect the pointing accuracy can be divided into reproducible and non-reproducible effects. The former include elastic deformations of the mirror support structure and the camera masts, and tilting of the elevation-azimuth axes. The latter are a combination of environmental conditions, such as changing wind loads on the mirrors, and visco-elastic or plastic deformations of the telescope structure. Of particular importance for this thesis is the deformation behavior of the mechanical components that make up the mirror alignment system. The deformation behavior of

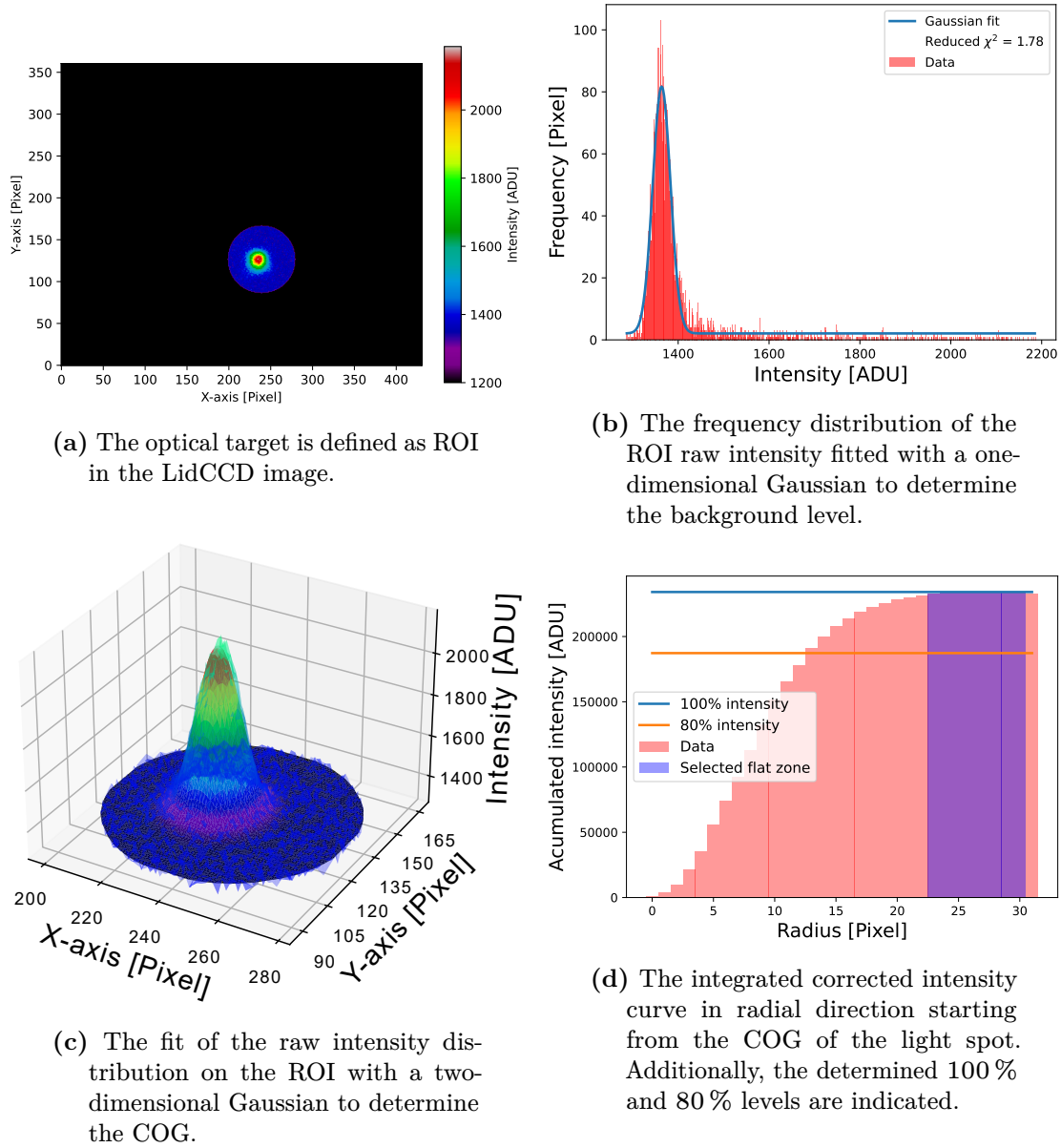


Figure 3.8. Workflow of the radial profile algorithm to determine the $r_{80\%}$ for a PSF calibration run for FlashCam at CT5. More details in the text. Plots generated with the radial profile algorithm developed by Arroyo Salas (2023).

the mechanical components consists of backlash, elastic and visco-elastic components, which are a non-negligible contribution. They introduce an additional tilt on the mirrors, which depends on the observation conditions. There is a need to quantify these non-reproducible effects through detailed simulations of the telescope structure and all its subcomponents, as well as through quality control of the mechanical components of the mirror alignment system. The latter is the focus of this thesis and is described in detail in Part II.

The reproducible effects are corrected by generating a pointing model that describes the movement of the optical axis in the focal plane as a function of the telescope position. The result of this pointing model is essentially a field of displacement vectors in the focal plane to correct the observed coordinates of the primary particle to its true coordinates depending on the elevation-azimuth position of the telescope. This pointing model can be applied offline to the observational data. An offline application to the data for IACTs is possible due to the short image integration timescales on the order of ~ 10 ns and their relatively large FOV of $\geq 3^\circ$. The pointing correction for the H.E.S.S. telescopes is described in detail in Gillessen (2004) and Braun (2007). The following paragraph is based on Gillessen (2004).

To determine the pointing corrections, the same workflow is used as for the PSF measurements¹⁰. At the edge of the focal plane cameras, Light-Emitting Diodes (LEDs) are installed. These LEDs are visible in the LidCCD images and serve as a reference from which the center of the camera can be calculated (see Figure 3.9, left). The mispointing for an individual pointing run is then given as the difference between the COG of the light spot of the tracked star and the camera center derived from the position of the LEDs. A set of pointing runs, usually spanning one or two observation periods, is used to derive the pointing model. There are several approaches to determine a pointing model. In H.E.S.S., a mechanical model is fitted to the resulting vector field¹¹ (see Figure 3.9, right). The mechanical model consists of a set of fit parameters that represent some mechanical effect of the telescope. The advantage is that the resulting parameters have a physical meaning and thus allow monitoring of the mechanical stability of the telescope. The pointing accuracies achieved with these pointing models are $\leq 20''$ and $\leq 60''$ for CT1-4 and CT5, respectively.

Compared to optical astronomy, a coordinate correction using stars in the FOV of the telescope is difficult with IACTs for two reasons. First, the pixels of the focal plane camera are too coarse for a sufficient pointing accuracy, which would be on the order of the camera pixel size, since the optical PSF is smaller than the camera pixel size. Second, an additional CCD camera installed in the reflector as star tracker does not know the position of the optical axis. Nevertheless, the information from the star tracker camera can be used in H.E.S.S. as additional information to partially compensate for the non-reproducible effects present when observing an astronomical source and to provide an additional correction to the standard pointing model. With this precision pointing mode the pointing accuracy can be improved down to $6''$ for CT1-4, depending on the quality of the data set (HESS Collaboration et al. 2010).

¹⁰Another possibility to derive the pointing model is to use the current of the photosensitive devices of the focal plane camera when observing a star. Such an approach is described in Pühlhofer et al. (1997).

¹¹Another possible approach would be to fit a two-dimensional Fourier series to the measurement data with the advantage of an analytical solution without any minimization routine. The disadvantage

3.1.2. Cameras

The task of the cameras is to detect (i.e. trigger on) and record the Cherenkov light emitted by the EAS and the characteristics thereof drive the camera design. Photosensitive devices with high quantum efficiency are required to convert the weak signal of the Cherenkov light into an electrical signal. In addition, the short duration of the Cherenkov light on the order of $\sim$ ns requires electronics with high sampling frequencies to detect the generated electrical signal. The cameras of all H.E.S.S. telescopes use PMTs as photosensitive devices and are equipped with Winston cones on top. Winston cones are non-imaging light collectors to minimize light losses and reduce the impact of stray light. The cameras installed in CT1-4 are of the same type, while the camera of CT5 follows a different design (Pühlhofer et al. 2024). They are explained in more detail below.

All five cameras originally installed in the respective telescopes have been upgraded over the past nine years. The main objectives of these upgrades have been to reduce the failure rates and increase the serviceability of the cameras in order to minimize camera-related downtime and operate the telescope array at high efficiency (Pühlhofer et al. 2024). For CT1-4, the cameras underwent an electronics upgrade in 2015 and 2016. An additional goal of this upgrade was to reduce the dead time of the camera in order to lower the trigger threshold and thus increase the number of coincident triggers with CT5. The new electronics are based on the NECTAr¹² digitizer chip, a technology developed for the CTAO. The cameras with the new electronics are called HESS1U cameras (Ashton et al. 2020). For CT5, the original camera was replaced by the first fully functional FlashCam in October 2019. Like the NECTAr chip, FlashCam is a technology proposed for use in the telescopes of the CTAO (Bi et al. 2021). Both camera upgrades proved to be a success for H.E.S.S., as a data taking efficiency of $\sim 98\%$ was achieved by 2020 and 2021 for the CT1-4 cameras and the FlashCam at CT5, respectively (Ashton et al. 2020; Bi et al. 2021). Therefore, from a camera perspective, H.E.S.S. is well prepared to extend operations beyond 2024. The cameras are discussed in more detail below.

HESS1U Cameras (CT1-4)

The camera upgrade included the complete camera electronics, leaving only the PMTs and high voltage power supplies from the previous camera. The upgraded camera and its working principle is described in detail in Ashton et al. (2020). The following provides a brief overview of the HESS1U cameras according to Ashton et al. (2020).

The HESS1U camera can be divided into four main subsystems. First, the front-end electronics, which is responsible for the detection, analog processing, and digitization of the incoming signal. Second, the back-end electronics, which is responsible for the camera-level trigger generation, the interface to the central trigger of the array, and the camera slow controls, among other things. In addition, the back-end electronics interface with the auxiliary devices, which can be summarized as the third major subsystem and consist of several devices required to calibrate and monitor the camera. The fourth subsystem is the camera server, which is the end point of the monitoring, logging and event data streams. It also provides the interface to the H.E.S.S. Data

is that the resulting fit parameters have no direct physical meaning.

¹²New Electronics for the Cherenkov Telescope Array

Acquisition (DAQ). The main technical parameters of the camera and the camera electronics are summarized in Table 3.4. The signal processing is described below.

A total of 960 pixels are organized in 60 drawers, providing a pixel angular diameter of 0.16° . This results in a camera FOV of 5° . One drawer is controlled by a FPGA and an ARM-based single board computer mounted on a slow control board. In addition, two analog boards are connected to a single drawer. The analog boards are responsible for processing the PMT signals. Each analogue board has a total of eight channels, one per PMT. After the signal is sent to the respective channel on the analog board, it is pre-amplified and then split into three branches. One of these branches consists of a fast comparator that sends its digital output to the FPGA on the slow control board and is used for the trigger decision of the drawer. This is the level 0 trigger signal, which is then processed by the back-end electronics to determine the camera-wide trigger signal. The other two branches of the channel go to the two input channels of the NECTAr chip. One of the channels has a high amplification factor (high gain) and the other has a low amplification factor (low gain). Their task is to amplify weak and strong signals, respectively. Each of the amplified signals is then stored in analog ring memory buffers with 1024 cells. Switching from cell to cell is done with a frequency of 1 GHz, so a signal of up to 1024 ns can be stored before the stored signal is overwritten. In the case of a camera-wide trigger signal, a defined number of cells are read out and digitized by a 12-bit 21 MHz Analogue-to-Digital Converter (ADC) and the digital signal is integrated by the FPGA. For standard H.E.S.S. observations, the time window corresponds to a duration of 16 ns. The integrated charge per PMT and gain channel is then sent to the camera server (Ashton et al. 2020; Pühlhofer et al. 2024).

Camera performance has improved with the upgraded electronics. The camera dead time was reduced by a factor of 60 from $\sim 450 \mu\text{s}$ to $\sim 7 \mu\text{s}$ (Ashton et al. 2020). As a result, the number of trigger events with CT5 increased by a factor of two (Pühlhofer et al. 2024). The camera installed in CT5 is described in the following.

Table 3.4. Main technical parameters of the CT1-4 and CT5 camera electronics. Information taken from Ashton et al. (2020), Salzmann (2020), and Pühlhofer et al. (2019).

Parameter		CT1-4	CT5
Photodetector	type	Photomultiplier Tube	
	angular diameter	0.16°	0.08°
No. drawers / PDP modules		60	147
No. pixels		960	1758
Camera FoV		5°	3.4°
Signal	processing	analogue	digital
	writing rate	1000 MHz	250 MHz
	reading rate	21 MHz	250 MHz
No. gain channels		2	1

FlashCam (CT5)

The FlashCam concept was originally proposed in 2008 by Hermann et al. (2008) and further advertised as a camera concept for the CTAO in Pühlhofer (2011). Since

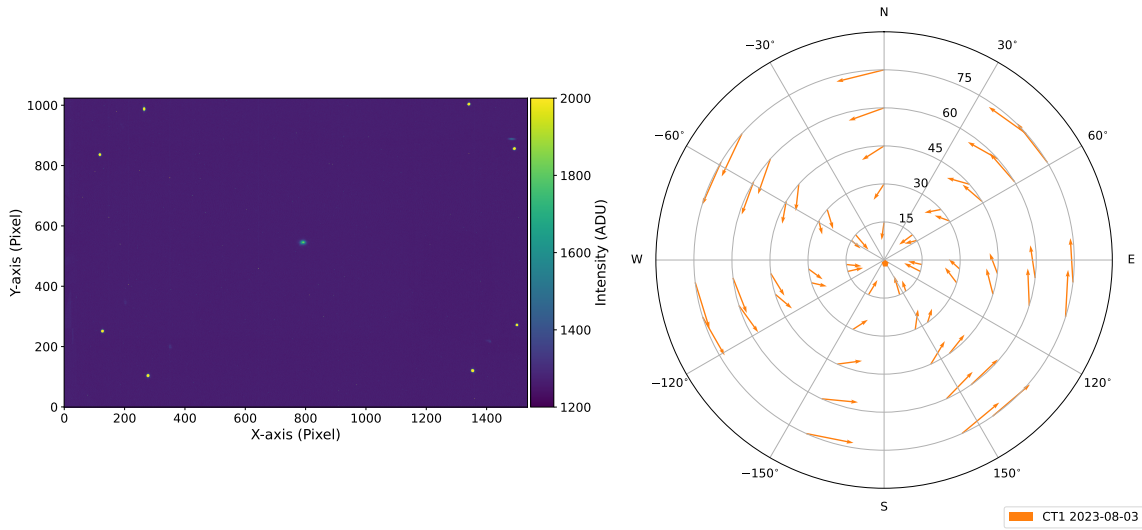


Figure 3.9. LidCCD image of a pointing run (left) and an exemplary pointing model (right) for H.E.S.S. CT1. In the LidCCD, eight LEDs at the corner of the camera in the focal plane and the reflected light spot of the tracked star are visible. The pointing model is displayed in polar coordinates and the center corresponds to a zenith angle of 0° . The scale of the arrows corresponds to $20''/\text{deg}$. Pointing model provided by E. Rol (H.E.S.S. Collaboration).

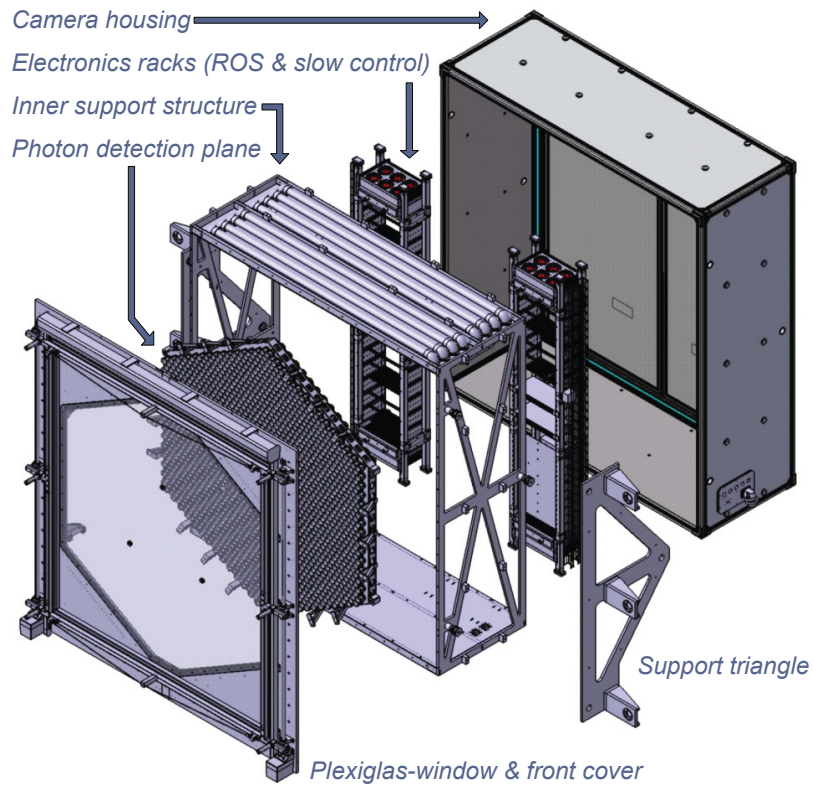


Figure 3.10. Exploded view of FlashCam. Taken from Pühlhofer et al. (2024).

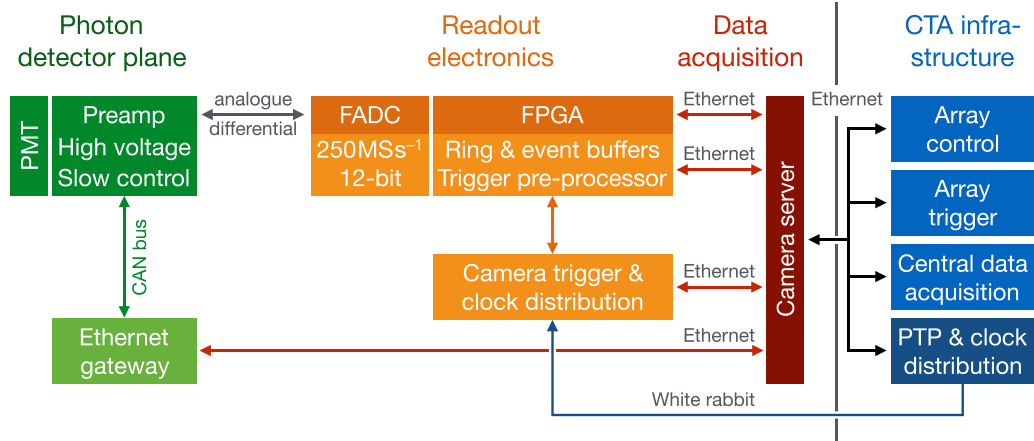


Figure 3.11. Three main subsystems of FlashCam camera. Additionally, the interface to array infrastructure is displayed. Taken from Werner et al. (2017).

then, the camera has undergone intensive testing, including first performance tests of the system in 2016 (Werner et al. 2017), installing and operating the camera in a MST prototype telescope for CTAO for several weeks in 2017, and verifying the camera trigger between lab measurements and camera simulations (Sailer et al. 2019). A short overview of the tests performed is given in Pühlhofer et al. (2019). All performed tests proved that FlashCam works reliably and is a mature camera concept for the use in IACTs. Consequently, it was decided to install the first fully functional FlashCam in H.E.S.S. CT5 in 2019 to benefit from increased reliability and sensitivity after the initial camera had already been operating for seven years in the harsh environment of Namibia (Pühlhofer et al. 2019). The installation of FlashCam at CT5 took place in October 2019, and after a short commissioning phase, the camera has been taking nominal science data since mid-December 2019. The results of the science verification phase are reported in Pühlhofer et al. (2021) and the technical performance of the camera until 2021 in Bi et al. (2021). Here, the camera design and operating principle will be described further.

The description of the camera design is based on Werner et al. (2017) with the specifics regarding the FlashCam installed in CT5 based on Bi et al. (2021) and Pühlhofer et al. (2021). An exploded view of FlashCam and the three main subsystems of FlashCam are shown in Figure 3.10 and Figure 3.11, respectively. The Photon Detector Plane (PDP) consists of 1758 PMTs as photosensitive devices¹³ organized into 147 PDP modules and is covered by a UV-transparent acrylic window. The angular diameter of an individual PMT in CT5 is 0.08° , resulting in a camera FOV of 3.4° . The PDP follows a hexagonal structure with a distance of 50 mm between each pixel. Each module holds up to 12 pixels and provides the high voltage, preamplifiers, and slow control. The incoming signal is converted by the PMTs into an electrical current, which is then amplified by the preamplifier. The signal is linearly amplified in a single amplifier channel up to an amplitude of ~ 250 p.e. Beyond ~ 250 p.e., the signal saturates in a controlled manner and the incoming charge is derived after the digitization in the ROS by the time duration of the signal. This amplification

¹³The PDP has room for up to 1764 pixels. However, three pixels are replaced by struts for the UV transparent window that covers the front of the camera. In addition, three more pixels are partially masked for calibration purposes.

scheme maintains linearity and sub-p.e. resolution for signal amplitudes < 250 p.e. while extending the dynamic range to > 3000 p.e. The amplified analog signals are then transmitted over CAT.5E Ethernet cables to the Readout Electronics (ROS). The ROS follows a fully digital approach in that the incoming analog signals are continuously sampled by a 12-bit FADC¹⁴ at a sampling rate of 250 MSs^{-1} . The resulting samples are then buffered in FPGAs and processed to derive a camera internal trigger decision. The trigger itself is freely programmable and time slices up to $15.6 \mu\text{s}$ with an offset relative to the trigger time can be read out. The ROS is connected to the Data Acquisition (DAQ) system with up to four ethernet cables. The DAQ system consists of a camera server, which is responsible for the transfer of the triggered data as well as event building, optional zero suppression and event selection. It also provides the interface between the camera and the array-wide data acquisition, exchanges the array trigger, and transmits the triggered data to the DAQ of the array. Two Ethernet cables are used for slow control and monitoring as well as for the distribution of the array-wide clock signal, the latter being implemented using a White Rabbit system. The main technical parameters of the CT5 camera are summarized in Table 3.4.

The camera's trigger system uses temporal and spatial coincidences to derive a trigger signal. The camera is divided in 588 non-overlapping patches of three adjacent pixels. A trigger patch consists of three overlapping three pixel patches, for which the trigger sum is continuously calculated in a sliding window and evaluated by the trigger system. To reduce the impact of NSB-induced Poisson fluctuations on the trigger and thus improve operational stability, pixels with a NSB rate above a defined NSB limit are excluded from the trigger sum calculation (Bi et al. 2021). The trigger settings of the FlashCam installed in CT5 are listed in Table 3.5. The different trigger settings depend on the brightness of the source region and whether the observations are performed during dark time or under moderate moonlight conditions. Currently the only repeatedly observed source region classified as bright is Eta Carinae. Additionally, as part of this thesis, a reduced trigger setting was introduced, which has a $\sim 15\%$ reduced threshold compared to the dark time trigger setting of the standard observing run. This trigger setting is used for astronomical sources where the energy range of tens of GeV is of increased importance. For example, observations of pulsars detected by the Fermi Gamma-Ray Space Telescope. The observational data analysis of the reduced trigger threshold observations is described in Part III.

In principle, FlashCam can be operated with a trigger rate of up to 30 kHz without any dead time due to the fully digital approach of the camera electronics. However, for the FlashCam installed in CT5, two adjustments were made to limit the data volume to a level acceptable for the H.E.S.S. DAQ system, as well as the storage capacity and outgoing bandwidth. First, the trigger threshold has been adjusted to limit the fraction of random triggers due to NSB fluctuations to $\lesssim 1\%$. Second, instead of sending the full signal shape, only the integrated signal shape and the timing information per event are sent to the H.E.S.S. DAQ (Pühlhofer et al. 2021). The H.E.S.S. DAQ is described in its most recent version in Zhu et al. (2021). The central trigger system and the event timing is described below.

¹⁴Flash Analogue-to-Digital Converter

Table 3.5. Setup of the trigger system for FlashCam at CT5. The trigger setting depends on the brightness of the observed source region and whether the observations are performed under dark time or moonlight conditions (Bi et al. 2021). A reduced trigger threshold has been used for dedicated sources where the energy range of tens of GeV is of increased importance (e.g., pulsars). See the text for more details.

Run type	Trigger setting	Trigger threshold (p.e.)	NSB limit (GHz)
Observation run	Reduced	59	1.1
	Standard	69	1.1
	Bright	91	2.7
Moonlight observation run	Standard	104	2.7
	Bright	120	2.7

3.1.3. Central Trigger System and Event Timing

The central trigger system is the “brain” of the data acquisition – it implements the array trigger, the measurement of the system dead time, as well as the event synchronization between telescopes. Its main components is the hardware installed in the central control station and interface modules in each of the H.E.S.S. telescopes that connect the telescopes with the central trigger system via optical fibers (Pühlhofer et al. 2024).

The array trigger in H.E.S.S. is implemented at the hardware level and is applied during data acquisition. This has several advantages over a software-based array trigger applied after data acquisition. First, it reduces the amount of background events, mostly caused by muons, and thus reduces the amount of data written to disk. Second, in a system with a non-negligible camera readout dead time, the system dead time is reduced. This allows the use of a lower trigger threshold at the camera level and thus leads to a lower energy threshold of the entire array. Two array trigger are implemented in H.E.S.S. The stereoscopic array trigger requires a camera trigger in at least two of the small telescopes. Due to the lower energy threshold of CT5 compared to CT1-4, a new trigger scheme had to be implemented after the installation of CT5. The only requirement for the hybrid array trigger is a CT5 camera trigger. If this is the case, CT1-4 will be read out if they contain a camera trigger signal. During regular observations, CT5 triggers alone in $\approx 65\%$ – 70% of the cases. If only one of CT1-4 triggers, the event is discarded (Funk et al. 2004; Pühlhofer et al. 2024).

After a trigger signal is generated at the camera level, it is sent to the central trigger system. In both cases of array triggering, stereoscopic and hybrid, the central trigger system checks for a coincident trigger signal in one of the other telescopes taking into account the duration of the pointing-dependent light propagation of each telescope¹⁵. If the initially triggered telescope is one of CT1-4, a readout signal is issued to the cameras when a coincident trigger signal is found in at least one of the small telescopes. If CT5 is the initially triggered telescope, the central trigger system

¹⁵The proper size of the coincidence window has a direct impact on the efficiency of the trigger system. The coincidence window must be large enough not to lose valid coincidences, which are caused by electromagnetic showers. At the same time, it should not be too large to avoid an unacceptable rate of random coincidences, which would increase the array dead time. In H.E.S.S., the size of the coincidence window is 80 ns.

reads out CT5 and any of CT1-4 if they contain a trigger signal (Funk et al. 2004; Balzer et al. 2014).

After the central trigger system has issued an array trigger, a readout signal is sent to the interface modules in each camera. Each event is assigned a unique system-wide event number in order to synchronize the events of the individual telescopes and be able to build a system event from the data of the individual telescopes. Furthermore, each event is assigned a timestamp provided by a commercial *GPS167 Meinberg* GPS receiver. This GPS receiver provides a 1 Hz and 10 MHz clock signal that is synchronized to the UTC second (Funk et al. 2004). The clock signal is distributed to the camera interface modules with an Ethernet-based White Rabbit network system¹⁶. The central trigger system has a long-term accuracy of $< 2 \mu\text{s}$ (Funk et al. 2004). The event timestamps serve as input to the pulsar timing analysis described in Section 9.3.

3.2. Cherenkov Telescope Array Observatory

The Cherenkov Telescope Array Observatory (CTAO) is a future ground-based TeV astronomy facility with an energy coverage of 0.02 TeV – 300 TeV and builds on the proven concept of using an array of IACTs to indirectly detect VHE γ -rays. It combines the efforts of the three major collaborations operating arrays of IACTs, H.E.S.S., MAGIC and VERITAS to achieve full sky coverage and increased instrument sensitivity. In 2022, the Cherenkov Telescope Array Observatory Consortium consists of more than 1500 scientists from more than 30 countries (Hofmann et al. 2024).

The key scientific questions to be investigated with the CTAO can be divided into the following three topics:

- Understanding the origin and role of relativistic cosmic particles,
- probing extreme environments, and
- exploring frontiers in physics.

Answering these questions involves, among other things, studying the locations and mechanisms of particle acceleration of cosmic-rays, the physical processes active in the vicinity of neutron stars and the nature of dark matter. In order to fully exploit the potential of the data taken with the CTAO, it will be operated as a proposal-driven observatory with the data being made available to the general public after a defined period of time. This is the first observatory in the field of ground-based TeV astronomy to operate in this way. A complete description of the science with the CTAO is given in The Cherenkov Telescope Array Consortium et al. (2018).

In addition to the full sky and energy coverage of 0.02 TeV – 300 TeV, the design of the CTAO aims to improve the angular resolution and photon detection area of currently operating IACT arrays in order to achieve its scientific goals. The currently operating IACT arrays, like H.E.S.S., have photon detection areas of the order of the Cherenkov light pool at the Earth’s surface. Therefore, only particle showers with an impact point near the center of the IACT array are imaged by all telescopes, while

¹⁶This White Rabbit network was implemented together with the installation of FlashCam in October 2019. Since then, FlashCam has been receiving the timing signal over the White Rabbit network and the HESS1U cameras have been using this timing information since the beginning of 2022 (Pühlhofer et al. 2024). The White Rabbit network project is described in Moreira et al. (2009).

the majority of particle showers are not imaged by the full array. The design of the CTAO therefore includes a grid of telescopes with a spacing between telescopes on the order of the radius of the Cherenkov light pool on the ground. This improves the angular resolution by increasing the number of telescopes simultaneously imaging the emitted Cherenkov light, while at the same time increasing the photon detection area. The design of the individual telescopes in the array is influenced by the requirement to cover the energy range of 0.02 TeV – 300 TeV. To detect the Cherenkov light of particle showers initiated by γ -rays with energies of 20 GeV, telescopes with mirror areas of 400 m² – 600 m² are needed. On the other hand, to detect a large number of particle showers initiated by γ -rays with energies of 300 TeV, an area on the ground of ~ 10 km² must be covered by the telescopes. To achieve this in a cost-effective way, the design of CTAO includes three different types of telescopes, each optimized for parts of the energy range. The telescopes are located in La Palma in the northern hemisphere (CTAO-North) and in Chile in the southern hemisphere (CTAO-South) (Hofmann et al. 2024).

The three types of telescopes for the CTAO are described in Section 3.2.1. The first stage of the planned CTAO-North and CTAO-South array configurations and their performance are summarized in Section 3.2.2. The reader is referred to Hofmann et al. (2024) for a comprehensive overview of the CTAO.

3.2.1. Telescopes

The three telescope types of the CTAO are the Large-Sized Telescope (LST), Medium-Sized Telescope (MST), and Small-Sized Telescope (SST), which aim to detect γ -rays in the low, medium, and high energy ranges of the CTAO, respectively. Their main parameters are summarized in Table 3.6 and they are shown in Figure 3.12. The different telescopes are described in more detail below.

Large-Sized Telescope (LST)

The design of the LST is optimized to cover the energy range of 20 GeV – 150 GeV of the CTAO. To achieve this, the parabolic reflector has a diameter of 23 m and follows a tessellated mirror design consisting of 198 individual mirror facets. Taking into account the shadowing caused by the camera masts, the effective mirror area is 370 m². The structure is made of reinforced carbon fiber and steel tubes, resulting in a weight of 114 t. On the one hand, the lightweight telescope structure facilitates fast repositioning times of 20 s to any point in the sky, making LST ideal for follow-up observations of time-critical sources like GRBs. On the other hand, it is more susceptible to gravitationally-induced bending depending on the elevation angle of the observed astrophysical source. To compensate for the effects of this bending and to provide optimal imaging over the range of observed elevation angles, LST is equipped with an active mirror alignment system (Hofmann et al. 2024). The active mirror alignment system consists of two actuators and a fix point mounted on the back of each mirror facet as well as a near-infrared laser and a CMOS camera installed at each mirror facet as an optical feedback loop. The CMOS camera and the near-infrared laser are oriented towards the focal plane. The near-infrared laser serves as a reference spot in the focal plane for each individual mirror facet and is imaged by the CMOS camera to provide real-time feedback on the orientation of the mirror facet with respect to the optical axis of the telescope. Alignment is then a

Table 3.6. Main parameters of the three telescope types proposed for the CTAO. Three different configurations are under development for the Medium-Sized Telescope, two based on a modified Davies-Cotton and one based on the Schwarzschild-Couder layout. Information taken from Hofmann et al. (2024). The values denoted with † and ‡ are updated with respect to Hofmann et al. (2024) according to White et al. (2021) and Cortina et al. (2016).

Configuration	Large-Sized Telescope	FlashCam	Medium-Sized Telescope	Small-Sized Telescope
Energy range	(0.02 – 0.15) TeV		(0.15 – 5) TeV	(5 – 300) TeV
Optical design	Parabolic	Modified Davies-Cotton	Schwarzschild-Couder ^a	Schwarzschild-Couder
Primary reflector Ø	23.0 m	11.5 m		4.3 m
Secondary reflector Ø	–	–	–	1.8 m
Total no. mirror facets	198	86		19
Mirror alignment system	active		passive	passive
Effective mirror area ^b	370 m ²	88 m ²		~ 6 m ² (†)
Focal length	28.0 m	16.0 m		2.15 m
Field of view	4.5° (‡)	7.7°	7.9°	~ 9° (†)
No. pixels	1855	1758	1855	2048
Pixel size	0.100°	0.180°		0.190° (†)
Photodetector type	PMT	PMT		SiPM
Pointing accuracy	< 14"	< 7"		< 7"

^aSchwarzschild-Couder Telescope

^bEffective mirror area is the physical mirror area reduced by the shadowing caused by, e.g., the camera masts.

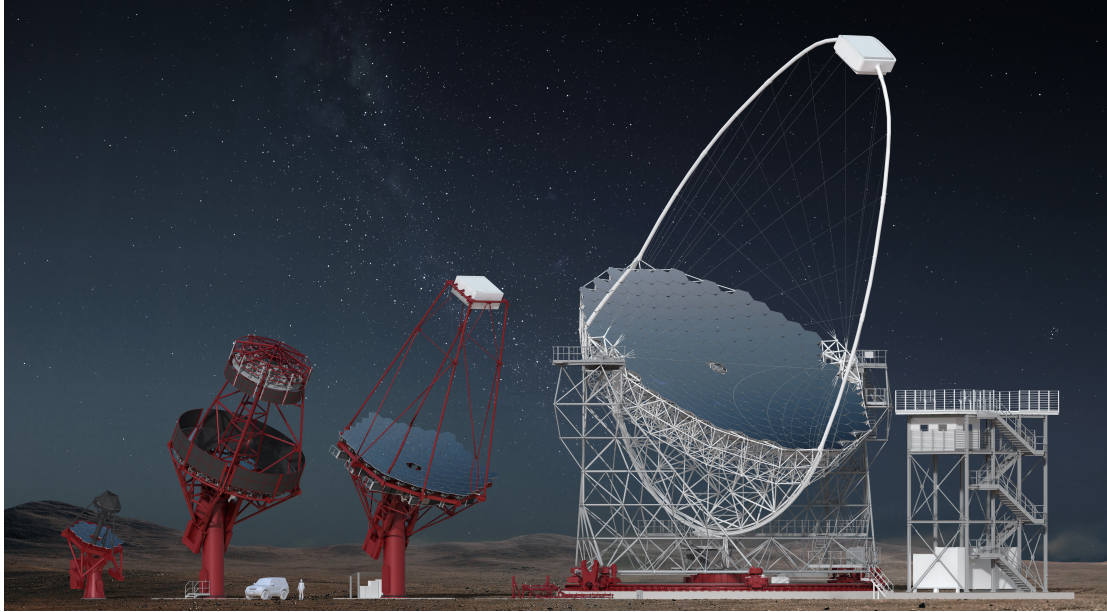


Figure 3.12. Different telescope types of the CTAO. From left to right: the Small-Sized Telescope, the Schwarzschild-Couder and the Davies-Cotton configurations of the Medium-Sized Telescope, and the Large-Sized Telescope. Image credit: G. Pérez Diaz (IAC).

two-stage process. During the initial alignment, the orientation of each mirror facet is determined from the reference laser position as a function of elevation angle and stored in a look-up table. During an observation, the mirrors are initially aligned according to the stored position from the look-up table. The orientation of the mirror facets is then fine-tuned based on the measured position of the reference laser. As the astronomical source is tracked, the alignment is updated every few minutes. The active alignment system and the alignment procedure are described in Hayashida et al. (2015). The requirements for the positioning accuracy of the active alignment system to compensate for the bending of the telescope structure must be stringent enough to provide a pointing accuracy of the telescope of $< 14''$.

To detect the Cherenkov light of the particle showers, a camera based on 1855 PMTs as photosensitive devices is installed in the focal plane of the telescope. The individual pixels have a diameter of 0.1° , resulting in a camera FOV of 4.5° . The camera design is related to the NectarCAM, a camera design proposed for the MST. More details about the camera can be found in Cortina et al. (2016). In addition, development of a next generation camera based on SiPMs is underway (Heller et al. 2023).

A prototype of the LST was inaugurated in October 2018 and has been taking science data since November 2019 as part of its commissioning phase. The first performance evaluation of the telescope with observations of the Crab Nebula and the Crab pulsar is reported in Abe et al. (2023).

Medium-Sized Telescope (MST)

The MST covers the core energy of $0.15 \text{ TeV} - 5 \text{ TeV}$ of the CTAO and is therefore essential for investigating the key scientific themes mentioned above. There are three planned configurations of the MST. Two of these telescope configurations are based

on the same modified Davies-Cotton reflector layout with a reflector diameter of 12 m and a focal length of 16 m. The reflector follows a tessellated mirror design with 86 mirror facets resulting in a total effective mirror area of $\approx 90 \text{ m}^2$ (Glicenstein 2021). A rigid steel structure provides adequate imaging over the range of observed elevation angles. Therefore, an initial mirror alignment system is foreseen for the Davies-Cotton MSTs. The optical system and the mirror alignment are described in more detail in Section 5.2. The two configurations differ only in their focal plane instrumentation. For the MSTs installed on the CTAO-North and the CTAO-South sites the NectarCAM and FlashCam cameras are foreseen, respectively. The FlashCam camera is described in Section 3.1.2 and the NectarCAM in Glicenstein (2016). Both camera designs provide comparable scientific performance.

The third telescope configuration of the MST uses a Schwarzschild-Couder layout of the reflector. Its potential advantage over the single mirror Davies-Cotton configuration is an improved optical PSF over the entire FOV due to the correction of spherical and comatic aberrations. The primary and secondary mirrors of the Schwarzschild-Couder configuration have diameters of 9.7 m and 5.4 m, respectively. They consist of a total of 72 mirror facets resulting in an effective mirror area of $\approx 50 \text{ m}^2$. In contrast to the cameras for the Davies-Cotton reflector layout which are based on PMTs as photosensitive devices, the camera of the Schwarzschild-Couder configuration is based on SiPMs. With its smaller pixel size of 0.067° , it offers a better resolution of the angular distribution of the Cherenkov light emitted by the particle shower (Glicenstein 2021).

All three configurations offer similar camera FOVs of $\sim 7.8^\circ$, making the MST ideally suited for the study of extended sources such as SNRs or PWNe. A first prototype of the Davies-Cotton layout was installed at Berlin Adlershof to study, among other things, telescope operation and the installation of the focal plane instrumentation (Glicenstein 2021). A prototype of the Schwarzschild-Couder layout was installed at the Fred Lawrence Whipple Observatory (Arizona, USA) and inaugurated in 2019. A detection of the Crab Nebula during the first observing campaign is reported in Adams et al. (2021). The Schwarzschild-Couder layout is planned for a future enhancement of the CTAO.

Small-Sized Telescope (SST)

The SSTs aim to detect γ -rays with energies in the range of 1 TeV – 300 TeV. To do this efficiently, a large number of telescopes must be distributed over an area of several km^2 . Therefore, the design of the SST emphasizes cost-effectiveness, reliability and maintainability. The SST follows a Schwarzschild-Couder reflector layout with a tessellated primary mirror with a diameter of 4.3 m and a monolithic secondary mirror with a diameter of 1.8 m. The resulting effective mirror area is $\sim 6 \text{ m}^2$. The Schwarzschild-Couder layout provides good imaging capabilities for images with large off-axis angles. This is combined with a camera design that offers a large FOV of $\sim 9^\circ$ and the ability to read the full waveform of a signal up to $\sim 100 \text{ ns}$ ¹⁷. Both of these design features are optimized to capture off-axis events with long transit times through the focal plane as expected from particle showers initiated by VHE γ -rays (White et al. 2021). The camera for SST is further described in Lapington (2023).

The SST structure is based on the ASTRI-Horn telescope on Mt. Etna, Italy.

¹⁷The size of the readout window is nominally set to 96 ns – 128 ns (White et al. 2021).

The ASTRI-Horn telescope validated the use of a Schwarzschild-Couder reflector layout for an IACTs (Giro et al. 2017). It also detected the Crab Nebula in 2018, as reported in Lombardi et al. (2020). This provided the proof of concept for the use of SST in the CTAO. The current planned array layout and its performance of the CTAO is described in the following.

3.2.2. Alpha Configuration

The originally planned Omega configuration of the CTAO envisioned a total of 118 telescopes distributed over the two sites, with 4 LSTs, 25 MSTs and 70 SSTs at the CTAO-South site, and 4 LSTs and 15 MSTs at the CTAO-North site. After it became clear that the expected costs of the Omega configuration would not be covered by the expected resources, the Omega configuration was reduced to the Alpha configuration, with the possibility of extending the Alpha configuration in the future (Hofmann et al. 2024). The two array layouts of the Alpha configuration are shown in Figure 3.13. The CTAO-North site consists of 9 MSTs and 4 LST and focuses on extragalactic science lacking SSTs. The CTAO-South site consists of 14 MSTs and 37 SSTs. It focuses on galactic science. With additional funding secured in 2022, the first extension phase of the Alpha configuration began with the planned installation of 2 to 3 LSTs and 5 SSTs (Antonelli 2023). The addition of LSTs to the CTAO-South site provides it with the designed energy coverage of the CTAO.

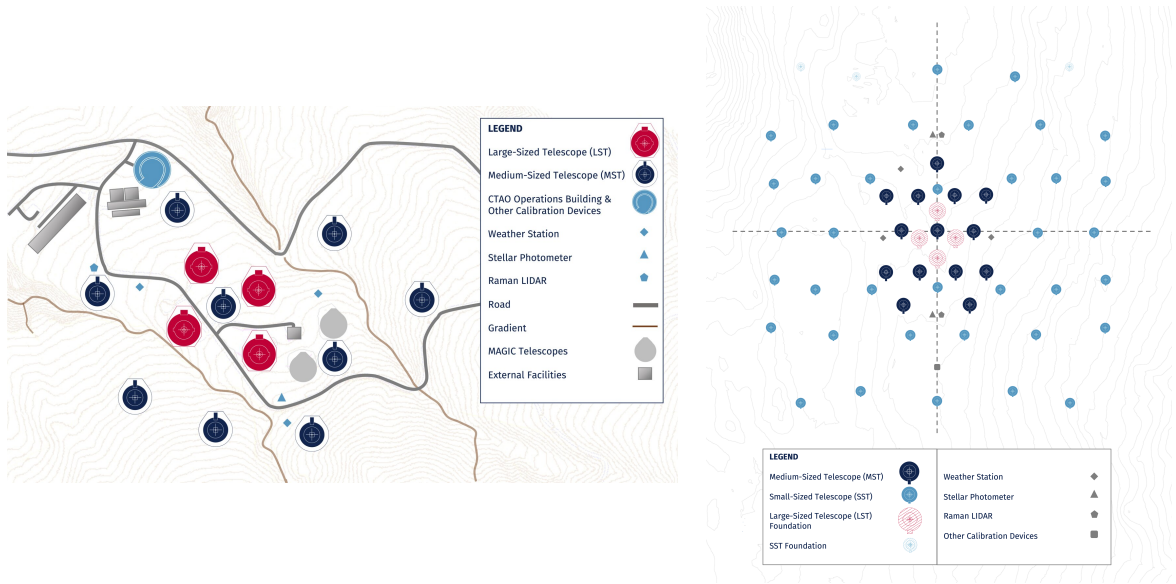


Figure 3.13. Layout of the CTAO-North (left) and CTAO-South (right) site for the Alpha configuration of the CTAO. Image credit: CTAO and the CTAO Consortium.

The differential flux sensitivity and angular resolution as function of the reconstructed energy of the initial γ -ray are shown on the left and right of Figure 3.14 for both CTAO sites with respect to other γ -ray instruments. The higher sensitivity of the CTAO-South site compared to the CTAO-North is explained by the presence of the SSTs in the south. Both CTAO sites provide increased sensitivity in the 0.1 TeV – 10 TeV range. Below 0.1 TeV, the space-based Fermi Gamma-Ray Space Telescope dominates the sensitivity for persisted sources, while for energies > 10 TeV

the ground-based LHAASO or the proposed Southern Wide-field Gamma-ray Observatory (SWGO) experiment dominate. However, CTAO is complementary to these instruments in this energy range as it offers a much better angular and energy resolution (Hofmann et al. 2024). The CTAO will therefore provide many groundbreaking insights in the field of TeV astronomy.

The construction plans for the Alpha configuration are gradually being implemented. As already mentioned, the first LST has been inaugurated at the CTAO-North site as a prototype, and the foundations for the other three LSTs of the Alpha configuration have begun construction in 2023. The most recent noteworthy achievement was the installation of the mirror support structure of the LST-4 telescope. The expected completion of all four telescopes is currently scheduled for 2026 (CTAO 2024). On the MST side, prototype telescopes for both sites are currently being planned and components are being procured. Current plans foresee the installation of a prototype telescope in 2025 (Bradascio 2023). As part of these preparations, the quality control of optical alignment components is an important contribution to the quality control of the entire telescope and to meeting the requirements for, e.g., pointing accuracy. Efforts in this area will be reported in the next part of this thesis. For the SSTs, the design of the telescope and camera is currently being optimized and prepared for mass production as reported in White et al. (2021) and Depaoli et al. (2024). The CTAO is on its way to becoming a major TeV astronomy facility towards the end of this decade.

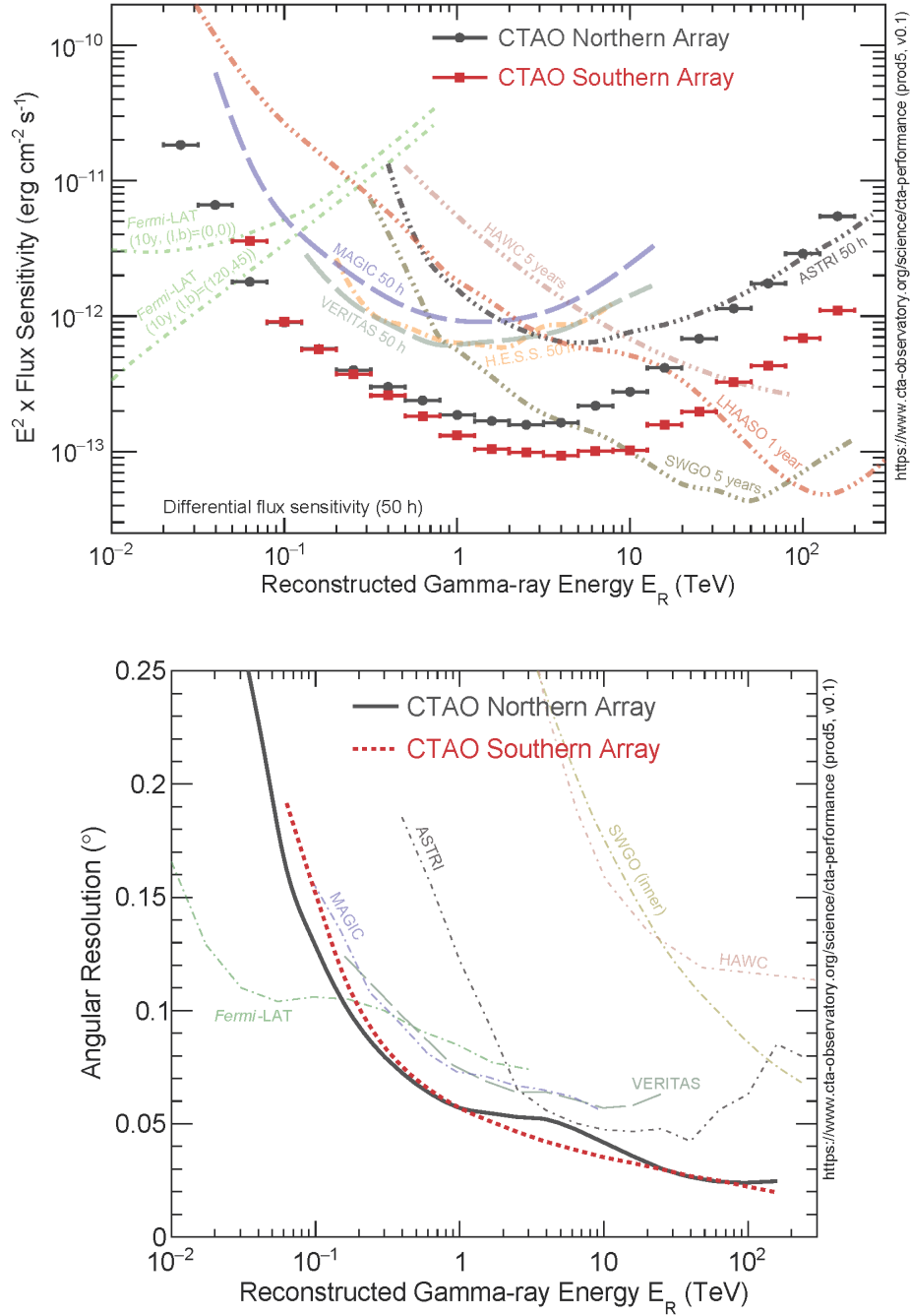


Figure 3.14. Performance of the CTAO in comparison with other γ -ray instruments based on the direct and indirect detection method of γ -rays. Left: The differential flux sensitivity of the two CTAO sites for the Alpha configuration for an observation time of 50 h. The higher sensitivity of the CTAO-South site compared to the CTAO-North site is explained by the presence of the SSTs. Right: The angular resolution as a function of the reconstructed energy of the initial γ -ray. The angular resolution of the CTAO is a clear advantage over other γ -ray instruments for energies above ~ 100 GeV. Taken from Cherenkov Telescope Array Observatory et al. (2021).

Part II

Quality Control of Mirror Alignment Components for the Cherenkov Telescope Array Observatory

If we knew what it was we were doing, it would not
be called research, would it?

ALBERT EINSTEIN

Quality Control and Verification

The purpose of the mirror alignment system is to precisely align each of the mirror facets so that their reflected light from a point source is focused into a single light spot in the focal plane of the telescope. Consequently, mirror alignment has a significant impact on the optical performance of the telescope, which in turn influences the image quality of the Cherenkov light distribution recorded by the focal plane instrumentation¹. The two most important optical performance parameters are the optical PSF and the pointing of the telescope. The former describes the response of the optical system to a point source located at infinity, while the latter is the position where the optical axis intersects with the focal plane. Here, the optical axis is defined as the symmetry axis of the mirror support structure. Both of the above mentioned parameters, the optical PSF and the pointing, are affected by the bending of the entire mirror support structure caused by varying gravitational loads at different elevation angles during observations². In addition, positioning uncertainties in the mechanical components of the mirror alignment system directly influence the tilt of the individual mirror facets of an IACT and thus the optical performance of the telescope. To achieve the scientific goals of the observatory, a certain scientific performance of the telescope is required. Therefore, a set of technical requirements is derived from the observatory's scientific requirements for the optical performance of the telescope. These requirements at the telescope level dictate the technical requirements at the level of the components of the mirror alignment system. To ensure that these technical requirements are met, quality control plays an important role.

The general process of quality control is shown in Figure 4.1 and explained according to Juran (1999). In quality control, a measurement is established to measure the performance of a test object against a predefined set of performance standards. After measurement, the actual performance is interpreted and compared to the predefined standards. If a difference between the actual performance and the predefined standard is detected, actions can be taken to address the difference. Thus, the process of quality control can be summarized as the evaluation of a test object, the comparison of its actual performance with the target performance, and the action on the possible performance difference. The main objective of quality control is to provide a certain level of stability in the quality of the test object. Therefore, it serves as direct feedback during, e.g., the production of the test objects.

The measurement or verification of the actual performance can be accomplished by

¹The quality of the image of the Cherenkov light distribution is characterized by the image shape and image position in the focal plane.

²Although to a much lesser degree, an example of another influence on the optical PSF and pointing of the telescope is the thermal expansion of the telescope structure, which results in a change in the position of the camera in the focal plane.

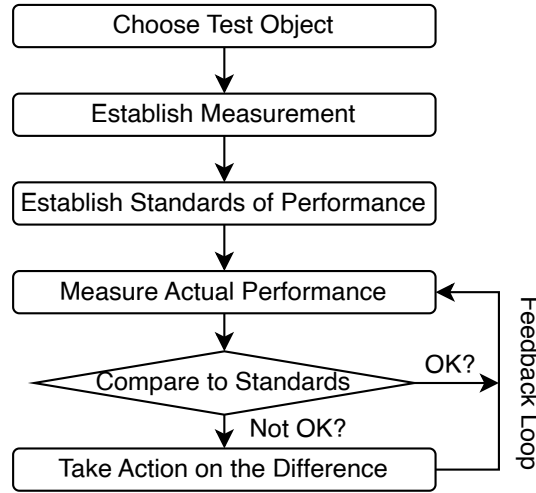


Figure 4.1. Quality control process with feedback loop according to Juran (1999).
Adapted from Juran (1999).

several methods with increasing levels of confidence, as described in Bely (2003). The lowest level of confidence provides a simple inspection of the test object in terms of its physical dimensions, design features and workmanship. The next step would be to analyze the design of the test object by computer modeling or hardware simulations. The highest level of confidence is provided by actual testing of the test object to verify that it meets the imposed performance standards. The tests themselves fall into two categories. Functional testing verifies the electrical and mechanical performance of the test object, while environmental testing verifies that the test object can withstand and perform adequately in its operating environment.

As part of the verification step in the quality control process, the hazard rate $h(t)$ of the test object is probed. The hazard rate of a test object is one of several distributions describing the time to failure T of a product and is given by

$$h(t) = \frac{f(t)}{1 - F(t)} \quad (4.1)$$

where $F(t) = \Pr(T \leq t)$ is the probability that a randomly selected test object will fail before time t and $f(t) = dF(t)/dt$ is the relative frequency of failure times as a function of time. Consequently, $h(t)$ can be understood as the number of failures per unit time per test object. A conceptual model of the hazard rate is shown in Figure 4.2. The bathtub curve describes the hazard rate of a test object over the test object's lifetime. During the infant mortality phase, an increased number of failures due to quality issues is expected. After the infant mortality phase, the hazard rate becomes approximately constant and a test object fails due to random external influences. Towards the end of the test object's life, the hazard rate increases again due to wear and tear on the test object (Juran 1999).

Given financial and time constraints, the quality control process should be designed to thoroughly review the performance of the test object and obtain as much

information as possible about its operation. Therefore, the outcome of the verification step and the entire quality control process should be a test object that meets its imposed performance standards and operates reliably under its specified operating conditions. Preferably, it operates outside of its infant mortality phase. Applying the quality control process described above to the specific example of the mirror alignment system, the mechanical components of the mirror alignment system are the test objects. Consequently, the performance standards are the technical requirements that the mechanical components must meet. The optical system and the mechanical components of the mirror alignment system of the MST are described in the next chapter.

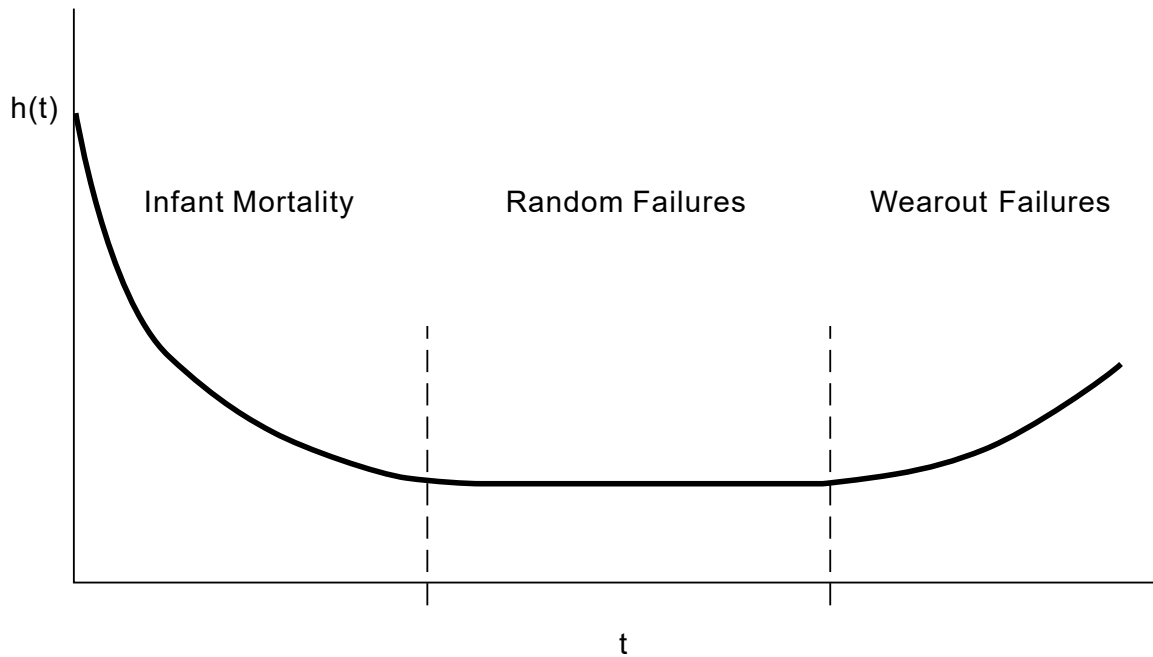


Figure 4.2. Conceptual model for the hazard rate $h(t)$ of a test object is the bathtub curve. The bathtub curve describes the hazard rate of a test object as a function of its lifetime t . An increased hazard rate is expected in the early and late phases of the lifetime due to quality-related failures (infant mortality) and wear-out failures, respectively. Taken from Juran (1999).

The Medium-Sized Telescope

The MST is one of three telescope types planned for the future CTAO and covers the core energy range of 0.15 TeV – 5 TeV as described in Section 3.2.1. In the Alpha configuration, it is the only telescope type foreseen for both sites, CTAO-North and CTAO-South. With its wide FOV of $\sim 7.8^\circ$, it is ideally suited to study extended astronomical sources such as SNRs or PWNe. The latest status of the MST project is described in Bradascio (2023).

This chapter focuses on the optical system of the MST configuration with the modified Davies-Cotton (DC) reflector layout, which is shown in Figure 5.1. The basic technical requirements that drive the design of the optical system are outlined in Section 5.1. The optical system and the MACs are described in Section 5.2 and Section 5.3, respectively.

5.1. Technical Requirements

A set of scientific requirements has been defined at the observatory level to investigate the key scientific questions of the CTAO described in Section 3.2. From these scientific requirements, the technical requirements at the telescope level are derived. The main technical requirements for the design of the optical system are listed in Table 5.1.

The two requirements relevant to the limits on the positioning uncertainties of the MACs are the pointing accuracy and the optical PSF requirement. The pointing calibration for the MST is a two-step approach. A standard pointing model is derived from calibration runs taken at the start and the end of a lunar cycle, providing averaged pointing corrections for the entire observation period. Then, on the basis of a single observation, a precision pointing model combines the information from the standard pointing model with additional corrections derived from the motion of the stars with respect to the focal plane camera during the observation to compensate for non-reproducible, short-term effects such as wind loads (Schwanke et al. 2022). The resulting pointing accuracy under precision pointing conditions must be better than $7''$. To provide reasonable imaging of off-axis light rays, the optical PSF must be better than 0.21° for angles of incidence of up to 2.8° from the optical axis. The optical PSF is quantified by the angular diameter $\Theta_{80\%}$ containing 80 % of the light intensity within a circle of 1° in the focal plane. The influence of these two technical requirements on the design specifications of the MACs is described in more detail in Section 5.3.3. The design of the optical system is described in the following.

Table 5.1. Main technical requirements relevant for the design of the optical system of the DC-MST. The CTAO internal requirement labels are B-TEL-0250, B-MST-0020, B-MST-0210, B-MST-0130, B-MST-0110 and B-MST-0140.

Requirement	Condition	Description
Tracking Accuracy	$< 0.1^\circ$	all azimuth angles, elevation angles from $20.0^\circ - 89.2^\circ$
Pointing Accuracy	$< 7''$	post-calibration, precision pointing conditions ¹
Repositioning Time	< 90 s	for wind speeds < 36 km h ⁻¹
Optical PSF ²	$< 0.21^\circ$	within 2.8° from the center of the camera FOV
Effective Mirror Area	> 88 m ²	corrected for shadowing
Time Dispersion RMS ³	< 0.8 ns	over 80 % of the camera FOV

¹ Precision pointing conditions are defined by a temperature gradient of $\leq 3^\circ\text{C h}^{-1}$, as well as maximum wind speeds of 15 km h⁻¹ and 11 km h⁻¹ for the CTAO-North and CTAO-South site, respectively. The wind speeds are calculated for an average time of 10 min.

² The figure of merit for the optical PSF is the angular diameter $\theta_{80\%}$ containing 80 % of the reflected light within a circle of 1° in the focal plane.

³ RMS stands for Root Mean Square.

5.2. Optical System

Some general design ideas for the various subsystems of the optical system of an IACT are outlined in the respective sections of Section 3.1.1. The following section focuses on the description of the respective subsystems for the MST. The telescope structure and drive system is described in Section 5.2.1, the reflector layout in Section 5.2.2, and the mirror alignment system and procedure in Section 5.2.3.

5.2.1. Telescope Structure and Drive System

The telescope structure can be separated into the positioner and the optical support structure and follows an altitude-azimuth mount. In addition to supporting the optical support structure, the positioner contains the azimuth and elevation drive systems and points the optical support structure toward the astronomical source to be observed. The azimuth and elevation drive systems consist of two and four motor units, respectively, and provide an absolute positioning accuracy of $\pm 20''$ for the respective axis (Garczarczyk et al. 2015). For normal operation, the range of movement in the azimuth and elevation axis are 540° and -21° to 91° , respectively. First tests with the prototype telescope structure in Berlin Adlershof have shown that the positioning accuracy in the azimuth and elevation axis is $< \pm 20''$ and that all astronomical targets above an elevation angle of 30° can be reached with a repositioning time of less than 90 s (Sternberger et al. 2022).

The optical support structure combines the counterweight, backbone, mirror support, and camera support structure (see Figure 5.1). The counterweight structure compensates the weight of the camera in the focal plane and balances the elevation axis. It is connected to the mirror support structure by the backbone structure, which is an important component to the overall stiffness of the optical support structure. The mirror support structure consists of a central plate and 12 radial beams connected by cross beams. Connected to the mirror support structure is the camera support structure, which holds the camera in the focal plane. The entire telescope structure

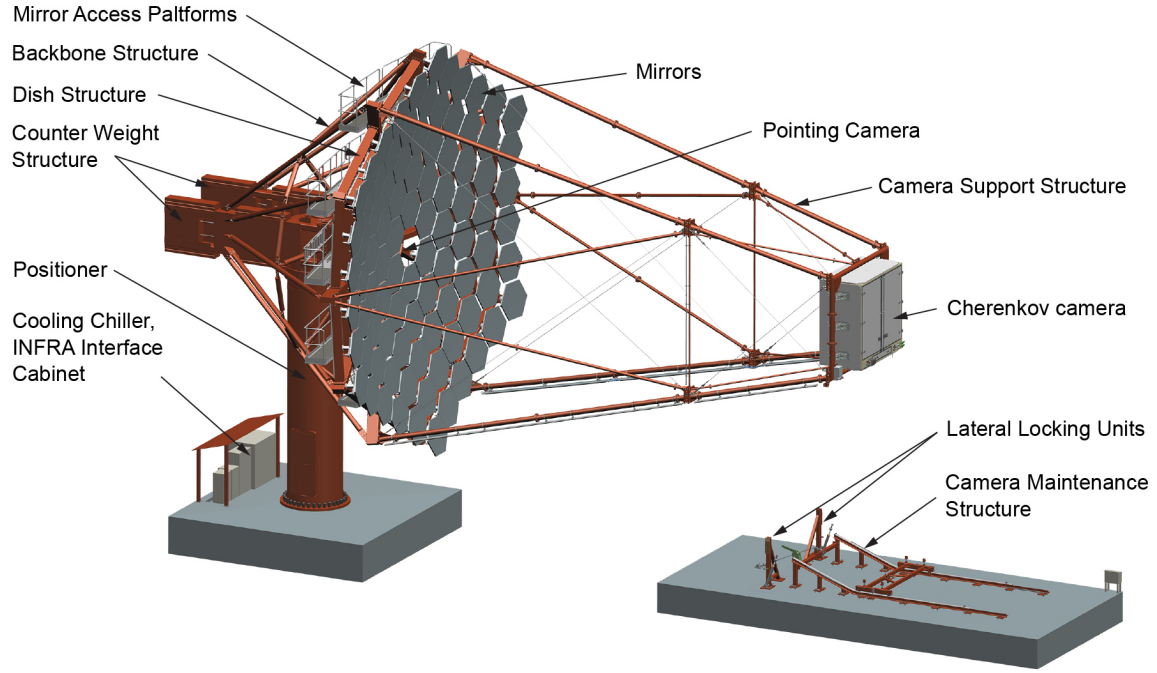


Figure 5.1. Design of the MST with the Davies-Cotton reflector layout. The two main subsystems of the telescope structure are the positioner and the optical support structure, which combines the backbone, counter weight, mirror support (dish), and camera support structure. Taken from Garczarczyk et al. (2023d).

is made of steel for various design reasons. The mirror support structure must be rigid enough to keep the overall reflector shape under varying gravitational loads for different observation angles. Furthermore, the camera support structure is designed to minimize shadowing of the mirror area while reducing camera displacements in the focal plane (Garczarczyk et al. 2023d). The layout of the reflector and the mirror system are explained in more detail in the following.

5.2.2. Reflector Layout and Mirror System

Before the reflector layout and mirror system of the MST are described, the optical characteristics of the general Davies-Cotton design are briefly outlined. The Davies-Cotton design was first introduced by Davies et al. (1957), and one of the first IACTs to use it was the 10 m Whipple reflector (Lewis 1990). A schematic diagram of the Davies-Cotton design is shown in Figure 5.2. The mirror support structure follows a spherical shape with a radius of curvature R , and the individual, usually spherical, mirror facets mounted on the mirror support structure have a radius of curvature of $2R$. The mirror facets are aligned such that their normal vector points at a distance of $2R$ from the center of the mirror support structure and such that incident light rays parallel to the optical axis are focused in the focal point located at the distance R . The optical PSF for incident light rays parallel to the optical axis (on-axis) is dominated by the quality of the individual mirror facets (e.g., the mirror facet PSF), the fact that the mirror facets are not located on the optical axis (e.g., leading to spherical aberration, comatic aberration, and astigmatism), and the precision of the mirror alignment (Cornils et al. 2003). The off-axis optical PSF is dominated by the

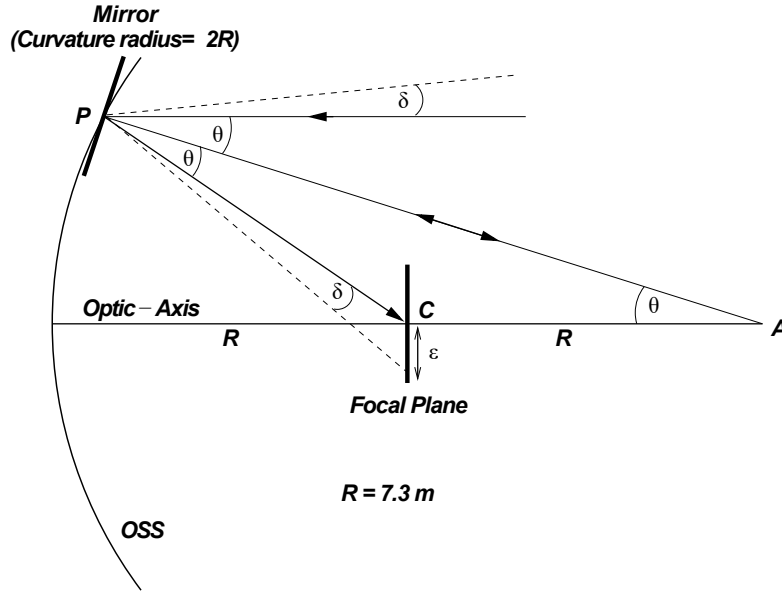


Figure 5.2. Schematic diagram of the Davies-Cotton reflector design. R defines the radius of curvature of the spherical shape of the mirror support structure. The points A, P and C define the center of a) the curvature of an individual mirror facet, b) an individual mirror facet, and c) the focal plane of the reflector. If the individual mirror facets are ideally aligned the triangle APC is isosceles. Light rays with an angle δ incident to the optical axis are displaced by the distance ϵ in the focal plane. Taken from Kildea et al. (2007).

overall shape of the reflector. This is caused by the fact that the individual mirror facets are not oriented tangentially to the mirror support structure, but are aligned at a distance of $2R$ from the center of the reflector. Consequently, light rays with an angle of incidence δ to the optical axis are not reflected to a single point in the focal plane. The reflected light of a mirror facet at an angle θ to the optical axis has a distance ϵ from the center of the focal plane, given by

$$\epsilon = \frac{R \tan \delta}{\cos \theta}, \quad (5.1)$$

where R is the radius of curvature of the reflector. This results in a comet shaped light ring in the focal plane. The on-axis PSF of a Davies-Cotton reflector design is slightly worse than for a parabolic layout, but the off-axis PSF is better (see Figure B.1) (Lewis 1990). A disadvantage of the Davies-Cotton design is that it is not isochronous resulting in a dispersion of the photon arrival times in the focal plane. The time spread is dominated by the mirror facets located near the center of the reflector (Bretz et al. 2013). A study investigating the design constraints of Davies-Cotton reflectors is described in Bretz et al. (2013).

A series of design studies have been performed to determine the properties of the reflector layout of the MST, assuming a reflector diameter of 12.5 m. One of the design parameters is the dispersion of photon arrival times in the focal plane, which can be reduced by increasing the radius of curvature of the mirror support structure. This is shown in Figure 5.3a for the standard and two modified Davies-Cotton reflector layouts. The modified Davies-Cotton layouts have a radius of curvature of

the mirror support structure that is increased by a factor of 1.2 and 1.4 compared to the standard design. The standard Davies-Cotton design violates the optical time dispersion requirement of < 0.8 ns, while both modified designs meet it. All three satisfy the optical PSF requirement up to an offset angle of 3° , as shown in Figure 5.3b. In the end, the modified 1.2 design was chosen because the 1.2 Davies-Cotton provided a more stable minimum of the optical PSF as a function of the focal length of the individual mirror facets for different offset angles, as shown in Figure 5.4. The design parameters of the resulting optical system are summarized in Table 5.2. The reflector follows a modified Davies-Cotton layout with a diameter of 12.5 m, a radius of curvature of $R = 19.2$ m, and a focal length of 16 m. The mirror system consists of 86 hexagonal mirror facets with a flat-to-flat diameter of 1.2 m resulting in an effective area of approximately 88 m^2 (Parsons et al. 2023)¹. The alignment system for the mirror facets and the alignment procedure are described below.

Table 5.2. Main design parameters of the mirror system and the single mirror facet for the MST. Information taken from Garczarczyk et al. (2023d).

Parameter		Value
Mirror System	Radius of Curvature	19.20 m
	Focal Length	16.00 m
	Diameter	12.50 m
	Total No. Mirror Facets	86
	Effective Area	$88 \text{ m}^2 - 90 \text{ m}^2$
Mirror Facet	Diameter (flat-to-flat)	1.20 m
	Radius of Curvature	32.14 m
	Type	Spherical

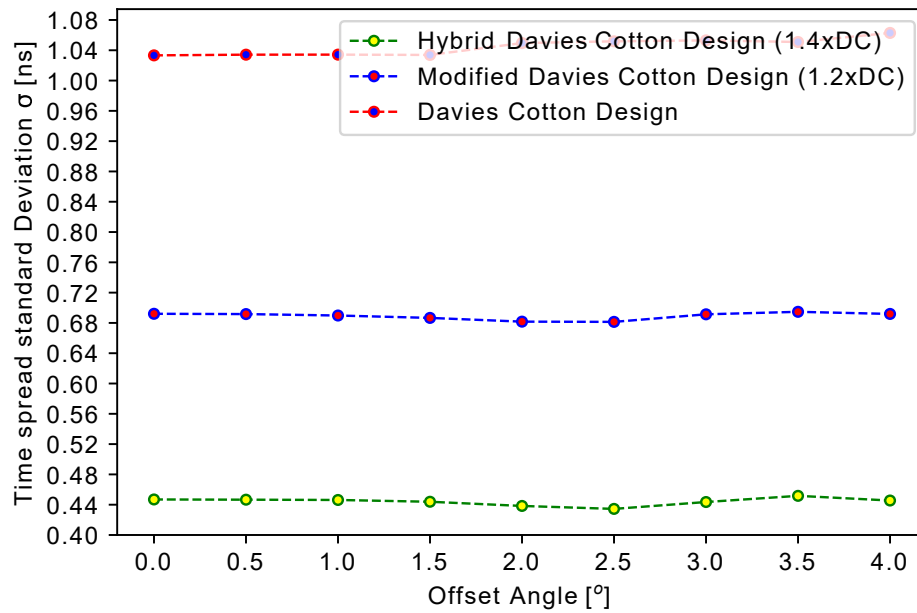
5.2.3. Mirror Alignment System and Alignment Procedure

The mirror alignment system is designed as an Active Mirror Control (AMC) system and allows active alignment of the mirrors as a function of elevation angle. Due to the high stiffness of the mirror support structure, the alignment of the mirrors is optimized for the range of elevation angles relevant for observations, and an adjustment of the mirror alignment as a function of elevation angle is currently not planned.

The tilt of each mirror facet can be adjusted by the MACs, which consists of two actuators and one fix point bolted to a metal plate glued to the back of each mirror facet. The actuators are adjustable in length and provide one and two Degrees of Freedom (1-DOF and 2-DOF), while the fix point has only rotational Degrees of Freedom and a fixed length. The mechanical components of the mirror alignment system are described in more detail in Section 5.3.

The two actuators and the fix point are mounted to the Mirror Support Unit (MSU), a cast aluminum triangle, that provides the interface between the mirror facet and the mirror support structure. The MSU is mounted on the mirror facet with the fix point at the top to support most of the weight of the mirror, and the

¹The effective area varies slightly due to shadowing for different elevation angles. For all elevation angles the effective area is within $88 \text{ m}^2 - 90 \text{ m}^2$ (Parsons et al. 2023).



(a) The time dispersion as a function of the offset angle.

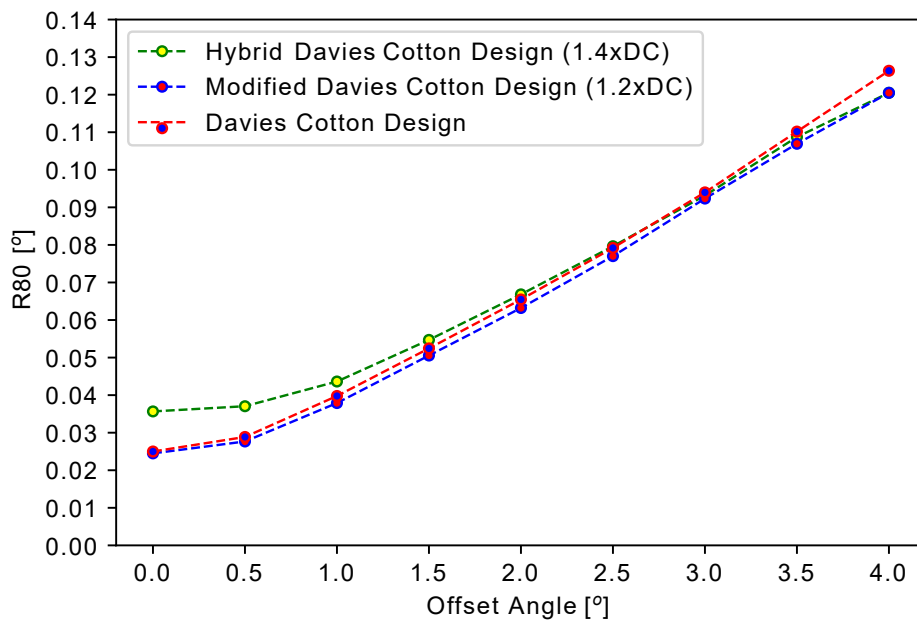
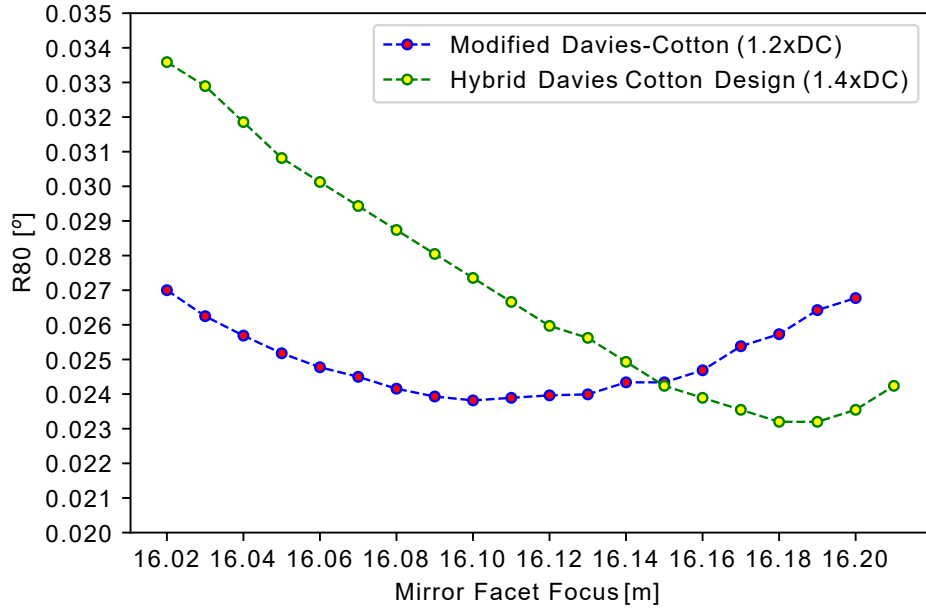
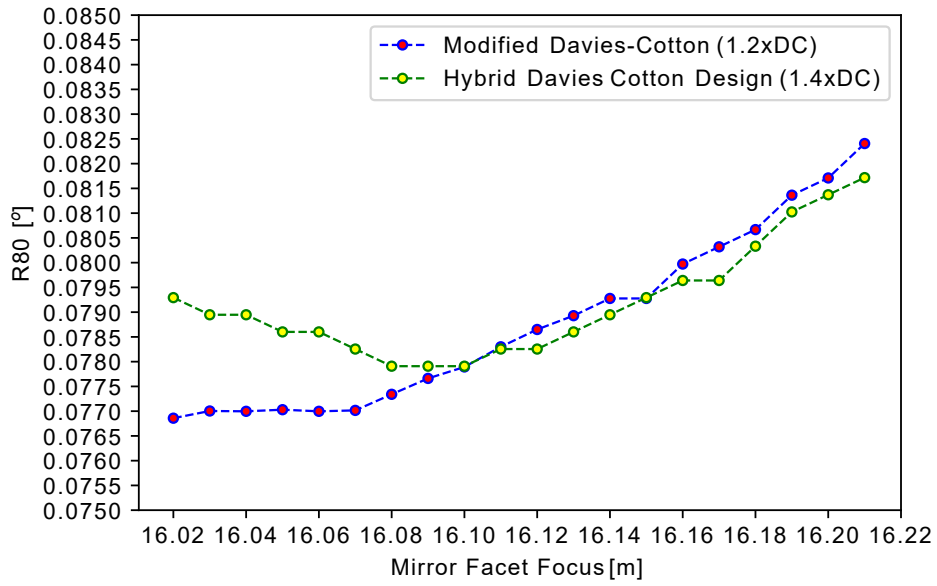
(b) The radial PSF R_{80} as a function of the offset angle.

Figure 5.3. Simulations of the optical PSF and the time dispersion for two modified Davies-Cotton designs and the standard Davies-Cotton design. The radius of curvature of the modified Davies-Cotton reflector designs are increased by a factor of 1.2 and 1.4 with respect to the standard Davies-Cotton design. Taken from Parsons et al. (2023).



(a) For an astronomical source located at an angle of 0° from the optical axis.



(b) For an astronomical source located at an angle of 2.5° from the optical axis.

Figure 5.4. Radial PSF R_{80} as a function of the mirror facet focal length for the 1.2 and 1.4 modified Davies-Cotton reflector layout. The 1.2 Davies-Cotton design offers a more stable minimum of the optical PSF as a function of the offset angle. Taken from Parsons et al. (2023).

two actuators at the bottom of the mirror facet. The MSU and the orientation of the MSU with respect to the mirror facet are shown on the left and right side of Figure 5.5, respectively. Consequently, the tilt of the mirror facet can be adjusted with two degrees of freedom (Murach et al. 2018).

The mirror facets are aligned so that light parallel to the optical axis is reflected at a distance of $2f + \Delta$ from the center of the telescope's reflector, where Δ is related to the distance of the mirror facet from the center of the reflector. The main goal of the mirror alignment procedure is to determine the response matrix R , which correlates the movement of the actuator with the movement of the light reflected by the mirror facet in the focal plane. This can be described by

$$\Delta \vec{p} = R \Delta \vec{a} \quad (5.2)$$

with the actuator position $\vec{a} = (a_0, a_1)$ and the light spot position $\vec{p} = (p_0, p_1)$. The optical feedback is provided by a CCD camera installed in the center of the mirror support structure, as shown on the left side of Figure 5.6 (Schwanke et al. 2022). The alignment procedure of the MST is divided into two steps and is described according to Murach et al. (2018).

A first coarse alignment of the mirror facets is done with the Bokeh method introduced by Ahnen et al. (2016). For the Bokeh method, an artificial light source is placed at a distance from the telescope greater than twice the focal length of the telescope. In this configuration, an unfocused image of each mirror facet is projected into the focal plane of the telescope. The resulting Bokeh image is recorded by the CCD camera. An example Bokeh image for an unaligned MST is shown on the right side of Figure 5.6. To determine the position of a mirror facet image, the actuators are moved in a defined sequence and images are taken with the CCD after each actuator movement. By calculating the difference of the resulting images, the position of the mirror facet is identified and a first approximation of the response matrix is derived. The mirror facet is then aligned so that the position of the image coincides with the position derived from the Bokeh template, which is a Bokeh image computed from ray tracing simulations for a well aligned reflector. Repeating this step for each mirror facet results in a coarse alignment of the reflectors with a PSF of $\theta_{80\%} < 0.5^\circ$. The Bokeh alignment has the advantage of using cloudy nights for mirror alignment. However, at this stage, it is limited to the alignment of mirrors for low elevations, since placing the artificial light source at elevations relevant for observations (e.g., using a drone) is not planned.

The second step of the mirror alignment procedure uses stars at elevation angles of $60^\circ - 70^\circ$ to perform a fine alignment, resulting in an optical PSF that meets the technical requirement of $\theta_{80\%} < 0.21^\circ$. The fine alignment procedure is similar to that of the H.E.S.S. telescopes (see Section 3.1.1). The mechanical components of the AMC are described in the following.

5.3. Mirror Alignment Components

The design of the actuators of the mirror alignment system is based on the actuator design of the MAGIC telescopes and was developed by the University of Zürich. The mechanical components for a single mirror facet are shown in Figure 5.7 and constitute one set of MACs. The two actuators are equipped with a 1-DOF and 2-DOF gimbal,

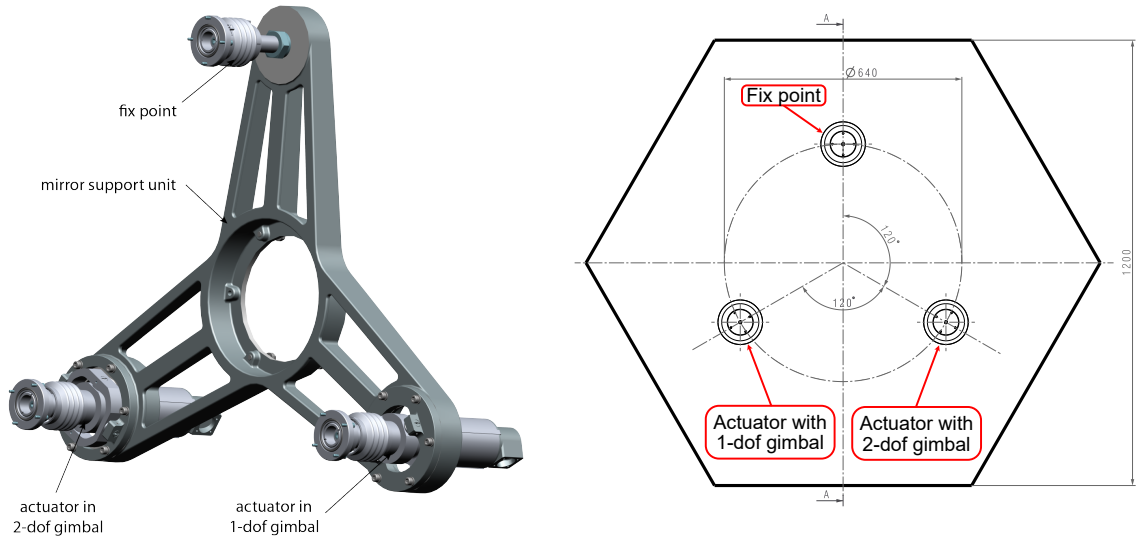


Figure 5.5. Mirror Support Unit equipped with the mechanical components of the mirror alignment system (left) and a technical drawing of a mirror facet (right). The orientation of the MSU is indicated in the technical drawing. Taken from Garczarczyk et al. (2023d).

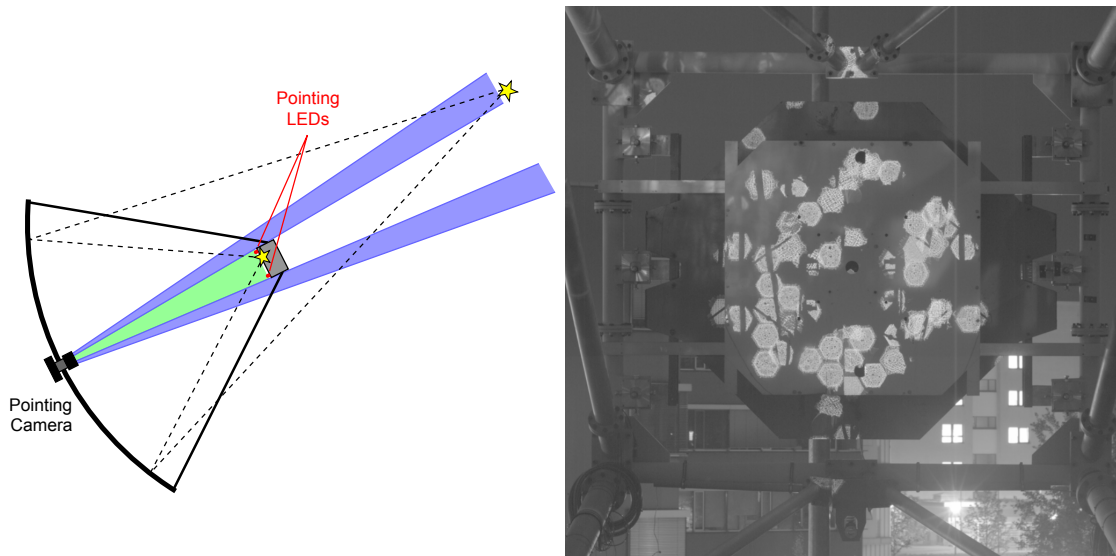


Figure 5.6. Pointing camera located at the center of (left) and Bokeh image for a misaligned (right) MST reflector. Taken from Schwanke et al. (2022) and Murach et al. (2018), respectively.

while the fix point consists of a steel rod fixed in length and tilt. The common part between the three MACs of a set is the mirror interface, which consists of the flange and the built-in spherical bearing. The spherical bearing and the actuator are described in Section 5.3.1 and Section 5.3.2, respectively. The considerations for the limits of the design specifications of the MACs of the AMC derived from the technical requirements at the telescope level are explained in Section 5.3.3.

5.3.1. The Flange Bearing

The parts of the flange bearing and a sectional drawing of the built-in spherical bearing are shown in the left and right side of Figure 5.8, respectively. The flange bearing consists of the base flange, the spherical bearing, and the threaded ring for fixing the spherical bearing. The flange bearing is the same part for all three mechanical components of an AMC set and is the interface to the mirror facet.

In general, a spherical bearing provides two rotational Degrees of Freedom around a central point. It consists of an outer ring, the joint socket, and an inner ring, the joint head. The sliding contact surface between the joint head and the joint socket can consist of a lubricant, a liner, or uses rolling elements (e.g., in the case of a roller bearing). The built-in spherical bearing is a plain bearing of the company Fluro with the serial number GE-16-EC-NIRO and the liner is a maintenance-free PTFE fabric².

5.3.2. The Actuator

In a general sense, an actuator or actuating system is a system that takes an input of electrical, pneumatic or hydraulic nature and produces a force, torque or displacement in a controlled way (Escudier et al. 2019). There is a wide range of categories of actuators. The actuator for the AMC is an electromechanical actuator, which takes the rotary movement of an electric motor and transforms it into a constant translation. The actuator design was developed by the University of Zürich and is based on the actuator design used for the mirror alignment system of the MAGIC telescopes. Except for a different communication interface to the actuators, the same actuators are used for the LSTs at the CTAO-North site³. The design has undergone several iterations, from the A-series installed on the MST prototype telescope in Berlin Adlershof to the current E-series produced for the LSTs at the CTAO-North site. In the following, the mechanical working principle, the determination of the absolute position and the communication with the actuator are described.

A sectional drawing of the actuator is shown in Figure 5.9. The stepper motor provides a rotary motion and is coupled to a spindle with a 1 mm thread pitch. The rotational motion of the spindle is translated into longitudinal motion of the actuator piston by a gear nut driven by the spindle and fixed to the piston. A sliding foil provides the necessary sliding contact surface between the piston and the outer housing, and rotation of the piston is eliminated by the guiding pin connecting the outer housing to the groove of the piston (Gadola 2018b). Consequently, the change of the piston position causes a change of the mirror tilt through the spherical bearing

²The details about the spherical plain bearing can be found under Fluro (2024b).

³For the LSTs at the CTAO-South site, the actuator design of the MST is used. The reasoning behind this decision is explained below.

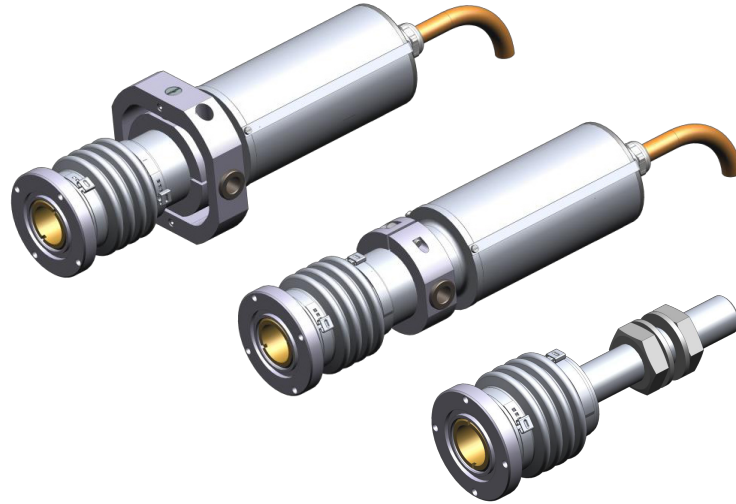


Figure 5.7. Mechanical MACs of a single set for an individual mirror facet. The two actuators are equipped with a 1-DOF and 2-DOF gimbal. Combined image from images taken from Garczarczyk et al. (2023a) and Garczarczyk et al. (2023c).

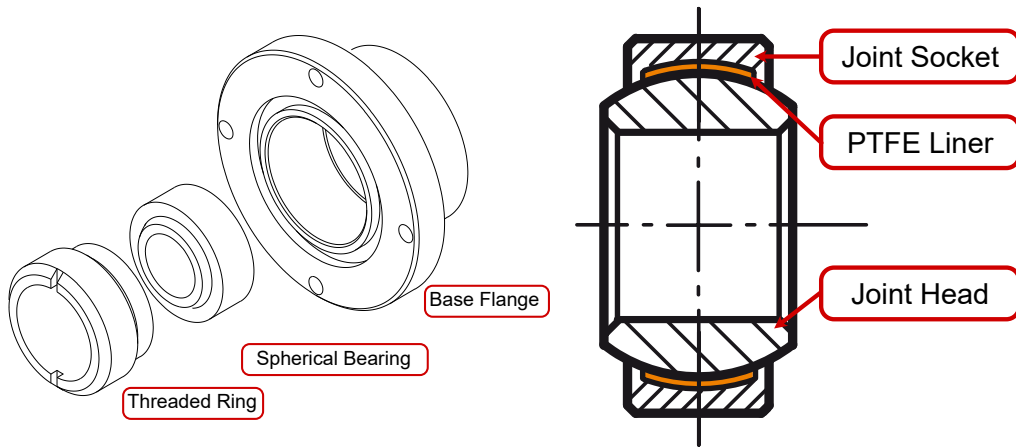


Figure 5.8. Different parts of the flange bearing of the MACs (left) and cross-sectional drawing of the built-in spherical bearing (right). The spherical bearing is a plain bearing using a PTFE liner as sliding contact surface. Adapted from Garczarczyk et al. (2023b) and Fluro (2024b), respectively.

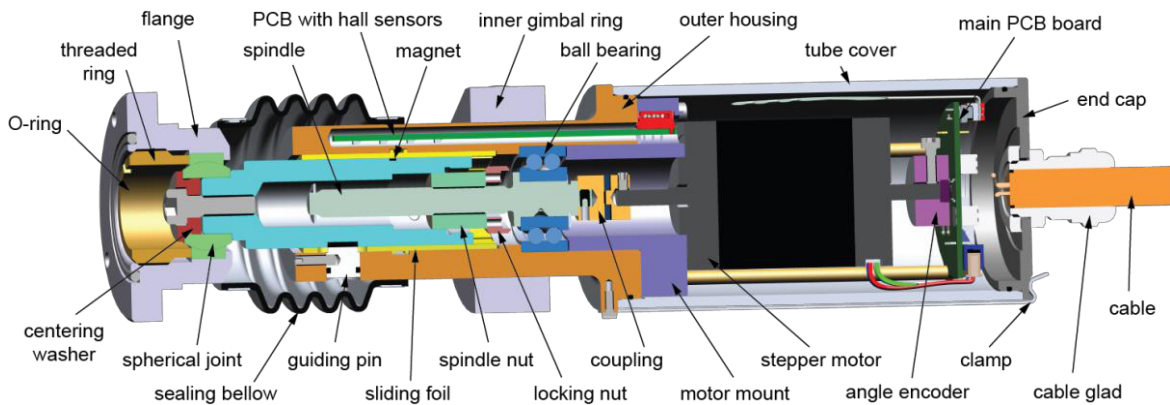


Figure 5.9. Cross-sectional drawing of an actuator for the AMC of the MST. Taken from Olivera et al. (2023).

installed in the mirror flange bearing, and it is controlled by the movement of the stepper motor.

The absolute position of the piston is determined by a two-part system based on Hall sensors. The first part consists of a magnet mounted on the piston and a set of four Hall sensors located along the path of the piston in the outer housing. The magnet induces a magnetic field in the Hall sensors, which convert the magnetic field into an electrical voltage. The voltage strength of each Hall sensor depends on the position of the piston relative to the outer housing. The resulting voltage pattern provides a coarse determination of piston position. To achieve finer position resolution, the information from the four Hall sensors is combined with the information from the second part, the angle encoder built into the stepper motor. The angle encoder detects the angular position of the stepper motor. It resolves a full revolution of 360° into 256 discrete steps, resulting in an angular resolution of 1.4° and a finite resolution of piston position of $3.9\mu\text{m}$. The longitudinal resolution of the actuator piston position is thus better than $5\mu\text{m}$ (Gadola 2018b).

The communication with the actuator was originally based on the wireless protocol standard IEEE 802.15.4⁴. However, as noted by Murach et al. (2018), stable communication with the majority of actuators proved to be a challenging task due to the steel structure of the MST. Therefore, a custom communication protocol based on the RS485 interface was developed and implemented for the actuators of the MSTs. While the actuators for the LSTs on the CTAO-North site are still equipped with the wireless protocol standard, the actuators for the LSTs on the CTAO-South site will have the same communication protocol as the MSTs. This is based on the modifications of the telescope structure of the CTAO-South LSTs due to environmental considerations. These modifications foresee a reinforcement of the carbon fiber based telescope structure with steel, as described by Antonelli (2023). Therefore, the decision was made to use the actuator design with the expected more reliable wired communication protocol.

The main parameters of the MACs of the AMC are summarized in Table 5.3.

5.3.3. Considerations on Design Specifications

The design specifications of the MACs of the mirror alignment system have a direct effect on the tilt of the mirror facet and are therefore constrained by the technical requirements on the pointing accuracy and the optical PSF listed in Table 5.1. There are two aspects to the design specifications. On the one hand, the accuracy of the mirror facet tilt is affected by the finite longitudinal resolution of the actuator piston position of $\pm 5\mu\text{m}$. On the other hand, the reproducibility of the mirror facet tilt is affected by the force-displacement characteristic, such as mechanical play, (visco-)elastic deformation, and possible plastic deformation of the MACs⁵. In addition, the reproducibility of the mirror facet tilt is influenced by the observation conditions, such as different wind loads on the mirrors and different weight loads. Especially the wind loads are part of the non-reproducible effects that affect the pointing accuracy and the optical PSF of the telescope. The expected forces on a single actuator as a function of the elevation angle of the MST for a wind speed of 0 km h^{-1} and

⁴This protocol standard is also referred to as ZigBee.

⁵The force-displacement characteristic is explained in more detail in Section 6.1.

Table 5.3. Design specifications for a set of MACs of the AMC. The design specifications on the total displacement and the longitudinal play have to be met for a maximum force in compression and tension of ± 150 N. Information adapted from Gadola (2018b) and Garczarczyk et al. (2023d).

Parameter	Design Specification
Longitudinal resolution	5.0 μm
Maximum piston stroke	36 mm
Operational piston stroke	34 mm
Elevation speed	1.2 mm s ⁻¹
Total actuator longitudinal displacement	(70 μm / 100 μm) (1-DOF/2-DOF)
Actuator longitudinal play (w/o spherical bearing)	10 μm
Gimbal longitudinal displacement	(35 μm /70 μm) (1-DOF/2-DOF)
Spherical bearing displacement	20 μm
Total fix point longitudinal displacement	30 μm
Positioning	Absolute, hall sensors
Max. moving force	0.7 kN
Longitudinal survival force	9.5 kN
Self locking	yes
Operation voltage	18 V – 24 V
Operation current	< 850 mA @ 24 V
Standby current	< 50 mA @ 24 V
Communication protocol	RS485 (wired)
Addressing	digital ID with dedicated chip
Tightness of the housing	IP68
Weight	
– 1-DOF actuator + gimbal	1716 g
– 2-DOF actuator + gimbal	1911 g
– Fix Point	601 g
Dimensions (length x diameter)	(261 mm – 297 mm) x 65 mm

36 km h⁻¹ are shown on the left and right side of Figure 5.10, respectively⁶. The latter wind speed is the maximum wind speed for which observations are conducted. The simulations consider the wind direction from the front and back of the reflector and derive the wind load at the bottom, center, and top of the reflector. A maximum force on a single actuator of ~ 130 N is expected for a wind speed of 36 km h⁻¹ and an elevation angle of $\sim 55^\circ$ for front wind at the bottom of the reflector. These wind loads define the limits of the force-displacement characteristic for which design specifications must be met.

The pointing accuracy and the optical PSF as a function of the actuator play derived from simulations are shown in the upper and lower panel of Figure 5.11, respectively. The technical requirement of the pointing accuracy dominates the design specifications of the total longitudinal displacement of the MACs over the technical requirement of the optical PSF. An actuator play of $\sim 100 \mu\text{m}$ results in a pointing accuracy of $\pm 4''$ and thus leaves a margin with respect to the technical requirement

⁶The underlying assumptions of the simulations are summarized in Table B.1.

to account for a possible play, (visco-)elastic deformation, and plastic deformation of, e.g., the mirror support structure as well. The design specifications of the MACs must be verified prior to installation of the MACs on the telescope, and therefore quality control of the MACs with respect to their overall functionality and their force-displacement characteristics is a critical task to ensure the scientific performance of the telescope. At the IAAT, a test stand for measuring the force-displacement characteristics of the MACs of the AMC has been developed and is described in detail in the next chapter.

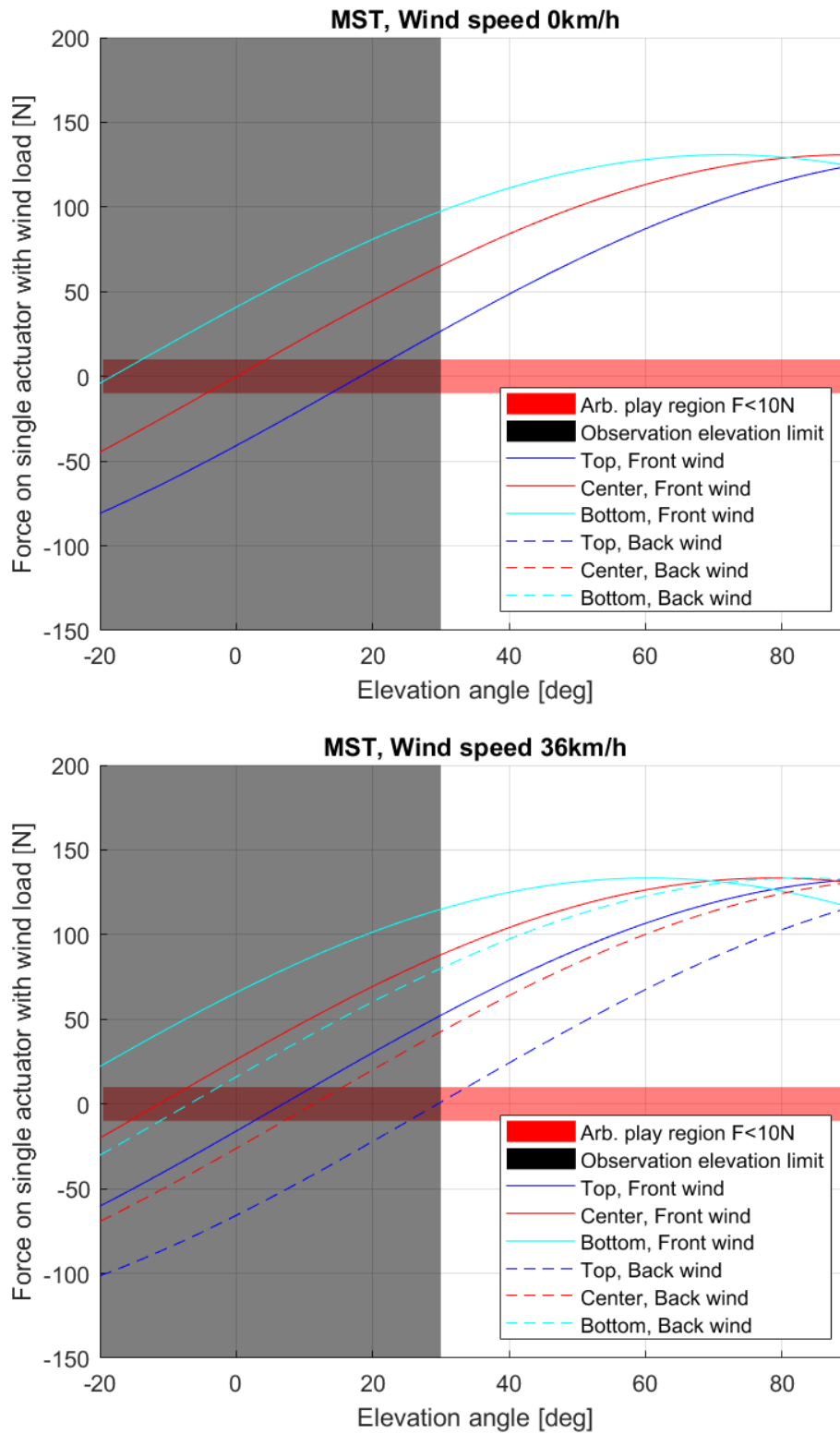


Figure 5.10. Force on a single actuator as a function of the elevation angle for a MST. The wind loads for three different parts of the reflector (top, center, bottom) and two wind directions (back and front wind) are determined. Top: For a simulated wind speed of 0 km h^{-1} . Bottom: For a simulated wind speed of 36 km h^{-1} . Taken from Gadola (2018a).

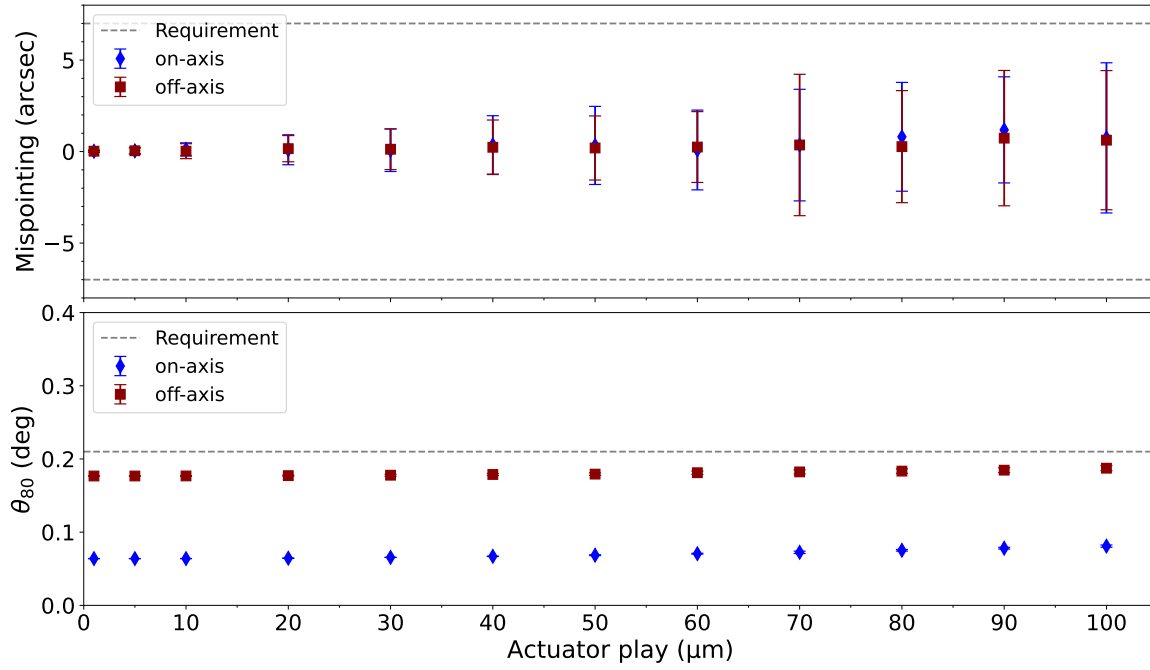


Figure 5.11. Simulated pointing accuracy (top) and optical PSF (bottom) as a function of the actuator play for a fully equipped MST. The underlying ray tracing simulation assumes a randomized, uniform distribution of actuator play Δ_{play} for each actuator within the range of maximum actuator play $\pm\Delta_{\text{play}}$ over the MST reflector. The simulation is iterated a hundred times for each Δ_{play} value to allow a systematic determination of the pointing accuracy and resulting optical PSF. In this simulation the play of the fix point is not considered. The simulations were performed by M. Garczarczyk (DESY).

The Actuator Displacement Test Stand

Initially, the expertise at the IAAT regarding actuator development for IACTs was obtained through the development of the control electronics and software for the mirror alignment system of the fifth H.E.S.S. telescope (Gottschall et al. 2015). Deep expertise has been obtained through the development and testing of an IAAT-developed actuator design proposed for the MST (Dick et al. 2015). After a consolidation of the actuator design between LST, MST (DC and SCT) and SST by the CTAO project office, the decision of the MST team fell towards the actuator design developed by the Universität Zürich (UZH) for LST. Consequently, the IAAT group focused on the verification of the design and the quality control of the actuators planned for the MST.

The result of these efforts is a test stand that has the objective to quantify the positioning uncertainties of the mechanical components of the mirror alignment system by measuring their force-displacement characteristics. The test stand is designed to primarily measure the longitudinal displacement of the test objects. The motivation behind that is the consideration that transversal forces on the MACs mainly lead to a shift of the individual mirror facets parallel to the focal plane. The consequent impact on the optical PSF and the pointing accuracy is considered small with respect to a mean elastic bending of the mirror support structure. The current test stand design was mainly developed by J. Dick and S. Diebold (IAAT), and is the result of previous design iterations described in Bressel (2015) and Müller (2017). The current design is described in Fritz (2018) and Salzmann et al. (2024), and is protected by a patent (Diebold et al. 2023). The work done within this thesis improved the understanding of the mechanical properties of the tested objects and contributed essential improvements of the measurement and mounting procedures, as well as the qualification and quantification of various error sources on the measured force-displacement characteristics of a test object.

The measurement theory including the description of the force-displacement characteristics of an actuator is described in Section 6.1. Section 6.2 covers the working principle of the test stand, which comprises the technical design, the force control and the measurement procedure. In Section 6.3, the accuracy of measuring the force-displacement characteristics is discussed. A second and third test stand of the current design were produced in 2021 and 2023 for the Max-Planck-Institut für Physik (MPP) and the University of California, Santa Cruz (UCSC) for testing the actuators foreseen for the LSTs of the CTAO-North and the MSTs, respectively. In Section 6.4, the verification plan of these test stands is briefly described.

6.1. Measurement Theory

When mounted at the telescope and under normal operating conditions, the mechanical components of the AMC need to withstand compressive and tensile loads from the mirror facet caused by gravity or wind¹. Their deformation behavior under these external loads is characterized through their mechanical properties such as the mechanical play, viscoelastic deformation, and plastic deformation. Through measuring the force-displacement characteristics, it is possible to identify these properties and derive the absolute positioning uncertainty for each MAC of the AMC.

The theory behind determining the mechanical properties of the test object is based on the assumption that each test object has a true force-displacement graph, which accurately describes the mechanical properties of the test object. However, the true force-displacement graph of a test object is an idealistic case and the measured force-displacement graph is influenced by various error sources such as the accuracy of the displacement measurement and the force setting, as well as the measurement procedure, the test stand assembly and the mounting procedure of the test object into the test stand. The proper test stand assembly has to ensure that the force and displacement measurement direction are aligned with the longitudinal axis of the test object, while the mounting procedure has to ensure that the test object is mounted with as little additional clearances as possible in the test stand to measure the longitudinal displacement of the test object precisely. The overall objective is to measure a force-displacement graph as close as possible to the true force-displacement graph by minimizing the uncertainties in the displacement measurement and the force setting, and optimizing the mounting and measurement procedure to measure the force-displacement graph accurately. However, to not underestimate the mechanical properties of the test object and thus falsely meet the design specifications, the overall approach is that the latter should be optimized in a way that it is more likely to overestimate the true force-displacement graph than to underestimate it.

The basics of the mechanical properties and their force-displacement characteristics are explained in Section 6.1.1. The force-displacement characteristics of an actuator as the most complex mechanical component of the mirror alignment system is explained in Section 6.1.2.

6.1.1. Mechanical Properties

The deformation behavior of a test object under an external load is characterized by its various mechanical properties such as mechanical play, (visco-)elastic deformation, and plastic deformation. Each one of these properties exhibits a different deformation behavior under an externally applied load². It depends, among other factors, on how the various parts of the test object are mounted together, as well as on the different

¹Furthermore, the mechanical components of the AMC need to provide stability against any environmental impact, such as e.g. earthquakes as well as snow and ice on the mirror facet. The quality control against these survival conditions are, however, not within the scope of this thesis.

²In engineering, the deformation behavior of a test object is often described by the quantities stress and strain. The former is simply the applied force as function of the area it is applied to, and the latter is the dimensionless relative change in deformation to the size of the test object without applied load. Consequently, a description of the mechanical properties in the context of a stress-strain curve would be consistent with engineering literature. However, here the term force-displacement graph is used as this is what is actually measured with the described test stand.

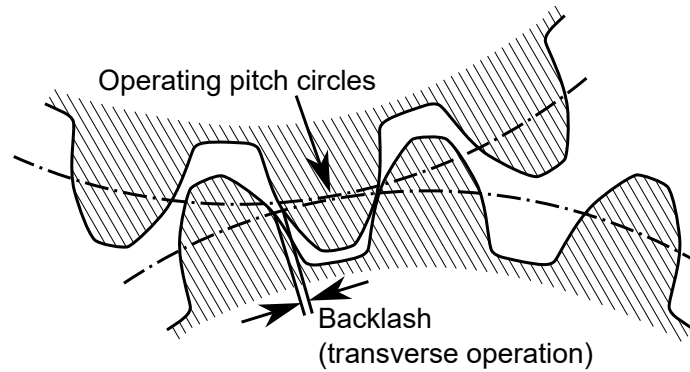


Figure 6.1. Backlash between two interacting gear wheels. Taken from Commons (2024) published under the license <https://creativecommons.org/licenses/by-sa/3.0/deed.en>.

materials that are used. In addition, changing temperatures can affect the mechanical properties of the built-in materials and thus the functionality of the test object. However, for the sake of simplicity, it is assumed that the effect of temperature on the test object within its designed operating temperature range is negligible and does not affect the mechanical functionality. Therefore, the effect of temperature is not considered in the following description of the different mechanical properties.

The clearance between two mechanical parts is the mechanical play, which is usually measured as the maximum distance between two respective end stops and is independent on the external applied load. A typical example is two interacting gear wheels, as shown in Figure 6.1. To avoid jamming and reduce abrasion, a finite amount of mechanical play is usually needed to allow the movement of the different parts of the test object with respect to each other. However, for the actuators of the mirror alignment system, where a high positioning precision is required, mechanical play introduces a non-reproducible positioning uncertainty and is thus limited to fulfill the technical requirements at the telescope level. To measure the mechanical play, in the ideal case with no static friction in the test object, an infinitesimally small load must be applied to reach the end stops of the test object. However, in a test object where various parts made out of different materials interact and static friction is present, it is non-trivial to disentangle the mechanical play from other contributions such as the elastic and plastic deformation.

The properties of (visco-)elastic and plastic deformation are described according to Callister et al. (2015). The given reference describes these mechanical properties in the context of materials engineering. However, the general concepts can be extended to a test object consisting of different materials and interacting mechanical parts. Elastic deformation is characterized by two main properties. Firstly, it is a reversible deformation depending on the externally applied load. Secondly, it completely recovers after the external load is removed. In addition, it is independent on time and there is no time-delay between the application of the external load and the deformation of the test object. A classic example of elastic deformation is linear elasticity, where the deformation is proportional to the applied external load according to Hooke's law. In contrast to elastic deformation, vicious deformation is depending on time and does not recover after the external force is removed. A combination of the two deformation behaviors, elastic and vicious deformation, is viscoelastic deformation, which is characterized by a time-dependent reaction to an external applied load and

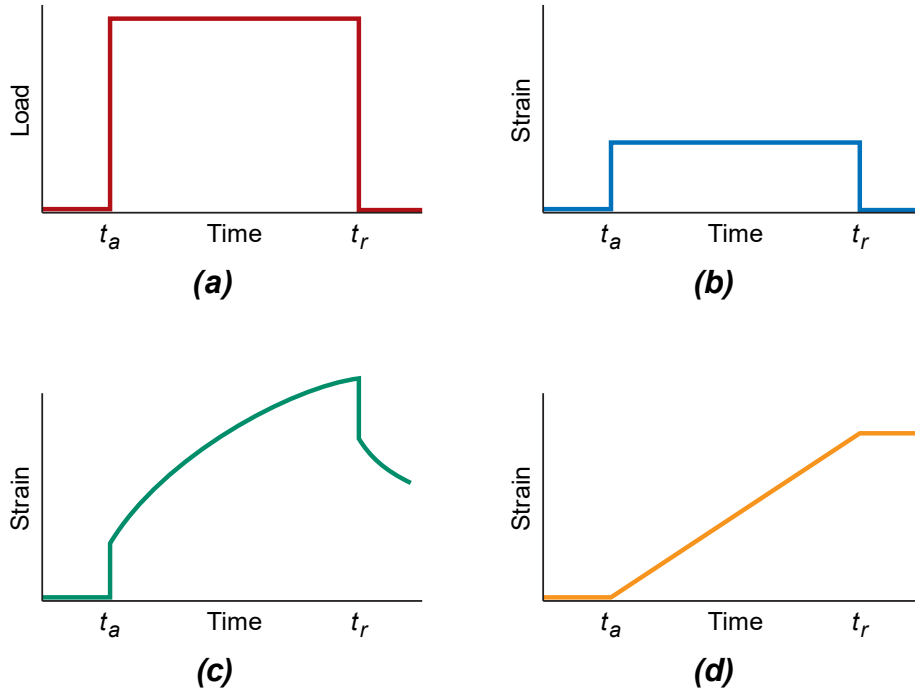


Figure 6.2. Schematic diagram showing the strain as a function of time for a given load-time cycle for materials exhibiting different deformation behaviors. The load is applied at the time t_a and released at t_r . The load cycle is depicted in (a), and the resulting strain diagrams for an elastic, viscoelastic, and vicious material in (b), (c) and (d), respectively. Taken from Callister et al. (2015).

it does not fully recover after the external load is removed. Furthermore, viscoelastic materials exhibit load relaxation and creep. The former is the decrease of the load to keep a given deformation constant, while the latter is an increase in deformation while keeping the load constant. The impact of an external load on an elastic, a viscoelastic, and a vicious material is shown schematically in Figure 6.2.

The last mechanical property is plastic deformation, which is a permanent and non-reversible deformation after the application of an external load. If the magnitude of plastic deformation exceeds a certain threshold, fracture of the test object occurs. The mechanical components of the mirror alignment system exhibit these various mechanical properties, which is explained in the following at the example of an actuator.

6.1.2. Actuator Force-Displacement Characteristics

The positioning inaccuracies of the mechanical components of the AMC can be quantified by measuring their force-displacement characteristics. The graphical representation thereof is the force-displacement graph. The actuator assembly consisting of the actuator, the spherical bearing and with either the 1-DOF or the 2-DOF gimbal is the most complex mechanical component of a MAC set, and thus its force-displacement characteristics is discussed in more detail here. The actuator assembly can be separated into the actuator, the flange bearing, and the gimbal. Each one of these parts has a contribution to the force-displacement graph. While the limiting design specification is the total longitudinal displacement of the actuator

assembly, it can be helpful to understand the contributions of the different parts to the force-displacement graph. If the actuator assembly does not fulfill the design specifications, this allows to identify the parts that need to be redesigned. In the following, the contribution of the different parts of an actuator assembly to the force-displacement characteristics is briefly described.

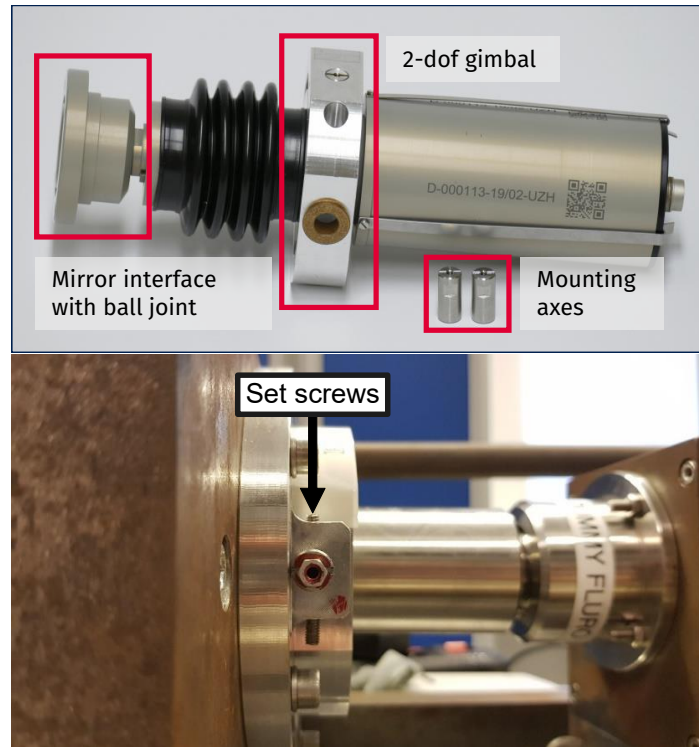


Figure 6.3. Actuator assembly with a 2-DOF gimbal (top) and the usage of set screws in the interface between actuator gimbal and telescope with the telescope replaced with the test stand here (bottom).

An actuator assembly with a 2-DOF gimbal is depicted in the top row Figure 6.3. The mechanical play of an actuator assembly can be caused by the actuator-internal components, the spherical bearing in the flange bearing, and the gimbal. The most relevant actuator-internal components in that regard are the spindle-nut interface and the movement of the spindle in the ball bearing. Apart from a contribution to the mechanical play, the spherical bearing in the flange bearing introduces a viscoelastic behavior in the force-displacement diagram due to the use of PTFE as sliding contact surface between the joint socket and the joint head. Furthermore, an additional mechanical play is present in the gimbal itself as well as in the interface between the gimbal and the MSU. However, when mounted at the telescope this contribution is minimized by the usage of set screws, as depicted for example at the test stand in the bottom row of Figure 6.3.

6.2. Working Principle

The main task of the actuator displacement test stand is the accurate determination of the displacement along the longitudinal direction of the mechanical components of the AMC for a given force. The longitudinal direction is defined as the direction along

the actuator piston, or steel rod of the fix point, whereas the transversal direction is perpendicular to it. For an accurate determination of the longitudinal displacement, the test stand needs to have a few intrinsic specifications.

First, a precise alignment of the force and measurement direction is needed to measure the longitudinal displacement accurately. This is not straightforward considering that the test objects are intrinsically tilting due to the built-in spherical plain bearings. In addition, this poses the additional challenge to mount the test object into the test stand such that it is tilted as little as possible to measure the force-displacement graph as close as possible to the true force-displacement graph of the test object. Second, the test stand needs to be able to produce a force of several 100 N to properly simulate the expected loads on the MACs. Third, the displacement measurement needs to have the required accuracy to properly determine the force-displacement graph, and consequently verify the technical design specifications of the MACs on the level of $\sim 10 \mu\text{m}$. This requires that the test stand in itself is not subject to measurable deformations under the forces to be measured. This was ensured through extensive FEM simulations and consequent optimization of the design described in Fritz (2018) resulting in an intrinsic deformation of the test stand smaller than the systematic measurement uncertainty of the displacement measurement device. And fourth, the setting of the desired force and the readout of the displacement of the test object need to be automated to provide an optimal user experience for potential mass testing of MACs of the AMC. The technical design of the actuator displacement test stand is described in Section 6.2.1. In Section 6.2.2, the force control and in Section 6.2.3 the measurement procedure are explained.

6.2.1. Technical Design

The test stand and its various components are shown in Figure 6.4. The required force is generated by the Actuator Control Unit (ACU)³, which is based on the latest IAAT actuator design. The generated force is translated from the ACU to the test object via two compression springs that are installed in the spring sled. The inside of the spring sled is shown in Figure 6.5. The main task of the compression springs is to provide a controlled force translation between ACU and the test object. This force translation has a linear relation between traveled ACU piston stroke and resulting force on the test object and is defined by the spring constant of the compression springs. The required spring constant is defined by the available stroke of the ACU piston and the required maximum force that should be applied to the test object. The use of two compression springs allows to apply a compressive (push direction) and a tensile load (pull direction) on the test object.

The force is measured by the force sensor, which is mounted between the spring sled and the mounting sled. The mounting sled provides the interface to the test object and offers the contact point for the dial gauge, which is placed within the mounting sled using a dedicated mounting and measures the displacement with a systematic accuracy of $\sim 1.5 \mu\text{m}$ ⁴. The mounting is attached to the test stand. Apart from measuring complete MACs, the test stand offers the possibility to measure single parts of the MACs such as the spherical bearings or the gimbals, as described

³The firm- and the hardware of the ACU was implemented by Jürgen Dick (IAAT).

⁴This value is determined by the manufacturer for each dial gauge individually. See Section 6.3.1 for more details.

in Section 7.3 for the latter.

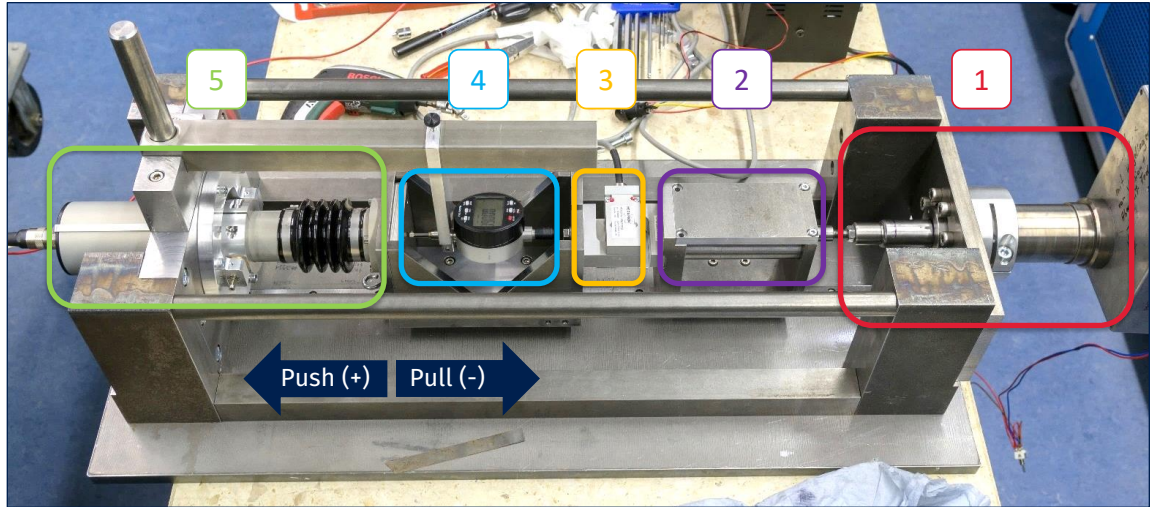


Figure 6.4. Force-displacement test stand developed at the IAAT for the quality control of mechanical components for mirror alignment systems. The various components of the test stand are: 1. Actuator Control Unit, 2. spring sled, 3. force sensor, 4. dial gauge in mounting sled, and 5. test object. The spring sled contains two compression springs that translate the force linearly from the ACU to the test object for the push (compression) and pull (tension) direction. Taken from Salzmann et al. (2024).

The precise alignment of the force and measurement direction is accomplished by connecting the ACU to the test object with the combination of the two sleds and the force sensor. The sleds are mounted on a pretensioned guiding rail with ball bearings. The communication with the test stand is realized with an external PC, which is connected to the dial gauge and the ACU via USB. A microcontroller implemented in the ACU controls the ACU and is connected to the force sensor realizing a feedback loop. This allows the measurement of the force-displacement graph to be performed in an automated way.

The accuracy of the displacement measurement is affected by the systematic measurement uncertainty of the dial gauge. However, the absolute measurement uncertainty of the mechanical properties of the test object is depending on various factors such as, e.g., the mounting procedure of the test object into the test stand. This is further discussed in Section 6.3.

The maximum load that can be applied to the test object is constrained by the design specifications of the ACU, the installed force sensor, and the compression springs. The latter limits the maximum load on the test object with their specified maximum static load of ~ 980 N. The allowed nominal load on the force sensor is in the same order of magnitude as the compression springs with 1 kN. According to the mechanical specifications, the ACU is able to withstand loads higher than that. However, the maximum load on the ACU was never tested and thus a load limit is not officially specified. In any case, a maximum load of ~ 500 N is a more than sufficient load for all realistic load cases on the MACs during observations. The working principle of the force control is described in more detail in the following.

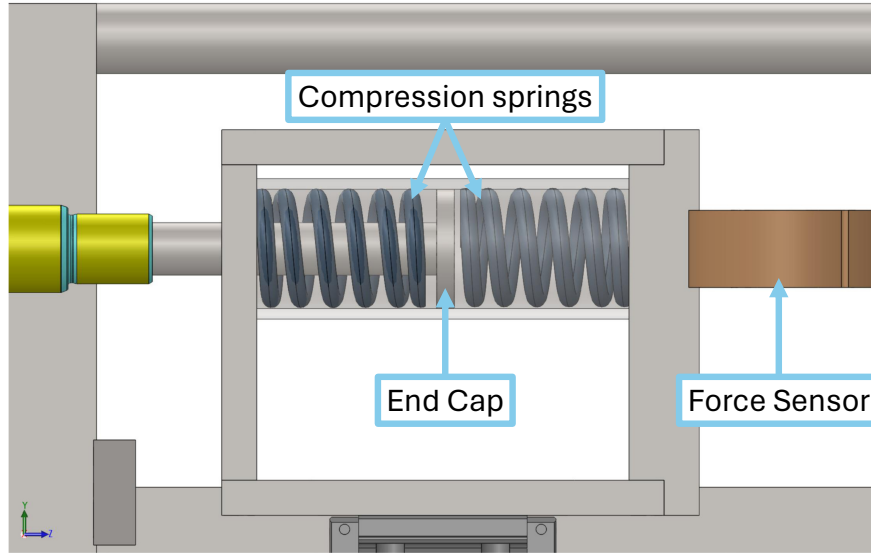


Figure 6.5. Side view of the spring sled with transparent hull around the compression springs. The two compression springs and the steel rod with the end cap are visible.

6.2.2. Force Control

The force control is implemented as a feedback loop of the force sensor with the ACU according to the three level hysteresis switching scheme with dead zone, a general concept in control engineering. The force sensor delivers a linear output voltage depending on the applied load, which is fed to the microcontroller in the ACU and is digitized by an on-chip ADC. A schematic diagram of the three level hysteresis switching scheme implemented for the ACU is shown in Figure 6.6. The movement of the ACU is defined by three states. The move in, stop, and move out state, whereby in and out relates to the movement direction of the ACU piston stroke. The horizontal axis corresponds to the output voltage of the force sensor U_{sensor} and represents the force value. The different states of the ACU are summarized in Table 6.1.

The dead zone and the hysteresis band for the move in and out direction can be defined separately with respect to the setpoint. When a force value is requested, the feedback loop monitors the output of the force sensor and keeps the requested force within the defined hysteresis band. A hysteresis band is necessary in order to avoid oscillations in the force-control loop⁵. A good empirical value for the hysteresis band proved to be in the order of $\pm 8 \text{ N}$, where ΔF_{hyst} corresponds to the voltage range of $\Delta U_{\text{start_in}}$ and $\Delta U_{\text{start_out}}$ in Figure 6.6 for the move in and move out direction, respectively. The calibration of the force sensor in combination with the microcontroller of the ACU and the impact of the force control on the measured force-displacement characteristics of a test object are discussed in Section 6.3.2.

⁵A second mode has been implemented in the force control. This so-called “single-shot” mode, moves the ACU to the setpoint value of the requested force and stops there. The difference to the feedback loop is that the force is then not monitored. This mode allows the measurement of a potential stress relaxation, i.e. a decrease of the applied force under constant displacement of the test object. However, all measurement results presented in this work have been derived with the feedback loop of the force control.

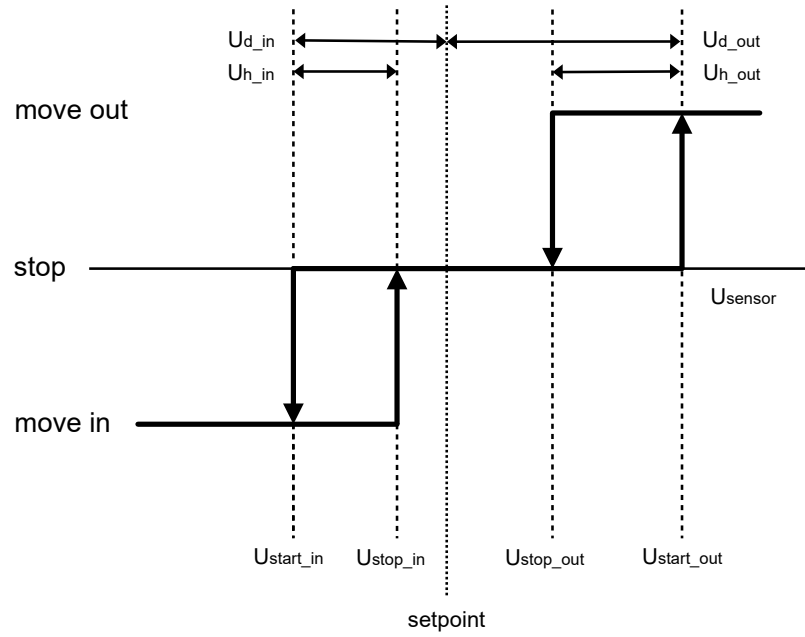


Figure 6.6. Schematic diagram of the force feedback loop implemented for the actuator displacement test stand. It is implemented according to the “Three level hysteresis switching with dead zone” scheme, a general concept in control engineering. The three levels represent the three movement states of the ACU and the horizontal axis represents the output voltage U_{sensor} of the force sensor, which realizes together with the ACU the feedback loop. The setpoint is the output voltage of the force sensor for the requested force value. Depending on U_{sensor} with respect to the setpoint voltage, the ACU stops, moves in, or moves out. The deadzone is defined by the voltage range $U_{\text{d_in,d_out}}$ and the hysteresis by the voltage range $U_{\text{h_in,h_out}}$ for the move in and move out direction, respectively. Credit: J. Dick (IAAT).

6.2.3. Measurement Procedure

In order to quantify the mechanical properties, the force-displacement graph $d(F)$ of a test object is measured by measuring the displacement d of the test object for a dedicated set of discrete force values F , where F denotes the absolute value of the force vector $\vec{F}$. While an arbitrary set of discrete force values can be measured, the nominal procedure foresees the full measurement of the force-displacement graph, which includes push and pull forces up to a maximum force value F_{max} . The schematic diagram of a force-displacement graph for a test object exhibiting mechanical play and viscoelastic properties is shown in Figure 6.7. The measurement force of 0 N is usually omitted as the determination of a mechanical play requires a finite force $F \geq 0$ N to ensure that the mechanical parts of the test object are in their respective mechanical end stops. In Figure 6.7, the four distinct cycles of the loading and unloading of the test object with the ACU are shown. Cycle 1 and 3 are the loading cycles during which the ACU compresses or stretches the test object, respectively. During the unloading cycles 2 and 4, the ACU releases the compressive and tensile load on the test object. A nominal test cycle includes the loading and unloading cycles 1 $\rightarrow$ 4 with an arbitrary set of discrete force values in between the a $\rightarrow$ c and d $\rightarrow$ f. The measurement positions a $\rightarrow$ f correspond to the dedicated points in the force-displacement graph of

Table 6.1. The different states of the ACU depending on the condition of U_{Sensor} .
Adapted from J. Dick (IAAT).

State	Condition	New State
stop	$U_{\text{sensor}} \leq U_{\text{start_in}}$	move in
	$U_{\text{sensor}} \geq U_{\text{start_out}}$	move out
move in	$U_{\text{sensor}} \geq U_{\text{stop_in}}$	stop
move out	$U_{\text{sensor}} \leq U_{\text{stop_out}}$	stop

- a. $d(F_{\text{load,release,push}})$
- b. $d(F_{\text{max,push}})$
- c. $d(F_{\text{unload,release,push}})$
- d. $d(F_{\text{load,release,pull}})$
- e. $d(F_{\text{max,pull}})$
- f. $d(F_{\text{unload,release,pull}})$.

An additional measurement type, the reduced force-displacement measurement, only measures the measurement positions a to f and no dedicated force-displacement points in-between.

It should be mentioned that the force-displacement characteristics of the viscoelastic parts in the mechanical components slightly differ during their first test cycle from consequent test cycles. This start-up behavior shows up after an intrinsic relaxation time and for low force values. The measurement procedure is consequently adapted to include a so-called initialization cycle, which only measures the dedicated points $a \rightarrow f$ with an increased maximum force with respect to the maximum force of the test cycles. Choosing a higher maximum force for the initialization cycle is in line with the general idea that it is better to overestimate the true force-displacement characteristics during laboratory tests instead of underestimating them to not falsely meet the design specifications. The initialization cycle has the purpose to compress and stretch the test object such that this start-up behavior is not present in the test cycles and puts the test object in a defined state.

The mechanical properties of a test object that can be calculated from the measured force-displacement graph are the mechanical play, the viscoelastic deformation in push and pull direction, and the absolute longitudinal displacement of the test object. This is shown in Figure 6.7. To disentangle the mechanical play from the viscoelastic deformation in push and pull direction is a challenging task for a complex mechanical test object consisting of different interacting parts with tight tolerances, which leads to an intrinsic static friction within the test object. This static friction needs to be overcome to ensure that the mechanical parts are in their respective end stops. Therefore, the common approach is to define a finite force $F_{\text{release}} \geq 0 \text{ N}$ that is reached after the unloading cycles of the ACU in push and pull direction, respectively. The mechanical play is consequently defined as

$$d_{\text{play}} = |d(F_{\text{unload,release,pull}}) - d(F_{\text{unload,release,push}})| \quad . \quad (6.1)$$

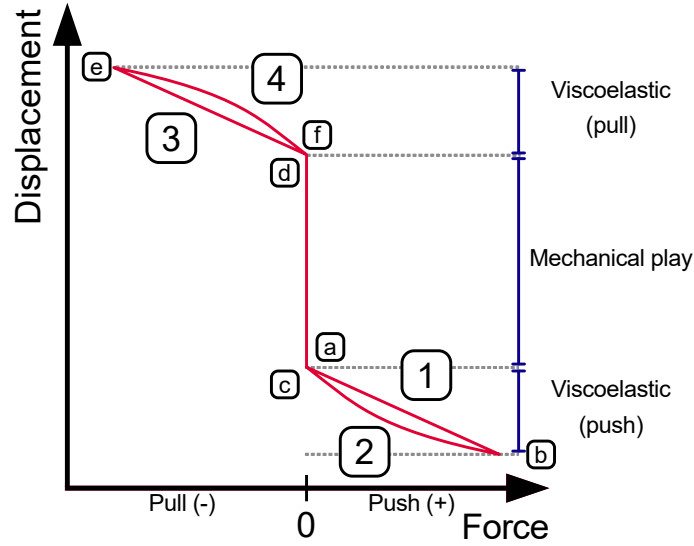


Figure 6.7. Schematic diagram of the force-displacement graph of a test object exhibiting mechanical play and viscoelastic properties. The loading (1, 3) and unloading (2, 4) cycles of the ACU for the measurement procedure are indicated. In addition, the determination of the mechanical properties of the test object from the force-displacement graph are shown. The absolute longitudinal displacement is given by the sum of the viscoelastic push and pull displacement and the mechanical play.

The viscoelastic deformation in push and pull direction, as well as the absolute longitudinal displacement are given by

$$d_{\text{ve,push}} = |d(F_{\text{max,push}}) - d(F_{\text{unload.,release,push}})|, \quad (6.2)$$

$$d_{\text{ve,pull}} = |d(F_{\text{max,pull}}) - d(F_{\text{unload.,release,pull}})|, \quad (6.3)$$

$$d_{\text{abs.disp.}} = |d(F_{\text{max,pull}}) - d(F_{\text{max,push}})|, \quad (6.4)$$

where $d(F_{\text{max/release,push/pull}})$ is the displacement at the respective maximum or release forces in push and pull direction. F_{release} should be defined close enough to 0 N to give a reasonable approximation of the mechanical play, while also be large enough to provide more likely an overestimation instead of an underestimation of the mechanical play. Considering the worse accuracy of the force sensor calibration close to 0 N with respect to $\gg 0$ N as described in Section 6.3.2, F_{release} is defined within ± 10 N to 15 N. This definition of the mechanical play introduces a dependency on the external applied load as it contains a contribution of the viscoelastic properties of the test object, which are depending on the external applied load.

A second approach to determine the mechanical play, as well as to quantify the viscoelastic deformation, is to fit the viscoelastic part of the force-displacement graph in the push and pull direction from $F_{\text{max,push/pull}}$ to $F_{\text{unload.,release,push/pull}}$. The mechanical play can then be determined as the difference of the y-axis intercepts from the two fits. However, the accuracy of this method mainly depends on a precise fitting of the viscoelastic behavior, which is not straightforward and might introduce additional errors in the determined mechanical play. Therefore, this approach is not used by default.

In conclusion, it should be emphasized that the absolute, non-reproducible posi-

tioning uncertainty of the mechanical components of the mirror alignment system are given by the absolute longitudinal displacement, and not only the mechanical play, as it is not clear during telescope operation in which state along the force-displacement characteristics the actuator is. In the next section, the measurement uncertainties of the test stand are discussed.

6.3. Measurement Accuracy

In metrology, the term measurement accuracy describes how close the measured value of a quantity is to its true value. It is the umbrella term for measurement precision and measurement trueness, where the former describes how close several measured values under the same measurement conditions are to each other and the latter describes by how much the average of an infinite number of measured values differ from their true value. According to these definitions, a measurement device is only accurate if it has a high measurement precision and a high measurement trueness (Joint Committee for Guides in Metrology 2012).

When translating these definitions to the test stand and the measurement of the force-displacement characteristics of a test object, a high measurement accuracy of the test stand means a precise measurement of the true force-displacement characteristics of a test object. An assessment of the trueness of the measured force-displacement characteristics is not straightforward, as the true force-displacement characteristics of a test object is not a priori known. To properly assess the measurement trueness of the test stand, a test object with precisely calibrated force-displacement characteristics would be needed. Such a test object is not available, but some brief considerations for the mathematical model of such a test object are given in Section 6.4. It should be noted, however, that there are currently no indications that the test stand has poor measurement trueness. The assessment of the measurement precision of the test stand is easier to accomplish. In the following, the various error sources impacting the measurement accuracy of the test stand with respect to its precision and trueness of the measured force-displacement characteristics are discussed.

The measurement accuracy of the test stand is impacted by various sources of measurement errors, which can be broadly separated in their systematic and statistical nature, as shown schematically in Figure 6.8. The systematic and statistical (or random) measurement errors are defined according to Joint Committee for Guides in Metrology (2012). For a measurement with the same measurement conditions, a systematic error is constant or changes in a predictable way, whereas a statistical error changes in an unpredictable way. In the idealistic scenario that the systematic and the statistical error are zero, the measurement records the true force-displacement characteristics of the test object. Hereby, the systematic and statistical measurement errors influence the measurement trueness and precision, respectively.

The following sections describe the impact of the various error sources on the measured force-displacement characteristics of an exemplary test object. In principle, the quantitative impact of the various error sources on the measured force-displacement characteristics are specific for the given test object. Therefore, in theory, they would need to be determined separately for each measured test object. The presented study only investigates that for a 2-DOF actuator assembly of the D-series of the actuator design for the mirror alignment system of the MST. This actuator is chosen as actuators of the E-series were not yet available at the time of this study. It should

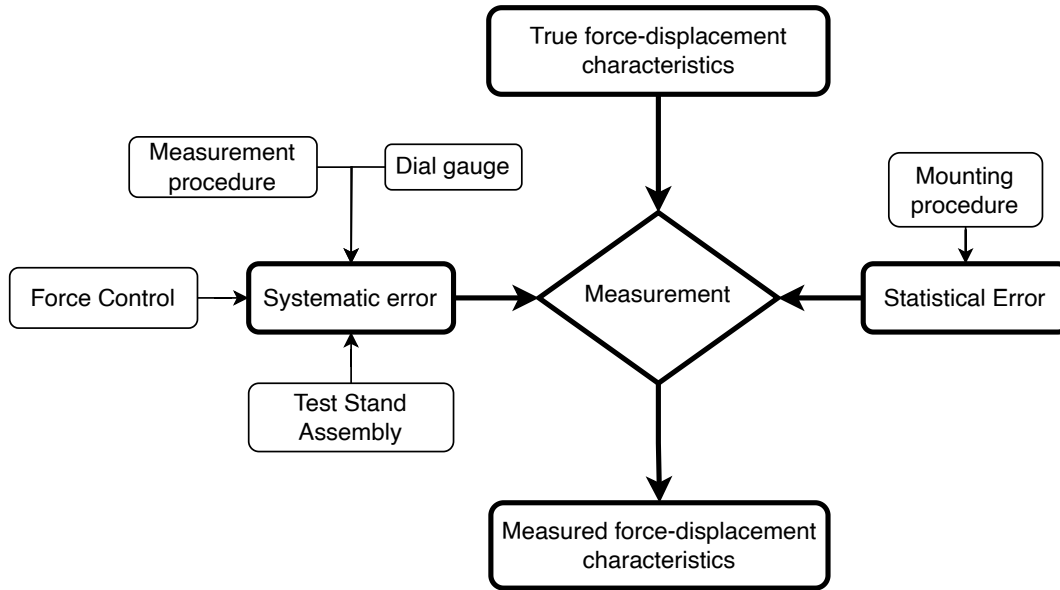


Figure 6.8. Schematic diagram of the measurement of the force-displacement characteristics of a test object and the associated error sources. The result is the measured force-displacement characteristics of a test object that should be as close as possible to the true force-displacement characteristics of the test object. Systematic and statistical error are defined according to Joint Committee for Guides in Metrology (2012).

be emphasized that the magnitude of the absolute longitudinal displacement and the mechanical play values is not representative for the actuator assemblies of the E-series, but it is assumed that impact of the error sources on the force-displacement characteristics are comparable⁶. In future, the study should be performed for a 1-DOF actuator assembly and a fix point. The study is performed with the test stand Tübingen due to the lack of availability of the other test stands.

In Section 6.3.1, the error contribution of the dial gauge to a single force-displacement measurement point and the calculated play and absolute deformation is described. In Section 6.3.2, the accuracy and the calibration of the force control is described. Furthermore, the impact on the measured force-displacement graph is discussed. The impact of the measurement procedure on the mechanical properties of the test object is described in Section 6.3.3. Section 6.3.4 covers the considerations for a proper assembly of the test stand and a proper mounting of the test object into the test stand. The measurement error of the quantities derived from the measured force-displacement characteristics is important for assessing the design specifications of the mechanical components of the mirror alignment system. A quantification of the statistical error introduced by several mounting acts of the test object into the test stand is presented in Section 6.3.5.

⁶A 2-DOF actuator assembly is selected as representative test object as the assumption is that the potential systematic error of the mounting procedure is the smallest for the 2-DOF actuator assembly in comparison to the fix point and the 1-DOF actuator assembly due to its higher Degrees of Freedom.

6.3.1. Dial Gauge

The systematic measurement error of the displacement measurement of a single force-displacement measurement point is given by the systematic error of the dial gauge.

The measurement error of the dial gauge has two contributions. The first contribution is the systematic measurement error $\Delta d_{\text{dg,sys}}$ that is determined for each dial gauge individually by the manufacturer⁷. A second, small statistical contribution to the measurement error of the dial gauge $\Delta d_{\text{dg,stat}}$ comes from the readout process of the dial gauge by the software performing the measurement procedure. The measured displacement value is averaged over a certain number of measurements that stay within an empirically defined maximum measurement range⁸. It is still accounted to the systematic error contribution of the dial gauge, because it is determined in a predictable way. The resulting error of the dial gauge is then given as the sum of the two contributions by

$$\Delta d_{\text{dg}} = \Delta d_{\text{dg,sys}} + \Delta d_{\text{dg,stat}} \quad . \quad (6.5)$$

The order of magnitudes for $\Delta d_{\text{dg,sys}}$ and $\Delta d_{\text{dg,stat}}$ are 1.0 μm to 1.5 μm and $< 0.5 \mu\text{m}$, respectively⁹.

The errors Δd_{play} and $\Delta d_{\text{abs.disp.}}$ on the play d_{play} (Equation 6.1) and the absolute displacement $d_{\text{abs.disp.}}$ (Equation 6.4) introduced by the systematic error of the dial gauge are calculated by treating the systematic error of the dial gauge $\Delta d_{\text{dg,sys}}$ independent from the statistical error of the respective measurement point, resulting in

$$\Delta d_{\text{play}} = \Delta d_{\text{dg,sys}} + \sqrt{(\Delta d_{\text{dg,stat}}(F_{\text{unload.,release,pull}}))^2 + (\Delta d_{\text{dg,stat}}(F_{\text{unload.,release,push}}))^2} \quad (6.6)$$

$$\Delta d_{\text{abs.disp.}} = \Delta d_{\text{dg,sys}} + \sqrt{(\Delta d_{\text{dg,stat}}(F_{\text{max,pull}}))^2 + (\Delta d_{\text{dg,stat}}(F_{\text{max,push}}))^2} \quad . \quad (6.7)$$

The respective forces are defined in Section 6.2.3 and are the release test force of the unloading cycle in pull and push direction $F_{\text{unload.,release,pull/push}}$ and the maximum test force in pull and push direction $F_{\text{max,pull/push}}$. An additional systematic error on the displacement measurement is introduced by the finite accuracy of the force that is applied to the test object. This is described in the next section.

6.3.2. Force Control Accuracy

The finite accuracy of the force control introduces a systematic error on the true force-displacement characteristics. This systematic error is a force-dependent error on the measured displacement and is influenced by the local force-displacement gradient of the test object.

⁷The dial gauges used at the displacement test stand are of the type MarCator 1086R from the manufacturer Mahr. The used product versions have an absolute measurement range of 12.5 mm.

⁸The dial gauge measures a data point every 1.2 s. If five consecutive measurement values stay within the defined measurement range of 1.5 μm , the five values are averaged and readout. The resulting statistical error is the standard deviation of these five values. In principle, the values can be defined as needed. However, these proved to be reasonable values for the underlying use case.

⁹The measurement results presented in Chapter 7 have a systematic dial gauge error of $\Delta d_{\text{dg,sys}} = 1.0 \mu\text{m}$.

The accuracy of the force control is affected by the calibration of the force control, i.e. the calibration of the force sensor in combination with the microcontroller of the ACU, and the hysteresis of the force feedback loop. They influence the trueness and the precision of the force setting, respectively. Both count as systematic errors, as the force control calibration is constant and the feedback loop operates in a predictable way under a defined set of rules. The force feedback loop is already explained in Section 6.2.2 and has usually a hysteresis band of ± 8 N. The following section deals with the calibration of the force control, the verification thereof and the quantification of the impact of different force control calibrations on the force-displacement characteristics of the selected test object as an example.

Force Control Calibration

The calibration of the force control was implemented by Jürgen Dick (IAAT) and the basic principles were discussed between him and the author of this thesis.

The trueness of the requested force values is determined by the force control calibration. The installed force sensor delivers a linear output voltage depending on the applied load and the main objective of the force control calibration is to correlate this output signal to the applied load by the ACU. Initially, the force control was calibrated by applying known static loads through the usage of weights in the push and pull direction on the force sensor and reading out its digitized output signal through the microcontroller of the ACU. However, this approach had mainly two shortcomings. First, as the force sensor is installed between the mounting sled and the spring sled, the output signal does not represent precisely the actually applied load at the position of the test object and a compensation of, e.g., the friction of the mounting sled needed to be determined separately. Second, the process of applying the force on the force sensor with a static load does not have the same dynamics as applying the load on the test object with the ACU via the compression springs. Both of these shortcomings introduced error sources into the force control calibration increasing the uncertainty of the force determination. Therefore, to make the force control calibration process as close as possible to the actual measurement process, a new, fully automated approach to the calibration of the force control has been implemented. It uses an, already calibrated, force gauge at the position of the test object as reference. This is shown schematically in Figure 6.9. This automated approach is performed with an external software and is briefly described in the following.

A set of predefined setpoints the phase space of the output voltage of the force sensor U_{sensor} in the move in and move out direction of the ACU are provided to the force control as input to the calibration process. For each one of these setpoints, the ACU is regulated by the feedback loop (see Figure 6.6). Upon reaching the requested setpoint, the resulting digital output signal of the force sensor is readout by the microcontroller of the ACU and the corresponding output value of the force gauge is recorded. The resulting distribution between the reference force values of the force gauge and the digitized output signal of the force sensor is fitted separately with a linear relation for the two movement directions of the ACU. An example for the result of the force control calibration within a force range of ± 350 N is shown in Figure 6.10. The difference in the offset between the move in and move out direction is an estimate of the friction of the mounting sled, as well as from a potential hysteresis in the compression springs. From the derived parameters of the linear regression, the

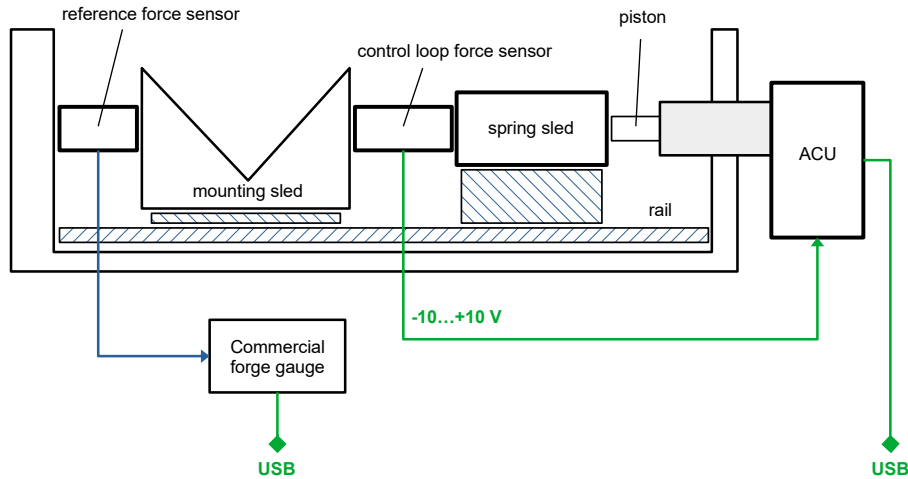


Figure 6.9. Schematic diagram showing the actuator displacement test stand for the automatic force control calibration. Adapted from J. Dick (IAAT).

external software converts a requested measurement force to the digital voltage signal as input for the force control such that the ACU can set the requested measurement force.

Verification

The accuracy of the force control calibration can then be verified by providing a set of requested force values and reading out the force gauge after the force control of the ACU reached the requested force. The result of this step for the exemplary force calibration in Figure 6.10 is shown in Figure 6.11. The results are averaged over a total of three verification cycles. The deviations between the requested force values and the reference force values can be explained by non-reproducible effects in the test stand such as, e.g., the friction of the mounting sled, as well as some hysteresis in the compression springs.

An additional impact on the accuracy of the force control calibration has the systematic accuracy of the reference force gauge, which is of the order of $\pm 0.3\%$ of the measured force (*Dynamometer PCE-PFG 2K* 2024). As shown in Figure 6.11, the resulting absolute uncertainty of the force calibration is in the order of $\pm 7 \text{ N}^{10}$. This accuracy might change from test stand to test stand, and therefore needs to be determined separately for each one. However, due to their identical design, no major differences of this accuracy are expected. Different force control calibrations impact the measured force-displacement characteristics, and consequently the derived mechanical properties of a test object. This is described in the following.

Quantification

The force control calibration and the feedback loop introduce a systematic error on the true force-displacement characteristics and consequently the derived mechanical

¹⁰While one can set a measurement force of 0 N, Figure 6.11 shows that the resulting force at the test object does not actually correspond to 0 N. While this force value is sometimes included in the measurement of the force-displacement characteristics, it is not taken for the calculation of the mechanical play as explained in Section 6.2.3.

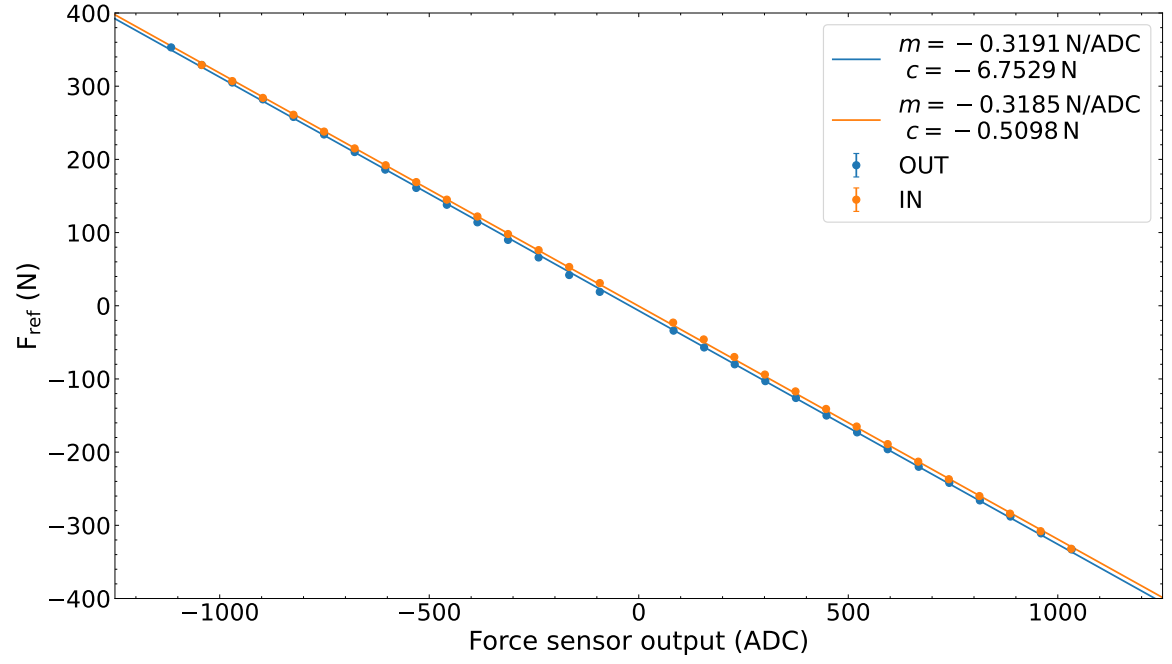


Figure 6.10. Example for the automatic force calibration for a force range of ± 350 N. The force sensor output is displayed in units of ADC. Credit: J. Dick (IAAT).

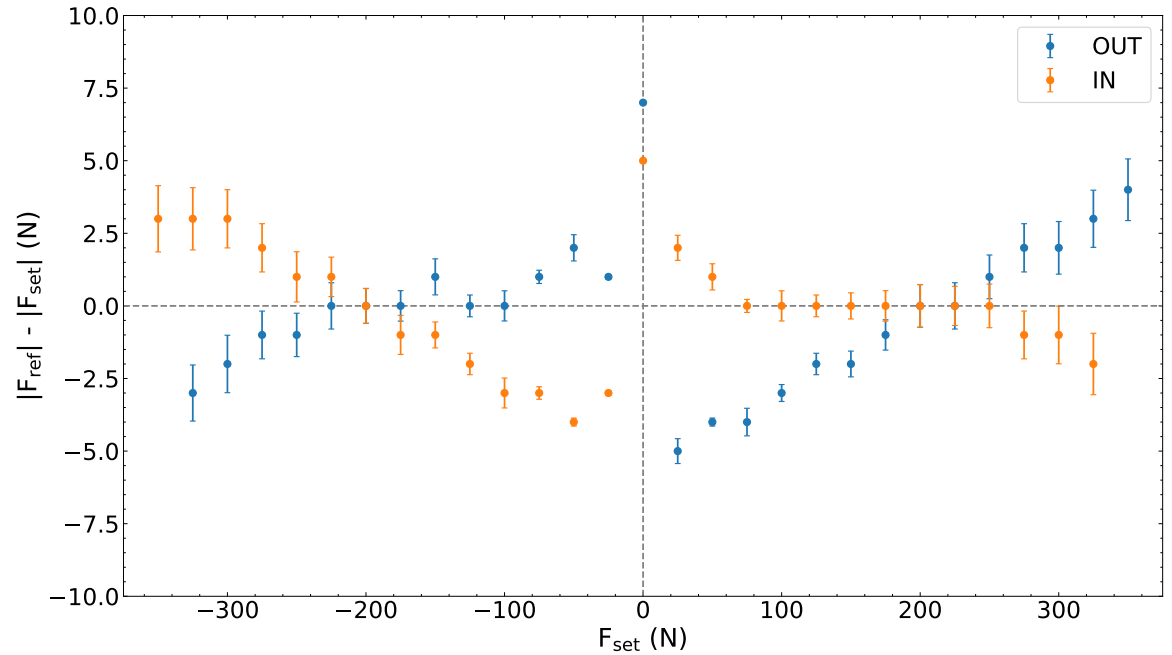


Figure 6.11. Verification of the force control calibration shown in Figure 6.10. The difference between the absolute force of the reference sensor F_{ref} and the absolute set force F_{set} by the ACU. The maximum difference is seen at 0 N. The error on the single force value is calculated as the root of the quadratic sum of the statistical error of F_{set} and the absolute error of F_{ref} . The latter is determined by the statistical error and the systematic error of F_{ref} . The systematic error of F_{ref} is determined from *Dynamometer PCE-PFG 2K* (2024) as 0.3 % of F_{ref} .

properties of a test object. This systematic error is a force-dependent error on the measured displacement and is influenced by the local force-displacement gradient of the test object.

Usually, for the mechanical components of the mirror alignment system, the impact is larger for forces closer to 0 N as the force-displacement gradient is higher at these forces, and smaller for forces $\gg 0$ N (see Figure 6.12a). To illustrate the qualitative impact of the force control calibration on the measured force-displacement characteristics, the selected test object was measured by applying three different force control calibrations without dismounting the test object from the test stand in-between the measurements to keep the other measurement conditions the same. Before each measurement, an initialization cycle with $F_{\text{init}} = \pm 500$ N was performed.

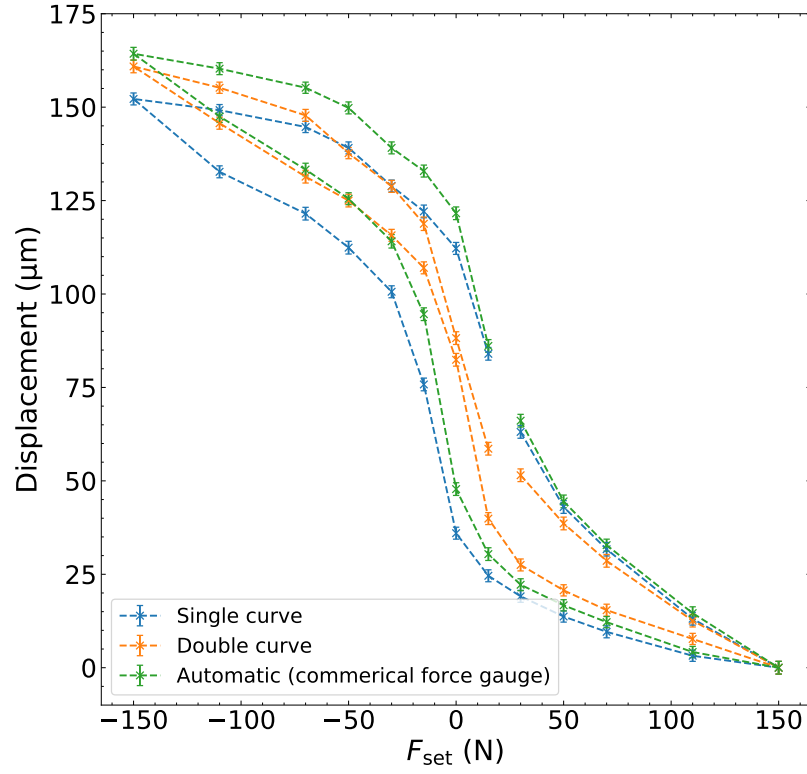
The three force control calibrations were determined with three different calibration approaches. The single curve calibration was determined using known static loads in the push and pull direction and the static friction of the spring and mounting sled were not considered during the calibration. The double curve calibration used also static loads and in addition considered the static friction of the spring and mounting sled in the move in and move out direction, respectively. The automatic calibration is the one described above. For all three calibration approaches, the difference between the reference force F_{ref} at the position of the test object and the set force F_{set} by the ACU were determined with the force gauge installed at the position of the test object. The results are shown in Figure 6.12b.

The resulting force-displacement characteristics for the three force control calibrations are shown in Figure 6.12a and the derived mechanical properties are summarized in Table 6.2. The mechanical play is determined at a force of ± 15 N. A maximum difference of $\sim 12 \mu\text{m}$ exists between the single curve and the automatic calibration in the absolute longitudinal displacement, while a difference of $\sim 24 \mu\text{m}$ exists in the calculated mechanical play between the double curve and the automatic calibration. This shows that the force control calibrations have different impacts on the force-displacement characteristics of the test object depending on the applied force with a special emphasis at forces ~ 0 N. Furthermore, this draws the conclusion that the force control calibration can have a non-negligible impact on the true force-displacement characteristics and the derived mechanical properties of a test object. The automatic calibration therefore serves as the new standard force control calibration going forward.

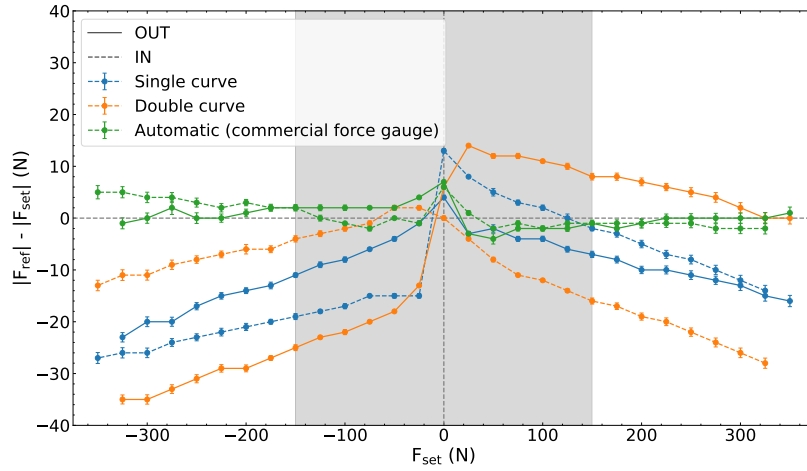
In principle, the remaining systematic error of the force control accuracy on the absolute displacement $d_{\text{abs. disp.}}$ and d_{play} is specific on the test object and depending

Table 6.2. Mechanical play d_{play} and the absolute longitudinal displacement $d_{\text{abs. disp.}}$ for the three different force control calibrations. The selected test object is a 2-DOF actuator assembly. The mechanical play is determined at a force of ± 15 N. The error on the mechanical play Δd_{play} and absolute displacement $\Delta d_{\text{abs. disp.}}$ are determined according to Equations 6.6 and 6.7. The respective force-displacement graphs are shown in Figure 6.12a.

Calibration Method	d_{play} (μm)	Δd_{play} (μm)	$d_{\text{abs. disp.}}$ (μm)	$\Delta d_{\text{abs. disp.}}$ (μm)
Single curve	97.5	1.7	152.2	1.7
Double curve	78.9	1.8	160.9	1.8
Automatic	102.5	1.7	164.3	1.8



(a) The measured force-displacement characteristics for the three different force control calibrations.



(b) The difference between the absolute reference force of the force gauge F_{ref} and the absolute requested force F_{set} as a function of F_{set} for the three different force control calibrations.

Figure 6.12. Impact of different force control calibrations on the measured force-displacement characteristics for the selected 2-DOF actuator assembly. Between the measurements, the test object was not dismantled from the test stand to keep the measurement conditions the same. The results are shown for three different force control calibrations. The single and double curve calibration were determined with applying known static loads in the push and pull direction. The former does not consider the static friction of the combination of mounting and spring sled while the latter does. The automatic calibration was derived with the force gauge as explained in Section 6.3.2.

on the local force-displacement gradient, which can be determined from the measured force-displacement characteristics. However, as can be seen in Figure 6.12b for the automatic calibration, the difference of the absolute set force F_{set} by the ACU to the absolute reference force F_{ref} of the commercial force gauge is of comparable absolute magnitude. In push direction, the set force slightly underestimates the actually applied force and in pull direction it slightly overestimates it. Under the assumption that the local force-displacement characteristics in push and pull direction of the ACU are comparable, the remaining systematic error of the automatic force calibration seems to cancel out. The impact of the measurement procedure on the mechanical properties of the test object are discussed next.

6.3.3. Measurement Procedure

It can be envisioned that the measured force-displacement characteristics of a test object change with a high number of consequent load cycles performed within a short timescale and under the same measurement conditions. This is certainly a valid assumption for a test object exhibiting viscoelastic behavior, where the magnitude of the viscoelasticity depends on the load history (see Section 7.2). Therefore, it is important to understand how an increasing number of load cycles affect the measured mechanical properties of the test object. This error is attributed to the measurement procedure and is characterized as a systematic error, because it (potentially) introduces a predictable error on the measured mechanical properties. The measurement procedure describes the procedure to measure the force-displacement characteristics and is therefore separated from the mounting procedure to mount the test object into the test stand. The latter is discussed in Section 6.3.4.

The force-displacement characteristics of the selected 2-DOF actuator assembly is shown in Figure 6.13. The measurement is performed with an initialization cycle using a maximum force of $F_{\text{max}} = \pm 500 \text{ N}$ and ten consequent load cycles with a maximum force of $F_{\text{max}} = \pm 150 \text{ N}$. The test object was not dismounted from the test stand in-between the test cycles to avoid contributions from the mounting procedure, as described in Sections 6.3.4 and 6.3.5, to the mechanical properties¹¹. For each test cycle, the mechanical play and the absolute longitudinal displacement are calculated according to Equations 6.1 and 6.4, and are listed in Table 6.3. The test force release for the calculation of the mechanical play $F_{\text{unload,release,pull/push}}$ was defined as $\pm 15 \text{ N}$.

The impact of the measurement procedure on the play and the absolute displacement is then estimated by calculating the weighted mean $\bar{d}$ by treating the results per test cycle as statistically independent. The weighted mean $\bar{d}_w$ is calculated according to

$$\bar{d}_w = \frac{\sum \frac{d_i}{\Delta d_i^2}}{\sum \frac{1}{\Delta d_i^2}} \quad (6.8)$$

with the measurement result d_i and the error Δd_i for the i -th test cycle. The standard deviation of the weighted mean value σ_w and is calculated according to

$$\sigma_w = \frac{1}{\sqrt{\sum \frac{1}{\Delta d_i^2}}} \quad (6.9)$$

¹¹On a side note, it should be added that no additional waiting time has been added in-between test cycles.

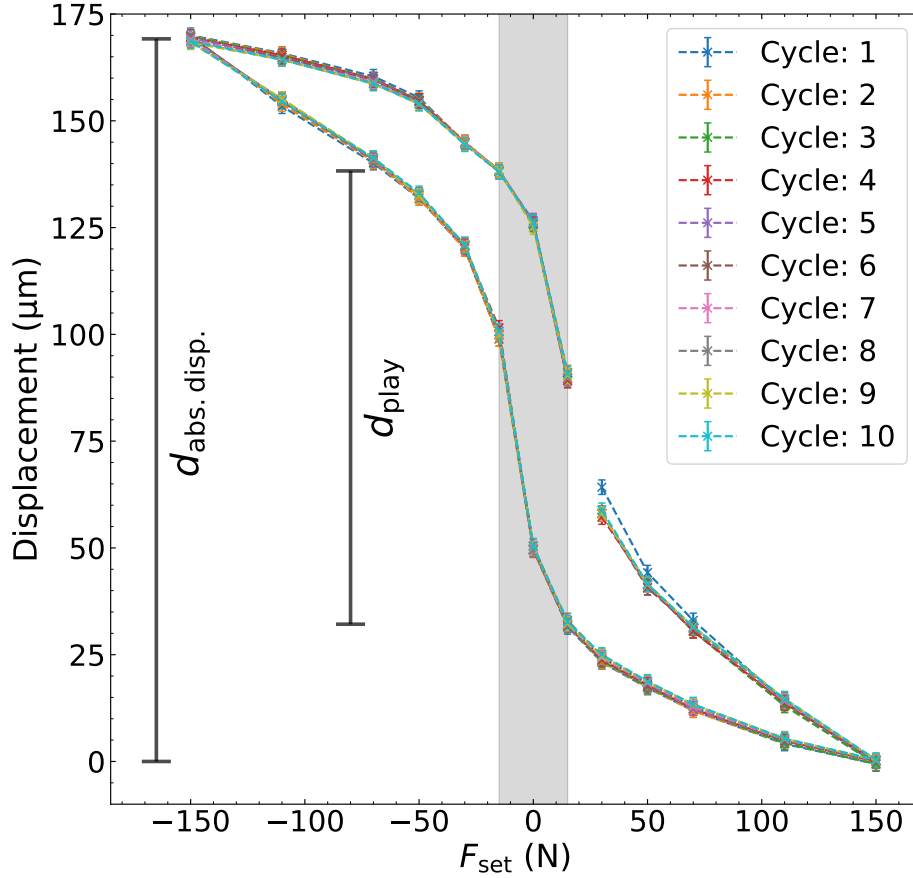


Figure 6.13. Force-displacement characteristics of a 2-DOF actuator assembly measured on August 8, 2024. A total of ten test cycles were performed and before the first test cycle an initialization cycle with a maximum push and pull force of 500 N was performed. The play and absolute longitudinal displacement are calculated according to Equations 6.1 and 6.4 and the definitions are indicated in the plot. The gray band indicates the $F_{\text{unload.,release,push/pull}} = \pm 15 \text{ N}$. The results for the ten measurements are summarized in Table 6.3.

and the standard deviation σ of the complete distribution according to

$$\sigma = \sigma_w \cdot \sqrt{n} \quad (6.10)$$

for n test cycles. The weighted mean and the standard deviation of the weighted mean for the play and the absolute displacement result in

$$d_{\text{play}} = \bar{d}_{\text{w,play}} \pm \sigma_{\text{w,play}} = (106.1 \pm 0.5) \mu\text{m}$$

and

$$d_{\text{abs.disp.}} = \bar{d}_{\text{w,abs.disp.}} \pm \sigma_{\text{w,abs.disp.}} = (169.2 \pm 0.6) \mu\text{m} \quad .$$

The standard deviations on the weighted mean of the mechanical play and the absolute displacement are well below the errors of the individual mechanical play and absolute displacement values determined for the different test cycles. The impact of the measurement procedure on the mechanical properties of the selected test object

Table 6.3. Measured play and absolute displacement for the selected 2-DOF actuator assembly. A total of ten test cycles were performed with a maximum test force of $F = \pm 150$ N. An initialization cycle with a maximum initialization force of $F_{\text{init}} = \pm 500$ N was performed before the first test cycle. The respective force-displacement characteristics is shown in Figure 6.13. The absolute displacement, play and their errors are calculated according to Equations 6.1, 6.4, 6.6 and 6.7. The play is calculated for a test force release of $F_{\text{unload.,release,push/pull}} = \pm 15$ N.

Test Cycle	d_{play} (μm)	Δd_{play} (μm)	$d_{\text{abs. disp.}}$ (μm)	$\Delta d_{\text{abs. disp.}}$ (μm)
1	106.7	1.7	170.6	1.8
2	106.2	1.7	170.3	1.8
3	106.5	1.7	170.3	1.8
4	106.4	1.7	169.5	1.8
5	106.2	1.7	169.4	1.8
6	106.1	1.7	168.7	1.8
7	106.2	1.7	168.7	1.8
8	105.4	1.7	168.2	1.8
9	106.2	1.7	168.0	1.8
10	105.4	1.7	168.2	1.8

is therefore small. A second test series with the same actuator assembly revealed the same order of magnitudes for the results (see Table B.2). Furthermore, this is in accordance with the qualitative experimental observations gained of testing the mechanical components, or parts of the mechanical components, of the AMC over the course of the last ~ 4 years. Therefore, it can be concluded that the measured force-displacement characteristics of the mechanical components do not change significantly with the number of load cycles. This is somehow expected, as a significant change of the force-displacement characteristics of a test object as a function of test cycles would indicate infant mortality or wear out failures depending on the lifetime of the test object (see Figure 4.2)¹².

For the testing of the mechanical mirror alignment components, a single test cycle therefore serves as reasonable approximation of the force-displacement characteristics of the measured test object. An additional impact on the true force-displacement characteristics on the measured test object is caused by the assembly of the test stand and the mounting procedure, which is discussed in the following.

6.3.4. Test Stand Assembly and Mounting Procedure

During the design phase, the production and the assembly of the test stand, a large emphasis is placed on a proper vertical and horizontal alignment of the test object with the force and displacement measurement direction to ensure a proper measurement of the longitudinal displacement. The mounting procedure then has the objective to not introduce any additional clearance that could distort the measurement of the

¹²However, one can imagine a long-term degradation of the force-displacement characteristics leading to an increase in the mechanical play and the absolute longitudinal displacement over many test cycles. To properly quantify this, long-term tests with a high number of consecutive test cycles would be necessary, which are currently not performed and not foreseen for mass production of mechanical components of the mirror alignment system for MST.

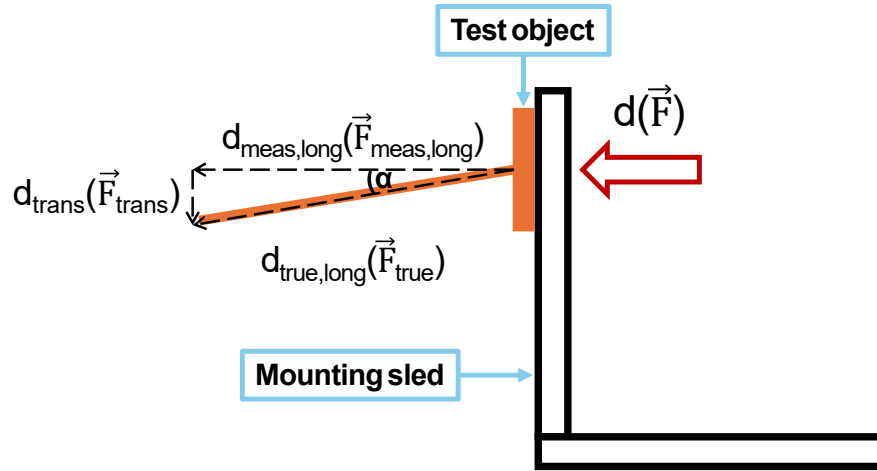


Figure 6.14. Schematic diagram of a test object, which is mounted with a tilting angle α in the test stand. The tilt of the test object distorts the measurement of the longitudinal displacement $d_{\text{true,long}}(\vec{F}_{\text{true}})$ component by introducing a transversal displacement component $d_{\text{trans}}(\vec{F}_{\text{trans}})$.

longitudinal displacement while mounting the test object into the test stand¹³. In combination, if the the test stand assembly and the mounting procedure are properly performed, they result in a mounted test object on which no shear or transversal forces are acting while no test force by the ACU is applied. This is the ideal, tilt-free state. Some qualitative considerations of an improper assembly of the test stand and an improper mounting of the test object and their impact on the measured force-displacement characteristics are discussed in the following.

Test Stand Assembly

A proper production of the various parts of the test stand and proper assembly thereof ensures that the test object is mounted with as little tilt as possible in the test stand. The systematic error of the production and assembly of the test stand on the measured longitudinal force-displacement characteristics could be caused by a potential misalignment between the longitudinal axis of the test object and the interface between the test object and the mounting sled in vertical or horizontal direction. In addition, this interface of the mounting sled needs to be perpendicular with respect to the test object. A further influence for the measurement of 1-DOF or 2-DOF actuator assemblies might be caused by the misalignment of the boreholes of the mounting ring, which is the telescope-sided interface for the actuators. If any of these error sources are present, they lead to a tilted test object.

One potential impact a tilted test object has is the introduction of a transversal displacement component to the measurement and consequently the true longitudinal displacement is distorted by the transversal displacement component. This is shown schematically in Figure 6.14. The measured longitudinal displacement $d_{\text{meas,long}}$ for a

¹³Matters are most likely more complex in reality than the simplified assumption made here. The simplified assumption is that a tilt of the test object is dominantly caused by misalignments between the force and displacement measurement direction and the test object in the assembly of the test stand. This assumption is made to be able to qualitatively disentangle the effects of the mounting procedure from the test stand assembly.

measured force $F_{\text{meas,long}}$ is given by

$$d_{\text{meas,long}}(F_{\text{meas,long}}) = \sqrt{d_{\text{true,long}}(F_{\text{true}})^2 - d_{\text{trans}}(F_{\text{trans}})^2} \quad , \quad (6.11)$$

where $d_{\text{true,long}}(F_{\text{true}})$ is the true longitudinal displacement and $d_{\text{trans}}(F_{\text{trans}})$ is the transversal displacement component. The true longitudinal and the transversal displacement component are depending on the respective force component of the measured longitudinal force $F_{\text{meas,long}}$ and are given by

$$\begin{aligned} F_{\text{true}} &= \frac{F_{\text{meas,long}}}{\cos \alpha} \quad , \quad \text{and} \\ F_{\text{trans}} &= F_{\text{meas,long}} \cdot \tan \alpha \quad , \end{aligned}$$

with the tilting angle α between the test object and the interface of the mounting sled. In the case of $\alpha = 0^\circ$, it follows that the measured longitudinal displacement corresponds to the true longitudinal displacement under the assumption that the test object is not mounted systematically wrong into the test stand. If $\alpha > 0^\circ$, it follows that

$$d_{\text{meas,long}}(F_{\text{meas,long}}) = d_{\text{true,long}}(F_{\text{meas,long}}) \quad .$$

In the case of $|\alpha| > 0^\circ$, the measured longitudinal displacement component is distorted by the transversal displacement component. The magnitude of this impact on the measured force-displacement characteristics depends on the transversal force-displacement characteristics of the test object. In the simple case that the transversal displacement component does not exhibit any mechanical play and has similar viscoelastic force-displacement characteristics as the longitudinal displacement component of the test object, the true longitudinal play and absolute displacement are underestimated.

Further effects of a tilted test object on the measured force-displacement characteristics can not be excluded, and their impact might be more dominant than the effect discussed above (e.g., shear forces on an actuator assembly introduced by a misalignment of the boreholes of the telescope-sided interface). A first understanding on the impact of these effects could be gained from FEM simulations of the test object and the test stand under different misalignments of the test object with the force and measurement direction. However, this is beyond the scope of this thesis.

Mounting Procedure

The mounting procedure needs to ensure that the test object is mounted into the test stand in a way that no additional clearances are introduced between the test object and the test stand. This can happen on both interface sides between the test stand and the test object. On the mirror side, this is the interface between the mounting sled and the test object. There are currently two basic solutions how the test object is fixed to the test stand on the mirror side, which are shown on the left and right side of Figure 6.15.

The screwing solution uses four screws to fix the flange to the mounting sled and uses the same approach as the installation of the mirror alignment components to the back of a MST mirror facet. An alternative, clamping solution was developed by the Max-Planck-Institut für Physik (MPP) to facilitate and accelerate the mounting of the mechanical components into the test stand during the mass production of

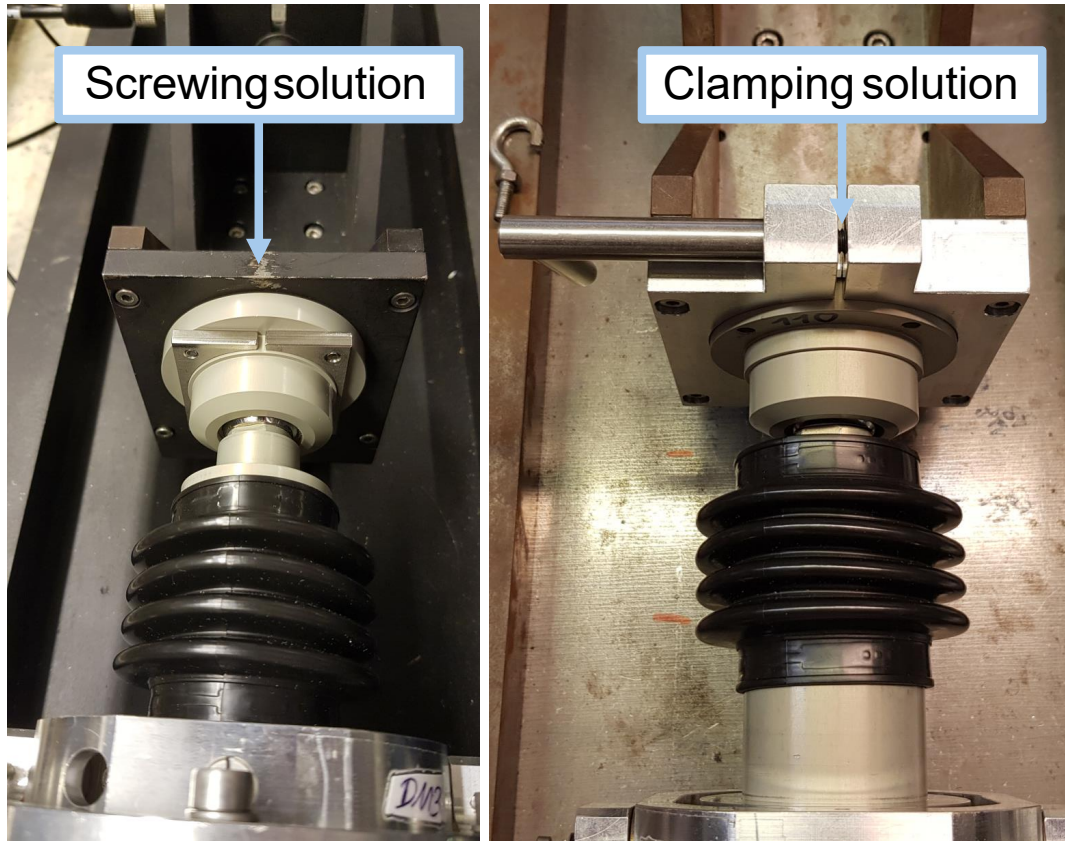


Figure 6.15. Two interface solutions between the test object and the mounting sled of the test stand. Left: The screwing solution with which the test object is fixed to the mounting sled using four M4 screws. Right: The clamping solution designed by the MPP to clamp the test object to the mounting sled for faster mounting.

mechanical components of the mirror alignment system for the LST2-4 telescopes. For both interface solutions, the test object is fixed to the mounting sled while it is pressed with a certain force against the interface to ensure that the test object flange is pressed plane to the mounting sled, as shown in Figure 6.16¹⁴. A manual check by the operator can provide additional certainty that the flange of the test object is plane with the interface.

On the telescope-sided interface, an additional clearance is present between the gimbal and the mounting ring for the 1-DOF and 2-DOF actuator assemblies. This clearance is minimized by installing set screws, which fixate the mounting axes with respect to the telescope interface in accordance with the installation of the actuators at the actual MSTs. The measurement of a gimbal with different combinations of installed set screws is described in Section 7.3.

When the same test object is demounted from and remounted into the test stand and the force-displacement characteristics are measured each time, the two above discussed error sources of the mounting procedure introduce a statistical error on the mechanical properties of the test object. An empirical estimation of this statistical error is described in the next section.

¹⁴A common value for this so-called touching force F_{touch} is $F_{\text{touch}} = 100 \text{ N}$.

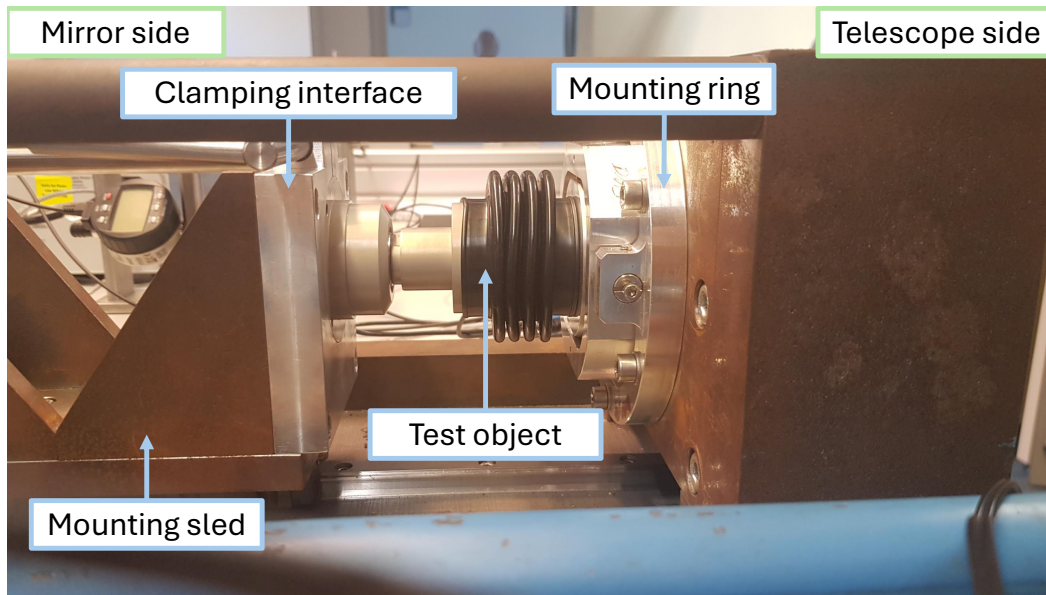


Figure 6.16. Close-up view of the mirror-sided and the telescope-sided interface of the test stand. During the mounting procedure, it needs to be ensured that the flange of the test object is plane to the interface of the mounting sled. In addition, the clearance in the mounting ring is reduced by using set screws.

6.3.5. Empirical Determination of Statistical Error

The mounting procedure introduces a statistical error on the measured force-displacement characteristics, if the same test object is demounted from and remounted into the test stand and measured each time. This statistical error is introduced by the potential error sources outlined in Section 6.3.4. In this section, the empirical determination of the statistical error for the selected test object is described. The same approach can be used to determine the statistical error on the mounting procedure of the other mechanical components of the mirror alignment system such as the 1-DOF actuator assembly and the fix point.

The measurements were performed according to a standardized mounting procedure and each measurement was performed with the same calibration of the force control¹⁵. The mounting and measurement conditions are summarized in Table 6.4. They resemble the procedures foreseen for the testing of the mechanical components during the mass production for the MST pathfinder. Three different human operators mounted the test object and performed the measurements. Hereby, operator 1 had less experience than operator 2 and 3. Three operators are used to investigate if there are systematic impacts of varying experience on the measurement results.

The frequency distributions of the measurement results of the mechanical play at $F = \pm 15$ N and the absolute displacement are shown in Figure 6.17. The calculated mean and standard deviation are summarized in Table 6.5¹⁶. There seems to be a

¹⁵The calibration of the force control that was used during the measurements is a predecessor version of the automatic force control calibration presented in Section 6.3.2. The comparison between the automatic and the force control calibration for the estimation of the statistical error is shown in Figure B.2.

¹⁶The errors on the mechanical play and the absolute displacement of the single measurement values summarized in Table B.3 are not considered in the calculation of the mean and the standard deviation of Table 6.5.

Table 6.4. Conditions of the mounting and the measurement procedure for the determination of the statistical error.

Parameter	Value
Set screws installed	yes
Touching force	100 N
Mirror-sided interface	Clamping
No. initialization cycles	1
Initialization force (push/pull)	± 500 N
No. test cycles	1
Maximum test force (push/pull)	± 150 N

small trend in the standard deviations visible depending on the experience level of the operator, but given the limited statistics this trend is deemed not significant¹⁷. With the given statistics, the statistical error on the mounting procedure for the given test object is estimated to be $\pm 5 \mu\text{m}$, both, for the mechanical play and for the absolute displacement.

Future steps include the determination of this statistical error for the other mechanical components of the mirror alignment system and with the automatic force control calibration explained in Section 6.3.2. In addition, this should be determined for each test stand as, e.g., differences in the tolerances of the mirror-sided or telescope-sided interfaces influence the statistical error. Therefore, this step is a necessary step in the verification process of the test stands, which will be explained in the next section.

Table 6.5. Results of the empirical determination of the statistical error of the mounting procedure. The mean and the standard deviation of the single measurements summarized in Table B.3 are determined for the mechanical play at ± 15 N and the absolute longitudinal displacement at ± 150 N. The results are calculated for each of the three human operators as well as for the complete data set.

Operator	No. Meas.	$\bar{d}_{\text{play}}$ (μm)	$\sigma_{d_{\text{play}}}$ (μm)	$\bar{d}_{\text{abs. disp.}}$ (μm)	$\sigma_{d_{\text{abs. disp.}}}$ (μm)
1	7	102.0	3.5	174.0	6.3
2	6	99.5	2.9	172.0	5.3
3	11	102.9	2.0	173.6	3.0
Complete	24	101.8	3.0	173.3	4.6

6.4. Test Stand Verification

For the proper verification of the test stand and its measurement accuracy, a test object with defined force-displacement characteristics is necessary. Currently, such a test object does not exist. A first step for the design of such a test object is the

¹⁷One could imagine that the mechanical properties of the test object are influenced by the measurement procedure and the consequent application of the high initialization force of F_{init} in the case that the measurements are performed on short timescales. Therefore, the difference of the mechanical play and the absolute displacement for consequent measurements is calculated as a function of the time difference between measurements. There is no significant trend visible, as shown in Figure B.3.

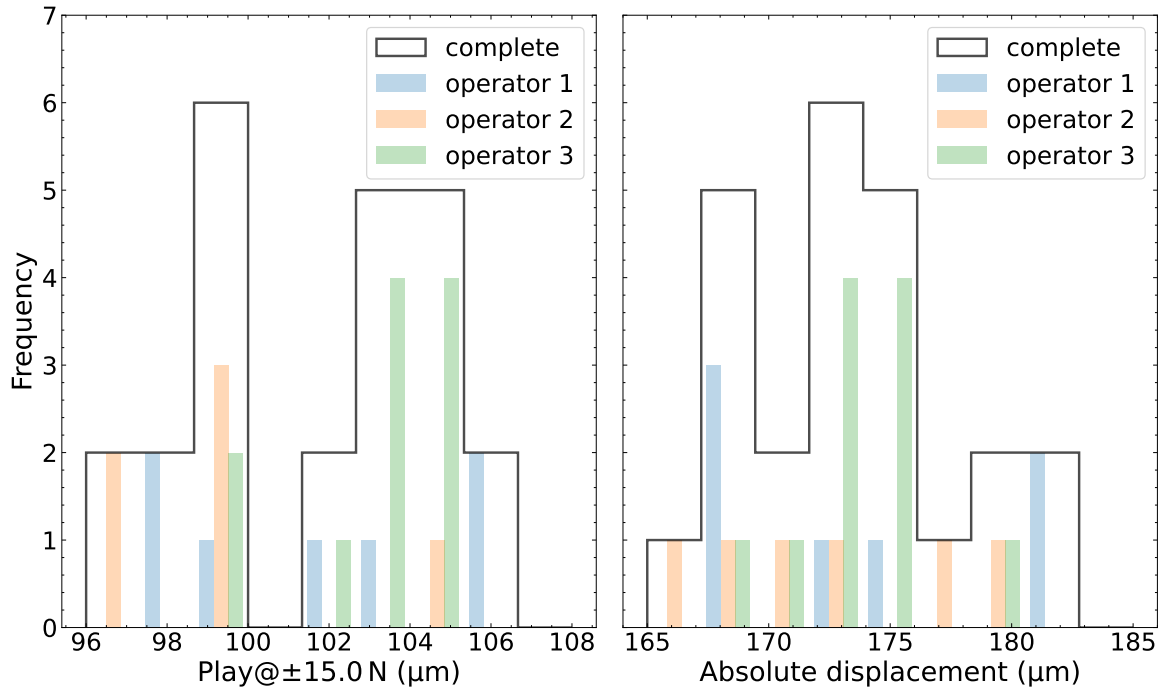


Figure 6.17. Frequency distributions for the mechanical play (left) and the absolute displacement (right) for the measurements assessing the statistical error of the test stand. The measurements are shown for the three human operators as well as the complete distribution combining the measurements of the three operators. The measurement values are summarized in Table B.3 and the calculated mean and standard deviations in Table 6.5.

generation of a mathematical model that describes the mechanical properties of the test object. A starting point to mathematically model the viscoelastic properties of a test object is the Kelvin-Voight model, which is a parallel arrangement of a spring and a dashpot. A detailed discussion is beyond the scope of this thesis. A further description of the Kelvin-Voight model is given in, e.g., Guedes (2011).

The currently performed verification procedure has three main objectives. First, to verify that the test stand is fully functional. This includes the proper working of the technical components such as the ACU as well as the software components such as the control software running on the external PC. Second, the verification of the force control calibration and the quantification of the mounting procedure as described in Section 6.3.2 and Section 6.3.5. The third objective is to provide cross-verification between the various test stands, i.e. that the test stand stationed in Tübingen provides consistent measurement results of the same test objects with the test stand of the MPP and UCSC. An exemplary verification measurement between the test stand Tübingen and the test stand MPP is shown in Figure B.4. For this objective, each one of the mechanical components of the mirror alignment system should be measured.

After the verification phase, the test stand is ready for use. The measurements of the performance evaluation of actuator parts for the E-series actuators foreseen for the LSTs and MSTs are summarized in the next chapter.

Performance Evaluation of Actuator Parts

The actuator force-displacement test stand is a key setup to evaluate the performance of MACs for the MSTs and LSTs. The measurements and results of the performance evaluation of three types of differently specified spherical bearings and two gimbal designs for the E-series actuator assemblies of the LST2-4 telescopes are presented in this chapter. As described in Section 5.3.2, the same parts will be used for the actuator assemblies of the MSTs and are therefore representative of the parts that will be used for the MST MACs.

In Section 7.1, the motivation for the redesign of the parts of the actuator assembly from the D-series is given. In Section 7.2 and in Section 7.3 the results for the evaluated spherical bearings and the gimbals are described, respectively. In Section 7.4, the insights gained from the performance evaluation are discussed and summarized.

7.1. Motivation

In 2019, 55 MAC sets of the D-series design manufactured upon order by the UZH were shipped to IAAT and their performance was evaluated with the actuator displacement test stand as reported by Diebold (2020). As primary performance parameter served the mechanical play of the actuators as the viscoelastic impact of the spherical bearing in the flange bearing was not well understood at this time yet. The result of this performance evaluation revealed one potential and one necessary improvement point for the design of the E-series actuator assemblies. The former are the spherical bearings in the flange bearing. The spherical bearings had tight tolerances, which lead to a high breakaway torque if the spherical bearing is not moved for some time. After several consequent movements in a short time interval, this torque significantly decreases. When the actuators are mounted at the telescope, a too high breakaway torque of the spherical bearings can lead to a deformation of the mirror when the actuator moves and, in the worst case scenario, that the interface between the mirror and the actuator breaks. Consequently, a total of 15 fix points with five each with differently specified spherical bearings were sent to IAAT for evaluation.

The second improvement point are the gimbals, as they were identified to not comply with the required design specifications¹, while the actuators showed satisfactory performance. Therefore, the already existing design of the gimbal was redesigned with tighter mechanical tolerances. In addition, a new design was developed and evaluated for a potential performance improvement with respect to the existing design.

¹After the performance evaluation of the D-series actuator assemblies, the design specifications were adapted slightly and are shown in Table 5.3.

Table 7.1. Different grades of the transversal play for the “GE 16 EC-NIRO” spherical bearings of the manufacturer Fluro. The transversal play for the “GE 16 EC-NIRO” spherical bearing is specified to be $0\text{ }\mu\text{m} - 40\text{ }\mu\text{m}$. Information taken from Fluro (2024a).

Bearing Grade	Specification Transversal Play
C0/C1	With torque
C2	Reduced
C3	Enlarged

The performance of the spherical bearings and the gimbal designs were evaluated at IAAT in late summer 2021 and the results are reported in Section 7.2 and Section 7.3 for the fix points and the gimbals, respectively. Hereby, the evaluation of the fix points serves as performance indicator of the spherical bearings as the steel rod is not suspected to contribute significantly to the force-displacement characteristics.

For completeness, it should be mentioned that the measurements were performed with two different test stands, the test stand MPP and IAAT for the measurements of the fix points and the gimbals, respectively. Both of these test stands used the single curve approach of the force sensor calibration that does not consider the static friction of the mounting-spring sled combination. Therefore, the absolute values derived for the fix points and the gimbals are affected by the systematic errors discussed in Section 6.3.2 and should not be taken as absolute representative values for the performance of the gimbals and spherical bearings in the mass production of MACs of the AMC for the LST2-4 and MST. Furthermore, a direct comparison of the derived values to the design specifications listed in Table 5.3 is not possible as those have to be met for different maximum push and pull test forces. Therefore, the main focus of the performance evaluation is the comparison between the different designs under the same systematic and statistical errors.

7.2. Fix Point Study

The built-in spherical bearings in the flange bearing of the fix points are the “GE 16 EC-NIRO” bearings of the manufacturer Fluro. The manufacturer specifies a transversal play between $0\text{ }\mu\text{m} - 40\text{ }\mu\text{m}$ and defines the longitudinal play as up to three times of the transversal play. However, within this specified limit, the spherical bearings can be procured with different grades upon request. The different grades are summarized in Table 7.1. The manufacturer specifies them to have torque for the C0 and C1 grade, as well as reduced and increased transversal play for the C2 and C3 grade. Consequently, the different grades do not have strict limits on the transversal play, but are merely categorized on a relative scale within the specified limit (Fluro 2024a).

A total of 15 fix points were delivered to IAAT of which five each had built-in spherical bearings of the grade C0, C1 and C2. The force-displacement characteristics was only studied for a sample of the fifteen fix points, while the mechanical properties and the breakaway torque were quantified for every fix point. Unlike actuator assemblies, the fix points do not have a dedicated identifier. Therefore, fix points were labeled by the grade of their spherical bearing and a numeric identifier from 1 to 5. The study of the force-displacement characteristics is described in the following.

In Section 7.2.2 and Section 7.2.3, the determination of the mechanical properties and the breakaway torque measurements are explained, respectively.

7.2.1. Force-Displacement Characteristics

The force-displacement characteristics for one sample fix point per spherical bearing grade are shown in Figure 7.1 and the corresponding measurement conditions are summarized in Table 7.2. As can be seen and as expected, the force-displacement characteristics of the fix points depend on the bearing grade. All spherical bearings show a viscoelastic behavior, which is most likely caused by the PTFE used as a contact sliding surface. During the unloading cycles 2 and 4 (see Figure 6.7), the PTFE in the spherical bearing relaxes, but does not recover its original geometry and a finite displacement remains. The magnitude of this displacement depends on the loading time and the loading level, i.e. the maximum applied force. This is illustrated in Figure B.5 for several overlaid measurements with a varying maximum force.

After an intrinsic relaxation time under no external applied load, the PTFE recovers its initial geometry, which explains the start-up behavior at the beginning of the first cycle of each fix point measurement. This intrinsic relaxation time has not been quantified for the different bearing grades. The good reproducibility between the different test cycles indicates that the PTFE behaves similarly provided that the same force sequence is measured.

One of the conclusions drawn from this study is the introduction of an initialization cycle into the measurement procedure to avoid the start-up behavior of the spherical bearings and to bring the spherical bearings in a defined state. Furthermore, the definition of a mechanical play for the spherical bearings is not clear. Either, the mechanical play can not be resolved with the given force-displacement resolution of the test stand (e.g., C0 in Figure 7.1) or it is dominated by the viscoelastic behavior of the spherical bearing (e.g., C1 and C2 in Figure 7.1). Therefore, a mechanical play, as derived from the procedure described in Section 6.2.3, strongly depends on the definition of the test force released value $F_{\text{load.,release,push/pull}}$. Some further conclusions affecting the definition of the performance parameter for the evaluation of the mechanical components of the AMC is discussed in Section 7.4. The determination of the mechanical properties of the 15 fix points is described in the following.

Table 7.2. Conditions for the measurement of the force-displacement characteristics of the sample of fix points. The touching force was slightly varied between the test objects but is in the order of 100 N.

Parameter	Value
Measurement type	Force-displacement
No. test cycles	3
Maximum test force (push/pull)	± 475 N
Touching force	~ 100 N
Mirror-sided interface	Screwing

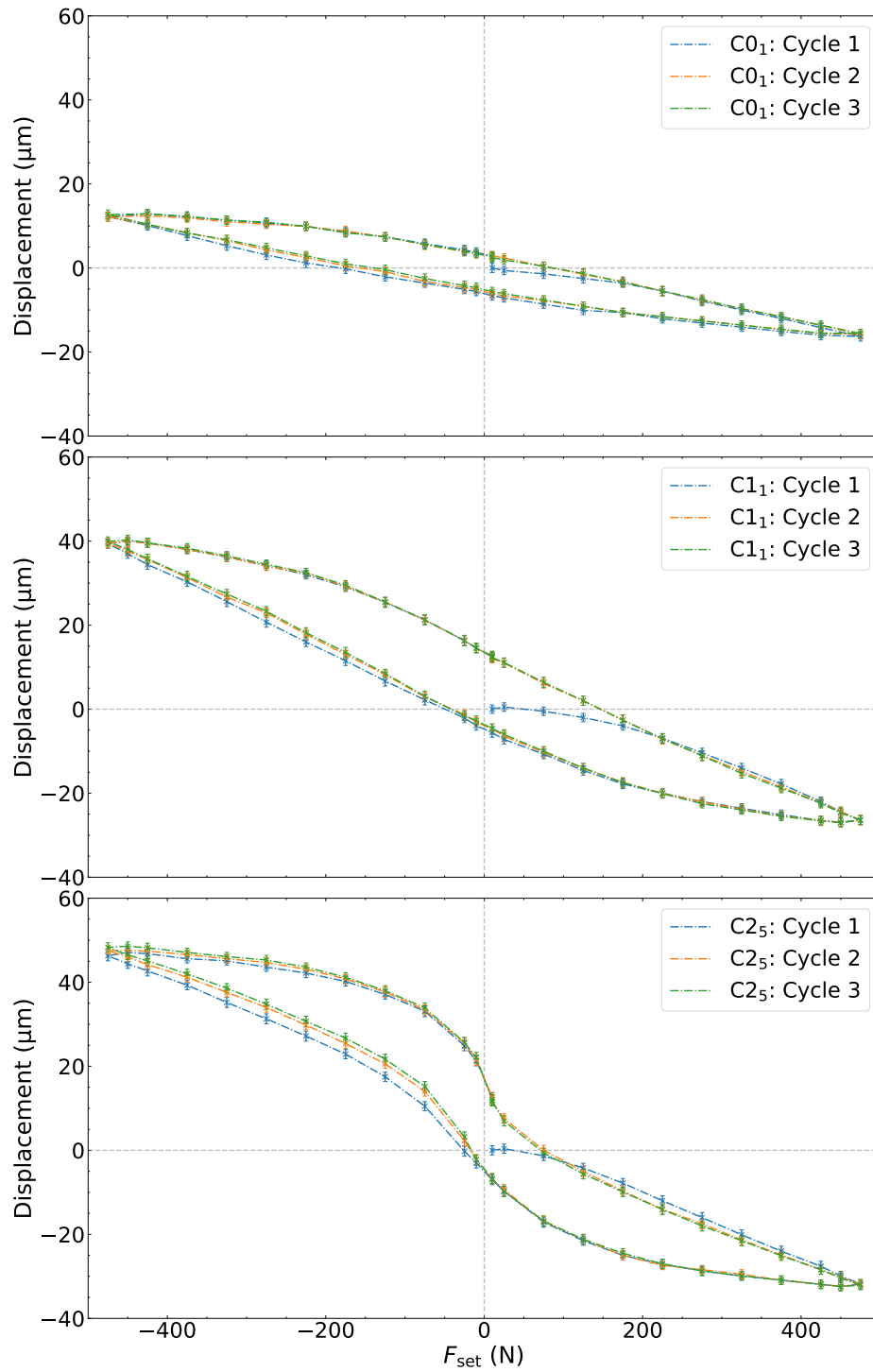


Figure 7.1. Force-displacement characteristics for three fix points with different graded spherical bearings. A maximum force of $F_{\text{max}} = \pm 475 \text{ N}$, a total of 3 test cycles and no initialization cycle was used. For each of the graded spherical bearings, a start-up behavior at the beginning of the first cycle is visible.

7.2.2. Mechanical Properties

The conditions of the measurements of the fix points are summarized in Table 7.3. The maximum test forces of $F_{\max,\text{push}} = +150 \text{ N}$ and $F_{\max,\text{pull}} = -100 \text{ N}$ were provided by the MPP and simulate the wind load and the gravity-induced load during measurement conditions for various elevation angles on a LST mirror. The frequency distribution of the determined absolute displacement for the fix points is shown Figure 7.2. The calculated mean and standard deviation for the different bearing grades is listed in Table 7.4.

The calculated absolute displacement for the different bearing grades follows the expectations as defined by the manufacturer with the C0, C1 and C2 providing increasing values of absolute displacement. While the C0 seem like the ideal choice from the point of view of the determined absolute displacement, they require quite a bit of breakaway torque. This is described in the next section.

Table 7.3. Conditions for the measurement of the 15 fix points. The measurement procedure is described in Section 6.2.3.

Parameter	Value
Measurement Type	Reduced Force-Displacement
No. initialization cycles	1
Initialization force (push/pull)	$\pm 500 \text{ N}$
No. test cycles	3
Maximum test force (push/pull)	$+150 \text{ N} / -100 \text{ N}$
Touching force	$+100 \text{ N}$
Mirror-sided interface	Screwing

7.2.3. Breakaway Torque

After a sufficiently long relaxation phase, the fix points with a maximal tilted flange bearing are mounted into the test stand as shown in Figure 7.3. A force sequence consisting of push forces from $25 \text{ N} - 200 \text{ N}$ in steps of 25 N are applied to each fix point. A manual check determines the force range $F_{b,\min}$ to $F_{b,\max}$ in-between which the bearing flange starts moving and is pressed planar to the mounting sled. The breakaway torque τ_b can then be calculated by

$$\tau_{b,\min/\max} = F_{b,\min/\max} \cdot r_{\text{flange}} \quad (7.1)$$

with the radius r_{flange} of the flange bearing. The radius of the flange bearing is $r_{\text{flange}} = 32.5 \text{ mm}$. For each fix point, the mean torque is then determined as

$$\tau_{\text{mean,fp}} = \frac{\tau_{b,\max} - \tau_{b,\min}}{2} \quad (7.2)$$

The mean torque $\tau_{\text{mean,bg}}$ per bearing grade is determined as the mean of Equation 7.2. The lower and upper error are estimated as the maximum difference to $\tau_{b,\min}$ and $\tau_{b,\max}$, respectively. The results per bearing grade are summarized in Table 7.5.

Even considering the limited statistics and the rather large errors of up to $\sim 80 \%$, there is a trend noticeable between the different bearing grades. The C0 and C2

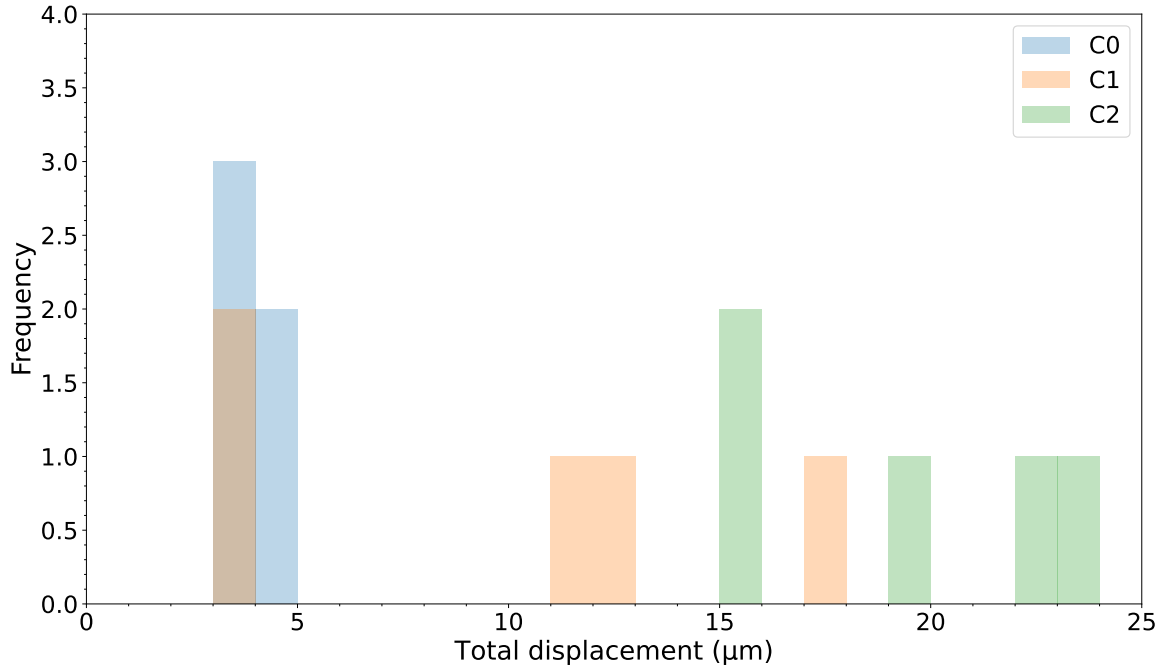


Figure 7.2. Frequency distribution of the absolute displacement for the 15 fix points. Of the 15 fix points, five each have a different spherical bearing grade labeled C0, C1 and C2. The measurement conditions are summarized in Table 7.3.

Table 7.4. Mean $\bar{d}_{\text{abs. disp.}}$ and the standard deviation σ of the absolute displacement for the fix point study. The result for each fix point is listed in Table B.4.

Bearing Grade	$\bar{d}_{\text{abs. disp.}}$ (μm)	σ (μm)
C0	3.8	0.4
C1	9.9	6.2
C2	19.2	3.9

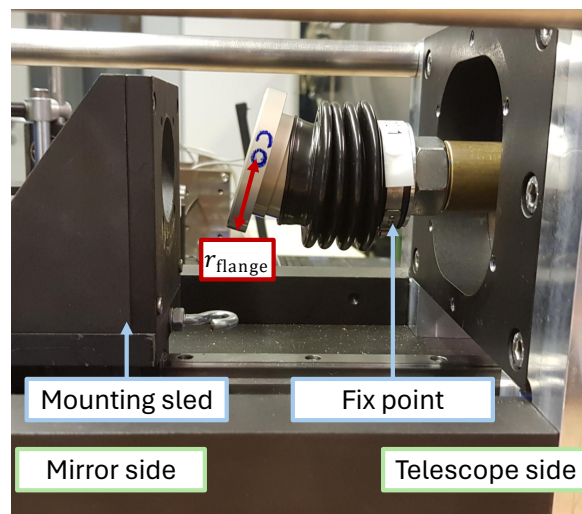


Figure 7.3. Set-up to determine the breakaway torque for the spherical bearing of the fix point.

bearings exhibit the highest and lowest breakaway torque, respectively. This is according to the expectations. While both, the C0 and the C1 bearing grade, offer satisfactory performance with respect to the absolute displacement, the C1 bearings display a lower breakaway torque. Consequently, the C1 graded spherical bearings have been chosen for the mechanical components of the mirror alignment system of the LST2-4, LST-South and MST telescopes.

Table 7.5. Mean torque $\tau_{\text{mean,bg}}$ per bearing grade. The lower and upper error were determined as the maximum difference to the minimum and maximum breakaway torque. The complete results for each fix point are listed in Table B.5.

Bearing Grade	$\tau_{\text{mean,bg}}$	$\begin{smallmatrix} +\text{upper} \\ -\text{lower} \end{smallmatrix}$ (N m)
C0	4.3	$\begin{smallmatrix} +1.4 \\ -1.9 \end{smallmatrix}$
C1	2.7	$\begin{smallmatrix} +2.2 \\ -1.9 \end{smallmatrix}$
C2	1.5	$\begin{smallmatrix} +0.9 \\ -0.8 \end{smallmatrix}$

7.3. Gimbal Study

The two designs of the 2-DOF gimbal by MPP are show on the left and right side of Figure 7.4, respectively. The baseline design uses a Sinter bush, which is a plain bearing made out of bronze as interface between the gimbal and the mounting axes, whereas for the ball bearing version this interface is a ball bearing. While the Sinter bush is characterized by its simplicity and ease of manufacturing and mounting of the axes, the ball bearing aims to minimize, or even eliminate, the mechanical play in the interface to the gimbal by exerting a radial load on the mounting axes. However, one disadvantage of the ball bearing version is the mounting of the gimbal to the telescope-sided interface. The set screws need to be fixated while the ball bearing is under a constant load.

The performance of the two gimbal designs were evaluated for four different configurations of mounted set screws, which are listed in Table 7.6. They vary by

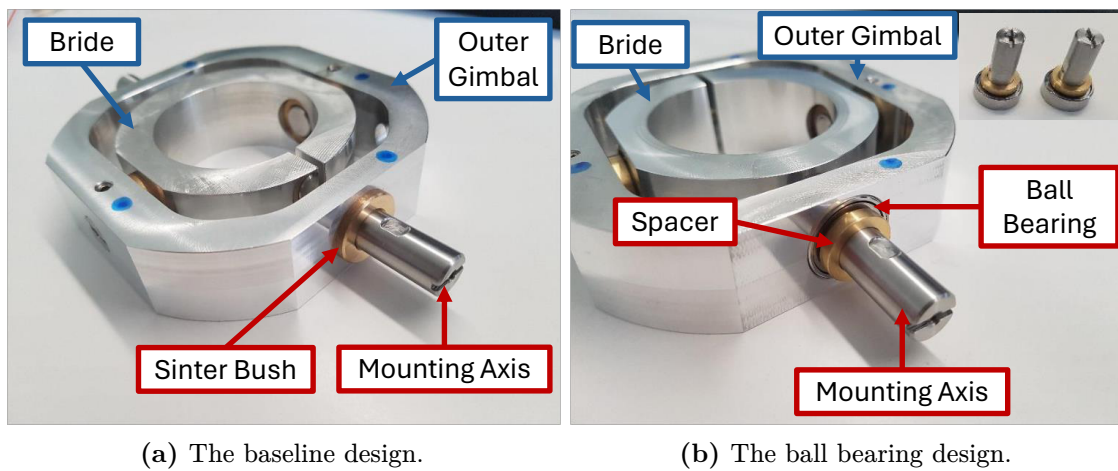


Figure 7.4. Two 2-DOF gimbal designs for the performance evaluation. The inlet in the right image is a close-up of the mounting axes together with the ball bearing and the spacer. Image credit belongs to H. Wetteskind (MPP).

Table 7.6. Configurations for the set screws for the performance evaluation of the two gimbal designs. “Tight” and “Loose” provide a qualitative measure of the applied torque during the mounting of the set screws. “No” indicates that the respective set screws are not mounted.

Config	Mounting Ring		Bride	
	Blue Side	Red Side	Blue Side	Red Side
1	Tight	No	Tight	Loose
2	Tight	Tight	Tight	Loose
3	Tight	Tight	Tight	Tight
4	Tight	No	Tight	Tight

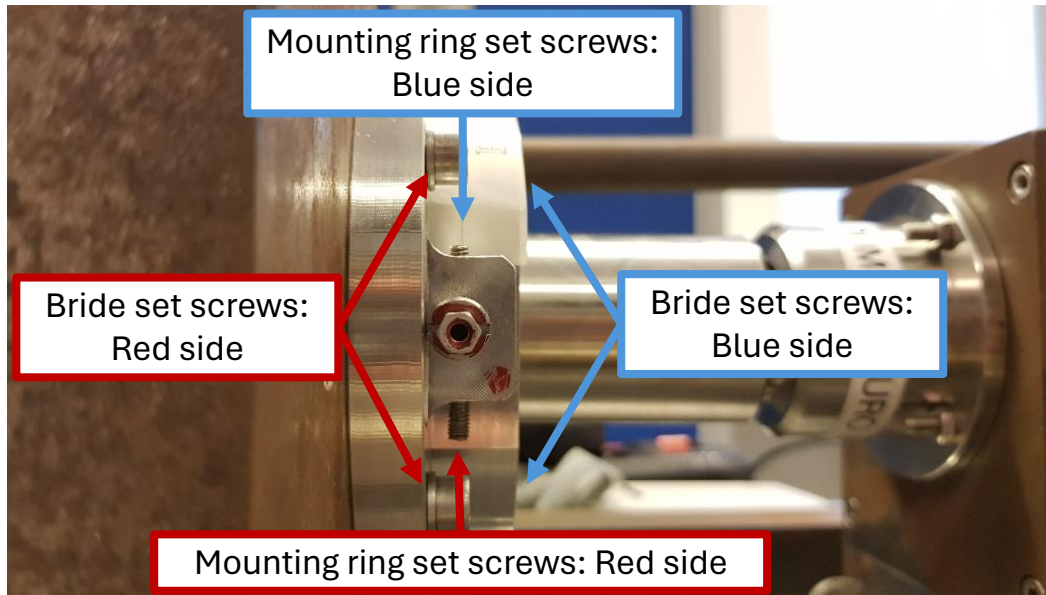


Figure 7.5. Definition of blue and red side for the set screw configurations.

the qualitatively applied torque during installation and their installation position, as shown in Figure 7.5. The installation of set screws aims to minimize the mechanical clearances in the telescope-sided interface, as well as in the interface between the bride and the outer gimbal in the 2-DOF gimbal configuration. In doing so, they influence the force and movement dynamics between the outer gimbal, the mounting axes and the mounting ring or, respectively, the bride, the mounting axes and the outer gimbal.

Therefore, the study of the gimbal designs had two objectives. First, to evaluate which one of the two gimbal designs offers better performance in terms of their mechanical properties. Second, to determine the best set screw configuration. The measurement procedure is described in the following. The resulting force-displacement characteristics and the derived mechanical properties for the baseline and the ball bearing version are presented in Section 7.3.2.

7.3.1. Measurement Procedure

The measurement conditions are listed in Table 7.7. To evaluate the gimbals, they are mounted on a dummy actuator together with a spherical bearing in a dedicated flange bearing. The dummy actuator and the flange bearing are shown in Figure 7.6a.

Table 7.7. Conditions for the measurement of the baseline and the ball bearing gimbal design. The measurement procedure is described in Section 6.2.3.

Parameter	Value
Measurement Type	Force-displacement
No. initialization cycles	1
Initialization force (push/pull)	± 500 N
No. test cycles	3
Maximum test force (push/pull)	+150 N / -100 N
Touching force	+100 N
Mirror-sided interface	Screwing

The test object stays mounted in the test stand in-between measurements for different set screw configurations to avoid introducing an additional error, as discussed in Section 6.3.4.

To differentiate the force-displacement characteristics of the gimbal from the mounting ring and the spherical bearing, so-called dummy measurements are performed. For a dummy measurement, the gimbal is replaced by the dummy end piece, which eliminates the play in the gimbal side of the interface between mounting ring and gimbal. Therefore, the dummy measurement only replicates the movement of the axes in the mounting ring and the behavior of the spherical bearing. The dummy measurement is performed with the same measurement conditions as the gimbal measurement and with the same set screw configurations of the mounting ring to resemble the gimbal measurements as close as possible.

For the ball bearing version the mounting axis has two different diameters over its axial length to fit in the ball bearing, as indicated in Figure 7.6b. The dummy end piece was not adapted for the ball bearing axes and consequently no dummy measurement that closely replicates the measurement of the ball bearing version could be performed. However, under the assumption that the mounting axes of the baseline have the same diameter with the same tolerances as the outer diameter of the mounting axes of the ball bearing version the comparison of the uncorrected absolute displacement values between the baseline and the ball bearing version allows an evaluation of their relative performance, which is discussed next.

7.3.2. Measurement Results

The results of the absolute displacement for the baseline gimbal, the ball bearing gimbal and the dummy measurement are summarized in Table 7.8 for the different set screw configurations. The dummy measurements for set screw configuration 1 and 2 agree within errors. This indicates that there is no major additional play introduced in the mounting ring by installing the set screws on the red side (see Figure 7.5).

For both gimbal versions, the set screw configuration 1 offers the best performance with an uncorrected absolute displacement of $(109.1 \pm 1.2) \mu\text{m}$ and $(39.0 \pm 1.2) \mu\text{m}$, respectively. Furthermore, the baseline option clearly outperforms the ball bearing version by a rather large margin of $\sim 70 \mu\text{m}$. The differences between the various set screw configurations can be explained by changing force dynamics between the outer gimbal, the mounting axis and the mounting ring for configuration 1 and 2, and the outer gimbal, the mounting axis and the bride for configuration 3 and 4. The impact

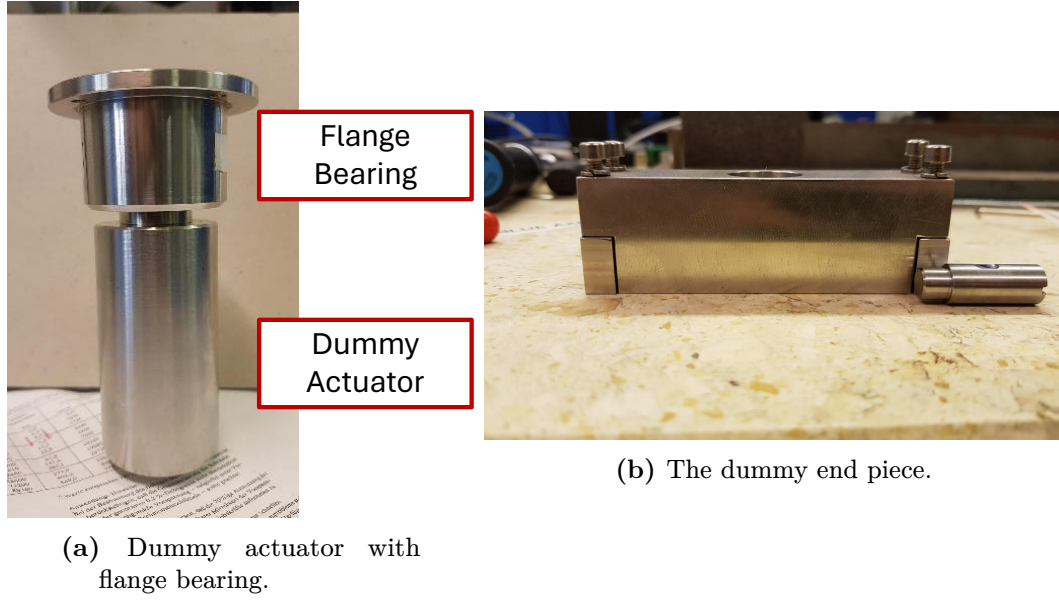


Figure 7.6. Dummy actuator with flange bearing and the dummy end piece. Left: The dummy actuator eliminates the contribution of the actuator. Right: The dummy end piece eliminates the play originating from the gimbal-side of the gimbal-mounting ring interface. In addition, the different diameter of the mounting axis of the ball bearing version is visible.

of the two set screw configurations on the dummy measurement is smaller as the mounting axes are fixated on the gimbal side.

A simplified schematic diagram of the forces acting on the mounting axes in set screw configuration 1 and 2 is shown on the left and right side of Figure 7.7, respectively. For configuration 1, the force $\vec{F}_{\text{set screw, blue}}$ of the blue-side set screws acts at a single point of contact on the mounting axes and presses them against the mounting ring. If now a test force in push and pull direction acts on the test object, parts of the force are transferred via the mounting axes directly to the mounting ring. The mounting axes is in a balanced state. For configuration 2, the mounting axes experience the full test force that is applied to the test object. The mounting axes are consequently in an unbalanced state. The same considerations apply for the set screws installed between the bride and the outer gimbal. For both gimbal versions, an increase in the absolute displacement from configuration 3 to 4 is visible. One possible explanation is that the installation of the set screws on the red side of the mounting ring with already installed blue set screws changes the force and the point

Table 7.8. Absolute displacement of the study of the different set screw configurations. The absolute displacement and the error is calculated according to Equations 6.8 and 6.10. The results for the two gimbal versions as well as the dummy is listed.

Config	Ball Bearing	Baseline	Dummy
1	$(109.1 \pm 1.2) \mu\text{m}$	$(39.0 \pm 1.2) \mu\text{m}$	$(20.9 \pm 1.1) \mu\text{m}$
2	$(147.4 \pm 1.2) \mu\text{m}$	$(44.2 \pm 1.1) \mu\text{m}$	$(20.0 \pm 1.1) \mu\text{m}$
3	$(150.7 \pm 1.2) \mu\text{m}$	$(43.3 \pm 1.1) \mu\text{m}$	-
4	$(158.9 \pm 1.1) \mu\text{m}$	$(54.2 \pm 1.1) \mu\text{m}$	-

of contact of the blue set screws. A consequent removal of the red set screws without a retightening of the blue set screws leaves a higher clearance in the mounting ring and the mounting axes. The force-displacement characteristics for the baseline and the ball bearing gimbal are shown in Figure 7.8 for the set screw configuration 1.

To disentangle the contribution of the flange bearing from the gimbal measurement, the approach used by Salzmann et al. (2024) is used and the absolute displacement of the baseline gimbal version is corrected by the dummy measurement with the same set screw configuration. The corrected absolute displacement of the baseline gimbal version yields

$$d_{\text{baseline,corr.}} = (18.0 \pm 1.6) \mu\text{m}$$

for set screw configuration 1. Even under the consideration that this is for a slightly different force configuration than the defined design specifications in Table 5.3, the baseline version offers satisfactory performance for the use at the mechanical components of the mirror alignment system for the LSTs and MSTs. Therefore, it is chosen as the gimbal design for the E-series actuators.

7.4. Conclusions

Four conclusions can be drawn from the performance evaluation of the actuator parts. First, the fix point study revealed that the spherical bearings with the bearing grade C1 offer satisfactory performance with respect to their absolute displacement as well as their breakaway torque. Therefore, they are chosen as the spherical bearings for the LST and also for the MST mechanical components of the AMC. Second, the gimbal with the baseline design offers an improved performance with respect to its absolute displacement compared to the gimbals evaluated for the D-series actuators by Diebold (2020). Furthermore, the performance is satisfactory for the use with the LST and MST actuator assemblies and most likely fulfills the design specifications summarized in Table 5.1, which are defined for a different test force combination. Third, the best set screw configuration for mounting the actuator assemblies to the telescope-sided interface is identified as the set screw configuration, which fixates the mounting axes by a single point of contact.

The fourth and main conclusion affects the performance parameter, which is chosen as the figure of merit for the quality control of the mechanical components of the AMC. The fix point study revealed that the built-in spherical bearings of the base flange introduce a viscoelastic behavior into the force-displacement characteristics of the mechanical components of the AMC. In the case that the mechanical components are characterized only by mechanical play and elastic deformation, and provided the simplified assumption that the elastic deformation is the same for every mechanical component of the AMC, the optical PSF would not change due to the elastic deformation and only the pointing of the telescope would be affected. However, the elastic deformation of the mechanical components of the AMC would only contribute to the reproducible effects that affect the pointing accuracy and could therefore be corrected by the pointing model (see Section 3.1.1). Then, the non-reproducible positioning uncertainty of the mechanical components would be dominated by the mechanical play. However, in the realistic case that the mechanical components exhibit a viscoelastic behavior, which is a) very difficult to disentangle from the

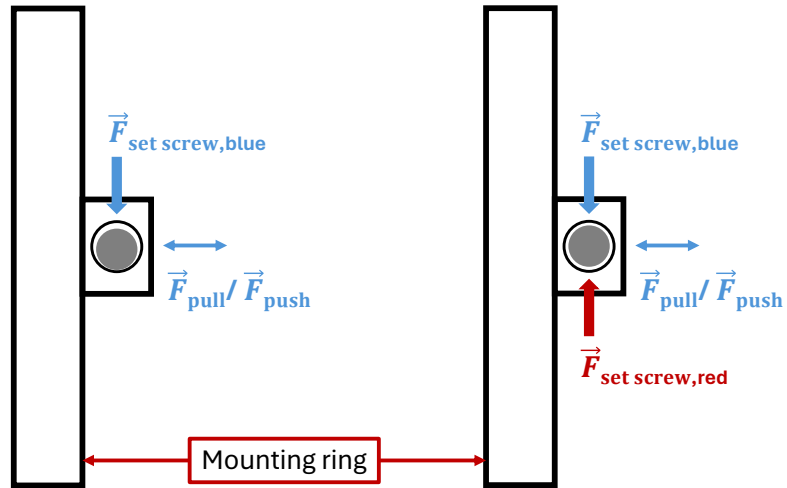


Figure 7.7. Schematic diagram of the mounting ring and the forces acting on the mounting axes. Left: For set screw configuration 1, the $\vec{F}_{\text{set screw,blue}}$ presses the mounting axis with a single point of contact against the interface to the mounting ring. Right: For set screw configuration 2, the forces of the set screws acting from the blue and red side $\vec{F}_{\text{set screw,blue}}$ and $\vec{F}_{\text{set screw,red}}$ put the mounting axis in a unbalanced state.

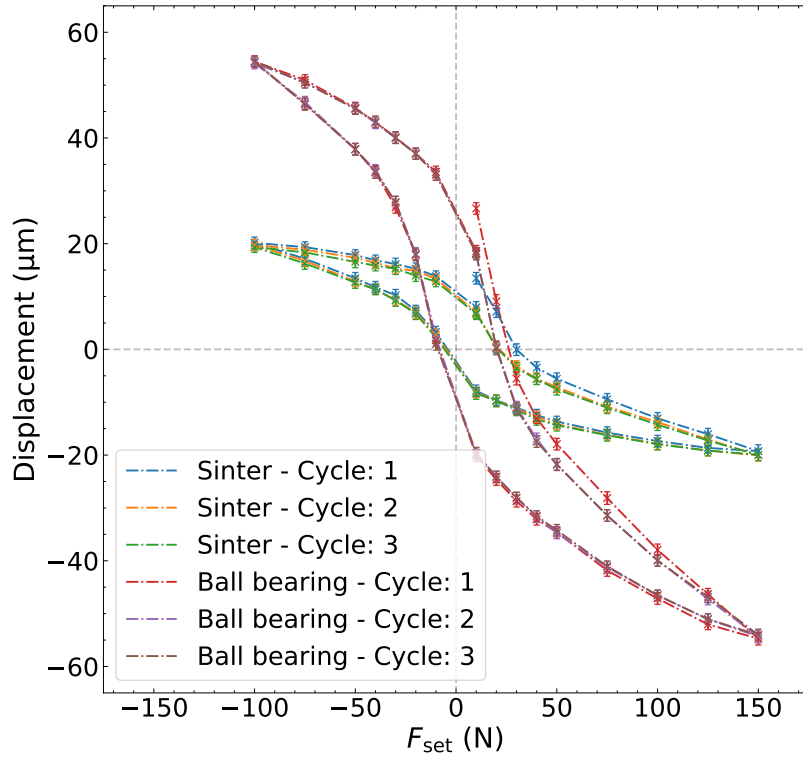


Figure 7.8. Force-displacement characteristics for the two gimbal designs of the performance evaluation. The results for the set screw configuration 1 are shown.

elastic contribution to the force-displacement characteristics, and b) the magnitude of the viscoelastic behavior is depending on the unknown load history and load level, further complicates the positioning uncertainties of the mechanical components. Therefore, the absolute displacement has to be the figure of merit for the quality control. The absolute displacement of the design specifications (see Table 5.3) is defined for a maximum test force that resembles the realistic wind and gravity-induced loads on the mechanical components present during observation conditions. The absolute displacement is therefore the maximum expected non-reproducible positioning uncertainty.

Part III

Pulsar Analysis with H.E.S.S. CT5

I would like to mention astrophysics; in this field, the strange properties of the pulsars and quasars, and perhaps also the gravitational waves, can be considered a challenge.

WERNER HEISENBERG

Motivation

Pulsars are fast rotating neutron stars and are one of several possible endpoints of stellar evolution as the result of, e.g., a supernova explosion. They are characterized by their strong magnetic fields of $\sim 10^{12}$ G, as well as their high rotation speeds leading to spin periods of the order of ~ 1 s down to ~ 1 ms. Their strong magnetic fields accelerate charged particles leading to the consequent emission of electromagnetic radiation, which shows a pulsed nature in case the rotation axis and the magnetic field axis are not aligned. Hereby, the power of the electromagnetic radiation originates from three possible scenarios. First, from the rotational energy of the pulsar. Second, from the accretion of charged particles in binary systems between a neutron star and a companion star. Third, by the decay of the magnetic field. After the initial detection of a pulsar in the radio waveband by Hewish et al. (1968), pulsars were detected all across the electromagnetic spectrum up to the γ -ray waveband by space-based observatories such as the Fermi Gamma-Ray Space Telescope (e.g. Collaboration, The Fermi-LAT 2020), as well as ground-based experiments such as MAGIC (Aliu et al. 2008) and H.E.S.S. (H.E.S.S. Collaboration et al. 2018a). In addition, H.E.S.S. reported the detection of the Vela pulsar up to TeV energies opening the door for studying the spectral properties of pulsars to even higher energies (The H.E.S.S. Collaboration et al. 2023).

The processes and the regions of the high energy emission are still under study with three major emission regions – the polar cap, the slot gap and the outer gap region – as possible candidates. These are indicated in Figure 8.2. The reader is referred to Venter et al. (2018) and Cerutti et al. (2017) for a review of the high energy emission of pulsars, as well as the electrodynamics in the pulsar magnetosphere, respectively.

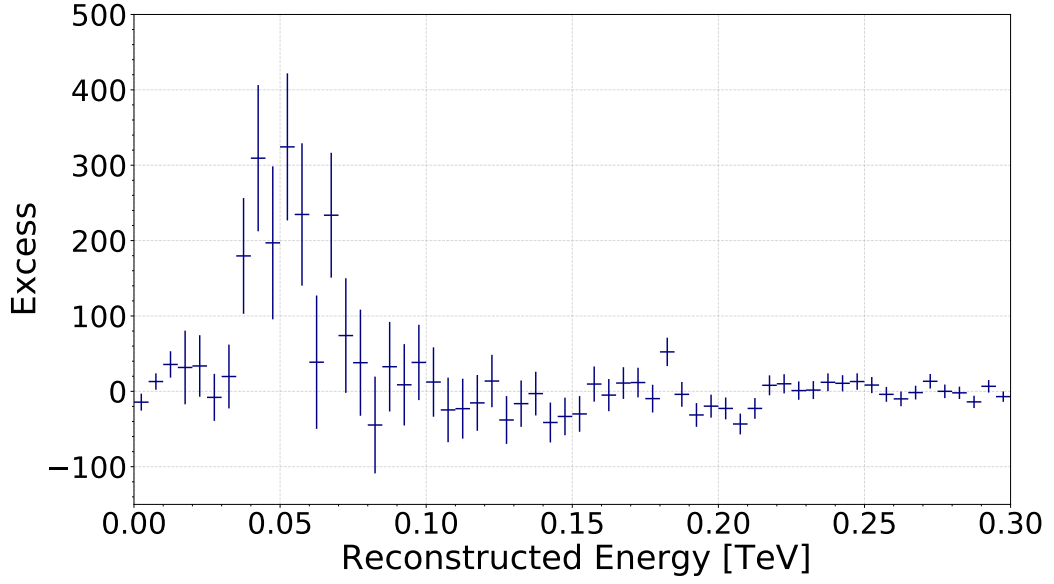
To further constrain the high energy emission of pulsars, ground-based experiments such as the 28 m telescope (CT5) of H.E.S.S. bridge the gap to space-based observatories and offer the possibility to study the spectral cut-off region in the ~ 10 GeV energy range of the Fermi Gamma-Ray Space Telescope detected pulsars with high statistics. Two of these pulsars are already detected with H.E.S.S. CT5. The Vela pulsar with a statistical significance of 15.6σ (H.E.S.S. Collaboration et al. 2018a), and the pulsar B1706-44 with 4.7σ (Spir-Jacob et al. 2019).

After the installation of a FlashCam in H.E.S.S. CT5 in October 2019, the timing system of the camera was verified with observations of the Vela pulsar in 2020. Furthermore, a preliminary analysis of this data set of the Vela pulsar revealed that the majority of the excess events is reconstructed with energies of ~ 50 GeV with an energy bias of $\sim 50\%$, as shown in Figure 8.1. Due to the steep spectrum of the Vela pulsar of $\propto E^{-4}$ at 20 GeV (H.E.S.S. Collaboration et al. 2018a)), the energy excess distribution is a good indicator of the energy threshold of the instrument and the conclusion that the majority of the events has energies close to the hardware trigger threshold of the FlashCam is plausible. In addition, the nominal hardware

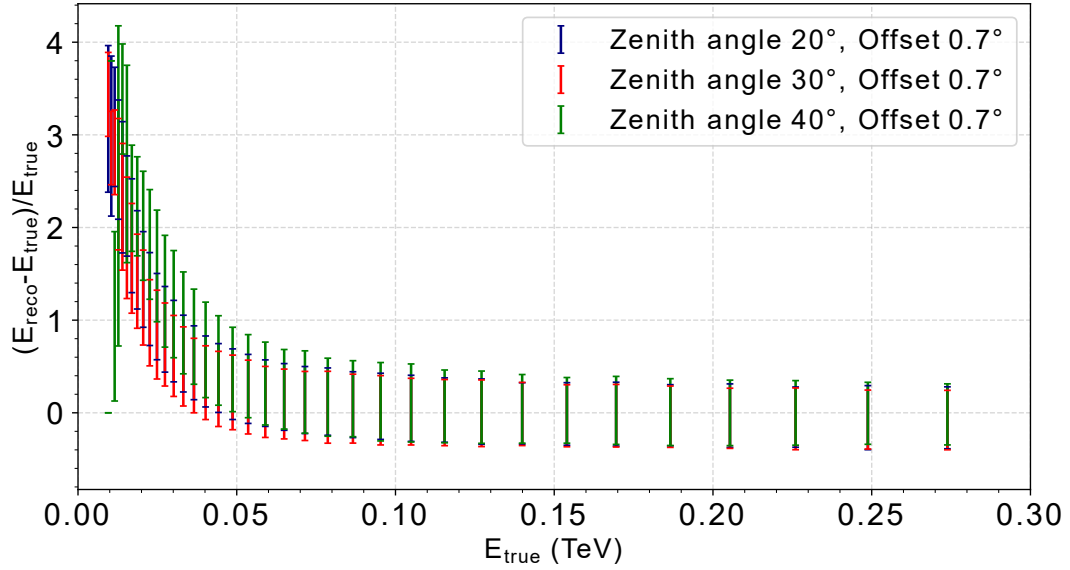
trigger settings provide some margin to permit stable operating conditions under different NSB levels. To explore the low energy potential of the FlashCam in CT5 and potentially further optimize the hardware trigger settings of the FlashCam in CT5, observations on the Vela pulsar and the B1706-44 were performed with a reduced, compared to the nominal, trigger setting in 2021. This trigger setting is interesting for sources where the energy range in the order of ~ 10 GeV is of importance, such as pulsars or GRBs. Hereby, pulsars provide an ideal testing ground as the γ -ray analysis of their pulsed signal can be performed in the same field of the instrument FOV, reducing the impact of systematic effects coming from different positions in the instrument FOV on the analysis.

End-to-end Monte Carlo simulations of the Cherenkov light emitted by the particle shower and the instrument response are of major importance for the analysis of data acquired with IACTs. They serve as input to the algorithms responsible for reconstructing the energy and direction of the γ -ray events, as well as for differentiating the γ -ray events from hadronic background events. Furthermore, the instrument response functions are derived from MC simulations, which are necessary to produce higher level analysis products such as spectra. Ideally, they represent accurately the instrument conditions, as well as the observation conditions such as the atmospheric transparency and the NSB level.

This part of the work covers the analysis of the reduced trigger threshold data acquired on the Vela pulsar and B1706-44 using a preliminary analysis configuration. In addition, the observations of the Vela pulsar taken with nominal trigger settings are analyzed to serve as comparison. In Chapter 9, the methods of the γ -ray data analysis is described, which includes the adaptation of the MC simulations to the reduced hardware trigger setting and the environmental conditions of the Vela pulsar and B1706-44 observations. Furthermore, this chapter covers the comparison of the IRFs derived from the MC simulations using the nominal trigger setting to the ones derived using the reduced trigger setting. In Chapter 10, the results of the observational data analysis are presented, which includes the application of the IRFs derived from the MC simulations with the reduced trigger setting to reconstruct the spectra of the Vela pulsar and the pulsar B1706-44.



(a) Energy excess distribution.



(b) Energy bias for the preliminary analysis configuration.

Figure 8.1. Results of a preliminary analysis of the Vela pulsar data taken as part of the science verification of FlashCam at CT5. The excess and energy bias are explained by Equations 9.2 and 9.9.

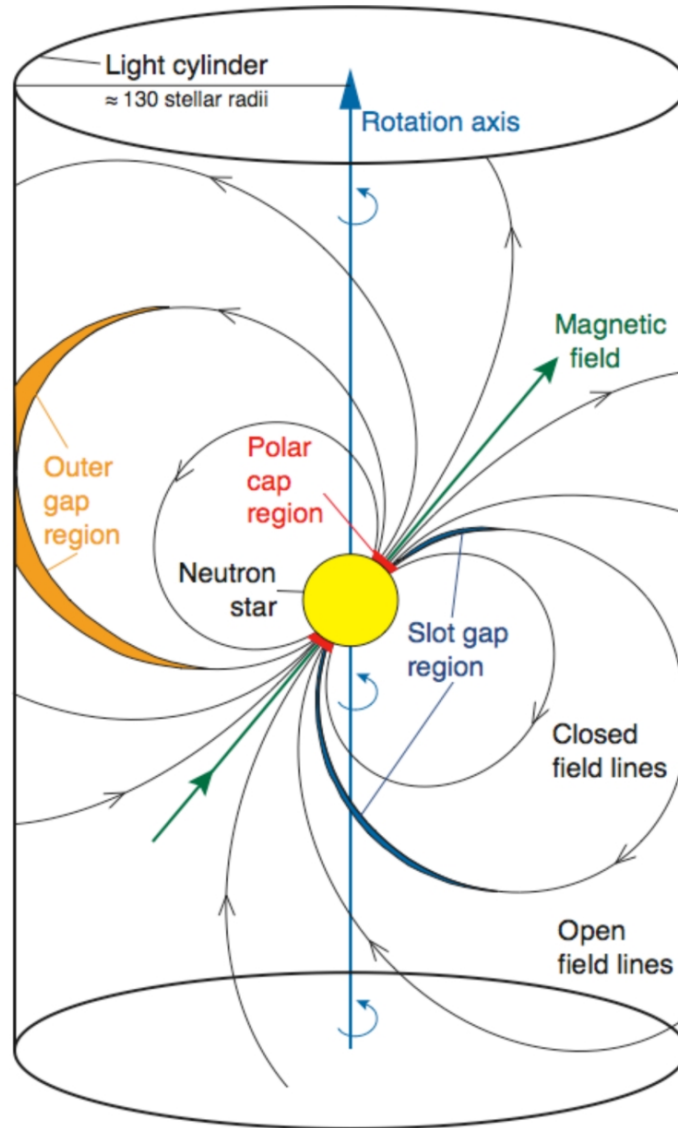


Figure 8.2. Schematic diagram of a rotation powered pulsar. The rotation axis, the magnetic field and the three regions (polar cap, slot gap, outer gap) of high energy emission are indicated. Taken from Aliu et al. (2008).

Data Analysis Methods

The processing and analysis of γ -ray data acquired with IACTs is visualized in Figure 9.1. The processing chain can be separated in various data levels, as described by, e.g., Nigro et al. (2021). In the following, the data levels are described according to Nigro et al. (2021) and Pühlhofer et al. (2024) with the latter providing the specifics for the H.E.S.S. data processing chain.

Data Level (DL) 0 refers to the raw signals of the cameras for an event, which fulfills the specific camera and array trigger criteria, as described in Section 3.1.3. The step from DL0 to DL1 comprises the calibration (conversion of the camera pixel signal from digital counts to p.e.) and zero-suppression (removing pixels without a signal). The step from DL1 to DL2 involves the cleaning (removing pixels with a signal uncorrelated to the Cherenkov light emitted by the particle shower) and a first parametrization of the camera images, where a camera image is a representation of the recorded Cherenkov light distribution in terms of p.e. per pixel. The main aim of the cleaning step is to remove camera pixels that contain a signal uncorrelated to the Cherenkov light emitted by the particle shower, as caused, e.g., by NSB. One common approach is the tailcut cleaning with varying threshold levels on the signal amplitude of the camera pixel. For example, the “0407” cleaning only keeps pixels with a signal amplitude > 4 p.e. and which have an adjacent pixel with a signal amplitude > 7 p.e., or vice versa, in the camera image. Especially for low energy showers with few pixels in the camera image, this cleaning approach has the downside that potentially important information about the shower shape is lost. An approach that aims at containing more shower information, is the time cleaning that only keeps pixels that are temporally correlated. This is expected behavior for pixels contained in the Cherenkov light wavefront of an EAS while the NSB pixels are temporally uncorrelated. The time cleaning has been implemented in the H.E.S.S. analysis for testing purposes, as described by Steinmassl (2023). In H.E.S.S., there are two basic approaches for the parametrization and reconstruction of events in order to derive the shower properties, i.e. the energy, the direction and the type of the primary particle. The first approach is based on the analysis of the mathematical moments of the light distribution of the camera image, while the second approach uses the comparison of the camera image to predicted camera images derived from an semi-analytical description of the shower or from MC simulated γ -rays. The first approach are the Hillas parameters introduced by Hillas (1985) and described within the context of the H.E.S.S. analysis by Aharonian et al. (2006). The second approach can be separated in the pixel-wise fit of the recorded camera image to camera image templates derived from MC simulated γ -rays (Parsons et al. 2014) and the fit of the recorded camera image to the predicted camera images derived from a semi-analytical shower model (De Naurois et al. 2009). For the first approach the calculated Hillas parameters and for the latter approaches additional information about the shower for later input

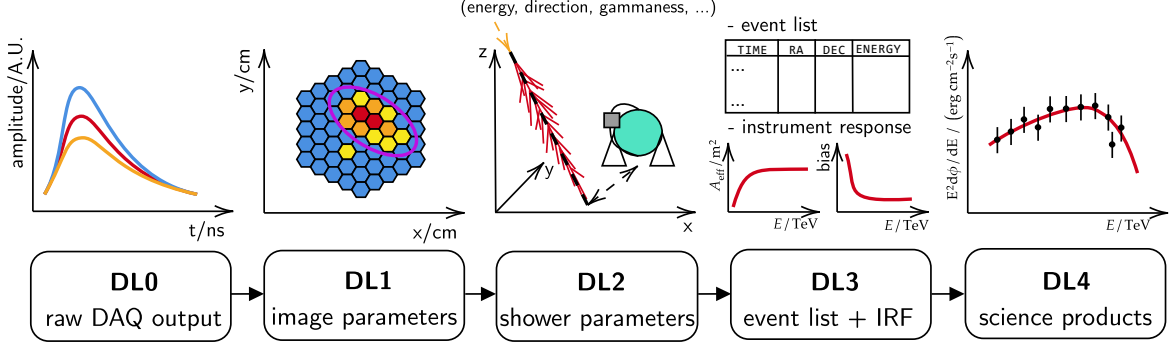


Figure 9.1. Schematic diagram of a common data processing chain for IACTs.

The different data levels refer to 1. DL0: the raw output of the cameras, 2. DL1: the calibrated, cleaned and parametrized camera images, 3. DL2: the parameters of the Cherenkov light distribution derived from the camera images with different reconstruction algorithms, 4. DL3: the event list containing γ -ray like events after background rejection and the IRFs, and 5. DL4: the high-level science products such as sky maps, light curves and spectra. Taken from Nigro et al. (2021).

to the respective reconstruction algorithms are stored in the Data Summary Tables (DSTs), which resemble the DL2 in H.E.S.S.

The DL3 consists of two parts. The first part is a list of events that pass a set of γ -ray selection cuts, which aim to reject events which are induced by hadrons instead of γ -rays. For the reconstruction algorithms based on the Hillas parameters, the background rejection can happen using simple selection cuts on the Hillas parameters (Aharonian et al. 2006), using more advanced approaches based on a tree classification method (Ohm et al. 2009), or neural networks (Murach et al. 2015). The more sophisticated reconstruction algorithms usually use the difference between the recorded camera images to the predicted camera images as figure of merit for the background rejection. There exist various sets of γ -ray selection cuts, which are optimized to provide optimal sensitivity for soft, Crab-like and hard source spectra (Aharonian et al. 2006). The application of the γ -ray selection cuts and the chosen event reconstruction algorithm deliver an event list of γ -ray like events. An additional step specific to the analysis of pulsars is the calculation of the rotational phase and the phase folding for each event of the event list using a timing solution, as described in Section 9.3. The second part of DL3 are the Instrument Response Functions (IRFs), which are derived from MC simulations of the Cherenkov light emitted by the particle shower and the respective response of the Cherenkov detector. They are crucial to determine the energies of the primary particle and serve as input to calculate the higher level science products of the DL4 such as, e.g., spectra. One of the data formats for DL3 is the Flexible Image Transport System (FITS) format.

The analysis from the DL0 to DL4 was performed with proprietary software by the different collaborations operating IACTs. With the emergence of the CTAO and its operation as an observatory, the need for open source analysis tools became obvious. The official analysis tool for CTAO is Gammapy (Donath et al. 2023), which was also adapted within H.E.S.S. as the high-level analysis tool. In the context of this thesis, the DL3 data is generated with the H.E.S.S. proprietary H.E.S.S. Analysis Program (HAP) framework and the consequent high-level analysis is performed with

Gammapy¹.

At the moment, the possible analysis configurations within H.E.S.S. are limited to a specific array configuration, which has to be chosen a priori depending on the source and the aim of the analysis, as well as the available array configuration. A mono analysis only uses events reconstructed by CT5, while a stereo analyses uses events reconstructed by at least two telescopes of CT1-4. A hybrid analysis using events reconstructed by at least two telescopes of either CT1-4 or CT5 is implemented, but is not used by standard. The implementation of event classes, that categorize events according to specific properties of the camera image and array trigger configuration in various, complementary classes, aims to work around this limitation to fully exploit the capabilities of the full array. The implementation of event classes is currently on-going within the H.E.S.S. collaboration.

The analysis of the two pulsars is performed with a monoscopic analysis configuration, as events with energies of < 100 GeV are of interest. It is based on the Hillas parameters and a set of additional parameters as input to a neural network for the energy and direction reconstruction, and as input to a Boosted Decision Tree (BDT) for the event selection and background rejection. The Hillas parameters and the reconstruction algorithm are described in Section 9.1. In Section 9.2, the signal extraction and background estimation are explained and Section 9.3 covers the calculation of the rotational phase of the pulsar and the phase folding. The adaptation of the MC simulations to the reduced hardware trigger threshold and a comparison of the IRFs between the reduced and the nominal trigger threshold simulations is performed in Section 9.4. For an extensive review of the analysis methods of γ -ray data, the reader is referred to, e.g., Malyshev et al. (2024).

9.1. Event Selection and Reconstruction

The reconstruction algorithm used for the pulsar analysis is based on the MonoReco algorithm described in Murach et al. (2015) and Murach (2017). The original MonoReco algorithm is modified with respect to the event selection and background rejection by Bedur Ramesh (2024), and the energy and direction reconstruction by Deka Baruah (2024). But at first, the Hillas parameters that serve as input to the event reconstruction and background rejection are explained.

As described in Section 2.3.2, the angular distribution of the Cherenkov light of an electromagnetic shower looks like a compact ellipse in the camera, where the minor and major axis of the ellipse represent the lateral and longitudinal extent of the shower. An hadronic shower is more diffuse and the recorded intensity distribution in the camera is less compact due to several electromagnetic subshowers (see Figure 2.16). The Hillas parameters introduced by Hillas (1985) characterize the Cherenkov light distribution in the camera image with a set of parameters, as shown in the schematic diagram of an electromagnetic shower in Figure 9.2. The Hillas parameters are the length of the minor and major axis of the ellipse (length and width), the integrated intensity of the light enclosed in the ellipse (image amplitude), the nominal distance between the camera center and the COG of the light distribution enclosed in the ellipse, the azimuth angle ϕ between the camera center and the COG of the ellipse, and the angle α describing the orientation of the ellipse in the camera. In case the

¹The used Gammapy version for the data analysis is version 1.2.

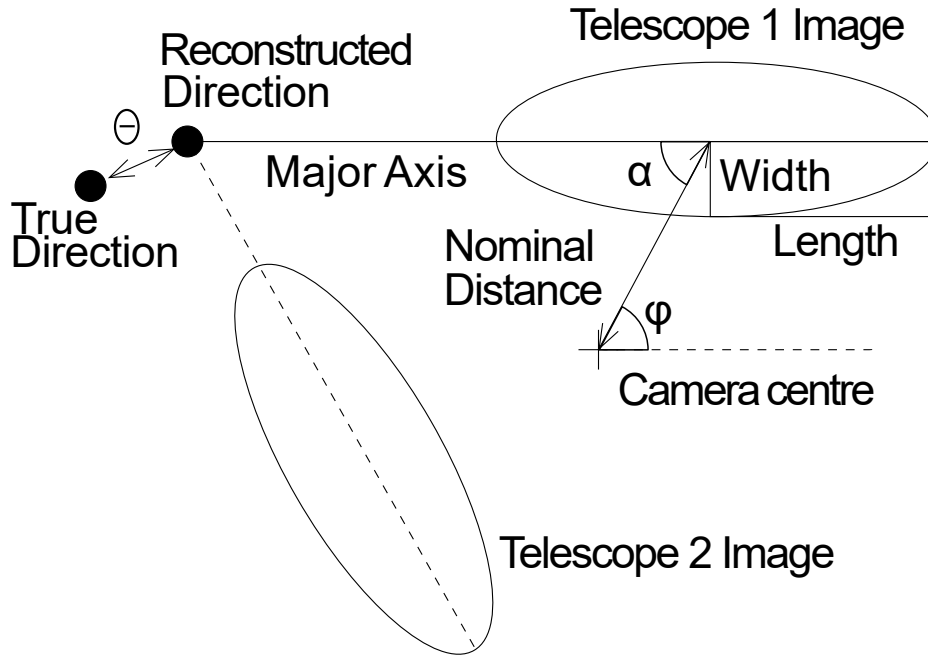


Figure 9.2. Schematic diagram of the superimposed camera images from two telescopes for an electromagnetic shower. The Hillas parameters by Hillas (1985) are shown in the image for telescope 1. They constitute the width and the length of the ellipse, the nominal distance to the camera center, the azimuth angle ϕ between the camera center and the COG of the ellipse, and the orientation angle α of the ellipse in the camera. The direction of the primary particle is located along the major axis of the ellipse. In the case of a stereoscopic observation of the same shower, the direction of the primary particle can be calculated from the intersection of the two major axes. The angular offset between the true and the reconstructed direction is given by the angle Θ . Adapted from Aharonian et al. (2006).

same particle shower is reconstructed with two telescopes, the camera images can be superimposed and the intersection of the major axis of the ellipses correspond to the direction of the primary particle, as indicated in Figure 9.2.

Some of the Hillas parameters and an additional set of parameters describing the image properties serve as input to the training of the BDTs for the event selection and background rejection, as well as the neural networks used for the energy and direction reconstruction. The BDT and neural networks need to be trained with signal-like and background-like data sets. For the former, MC simulations of γ -ray showers are taken, while for the latter so-called off runs, i.e. runs with no detected γ -ray signal, are taken. The event selection and background rejection is described in Section 9.1.1, and the reconstruction of the particle energy and direction in Section 9.1.2. Some known limitations of the reconstruction algorithm and possible improvements to further increase the low-energy performance are outlined in Section 9.1.3.

9.1.1. Event Selection and Background Rejection

The main objective of the event selection is to effectively reject events induced by hadrons, while minimizing the number of falsely rejected events induced by γ -rays. For the modified MonoReco algorithm, the camera images are cleaned using a time

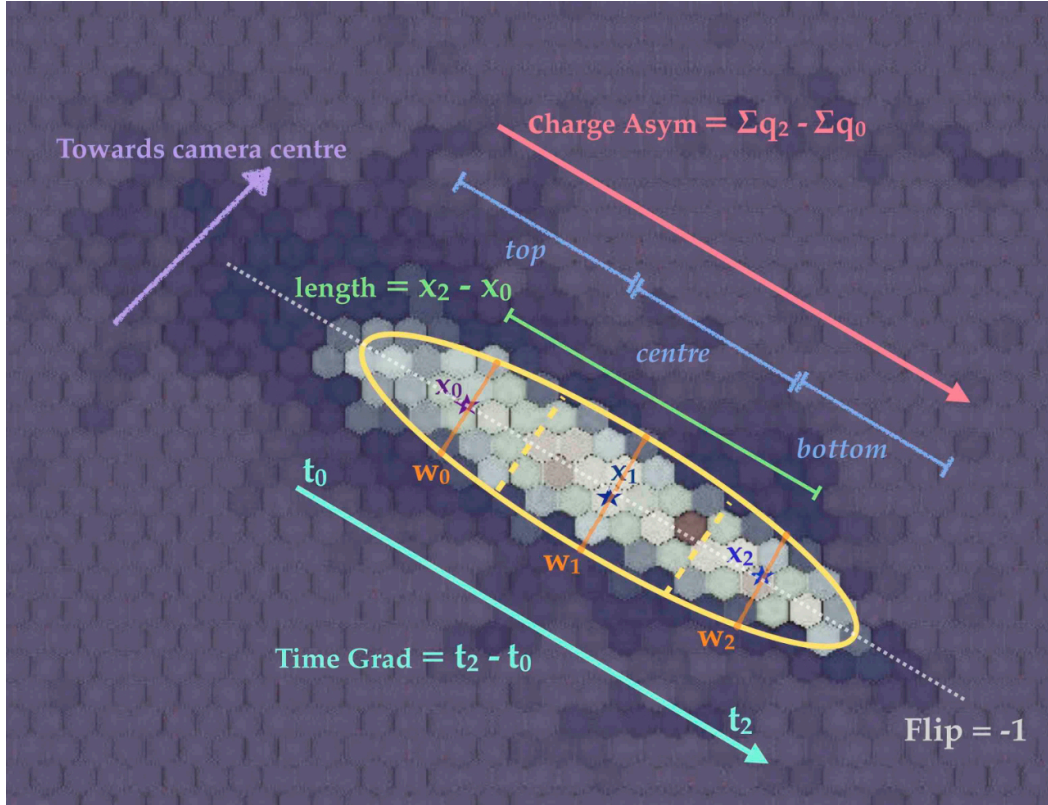


Figure 9.3. A parameterized shower image of an electromagnetic shower. The Hillas ellipse is separated into three sectors from which additional parameters used for the event selection and event reconstruction are derived. This is described by Bedur Ramesh (2024) and Deka Baruah (2024). Taken from Deka Baruah (2024).

cleaning approach that uses the temporal and spatial correlation of the relative signal amplitude times in the pixels as indicator for the Cherenkov light signal of a particle shower. This approach aims to retain more information about the shower compared to the standard tail cut cleaning using fixed threshold cuts on the pixel amplitudes, especially for low intensity showers consisting only of a handful of pixels. The time cleaning implemented in H.E.S.S. is described in Steinmassl (2023). An additional preselection step performs threshold cuts on the image amplitude, the number of pixels and the local distance between the COG of the shower and the camera center. The former two impact mainly the amount of low intensity events that are kept, while the latter aims to avoid the truncation of the shower image at the edge of the camera FOV, which is more dominant for high intensity showers. The used preselection cuts are listed in Table 9.1.

The consequent classification of the events in a γ -ray or a hadron is done by a trained BDT, a machine learning algorithm that classifies events of unknown type according to a set of input parameters that characterize the events. The training of the BDT is performed with events of known type, using MC simulations² for γ -rays and off runs for hadronic background as training sets, and its output is a classifier value ζ that gives a probability for the event being γ -ray-like or hadron-like (Ohm et al. 2009). This classifier output ζ is often scaled to a value ζ_{BDT} that

²The BDT of the modified MonoReco algorithm is trained on MC simulations assuming a point source of γ -rays with a spectral index Γ of -2 (Bedur Ramesh 2024).

Table 9.1. The selection cuts of the ultraloose analysis configuration. The γ -ray selection cuts are optimized for a source with spectral index $\Gamma = -4$. Adapted from Bedur Ramesh (2024).

Parameter	Value	Step
Tailcut Cleaning	HillasTimingN5	-
Image Amplitude	> 60 p.e.	Preselect
Local Distance	$< 0.8^\circ$	Preselect
No. Pixels	> 6	Preselect
ζ_{BDT}	0.78	Postselect
Θ_0^2	$< 0.05 \text{ deg}^2$	Postselect

corresponds to the signal efficiency, i.e. the fraction of signal events that are kept by selecting a cut on the respective ζ value. For the training of the BDT of the modified MonoReco algorithm, the input parameters of the MonoReco algorithm summarized in Table 9.2, and an additional set of parameters introduced by Bedur Ramesh (2024), summarized in Table 9.3, are used. One of the objectives of the new parameters is to more efficiently remove background induced by muons, which have an arc-like shape, closely resemble the shape γ -ray showers at low intensities and constitute one of the main contributions to the background of a monoscopic observation. To accomplish this, the Hillas ellipse is separated in three sectors and for each sector geometrical parameters, such as the COGs $x_0 - x_2$, are derived and combined with the temporal evolution of the shower and the charge information $q_0 - q_2$ in each sector (Bedur Ramesh 2024). This is shown in Figure 9.3.

Table 9.2. The training parameters used for the MonoReco reconstruction algorithm. The image amplitude A of the Hillas ellipse serves as input for the calculation of the density D and the length over size LoS . The kurtosis and the skewness are the third- and fourth-order moments of the light distribution enclosed in the Hillas ellipse. Information taken from Murach (2017).

Parameter	Definition
Width W	Hillas Width
Length L	Hillas Length
Density D	$\log(A/(L * W))$
Length over Size (LoS)	$L/\log(A)$
Kurtosis	Third-order moment
Skewness	Fourth-order moment

The γ -ray selection cuts on the ζ_{BDT} value and the reconstructed direction of the shower θ are optimized by maximizing the significance of the γ -ray signal. Different selection cut configurations optimized for different source spectra are derived. For the pulsar analysis, the aim is to keep many low intensity events at the expense of a higher amount of background events. This is acceptable as the signal and background events are derived using the phasing information of the events, as described in Section 9.3. Therefore, the ultraloose γ -ray selection cut configuration used for the pulsar analysis is optimized for a steep spectrum with a spectral index Γ of $\Gamma = -4$ (Bedur Ramesh 2024). The resulting γ -ray selection cuts are listed in Table 9.1. Here, θ_0^2 is the squared angular distance around the source position within which events are accepted.

Table 9.3. The new training parameters of the modified MonoReco algorithm. In addition to the parameters listed in Table 9.2, the parameters $\text{BDT}_{\text{Event}}$, NN_d and NN_{flip} serve as input to the training of the BDT for the event selection, the neural network for the displacement determination and the neural network for the flip factor determination, respectively. The definition of the parameters is shown in Figure 9.3. Information taken from Deka Baruah (2024) and Bedur Ramesh (2024).

Parameter	Definition	$\text{BDT}_{\text{Event}}$	NN_d	NN_{flip}
Time Gradient	$(t_2 - t_0)/(x_2 - x_0)$	yes	yes	yes
Charge Asymmetry	$(q_2 - q_0)/(q_0 + q_1 + q_2)$	yes	yes	yes
Length	$x_0 - x_2$	yes	no	yes
Width w_0	Width of sector 0	yes	no	yes
Width w_2	Width of sector 2	yes	no	yes
Radius	R_C^1 of x_0 , x_1 and x_2	yes	no	no
Local Distance	Camera center $\leftrightarrow$ image COG	no	no	yes
No. Pixels	No. pixels in image	no	no	yes

¹ Radius of curvature

However, not all background events are rejected. The estimation of the remaining background and the extraction of the signal are described in Section 9.2. The energy and direction reconstruction are described in the following.

9.1.2. Energy and Direction Reconstruction

Neural networks are used to reconstruct the energy and the direction of the primary particle from a set of given input parameters characterizing the event. Like BDTs, they are trained using MC simulations as γ -ray events and off runs as background events. Neural networks operate in two modes. In the regression mode, a numerical output value is derived, while in the classification mode a binary output value is delivered. The neural network for the energy reconstruction works in regression mode, and is described in Deka Baruah (2024). The direction reconstruction is explained in the following according to Murach (2017) and Deka Baruah (2024) with the latter reference outlining the changes of the modified MonoReco algorithm with respect to the original algorithm.

From geometrical considerations, the direction of the primary particle is located along the major axis of the Hillas ellipse. It can be derived from three properties of the camera image. Two of these properties, the orientation of the image in the camera and the COG of the image, can be measured. The third property, the displacement d between the reconstructed position of the primary particle and the COG of the image, can not be measured and is determined with a neural network taking the parameters listed in Table 9.2, as well as the time gradient and the charge asymmetry from Table 9.3 into account. The returned value for d is a positive value. Therefore, the position of the primary particle can be located on either side of the COG of the image. Especially for low energy events resulting in low intensity camera images with the signal contained in only a few pixels, resolving this degeneracy is a difficult task.

The original MonoReco algorithm used the skewness of the enclosed light distribution in the image to resolve this degeneracy. For the modified MonoReco algorithm, a second neural network is trained to determine a so-called flip factor of -1 or 1 depend-

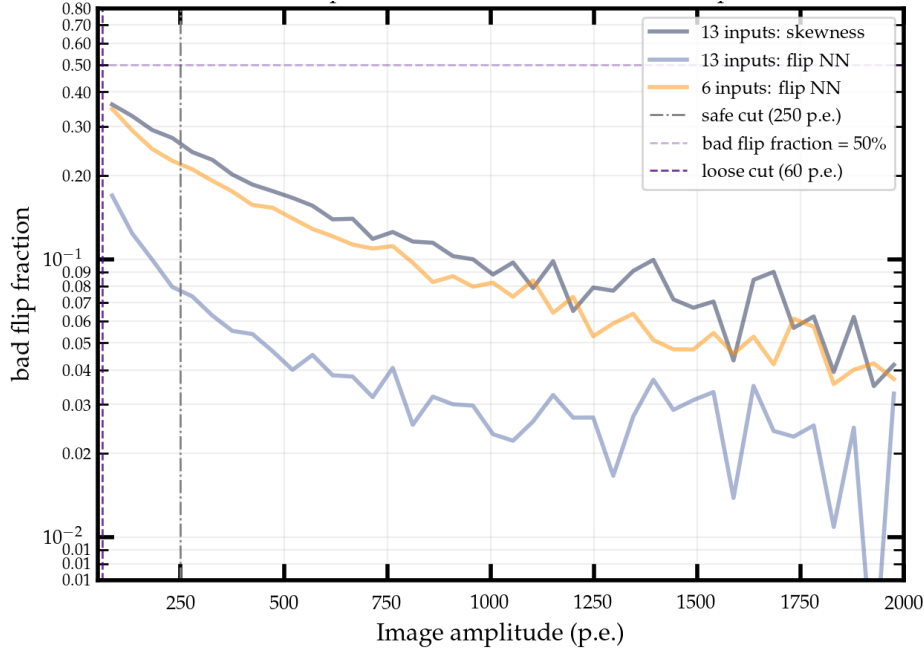


Figure 9.4. The bad flip fraction as a function of the image amplitude. The bad flip fraction is calculated for MC simulations of a γ -ray point source. Three cases are shown. The bad flip fraction for the direction reconstruction with a) the additional training parameters and the skewness to determine the flip (gray), b) the additional training parameters using the neural network to determine the flip (light blue), and c) the original parameters and the neural network to determine the flip (yellow). Of the three displayed cases, the modified MonoReco algorithm performs the best with respect to the bad flip fraction. Taken from Deka Baruah (2024).

ing on which side of the major axis the direction of the primary particle is located. This flip factor can be determined from simulations where the true direction of the primary particle is known. The input parameters for the flip factor neural network are the parameters of the original MonoReco algorithm and respective parameters listed in Table 9.3.

To evaluate the performance of the direction reconstruction of the modified to the original MonoReco algorithm, the bad flip fraction BFF can be calculated according to

$$BFF = \frac{N_{wf}}{N_{tot}}, \quad (9.1)$$

with the number of wrongly flipped N_{wf} and the total number N_{tot} of events. This is shown in Figure 9.4 for MC simulations of a γ -ray point source. A clear improvement of the direction reconstruction with the flip neural network in comparison to the skewness based direction reconstruction is visible (Deka Baruah 2024).

Some known limitations of the event selection and the event reconstruction of the used ultraloose analysis configuration is described in the following.

9.1.3. Known Limitations and Possible Improvements

The modified MonoReco algorithm in its present state has two issues that were not yet fully resolved at the time of this thesis. Both of these issues are caused by the way

the MC simulations are performed. For the MC simulations simulating a γ -ray point source, the point source is, depending on the simulated offset angle, offset along the x-direction of the camera and located at $y = 0$, as shown schematically in Figure 9.5 (Lang et al. 2024). This has consequences with respect to the event selection and the direction reconstruction using a neural network, which are discussed in the following.

As already mentioned, γ -ray point source MC simulations are used as the signal events and off runs as background events for the training of the BDT for the event selection and background rejection. Therefore, γ -ray shower images have a tendency to be located in camera quadrants 1 and 4, whereas background events are isotropically distributed over the camera quadrants. An indirect dependency on the direction of the simulated shower is introduced for the BDT training by flipping the widths w_0 and w_2 of the head and tail of the shower, as well as the charge asymmetry and the time gradient with respect to the camera center using the skewness of the image. This indirect dependency introduces a dependency of the classifier output ζ on the different camera quadrants resulting in a varying probability of selecting an event as γ -ray-like or hadron-like, as shown in Figure 9.6a for MC simulations of diffuse γ -rays (Bedur Ramesh 2024). The impact of this dependency on the higher level analysis products such as the derived flux is assumed by Bedur Ramesh (2024) to be within the 20 % systematic uncertainties of the flux reconstruction of H.E.S.S. (Aharonian et al. 2006).

For the direction reconstruction, the source is reconstructed by default to the right side of the Hillas ellipse during the training, restricting the direction to an interval between $-\pi/2$ and $\pi/2$. This leads to an asymmetry between the number of events that need a flip and the ones that do not. This asymmetry is not present during real observations where the source is observed with varying offset angles in declination and right ascension with respect to the (expected) source position. This results in a systematic dependency of the bad flip fraction on the camera quadrant and a consequent deterioration of the performance of the direction reconstruction when applied to real observational data with respect to γ -ray point source MC simulations. To demonstrate this, the direction reconstruction is applied to MC simulations of diffuse γ -rays, as shown in Figure 9.6b. Even given the lack of statistics for the diffuse γ -ray simulations, a clear worsening of the performance of the direction reconstruction between diffuse and point source γ -ray simulations is visible (Deka Baruah 2024; Lang et al. 2024). On the higher analysis levels, the increase in bad flip fraction leads to a worsening of the angular resolution of the instrument.

The training of the BDT and the neural network is not performed with MC simulations of diffuse γ -rays, as these simulations are computationally more intensive. However, there is currently work ongoing within HAP to resolve this issue by translating and rotating half of the events of a set of training events in the camera image before they are fed into the training of the event selection and the event reconstruction (Lang et al. 2024). The general on-going improvements of the monoscopic analysis is subject to a paper, which is currently in preparation by Unbehaun, Tim et al. (2025).

To improve the analysis configuration with the objective to explore the full potential of the data acquired with the reduced trigger threshold, the training of the BDT and the neural networks of the event reconstruction should be performed using the MC simulations adapted to the reduced trigger threshold³. In addition, the low energy

³At the moment, no off runs exist for the reduced trigger threshold setting. However, as training samples for the background the events from the pulsars off-phase could be taken. The timing

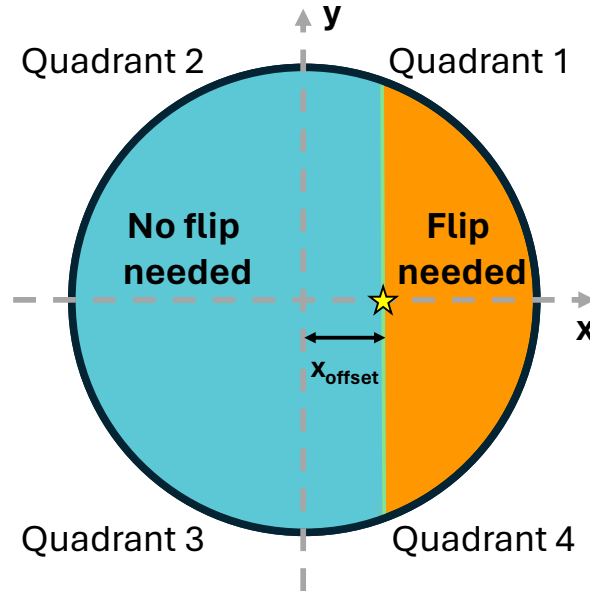


Figure 9.5. Schematic diagram of the location of a simulated γ -ray point source in the camera FOV. The point source is offset along the x-axis by x_{offset} for a given offset angle. Based on Lang et al. (2024).

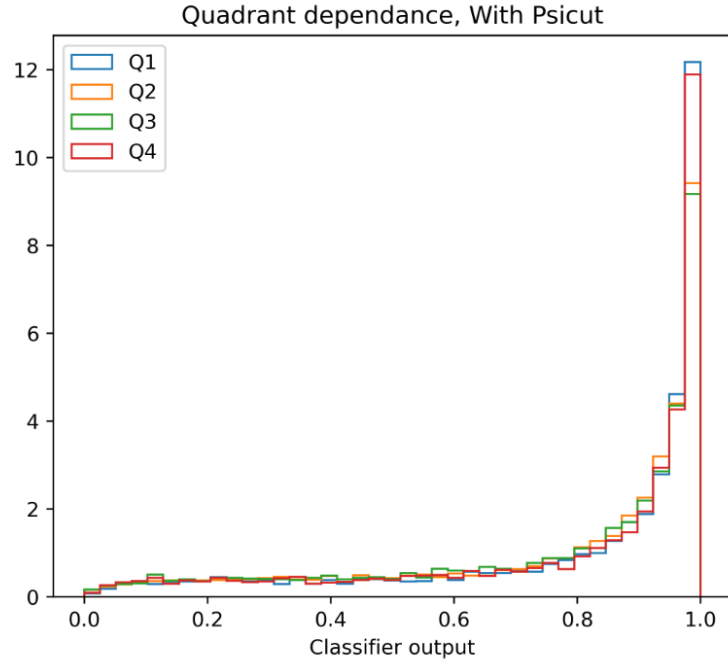
performance could be explored by further reducing the image amplitude cut and the number of pixels cut of the ultraloose analysis configuration. For a pulsar analysis where the lowest energies of CT5 are of prime interest and where the instrument systematic in the determination of the remaining background are less of a concern due to the pulsed nature of the γ -ray signal, this might be a feasible approach. These optimizations are not performed within the scope of this thesis. Despite the limitations of the used analysis configuration, however, the goal of this part of the thesis was to perform a first analysis of the data acquired with the reduced trigger setting, while keeping in mind that the lack of optimization leads to no, or only a limited, improvement of the spectral information towards lower energies compared to the nominal trigger setting. The signal extraction and background estimation is described in the following.

9.2. Signal Extraction and Background Estimation

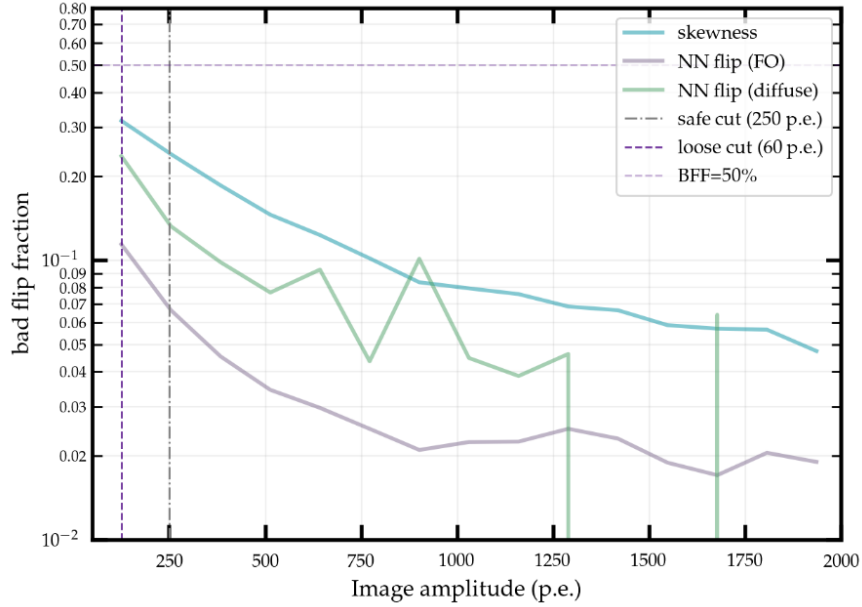
Even after the event selection and background rejection, there are γ -ray-like background events left. These background events originate from diffuse γ -rays, falsely classified hadrons, as well as electromagnetic showers induced by cosmic-ray electrons. A proper estimation of this background is relevant to accurately determine the excess of the γ -ray like signal events with respect to the γ -ray-like background events and to determine the statistical significance of the γ -ray signal of a potential source.

There are various methods to determine the background for a given observation, which can be differentiated in two basic approaches. In the first approach, the background is estimated from separate observations of a sky region with no known γ -ray signal for similar instrument and observation conditions as the observation with the predicted γ -ray source. For the second approach, the background is estimated

analysis of pulsars is explained in Section 9.3.



(a) Dependency of the classifier output ζ for the event selection on the camera quadrant.



(b) The bad flip fraction for γ -ray point source (gray) and diffuse γ -ray (green) MC simulations.

Figure 9.6. The dependency for the event selection and direction reconstruction on the camera quadrant. The performance is shown for MC simulations of diffuse γ -rays. Top: The classifier output ζ is depending on the camera quadrant when classifying events in background (0) and γ -ray (1). Bottom: The bad flip fraction determined for MC simulations of a γ -ray point source (gray) and diffuse γ -rays (green). The strong fluctuations and large gap between image amplitudes of ~ 1300 p.e. – 1700 p.e. is related to less statistics of the diffuse γ -ray simulations in comparison to point source simulations. Images taken from Bedur Ramesh (2024) and Deka Baruah (2024), respectively.

either from different sky regions in the same camera FOV or, in the case of the timing analysis of pulsars, from the same sky region, but from a different phase range in the rotational phase space of the pulsar, as described in Section 9.3. The first approach is used for sources that are extended and have structures in the order of the instrument FOV, while the latter approach is used for point or moderately extended sources. In both cases, a correct understanding of the instrument, or system, acceptance of γ -ray-like background events is important to properly estimate the background. It describes the probability of detecting a γ -ray-like background event after the application of all selection cuts along the data taking and processing chain from the telescope-level (e.g., trigger threshold) to the analysis level (e.g., γ -ray selection cuts) (Berge et al. 2007). The system acceptance and the signal extraction are briefly described according to Berge et al. (2007). In the end, the specifics of the signal extraction and background determination for a pulsar analysis are described.

The system acceptance changes with the reconstructed offset of the event in the camera FOV, the observation conditions (e.g., zenith angle, sky direction), and the reconstructed energy of the event. In addition, it depends on the observation time as the system response changes with time through, e.g., degradation of the mirror reflectivity. The reconstructed offset and the zenith angle of the observation result in two spatial gradients in the camera FOV. The former, leads to a radial component, which is caused by the limited size of the camera FOV. The limited FOV of the camera leads to a) a lack of high-quality images of the Cherenkov light distribution towards the edge of the FOV that can be properly reconstructed (further influenced by, e.g., vignetting due to the worsening of the telescope's optical PSF), and b) the preselection cut on the local distance to reject images that are truncated at the edge of the camera FOV. The latter introduces a linear gradient along the camera FOV due to the increasing system energy threshold with zenith angle caused by the absorption of lower energy showers in the atmosphere.

The understanding of the system acceptance is important as it influences the determination of the γ -ray excess N_{excess} , which is calculated with

$$N_{\text{excess}} = N_{\text{on}} - \alpha N_{\text{off}} \quad , \quad (9.2)$$

where N_{on} is the number of events in a test region and N_{off} the number of events in one, or multiple, background control regions. The normalization factor α is expressed as

$$\alpha = \frac{\int_{\text{on}} A_{\text{on}}^{\gamma}(\theta_x, \theta_y, \phi_z, t) d\theta_x d\theta_y d\phi_z dt}{\int_{\text{off}} A_{\text{off}}^{\gamma}(\theta_x, \theta_y, \phi_z, t) d\theta_x d\theta_y d\phi_z dt} \quad (9.3)$$

with the system acceptances $A_{\text{on,off}}^{\gamma}$ for the offset position (θ_x, θ_y) in the camera FOV, the zenith angle ϕ_z of the observation, and the exposure time t .

The selection of a proper background model to correctly estimate α and N_{off} in Equation 9.2 depends on the objective of the analysis such as the generation of a sky map or the determination of a spectrum. The advantages and disadvantages of different background models for various purposes are discussed by Berge et al. (2007).

The statistical significance S of the γ -ray signal is calculated with the likelihood

ratio method by Li et al. (1983) according to

$$S = \sqrt{-2 \ln \lambda}$$

$$= \sqrt{2 \left(N_{\text{on}} \ln \left(\frac{1 + \alpha}{\alpha} \left(\frac{N_{\text{on}}}{N_{\text{on}} + N_{\text{off}}} \right) \right) + N_{\text{off}} \ln \left((1 + \alpha) \left(\frac{N_{\text{off}}}{N_{\text{on}} + N_{\text{off}}} \right) \right) \right)} \quad (9.4)$$

with the normalization factor α , the number of events N_{on} in a test region and the number of events N_{off} in a background control region. λ is the maximum likelihood ratio of the likelihood functions estimating N_{on} and N_{off} . The analysis results in Chapter 10 are calculated with Gammapy using the Poisson likelihood function WStat, as recommended by Donath et al. (2023) for the case that the number of background events is unknown and are from a measurement where only background events are expected⁴.

For pulsars, N_{on} and N_{off} can be derived from the phase range of the rotational phase of the pulsar, as described in Section 9.3. This simplifies Equation 9.3 to

$$\alpha = \frac{\psi_{\text{on}}}{\psi_{\text{off}}} \quad (9.5)$$

where ψ_{on} and ψ_{off} are the phase range of the On- and Off-phase, respectively. This removes any dependency on the system acceptance and eliminates any uncertainties associated with the relation between A_{on}^{γ} and A_{off}^{γ} , as the test and the background control regions are from the same reconstructed geometrical area in the camera FOV.

9.3. Pulsar Timing Analysis

The electromagnetic radiation of a pulsar is observed during the short time interval the pulsars emission region is aligned with the observer. For the timing analysis, the arrival times of the primary γ -rays at the observer are of importance. For H.E.S.S., the recorded events are time-tagged with an accuracy of $< 2 \mu\text{s}$, as described in Section 3.1.3. The timing accuracy is sufficient to perform timing analysis of pulsars with common periods of $\sim 1 \text{ ms} - 1000 \text{ ms}$.

The orientation of the pulsars emission region in a comoving reference frame is described by the rotational phase. To calculate the rotational phase, the measured arrival times of the γ -ray in the observers reference frame t_{obs} need to be transferred in the reference frame of the pulsar according to

$$t_{\text{em}} = t_{\text{obs}} - \Delta \quad (9.6)$$

with the time of emission in the pulsars reference frame t_{em} and the time delay Δ , which characterizes the total propagation time of the γ -ray from the pulsar to the observer (Luo et al. 2021). The time delay Δ is subject to a wide variety of physical processes, which impact the propagation of the γ -ray from the pulsar to the observer and are described in more detail by, e.g., Lorimer et al. (2004). An overview of the order of magnitudes of different contributions to the time delay is given in Table 2 of Hobbs et al. (2006).

⁴Some further information are available under Gammapy (2024).

The rotational phase of the pulsar $\phi(t)$ can then be calculated with a Taylor expansion according to

$$\phi(t) = \phi_0 + \nu_0(t - t_0) + \frac{1}{2}\dot{\nu}_0(t - t_0)^2 + \frac{1}{6}\ddot{\nu}_0(t - t_0)^3 + \dots \quad (9.7)$$

with the phase ϕ_0 at a reference time t_0 , ν_0 the pulse frequency, $\dot{\nu}_0$ and $\ddot{\nu}_0$ the first and second time derivative of the pulse frequency, respectively (e.g., Lorimer et al. 2004). It is often given as the fractional rotational phase and scaled between $[0,1)$ resembling a full rotation of the pulsar. A stacking of events according to their fractional rotational phase results in a phasogram. The signal and background events can be estimated from the fractional phase range during which the pulsar is aligned with and not aligned with the observer, respectively.

The information about the time delay Δ in Equation 9.6 and the rotation behavior of the pulsar in Equation 9.7 are summarized in a timing solution or ephemeris. These timing solutions have a given temporal validity due to uncertainties in, e.g., the description of the rotation behavior of the pulsar. For the pulsar analysis described in Chapter 10, the phase of each event is calculated from the timestamps issued by the central trigger using the Python package PINT and timing solutions derived from data acquired with the Large Area Telescope (LAT) instrument of the Fermi Gamma-Ray Space Telescope for the Vela pulsar or the Parkes radio telescope for the pulsar B1706-44. PINT is described by Luo et al. (2021), and the general approach of deriving timing solutions using the LAT instrument by Ray et al. (2011) and Kerr et al. (2015), and with the Parkes radio telescope by, e.g., Weltevrede et al. (2010). Both ephemerides were provided by M. Kerr and D. A. Smith of the Fermi-LAT Collaboration. Some general considerations on the timing analysis with IACTs and, specifically with H.E.S.S., are given by Gajdus (2016).

9.4. Instrument Response Functions

Instrument Response Functions (IRFs) are the second part of the DL3 data products and are crucial to derive physical quantities from the instrument reconstructed properties. As described by, e.g., Donath et al. (2023), the instrument response $R(p, E|p_{\text{true}}, E_{\text{true}})$ to a γ -ray with true energy E_{true} and true direction p_{true} can be expressed by

$$R(p, E|p_{\text{true}}, E_{\text{true}}) = A_{\text{eff}}(p_{\text{true}}, E_{\text{true}}) \cdot PSF(p|p_{\text{true}}, E_{\text{true}}) \cdot E_{\text{disp}}(E|p_{\text{true}}, E_{\text{true}}) \quad (9.8)$$

with the effective area $A_{\text{eff}}(p_{\text{true}}, E_{\text{true}})$, the Point Spread Function $PSF(p|p_{\text{true}}, E_{\text{true}})$ and the energy dispersion $E_{\text{disp}}(E|p_{\text{true}}, E_{\text{true}})$ as the three individual IRFs. The response of the instrument results in a γ -ray with reconstructed energy E and reconstructed direction p . Each of the three individual IRFs describe a different aspect of the instrument response, and are briefly described in the following.

The effective area $A_{\text{eff}}(p_{\text{true}}, E_{\text{true}})$ is the convolution of the collection area of the instrument and the γ -ray detection efficiency. Therefore, it serves as input to calculate the actual γ -ray flux of a source from the instrument recorded γ -ray flux. The angular resolution of the instrument is described by the $PSF(p|p_{\text{true}}, E_{\text{true}})$, and is the probability distribution to reconstruct a γ -ray with true energy E_{true} and true direction p_{true} at the position p . The PSF is often expressed by the radius

in which 68 % of the events are contained. For low and high energy events, the angular resolution worsens due to limited information to reconstruct the direction and truncation of the shower at the edge of the camera FOV, respectively. The energy dispersion E_{disp} describes the energy resolution of the instrument and correlates the reconstructed particle energy E with the true energy E_{true} and direction p_{true} . For some types of analyses, the background rate as function of the reconstructed energy and direction is needed as fourth IRF. It is determined from observations with no known γ -ray source (Donath et al. 2023). For the pulsar analysis, the background is determined from the rotational phase, as described in Section 9.3.

In the case of IACTs, the various IRFs are parameterized as function of the instrument pointing direction (azimuth and elevation angle), and the reconstructed position of the γ -ray with respect to the camera center (offset). A more general description of IRFs for γ -ray missions is given in Charles et al. (2024).

The instrument energy threshold is a further performance metric, which is a convolution of the hardware trigger threshold and selection cuts applied in the analysis. For a spectral analysis, a safe energy threshold is usually determined as either the energy range where the bias of the energy reconstruction is below 10 %, or the energy range where the effective area is at least 10 % of the maximum effective area. The energy bias is defined as

$$\Delta E = \frac{E_{\text{reco}} - E_{\text{true}}}{E_{\text{true}}} \quad (9.9)$$

with the true energy E_{true} and the reconstructed energy E_{reco} of the γ -ray. Another approach is to determine the energy threshold as the maximum of the γ -ray detection rate by folding the effective area with the expected source flux, as described by Konopelko (1999). In addition, the instrument energy threshold can be quantified with the γ -ray excess distribution as a function of reconstructed energy E_{reco} (see Figure 10.5).

The IRFs in Equation 9.8 are determined with detailed MC simulations that describe the shower propagation in the atmosphere and the corresponding response of the instrument. MC simulations and the adaptation to the reduced trigger threshold and the environmental conditions of the pulsar observations are described in Section 9.4.1. A comparison of the energy bias and the effective area for the reduced and the standard trigger threshold is explained in Section 9.4.2.

9.4.1. Monte Carlo Simulations

The HAP analysis framework in H.E.S.S. uses a combination of the CORSIKA and the `sim_telarray` toolkit to simulate the propagation of the Cherenkov air shower and the response of the instrument, respectively (Heck et al. 1998; Bernlöhner 2008). To properly derive the physical quantities of the reconstructed γ -ray events for the high-level analysis products, MC simulations that accurately represent the hardware configuration of the instrument and the environmental conditions during an observation are necessary. The former is usually stable for an extended period of time and allows to simulate the instrument response for a given hardware phase during which the hardware configuration of the instrument stays unchanged. The latter such as the atmospheric transparency vary seasonally or even within a given night (e.g. Charles et al. 2024; Pühlhofer et al. 2024). Understanding the optical

efficiency of the telescope and the atmospheric conditions is important for, e.g., properly reconstructing the energy of the primary particle, which is explained in more detail in the following.

The Cherenkov light yield of an EAS is proportional to the energy of the primary particle (see Equation 2.20). Therefore, to properly correlate the primary energy reconstructed from the amount of detected Cherenkov photons to the true energy of the primary particle, the optical efficiency of the telescope, as well as the transparency of the atmosphere need to be monitored and correlated to the simulations for a given telescope optical efficiency and atmospheric transparency. The optical efficiency of the telescope describes the number of Cherenkov photons that are detected by the telescope to the total number of incoming Cherenkov photons and is a convolution of the mirror reflectivity and the quantum efficiency of the camera pixels. For FlashCam, this includes the transparency of the window and the Winston cones in front of the PMTs.

The optical efficiency of the telescope can be monitored and calibrated using muons, as described, e.g., by Mitchell (2016) within the context of H.E.S.S. or Gaug et al. (2019) within a more general context. Muons are suitable candidates for the optical efficiency calibration due to two main reasons. First, their characteristic ring-shape allows an easy identification within the camera image of a single IACT. Second, their intensity can be calculated analytically and compared to the measured image intensity. To correlate the measured optical efficiency to the simulated optical efficiency, the measured muon efficiency is compared to the muon efficiency derived from simulations for a given telescope optical efficiency.

The atmospheric transparency to Cherenkov photons is affected, among other factors, by clouds and the aerosol content in the atmosphere. The presence of clouds can be monitored, e.g., using radiometers that measure the water vapour content in the atmosphere⁵. The atmospheric transparency for a given observation can be assessed using the Cherenkov Transparency Coefficient (CTC) derived from the telescope trigger rates (Hahn et al. 2014) or the measurement of the Aerosol Optical Depth (AOD) (Holch et al. 2022).

There are two principle approaches to account for changing hardware and atmospheric conditions in simulations according to Charles et al. (2024). First, to perform simulations that represent the conditions on an observation basis, as described by Holler et al. (2020). The second approach uses the fact that the hardware configuration and therefore the instrument response is usually stable over longer timescales. In this case, simulations are performed assuming a given nominal atmospheric transparency for a given hardware phase, which is characterized, among other factors, by a given telescope optical efficiency.

The latter approach is used within HAP. The standard simulations comprise four sets of MC simulations that assume two different telescope optical efficiencies and two different atmospheric corrections, which are summarized in Table 9.4. The derived IRFs from these sets of MC simulations are then corrected in a two-stage process. At the first stage, the IRFs are corrected for the telescope optical efficiency using the long-term trends of the muon efficiency for a defined hardware phase. At the second stage, an atmospheric correction factor is applied that is derived using the coincident

⁵The information from the radiometers of CT1-4 is used to perform an empirical data quality selection as described in Section 10.2.

Table 9.4. Parameters for the telescope optical efficiency and atmospheric transparency for the standard MC simulations in HAP. The optical efficiency is listed for CT5 and the atmospheric transparency is labeled according to the transmission profiles derived by T. Holch (Deutsches Elektronen-Synchrotron (DESY)) using the Py6S framework. Information taken from Bernlöhner et al. (2024).

Identifier	Optical Efficiency (CT5)	Atmospheric Transparency
2000	0.76	Mixed
2001	0.69	Mixed
2002	0.76	Bad
2003	0.69	Bad

trigger rates of CT1-4 on an observational basis⁶.

The validation of the MC simulations for the HAP framework is described by Leuschner et al. (2023). The MC simulations were validated for the hardware phase since the installation of FlashCam into CT5 and the validation efforts followed a bottom-up approach starting from single telescope-specific quantities (e.g., optical PSF, pedestal width for the NSB determination) up to DL3 quantities of the reconstructed shower properties (e.g., Hillas parameters). The validation of the MC simulations is discussed extensively in Steinmassl (2023), Schäfer (2023), and Leuschner (2025). The MC simulations used to derive the IRFs for the pulsar analysis are based on these fully validated MC simulations with adaptations to the reduced trigger threshold setting of FlashCam. In addition, the NSB level and the atmospheric transparency are modified to represent the ones of the observation. This is described in the following.

Hardware Trigger Threshold

The reduced trigger setting is lowered by 15 % with respect to the nominal trigger setting. The latter was validated between MC simulations and observational data by Steinmassl (2023) and a similar approach is described here for the reduced trigger setting, after a brief explanation of the trigger working principle of FlashCam.

The camera trigger consists of 588 non-overlapping trigger patches with each combining the signal of three pixels. The trigger sum is continuously calculated and evaluated combining the information from three overlapping three pixel patches, i.e. a three pixel patch contributes to various trigger patches (Bi et al. 2021; Sailer 2020). For the MC simulations, the trigger setting in the camera configuration is defined in hardware units of TLSB⁷, which corresponds to the setting of the camera-internal FPGA that derives the trigger decision from the sum over the three pixel patches. The nominal and reduced trigger setting in physical and hardware units are summarized in Table 9.5.

To quantify the trigger decision, the brightest 9-pixel-sum for a given event is characteristic (Steinmassl 2023). Proton simulations are used to quantify the simulated trigger setting of the camera. In principle, to quantify the trigger setting from observations, off-runs with no known γ -ray source should be used. However, as no

⁶For CT5 observations that are taken in a sub-array configuration, i.e. with CT1-4 and CT5 observing different astronomical sources, no atmospheric correction is currently applied.

⁷The unit of TLSB describes the trigger amplitude in hardware units of Least Significant Bit (LSB) (Sailer 2020).

Table 9.5. Nominal and reduced trigger settings for FlashCam in physical and hardware units. The hardware units are defined according to the `sim_telarray` configuration file used as input to the MC simulations and slightly deviate from the hardware settings applied in the field ($\lesssim 5\%$).

	Physical Units (p.e./9-pixel-sum)	Hardware Units (TLSE/9-pixel-sum)
Nominal	69	76
Reduced	59	65

off-runs with the reduced trigger setting are taken at this point in time, observations of the Vela pulsar and B1706-44 are used as comparison. The events are selected at the DL1 stage without any applied event selection and therefore, even with the pulsar in the FOV, these events are still dominated by hadronic showers. Therefore, this approach is fully valid to validate the observations against the MC simulations. A histogram of the brightest 9-pixel sum for the proton simulations and three observations of the Vela pulsar and B1706-44 are shown in Figure 9.7. The trigger threshold is then defined as 50 % of the maximum of the intensity distribution. It is derived for observation runs on the Vela pulsar and B1706-44 fulfilling the “detection” data quality selection criteria, which is introduced in Section 10.2. The distribution of the resulting trigger threshold and the comparison to the MC simulations is shown in Figure 9.8. The resulting mean and the standard deviation for the Vela pulsar and B1706-44 runs in comparison to the MC simulations is listed in Table 9.6. The calculated trigger settings agree within errors with the trigger setting from the MC simulations. The determination of the NSB level is described in the following.

Table 9.6. Trigger threshold determined from observation runs and MC simulations. The observation runs pass the “detection” data quality selection criteria introduced in Section 10.2.

Source	Trigger Setting (p.e.)
Vela Pulsar	59.6 ± 0.4
B1706-44	59.2 ± 0.6
MC Simulations	59.5

Night Sky Background

NSB describes the ever present illumination at night that has either a terrestrial or an astronomical origin. The terrestrial contributions to the NSB include, e.g., the light caused by cities, planes or satellites, while the astronomical contributions include starlight, night airglow or moderate moonlight, if the observations are performed during moonlight conditions. Under dark time conditions, night airglow is identified as main contributor to the NSB by Preuß et al. (2002), which is caused by photo-chemical processes in the atmosphere.

NSB photon rates are in the same order of magnitude or even higher than the rate of incoming Cherenkov photons generated by an electromagnetic shower with the former reaching intensities of $10^3 \text{ photons m}^{-2} \text{ ns}^{-1} \text{ sr}^{-1}$ and the latter resulting in a yield of $\sim 100 \text{ photons m}^{-2} \text{ TeV}^{-1}$ arriving within $\sim \text{ns}$ at the camera pixels (Preuß

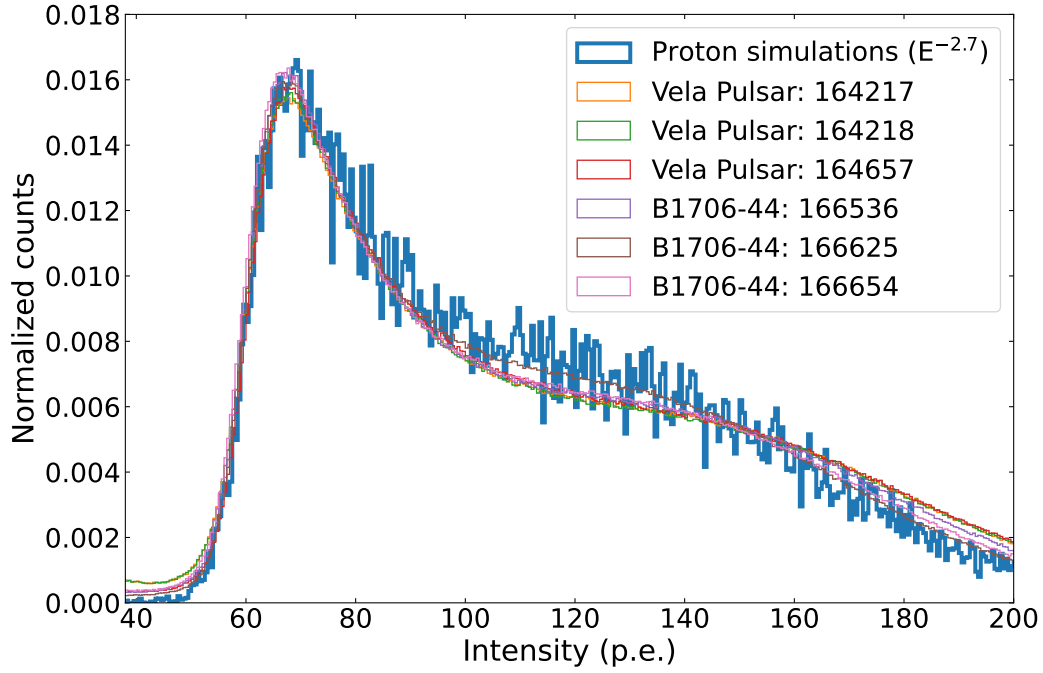


Figure 9.7. Normalized intensity distribution of the brightest 9-pixel-sum for FlashCam with the reduced trigger setting. The results are shown for proton simulations weighted to $E^{-2.7}$ and a total of six observation runs, three each on the Vela pulsar and B1706-44.

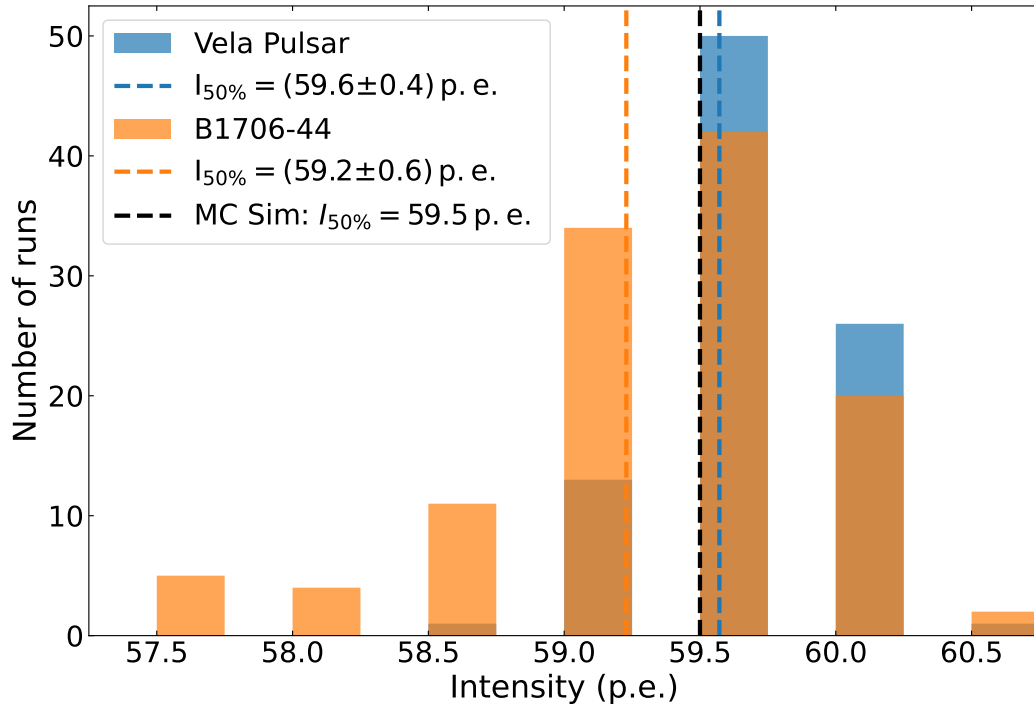


Figure 9.8. Hardware trigger threshold derived from observation runs and compared to the MC simulations for the reduced trigger setting. The trigger threshold is defined as 50 % of the maximum in the intensity distribution of the brightest 9-pixel-sum.

et al. 2002). The Cherenkov photons of a shower are differentiated from the NSB photons by taking the temporal correlation of the Cherenkov signal distributed over several camera pixels into account. NSB is an ever-present photon background for an IACT and impacts the trigger behavior of the camera as well as the quality of the taken observational data.

The trigger behavior is impacted through the reduction of the effective trigger threshold of the camera by NSB as the NSB photons contribute to the integration window over which the trigger decision is calculated. Therefore, the number of Cherenkov photons that are necessary to trigger the camera are reduced. Consequently, the camera trigger rate is higher under NSB conditions (Leuschner 2025). For the FlashCam installed in CT5, pixels with trigger rates above a certain rate limit are excluded from the trigger decision to improve the operational stability (NSB limit, see Table 3.5).

In addition, the NSB impacts the quality of the observational data by increasing the pedestal width. The pedestal position is the mean ADC value per pixel used to convert the signal in each pixel from digital units of ADC to the physical units of p.e. In the absence of NSB, the pedestal is a narrow Gaussian distribution influenced by the electronics noise of the readout electronics. The presence of NSB leads to a widening of the Gaussian distribution. Therefore, the pedestal width serves as an indicator of the NSB in the pixel FOV⁸. During regular observations, the pedestal is continuously determined from the camera pixels that do not contain a signal from the Cherenkov light of the EAS. As part of the calibration step from DL0 to DL1 and before converting the measured signal from ADC to p.e., the mean pedestal is subtracted from the measured Cherenkov signal (Aharonian et al. 2004)⁹. The finite width of the pedestal introduces an uncorrectable error in this subtraction, which plays a larger role for events that are closer to the trigger threshold. While these events are usually rejected in the high-level analysis due to the sufficiently large preselection cuts on the image amplitude and the number of pixels, for an analysis focused on events that are closer to the trigger threshold of the telescope the impact of this error could impact the high-level analysis (Leuschner 2025). Therefore, a correct simulation of the NSB present during the observation is important to derive the IRFs for the high-level analysis. The validation of the NSB between MC simulations and observational data is described by Leuschner (2025). The adaptation of the NSB settings resembling the Vela and the B1706-44 sky field is described in the following.

The pedestal width is simulated for NSB levels ranging from 0.2 GHz – 2.5 GHz using `sim_telarray`. The NSB levels that are provided to `sim_telarray` are multiplied with the degraded optical reflectivity of the telescope, which was assumed to be 0.79 for CT5. A good match between MC simulations and the pedestal width derived for the Vela and the B1706-44 observations taken in 2021 is found for a simulated NSB level of 500 MHz. The comparison of the pedestal width mean per pixel is shown in Figure 9.9. The differences between the observation runs and the MC simulations are within $\sim 1\%$. This NSB level resulted in an average NSB rate per

⁸A constant baseline current is set to the DC-coupled PDPs of FlashCam. Therefore, the NSB can be estimated from a shift of this baseline current (Leuschner 2025). However, as described by Leuschner (2025), the estimation of the NSB from the pedestal width is in better agreement with the MC simulations than the estimation of the NSB from the baseline shift.

⁹The given reference describes the calibration of the previous CT1-4 cameras. However, the general considerations with respect to the calibration are still relevant for the HESS1U cameras and FlashCam.

pixel of $0.395 \text{ p.e. ns}^{-1}$. To adapt the NSB level determined with the assumed CT5 optical efficiency of 0.79 to the optical efficiency of CT5 of 0.76 used for the standard simulations (see Table 9.4), the NSB level f_{NSB} is consequently corrected to

$$f_{\text{NSB}} = \frac{0.395 \text{ p.e. ns}^{-1}}{0.76} = 519.7 \text{ MHz} \quad . \quad (9.10)$$

The resulting NSB level is used as input for the reduced trigger threshold simulations with a CT5 optical efficiency of 0.76.

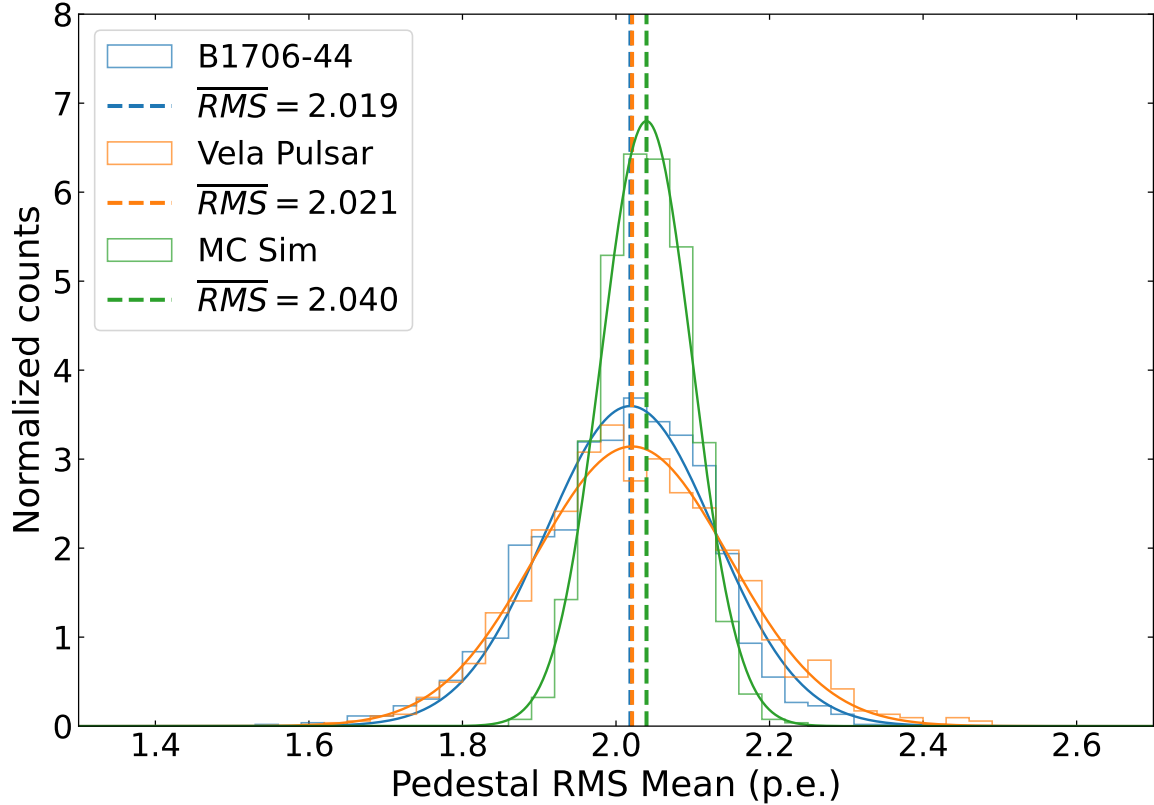


Figure 9.9. Pedestal width mean for MC simulations and observation runs on the Vela pulsar and B1706-44. The pedestal width is simulated for a NSB level of 500 MHz under an assumed optical efficiency of CT5 of 0.76. It is quantified by the RMS. The observation runs are selected according to the “detection” data quality selection criteria described in Section 10.2.

Atmospheric Transparency

Since 2016, an instrument of the Aerosol Robotic Network (AERONET) is installed on the H.E.S.S. site and measures the aerosol content of the atmosphere in the wavelength range of 340 nm – 1640 nm during the day and in nights where the moon illumination is $> 50\%$ (Holch et al. 2022)¹⁰. The atmospheric transparency for the reduced trigger threshold observations of the Vela pulsar and B1706-44 in 2021 are assessed using measurements of the AERONET measurement device installed on the H.E.S.S. site. Although no AERONET measurements are taken during the

¹⁰The AERONET project is described by Holben et al. (1998).

observation runs, they serve as indicator for the atmospheric conditions before or after the respective observation runs.

The probability that photons with a certain wavelength and emitted at a certain altitude reach the telescope is described by the transmission profile, which is one of the ingredients to describe the atmospheric conditions. Transmission profiles are calculated by performing radiative transfer equations and using measurements of different atmospheric conditions as input. The input aerosol profile is scaled with the AOD value at a wavelength of 550 nm AOD_{550} , which is interpolated from measurements of the AERONET instrument installed at the H.E.S.S. site (Holch et al. 2022). A total of three transmission profiles are generated by T. Holch (Deutsches Elektronen-Synchrotron (DESY)) and provided as reference for the MC simulations in HAP. The corresponding AOD_{550} values are

$$\text{Bad: } \text{AOD}_{550} = 0.15 \quad (9.11)$$

$$\text{Mixed: } \text{AOD}_{550} = 0.03 \quad (9.12)$$

$$\text{Nonbmb: } \text{AOD}_{550} = 0.042 \quad (9.13)$$

The AOD_{550} values that are closest to the times of the pulsar observations with the reduced trigger setting are shown in Figure 9.10. No data quality selection cuts are performed on these observations. In addition, the three reference transmission profiles are displayed. To determine the transmission profile that best resembles the atmospheric conditions for the pulsar observations, for each pulsar observation the difference $\Delta\text{AOD}_{550}(i)$ is calculated according to

$$\Delta\text{AOD}_{550}(i) = \text{AOD}_{550}(i) - \text{AOD}_{550,\text{ref}} \quad (9.14)$$

with $\Delta\text{AOD}_{550}(i)$ the AOD measurement closest to the i -th pulsar observation and $\text{AOD}_{550,\text{ref}}$ the reference value of one of the three transmission profiles. The mean and standard deviation of Equation 9.14 separated by pulsar and daily and nightly AOD measurements serve as figure of merit to quantify the best fitting transmission profile. The results are summarized in Table 9.7 and the corresponding distributions are shown in Figure C.1. There is no significant difference between the nightly and the daily determined values present. Furthermore, for the same transmission profile the differences between the Vela pulsar and B1706-44 are negligible and they agree within errors. Independent of the source, the “Bad” transmission profile resembles the atmospheric conditions the least. While the “Nonbmb” transmission profile seems to be a slightly better fit compared to the “Mixed”, the latter still offers a satisfactory representation of the atmospheric conditions of the pulsar observations. To stay consistent with the standard MC simulations within HAP, the “Mixed” atmosphere is chosen for the simulations with the reduced trigger setting.

Summary

In addition to the standard simulations listed in Table 9.4 for HAP, the simulations with the reduced trigger setting are performed with the “Mixed” atmosphere and an optical efficiency of CT5 of 0.76. An additional difference to the standard simulations is the increased NSB level of 519.7 MHz with respect to the NSB level of 316.01 MHz of the standard simulations. The latter value is derived by Leuschner et al. (2023) and the details are given by Leuschner (2025). The validated trigger setting and the

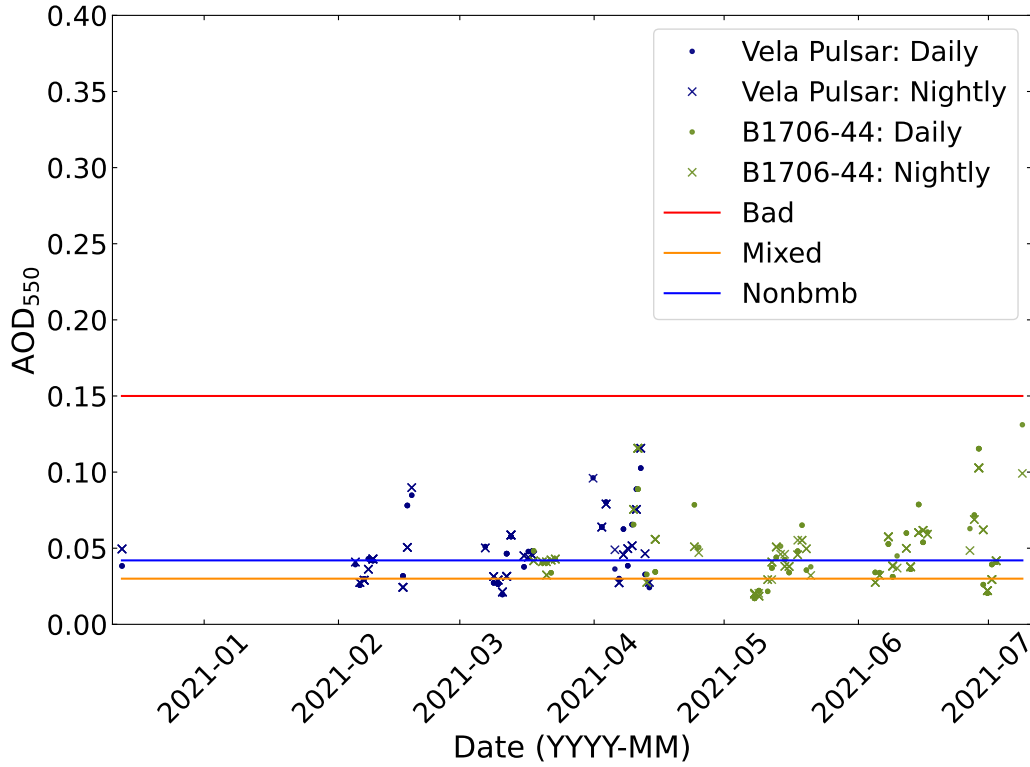


Figure 9.10. AOD_{550} for the pulsar observations performed with the reduced trigger setting. Three reference transmission profiles generated by T. Holch (DESY) are shown as a reference to the daily and nightly AOD_{550} values derived with the AERONET instrument at the H.E.S.S. site.

adapted NSB level and atmospheric transparency to the pulsar observations with the reduced trigger setting are provided as input to K. Bernlöhr (Max-Planck-Institut für Kernphysik (MPIK)) for the simulations. In addition to the reduced trigger setting simulations, simulations with nominal trigger setting and the same telescope and environmental conditions are performed to compare the derived IRFs, which is described in the next section.

9.4.2. Comparison: Reduced versus Nominal Trigger Setting

The IRFs are derived from the simulations with the reduced trigger setting and the matching simulations with nominal trigger setting using the selection cuts in Table 9.1. For the comparison, the instrument energy threshold is of special interest.

Table 9.7. Mean and standard deviation of the AOD_{550} values determined according to Equation 9.14. The values are separated by source and nightly and daily AOD measurements by AERONET.

Reference	Vela Pulsar		B1706-44	
	Daily	Nightly	Daily	Nightly
Bad	-0.102 ± 0.021	-0.104 ± 0.021	-0.103 ± 0.024	-0.102 ± 0.024
Mixed	0.018 ± 0.021	0.016 ± 0.021	0.017 ± 0.024	0.019 ± 0.024
Nonbmb	0.006 ± 0.021	0.004 ± 0.021	0.005 ± 0.024	0.007 ± 0.024

As the energy threshold is defined according to the maximum effective area or the energy bias, a closer look at these two IRFs is taken in the following. The IRFs are compared for zenith angles of 20° and 30° and an offset angle of 0.75° , as the majority of the observations are taken under these observation conditions. The offset angle is defined by the wobble observation mode, where the source is offset from the camera center in right ascension or declination alternating from positive to negative, such that the region opposite of the source is usable as control region for the background estimation. As mentioned in Section 9.2, this is not necessary for pulsar observations. However, the standard observation mode was kept to have the possibility of an alternate background determination.

Effective Area

The effective area A_{eff} as a function of true energy E_{true} is shown in Figure 9.11 for the reduced and the nominal trigger setting. The comparison is shown for a true energy range of 5 GeV – 150 GeV for two reasons. First, this is the energy range where the reduced trigger setting has the largest impact and second, it is the energy range of interest for the pulsar observations. The comparison of the effective area for up to ~ 100 TeV is shown in Figure C.2. For a better quantification of the differences of the two trigger settings, the ratio of the effective area between the reduced and the nominal trigger setting is shown in Figure 9.12.

For both zenith angles, the reduced trigger setting has a slightly larger effective area for true energies < 80 GeV. Above this energy, there is no difference in effective area between the reduced and the nominal trigger setting visible. Furthermore, there is no significant difference in the energy threshold defined with $0.1 \cdot A_{\text{eff,max}}$, as listed in Table 9.8. The energy threshold is determined by the lowest bin that is located above the given threshold and the error on the energy is given by the bin width. With increasing zenith angle the energy threshold of the instrument increases due to the fact that the low energy showers are absorbed in the atmosphere. The energy bias for the nominal and the reduced trigger setting is compared in the following.

Table 9.8. Energy threshold determined as $0.1 \% \cdot A_{\text{eff,max}}$ for the reduced and nominal trigger setting. The results are derived for the zenith angles of 20° and 30° and an offset angle of 0.75° .

Zenith angle ($^\circ$)	Nominal (GeV)	Reduced (GeV)
20	41^{+5}_{-4}	41^{+5}_{-4}
30	59^{+7}_{-6}	59^{+7}_{-6}

Energy Bias

The energy bias ΔE according to Equation 9.9 for the reduced and nominal trigger setting is shown in Figure 9.13 for a true energy range of ~ 10 GeV – 150 GeV. For energies < 60 GeV an increase of the energy bias is visible, which is due to a selection effect. Only events with energies that are reconstructed too high are selected. There is no significant difference between the reduced and the nominal trigger setting visible. The energy thresholds defined as the smallest energy bin below $0.1 \cdot \Delta E$ for the two trigger settings and the two zenith angles are summarized in Table 9.9. The

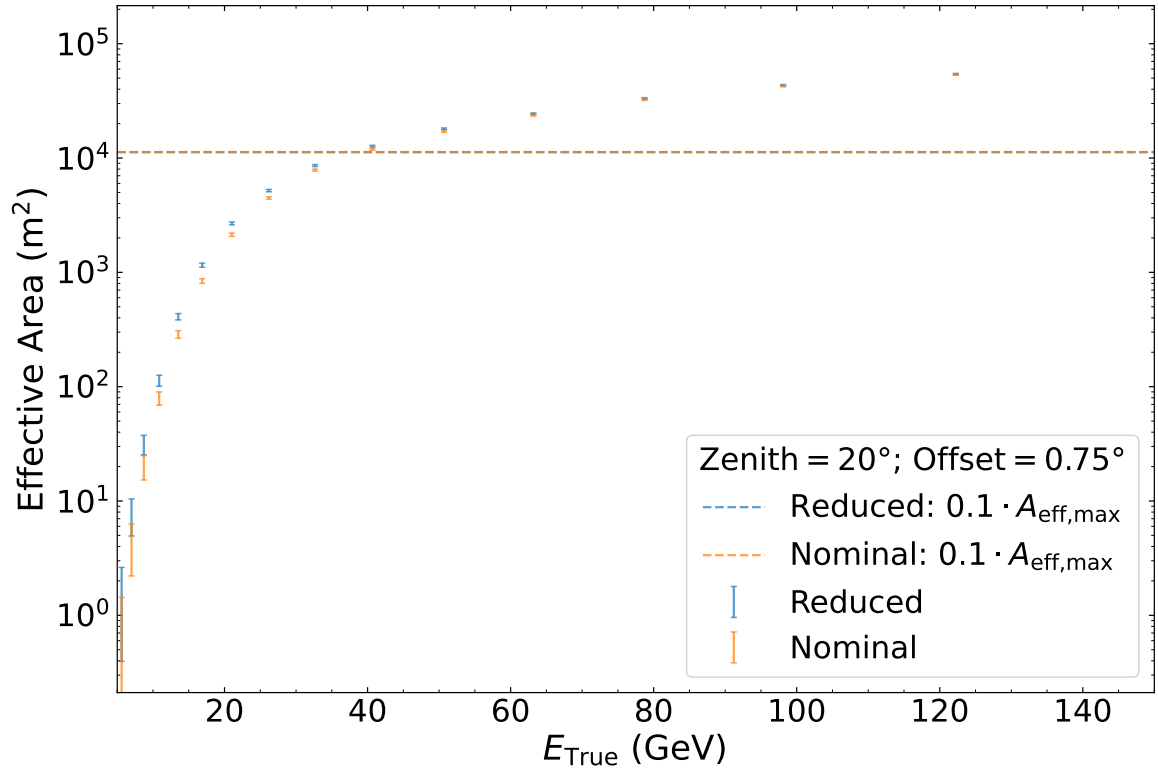
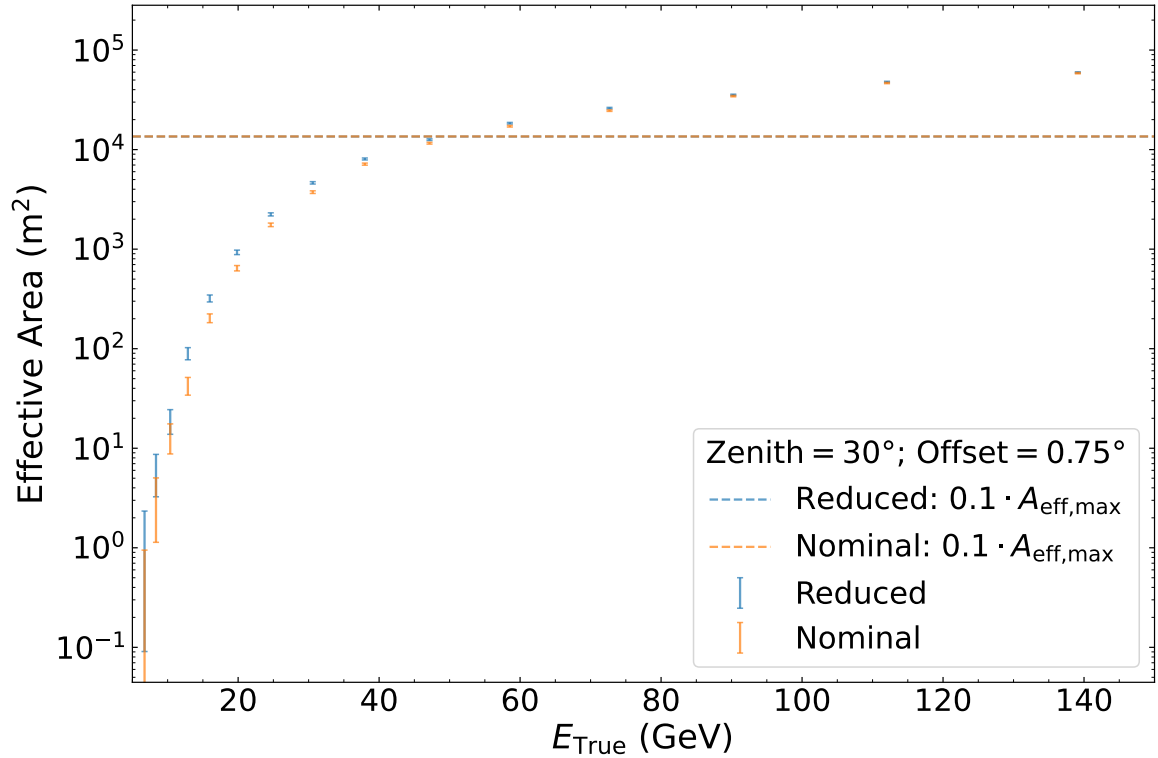
(a) For a zenith angle of 20° and an offset angle of 0.75° .(b) For a zenith angle of 30° and an offset angle of 0.75° .

Figure 9.11. Comparison of the effective area A_{eff} between the reduced and the nominal trigger setting for the true energy range of 5 GeV – 150 GeV. In addition, 10 % of the maximum of the effective area $A_{\text{eff,max}}$ is indicated.

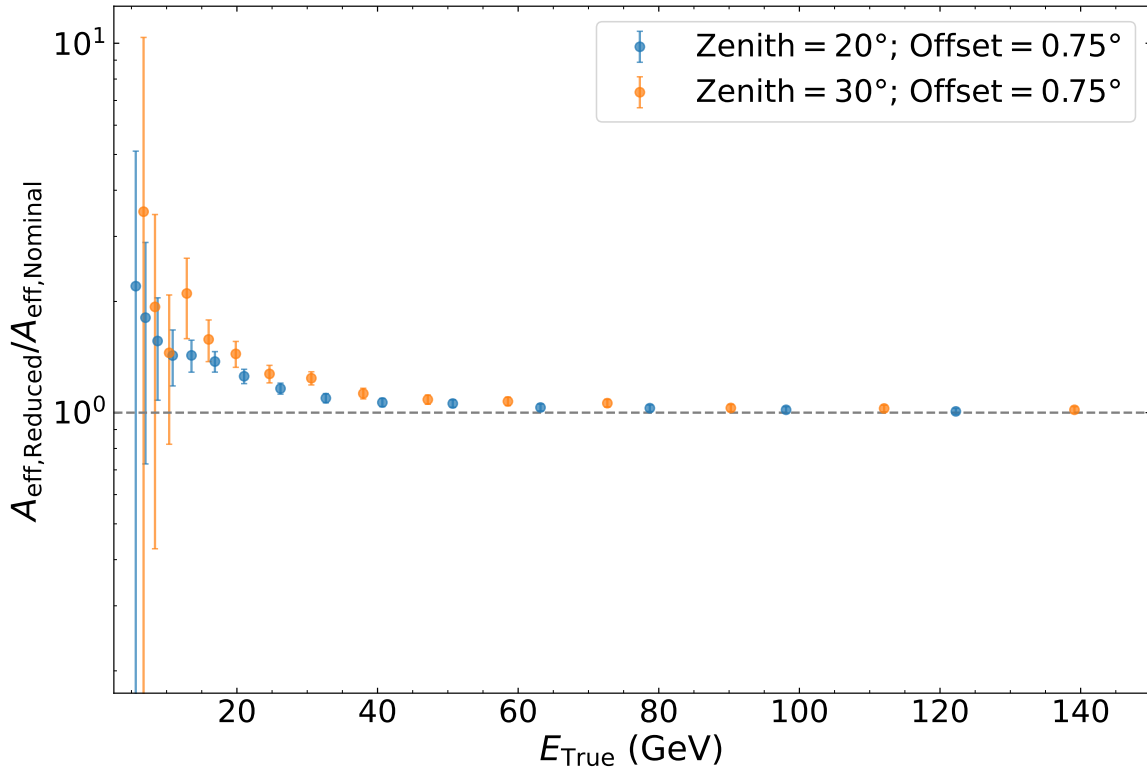


Figure 9.12. Ratio of the effective area between the reduced and the nominal trigger setting.

instrument energy threshold increases with increasing zenith angles. A brief summary and an outlook is given in the following.

Table 9.9. Energy threshold determined as $0.1\% \cdot \Delta E$ for the reduced and nominal trigger setting. The energy bias ΔE is calculated with Equation 9.9. The results are derived for the zenith angles of 20° and 30° and an offset angle of 0.75° .

Zenith angle ($^\circ$)	Nominal (GeV)	Reduced (GeV)
20	49^{+2}_{-2}	49^{+2}_{-2}
30	54^{+3}_{-2}	54^{+3}_{-2}

Summary and Outlook

With the currently applied analysis, there is no significant difference in the safe energy threshold derived from the energy bias and the effective area, and which is relevant for the spectral analysis, between the nominal and reduced trigger setting present. However, as is shown in Figure 9.12, a significant increase of the effective area for $E_{\text{true}} \lesssim 80$ GeV is visible for the reduced trigger setting. This increase might contribute to the increased excess and significance rates determined in Section 10.4.

As discussed in Section 9.1.3, the used analysis configuration has several caveats, which influence the above performed comparison. First, further additional events of the reduced trigger setting with respect to the nominal setting could be rejected due to the applied image amplitude and number of pixels cut listed in Table 9.1. Second, the classification training of the γ -ray and hadrons is performed on the

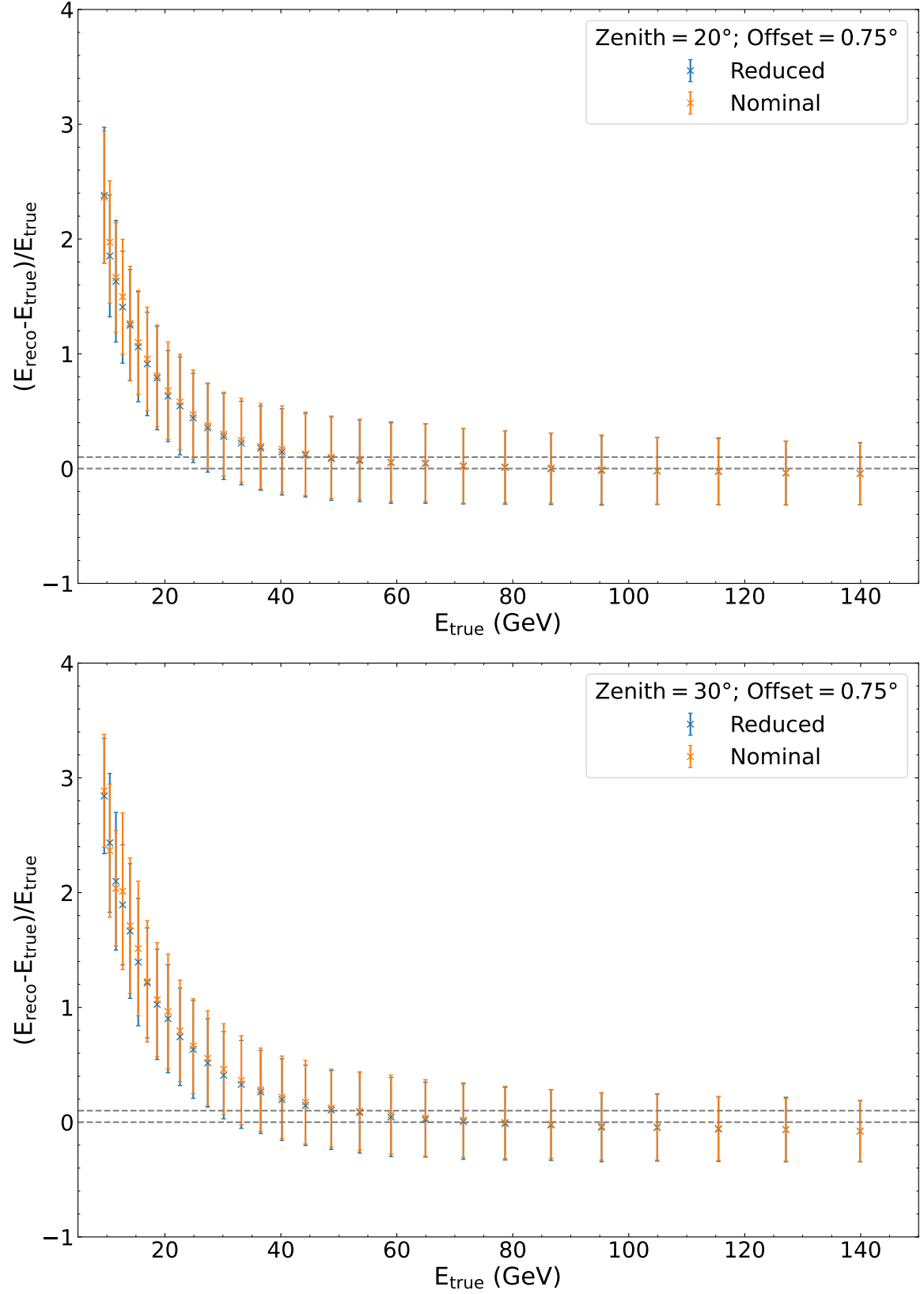


Figure 9.13. Comparison of the energy bias between the reduced and the nominal trigger setting for the true energy range of ~ 10 GeV – 150 GeV for a zenith angle of 20° (top) and 30° (bottom). In addition, 0 % and 10 % of the energy bias are indicated.

MC simulations with the nominal trigger setting and the standard NSB setting of 316.01 MHz. Therefore, the additional events acquired with the reduced trigger setting could be wrongly classified as hadrons as the training is not sensitive to the events. Furthermore, the training of the energy reconstruction should be performed on the MC simulations with reduced trigger setting in order to improve the energy bias.

The comparison of the IRFs is mainly relevant for the determination of the spectrum described in Section 10.5. An assessment of the additional event statistics with the reduced compared to the nominal trigger settings is described in Section 10.4.

Data Analysis of the Vela Pulsar and the Pulsar B1706-44

After the installation of FlashCam in CT5 in October 2019, the timing of the camera has been verified by the author of this thesis using observations of the Vela pulsar taken in 2020. The results of the timing verification are reported by Pühlhofer et al. (2021). Consequently, the Vela pulsar has been observed in each of the following observation periods from 2020 to 2023 and, in addition, the pulsar B1706-44 has been observed in the 2021 observation period. The data sets of both pulsars of the 2021 observation period are taken with the reduced trigger setting of the FlashCam (see Table 9.5), while the Vela pulsar has been observed with the nominal trigger setting in 2020, 2022, and 2023. The observational data analysis of the data acquired on the Vela pulsar in 2020 to 2022 and the pulsar B1706-44 in 2021 is presented in this chapter. The Vela pulsar data of the 2023 observation period set is not analyzed as the long-term muon efficiencies necessary for the correction of the IRFs are not yet available at the time of writing (L. Mohrmann (MPIK), priv. comm. July 2024).

The main characteristics of the two pulsars are briefly covered in Section 10.1. In Section 10.2, the analyzed data sets and the determination of preliminary data quality selection criteria are described. The analysis is performed with the modified MonoReco algorithm presented in Section 9.1 and with the ultraloose γ -ray selection cuts listed in Table 9.1. The DL3 event lists are generated with HAP and the high-level analysis is performed with the Python package Gammapy¹ described by Donath et al. (2023). The results of the timing analysis and the sky maps are shown in Section 10.3. Due to the known limitations of the analysis configuration described in Section 9.1.3, a detailed scientific interpretation of the analysis results, e.g., the spectra derived in Section 10.5 is not performed. The main focus is two-fold. First, to quantify the impact of the reduced trigger setting with respect to the nominal trigger setting on the event statistics, as is relevant for the detection of a source. This is accomplished by comparing the excess and significance rate as function of zenith angle using the Vela pulsar observations taken with the reduced and the nominal trigger setting, and described in Section 10.4. Second, the working principle of the derived IRFs using the MC simulations adapted to the observation conditions presented in Section 9.4 and the calculation of the spectra for the Vela pulsar and B1706-44. This is described in Section 10.5.

¹The software version is 1.2.

10.1. Pulsar Characteristics

The Vela pulsar has a spin period of 89.3 ms and a characteristic age of 11.3 kyrs (Manchester et al. 2005). The high energy emission above $\sim$ GeV is characterized by three peaks, which are labeled P1, P2 and P3 with the most dominant one being the P2 peak (Abdo et al. 2009).

The pulsar B1706-44 has a spin period of 102.5 ms and a characteristic age of 17.5 kyrs (Manchester et al. 2005). The high energy emission above $\sim$ GeV is characterized by two peaks, which are connected by a bridge with a high amplitude emission (Abdo et al. 2010).

Both pulsars have already been detected with H.E.S.S. and the results are reported by H.E.S.S. Collaboration et al. (2018a) and Spir-Jacob et al. (2019) for the Vela pulsar and B1706-44, respectively. The On- and Off-phase range is defined for both pulsars according to the respective previous H.E.S.S. publication. The main characteristics of the two pulsars are summarized Table 10.1. The three data sets and the quality selection thereof is described in the next section.

Table 10.1. Main characteristics of the Vela pulsar and pulsar B1706-44. For the Vela pulsar, the definition of the On-phase refers to the P2 peak, as defined by Abdo et al. (2009). The phase definitions are in accordance with the previous H.E.S.S. publications by H.E.S.S. Collaboration et al. (2018a) and Spir-Jacob et al. (2019) for the Vela pulsar and B1706-44, respectively.

Parameters	Vela Pulsar	B1706-44
Spin Period (ms) ^a	89.3	102.5
Characteristic Age (kyrs) ^a	11.3	17.5
Distance (kpc) ^{b,c}	0.29 ± 0.02	$1.8 - 3.6$
Spin-down Power (erg s^{-1}) ^{d,e}	6.9×10^{36}	3.4×10^{36}
No. Peaks ^{d,e}	3	2
On-Phase ^{d,e}	$0.50 - 0.60$	$0.25 - 0.55$
Off-Phase ^{d,e}	$0.70 - 1.00$	$0.60 - 0.20$

^a Reference: Manchester et al. (2005).

^b Reference: Dodson et al. (2003).

^c Reference: Koribalski et al. (1995).

^d Reference: Abdo et al. (2009).

^e Reference: Abdo et al. (2010).

10.2. Data Sets and Quality Selection

The live time overview of the different data sets for both pulsars is given in Table 10.2. The table lists the available live time in HAP (HAP DSTs) and the resulting live time of the DL3 data. For the Vela 2020, 2022 and the B1706-44 2021 data set a few observation runs failed the conversion to the DL3. In addition, during the observation period of 2021, a substantial amount of the Vela pulsar data was taken in monoscopic observation mode, i.e. with CT5 and CT1-4 observing different astronomical sources. The live time taken in the monoscopic observation mode is shown in parentheses. Furthermore, Table 10.2 lists the live time for three different data quality selection

Table 10.2. Live time overview of the different data sets for the Vela pulsar and pulsar B1706-44. The live time available as DSTs in HAP, as DL3 data, and the three different quality selection criteria is listed. In the 2021 observation period, the Vela pulsar was partly observed in monoscopic mode, i.e. with CT5 observing independently of CT1-4. The live time taken in monoscopic mode is displayed in parentheses.

Criteria	Vela Pulsar			B1706-44	
	2020	2021	2022	2021	
HAP DSTs (h)	10.49	44.64 (28.11)	34.93	59.87	
DL3 data (h)	10.44	44.64 (28.11)	28.9	58.93	
Detection (h)	6.79	42.59 (26.07)	25.96	53.18	
Spectral-1 (h)	6.79	37.75 (23.73)	21.89	44.27	
Spectral-2 (h)	-	-	-	49.41	

criteria called “Detection”, “Spectral-1”, and “Spectral-2”. The three selection criteria are explained in the following².

The aim of the data quality selection criteria is to reject data with doubtful quality in order to not corrupt the analysis results. That is in particular important for the calculation of spectra, where On- and Off-events are taken from different observations. For the calculation of a detection significance, however, this is not a (major) concern where the On- and Off-events are taken from the same observations. It should be emphasized that the presented selection criteria are preliminary, derived empirically and serve only as a rough estimate to reject potentially problematic runs. The nominal duration of an observation run is 28 min and runs with a much shorter duration indicate hardware, environmental or operational related problems. Therefore, the detection criteria reject runs with a duration of < 10 min. In addition, the detection criteria rejects runs taken with a wrong trigger setting in order to provide a data set with a homogeneous hardware configuration. This includes observation runs with moonlight trigger settings for the data sets taken with the nominal and reduced trigger setting, as well as runs taken with the nominal trigger settings for the data sets taken with the reduced trigger setting.

Based on the detection criteria, the spectral-1 criteria is determined. A fluctuating trigger rate indicates clouds in the FOV of the telescope due to the attenuation of the Cherenkov light emitted by the particle shower and a reduced trigger probability. Therefore, the RMS of the CT5 trigger rate $R_{\text{True, RMS}}$ is used as an indicator and rejects runs for which the condition

$$R_{\text{True, RMS}} > 200 \text{ Hz} \quad (10.1)$$

is fulfilled.

Radiometers are installed at the four small H.E.S.S. telescopes CT1-4, which are aligned with the pointing direction of the telescope and measure the temperature of the atmosphere. A change in the measured radiometer temperature indicates clouds in the telescope FOV. Problems during data taking were observed for the observations with the reduced trigger setting, which resulted in dips in the CT5

²The live time as function of the mean zenith angle of the observation for the four data sets is shown in Figures C.4 and C.5.

trigger rate and translated to dips in the system trigger rate. The reason for the dips in the CT5 trigger rate was traced back to a too high computational load on the CT5 camera server during unfavorable observation conditions with high NSB. The issue was fixed by F. Werner (MPIK) and the operations with the reduced trigger setting went smoothly afterwards, as shown in Figure C.6. For the runs with dips in the CT5 trigger rate, there are currently no hints that the timing information of the camera is affected. However, a first investigation revealed a higher camera dead time for these observation runs. The issues are more dominantly for the B1706-44 observations compared to the Vela observations with the reduced trigger setting. To differentiate between observation runs taken during bad weather conditions and observation runs with problems during data taking, the information from the CT1-4 radiometers is taken into account. In the case of bad weather, both, the radiometer temperature and the trigger rate fluctuate, while in the case of problems during data taking, the radiometer temperature is stable and the CT5 trigger rate fluctuates. This is illustrated exemplary for a bad weather run in Figure C.7. Therefore, the spectral-2 criteria is based on the detection criteria and rejects observation runs, which fulfill the condition in Equation 10.1 and the condition

$$\bar{T}_{\text{Radio,Std}} > 2.5 \quad (10.2)$$

with the standard deviation of the radiometer temperature $\bar{T}_{\text{Radio,Std}}$ averaged over CT1-4. Therefore, the spectral-2 criteria includes the observation runs which exhibit the problems during data taking and serves as comparison to the spectral-1 criteria in order to provide a qualitative assessment of the impact of the runs with problems during data on the high-level analysis results. The distribution of the $R_{\text{True, RMS}}$ as a function of $\bar{T}_{\text{Radio,Std}}$ for the B1706-44 runs is shown in Figure 10.1. The different data quality criteria are indicated. The spectral-2 criteria is not derived for the Vela data set of the 2021 observation period, because the radiometer temperature is only available for a live time of ~ 16 h. For the other ~ 28 h of the data set, CT5 observed in monoscopic mode.

The detection criteria is applied to derive the analysis results described in Sections 10.3 and 10.4. The spectral-1 and spectral-2 criteria are applied to derive the results in Section 10.5.

10.3. Timing Analysis and Sky Maps

The results of the timing analysis and the derived significance sky maps are presented in this section. In addition, the excess distribution as function of reconstructed energy is shown at the end of the section. The results are derived with the applied detection criteria and under an assumed angular cut around the source position of $\theta_0^2 < 0.05 \text{ deg}^2$. The On- and Off-phase in the rotational phase space are defined according to Table 10.1. This results in normalization factors of

$$\alpha_{\text{Vela}} = \frac{\Psi_{\text{on}}}{\Psi_{\text{off}}} = \frac{0.1}{0.3} = \frac{1}{3} \quad (10.3)$$

for the Vela pulsar and

$$\alpha_{\text{B1706-44}} = \frac{\Psi_{\text{on}}}{\Psi_{\text{off}}} = \frac{0.3}{0.6} = \frac{1}{2} \quad (10.4)$$

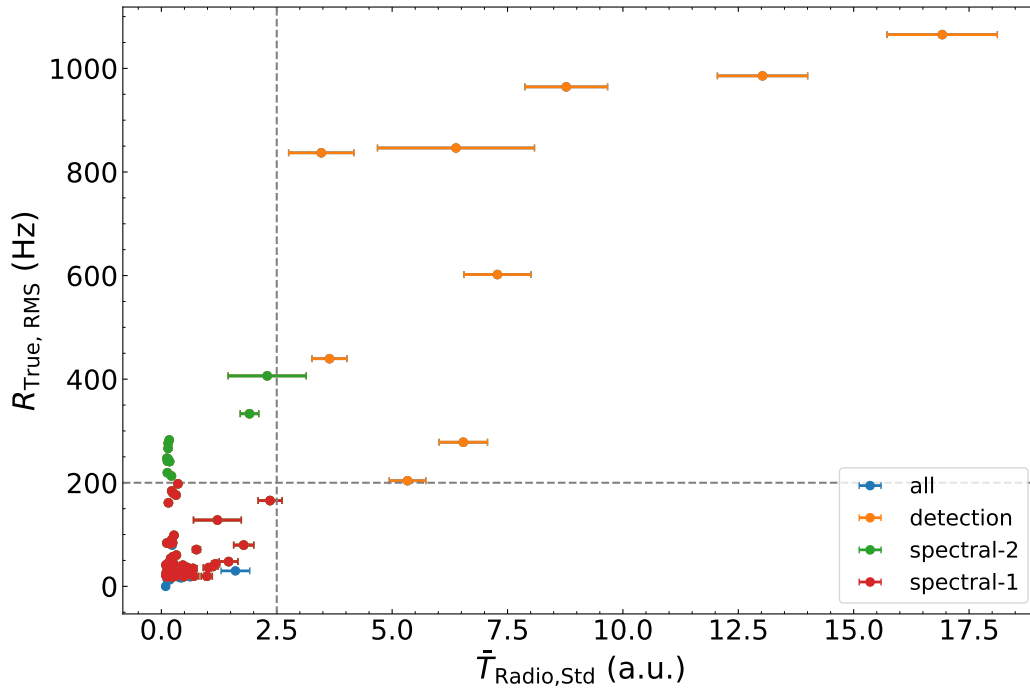


Figure 10.1. CT5 trigger rate RMS $R_{\text{True, RMS}}$ as function of CT1-4 averaged standard deviation of the radiometer temperature $\bar{T}_{\text{Radio, Std}}$. The error on $\bar{T}_{\text{Radio, Std}}$ is the standard deviation of the single telescope radiometer temperature standard deviations. The three data quality criteria detection, spectral-1 and spectral-2 as well as the respective conditions of Equations 10.1 and 10.2 are shown.

for the pulsar B1706-44. The results of the timing analysis are summarized in Table 10.3 for the different data sets. In addition to the four data sets introduced in Section 10.2, the results of the Vela pulsar observations with the nominal trigger setting are combined to the 2020 + 2022 data set comprising the observation periods 2020 and 2022. The P2 peak of the Vela pulsar is detected with a significance of 6.1σ , 27.3σ and 4.1σ in the observation periods 2020, 2021, and 2022, respectively. Therefore, the timing of the camera is verified for each of the three observation periods. In addition, the Vela pulsar is detected with a significance of 6.8σ with the combined data set. Although the 2022 data set has a higher live time of ~ 26 h compared to the 2020 data set with ~ 7 h, the detection significance of the P2 peak is smaller with 4.1σ compared to 6.1σ . This is explained by the majority of the live time of the 2022 data set being taken with zenith angles $> 40^\circ$ (see Figure C.4b), where the signal detection efficiency is small (see Figure 10.7). The pulsed emission of the pulsar B1706-44 is detected with a significance of 5.7σ .

The phasograms of the Vela pulsar for the data sets of the reduced and nominal trigger setting, as well as of the pulsar B1706-44 are shown in Figure 10.2. For the Vela pulsar, the P2 peak is clearly visible in the phasogram. Furthermore, for the Vela pulsar in the observation period 2021, there are hints of the P1 and P3 peak, as already reported by Bedur Ramesh (2024). Following the phase definitions by H.E.S.S. Collaboration et al. (2018a) of the P1 and P3 peak of $0.1 - 0.2$ and $0.2 - 0.4$, respectively, the significance of the P1 peak S_{P1} is evaluated to

$$S_{\text{P1}} = 2.96\sigma \quad (10.5)$$

Table 10.3. Results of the timing analysis for the different data sets with applied detection data selection criteria. The excess and significance are calculated according to Equations 9.2 and 9.4. The error of the excess is determined from the Poisson likelihood function WStat of Gammapy (Gammapy 2024).

Parameter	Vela Pulsar				B1706-44
	2020	2021	2022	2020 + 2022	2021
No. Total Events	178513	1407376	468153	646666	1969254
No. On-Events	18755	150958	47595	66350	594372
No. Off-Events	53401	417040	139669	193070	1177971
N_{excess}	955^{+157}_{-157}	11945^{+444}_{-444}	1039^{+251}_{-251}	1993^{+297}_{-296}	5387^{+943}_{-943}
$S (\sigma)$	6.1	27.3	4.1	6.8	5.7

Table 10.4. Fit parameters of the one-dimensional Gaussian distribution of the excluded significance map for the three data sets. The results for the mean μ and the standard deviation Σ are listed.

Data Set	$\mu (\sigma)$	$\Sigma (\sigma)$
Vela Pulsar 2020 + 2022	0.11 ± 0.05	0.88 ± 0.04
Vela Pulsar 2021	0.29 ± 0.06	0.97 ± 0.05
B1706-44 2021	0.02 ± 0.05	0.85 ± 0.04

and for the P3 peak S_{P3} to

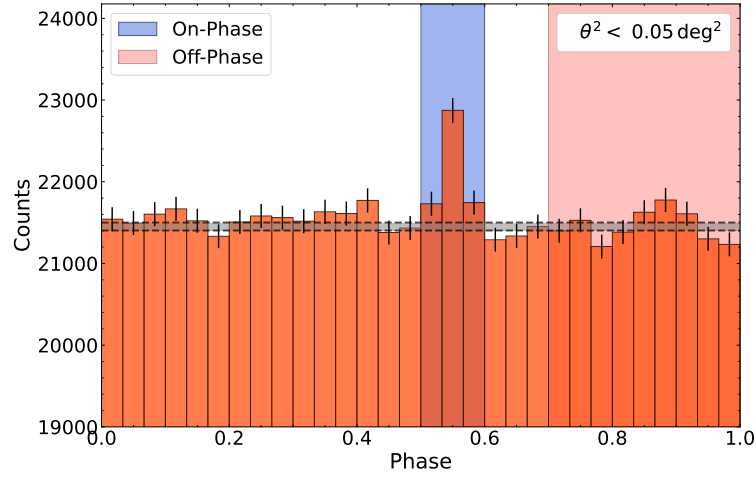
$$S_{\text{P3}} = 3.95 \sigma \quad . \quad (10.6)$$

For the pulsar B1706-44, a broad peak is visible in the On-phase range, but no well-defined structure is recognizable.

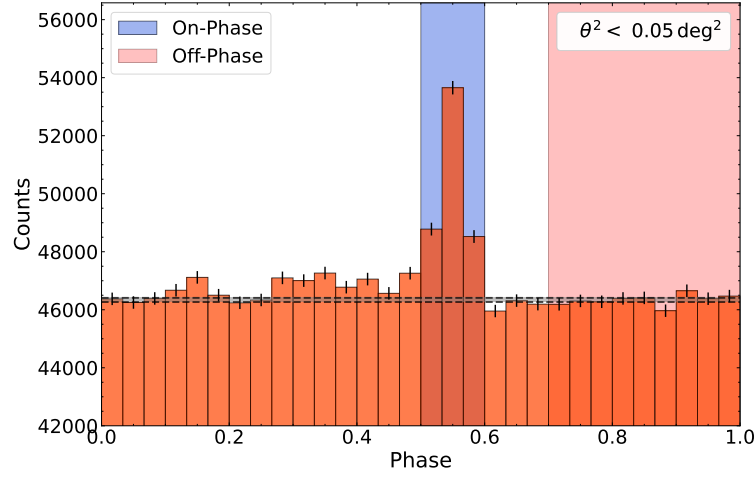
The γ -ray events are binned in a two-dimensional map according to their reconstructed positions. A significance sky map can be calculated from an On-map containing the events from the On-phase region, and subtracted by the Off-map containing the events from the Off-phase region multiplied with the normalization factor α . The significance map is smoothed with a two-dimensional Tophat filter kernel with a correlation radius of $\sqrt{\theta_0^2}^3$. The significance sky maps for the data sets of the Vela pulsar with the nominal and reduced trigger setting are shown in Figure 10.3, and for the pulsar B1706-44 in Figure 10.4. For each of the three data sets, there is a distinct signal visible at the position of the respective pulsar.

To verify the background normalization, the signal region is masked with a circular exclusion region with a radius of 0.6° . The resulting one-dimensional excluded significance distribution is fitted with a Gaussian distribution. If the background outside of the exclusion region is purely of statistical nature, the resulting mean of the distribution should be 0 and the standard deviation should be 1. The fit parameters of the fitted Gaussian distribution for the three data sets are summarized in Table 10.4. As can be seen, the parameters for the three data sets slightly deviate from the expectations with the largest deviation present for the mean of the Vela 2021 data set. However, given the known limitations in the angular reconstruction of the used analysis configuration, this is not deemed worrisome. Furthermore, this test is mainly important for background methods, which use different regions in the FOV to perform the background estimation. For the pulsar analysis, this does not add to

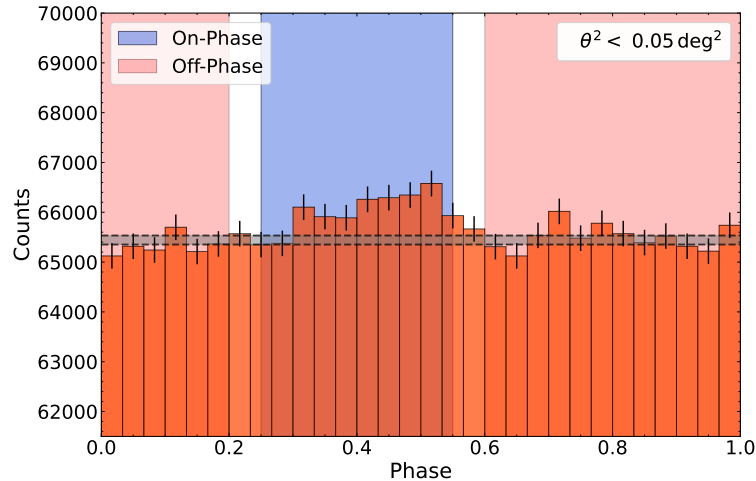
³The Tophat filter kernel is implemented in the Python package astropy as Tophat2DKernel.



(a) Vela pulsar with nominal trigger setting for the combined observation period of 2020 and 2022.

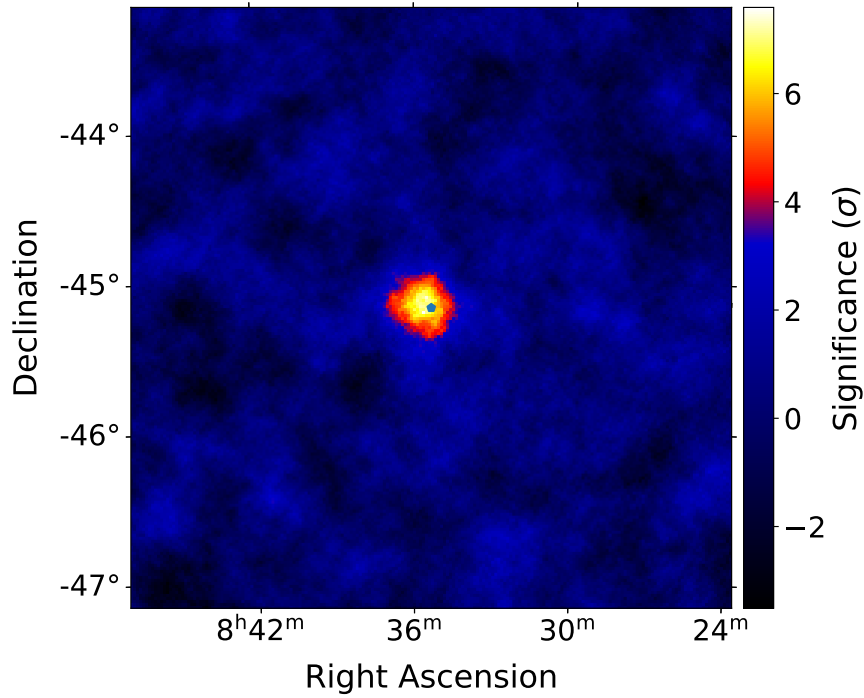


(b) Vela pulsar with reduced trigger setting for the observation period 2021.

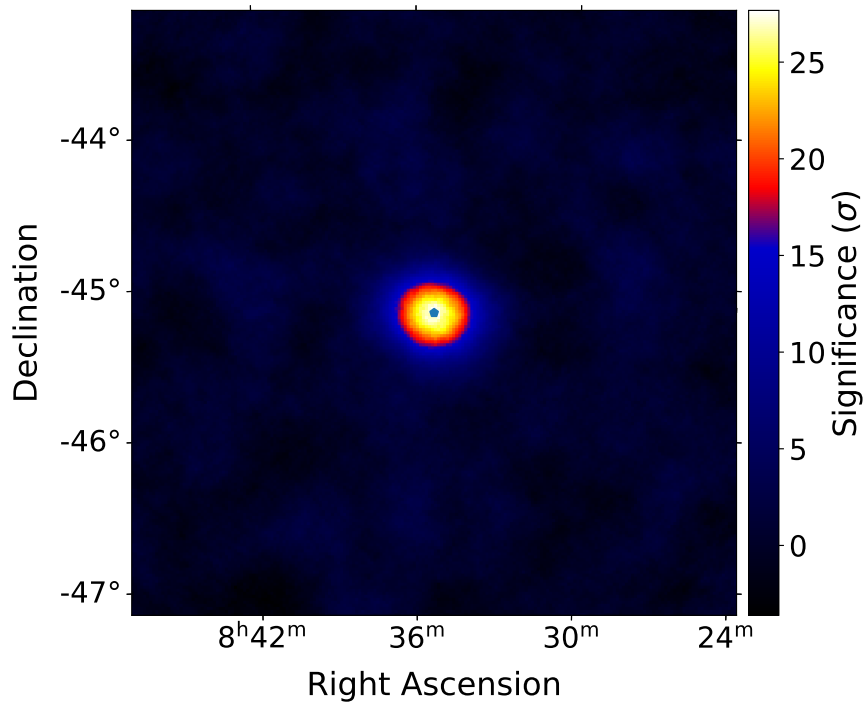


(c) Pulsar B1706-44 with reduced trigger setting for the observation period 2021.

Figure 10.2. Phasograms of the timing analysis of the Vela pulsar for reduced and nominal trigger setting observations, and the pulsar B1706-44. The timing analysis is performed for the data sets with applied detection data selection criteria and according to the phase space definitions summarized in Table 10.1. The mean background level is indicated as gray band.



(a) Vela pulsar with nominal trigger setting for the combined observation period of 2020 and 2022.



(b) Vela pulsar with reduced trigger setting for the observation period 2021.

Figure 10.3. Significance maps of the Vela pulsar observations with the nominal and reduced trigger setting. The pulsar position is indicated by the blue pentagon.

the systematic errors. The significance maps with the excluded source region and the corresponding excluded significance distributions are shown in Figures C.8 and C.9, respectively. The normalized excess distribution as function of reconstructed energy

for the three data sets is shown in Figure 10.5. For all three data sets, the maximum excess is visible at $E_{\text{reco}} \sim 35$ GeV and the majority of the events is constrained to an energy range $\lesssim 150$ GeV.

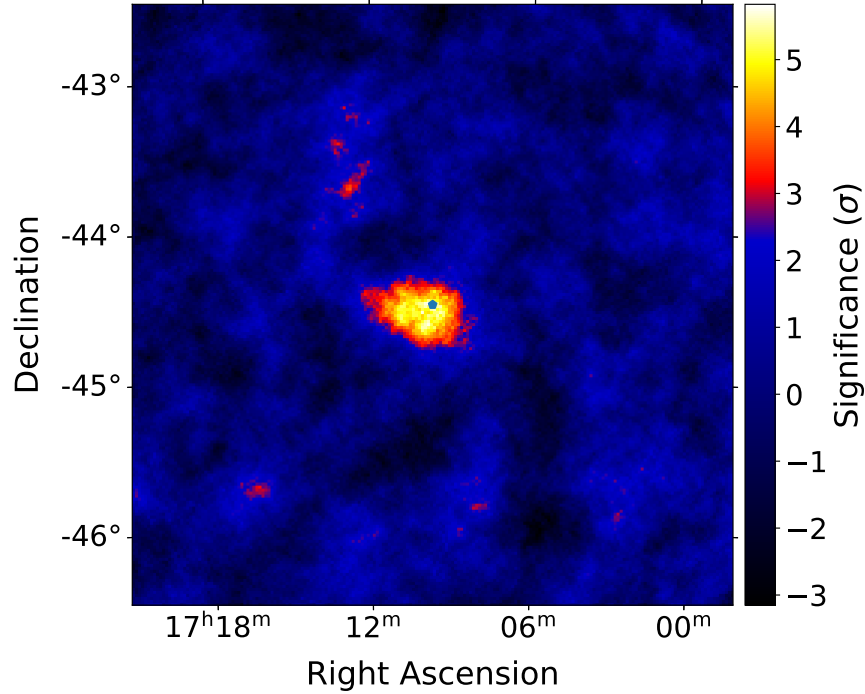


Figure 10.4. Significance map of the 2021 data set of the pulsar B1706-44. The pulsar position is indicated by the blue pentagon.

10.4. Rate Comparison

To quantify the improvement of the reduced trigger setting with respect to the nominal trigger setting for the given analysis configuration with respect to the event statistics, the excess and significance rate as function of the zenith angle is evaluated for the Vela data set of the 2021 observation period and compared to the Vela data set of the 2020 and 2022 observation period. Hereby, the detection quality selection criteria is applied to the data sets. Furthermore, the rates calculated in this section are not subject to the safe energy threshold cut on the energy bias or the maximum of the effective area described in Section 9.4. The excess rate R_{excess} is calculated according to

$$R_{\text{excess}} = \frac{N_{\text{excess}}}{t} \quad (10.7)$$

with the excess N_{excess} determined with Equation 9.2 and the observation time t . The error on the excess rate is calculated with

$$\Delta R_{\text{excess}} = \frac{1}{t} \quad . \quad (10.8)$$

The significance rate $R_{\text{significance}}$ is given by

$$R_{\text{significance}} = \frac{S}{\sqrt{t}} \quad (10.9)$$

with the significance S determined according to Equation 9.4 and the observation time t . The error on the significance rate is consequently given by

$$\Delta R_{\text{significance}} = \frac{1}{\sqrt{t}} \quad (10.10)$$

The live time as function of the mean zenith angle of the observation for the three data sets is shown in Figure 10.6. The 2021 data set has a high live time coverage for zenith angles between $20^\circ - 27.5^\circ$, while the 2020 and 2022 data sets are more broadly distributed between $20^\circ - 37.5^\circ$. In addition, the 2022 data set covers the zenith angle range of $42.5^\circ - 55^\circ$. For the comparison of the excess and significance rates, the three data sets are separated in zenith angle bands of different ranges for an approximate comparison. The live time per zenith angle band is summarized in Tables 10.5 and 10.6 for the data sets with nominal and reduced trigger setting, respectively.

Table 10.5. Live time per zenith angle band for the Vela pulsar data sets taken with nominal trigger setting.

Zenith Angle Band ($^\circ$)	Live Time (h)	
	Vela 2020	Vela 2022
20 – 30	4.04	4.67
30 – 40	1.87	5.36
40 – 50	0.47	10.61
50 – 60	0.41	5.32

Table 10.6. Live time per zenith angle band for the Vela pulsar data set taken with reduced trigger setting.

Zenith Angle Band ($^\circ$)	Live Time (h)
20.0 – 30.0	41.37
20.0 – 22.5	14.11
22.5 – 25.0	22.13
25.0 – 32.5	6.36

The excess and significance rates for the different zenith angle bands are shown in Figure 10.7. A number of conclusions can be drawn from the corresponding plots. First, the sensitivity decreases with increasing zenith angle, which holds true for both trigger settings. For the Vela pulsar, only a marginal signal is detected for zenith angles $> 30^\circ$ with CT5. Second, a comparison of the 2020 and 2022 rates reveal slightly higher rates at the lowest zenith angle band for the former data set indicating a slight degradation of the instrument from 2020 to 2022. However, the rates across the zenith angle bands are within their errors, so the degradation is not significant. Third, the reduced trigger setting offers a gain in sensitivity with respect to the nominal trigger setting by a factor of $\sim 1.3 - 1.8$ in excess rate and

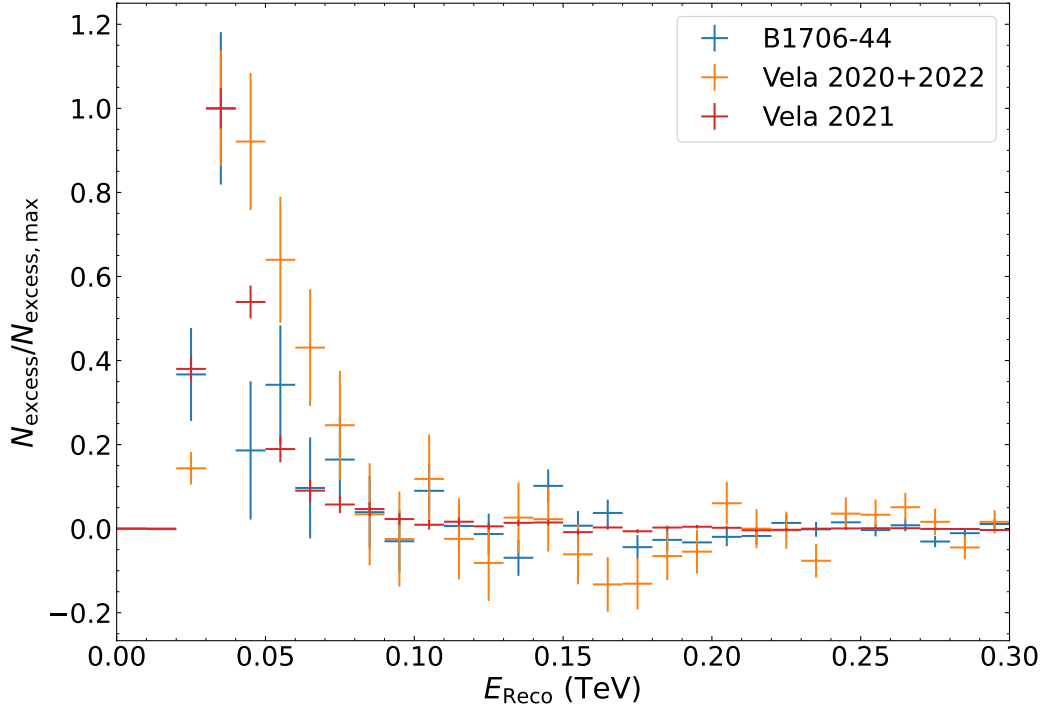


Figure 10.5. Energy excess distribution for the three data sets. The distributions are normalized to the maximum of the respective excess distribution $N_{\text{excess,max}}$. The maximum excess is seen at reconstructed energies of ~ 35 GeV.

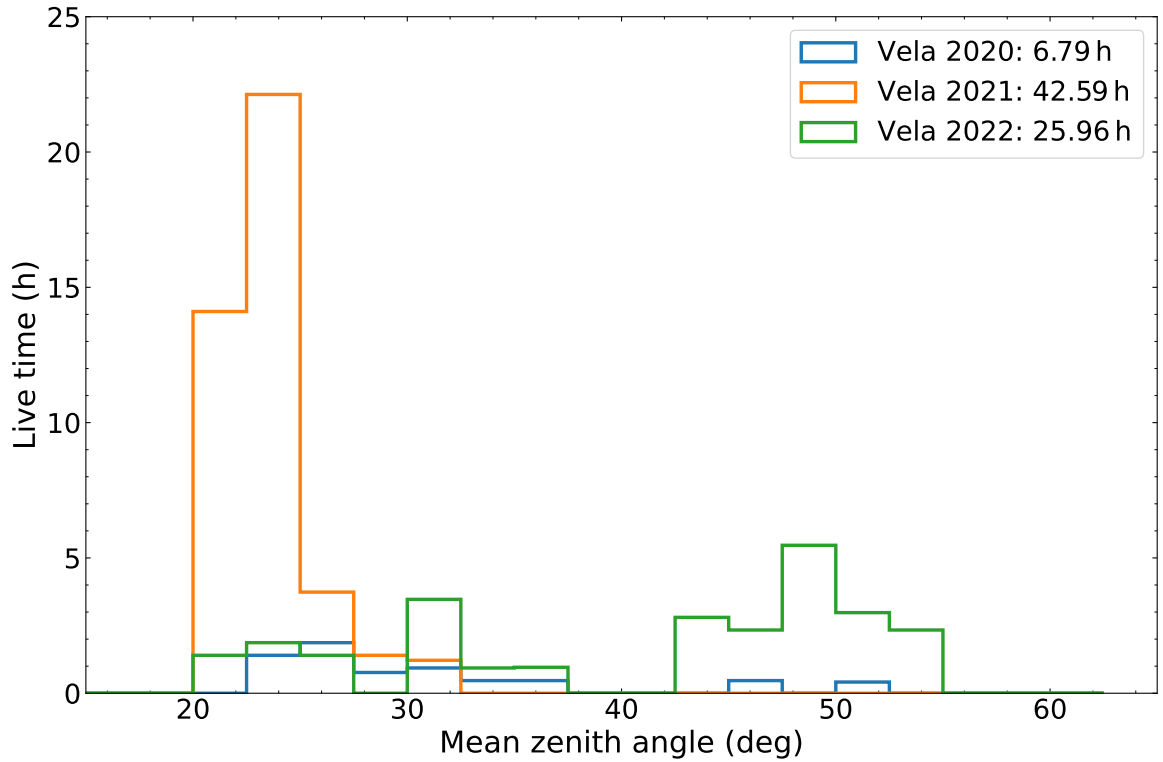


Figure 10.6. Live time distribution as function of the mean zenith angle of the observation for the three Vela pulsar data sets. The data is selected according to the detection criteria.

$\sim 1.4 - 1.8$ in significance rate. The factor range is determined by comparison to the 2020 and 2022 data set, respectively. The calculated rates per zenith angle band are summarized in Tables C.1 and C.2.

In conclusion, the reduced trigger setting is a good observational strategy for astronomical sources with a steep spectrum. Even for the used analysis configuration with the known limitations outlined in Section 9.1.3, the reduced trigger setting offers a gain in sensitivity. Furthermore, the data taken with the reduced trigger setting offers potential for further sensitivity gains, which, however, require additional work on the analysis side by , e.g., decreasing the image amplitude and optimizing the event reconstruction and selection with the reduced trigger setting MC simulations.

10.5. Spectral Analysis

The spectral analysis is performed for the data sets of the Vela pulsar with the nominal trigger setting and the reduced trigger setting using the spectral-1 data selection criteria. The spectral analysis of the pulsar B1706-44 is performed using the spectral-1 and spectral-2 data selection criteria⁴. The differential flux as function of energy E is fitted with a power law according to

$$\Phi(E) = \frac{dN}{dE} = \Phi_0 \cdot \left(\frac{E}{E_0} \right)^{-\Gamma} \quad (10.11)$$

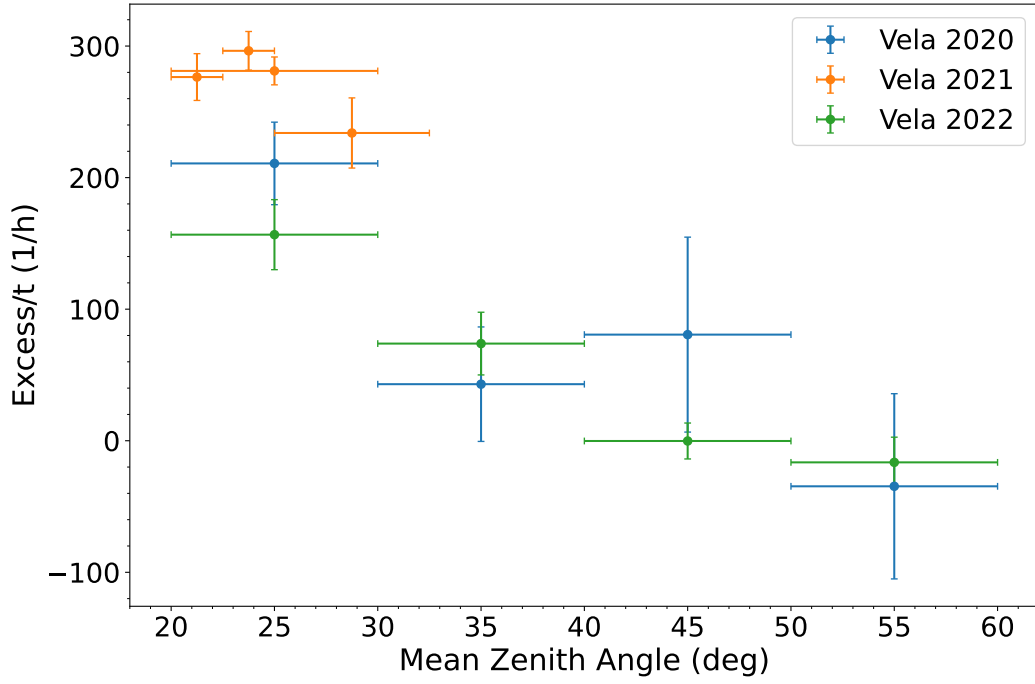
with the normalization factor Φ_0 , the reference energy E_0 and the spectral index Γ . The decorrelation energy E_d of the fit is determined according to

$$E_d = E_0 \cdot \exp \left(\frac{cov(\Phi_0, \Gamma)}{\Phi_0 \Delta \Gamma^2} \right) \quad (10.12)$$

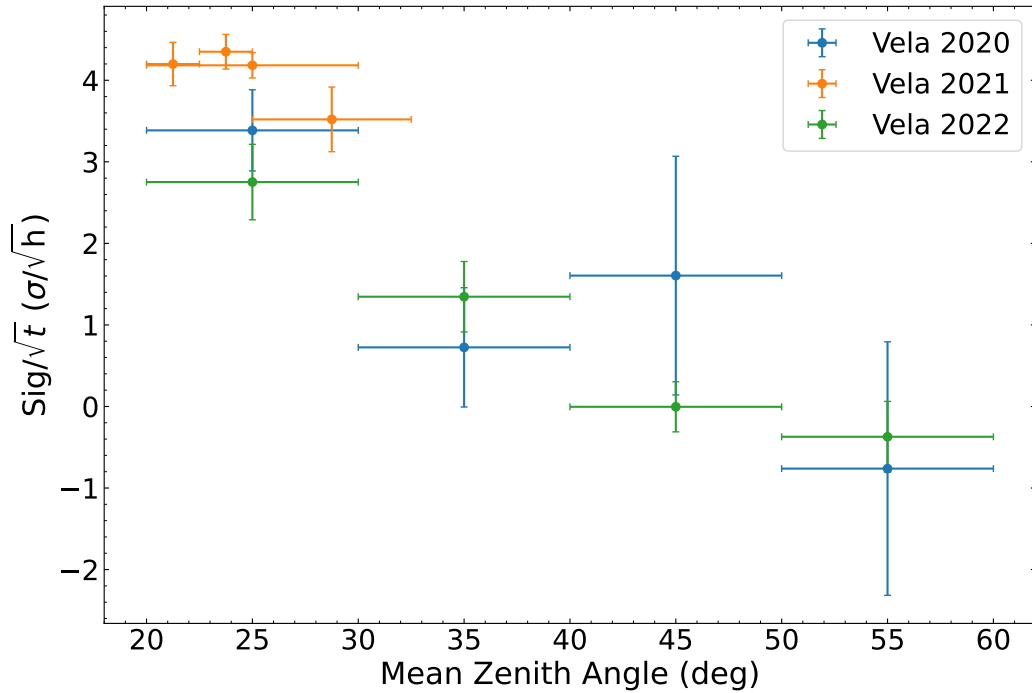
with the covariance $cov(\Phi_0, \Gamma)$ and the error of the spectral index $\Delta \Gamma$ (Equation 1 by Fegan et al. 2009). The fit is performed by applying a safe energy threshold of 10 % of the maximum of the effective area $A_{\text{eff,max}}$. The safe energy threshold is usually applied in the true energy phase space. However, the used version of Gammapy is affected by a bug that effectively applies the safe energy threshold in reconstructed energies neglecting the energy bias⁵. The range of reconstructed energies taken into consideration for the spectral fits is 20 GeV – 110 GeV, which is determined from the positive excess range (see Figure 10.5), and the flux points are calculated for a total of 5 energy bins. The lowest significant energy bin $E_{\text{min,bin}}$ and the highest significant energy bin $E_{\text{max,bin}}$ and their respective significances $\Sigma_{E_{\text{min,bin}}}$ and $\Sigma_{E_{\text{max,bin}}}$ are derived from the spectral fit as well. A bin with a statistical significance of $> 2\sigma$ is determined as significant. The results of the spectral analysis for the Vela pulsar and the pulsar B1706-44 are described in Section 10.5.1 and Section 10.5.2, respectively.

⁴The results of the timing analysis for the respective data selection criteria are summarized in Table C.3 and Table C.4 for the Vela pulsar and B1706-44, respectively.

⁵This is reported as warning by <https://docs.gammapy.org/1.2/api/gammapy.makers.SafeMaskMaker.html> (last visited on September 20, 2024).



(a) Excess rate as function of mean zenith angle.



(b) Significance rate as function of mean zenith angle.

Figure 10.7. Rate comparison between the nominal and reduced trigger setting of FlashCam at CT5. The comparison is performed with the data sets of the observation periods 2020 and 2022 for the nominal trigger setting, and the data set of the observation period of 2021 for the reduced trigger setting.

10.5.1. Vela Pulsar

The spectral fit for the two Vela pulsar data sets and the published spectral fit by H.E.S.S. Collaboration et al. (2018a) is shown in Figure 10.8 and the corresponding fit parameters are summarized in Table 10.7. The residuals of the spectral fit for the nominal and reduced trigger setting data set are shown in Figure C.10.

Table 10.7. Results of the spectral fits of the nominal and reduced trigger setting data set of the Vela pulsar with applied spectral-1 data selection criteria. A power law according to Equation 10.11 is fitted. For the published results the lower and upper end of the lowest $E_{\min,\text{bin}}$ and the highest significant bin $E_{\max,\text{bin}}$ are given, respectively. The published results are taken from H.E.S.S. Collaboration et al. (2018a).

	Vela 2020+2022	Vela 2021	Published
Γ	5.02 ± 0.52	4.37 ± 0.16	4.06 ± 0.16
Φ_0 ($10^{-8}\text{TeV}^{-1}\text{cm}^{-2}\text{s}^{-1}$)	3.84 ± 0.60	3.28 ± 0.15	3.06 ± 0.19
E_0 (GeV)	25	25	25
E_d (GeV)	28.1	26.2	21.5
$E_{\min,\text{bin}}$ (GeV)	39.8 – 50.1	25.1 – 39.8	10.0
$\Sigma_{E_{\min,\text{bin}}} (\sigma)$	4.7	16.6	-
$E_{\max,\text{bin}}$ (GeV)	50.1 – 79.4	79.4 – 100.0	110.0
$\Sigma_{E_{\max,\text{bin}}} (\sigma)$	5.4	4.1	3.3

The combined Vela data set has a steeper spectral index and a higher reconstructed flux Φ_0 at 25 GeV compared to the Vela 2021 and the published Vela results. This could be caused by the lack of statistics for small energies, caused by the lack of observation time at small zenith angles. However, taking the systematic uncertainties derived by H.E.S.S. Collaboration et al. (2022) on the flux normalization of 20 % and on the spectral index of 0.15 into account, the results agree within errors. The spectral index and the reconstructed flux Φ_0 for the Vela 2021 data set agrees within errors with the published results, indicating a proper working principle of the IRFs derived from the adapted MC simulations for the reduced trigger setting. The lowest significant bin of the Vela 2021 data set is smaller than the lowest significant bin of the combined Vela data set taken with the nominal trigger setting, but is still larger than the lower energy bound of the lowest significant bin of the published result. Therefore, further work optimizing the analysis configuration towards lower energies is necessary.

10.5.2. B1706-44

The spectral fit for the two data quality selection criteria of the pulsar B1706-44 and the published spectral fit by Spir-Jacob et al. (2019) is shown in Figure 10.8 and the corresponding fit parameters are summarized in Table 10.8. The residuals of the spectral fit are shown in Figure C.11.

The fit results derived for the spectral-1 and spectral-2 data quality selection criteria agree with each other and the published result. The results for the spectral-2 criteria including the observation runs with problems during data taking has a steeper index than the spectral-1 criteria, but no significant difference is observed. The

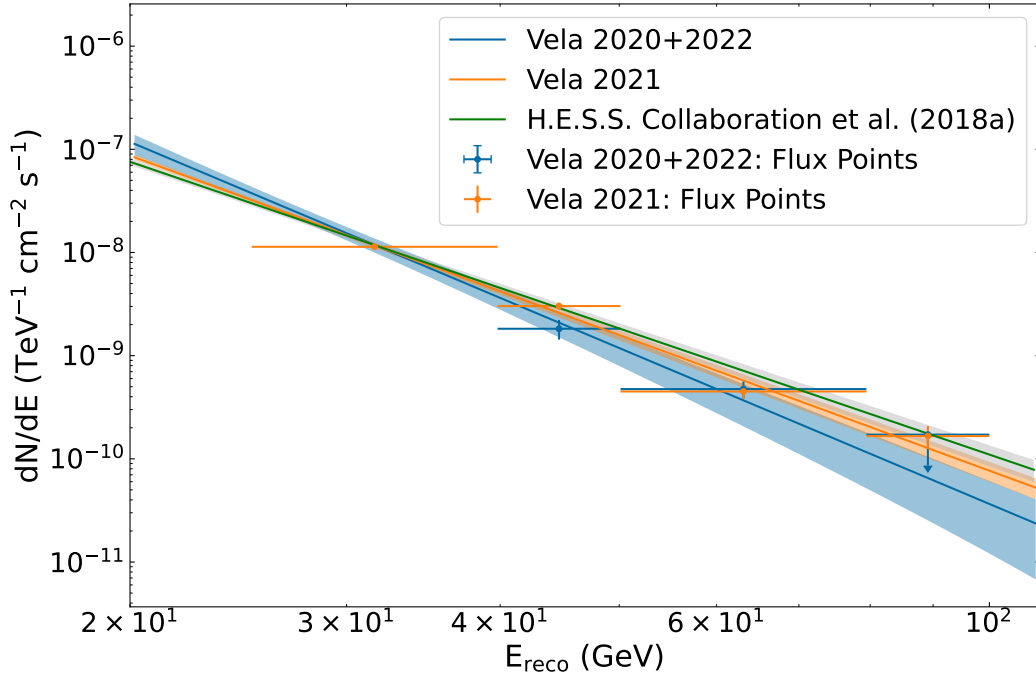


Figure 10.8. Spectral fit results for the nominal (Vela 2020+2022) and reduced trigger setting data set (Vela 2021) of the Vela pulsar. In addition, the spectral fit by H.E.S.S. Collaboration et al. (2018a) is shown as comparison. The fit residuals are shown in Figure C.10 and the fit parameters are summarized in Table 10.7.

Table 10.8. Results of the spectral fits of the data set of the pulsar B1706-44 with applied spectral-1 and spectral-2 data selection criteria. A power law according to Equation 10.11 is fitted. For the published results the lower and upper end of the lowest $E_{\min, \text{bin}}$ and the highest significant bin $E_{\max, \text{bin}}$ are given, respectively. The published results are taken from Spir-Jacob et al. (2019).

	Spectral-1	Spectral-2	Published
Γ	4.61 ± 0.72	4.29 ± 0.55	3.76 ± 0.36
Φ_0 ($10^{-8} \text{TeV}^{-1} \text{cm}^{-2} \text{s}^{-1}$)	3.7 ± 0.8	3.4 ± 0.8	4.3 ± 0.9
E_0 (GeV)	20	20	20
E_d (GeV)	23.8	26.2	21.5
$E_{\min, \text{bin}}$ (GeV)	28.7 – 38.3	28.7 – 38.3	10.0
$\Sigma_{E_{\min, \text{bin}}} (\sigma)$	4.4	4.7	-
$E_{\max, \text{bin}}$ (GeV)	56.2 – 75.0	56.2 – 75.0	62.7
$\Sigma_{E_{\max, \text{bin}}} (\sigma)$	2.2	2.3	-

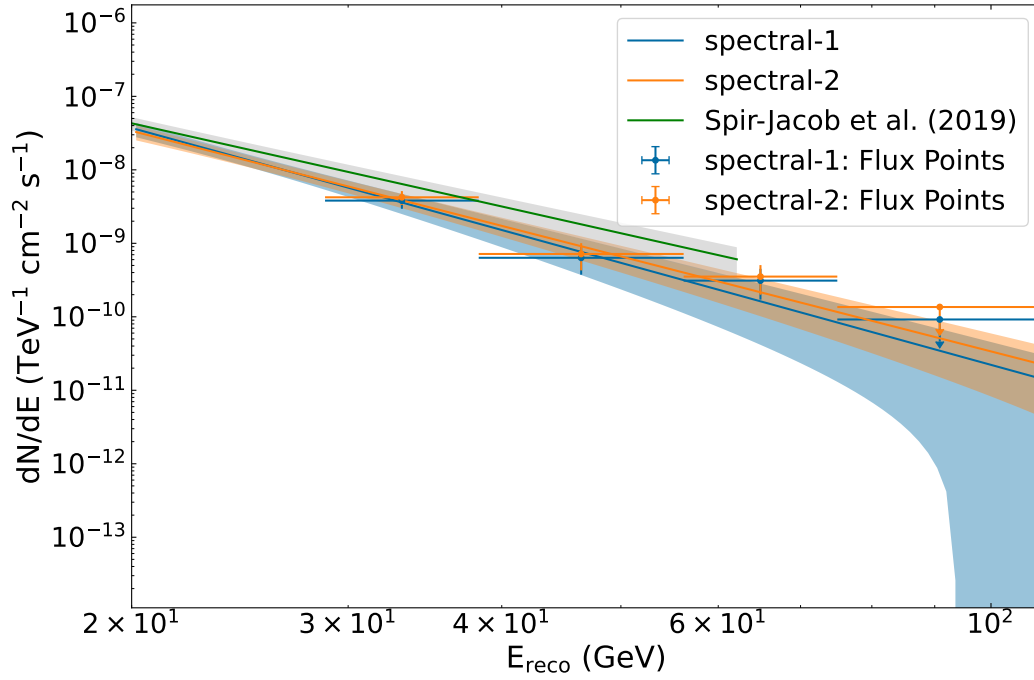


Figure 10.9. Spectral fit results for the reduced trigger setting data set of the pulsar B1706-44. In addition, the spectral fit by Spir-Jacob et al. (2019) is shown as comparison. The fit residuals are shown in Figure C.11 and the fit parameters are summarized in Table 10.8.

agreement with the published results indicate the proper working principle of the IRFs from the adapted MC simulations and no significant impact of the observation runs with problems during data taking on the spectral fit. However, a bottom-up approach to investigate the problematic observation runs to understand the impact of the dips in the CT5 trigger rate on the low- and high-level analysis products is recommended.

Part IV

Summary and Conclusion

No man should escape our universities without
knowing how little he knows.

JULIUS ROBERT OPPENHEIMER

Summary and Conclusion

11.1. Quality Control of Mirror Alignment Components

The first part of this work deals with the quality control of mirror alignment components for the Large-Sized Telescopes (LSTs) and Medium-Sized Telescopes (MSTs) foreseen for the future Cherenkov Telescope Array Observatory (CTAO), a ground-based TeV astronomy facility using Imaging Atmospheric Cherenkov Telescopes (IACTs) of different sizes to detect the Cherenkov light of secondary particle showers initiated by γ -rays with photon energies of $\sim 10^{-2} \text{ TeV} - 10^2 \text{ TeV}$. Because of cost-efficiency and due to reflector design reasons, the reflector of these IACTs consist of up to several hundred individual mirror facets. Each mirror facet is mounted on the mirror support structure with two actuators adjustable in length, and a fixed-length fix point. The tilt of each mirror facet is controlled by the two actuators. The objective of the mirror alignment is to align the mirrors such that each mirror facet reflects the light of a point source into a single point in the focal plane. Consequently, positioning uncertainties in the mirror alignment components impact the optical performance of an IACT and thus the quality of the image of the Cherenkov light distribution recorded by the focal plane instrumentation. The image of the Cherenkov light distribution is characterized by its shape and its position in the focal plane, which are influenced by the optical Point Spread Function (PSF) and the pointing accuracy, the two main performance parameters of the optical system of an IACT, respectively. To fulfill the scientific requirements of the telescope, technical requirements on the mirror alignment components with respect to their mechanical properties are derived. Therefore, the quality control of mirror alignment components plays an important role in ensuring the optical, and thus, the scientific performance of the telescope.

A test stand to quantify the positioning uncertainties of the mirror alignment components by measuring their force-displacement characteristics was designed and developed at the Institut für Astronomie und Astrophysik Tübingen (IAAT) and is patented under Diebold et al. (2023). It allows the application of compressive and tensile loads on a tested object with rotational interfaces (e.g., a cardanic mounting), and the measurement of the respective displacement of the tested object for a given load with a displacement resolution of $\sim 10 \mu\text{m}$. The test stand offers the possibility to measure the different mirror alignment components (actuators and fix points), as well as single parts thereof. The single parts comprise the spherical bearings used as mirror-sided interface of the mirror alignment component and the gimbals with 1-DOF and 2-DOF of the actuators for the telescope-sided interface. The measurement of the force-displacement characteristics is automated by using a force control, which is implemented as a feedback loop, and the displacement is measured by a dial gauge with a systematic measurement uncertainty of $\leq 2 \mu\text{m}$ controlled by an external PC.

This thesis provides key insights into the measurement theory and the assessment of the systematic and statistical errors affecting the measurement accuracy of the mechanical properties of a tested object.

The force-displacement characteristics of the mirror alignment components are characterized by elastic and viscoelastic behavior, as well as mechanical play. From the measured force-displacement characteristics the mechanical properties can be derived, which are the mechanical play, viscoelastic deformation and the absolute displacement for a given maximum compressive and tensile load. The viscoelastic behavior is attributed to the Polytetrafluoroethylene (PTFE) used as contact sliding surface in the spherical bearing. For the actuators, a mechanical play is introduced by, e.g., the gimbal as shown by Salzmann et al. (2024).

The measurement accuracy of the force-displacement test stand was assessed qualitatively and, whenever possible, quantitatively regarding the systematic and statistical errors that are present during a measurement. The error sources are defined as systematic or statistical (random) errors according to the convention of Joint Committee for Guides in Metrology (2012). For a measurement with the same measurement conditions, a systematic error remains constant or changes in a predictable way, whereas a statistical error changes in an unpredictable way. According to these definitions, the measurement error of the dial gauge, the force control, the measurement procedure, and the assembly of the test stand are classified as systematic error. While the dial gauge affects the measured displacement directly, the other three systematic error sources affect it indirectly. The study of the measurement procedure revealed that a single load cycle is sufficient for a measurement of the force-displacement characteristics of the mirror alignment components. An error on the force control value after introducing a new, automatic force calibration has a negligible impact on the measured force-displacement characteristics of a typical mirror alignment component. The qualitative assessment of the test stand assembly emphasizes the need for a precise alignment of the force and displacement measurement direction with the test object. The procedure to mount the test object into the test stand introduces a statistical error, which is present for repeated measurements of the same test object when it is de- and remounted from the test stand. The statistical error is caused by clearances in the telescope-sided and mirror-sided interface of the test stand. This statistical error on the mechanical properties was quantified for an exemplary actuator with a 2-DOF gimbal. The statistical error is $\pm 5 \mu\text{m}$ on the mechanical play and the absolute displacement. In future, the statistical error needs to be quantified for the fix point and the actuator with the 1-DOF gimbal as well. In principle, a test object with defined force-displacement characteristics would be needed for a detailed quantitative verification of the measurement accuracy of the test stand. Such a test object is not straightforward to design and does not exist currently. Some brief considerations on the mathematical model of such a test object are given in this thesis.

The test stand was already used successfully for the performance evaluation of D-series actuators foreseen for LSTs and MSTs. As reported by Diebold (2020), the two main conclusions of this investigation was the reevaluation of the spherical bearings and the gimbals of the actuators. Within the scope of this thesis, the performance evaluation of 15 fix points and two 2-DOF gimbal design was performed in late summer 2021 for the Max-Planck-Institut für Physik (MPP). Five each of the fix points were equipped with different graded spherical bearings. The bearing grades

are labeled C0, C1 and C2 with increasing mechanical play along the longitudinal direction. Three characteristics of the spherical bearings were investigated. First, the force-displacement characteristics revealed the viscoelastic properties of the spherical bearing, which is attributed to the Polytetrafluoroethylene (PTFE) used as contact sliding surface between joint head and joint socket. Second, the absolute displacement for a given set of compressive and tensile loads representing the expected observation conditions was evaluated. Third, the breakaway torque of the spherical bearings was investigated. When the actuators are mounted at the telescope, a too high breakaway torque of the spherical bearings can lead to a deformation of the mirror when the actuator moves and, in the worst case scenario, that the interface between the mirror and the actuator breaks. In the end, the decision fell toward the C1 graded spherical bearing as they offered satisfactory performance with respect to the absolute displacement ($\bar{d}_{C1,abs.disp.} = (9.9 \pm 6.2) \mu\text{m}$) and breakaway torque ($\tau_{mean,C1} = 2.7^{+2.2}_{-1.9} \text{Nm}$).

The two gimbal designs differed in the type of bearing used as interface between the mounting axes and the telescope-sided interface. For the ball bearing design, this interface is a ball bearing, while for the baseline design this interface is a plain bearing. In addition, this study investigated the effect of different set screw configurations to fixate the mounting axes with respect to the telescope-sided interface. The set screw configuration, which fixates the mounting axes by a single point of contact is identified as the best set screw configuration. For this set screw configuration, the baseline version offered a better performance with an absolute displacement of $d_{baseline} = (39.0 \pm 1.2) \mu\text{m}$ compared to the ball bearing version $d_{ball\ bearing} = (109.1 \pm 1.2) \mu\text{m}$. Therefore, the baseline gimbal design is used for the actuators of the LSTs and MSTs. The identified set screw configuration is recommended for the installation of actuators at the telescope.

The last and main conclusion from this study was that the absolute displacement of a test object needs to be the figure of merit for the quality control. The absolute displacement is derived for a maximum tensile and compressive load, which are expected during observations. This conclusion is motivated by the fact that the spherical bearings introduce a viscoelastic behavior into the force-displacement characteristics of the mirror alignment components. These viscoelastic effects are a) very difficult to disentangle from the elastic contributions to the force-displacement characteristics, and b) are depending on the unknown load history and load level during observations. Both of these effects influence the positioning uncertainties of the mirror alignment components in a non-reproducible way. Therefore, they can not be corrected for with respect to the pointing accuracy and the optical PSF of the telescope and need to be verified beforehand against the requirements derived from the telescope scientific requirements.

As a final result of these studies, there exists a force-displacement test stand for the performance evaluation and quality control of the large-scale production of mirror alignment components for the MSTs and LSTs (CTAO-South), which is about to start at the end of this thesis work.

During operations, the mirror alignment status and the optical performance of an IACT is monitored by measuring the optical PSF in regular time intervals. The optical PSF monitoring of the five IACTs of the High Energy Stereoscopic System (H.E.S.S.) experiment was the service work of the author within the H.E.S.S. collaboration. As

part of this service work, the author did the day-to-day supervision of the master's project by Arroyo Salas (2023). Within this master's project, an algorithm to determine the optical PSF of the FlashCam installed in the 28 m telescope of H.E.S.S. was developed. As FlashCam is a camera foreseen for the MST, the algorithm is a valid solution for the future PSF monitoring of FlashCam-equipped MSTs.

11.2. Pulsar Analysis with H.E.S.S. CT5

The second part of this work deals with the analysis of two pulsars using the 28 m telescope (CT5) of the currently operating ground-based TeV astronomy facility High Energy Stereoscopic System (H.E.S.S.). Pulsars are rapidly rotating neutron stars with strong magnetic fields that accelerate charged particles leading to the consequent emission of electromagnetic radiation, which shows a pulsed nature in case the rotation axis and the magnetic field axis are not aligned. The high energy emission of pulsars can be constrained using CT5, which can bridge the gap to space-based observatories and offers the possibility to study the spectral cut-off region in the ~ 10 GeV region with high statistics. Emission in the 10 GeV – 100 GeV range from both of the pulsars studied in this thesis, the Vela pulsar and the pulsar B1706-44, have been detected with H.E.S.S. CT5 already with a statistical significance of 15.6σ and 4.7σ , respectively (H.E.S.S. Collaboration et al. 2018a; Spir-Jacob et al. 2019). After the installation of a FlashCam, a camera type foreseen for the MST of the CTAO, in H.E.S.S. CT5 in October 2019, the timing system of the camera was verified with observations of the Vela pulsar in 2020. This was done by the author and is reported in Pühlhofer et al. (2021). The observations of the Vela pulsar motivated the reduction of the nominal camera trigger settings of FlashCam at CT5 by 15 % to further explore the low energy potential of the camera. With this reduced camera trigger setting, both pulsars were observed in the observation period of 2021 and a first comprehensive analysis with a preliminary analysis configuration is reported in this thesis.

End-to-end Monte Carlo (MC) simulations of the Cherenkov light emitted by the secondary particle shower and the instrument response are of major importance for the analysis of data acquired with IACTs. They serve as input to the algorithms responsible for reconstructing the energy and direction of the γ -ray events, as well as for differentiating the γ -ray events from hadronic background events. Furthermore, the instrument response functions are derived from MC simulations, which are necessary to produce higher level analysis products such as spectra. Ideally, they represent accurately the instrument conditions, as well as the observation conditions such as the atmospheric transparency and the NSB level. In this thesis, the fully validated MC simulations for the H.E.S.S. Analysis Program (HAP) analysis chain are adapted to the reduced camera trigger setting and the environmental conditions present during the pulsar observations. The validation of the MC simulations is described by Leuschner et al. (2023).

The trigger threshold derived from the observations of (59.6 ± 0.4) p.e. and (59.2 ± 0.6) p.e. for the Vela pulsar and pulsar B1706-44, respectively, agree within errors with the trigger setting derived from MC simulations of 59.5 p.e. The Night Sky Background (NSB) level for the MC simulations that represents the NSB in the sky fields of the two pulsars within $\sim 1\%$ results in 519.7 MHz for a CT5 optical efficiency

of 0.76. As a third quantity, the atmospheric transparency was investigated using aerosol measurements of an instrument of the Aerosol Robotic Network (AERONET) project installed at the H.E.S.S. site for the time of the pulsar observations and compared to three different transmission profiles that are used as standard for the MC simulations of HAP. The derived conditions for the NSB level and atmospheric transparency, as well as the reduced trigger setting were provided as input to K. Bernlöhner at the Max-Planck-Institut für Kernphysik (MPIK) for the simulations.

As a next step, the Instrument Response Functions (IRFs) between the reduced and the nominal trigger setting for the same environmental conditions were compared, which resulted in two main conclusions. First, with the currently applied analysis, no significant difference in the safe energy threshold derived from the effective area and the energy bias between the reduced and the nominal trigger setting is present. The safe energy threshold determines the lower energy range for a spectral analysis. However, this could be caused by the fact that the algorithms to reconstruct the energy and direction, as well as separate γ -rays from hadronic background events, are not trained on the MC simulations with the reduced trigger setting for the applied analysis. Second, there is a significant increase of the effective area for energies $\lesssim 80$ GeV, which contributes to the increased excess and significance rates reported next.

The last step included the analysis of the data acquired on the Vela pulsar and pulsar B1706-44 with the reduced trigger setting. In addition, Vela data taken in 2020 and 2022 with the nominal trigger setting was used as a comparison. A set of empirical, preliminary data quality selection criteria for the detection and the spectral analysis were derived. For the Vela data sets, the pulsed emission of the P2 was detected with a statistical significance of 27.3σ and 6.8σ for the reduced and the combined nominal trigger data sets, respectively. In addition, as first reported by Bedur Ramesh (2024), there are hints of the P1 and P3 peak of the Vela pulsar with the reduced trigger data set. The P1 and P3 peak are seen with a statistical significance of 2.96σ and 3.95σ , respectively. The pulsed emission of the pulsar B1706-44 is seen with a statistical significance of 5.7σ .

The main focus of the data analysis was then two-fold. First, to quantify the impact of the reduced trigger setting with respect to the nominal trigger setting on the event statistics, which are relevant for the detection of a source. This was accomplished by binning the Vela data sets of the three observation periods 2020, 2021 and 2022 into various zenith angle bins and calculating the respective excess and significance rates. For the zenith angle range of $20^\circ - 30^\circ$, the reduced trigger setting offers a gain in sensitivity with respect to the nominal trigger setting by a factor of $\sim 1.3 - 1.8$ in excess rate and $\sim 1.4 - 1.8$ in significance rate. The factor range is determined by comparison to the 2020 and 2022 data set, respectively. In addition, there is the possibility for a further increase in sensitivity, which requires optimization work on the analysis side.

Second, the working principle of the derived IRFs using the MC simulations adapted to the observation conditions and the calculation of the spectra needs to be verified. For the Vela pulsar, the derived flux and spectral index of the data set using the nominal trigger setting and the reduced trigger setting agree within errors with the published results by H.E.S.S. Collaboration et al. (2018a). For the pulsar B1706-44, the derived spectra agrees within errors with the published results by

Spir-Jacob et al. (2019). Therefore, the working principle of the IRFs derived from the MC simulations with the reduced trigger setting is verified.

The main conclusion is that the reduced trigger setting is a good observational strategy for astronomical sources with a steep spectrum. Even given the limitations of the applied analysis, the reduced trigger setting offers a gain in sensitivity with respect to the event statistics and source detection. Furthermore, it offers potential for further improvement for a spectral reconstruction, which, however, requires additional work on the analysis side.

Part V

Appendix and Bibliography

Appendix A

Part I

A.1. CT1-5: Optical Point Spread Function vs. Time

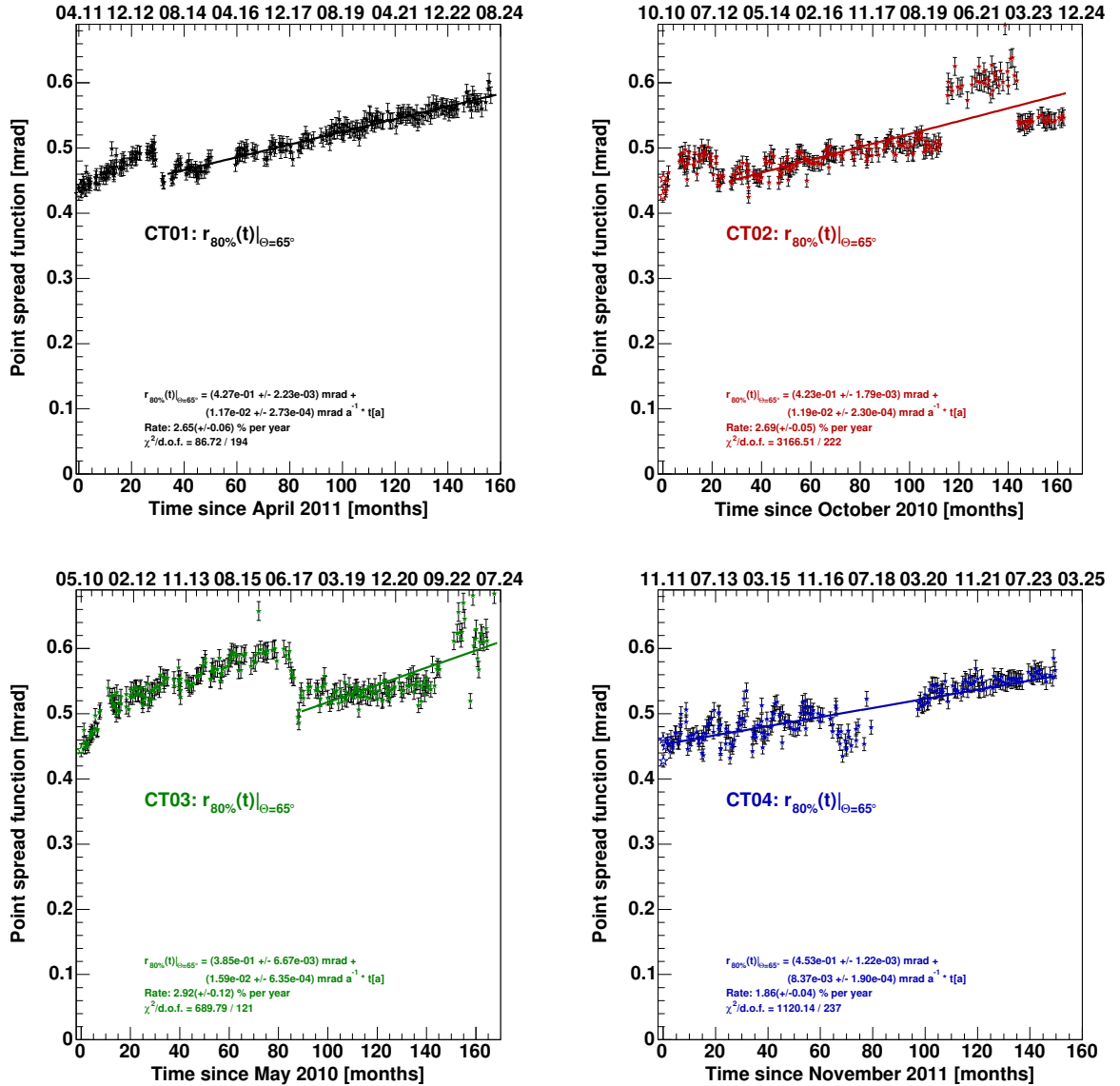


Figure A.1. Temporal evolution of the optical PSF for CT1-4 as of May 3, 2024.

The $r_{80\%}$ is evaluated at an elevation angle of 65° from the elevation-dependent $r_{80\%}$ distribution. The observed deviations from the trend for CT2 (upper right) and CT3 (lower left) coincident with hardware changes of the LidCCD. It was verified that these are no telescope caused deviations.

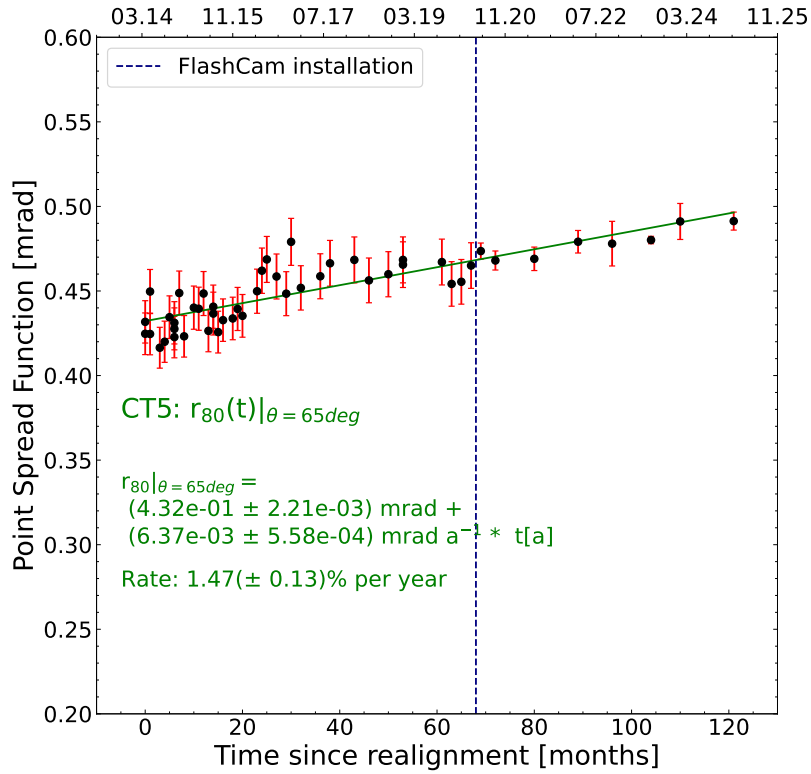


Figure A.2. Temporal evolution of the optical PSF for CT5 as of May 3, 2024.

The $r_{80\%}$ is evaluated at an elevation angle of 65° from the elevation-dependent fit of the model to the $r_{80\%}$ distribution. The dashed vertical line indicates the point in time at which FlashCam was installed into CT5. Before that, the $r_{80\%}$ is determined with the SpotExtraction algorithm described in Cornils (2006) and after that with the radial profile algorithm described in Arroyo Salas (2023). The error bars are determined differently between the two algorithms.

Appendix B

Part II

B.1. Davies-Cotton versus Parabolic Reflector Layout

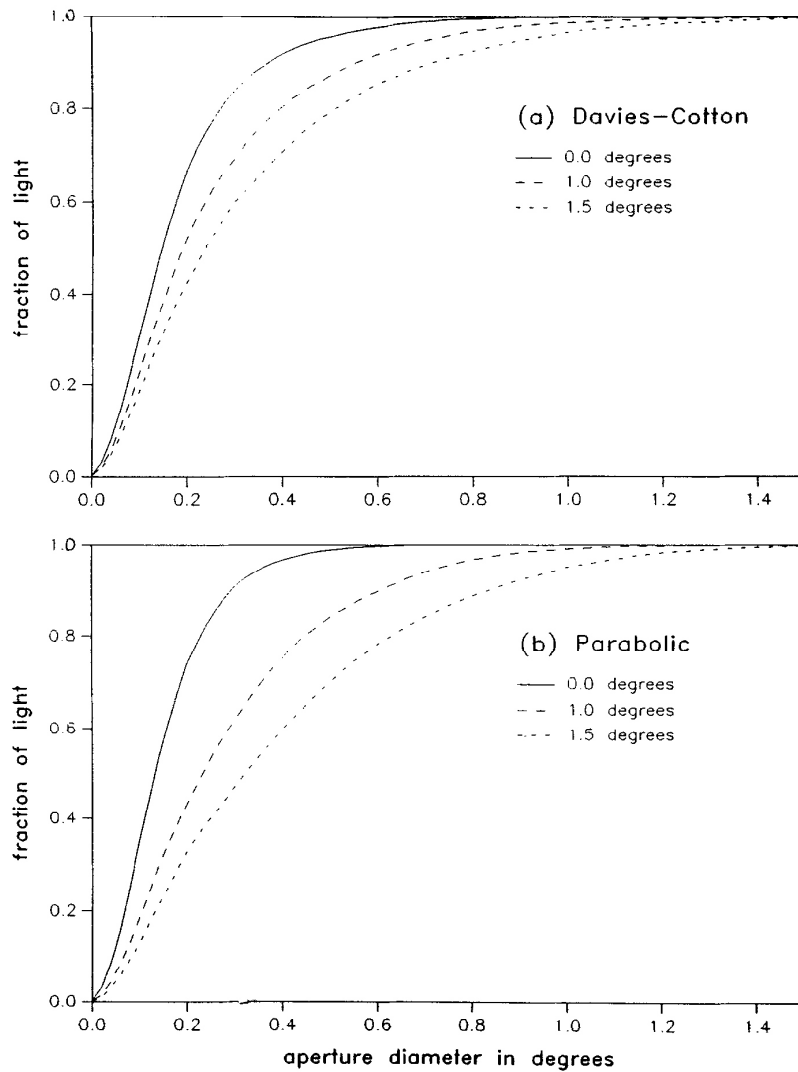


Figure B.1. Simulated integrated light intensity for a Davies-Cotton (top) and a parabolic shaped reflector (bottom). Both reflectors have a diameter of 10 m. The integrated light intensity is calculated for a source with offset angles of 0.0° , 1.0° and 1.5° as a function of the diameter of a circle, which is centered at the position of the image and is located in the focal plane. While the parabolic design offers a better PSF close to the optical axis, the Davies-Cotton design offers a better optical for increasing offset angles. Taken from Lewis (1990).

B.2. Wind Load Simulations

Table B.1. Assumptions for the simulations of the load on a single actuator for the MST depending on the wind speed, wind direction, and elevation angle. Information taken from Gadola (2018a).

Parameter	Value
Wind Speed	36 km h ⁻¹
Wind Direction	parallel to ground, front and back
Drag Coefficient	1.2
Air Density (@1800 m and -5°)	1.05 kg m ⁻³
Mirror weight	40 kg
Radius of Curvature Mirror System	19.2 m
Mirror Diameter (flat-to-flat)	1.2 m

B.3. Actuator Displacement Test Stand

Table B.2. Measured play and absolute displacement for the selected 2-DOF actuator assembly. A total of ten test cycles were performed with a maximum test force of $F = \pm 150$ N. An initialization cycle with a maximum initialization force of $F_{\text{init}} = \pm 500$ N was performed before the first test cycle. The absolute displacement, play and their errors are calculated according to Equations 6.1, 6.4, 6.6 and 6.7. The play is calculated for a test force release of $F_{\text{unload.,release,push/pull}} = \pm 15$ N. The weighted mean of the play and absolute displacement and their respective errors (Equations 6.8 and 6.9) result in $d_{\text{play}} = (107.1 \pm 0.5) \mu\text{m}$ and $d_{\text{abs. disp.}} = (168.3 \pm 0.6) \mu\text{m}$. The measurement was performed on August 8, 2024, at 17 : 36 : 54.

Test Cycle	$d_{\text{play}} (\mu\text{m})$	$\Delta d_{\text{play}} (\mu\text{m})$	$d_{\text{abs. disp.}} (\mu\text{m})$	$\Delta d_{\text{abs. disp.}} (\mu\text{m})$
1	108.0	1.7	169.4	1.8
2	107.7	1.7	169.5	1.8
3	107.5	1.7	169.1	1.8
4	107.1	1.7	168.7	1.8
5	107.0	1.7	168.3	1.8
6	107.1	1.7	168.0	1.8
7	106.6	1.7	167.9	1.8
8	107.2	1.7	167.4	1.8
9	106.5	1.7	167.4	1.8
10	106.1	1.7	167.1	1.8

Table B.3. Results of the measurement of the selected 2-DOF actuator assembly to determine the statistical error of the mounting procedure. See Section 6.3.5 for more details.

Operator	d_{play} (μm)	Δd_{play} (μm)	$d_{\text{abs. disp.}}$ (μm)	$\Delta d_{\text{abs. disp.}}$ (μm)
1	103.1	1.7	175.9	1.7
	105.9	1.7	182.0	1.8
	102.6	1.8	172.8	1.8
	106.4	1.7	182.2	1.7
	99.5	1.7	168.2	1.8
	98.2	1.8	169.0	1.8
	98.0	1.7	167.6	1.7
2	104.4	1.6	179.0	1.8
	100.0	1.7	170.5	1.7
	99.9	1.7	176.9	1.8
	96.7	1.7	167.7	1.7
	96.2	1.8	165.4	1.7
	99.7	1.8	172.6	1.7
3	102.9	1.7	175.7	1.7
	105.2	1.8	179.2	1.8
	101.6	1.7	172.9	1.8
	104.5	1.8	175.1	1.7
	103.1	1.8	173.3	1.8
	103.4	1.7	172.4	1.7
	102.9	1.7	172.7	1.8
	99.1	1.7	167.8	1.8
	100.0	1.8	170.2	1.8
	104.3	1.7	174.9	1.6
	104.8	1.8	175.8	1.8

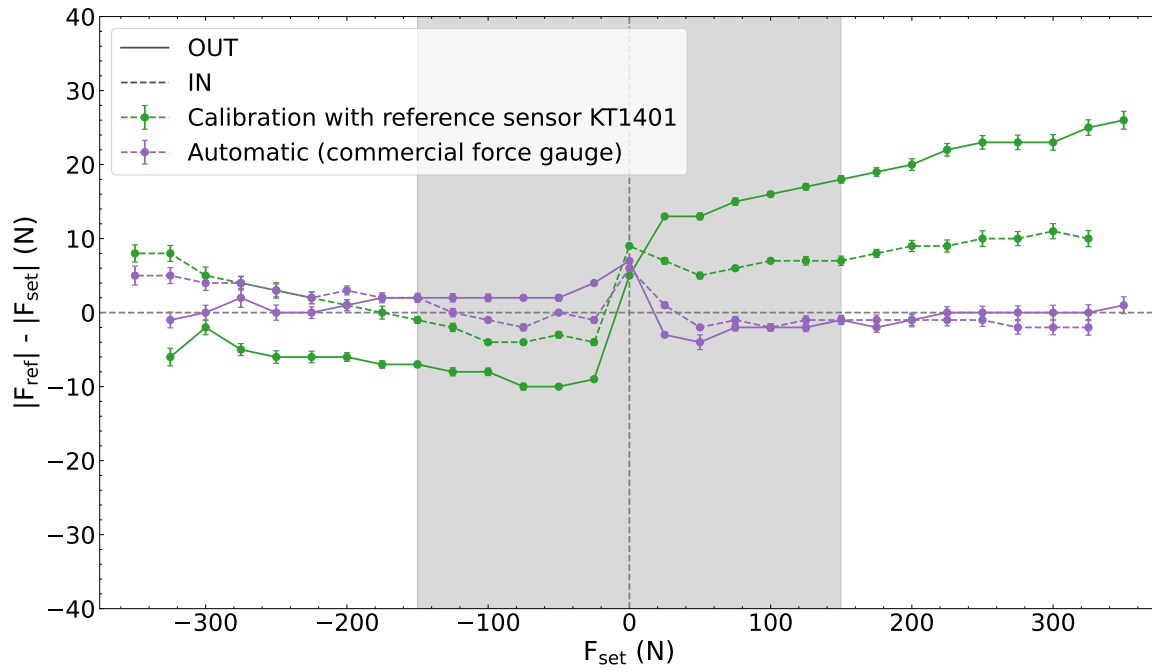


Figure B.2. Comparison of two calibrations of the TSAMP 100 force sensor. The difference of the absolute reference force F_{ref} of the commercial force gauge at the position of the test object and the absolute set force of the ACU F_{set} is shown as a function of F_{set} . One calibration was determined with the force sensor KT1401 at the position of the test object (*Datenblatt für Kraftsensoren - Serie KT1401* 2024) and the automatic one with the commercial force gauge (*Dynamometer PCE-PFG 2K* 2024).

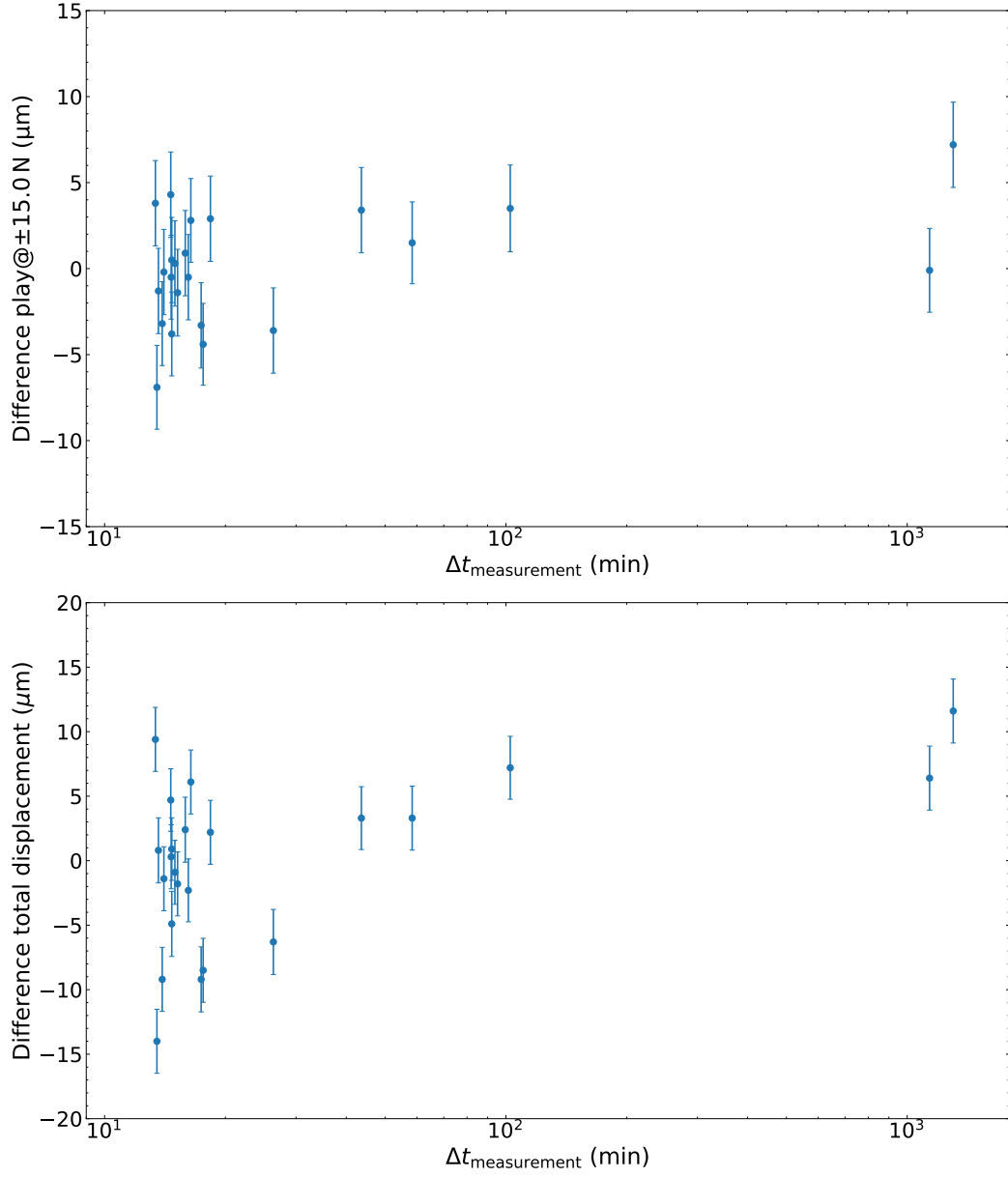


Figure B.3. Difference of the mechanical play (top) and the absolute displacement (bottom) of a series of measurements as a function of the time difference between measurements $\Delta t_{\text{measurement}}$.

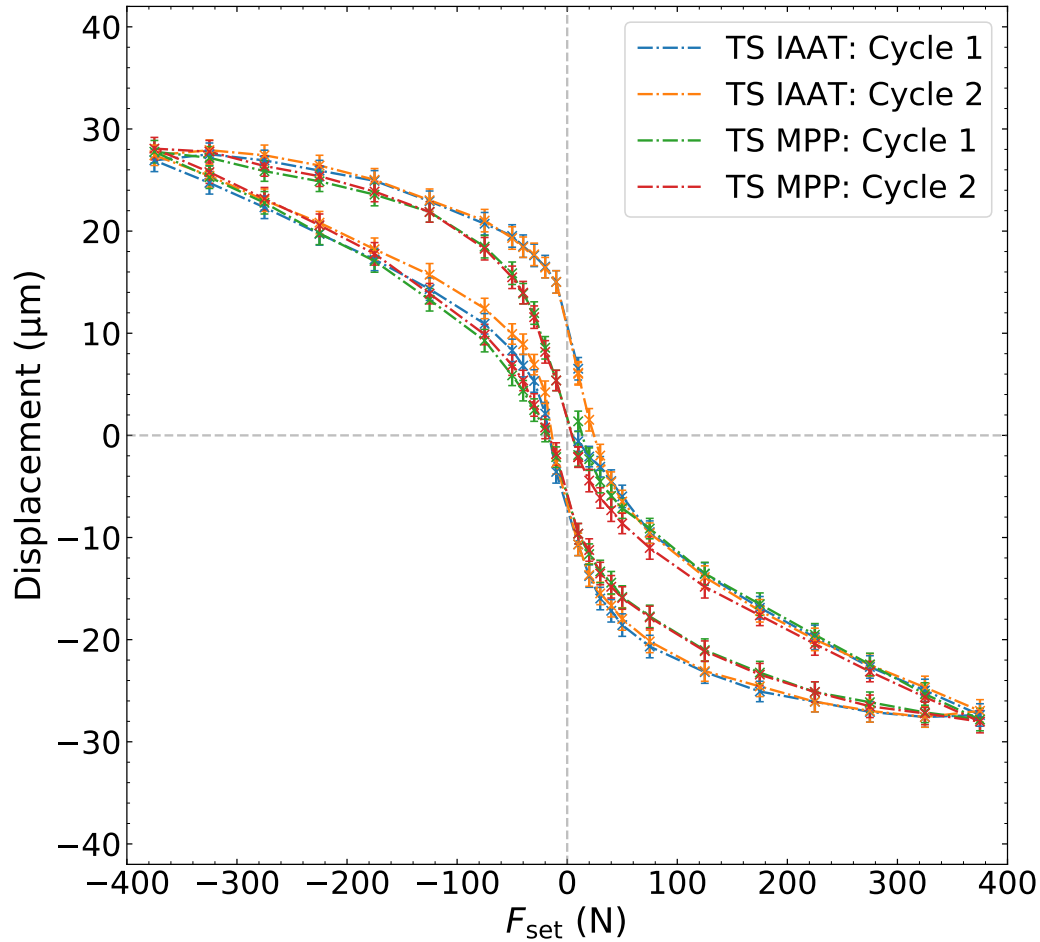


Figure B.4. Verification measurement between the test stand IAAT and the test stand MPP. The test object is a dummy actuator with a 2-DOF gimbal and a spherical ball bearing. A dummy actuator is a steel rod as replacement of the actuator. For the test stand IAAT a single curve calibration without correction for the static friction of the mounting sled is used and for the test stand MPP the double curve calibration approach with correction for the static friction is used. The absolute displacement of the two measurements agrees within $\sim 5 \mu\text{m}$. Some differences are visible close to $\sim 0 \text{ N}$, which is expected due to the two different calibrations.

B.4. Measurement Results

Table B.4. Complete results of the mechanical properties of the fix point study. Over the three test cycles, the weighted mean $\bar{d}_{w,abs. disp.}$, the standard deviation of the weighted mean $\sigma_{w,abs. disp.}$ and the standard deviation of the distribution $\sigma_{abs. disp.}$ are calculated according to Eqs. 6.8 to 6.10, respectively.

Label	$\bar{d}_{w,abs. disp.}$ (μm)	$\sigma_{w,abs. disp.}$ (μm)	$\sigma_{abs. disp.}$ (μm)
C0 ₁	3.1	0.6	1.0
C0 ₂	3.7	0.6	1.1
C0 ₃	4.1	0.6	1.1
C0 ₄	3.8	0.7	1.1
C0 ₅	4.2	0.6	1.1
C1 ₁	17.7	0.7	1.2
C1 ₂	3.1	0.6	1.1
C1 ₃	13.0	0.7	1.1
C1 ₄	11.8	0.6	1.1
C1 ₅	3.9	0.6	1.0
C2 ₁	15.4	0.6	1.1
C2 ₂	23.7	0.7	1.1
C2 ₃	19.0	0.7	1.1
C2 ₄	15.5	0.7	1.2
C2 ₅	22.4	0.7	1.1

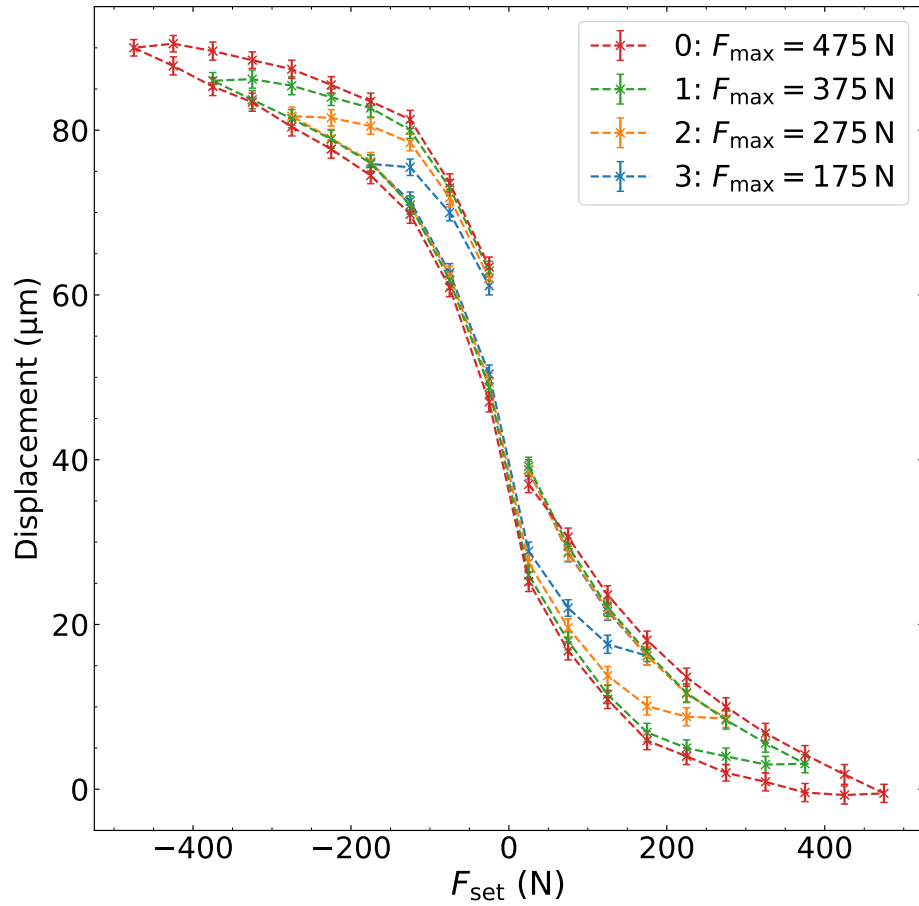


Figure B.5. Force-displacement characteristics for different maximum force values. The measured test object is a dummy actuator with a 1-DOF gimbal and an exemplary spherical bearing. The dependence of the relaxation behavior of the spherical bearing on the loading level is visible. The first number in the legend indicates the time sequence of the measurements.

Table B.5. Results of the breakaway torque study of the 15 fix points measured at IAAT. The minimum and maximum breakaway torque $\tau_{b,\min}$ and $\tau_{b,\max}$ are determined with Equation 7.1 and using the radius of the flange bearing $r_{\text{flange}} = 32.5 \text{ mm}$. The mean breakaway torque per fix point $\tau_{\text{mean,fp}}$ is determined with Equation 7.2.

Fix Point	$F_{b,\min}$ (N)	$F_{b,\max}$ (N)	$\tau_{b,\min}$ (N m)	$\tau_{b,\max}$ (N m)	$\tau_{\text{mean,fp}}$ (N m)
C0 ₁	125	150	4.1	4.9	4.5
C0 ₂	125	150	4.1	4.9	4.5
C0 ₃	75	100	2.4	3.3	2.8
C0 ₄	125	150	4.1	4.9	4.5
C0 ₅	150	175	4.9	5.7	5.3
C1 ₁	25	50	0.8	1.6	1.2
C1 ₂	75	100	2.4	3.3	2.8
C1 ₃	50	75	1.6	2.4	2.0
C1 ₄	75	100	2.4	3.3	2.8
C1 ₅	125	150	4.1	4.9	4.5
C2 ₁	25	50	0.8	1.6	1.2
C2 ₂	25	50	0.8	1.6	1.2
C2 ₃	50	75	1.6	2.4	2.0
C2 ₄	50	75	1.6	2.4	2.0
C2 ₅	25	50	0.8	1.6	1.2

Part III

C.1. Data Analysis Methods

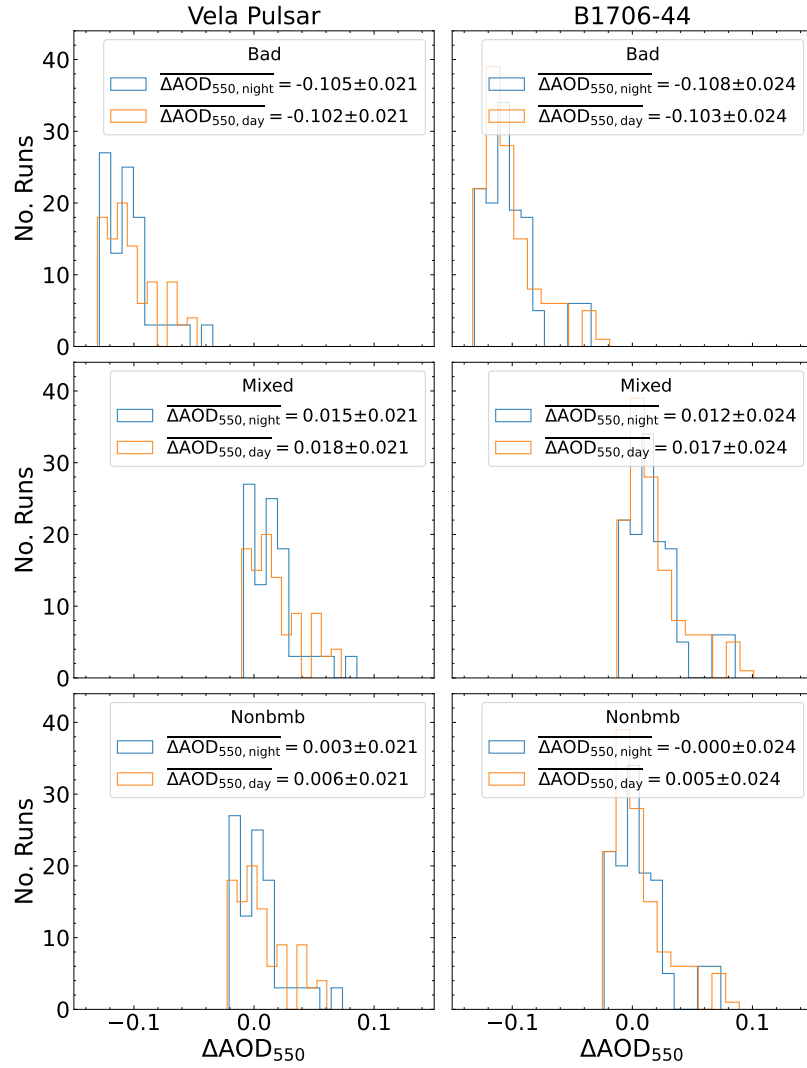
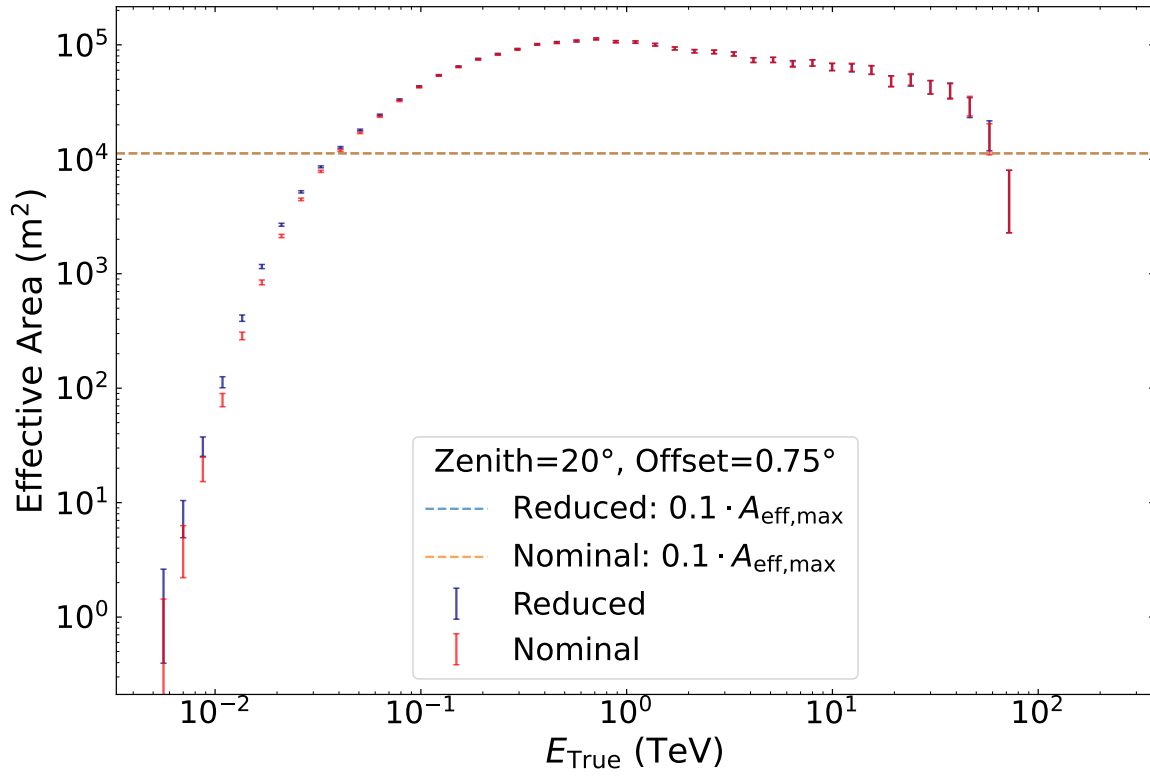
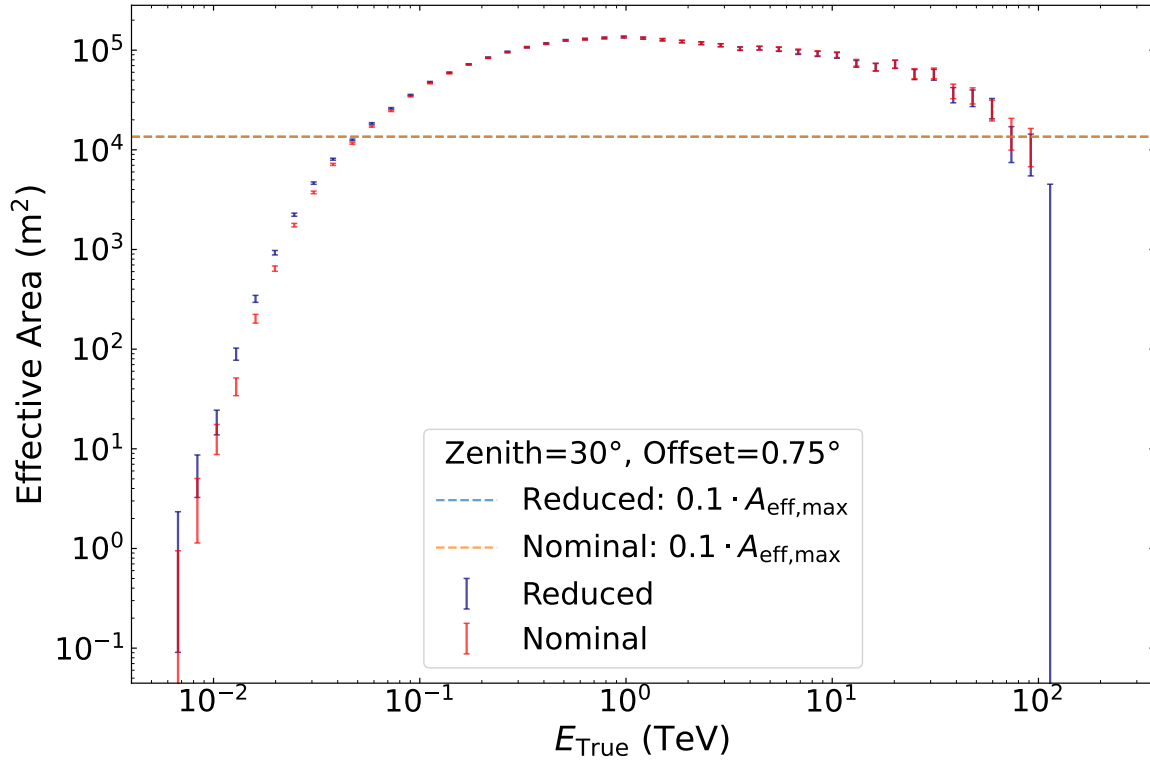


Figure C.1. Distribution of $AOD_{550}(i)$ values calculated according to Equation 9.14 for the pulsar observations with reduced trigger setting. The results are shown for the Vela pulsar (left column) and B1706-44 (right column) for the three reference transmission profiles "Bad" (top row), "Mixed" (middle row), and "Nonbmb" (bottom row). The transmission profiles are provided by T. Holch (DESY).



(a) For a zenith angle of 20° and an offset angle of 0.75°.



(b) For a zenith angle of 30° and an offset angle of 0.75°.

Figure C.2. Comparison of the effective area A_{eff} between the reduced and the nominal trigger setting. In addition, 10% of the maximum of the effective area $A_{\text{eff,max}}$ is indicated.

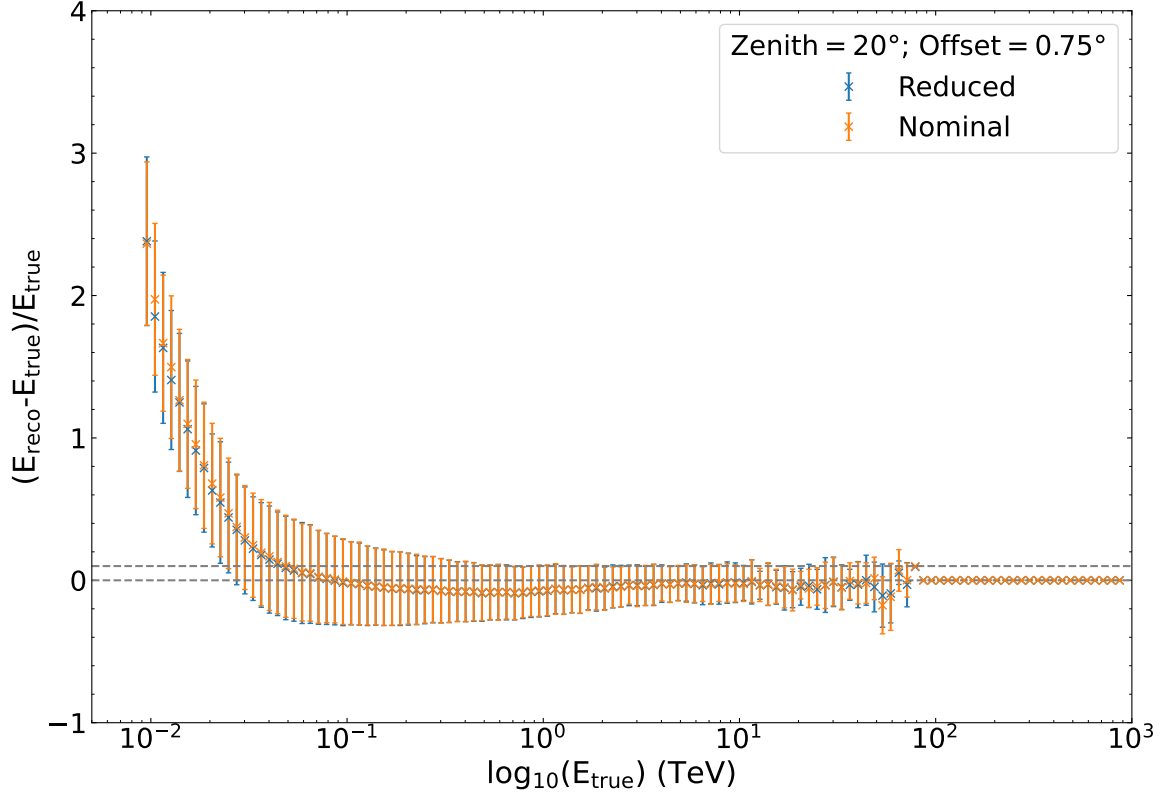
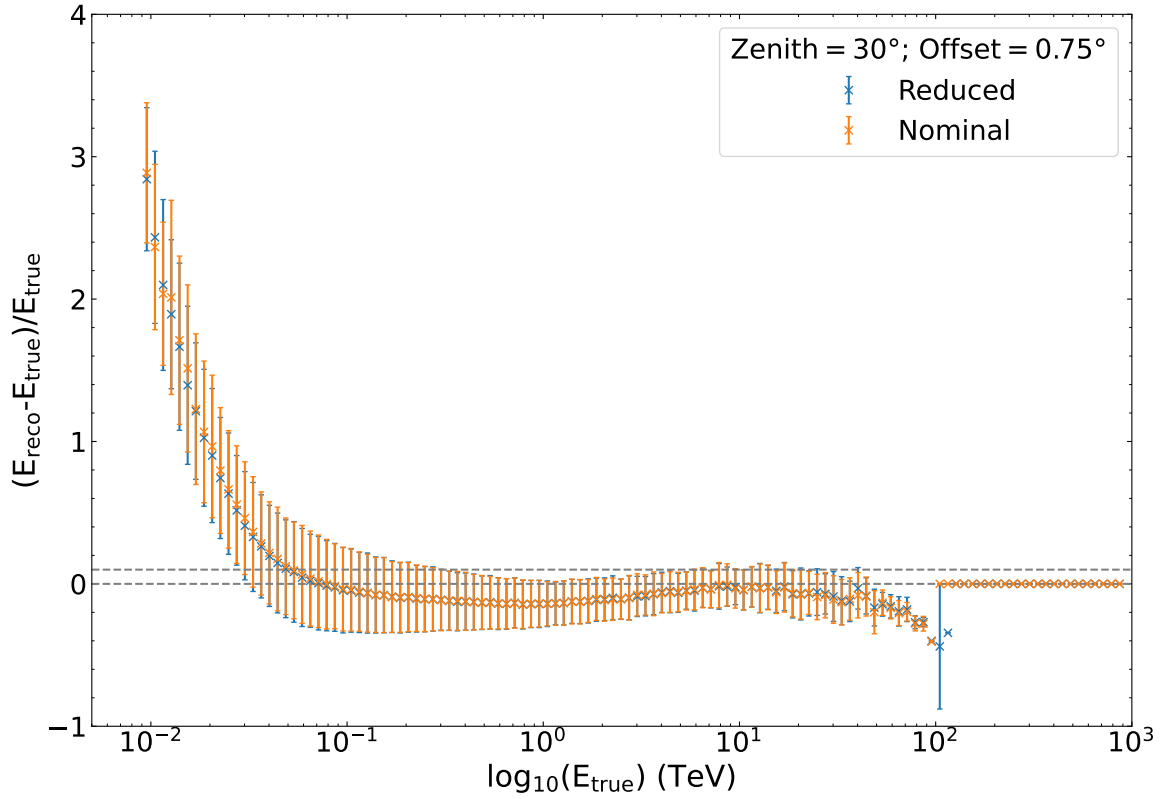
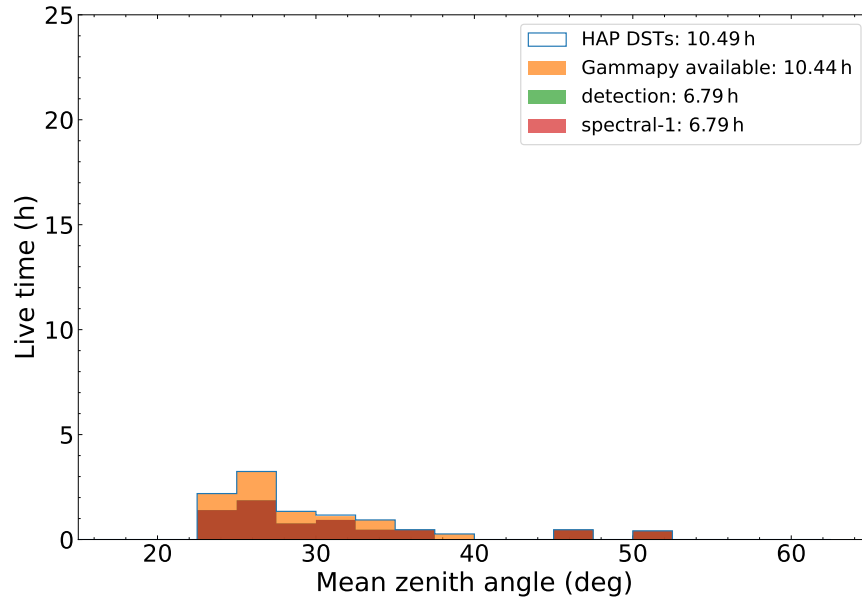
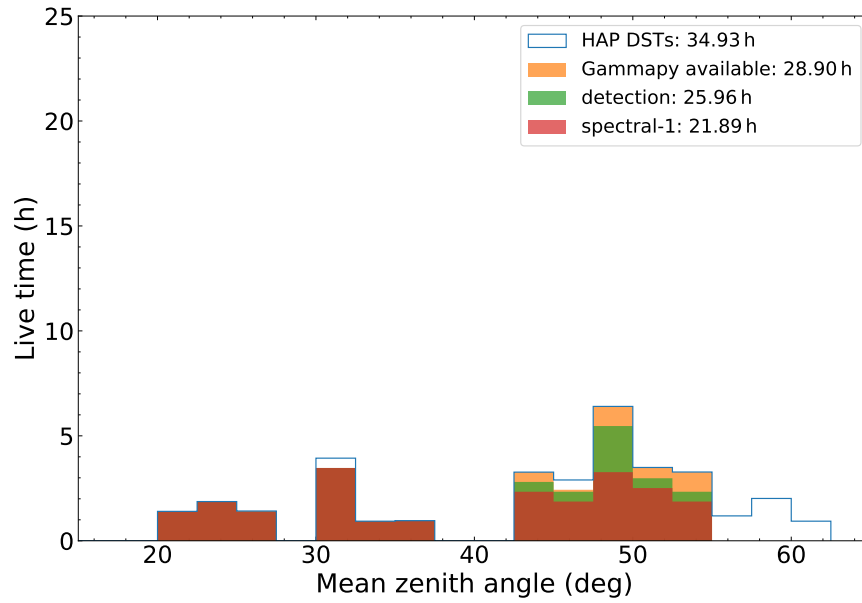
(a) For a zenith angle of 20° and an offset angle of 0.75° .(b) For a zenith angle of 30° and an offset angle of 0.75° .

Figure C.3. Comparison of the energy bias between the reduced and the nominal trigger setting. In addition, 0 % and 10 % of the energy bias are indicated.

C.2. Data Analysis of the Vela Pulsar and the Pulsar B1706-44

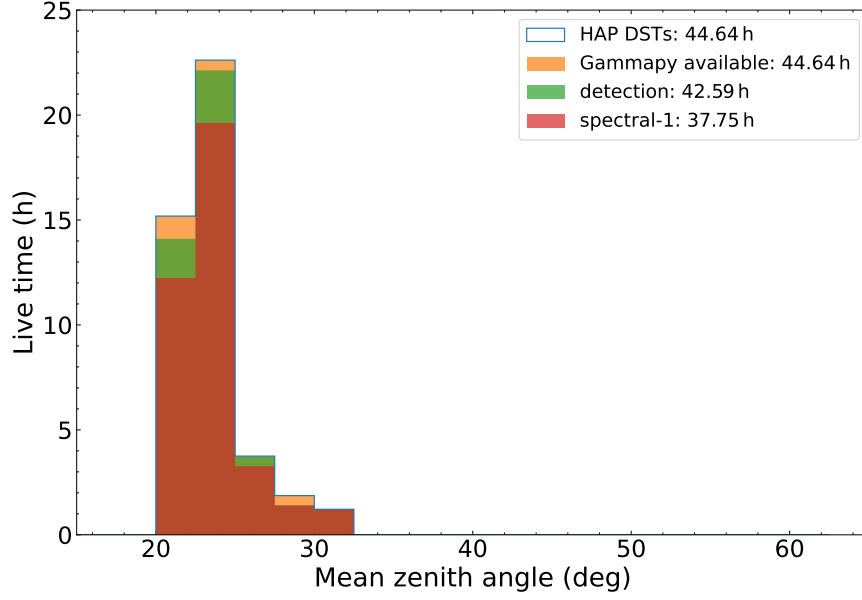


(a) For the observation period 2020.

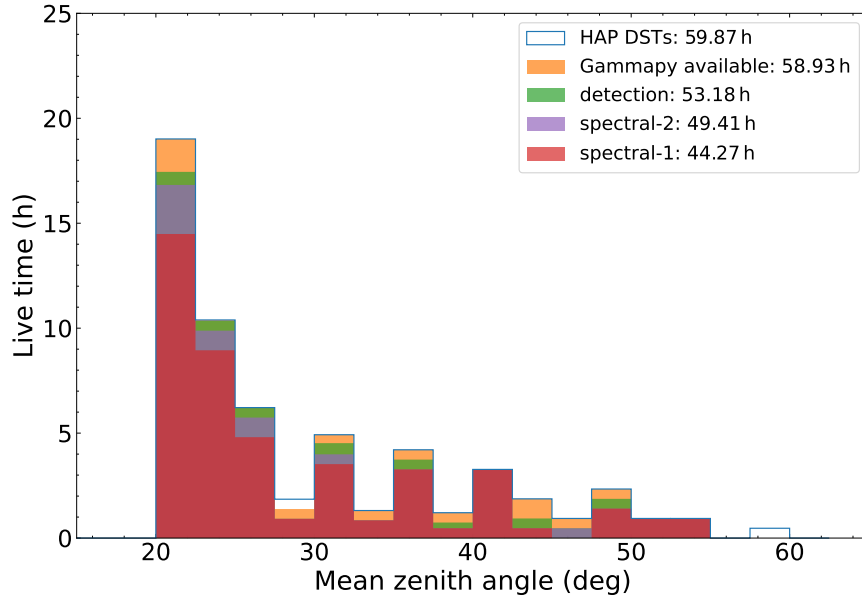


(b) For the observation period 2022.

Figure C.4. Live time as function of the mean zenith angle for the Vela pulsar data sets acquired with the nominal trigger setting. The fraction of the data for the different data selection criteria is indicated.



(a) For the Vela pulsar.



(b) For the pulsar B1706-44.

Figure C.5. Live time as function of the mean zenith angle for the pulsar data sets acquired with the reduced trigger setting. The fraction of the data for the different data selection criteria is indicated.

Table C.1. Excess R_{excess} and significance rate $R_{\text{significance}}$ of the different zenith angle bands for the Vela data sets with nominal trigger setting. The rates are calculated according to Equations 10.7 and 10.9 and the respective errors according to Equations 10.8 and 10.10.

Zenith Angle Band $^{\circ}$	R_{excess} (1/h)		$R_{\text{significance}}$ ($\sigma \text{ h}^{-1}$)	
	Vela 2020	Vela 2022	Vela 2020	Vela 2022
$20^{\circ} - 30^{\circ}$	211 ± 31	157 ± 27	3.39 ± 0.50	2.75 ± 0.46
$30^{\circ} - 40^{\circ}$	43 ± 44	74 ± 24	0.72 ± 0.73	1.35 ± 0.43
$40^{\circ} - 50^{\circ}$	81 ± 74	0 ± 14	1.60 ± 1.46	0.00 ± 0.31
$50^{\circ} - 60^{\circ}$	-35 ± 70	-16 ± 19	-0.76 ± 1.55	-0.37 ± 0.43

Table C.2. Excess R_{excess} and significance rate $R_{\text{significance}}$ of the different zenith angle bands for the Vela data set with reduced trigger setting. The rates are calculated according to Equations 10.7 and 10.9 and the respective errors according to Equations 10.8 and 10.10.

Zenith Angle Band ($^{\circ}$)	R_{excess} (1/h)	$R_{\text{significance}}$ ($\sigma \text{ h}^{-1}$)
20.0 – 30.0	281 ± 11	4.18 ± 0.16
20.0 – 22.5	276 ± 18	4.20 ± 0.27
22.5 – 25.0	296 ± 15	4.35 ± 0.21
25.0 – 32.5	234 ± 27	3.52 ± 0.40

Table C.3. Results of the timing analysis for the different data set with applied spectral-1 data selection criteria for the Vela pulsar. The excess and significance are calculated according to Equations 9.2 and 9.4. The error of the excess is determined from the Poisson likelihood function WStat of Gammapy (Gammapy 2024).

Parameter	Vela 2020	Vela 2021	Vela 2022	Vela 2020+2022
	Spectral-1	Spectral-1	Spectral-1	Spectral-1
No. Total Events	178513	1273206	423587	602100
No. On-Events	18755	136752	43219	61974
No. Off-Events	53401	376946	126325	179726
N_{excess}	955^{+157}_{-157}	11103^{+423}_{-422}	1111^{+240}_{-239}	2065^{+286}_{-286}
S (σ)	6.1	26.6	4.7	7.3

Table C.4. Results of the timing analysis with the applied spectral-1 and spectral-2 data selection criteria for B1706-44. The excess and significance are calculated according to Equations 9.2 and 9.4. The error of the excess is determined from the Poisson likelihood function WStat of Gammapy (Gammapy 2024).

Parameter	B1706-44	
	Spectral-1	Spectral-2
No. Total Events	1665731	1872654
No. On-Events	502742	565324
No. Off-Events	996280	1119961
N_{excess}	4602^{+867}_{-867}	5343^{+920}_{-919}
S (σ)	5.3	5.8

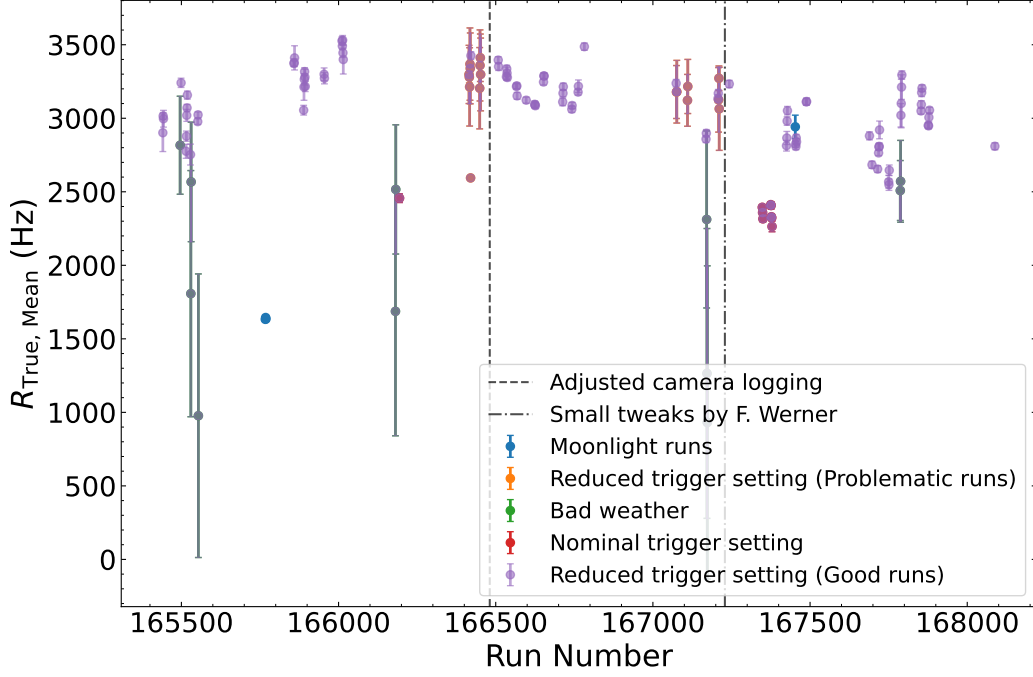
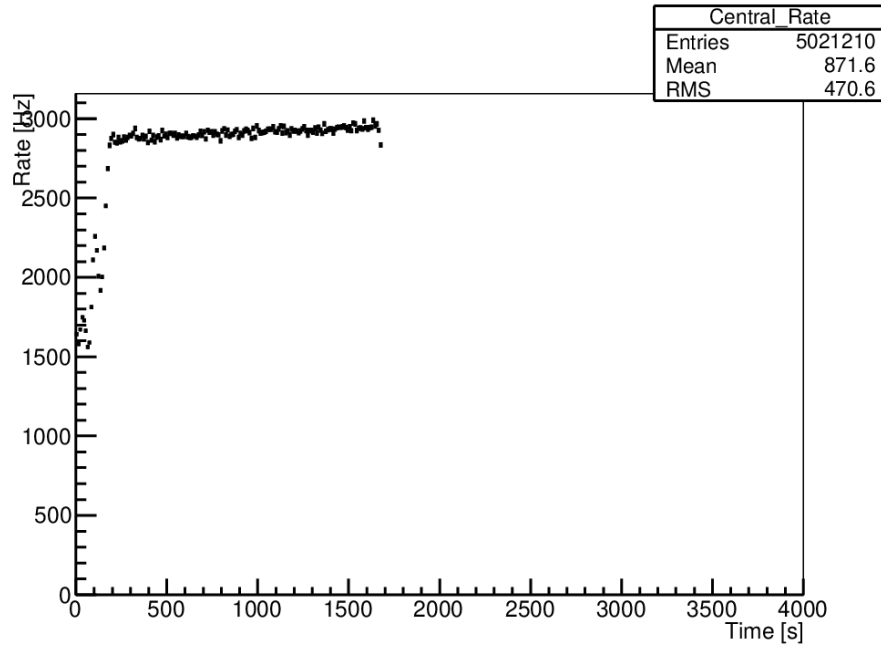
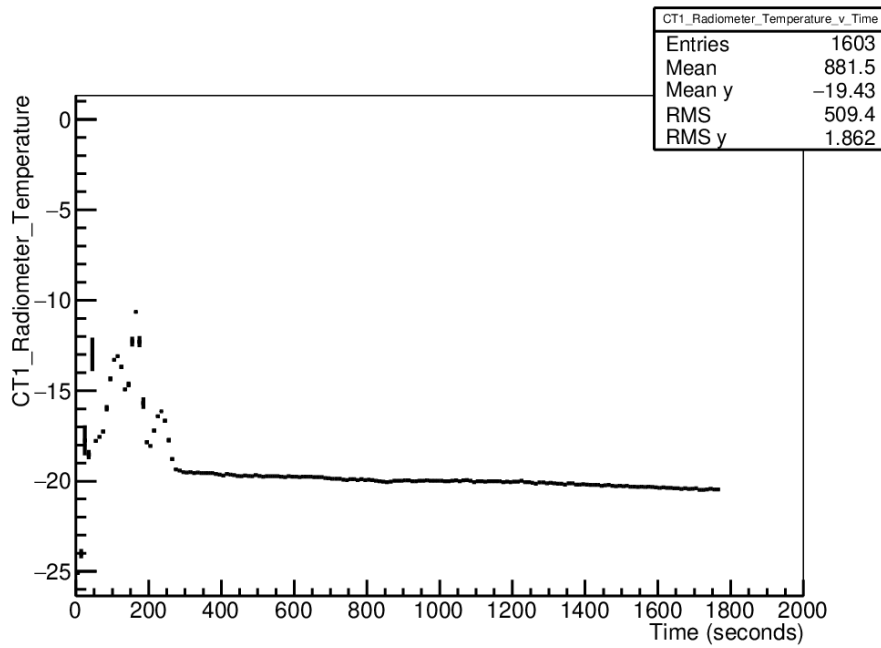


Figure C.6. Mean CT5 trigger rate $R_{\text{True, Mean}}$ as function of the observation ID for the B1706-44 observations. The runs with reduced trigger setting with problems during data taking (orange) and the reduced trigger setting without problems during data taking (purple) are indicated. The problems are more dominant for the B1706-44 runs, which is why only they are shown for better visibility. Two adjustments to reduce the computational load on the FlashCam camera server by F. Werner (MPIK) are indicated around observation IDs 166481 (May 10, 2021) and 167229 (June 9, 2021), respectively. No more problems are detected after the second adjustment.



(a) Central trigger rate as function of observation run duration.



(b) CT1 radiometer temperature as function of observation run duration.

Figure C.7. Impact of clouds in the telescope FOV on the data taking. A temporal correlation between fluctuations in the central trigger rate and the radiometer temperature is visible and indicates clouds in the telescope FOV. The central trigger rate is the array trigger rate recorded by the central trigger system and is dominated by the CT5 trigger rate due to its lower threshold with respect to CT1-4. The exemplary run has the observation ID 165496. Credit: H.E.S.S. Collaboration.

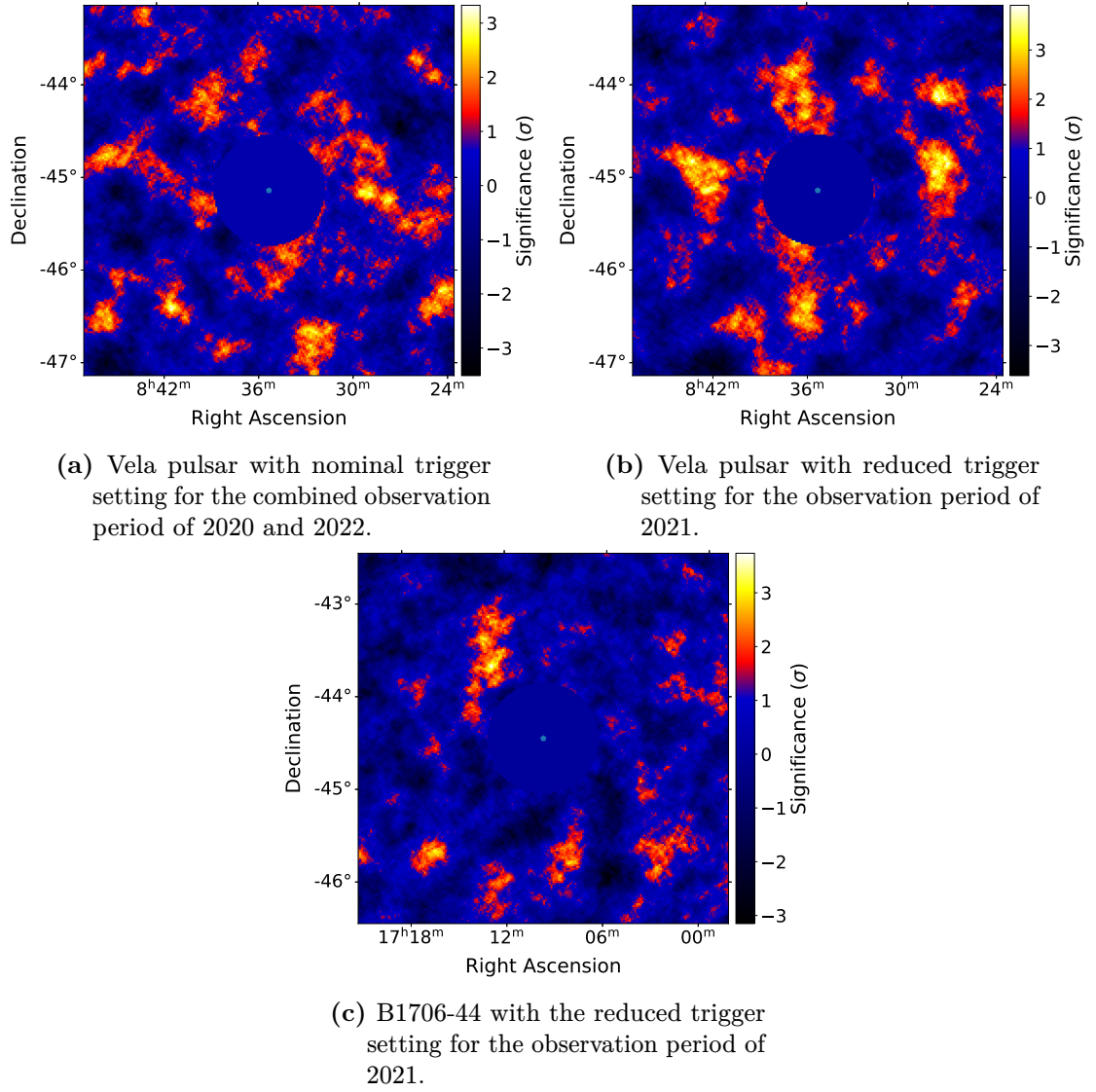


Figure C.8. Significance maps for the three data sets with the source region masked. The source region is masked with a circular region with a radius of 0.6° .

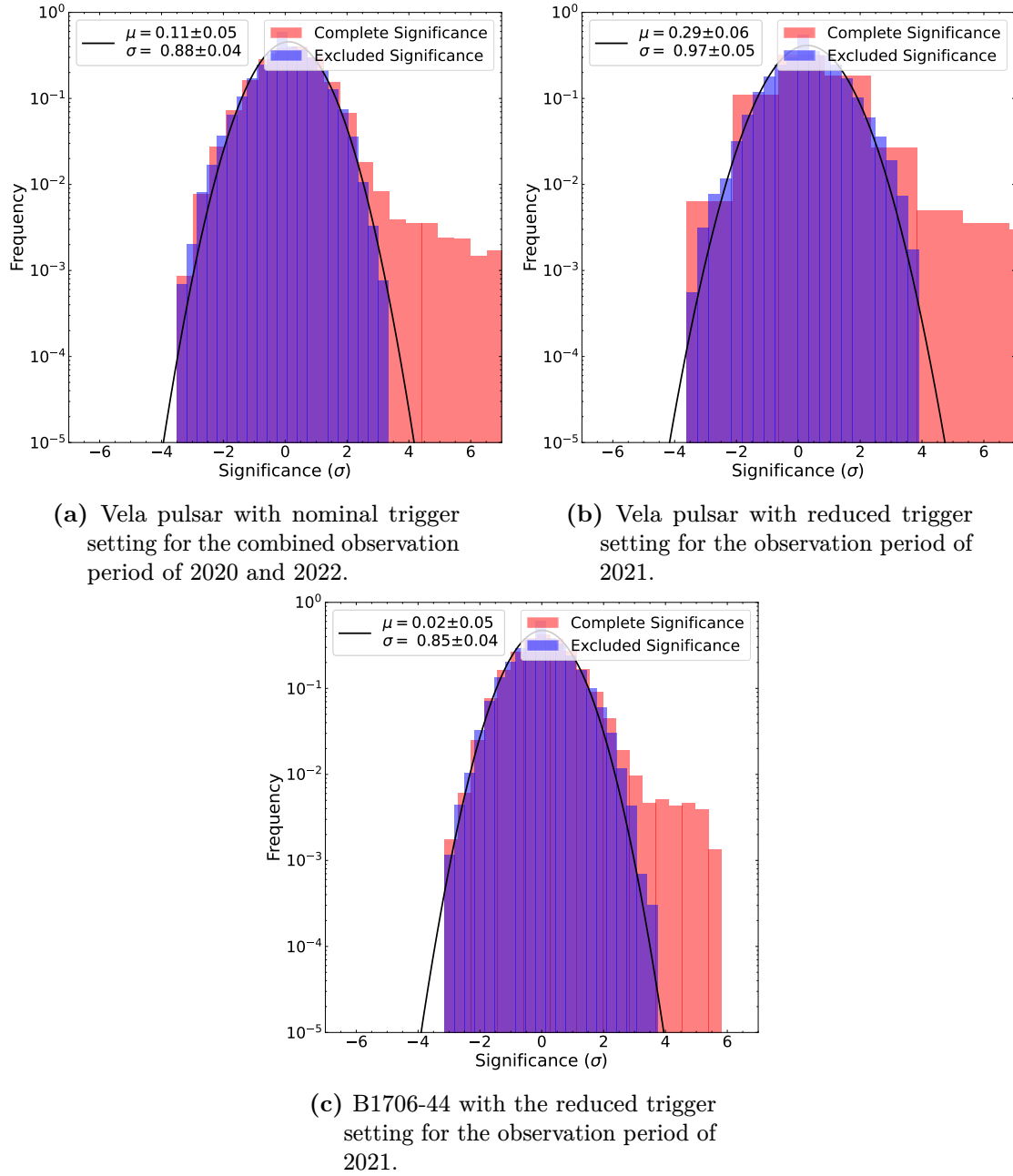


Figure C.9. Distribution of the significance and excluded significance derived from the significance sky maps. The excluded significance is derived for a circular exclusion region with a radius of 0.6° and is fit with a one-dimensional Gaussian distribution to check the background normalization.

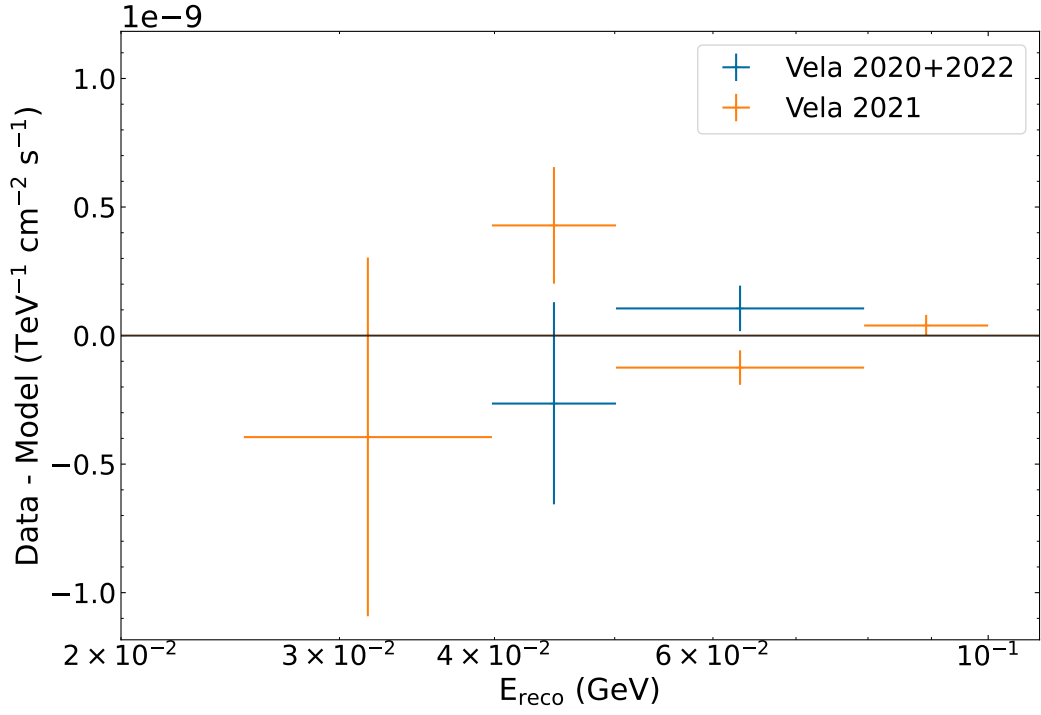


Figure C.10. Fit residuals of the spectral fits for the nominal (Vela 2020+2022) and reduced trigger setting data set (Vela 2021) of the Vela pulsar. The spectral fit is shown in Figure 10.8.

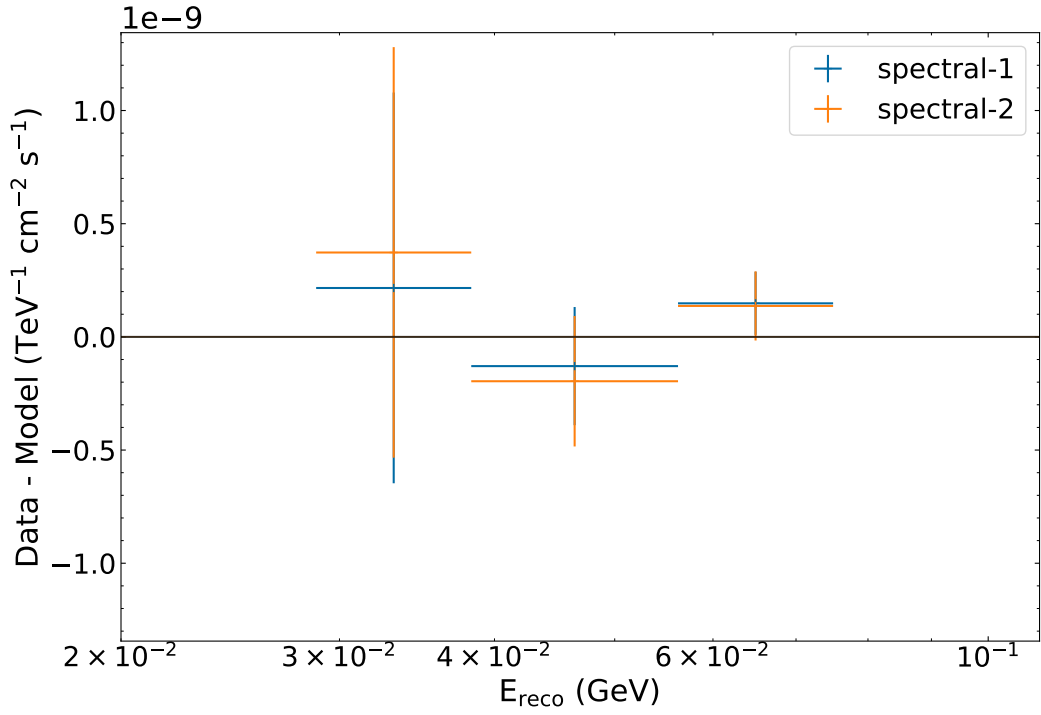


Figure C.11. Fit residuals of the spectral fits for the reduced trigger setting data set of the pulsar B1706-44. The spectral fit is shown in Figure 10.9.

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Acknowledgments

And as this work draws towards an end, the last chapter is dedicated to the people who helped bringing it into existence and, along the way, made it a memorable journey. A substantial amount of them will be highlighted in the following, but the list is not complete and many more people influenced me without explicitly being aware of it. I am not any less indebted to them.

I want to start with Prof. Andrea Santangelo who was a constant presence throughout my academic journey starting from the first physics lecture up to supervising my Bachelor's, Master's and doctoral theses. I can assure you that I am still working on improving both, my physics and my Italian skills. Next up, I want to thank Dr. Gerd Pühlhofer for his thoughtful guidance, as well as his knowledgeable answers to any of my many questions. In addition, both of them, as well as Prof. Beate Stelzer and Prof. Klaus Werner I want to thank for serving on the examination committee for my doctoral defense. At this stage, I also want to extend my gratitude to Prof. Josef Jochum for his willingness to serve as the second supervisor of my doctoral thesis.

I extend my gratitude to the H.E.S.S. on-site crew – Bernd, Frikkie, Kai, Sennae and Toni – who welcomed me with open arms for my on-site shift in October 2022. This extends to Volker as well who welcomed me in his home in Swakopmund during my consequent trip. Truly experiences that I'll always cherish and will never forget. In addition, many thanks belong to the many collaborators within the H.E.S.S. collaboration which were always open to help out in case of any problems.

There are many people at IAAT that deserve my gratitude and which contributed to it being a pleasant working environment. I want to start off with Sabine for running the administrative side of things smoothly and for guiding an aspiring PhD student through the jungle of bureaucracy. Combined with her serene personality, every interaction was a pleasant one. My special thanks belong to Jürgen. Not only for providing crucial feedback whenever necessary, but also for the many hours that we spent together performing tests in the lab – with opened windows during winter due to Covid measures – all while being in a short-sleeved shirt. Memories that will never be forgotten. Furthermore, my deepest gratitude belongs to the mechanics workshop headlined by Siegbert and Sonja, and their various apprentices. They were crucial in transforming a simple, ambitious sketch on a sheet of paper into an actual mechanical part, all while providing hands-on insight how to make things happen.

I want to extend my gratitude to my many coworkers that were there for providing support and laughs whenever necessary, and mostly, for contributing to an environment in which, during my six years at IAAT, I never dreaded a single day to go to work. The group is headlined by the vintage A112 office, Christian, Fabian and Inga. Christian for providing useful advice in all kind of work- and life-related things, Fabian for his calming presence and Inga for keeping things in perspective. Hard to describe what IAAT life would have been like without the many coffees and stories we shared. Along that line, Baiyang deserves many thanks for always being open to help and for inspiring me to move to another continent for my first postdoc. Camille

for always being open to get a dinner even if it collided with her well-intentioned plan of working out. Enza for her approach that every problem is easier discussed over a glass of good wine and for introducing me to the concept of “La dolce vita”. Lorenzo for always being open to share a coffee, cake or chocolate, and for having the bandwidth from enjoying the most mundane jokes up to having the most serious discussions. Marvin & Moritz (which I still can’t tell apart) for their constant stream of memes and their joyful personalities. Paul for his keen eye for the fundamental things of work (and life). Samu for his “everyday is a good day to grill” attitude. Alejandro, Anto, Bastian, Charles, Jörg, Wilhemina, and the many other people at IAAT each of whom contributed to make work trips, lunch breaks or Grilldays more fun, and contributing to an overall pleasant working atmosphere.

And as this last section is drawing to an end, there are only so many thanks remaining. The team I started studying with in 2014 (Fabian, Flo, Georg, Konrad, Leo & Lukas) deserves my thanks, as do my childhood, school and hometown friends who always kept me grounded.

In the end, I want to extend my deepest gratitude to my parents, as well as my brother, not only for their unwavering support but also for providing the necessary life framework and for putting me in a position to succeed. Without you, all of this would not have been possible. Thank you.