Bachelor Thesis

Major - Aerospace Computer Science

Follow-up-Observations of Transient Events in Cherenkov Astronomy

Marcel Vorbrugg

Würzburg, June 27, 2024

Julius-Maximilians-Universität Würzburg

Faculty of Physics and Astronomy

First Reviewer: Prof. Dr. Sergio Montenegro

Second Reviewer: Prof. Dr. Karl Mannheim

Supervisor: Dr. Daniela Dorner

Abstract

Gamma-ray astronomy involves the study of the most energetic phenomena in the universe, necessitating advanced detection methods and rapid response systems to capture transient events such as Gamma-Ray Bursts (GRBs) and follow-up multi-messenger alerts like for very-high-energy (VHE) neutrinos. Imaging Atmospheric Cherenkov Telescopes (IACTs) play a crucial role by detecting gamma-rays through the Cherenkov radiation produced when these high-energy particles interact with the Earth's atmosphere. This thesis examines two IACTs: the First G-APD Cherenkov Telescope (FACT) and the Large Size Telescope (LST), of the future Cherenkov Telescope Array (CTA), highlighting their roles in rapid detection and structural monitoring.

The First G-APD Cherenkov Telescope (FACT), located on the Canary Island of La Palma, employs silicon based photomultipliers (SiPMs), to monitor bright gamma-ray sources at TeV energies. FACT's follow-up program is distinguished by its pursuit of emission from potential gamma-ray candidates through automated follow-up of multi-messenger alerts, including gamma-ray bursts and public neutrino alerts from IceCube. The automation enables quick response times, with a minimum delay of 13 seconds, crucial for capturing transient phenomena. This thesis analyzes the outcomes and automated observations from FACT's follow-up program over the past decade, aiming to detect TeV emissions or set upper limits on such emissions from GRBs and neutrino sources.

The Large Size Telescope (LST), part of the Cherenkov Telescope Array (CTA) and located on La Palma as well, is a crucial instrument for observing gamma-ray events. Ensuring its stability and structural integrity is paramount for minimizing observational downtime and maintaining reliable performance. This thesis details the implementation of continuous structural monitoring using SmartCheck sensors, which have powerful analysis tools to help in, for example, identifying the eigenfrequencies of the telescope. Understanding these frequencies is a critical step towards predictive maintenance, aimed at preventing mechanical failures before they cause significant downtime. Investigating some already arisen issues, such as the high torque oscillations that trigger emergency stops, various potential causes were considered. While many variables were ruled out, the consistent observation of incidents at specific zenith directions suggests a possible link to telescope balance or an emergency braking system, warranting further investigation.

Overall, this work underlines the importance of both rapid observational capabilities and robust structural health monitoring in ground-based gamma-ray astronomy. The insights gained from this research contribute to improving the operational reliability and scientific output of these advanced telescopic systems, ensuring they remain at the forefront of astronomical discoveries.

Zusammenfassung

Die Gamma-Astronomie beschäftigt sich mit der Untersuchung der energiereichsten Phänomene im Universum und erfordert fortschrittliche Detektionsmethoden sowie schnelle Reaktionssysteme, um transiente Ereignisse wie Gamma-Ray Bursts (GRBs) und sehr hochenergetische (VHE) Neutrinos zu erfassen. Imaging Atmospheric Cherenkov Teleskope (IACTs) spielen dabei eine entscheidende Rolle, indem sie Gamma-Strahlen durch die Messung des bei der Wechselwirkung dieser hochenergetischen Teilchen mit der Erdatmosphäre erzeugte Cherenkov-Strahlung nachweisen. Diese Arbeit untersucht zwei bedeutende IACTs: das First G-APD Cherenkov Telescope (FACT) und das Large Size Telescope (LST), wobei deren Rollen bei der schnellen Detektion und Strukturüberwachung hervorgehoben werden.

Das First G-APD Cherenkov Telescope (FACT), das sich auf der Kanareninsel La Palma befindet, verwendet Geiger-Mode Avalanche Photodioden (G-APDs), um helle Gamma-Quellen bei TeV-Energien für kontinuierliche Langzeitbeobachtungen zu überwachen. Das Follow-up-Programm von FACT zeichnet sich durch die Nachbeobachtung von Emissionen potenzieller Gamma-Kandidaten durch automatisierte Nachverfolgung von Multi-Messenger-Alerts aus, einschließlich Gamma-Ray Bursts und öffentlichen Neutrino-Alerts von IceCube. Die Automatisierung ermöglicht schnelle Reaktionszeiten mit einer bisher minimalen Verzögerung von 13 Sekunden, was entscheidend für die Erfassung transitanter Phänomene ist. Diese Arbeit analysiert die Ergebnisse und automatisierten Beobachtungen des Follow-up-Programms von FACT im letzten Jahrzehnt mit dem Ziel, TeV-Emissionen zu erkennen oder obere Grenzwerte für solche Emissionen von GRBs und Neutrinoquellen festzulegen.

Das Large Size Telescope (LST), das Teil des Cherenkov Telescope Array (CTA) ist und sich ebenfalls auf La Palma befindet, ist ein wichtiges Instrument zur Beobachtung von Gamma-Strahlung. Die Sicherstellung seiner Stabilität und strukturellen Integrität ist entscheidend, um Ausfallzeiten bei der Beobachtung zu minimieren und eine zuverlässige Leistung zu gewährleisten. Diese Arbeit beschreibt die Implementierung einer kontinuierlichen Strukturüberwachung mittels SmartCheck-Sensoren, die leistungsstarke Analysetools bieten, um beispielsweise die Eigenfrequenzen des Teleskops zu identifizieren. Das Verständnis dieser Frequenzen ist ein wichtiger Schritt in Richtung vorausschauender Wartung, die darauf abzielt, Probleme zu verhindern, bevor sie zu erheblichen Ausfallzeiten führen. Bei der Untersuchung einiger bereits aufgetretener Probleme, wie den hohen Drehmoment-Oszillationen, die Notabschaltungen auslösen, wurden verschiedene potenzielle Ursachen in Betracht gezogen. Obwohl viele Variablen ausgeschlossen wurden, deutet die konsistente Beobachtung von Vorfällen bei bestimmten Zenitwinkeln auf einen möglichen Zusammenhang mit dem Teleskopgleichgewicht oder ein Nottbremssystem, was weitere Untersuchungen rechtfertigt.
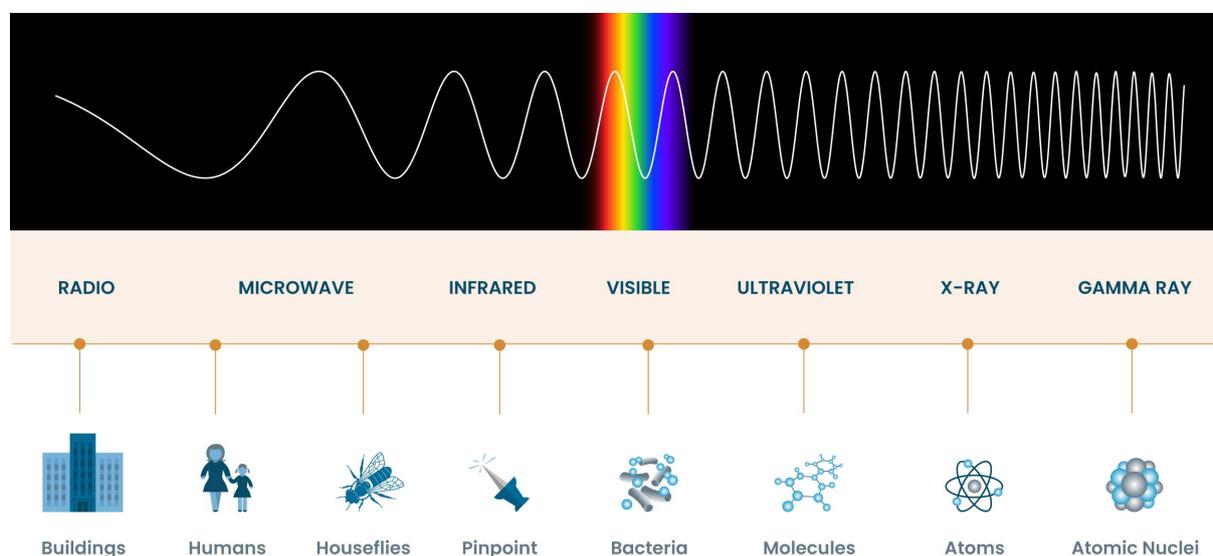
Insgesamt unterstreicht diese Arbeit die Bedeutung sowohl schneller Beobachtungs-fähigkeiten als auch einer robusten Strukturüberwachung in der erdgebundenen Gamma-Astronomie. Die gewonnenen Erkenntnisse tragen dazu bei, die Betriebssicherheit und den wissenschaftlichen Ausgabe dieser fortschrittlichen Teleskopsysteme zu verbessern und sicherzustellen, dass sie an der Spitze astronomischer Entdeckungen bleiben.

Contents

Introduction

1.1   Transient Gamma-ray Astronomy

Figure 1.1: All the different types of lights of the Electromagnetic Spectrum comparing their wavelength sizes and frequencies. Credit: NASA - HubbleSite

Gamma-ray astronomy is a rapidly evolving branch of astronomy that focuses on the study of gamma-ray emissions from celestial objects.

As seen in Fig 1.1, gamma(γ) rays are the most energetic form of electromagnetic radiation, with wavelengths shorter than X-rays and carrying energies greater than 100 keV (kilo-electronvolts).

The detection of high energy $\gamma-$rays is the final step to use the whole electromagnetic spectrum for the study of the most extreme and energetic processes in the universe, such as neutron stars and pulsars, supernova explosions and regions around black holes.

It is also important to distinguish, that $\gamma-$rays cover up a very broad band of energy ranges as seen in Table 1.1 of [1]:

Gamma-ray energies	Shorthand	Range	Observations
Low/Medium	LE/ME	100keV-30MeV	Space-based
High	HE	30MeV-100GeV	Space-based
Very High	VHE	100GeV-100TeV	Ground-based
Ultra High	UHE	>100TeV	Ground-based

Table 1.1: Adapted table of [1], distinguishing gamma ray-bands

There are also two intriguing phenomena with great relevance in the understanding of $\gamma-$ray emissions: Gamma-ray-bursts (GRBs) and neutrino events. The detection of neutrino events in association with other cosmic events, such as GRBs or the mergers of neutron stars, has opened new avenues for studying the most energetic processes in the universe and has the potential to reveal the underlying physics and astrophysical phenomena responsible for the production of high-energy particles and radiation.

1.1.1 Gamma-ray Bursts (GRBs)

Gamma-ray bursts are one of the most energetic and the most luminous phenomena in the universe. They are short, intense bursts of $\gamma-$ray light that can emit more energy in a few seconds than our Sun will emit in its entire lifetime.

Observations have shown they can be divided in two classes of bursts: short-duration (typically from a few milliseconds to 2 seconds) and long-duration (lasting from 2 seconds to some minutes). Due to its transitory time duration, it is crucial to have a tool for the follow-up of those events.

GRBs are believed to be produced during the collapse of massive stars, the merger of neutron stars, or the accretion of material onto black holes.

1.1.2 Neutrino Alerts

Neutrinos are subatomic particles with almost no mass and no electric charge, making them extremely hard to detect.

Despite being so elusive, neutrinos play a crucial role in many cosmic processes and can provide valuable information about the most extreme and energetic phenomena in the universe.

Neutrino alerts refer to the notification of a detection of high-energy neutrino events by neutrino observatories, such as IceCube at the South Pole.

These alerts are crucial for multi-messenger astronomy, where observations of neutrinos are combined with data from other cosmic messengers (e.g., gravitational waves) and electromagnetic radiation across different wavelengths to gain a comprehensive understanding

of astrophysical sources and phenomena [2].

1.2 Imaging Atmospheric Cherenkov Telescope (IACT)

Having a background of these occurring phenomena, the question now is, how can they be detected?

High-Energy (HE) and lower energy $\gamma-$rays can not be detected on Earth (Table 1.1), due to Earth's atmosphere, which effectively blocks electromagnetic radiation greater than 10eV. However, there is a possibility to detect Very-High-Energy (VHE) or higher $\gamma-$rays by the electromagnetic cascade shower [1]. When a VHE particle (a photon) enters the Earth's atmosphere, it collides with air molecules, producing a cascade of secondary particles, as shown in Fig 1.2.
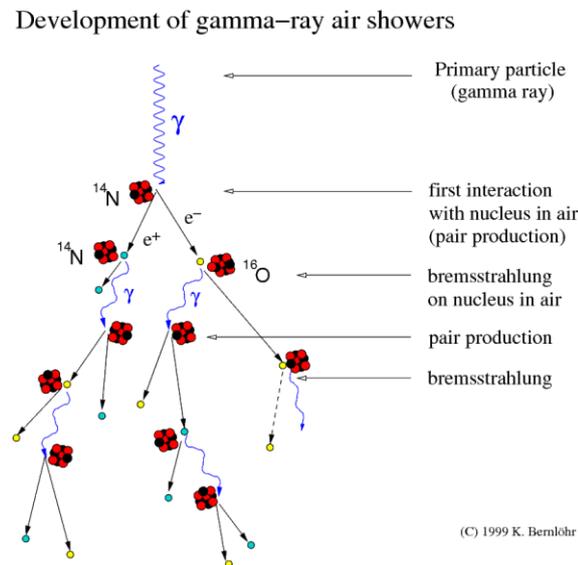
Figure 1.2: Schematic of a particle air shower originated by a gamma-ray. Credit: Konrad Bernlöhr

In this process, when a gamma-ray interacts with the atmosphere, the primary photon generates secondary particles through a series of interactions. Initially, the photon undergoes pair production, creating an electron and a positron. Each of these secondary particles then possesses roughly half the energy of the primary photon. This process repeats as the secondary particles interact with the atmosphere, creating further pairs and producing a cascade, or shower, of particles. The cascade continues until the average energy of the particles drops to a point where ionization energy losses and radiation losses balance each other.

During this cascade, some of the secondary particles travel faster than the speed of light

in air, emitting Cherenkov radiation. This Cherenkov radiation, in the form of light, can be detected by Imaging Atmospheric Cherenkov Telescopes (IACTs).

These telescopes, or arrays of telescopes, collect the Cherenkov light using large mirrors and project it onto cameras equipped with photomultiplier tubes. These photomultiplier tubes then convert the light signals into electrical signals, allowing for the detection and analysis of the original gamma-ray event.

The goal is to determine the time of arrival, the energy and the point of origin of the incoming particle, to then create a possible map of sources of celestial bodies, also known as skymaps.

To be able to catch these very rapid and brief events, several IACTs and Water Cherenkov Telescopes have been designed:

- The Very Energetic Radiation Imaging Telescope Array System (VERITAS).

- The Cherenkov Telescope Array (CTA), divided in CTA North and CTA South.

- The Major Atmospheric Gamma-Ray Imaging Cherenkov (MAGIC) Telescopes.

- The First G-APD Cherenkov Telescope (FACT)

- The High Altitude Water Cherenkov (HAWC) Experiment

- The High Energy Stereoscopic System (H.E.S.S)

- The Large High Altitude Air Shower Observatory (LHAASO)

In this thesis the FACT and Large Size Telescope (LST) of the CTA-North will be the main focus.

1.2.1 First G-APD Cherenkov Telescope (FACT)

The First G-APD Cherenkov Telescope is a small telescope with a mirror area of $9.5\,m^2$ located at the Observatorio del Roque de los Muchachos on the Canary Island of La Palma at a height of 2200 meter above sea level.

As explained in [3], the main innovation of the telescope with respect to the other IACTs, is the usage of Silicon photomultipliers (SiPMs) (one SiPM, consists of several Geiger-mode Avalanche Photodiodes, G-APDs), instead of photomultiplier tubes (PMT), which require no extra calibration. They also provide a higher efficiency converting photons into electrical signals, single-photon resolution, lower operating voltage and power consumption, an improved reliability and therefore a reduced cost.

Figure 1.3: FACT during the day [4].

The main goal of the telescope since its start of operating in October 2011, is the long-term monitoring of blazars. Blazars are a unique class of active galactic nuclei (AGN) powered by supermassive black holes that emit intense and variable emissions across the electromagnetic spectrum. Monitoring these sources allows a more dedicated study of the long-term variability, periodic behaviour as well as the analysis of possible subtle changes and unexpected events.

Another key program is the Target of Opportunity Program, which consists of observations of incoming alerts from different instruments. This program will be deeper analyzed and explained in this thesis.

1.2.2 Large Size Telescope (LST) - Cherenkov Telescope Array (CTA) North

The LST is the largest telescope out of three types of telescopes in the Chrenkov Telescope Array: Small-Sized-Telescope (SST), Medium-Sized-Telescope (MST) and Large-Sized-Telescope. In the Northern Site of the CTA, also located at the Observatorio del Roque de los Muchachos on the Canary island of La Palma four of them are planned to be built, were one of them, the prototype LST-1 is already completed and was inaugurated on October 2018.

Figure 1.4: LST-1 fully operable.
Credit: Tomohiro Inada

Figure 1.5: An artist rendition of four LST.
Credit: CTA Consortium, Akihiro Ikeshita, Mero-TSK, International

As described in [5], it has a $23\,m$ parabolic dish diameter with a mirror area of $\sim 400\,m^2$ pointing to a $3\,m\,\mathrm{x}\,3\,m$ camera connected to 1855 PMTs. It is also relatively light-weight, with a total moving mass of $120\,$tons, which has a high relevance for the repositioning for the alerts of brief occurring $\gamma-$rays. It has also shown a great performance and some first scientific observations. For this thesis the focus will lie on the condition of such a big and heavy telescope which performs highly fast movements to observe GRBs during their prompt emission.

1.3   Gamma-ray Follow-ups of Transient Events

As previously mentioned in section 1.2, the IACTs detect transient events. They can be detected either while monitoring, or with another program named Target-of-Opportunity (ToO) program. This program is a specialized observational strategy designed to respond and follow-up when a transient event occurs. It is a flexible and dynamic program, which allows a repositioning of the telescope in the critical early phases of the event.

Fig 1.6 extracted from [6] shows the delay vs exposure time from follow-ups of neutrino alerts by the FACT, H.E.S.S, MAGIC and VERITAS collaborations. It is divided in single events or flares (multiplets). The exposure in hours represents the time that the source was observed from each telescope. The delay describes the time passed between the discovery of the neutrino and the start of the observation. For observations with a response time of less than 1 hour or an exposure of more than 4 hours, the names of the events are indicated.

FACT single events, presented in a pink colour, have some significant values with a very low delay time. In this thesis, a whole analysis of these FACT results will be conducted joint with all of its results of its Target of Opportunity Program.
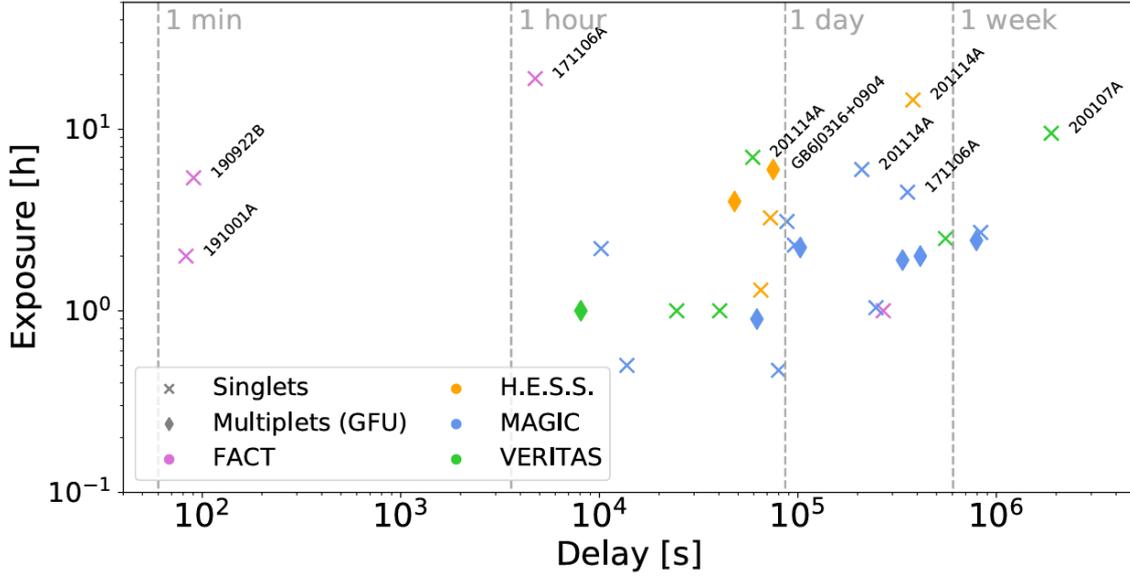
Figure 1.6: Plot extracted from [6], in a joint study by IACT's and IceCube Collaborations. It shows the delay vs exposure times for the telescopes follow-ups of neutrino alerts from October 2017 until December 2020.

However, achieving reliable and high-quality observational data requires a robust telescope infrastructure. Therefore, this thesis will also detail the telescope construction, emphasizing the challenges involved in maintaining a stable and continuous observing platform, through effective monitoring methods. Due to its recent construction of an LST and the emerging array of three LSTs, the CTA-North telescopes will be the perfect example for the examination of the difficulties of telescope engineering.

The successful integration of hardware and software components is essential for any functional astronomical observatory. By examining both the observational results produced by FACT and the maintenance of structural aspects of the LST-1, this thesis aims to provide a comprehensive understanding of the hardware infrastructure, observational outcomes and its relationship in the field of gamma-ray astronomy, where rapid movements of telescopes are vital.

Structure Monitoring of LST-1

Given the previously described characteristics in 1.2.2, and as detailed in [5], it is evident that the task of moving 120 tons with rapid maneuvers for possible $\gamma-$ray discoveries is challenging. With the construction phase completed successfully, attention turns to the critical task of maintaining the telescope. Structure monitoring has already been tested on an MST prototype. Further information is shown in [7]. The topic on the maintenance of an LST will be explored in detail in this chapter with cooperating work of Felix Pfeifle. The main objective of structure monitoring is preventing catastrophic crashes as well as foreseeable damage that could compromise the systems's operability. However, during very fast maneuvers such as GRB follow-ups, the risk for fatigue, corrosion or even the development of cracks or fractures increases. To minimize these risks, the structural health is monitored.

2.1   Drive System

One of the most important and critical components for a well-structured telescope is its drive system. As described in [8], the LST structure is based on six bogies equally spaced in a hexagonal array (see Fig 2.1). Each bogie has two wheels that move along a double rail system, ensuring stable movement. The drive system is divided into two main parts: azimuth and elevation. The azimuth system allows the telescope to rotate horizontally around its vertical axis. This is achieved through an inner spur gear mechanism driven by pinions powered by servomotors. The elevation system enables vertical movement of the telescope by rotating it around its horizontal axis. A semicircular drive ring on the back of the dish's space frame structure supports this movement. This system includes a chain-driven mechanism powered by a motor, allowing precise adjustments in the telescope's angle of elevation. With both, the azimuth and elevation systems, the telescope is able to track objects across the sky (see Fig 2.2).
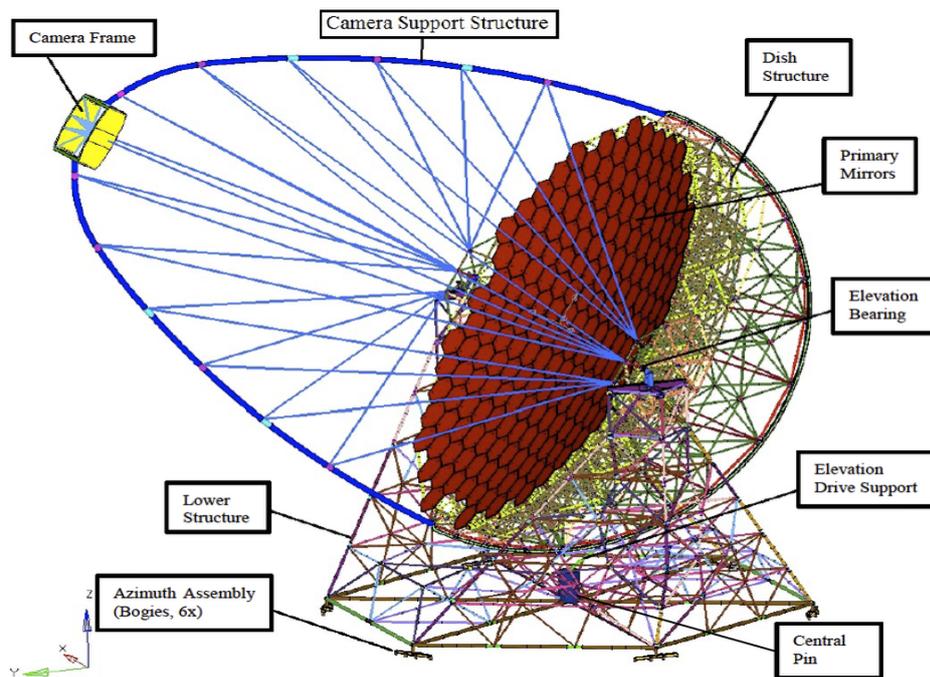
Figure 2.1: LST design and its components based on six bogies equally spaced in a hexagonal array. Schematics taken from [9], where also further details are explained.
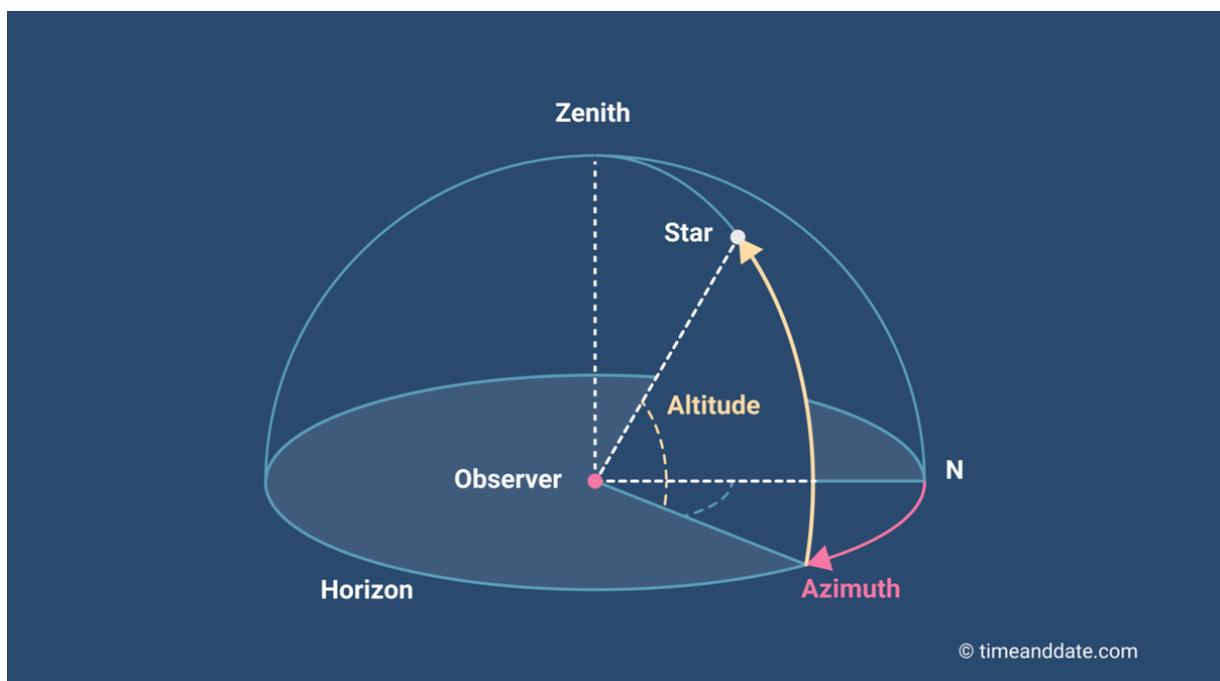
Figure 2.2: Illustration from,[10], depicting the horizontal-coordinate system as seen from an observer in the northern hemisphere. The figure shows both the elevation (also referred to as altitude) and azimuth movements of celestial objects. Elevation is the angle between the object and the observer's local horizon, while azimuth is the angle measured along the horizon, starting from the north and moving clockwise.

The goal of the drive system for fast repositioning (for example for transient events) is to repoint the telescope in any direction in less than 20s by driving the four azimuth drives (one master and three slaves) as well as the two elevation drives (one master and one slave) with servomotors [11].

2.2   Drive System Vibration Monitoring

One possibility of monitoring the telescopes structure is through the measurements of vibrations. Explaining the drive system, the illustration of its design Fig 2.1 was presented. The design illustrates six bogies, where four of them are passive (slaves), and the other two on the sides are motorized (masters). On every of those bogies, there is a vibration sensor for the measurements, where the placement of one of them is shown in Fig 2.3.

### 2.2.1   SmartCheck Vibration Sensors

Figure 2.3: SmartCheck vibration sensors placed on a bogie. Credit: Laura Eisenberger

The SmartCheck vibration sensors (Fig 2.3), developed by Schaeffler are triaxial piezo accelerometers designed for condition monitoring and predictive maintenance applications.

These sensors capture and analyze vibration measurement signals, as well as temperature signals, to detect abnormal machine behavior or identify potential faults.

2.2.2 SmartWeb Interface

For data analysis, the SmartCheck sensors offer the convenience of the SmartWeb interface, which provides the function of real-time monitoring and historical data analysis.
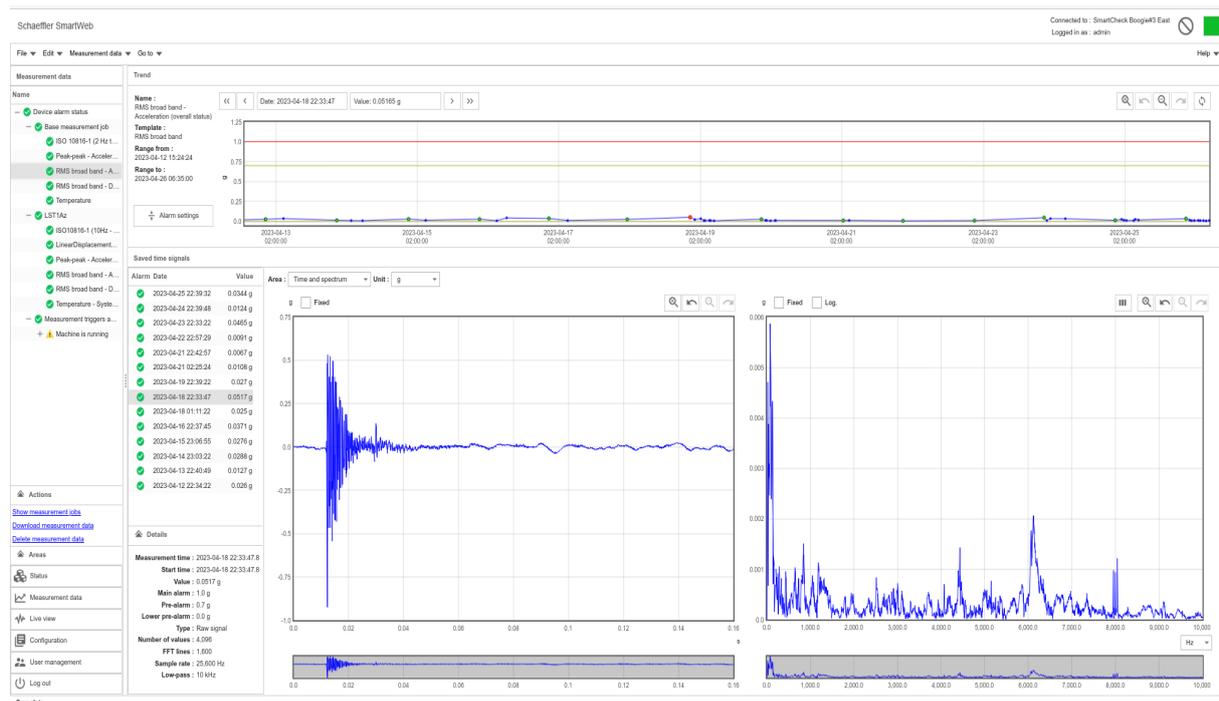
Figure 2.4: Example of the SmartWeb interface with several functions and tools for data analysis, as, e.g., an alarm setting, acceleration data, and a Fast Fourier Transformation (FFT)

Fig 2.4 illustrates the layout of the SmartWeb interface of one of the sensors mounted on the bogies, featuring an upper section dedicated to alarm configuration and lower sections divided into two plots. The left plot displays selectable historical acceleration data, offering flexibility for selecting various measurements and timeframes. The data is sampled at a frequency of approximately 10 Hz. On the right side, the plot presents the Fast Fourier Transformation (FFT) of the acceleration data.

2.2.3 LST1 Eigenfrequencies

Using the data from the sensors, several analyses were performed, with one of the most interesting questions being the determination of the telescope's eigenfrequencies. The eigenfrequency, or natural frequency, is a fundamental property of any structure, including buildings and telescopes. It refers to the specific frequencies at which a structure tends

to oscillate when subjected to a disturbance or external force. When a structure vibrates at its eigenfrequency, even a small input of energy can cause large oscillations due to resonance. Given that the telescope is constantly in motion and also subject to external influences like wind, understanding its eigenfrequencies is particularly challenging. By applying various analysis tools such as the FFT and the Welch Method, distinct peaks were identified. For active bogies, peaks were observed at approximately 18 Hz and 35 Hz, while for passive bogies, peaks occurred at around 22 Hz and 68 Hz. More information and plots will be found in the Bachelor thesis of Felix Pfeifle.

2.2.4   Predictive Maintenance

The next step with the SmartCheck sensors is to integrate a machine learning method that can analyze historical data to identify patterns leading to damage. By learning from past incidents, the system can immediately recognize trends that may indicate potential harm. This information can then be communicated via a traffic-light style alarm system, such as the one on the upper section of Fig 2.4, with predefined thresholds indicating various levels of risk in real-time data.

2.3   Damage Analysis

As the telescope and its maintenance system have been operational for some time, several issues have surfaced. These include fatigue damage in materials caused by vortex shedding or operational loads, potential failures in critical components such as the bolts labelled M48 or M27, which could have catastrophic consequences, and problems in the drive system related to torque values. In particular, the drive system has exhibited not understood switch-offs of the system coinciding with high torque values of the motors. This section will present and discuss the analysis of these torque-related problems in the drive system, exploring the potential causes and preventive measures.

2.3.1   Blocked Drive Mechanics by High Torque Values

As explained in section 2.1, the drive system moves the telescope along the elevation and azimuth axes, allowing for rapid repositioning of the large and heavy structure. However, this places significant constraints both the structure and the motors. One of the problems which were presented are events where torque values oscillate until reaching a certain limit which sometimes coincided with an emergency stop as shown in Fig 2.5. Torque values refer to the measurement of the telescope motors torque, which is a force that causes the telescope to rotate around an axis, measured in Newton-meters. In the context of

a telescope's drive system, torque values would indicate how much rotational force the motors are applying to move the telescope's azimuth and elevation mechanisms.
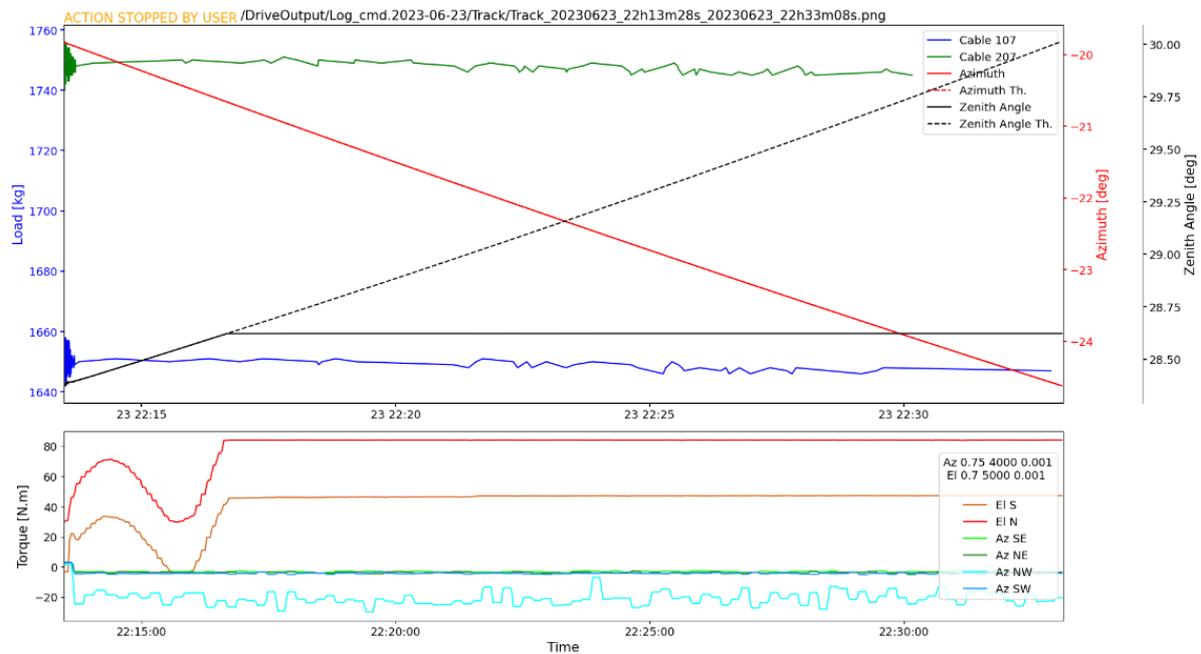
Figure 2.5: Plots from [12], where the movement of the telescope and the torque values in a period of time are presented. In the upper plot, the movements of the telescope is presented, where the zenith movement stops when the torque values reach an upper limit. in the lower plot, oscillations from the torque values of the elevation drive until reaching an upper limit are shown. Credit: Armand Fiasson.

Figure 2.5 shows an example of the previously mentioned events. The upper section of each plot illustrates the precise movement of the telescope over a specific time period, with the legend indicating which cable or drive system is moving and in which direction. During this period, the lower section of the plots presents the torque values for each drive system, differentiated by color. The torque values for either the elevation drive system oscillated until reaching a limit on $\sim 80\,Nm$ and $\sim 40\,Nm$. Exactly when these values hit the upper limit, and remain as a constant for the plotted period of time, the zenith direction also stopped the supposed trajectory it had to take.

2.3.2 Search of Events

Events similar to those shown in Fig 2.5 have occurred at various times over the past few years. In July 2021, the radial guide rollers on the elevation drive were replaced with smaller diameter versions. While this change reduced the frequency of these events, they

have not been completely eliminated.

Identifying the exact timing of these incidents was crucial to finding a potential cause. After successfully accessing and understanding the raw data, a Python script was developed to filter and analyze the events.
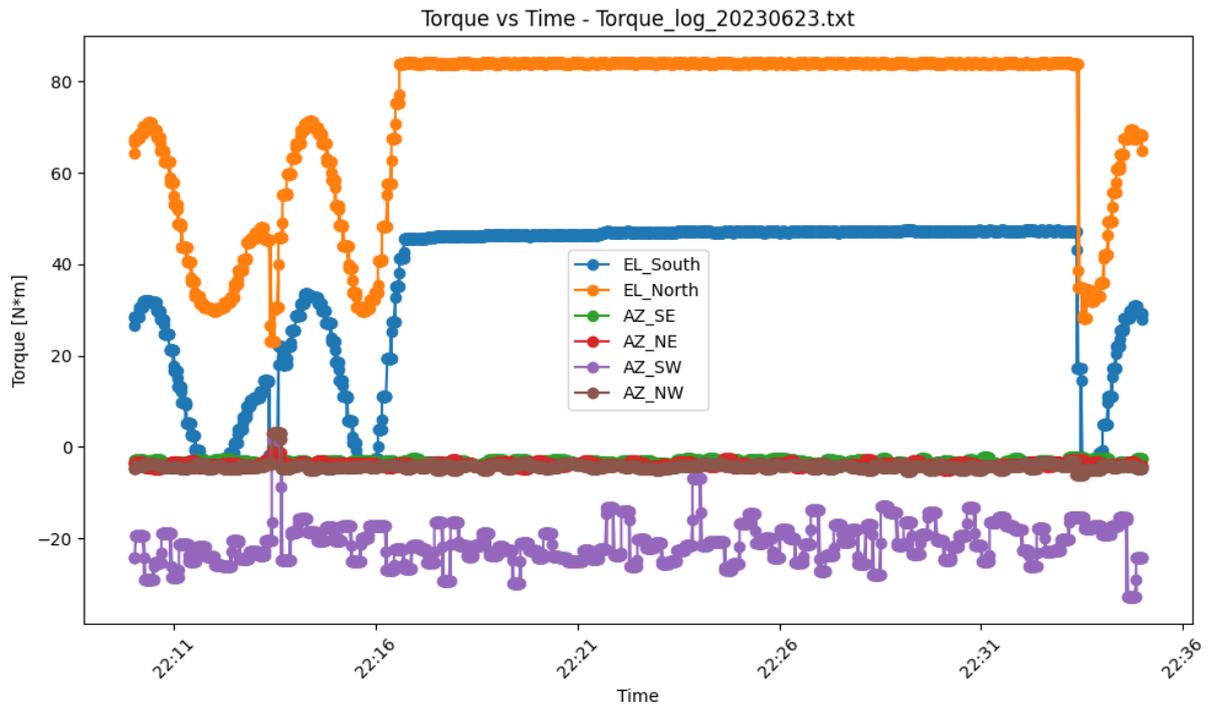
Figure 2.6: Recreation of the lower plot of Fig 2.5.

The evaluation with the new software confirm the behaviour found in the online analysis plots, as shown in Fig 2.5 in comparison with Fig 2.6. Afterwards, the raw data were filtered to create new plots to identify the specific incidents, successfully detecting all of them.

2.3.3   Potential Causes

With the selection of the recurring events identified, the question of their root cause can be analysed. Various possibilities have been discussed:

- High torque might be created due to the expansion of the structure during day when the rails and rods are exposed to the sun light. In that case, the incidents should happen at the beginning of the night after warm days, i.e. a correlation with the timestamp and the temperature might be expected.

- Also strong wind might cause high torque if it hits the telescope in an unfortunate way. In this case, a correlation with the wind speed and wind direction might be seen.

- The telescope is force-free at a zenith distance of about 30 degree. A change in the forces

around that position might cause high torque values as well. In this case an accumulation of the events in this zenith distance range would be expected.

To further explore these potential causes, auxiliary data e.g. from the LST weather station was taken into account. Subsequently, a Python script was developed to analyze the pymongo database and analyze the different factors. To identify potential connections a correlation matrix seemed a good approach.
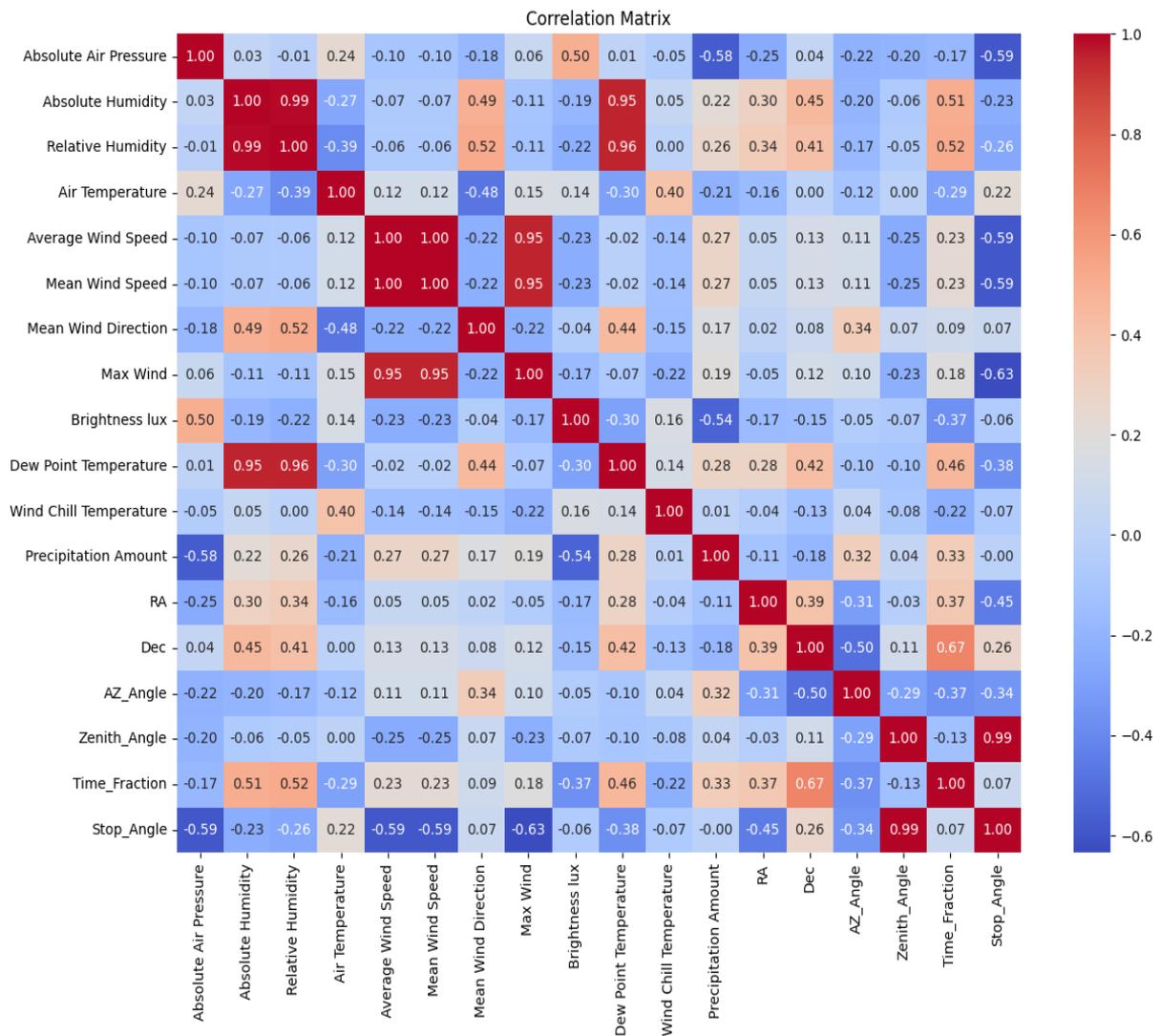

Figure 2.7: Correlation matrix between most of the data of LST Weather Station and some manually selected variables such as the timestamps and the positioning of the telescope.

Fig 2.7 presents the correlation of all non-empty data within a 30-minute window surrounding the oscillation events. Apart from some variables showing similar values (e.g., average/mean wind speed, absolute/relative humidity or zenith direction and it stop of movement), none exhibited a strong correlation with another variable on the time of the

oscillations. This indicates that no single variable had a sufficiently high correlation index to draw a definitive connection between the oscillation incidents and the measured parameters.

To verify different hypotheses more possibilities were examined. To quantify the frequency of all the 34 incidents, data were collected within a 25-minute range surrounding each event with a variable rate of a few seconds.

The possibility of events occurring at similar times on different nights does not appear to be a significant factor, as illustrated in Fig 2.8.
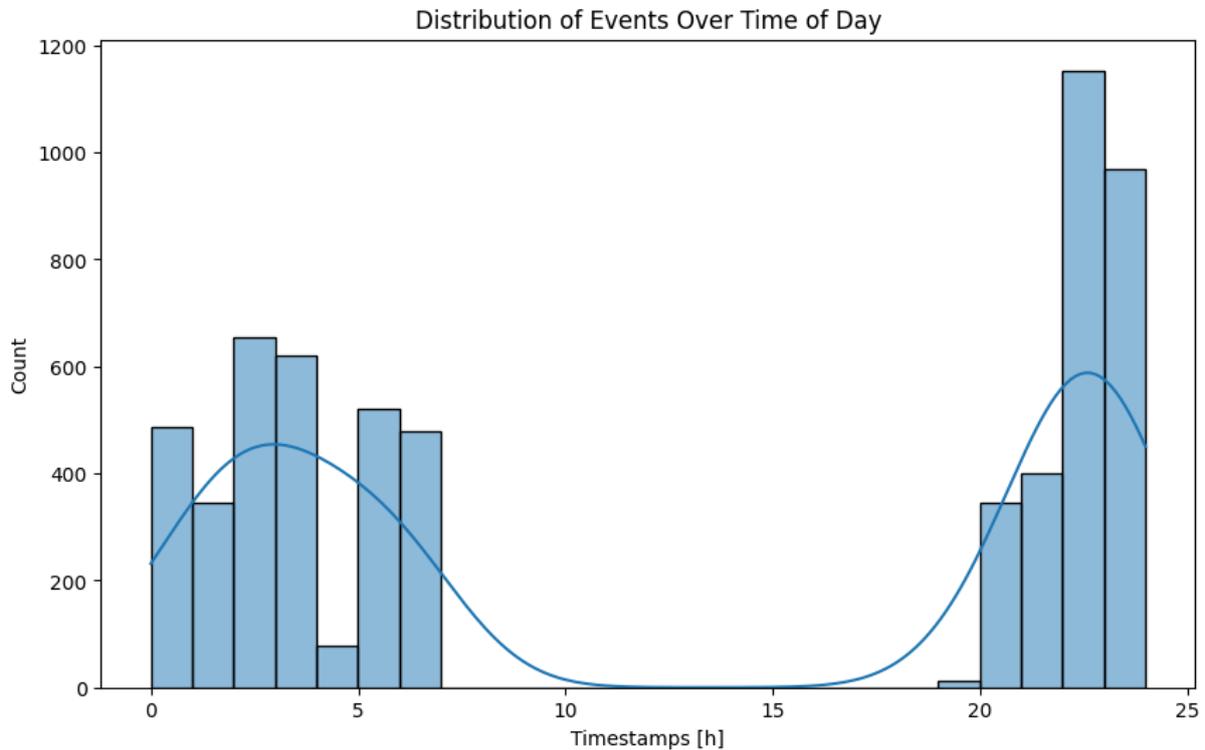
Figure 2.8: Distribution of event occurrences at different times of the day

The plot depicts the frequency of the appearing incidents at the different times of the day as histogram with a kernel distribution estimation to smooth the distribution, shown in the plot in form of a line. No clear trend emerges, as the events are evenly distributed across the observing nights.

Additional weather parameters were also analyzed to identify potential causes, yielding similar outcomes as observed for the timestamps. Figures 2.9, 2.10, and 2.11, present histograms with kernel density estimations for these parameters. Similar to 2.8, no distinct trend was observed.

However, one parameter did show clustering, indicating a potential cause: the zenith distance of the telescope.
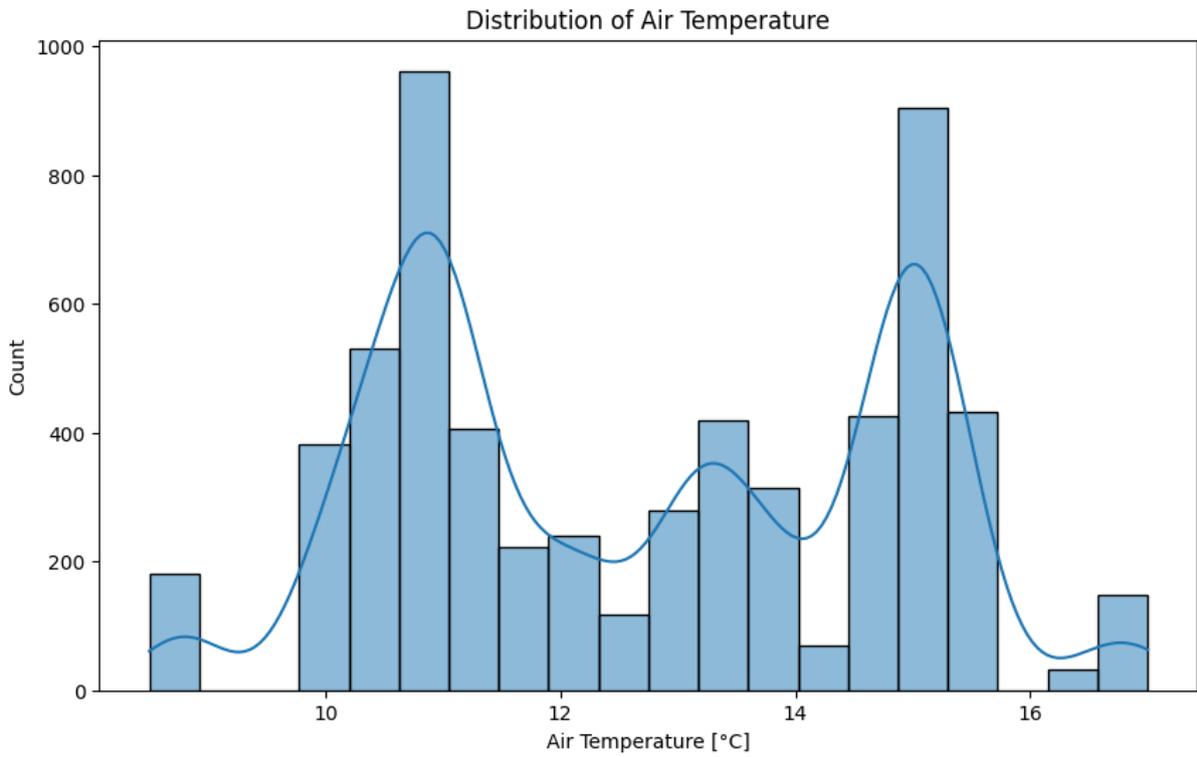
Figure 2.9: Distribution of the air temperature at the time of the incidents.
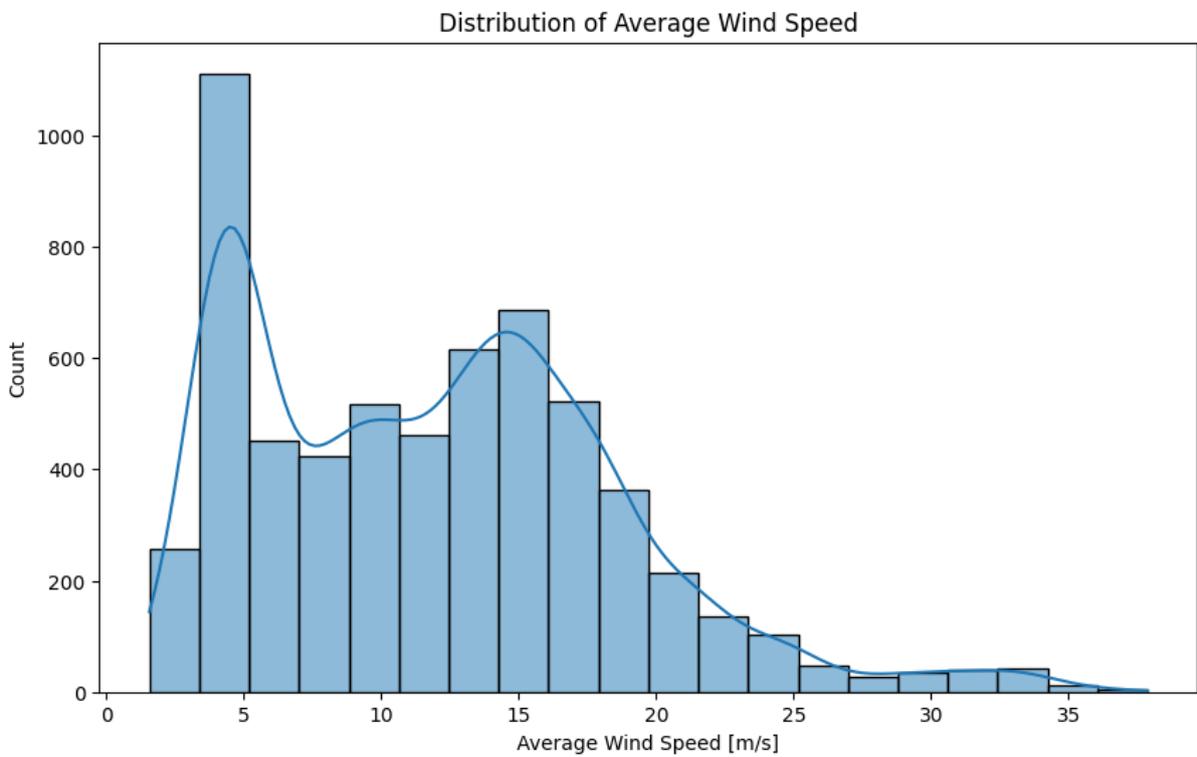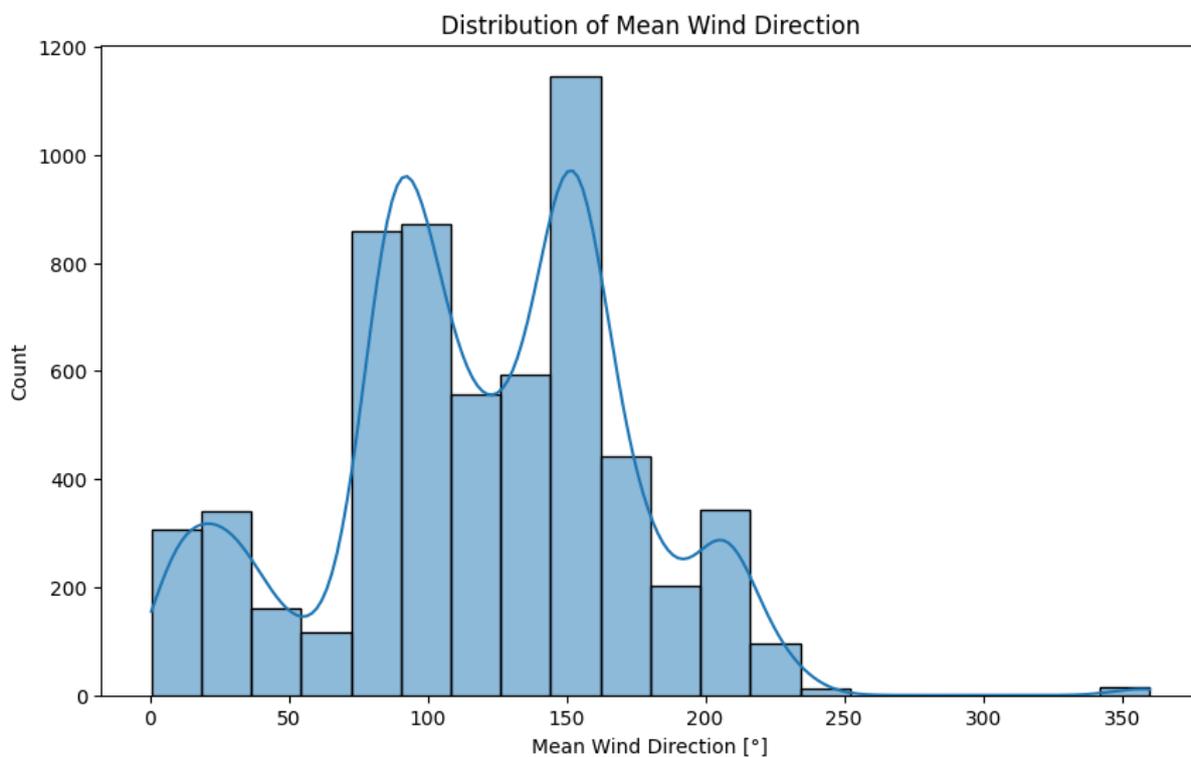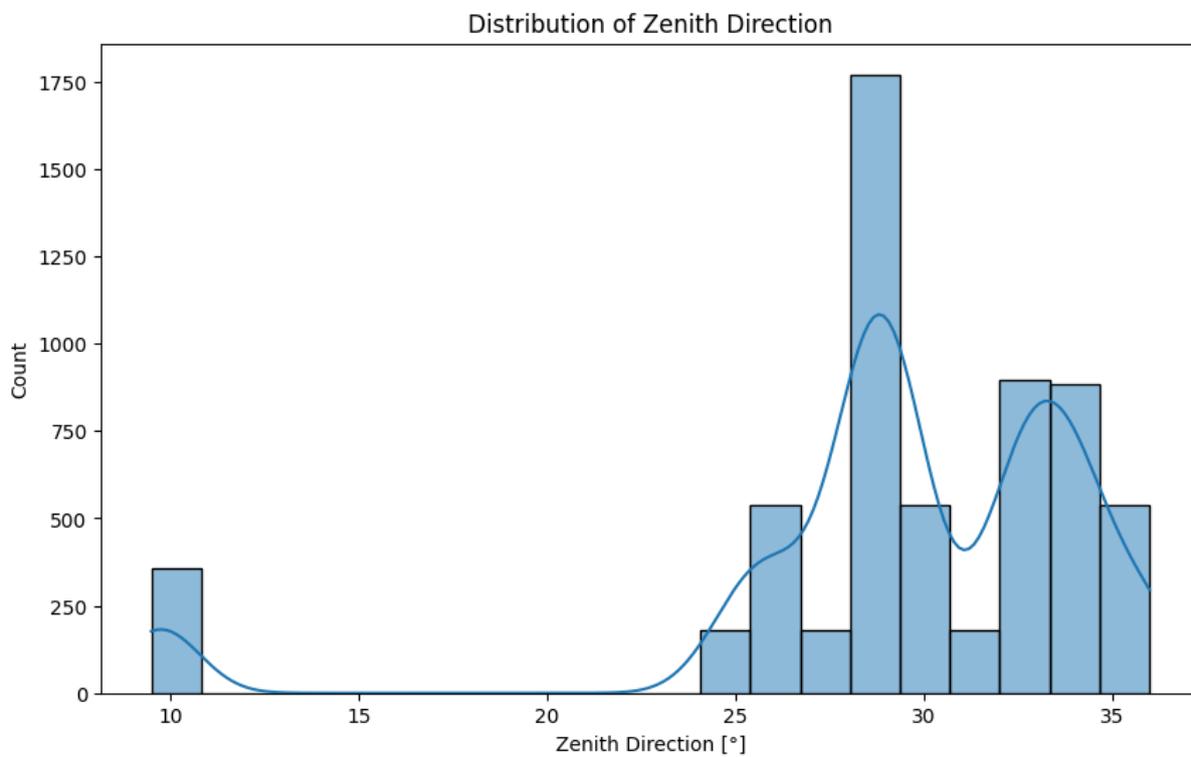

Figure 2.10: Distribution of the wind speed at the time of the incidents.

Figure 2.11: Distribution of the wind direction at the time of the incidents.

Figure 2.12: Distribution of the zenith direction in the process of the oscillation of the torque values.

The data depicted Fig in 2.12 reveal that the majority of incidents happened when the telescope was moving within a zenith distance range of 25 degrees to 35 degrees with an outlier at around 10 degrees.

In discussing this coincidence, several theories and potential causes emerged. One possibility is a shift in the distribution of forces acting on the telescope around 30 degrees, creating additional strain on the drive system. This imbalance might cause the master-slave system to compensate with increased motor movement, but if the encoder accuracy is not good enough for these fine adjustments, the effect of the toothed wheel might be seen in oscillations of the torque. Another discussed theory involved the scenarios where high torque values reach a critical constant threshold. This situation may trigger an emergency braking system, designed to halt telescope movement to prevent mechanical damage or instability. As these ideas are still theoretical, they will require further investigation, discussion, and in-depth analysis in future studies.

2.4   Concluding Remarks

The importance of structure monitoring in large, complex instruments like the LST-1 telescope cannot be overstated. The ability to continually observe and collect data without interruption is vital for the success of astronomical research, especially when capturing transient events that require fast and precise movements.

As demonstrated, various issues can arise that may compromise the operational integrity of the telescope. By implementing advanced monitoring systems like the SmartCheck sensors, it is possible to detect and address these problems early, preventing catastrophic failures and minimizing downtime. One noted issue was the oscillations in high torque values leading to emergency stops. During the analysis, various variables were considered and subsequently discarded as potential causes. However, a consistent observation emerged: incidents tended to occur at specific zenith directions, leading to new theories involving the master-slave drive system and errors in the adjustments of the encoders or the action of braking when reaching a certain torque value limit. While a definitive cause has yet to be identified, this pattern suggests a promising direction for further investigation. This underlines the complexity of finding solutions for various issues but also highlights the importance of quick resolution to minimize the risk of damage.

Observational results of FACT

Having discussed the importance of maintaining a robust telescope structure to minimize the risk of downtime and ensure continuous observation, the attention now shifts to the observational capabilities and studies conducted with a telescope like FACT. As explained before in section 1.3, basing on the comprehensive study of Fig 1.6, a subsample of FACT's neutrino follow-up observations over a time of 3 years has been compared with those of other IACTs. Thanks to its drive system, observational strategy, stable and robust performance and automatic follow-up procedure since May 2019, the fast response times of only 53 s and 63 s could be reached. How this results are composed and how the FACT Telescope is operated will be explained in this chapter.

3.1   Observational Strategy

As introduced in section 1.2.1, FACT employs a comprehensive observational strategy to optimize its scientific output, which includes continuous monitoring, multi-wavelength observations, and the Target of Opportunity (ToO) Program. To organize these observational tasks the automatic scheduling procedure of FACT plays an essential role in determining when and how the telescope should observe specific sources.

3.1.1   Monitoring

FACT's core program is the monitoring of blazars, so it spends most of its time observing well known sources. Fig. 3.1 shows the exact time spent by the telescope observing different sources. The standard monitoring samples are some of the brightest blazars ever observed: Mrk 501, Mrk 421, 1ES 1959+650, 1ES 2344+51.4. Results in form of light curves after some years of observation are presented in [13]. For calibration observations to the Crab Nebula. The Crab Nebula is a standard reference source used in astronomy due to its well-known emission characteristics across different wavelengths.

Source	NumRuns ▼	Time[h]
Mrk 501	78500	3404.81
Mrk 421	73505	3423.30
Crab	59474	2695.68
1ES 1959+650	51073	2420.27
1ES 2344+51.4	45477	2158.16
1H0323+342	24814	1213.95
PKS 0736+01	4044	168.65
LHAASO J2108+5157	2177	107.04
V404 Cyg	1705	79.54
IC 310	1269	49.63
TeV J2032+4130	1265	66.29
GC	1190	52.41
1ES 1218+304	996	38.56
H 1426+428	746	30.59
Dark Patch 3	424	14.90
IceCubeEHE20171106b	295	16.01
PG 1553+113	279	14.52
PKS 2155-304	256	11.02

Figure 3.1: A part of the completed observations by FACT, extracted from its Database [14]. Since its beginning, a total amount of over 15300 hours have been observed.

When the telescope is not occupied in continuous monitoring of its high-priority sources (the four just named blazars), the scheduling space is allocated to low-priority samples such as Multi-Wavelength Campaigns or specific sources based on special interest. Many of this low-priority samples are Extreme Hard Blazar-like Objects (EHBl). These objects are a subtype of blazars, which are a class of active galactic nuclei (AGN) characterized by their intense emissions across the electromagnetic spectrum, particularly at high energies. EHBl are denominated extreme hard due to its flatness in its spectrum.

3.1.2 Target of Opportunity (ToO) Observations

Finally, the last program which the FACT Telescope offers is the ToO Program, which is key for rapid responses and follow-up observations of transient and unpredictable events. This program is essential for collecting time-sensitive data in the critical early phases of events. Due to the importance of the required rapid response times, the telescope started to operate robotically since December 2017 and the automation of its scheduling software is active since May 2019. Therefore when an event occurs, the scheduler interrupts the current observation and starts pointing in the direction of the incoming alert. Prioritizing this high-priority events ensure that the telescope remains flexible, responsive and capable of capturing the opportunities presented by these possible transient events. To perform a ToO observation, the following conditions must be met: the sun elevation must be below 12°, the source's zenith angle must be less than 45°, the distance to the moon must fall

between $10°$ and $170°$, the predicted current must be below $110\mu A$, and the maximum relative threshold must not exceed 10.

3.2 Follow-up Observations

Once gained an insight in the ToO Program, the attention will now change to an in-depth examination of the follow-up program.

3.2.1 Datasample

The data sample collected by the follow-up program of ToOs of FACT are mainly GRBs and neutrino alerts, but also AGN flares. The timely detection and notification of these transient events are facilitated through various alert systems and observatories.

The incoming alerts signaling the occurrence of a transient event are primarily received via the Gamma-ray Coordinates Network (GCN) per socket, where they can be automatically rescheduled, or via e-mail from the Memoradum of Understanding (MoU) or the Astronomer's Telegram, and therefore can only be manually rescheduled. These networks bring together various observatories, experiments and research institutions around the world to work cooperatively on coordinated observation efforts.

The instruments involved in data collection and alert reception can be categorized in distinct alert streams.

3.2.1.1 Astronomer's Telegram

The Astronomer's Telegram is an internet-based short-notice publication service for quickly disseminating information about transient astronomical events. It is widely used by the astronomical community to report and receive alerts about new and ongoing astronomical phenomena, such as GRBs, supernovae, and other transient events. This platform facilitates rapid communication and collaboration among observatories and researchers, ensuring timely follow-up observations and data sharing. The availability of real-time alerts through the Astronomer's Telegram significantly enhances the effectiveness of multi-wavelength and multi-messenger observational campaigns [15].

3.2.1.2 Fermi Large Area Telescope (LAT)

The Fermi LAT is a space-based gamma-ray observatory, being the main instrument of the Fermi Gamma-Ray Space Telescope (FGST). Its high sensitivity, in the energy range of about $20\,\mathrm{MeV}$ to about $300\,\mathrm{GeV}$, and its wide Field of View (FoV), which is about 20% of the night sky, enables detailed studies of $\gamma-$ray emissions from e.g. AGNs [16].

3.2.1.3   Fermi Gamma-Ray Burst Monitor (GBM)

The Fermi GBM is a complementary instrument of the FGST. It is sensitive to X-rays and $\gamma-$rays between $8\,\mathrm{keV}$ and $40\,\mathrm{MeV}$ [17]. Combined with the main instrument, Fermi LAT, they provide a powerful tool to detect and monitor GRBs

3.2.1.4   AMON

The Astrophysical Multimessenger Observatory Network (AMON) is a collaborative network and alert system designed to identify and analyze multimessenger events involving high-energy neutrinos, Gamma-Ray Bursts, and other transient phenomena. AMON leverages data from the IceCube Neutrino Observatory and other experiments to detect neutrino events, correlate them with $\gamma-$ray sources, and provide timely alerts to observatories and research institutions worldwide for follow-up observations and detailed studies of multimessenger events [18].

3.2.1.5   AMON (Icecube)

The events are single neutrino events. AMON_ICECUBE can be categorized in HESE, which has been discontinued and replaced by ICECUBE_ASTROTRACK_GOLD, if they are in an energy range between sub-PeV to PeV and in EHE ,which has been discontinued and replaced by ICECUBE_ASTROTRACK_BRONZE, if they are in an energy range of several hundred TeV [18].

3.2.1.6   AMON (HAWC)

The AMON network collaborates with the High-Altitude Water Cherenkov (HAWC) Gamma-Ray Observatory to identify and analyze HAWC alerts from short time-scale searches looking for GRBs [18].

3.2.1.7   INTEGRAL

The INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL) is a space-based observatory dedicated to conduct $\gamma-$ray, X-ray and visible light observations, with one of its main focuses on GRBs. Its variety of instruments enables simultaneous and coordinated observations across different wavelengths, providing complementary data and insights into the properties, environments, and astrophysical processes occurring within gamma-ray sources and other celestial objects. INTEGRAL also provides pointing information through its instruments, which is crucial for multi-wavelength follow-up observations[19].

3.2.1.8   Swift

The Neil Gehrels Swift Observatory possesses three different instruments: the Burst Alert Telescope (BAT), which detects GRBs and provides alerts, and the X-Ray Telescope (XRT) and the Ultraviolet/Optical Telescope (UVOT), which perform follow-up observations in X-ray and ultraviolet/optical wavelengths, respectively. Swift's BAT is responsible for the initial detection of GRBs, while the XRT provides precise pointing information used for multi-wavelength follow-up observations. This combination allows for rapid response and detailed study of GRBs [20].

3.2.1.9   AGILE

The Astrorivelatore Gamma ad Immagini LEggero (AGILE) is an Italian space mission launched in 2007, dedicated to observing gamma-ray phenomena. Equipped with instruments like the Gamma-Ray Imaging Detector (GRID) and the Mini-Calorimeter (MCAL), AGILE focuses on transient events such as GRBs, providing valuable data for multi-messenger astronomy [21].

3.2.1.10   Cherenkov Telescopes

As introduced in 1.2, Cherenkov Telescopes also provide alerts in case of detection among them. FACT receives alerts from:

- The HAWC observatory, located on the flanks of the Sierra Negra volcano near Puebla, Mexico.

- The H.E.S.S Telescopes situated in the Khomas Highland in Namibia.

- The MAGIC Telescopes, also located on the Canary Islands, next to FACT and the CTA-North Telescopes.

- The VERITAS Telescopes in Arizona.

All of these ground-based telescopes are designed to detected and study VHE $\gamma-$ray emissions with an advanced technology and high sensitivity.

To summarize, in table 3.1 the different instruments with their FoV and their energy range are presented.

Table 3.1: Observational partners and instrument characteristics.

| Partner	Field of View (FoV)	Energy Range
Fermi LAT [16]	$\sim$ 2.4 sr	20 MeV - 300 GeV
Fermi GBM [17]	$\sim$ 8 sr	8 keV - 40 MeV
Swift [20]	XRT: $\sim$ 1.4° $\times$ 1.4°	X-ray, UV, Optical
	UVOT: $\sim$ 20° $\times$ 20°	
	BAT: $\sim$ 2 sr	15 keV - 150 keV
INTEGRAL [19]	IBIS/ISGRI: $\sim$ 9° $\times$ 9°	20 keV - 10 MeV
	JEM-X: $\sim$ 15° $\times$ 15°	3 keV - 35 keV
IceCube (AMON) [18]	Varies	EHE: $>$ 100 TeV
		HESE: sub-PeV - PeV
HAWC (AMON) [18]	$\sim$ 2 sr	TeV
AGILE [21]	$\sim$ 2.5 sr	30 MeV - 50 GeV
H.E.S.S. [22]	$\sim$ 5°	100 GeV - 100 TeV
MAGIC [23]	$\sim$ 3.5°	30 GeV - 100 TeV
VERITAS [24]	$\sim$ 3.5°	85 GeV - 30 TeV

3.2.2 Automatic ToOs

Since May 2019, alerts received via GCN have been followed-up automatically. This marks a significant advancement for quicker responses and repositioning, allowing to capture the early critical phases of the event.

Typically, when one of the beforehand declared instruments detect something, there is a latency of a few seconds between the event's discovery and the transmission of the alert. Then sending this alerts through the communication systems also has a duration of some seconds. But here the most import change comes. The alerts were manually received via email from various sources, including the Memorandum of Understanding (MoU) for AGN flares, HAWC for flare monitoring or all-sky hotspots, and the Astronomer's Telegram. When received, the alert experts discussed for the observation relevance before pointing to the position. This procedure could span from minutes to days, depending on various factors. However, with the incorporation in the automated scheduling system, it now prioritizes alerts and starts repositioning immediately if needed. This procedure in now, only is in a order of magnitude of seconds. Lastly, the movement of the telescope to point to the position of the incoming alert, is, thanks to its fast drive-system, also in a timescale of up to one minute, depending on where it has to reposition to. The improvement due to the automation of the reaction to the alerts is shown in Fig 1.6.

3.2.3   Results

FACT started operating in 2011 and its ToO Program in 2016, so now all of observations triggered by this program will be presented, showcasing the overall distribution and duration of the observations.To analyze these results, the data (from the FACT database) was extracted using SQL queries. The timestamps of the arrival of each event were obtained from the earlier presented instruments either from the GCN or from sent e-mails. By subtracting the arrival time from the start of each observation, the delay between detection and observation was calculated.

The first plot, Fig. 3.2, illustrates all of the alerts followed-up by FACT plotting the time each event as been observed (Exposure on y-axis) versus the duration between the discovery of the event and the start of the observation (Delay on x-axis). The difference between the manual alerts, presented in purple and labelled, and the automatic followed-up events are notable.
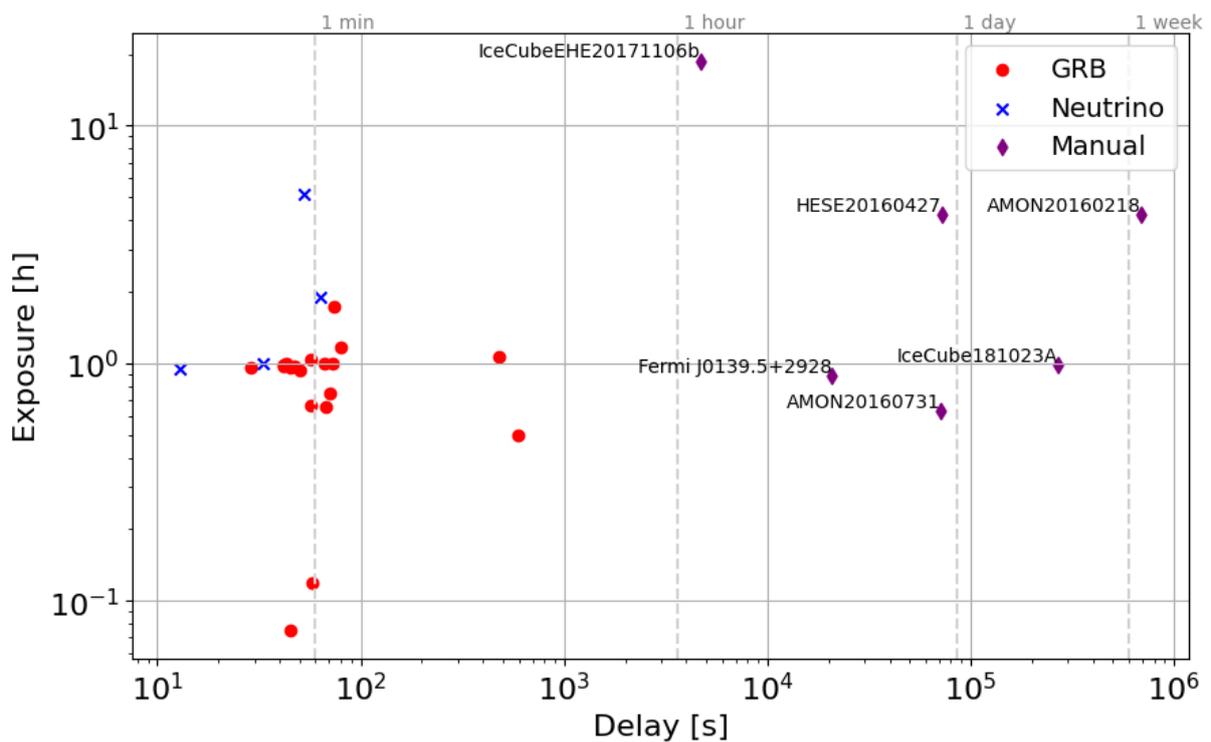
Figure 3.2: All events of FACT's ToO Program extracted from its database including manual alerts, in purple and labelled, and automatic alerts in red and circles for GRBs and in blue and crosses for neutrinos.
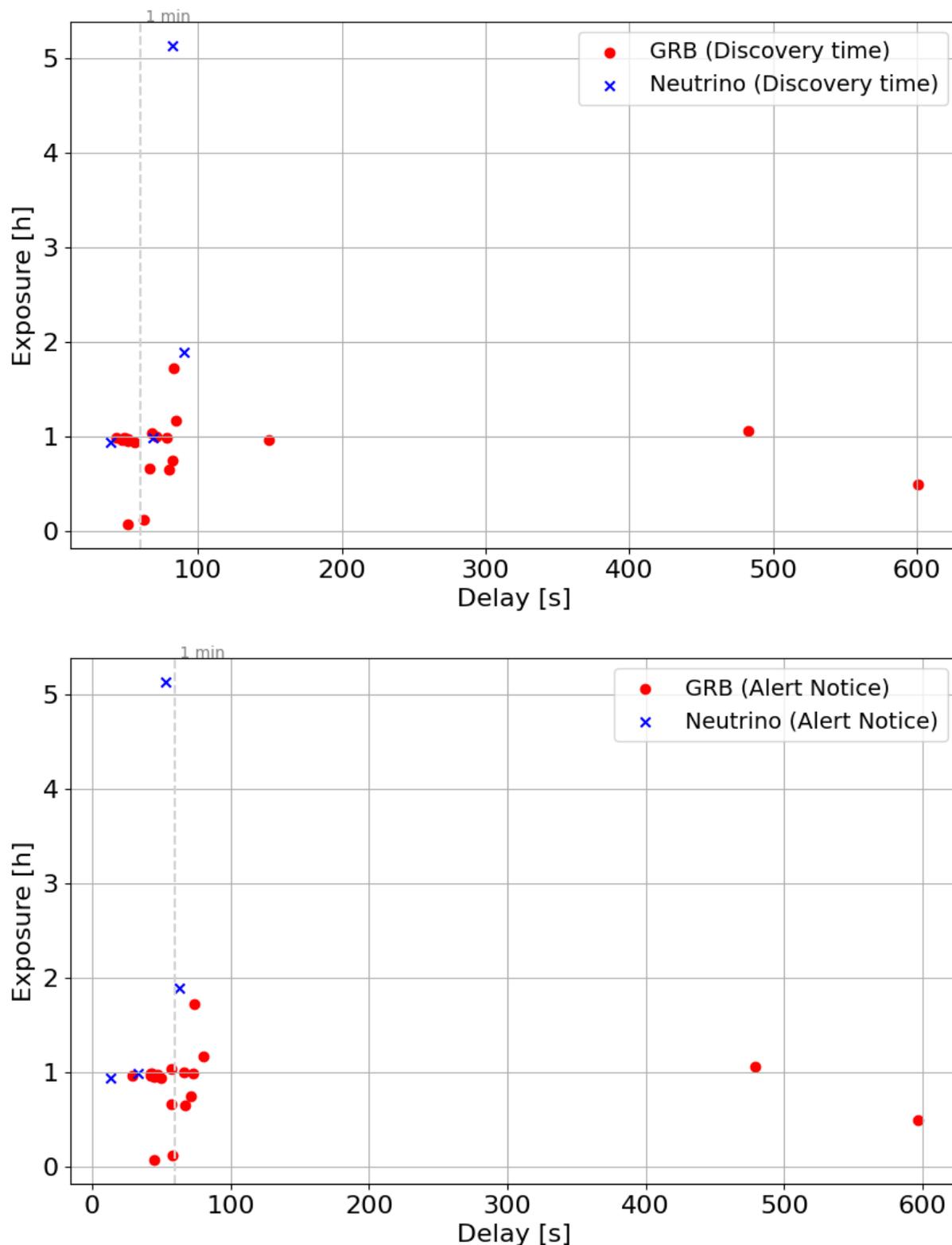
Figure 3.3: All of the automatic alerts ToOs, showing the exposure vs delay connection for neutrinos in blue and crosses and GRBs in red and circles. The upper plot represents the delay as the difference between the start of observation and the time the alert incomes, and the lower plot represents the delay as the difference between the start of observation and the discovery time of the event.

The automatic ones bestowed a significant speed-up, and are divided in two types of alerts, GRBs, represented in red and as dots, and neutrinos, represented in blue and as crosses. The manual ones were all neutrino alerts, except Fermi J0139.5+2928, which was a $\gamma-$ray source at GeV energies detected by Fermi-LAT.

To focus more on the automatic alert the next two plots are presented, Fig. 3.3, where the meaning of the legends and axes remain the same as in Fig. 3.2, but with a slight difference in the x-axis, reflecting the time difference. Besides three outliers, all of the observations started within 90 s or less (from discovery to start of observation).

Therefore, in Fig. 3.4, a zoom-ed in version is shown to have a detailed examination. This plot incorporates both previously discussed delays, to have a overview in how the time between delay is affected. In can be observed that there is a big cluster at 1 hour of exposure, and that is due to FACT's observation strategy. When an alert of an ToO incomes, it will immediately will be targeted for one hour. If there is further interest, the observation will be extended on manual interaction. Otherwise, the telescope will resume its interrupted schedule. All the alerts seen in the plot below 1 hour of exposure can be explained due to the interruption either by another consecutive alert, or that the telescope could not continue to observe because the end of the night was reached.
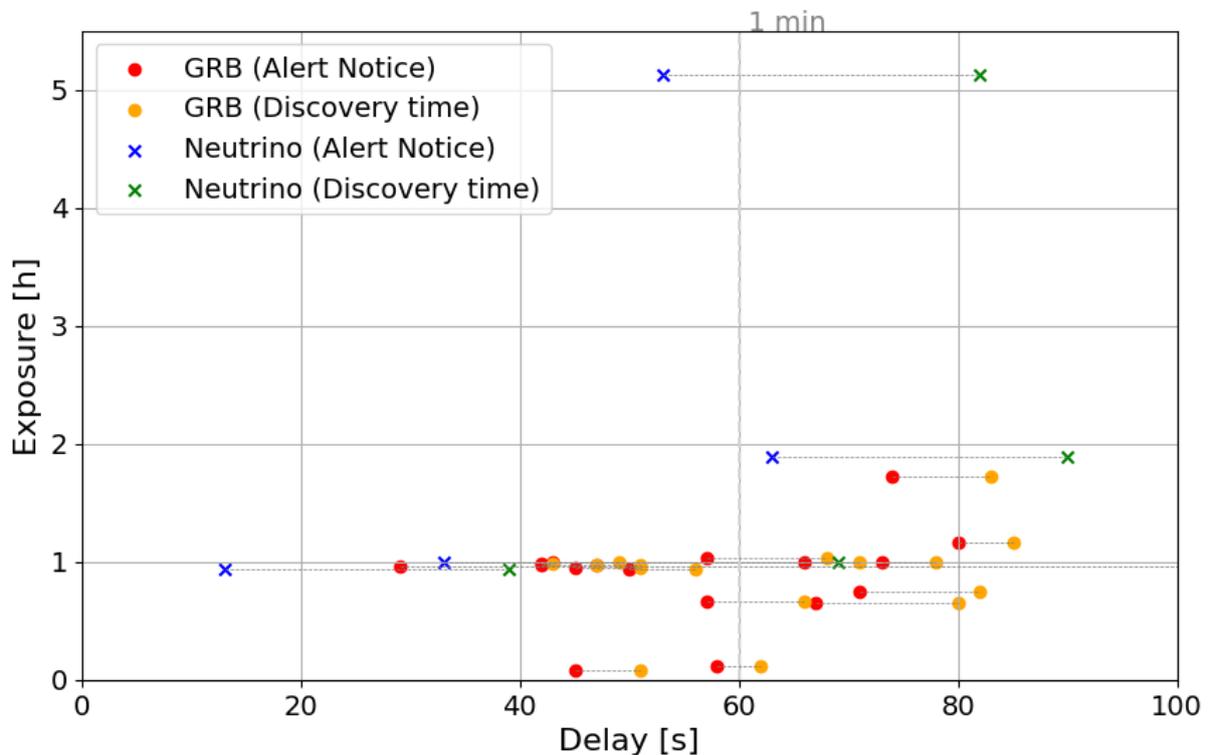

Figure 3.4: A zoom-ed in version of the automatic ToOs with combined times of the different delays explained in Fig. 3.3, for GRBs in red and orange and in form of circles and for neutrinos in blue and green in form of crosses.

Examining the plots, we find that the FACT telescope, thanks to its automation and fast drive system, is capable of reaching response times between 13 and 80 seconds, being the first one a very impressive achievement.

However, to the response times there is also some extra delay to be considered. In Fig. 3.5 the additional delay, as also seen in the previous plots, is depicted for all of the different events followed-up by FACT. Except one outlier, a clear trend emerges, where the time spent on the transmission for GRBs are around 15 seconds and lower, whereas the time spent for the neutrino alerts are about 30 seconds.

With all delays accounted for, only the movement time of the telescope remains. Thanks to its rapid drive system, FACT can cover any direction within under a minute, demonstrated in results like Fig 3.3.
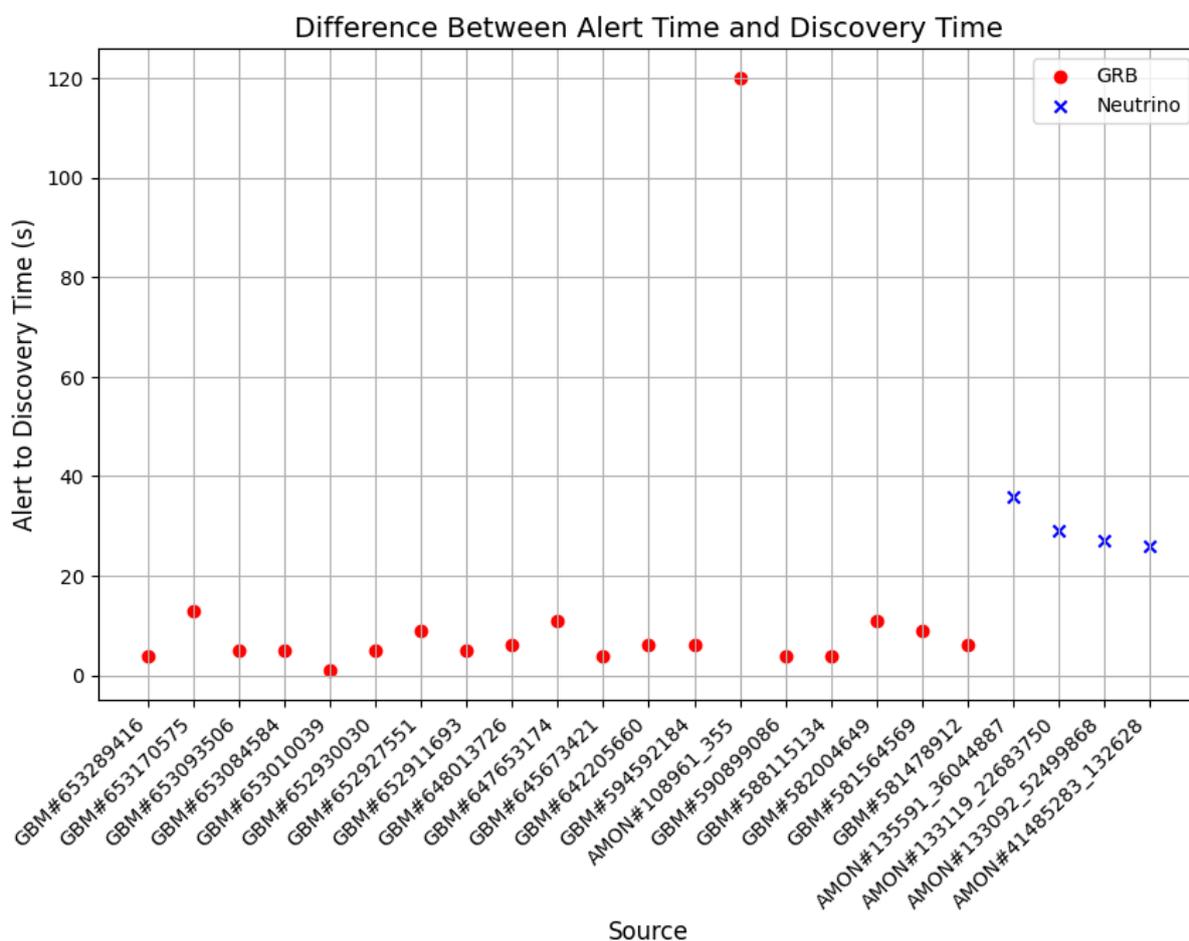
Figure 3.5: Time spent from the discovery of an event to the transmitted alert of every automatic alert from FACT ToO Program

3.3   Next Steps

FACT has demonstrated a remarkable capacity for rapid response for transient events, such as GRBs and neutrinos, thanks to its automation of the Target of Opportunity Program, including the scheduling and the movement of the telescope, and its fast drive system. The next step involves a detailed analysis of each alert to assess its relevance. Additionally, a comprehensive sky-map analysis of these alerts will be conducted to potentially detect TeV emission from gamma-ray bursts or neutrino source candidates or set upper limits on their very-high-energy emission and enhance the understanding of the observed phenomena.

Summary and Outlook

In the realm of gamma-ray astronomy, where transient events like Gamma-Ray Bursts or neutrinos occur and can be detected from ground-based telescoped with the Imaging Atmospheric Cherenkov Telescope, rapid response is crucial for capturing these phenomena. This work examines not only the importance of swift response times with telescopes like the First G-APD Cherenkov Telescope but also the stability and security of larger telescopes, such as the Large Size Telescope.

To prevent issues or downtime in observation, a continuous monitoring with the SmartCheck sensors has been shown. The use of the tools of their interface, as well as other analysis tools, has facilitated the identification of the telescope's eigenfrequencies, representing a step forward in developing predictive maintenance for the LST. For existing issues, such as the blocked drive system because of high torque values while oscillating, a thorough investigation has been conducted. Various potential causes have been considered, with many theories discarded and new ones emerging. While some parameters such as weather data showed no significant impact, the zenith distance appeared to be a consistent factor. Theories regarding imbalances and the master-slave system, potentially involving encoder adjustment errors or an emergency braking system when reaching a threshold, will be further studied.

On the observational side, the capabilities and strategies of FACT have been highlighted. Although its primary focus is blazar monitoring, its Target of Opportunity Program for multiwavelength and multi-messenger alerts is essential for transient events. Thanks to the automation of its scheduler and follow-up system for incoming alerts from collaborating instruments as well as its fast drive system, FACT achieved very rapid response times, with a minimum of 13 seconds. The majority of alerts have an exposure of one hour, and automatic quick-look analysis provides results on the observed position with a latency of ca. 15min. To further study these alerts, sky-map analysis will be carried out.

Bibliography

[1] T C Weekes. *Very High Energy Gamma-ray Astronomy.* Institute of Physics Publishing, Bristol and Philadelphia, 2003.

[2] IceCube Collaboration. Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector. *Science*, 342(6161):1242856, November 2013.

[3] M. et al. Noethe. FACT - Performance of the First Cherenkov Telescope Observing with SiPMs. In *35th International Cosmic Ray Conference (ICRC2017)*, volume 301 of *International Cosmic Ray Conference*, page 791, July 2017.

[4] ISDC - FACT. `http://isdc.unige.ch/fact/`. Last accessed: 2024-06-24.

[5] Federico Di Pierro. Status of the Large-Sized Telescope of the Cherenkov Telescope Array. In *Journal of Physics Conference Series*, volume 2429 of *Journal of Physics Conference Series*, page 012020. IOP, February 2023.

[6] The FACT Collaboration, The H. E. S. S. Collaboration, The Icecube Collaboration, The MAGIC Collaboration, and The VERITAS Collaboration. Searching for VHE gamma-ray emission associated with IceCube neutrino alerts using FACT, H.E.S.S., MAGIC, and VERITAS. In *37th International Cosmic Ray Conference*, page 960, March 2022.

[7] Victor Barbosa Martins and Markus Garczarczyk. The structure monitoring of the MST prototype of CTA. In Heather K. Marshall, Jason Spyromilio, and Tomonori Usuda, editors, *Ground-based and Airborne Telescopes VIII*, volume 11445 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, page 114456E, December 2020.

[8] The CTA Collaboration. The Cherenkov Telescope Array Large Size Telescope. In *International Cosmic Ray Conference*, volume 33 of *International Cosmic Ray Conference*, page 1139, January 2013.

[9] J. Cortina and M. Teshima. Status of the Cherenkov Telescope Array Large Size Telescopes. In *34th International Cosmic Ray Conference (ICRC2015)*, volume 34 of *International Cosmic Ray Conference*, page 943, July 2015.

[10] Altitude and azimuth: The horizontal coordinate system. `https://www.timeanddate.com/astronomy/horizontal-coordinate-system.html`. Last accessed: 2024-06-23.

[11] Quentin Piel, Laurent Brunetti, Josef Eder, Armand Fiasson, Gian Paolo Guizzo, Inocencio Monteiro, Koji Noda, and Thomas Schweizer. Simulations of the Large Size Telescope drive system. In Andrew D. Holland and James Beletic, editors, *High Energy, Optical, and Infrared Detectors for Astronomy VIII*, volume 10709 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, page 1070925, August 2018.

[12] LST1-Operations. `https://www.lst1.iac.es/operations/drive/`. Last accessed: 2024-06-12.

[13] D. et al. Dorner. FACT - Highlights from more than Five Years of Unbiased Monitoring at TeV Energies. In *35th International Cosmic Ray Conference (ICRC2017)*, volume 301 of *International Cosmic Ray Conference*, page 609, July 2017.

[14] FACT Database. `https://www.fact-project.org/run_db/db/fact_runinfo.php`. Last accessed: 2024-06-25.

[15] Astronomer's Telegram. `https://astronomerstelegram.org/`. Last accessed: 2024-06-27.

[16] Fermi - Large Area Telescope. `https://fermi.gsfc.nasa.gov/science/instruments/lat.html`. Last accessed: 2024-06-26.

[17] Gamma-ray Burst Monitor. `https://gammaray.msfc.nasa.gov/gbm/`. Last accessed: 2024-06-26.

[18] GCN/AMON Notices. `https://gcn.gsfc.nasa.gov/amon.html`. Last accessed: 2024-06-26.

[19] ESA - INTEGRAL. `https://www.esa.int/Science_Exploration/Space_Science/Integral_overview`. Last accessed: 2024-06-26.

[20] The Neil Gehrels Swift Observatory. `https://swift.gsfc.nasa.gov/about_swift/`. Last accessed: 2024-05-26.

[21] AGILE. `https://heasarc.gsfc.nasa.gov/docs/heasarc/missions/agile.html`. Last accessed: 2024-06-26.

[22] H.E.S.S. `https://www.mpi-hd.mpg.de/HESS/pages/about/`. Last accessed: 2024-06-26.

[23] MAGIC. `https://magic.mppmu.mpg.de/`. Last accessed: 2024-06-26.

[24] VERITAS. `https://veritas.sao.arizona.edu/about-veritas`. Last accessed: 2024-06-26.

Acknowledgements

Declaration of originality

I declare that I have authored this thesis independently, that I have not used other than the declared sources / resources, and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

Würzburg, June 27, 2024   Marcel Vorbrugg