



Bachelor's thesis

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Isabel Schraml

Supervisor: Prof. Dr. Claudio Kopper

***Analysis of Data from the Sweden Camera Calibration Device
in the IceCube Neutrino Observatory Upgrade***

Abstract

IceCube is a cubic-kilometer neutrino observatory at the South Pole designed to study astrophysical neutrinos, fundamental particles that act as messengers from high-energy cosmic events. This thesis presents an analysis of deployment data from the Sweden Camera during its descent into an IceCube Upgrade borehole. An image-preprocessing algorithm was developed to remove camera artifacts, enabling the extraction of optical parameters to reconstruct the ice stratigraphy. Internal accelerometer and magnetometer measurements were processed to analyze the camera's orientation. A comparison between extracted optical parameters and sensor-derived azimuth angles showed no discernible correlation, suggesting that further refinement of the accelerometer data processing is required. Finally, comparing the accelerometer data with independent IceCube supernova hit rate data suggests a visual correlation in the overall rotational movement during the camera drop, indicating potential for further detailed analysis.

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1 Introduction

Throughout history, humanity’s quest to comprehend the cosmos has relied primarily on optical observations of the night sky. However, because light is easily absorbed or deflected by cosmic matter, modern astrophysics utilizes neutrinos, invisible particles that travel unhindered across the universe, serving as unique messengers from extreme cosmic events. To detect these particles, the IceCube Neutrino Observatory at the South Pole was constructed as the world’s largest Cherenkov detector [1], instrumenting a cubic kilometer of deep Antarctic ice to study these high-energy astrophysical neutrinos [2]. To enhance its scientific capabilities, lower the energy detection threshold, and provide a platform to test new technologies for future extensions such as IceCube-Gen2 [3], the IceCube Upgrade was initiated [4]. During the austral summer deployment season, new detector strings equipped with advanced optical sensors are lowered into boreholes melted deeply into the glacial ice [5].

Accurate reconstruction of neutrino interactions relies on a precise understanding of the surrounding optical medium. Natural ice features, such as depth-dependent dust layers and flow-induced optical anisotropy, alter photon propagation [6, 7]. Additionally, localized disturbance effects within the drill holes, most notably the formation of a scattering-rich ”bubble column” during refreezing, introduce further complexities [8]. To characterize these optical properties and monitor the drill-hole environment during deployment, calibration devices such as the Sweden Camera are deployed into the boreholes [9].

This thesis focuses on the data analysis of the Sweden Camera during its descent into the polar ice. The first objective is to develop an image-preprocessing algorithm to detect and remove camera artifacts, enabling the extraction of visual features such as layer boundaries and scattering intensities to map the ice stratigraphy. The second objective is to analyze data from internal accelerometers and magnetometers across both control boards (Motor Controller and Camera Controller) to reconstruct the orientation of the camera during its drop. Thirdly, the sensor-derived orientation is cross-validated against supernova hit rates recorded simultaneously by surrounding IceCube optical modules, alongside an evaluation of potential correlations between visual frame characteristics and mechanical motions.

Chapter 2 of this thesis introduces the physical principles of neutrino detection and the IceCube observatory infrastructure. Chapter 3 describes the technical hardware and sensor setup of the Sweden Camera. Chapter 4 presents the image preprocessing algorithms and the resulting visual deployment data. Chapter 5 examines the accelerometer and magnetometer measurements to determine the spatial tracking of the device and evaluates visual-sensor correlations. Chapter 6 performs cross-validation between the accelerometer measurements and the independent optical direction extracted from the IceCube supernova hit rate data. Finally, Chapter 7 synthesizes the key findings and provides an outlook for future calibration endeavors.

2 The IceCube Neutrino Observatory

The IceCube Neutrino Observatory is a cubic-kilometer-sized Cherenkov detector deeply embedded in the Antarctic ice sheet at the geographic South Pole. To understand how this massive instrument reconstructs astrophysical events, it is essential to first establish the underlying physical detection principles and the optical properties of the medium.

2.1 Neutrinos

In the Standard Model of particle physics, neutrinos are elementary particles belonging to the lepton family (see Figure 1). They exist in three distinct flavors, each corresponding to a charged lepton partner: the electron neutrino (ν_e), the muon neutrino (ν_μ), and the tau neutrino (ν_τ).

Unlike their charged counterparts, neutrinos possess no electric charge and interact exclusively via the weak nuclear force (and gravitationally, though negligible at particle scales). Consequently, they exhibit extremely small interaction cross-sections, allowing them to pass through vast amounts of matter virtually unhindered [10].

Because they are electrically neutral and only weakly interacting, neutrinos serve as ideal cosmic messengers, preserving their original directional and spectral information from distant astrophysical sources.

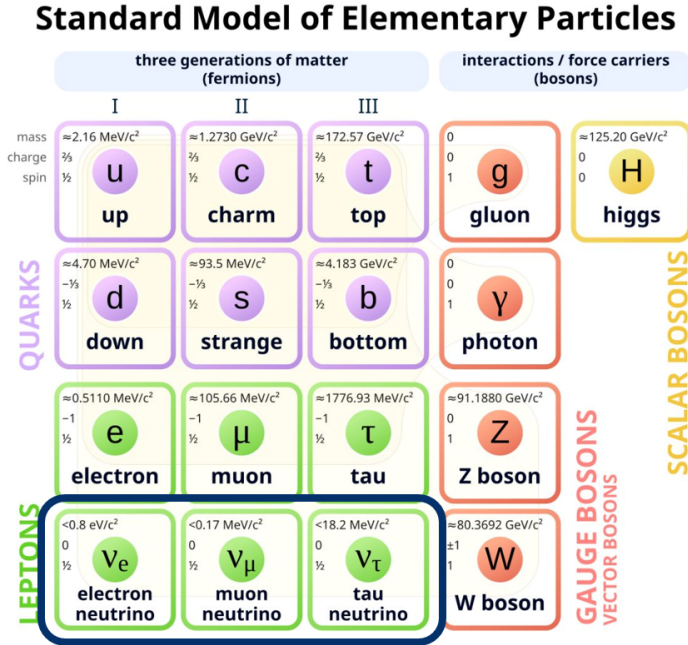


Figure 1: The Standard Model of elementary particles, structured into three generations of matter (fermions) and force carriers (bosons). The three electrically neutral neutrino flavors (ν_e , ν_μ , ν_τ) are highlighted in the lepton sector. Modified from [11].

2.2 Cherenkov Radiation

Cherenkov radiation can be understood as an optical phenomenon analogous to the acoustic sonic boom effect. When an electrically charged particle travels through a

dielectric medium, it polarizes the surrounding molecules along its track, creating temporary electrical dipoles. As these molecules return to their unpolarized ground state, they emit photons.

Under normal circumstances, these light waves interfere destructively and cancel each other out. However, if the particle moves at a velocity v that exceeds the phase velocity of light in that specific medium ($v > \frac{c}{n}$, where c is the speed of light in a vacuum and n is the refractive index of the medium), constructive interference occurs. As illustrated in Figure 2, the individual spherical wavefronts combine to form a coherent envelope emitted at a fixed angle ϑ_C . This creates a distinct light cone whose opening angle is mathematically described by:

$$\cos \vartheta_C = \frac{1}{n\beta} \quad \text{with} \quad \beta = \frac{v}{c} \quad (1)$$

The resulting light cone provides direct information about both the trajectory and the energy of the moving particle, which projects characteristic ring-like shapes when intersecting with a surface. In the IceCube Neutrino Observatory, secondary relativistic particles (such as muons) produced by neutrino interactions can exceed the phase velocity of light in the Antarctic ice, emitting the characteristic Cherenkov light that can subsequently be captured [12].

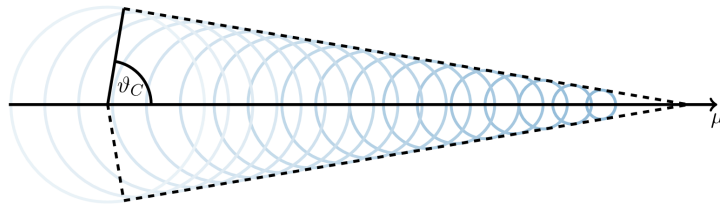


Figure 2: Formation of a Cherenkov light cone via constructive interference of elementary waves, emitted by an ultra-relativistic particle (μ) moving faster than the local speed of light [13].

2.3 Photomultiplier Tubes (PMTs)

PMTs are detectors used to detect photons, such as those resulting from the Cherenkov effect inside IceCube. When these photons arrive at the PMT’s photocathode, they cause the emission of primary electrons due to the photoelectric effect (see Figure 3). The electrons are then accelerated towards dynodes. Each dynode holds a higher voltage than the previous one, which allows for acceleration at every dynode. When such an accelerated electron with high energy arrives at the next dynode, it causes the emission of multiple low-energy electrons, which results in an avalanche of electrons. In the end, there is a high number of electrons, which arrive at the anode and can be detected as a sharp current pulse [14]. This electrical signal is then converted into a digital record called a “Hit” that is used to reconstruct the neutrino event [15].

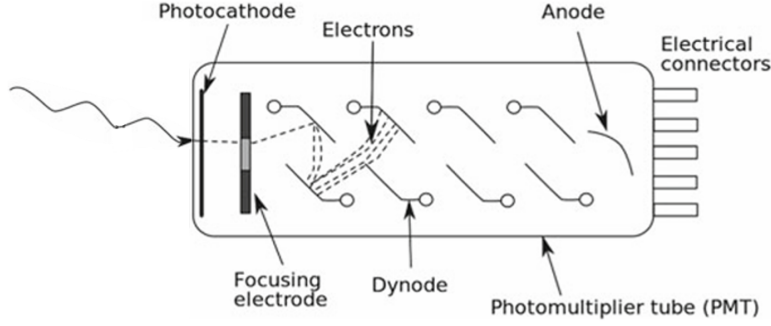


Figure 3: Schematic diagram of a Photomultiplier Tube (PMT) illustrating the electron multiplication process from the photocathode to the anode. Modified from [14].

2.4 The IceCube Neutrino Observatory, the IceCube Upgrade and IceCube-Gen2

The IceCube Neutrino Observatory, embedded in the South Pole ice, is a particle detector with a size that currently covers one cubic kilometer at a depth from 1,450 m to 2,450 m and is designed to measure high-energy neutrinos [2, 16].

Constructed between 2004 and 2011, the primary telescope structure comprises an in-ice array of 5,160 Digital Optical Modules (DOMs). These sensors are distributed across 86 vertical strings, which were frozen into boreholes with a diameter of 60 cm and positioned at intervals of 125 m. Each individual string is equipped with 60 DOMs. To detect neutrino interactions within the ice, every module utilizes a ten-inch photomultiplier tube (PMT) designed to register the Cherenkov radiation generated by secondary particles [16].

In order to analyze neutrino oscillations, the DeepCore subdetector was integrated as a denser configuration at the center of the array, lowering the observatory’s neutrino energy threshold to approximately 10 GeV. This high-density setup was achieved by deploying eight of the strings more compactly, reducing their horizontal separation to about 70 m and tightening the vertical DOM spacing to 7 meters [16].

To expand these scientific capabilities to lower energies, the IceCube Upgrade was initiated. It aims to enhance sensitivity to neutrino oscillations and dark matter, while improving both the reconstruction of neutrino-induced cascades and the calibration of the surrounding ice [4]. This first extension introduced five additional strings in the region of the DeepCore [17] (visible in Figure 4) and took place in the austral summer seasons between 2024 and 2026 [5].

The Upgrade also paves the way for future expansions by enabling the verification of next-generation detector prototypes [4]. Building on these developments, IceCube-Gen2 is the planned extension of the IceCube Neutrino Observatory, utilizing significantly wider string spacing. The primary scientific objective of this layout is the observation and analysis of high-energy cosmic neutrino sources at the PeV level [1]. By adding 120 strings equipped with 9,600 upgraded, three-times more sensitive optical modules at distances of 240 m, the in-ice optical array will expand its detection volume to 8 km³ and quintuple its sensitivity [18].

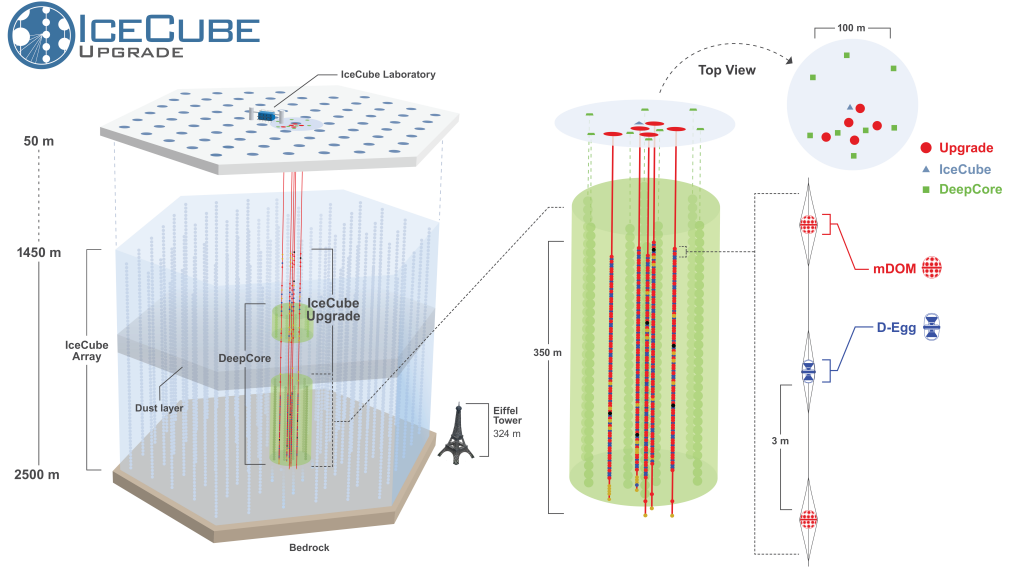


Figure 4: Layout of the IceCube Upgrade within the existing observatory infrastructure. Left to right: Three-dimensional view of the full instrumented volume, a close-up of the dense five-string upgrade configuration at the array core, a top-down view of the string spacing, and a schematic of the deployed sensor modules (mDOMs and D-Eggs) [19].

2.5 Drilling of the Holes and String Deployment

To instrument the deep ice with optical sensors, access holes extending down to several kilometers depth are required. Instead of using traditional mechanical drilling, which is impractical at these depths and temperatures, the holes are created by melting the ice. Once a water-filled column is melted, the detector components attached to a central cable can be lowered into the borehole. After the installation is complete, the surrounding water refreezes, permanently anchoring the instruments within the ice. The upper section of the ice sheet consists of compressed snow, the so-called "firn layer", which extends down to a depth of approximately 50 m. Because this porous layer cannot hold water, it has to be drilled separately using a dedicated firn drill. Below the firn layer, the main boreholes were created using the Enhanced Hot Water Drill (EHWD), which pumps high-pressure hot water to continuously melt the ice at a rate of approximately $2 \frac{\text{m}}{\text{min}}$ [16]. During the original IceCube construction, the entire drilling process for a single hole took an average of 48 hours [1].

Deployment of the original IceCube DOMs requires a minimum operational borehole diameter of 45 cm. To compensate for the continuous decrease in borehole radius caused by the refreezing of the surrounding ice during deployment [20], the holes were drilled with an expanded diameter of 60 cm. Once the drill is removed, the modules are attached one by one to the main cable and lowered to their final positions. It takes approximately 5 days for the water column to fully refreeze [21].

2.6 Ice Properties and Stratigraphy

At the ice depths utilized by the IceCube detector, the high pressure transforms all residual air bubbles into transparent clathrate hydrate crystals. This results in an exceptionally clear medium with unmatched optical transparency that is ideal for the detection of photons created by neutrino interactions [22].

Nevertheless, impurities such as dust (formed of dust grains on the micrometer scale) cause scattering or absorption of the Cherenkov light used for the detection of neutrinos. This makes it crucial to map the exact ice stratigraphy and layer undulations for ensuring the precision of event reconstructions. Here, ice stratigraphy refers to the vertical depth profile of the optical properties, which are governed by historical dust depositions (such as volcanic activity or climatic variations) that created distinct horizontal layers [6] made of volcanic ash inclusions and continental mineral dust [22] with varying scattering and absorption lengths over tens of thousands of years. Furthermore, these dust layers are not perfectly flat. So-called isochrones (layers formed at the same time with identical optical properties) follow the bedrock's topography at depth, thus forming layer undulations [6].

In the past, stratigraphies of IceCube's ice have been recorded by a so-called dust logger [22]. This device emits laser light into the ice while being lowered. Using a PMT, it detects light scattered by impurities inside the ice, thus gaining information about the stratigraphy. Figure 5 shows the stratigraphy obtained between 2004 and 2011 [22]. Within the depths instrumented by IceCube, the most pronounced dust feature is the

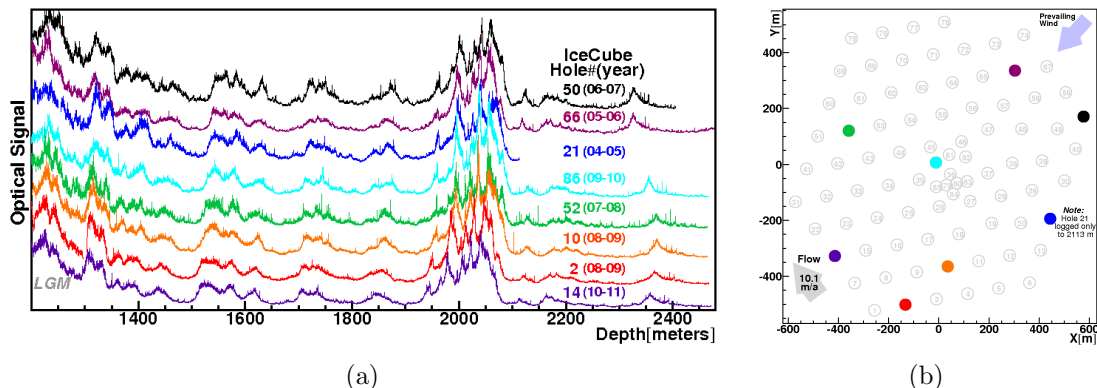


Figure 5: Ice stratigraphy measurements obtained with the original laser dust logger between 2004 and 2011. Left (a): Depth-dependent optical signal profiles for eight select drill holes. Right (b): Schematic footprint of the IceCube observatory showing the specific positions of the recorded strings [22].

so-called "dust layer" [6], which manifests as a significant peak between roughly 1950 m and 2100 m and dates back to approximately 60–70 ka [22].

The attenuation of Cherenkov photons is strongly influenced by the local impurity concentration inside the ice. However, it is also dependent on the direction of propagation of the photons. This anisotropy results from the ice flow, i.e., the ice at the South Pole is not static but instead moves approximately 10 m per year. Experimental data indicates that photon scattering is minimized along the glacier's flow axis, resulting in a more efficient light propagation parallel to the ice movement [7]. On a microscopic scale, this macroscopic anisotropy is caused by the birefringence of the oriented crystalline ice

structure [23].

While these large-scale dust stratigraphies and flow-induced anisotropies define the natural optical environment of the deep ice, localized optical features also develop directly within the borehole during the refreezing process. As the water column freezes from the outside in, the advancing ice front pushes dust particles and residual air bubbles inward, trapping a high concentration of air bubbles and impurities in the center. This localized refreezing process within the borehole results in a clear outer region and an inner core of ice roughly 8 cm in diameter with a very small scattering length [8] referred to as "bubble column" [24].

3 Sweden Camera

This chapter describes the hardware of the Sweden Camera (SweCam). Understanding the physical setup and the sensors is necessary to analyze the physical processes happening during the camera's drop into the ice at the South Pole. During this deployment, the system descended into the borehole while continuously recording video footage of an emitted laser beam. The laser served as an optical reference to analyze the ice and track dynamic motion during the descent.

3.1 Technical Setup and Sensors

To establish the physical foundation for the coordinate transformations and subsequent data analysis, this section details the mechanical and electronic configuration of the Sweden Camera system. The system is housed inside a pressure-resistant glass sphere deployed into the borehole ice and contains a Kurokesu C1Pro camera unit equipped with an 18-fold optical zoom [9].

3.1.1 Mechanical Construction and Rotational Axes

The internal frame of the camera system features stepping motors designed to orient the camera and its illumination systems within the borehole, as schematically illustrated in Figure 6:

- **Primary Axis (α):** A main-frame rotation allowing a full 360° movement around the horizontal axis of the camera body [25].
- **Secondary Axis (β):** An orthogonal inner-frame tilt mechanism that is mechanically limited within the glass sphere to a range of $\pm 45^\circ$ in order to avoid getting stuck [25].

The geometric orientation of the camera is defined relative to the waistband at the center of the glass sphere and the penetrator, which is the pressure-tight feedthrough for power and data cables [25]. For the deployment run analyzed in this thesis, the camera was locked at a fixed upward tilt of 22° relative to the horizontal waistband [26], corresponding to an angle of $\alpha = 112^\circ$.

3.1.2 Internal Control Units and Sensor Alignment

The control and readout instrumentation of the SweCam is divided between two separate circuit boards positioned at different locations within the frame, as illustrated in Figure 7 [9]:

- The **Motor Controller (MC)**, which manages the mechanical drive systems and axis positioning.
- The **Camera Controller (CC)**, which interfaces with the camera optical hardware, specifically a Kurokesu C1Pro camera unit equipped with an 18-fold optical zoom [9].

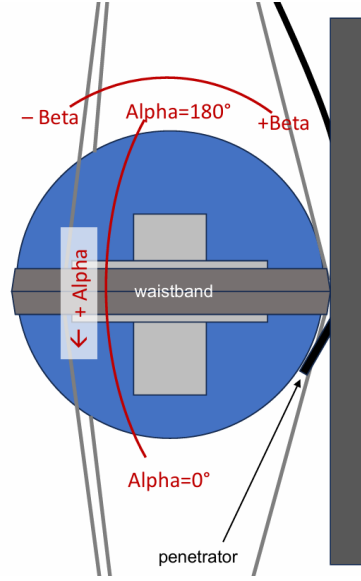


Figure 6: Schematic representation of the SweCam coordinate system. The primary rotation angle α and the secondary tilt angle β are defined relative to the waistband (horizontal plane) and the penetrator (longitudinal axis). Modified from [25].

Each board features, among others, an accelerometer and a magnetometer [9].

Because the MC and CC are mounted on different structural parts of the internal frame, their relative coordinate systems are rotated by approximately 90° in both azimuth and zenith.

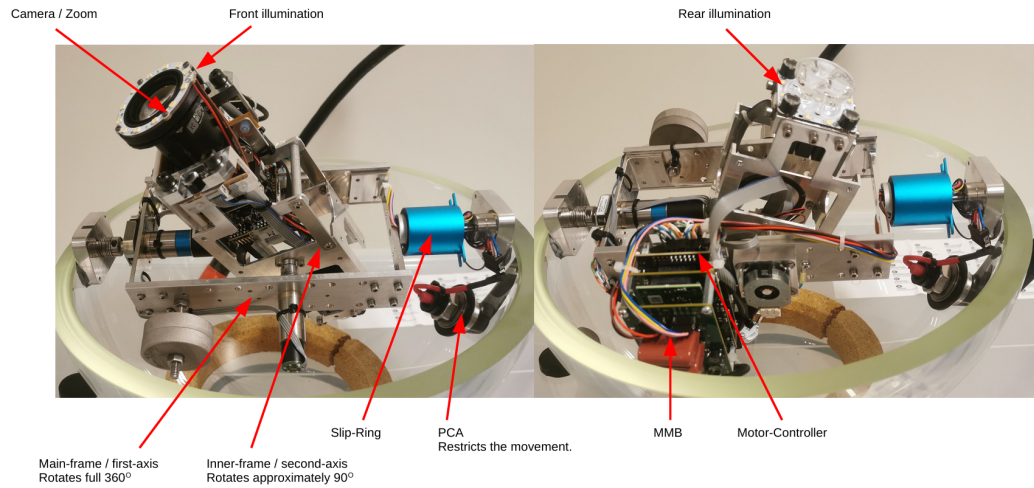


Figure 7: Mechanical construction of the SweCam internal frame, indicating the position of the motor controller (MC) on the right. The camera controller (CC) is mounted on the back of the camera unit and is not directly visible in this view [9].

3.1.3 Optical System and Illumination

The SweCam is equipped with both forward- and backward-pointing light sources [25]. The backward illumination comprises a back-torch system equipped with medium and wide white LEDs and was not in use during the deployment of the Sweden Camera. The forward illumination consists of two white LED setups and four laser diodes (as shown in Figure 8). The LEDs include a ring mounted around the camera lens for wide illumination and additional collimated LEDs placed on the side of the frame. The four laser diodes (two emitting green light and two emitting blue light, as shown in Figure 8) project collimated beams through the sphere [9]. During the deployment, all white LEDs were switched off. Although all four lasers were switched on, the light intensity was too low for two of them to emit any light at all, which means that the illumination was provided only by two of these lasers (one green and one blue). The green laser operates at an approximate emission intensity of 10^{15} photons per second, whereas the blue laser delivers a significantly higher intensity of approximately 10^{16} photons per second, emitting an order of magnitude more photons than its green counterpart [26].

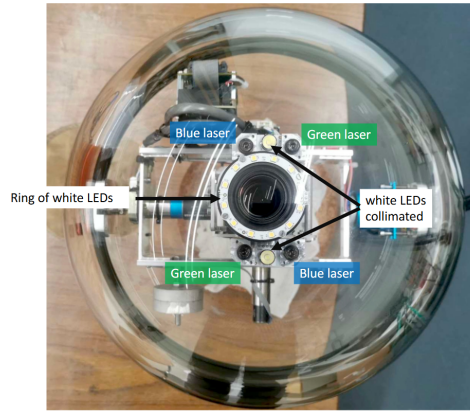


Figure 8: View of the forward illumination assembly, displaying the specific mounting of the laser diodes used to achieve near-parallel light beams exiting the glass sphere [25].

3.1.4 Accelerometer

The accelerometers integrated in the Sweden Camera (IIM-42652) are 3-axis accelerometers based on the linear spring-mass principle [27].

A linear spring-mass accelerometer consists of a proof mass that is suspended by elastic springs and connected to the sensor substrate. When an external acceleration is applied, the inertia of the proof mass causes a relative displacement between the mass and the sensor housing. This displacement is proportional to the applied acceleration and can be converted into an electrical signal using a transduction mechanism, such as a capacitive sensor [28].

Considering a simplified one-dimensional system along a single measurement axis x , the dynamic behavior of the spring-mass system is described by

$$m\ddot{x} + c\dot{x} + kx = ma_x, \quad (2)$$

where m is the proof mass, k is the spring constant, c is the damping coefficient, x is the displacement of the mass, and a_x is the applied acceleration [28]. Under steady-state conditions, the spring force balances the inertial force, resulting in

$$kx = ma_x. \quad (3)$$

Therefore, the displacement of the proof mass is directly proportional to the applied acceleration.

A three-dimensional accelerometer extends this principle by measuring acceleration along the three orthogonal axes x , y , and z . The sensor therefore provides the three acceleration components a_x , a_y , and a_z , which together form the measured acceleration vector [28].

The orientation of a three-axis accelerometer can be fully resolved across a spatial sphere by converting the measurement data into spherical coordinates [29]. However, because accelerometers rely on the Earth's gravitational vector, they are inherently insensitive to rotations about the vertical axis [30].

During the drop of the Sweden Camera, data was recorded using a variable sampling rate. The sampling interval fluctuated between 50 ms and 100 ms, corresponding to a sampling frequency of 10 Hz to 20 Hz.

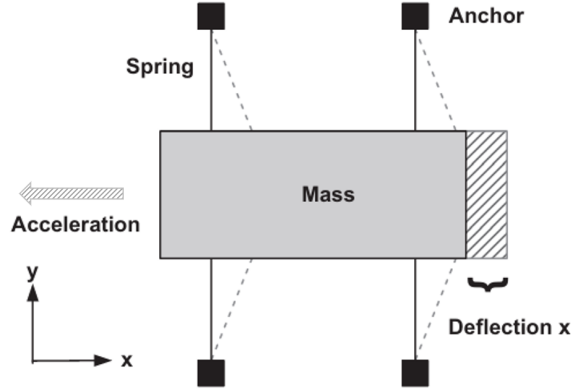


Figure 9: Working principle of a single-axis capacitive linear spring-mass accelerometer. An applied external acceleration deflects the suspended proof mass by a distance x , creating a measurable displacement relative to the sensor housing. Modified from [28].

3.1.5 Magnetometer

The magnetometer used for recording data during the drop of the Sweden Camera (MMC5633NJL) is an Anisotropic Magnetoresistive (AMR) sensor [31].

The AMR effect arises from spin-orbit interactions that cause conduction electrons to scatter anisotropically.

AMR sensors measure magnetic fields by utilizing thin ferromagnetic films. In these materials, the magnitude of the AMR effect depends on the relative orientation between the electrical current and the applied external magnetic field which allows the measurement of the magnetic field [32].

The magnetometer recorded data using the same variable sampling rate as that of the accelerometer. The sampling interval likewise fluctuated between 50 ms and 100 ms, corresponding to a sampling frequency of 10 Hz to 20 Hz.

Temperature Dependence The performance of AMR sensors is known to be affected by temperature-induced drift. The relationship between temperature drift and magnetic field sensor measurements is linear. The effect of temperature on the measured magnetic field can be expressed as:

$$B' = B_0 + k\Delta T$$

where B' is the measured magnetic field, B_0 is the initial true magnetic field, ΔT is the change in temperature, and k represents the temperature coefficient of the sensor. Consequently, any variation in the ambient temperature of the sensor will influence the sensor's output [33].

3.2 Data Application and Physical Processes

The Sweden Camera was designed to monitor the freeze in process and analyze the optical characteristics of the drill hole. Beyond these functions, the video recorded during the deployment can be used to analyze the stratigraphy of the ice instrumented by the IceCube detector [6].

3.2.1 Using Sweden Camera Data to Obtain the Stratigraphy

The video of 2:08:55 h recorded by the Sweden Camera during the drop on the evening of 20 January 2026, starting shortly after 22:00 UTC, contains a total of 232,056 frames, recorded at a rate of 30 frames per second. During this deployment, the camera was tilted upward by 22° relative to the horizontal plane to allow it to look past the waistband of the camera, as shown in Figure 10. The analysis was based on a blue laser shining into the ice [26].

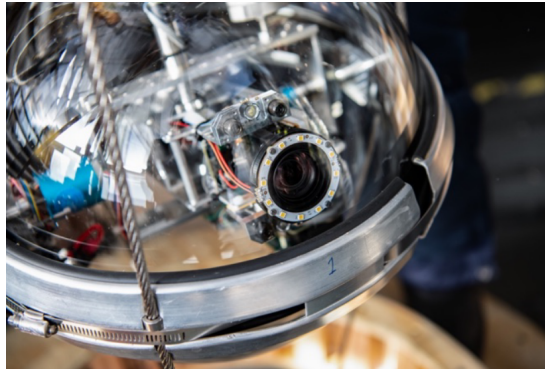


Figure 10: The Sweden Camera system mounted inside its glass pressure housing during deployment. The camera optical axis is physically tilted upwards by 22° relative to the horizontal plane to optimize the field of view within the borehole.

As a consequence of the hot-water drilling process, frames that are suitable for the stratigraphy reconstruction depict the laser beam crossing three distinct zones: the remaining liquid water column, the newly refrozen hole ice, and the surrounding glacier

ice (see Figure 11). These distinct regions can be identified based on their varying

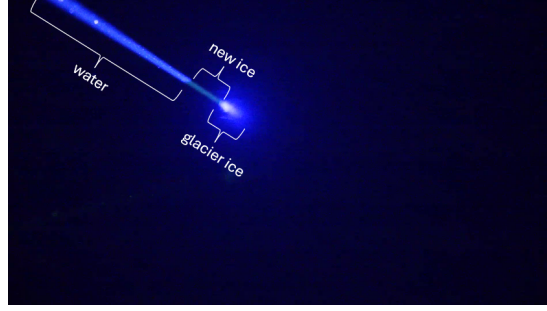


Figure 11: Raw camera frame from the Sweden Camera video showing the blue laser beam coming from the upper left corner of the image and shining towards the center of the image passing through the water column, the new hole ice, and the natural glacier ice.

brightness levels, which result from differences in light scattering properties between the media. Inside the water, the light is strongly scattered, whereas the new ice is highly transparent and thus exhibits weaker scattering properties. Scattering inside the glacier ice, also referred to as bulk ice, is stronger than in the new ice and depends on local impurities of the ice [6].

To find the boundaries between the different layers, the analysis focuses only on the area around the laser beam. As illustrated in Figure 11, the laser propagates diagonally across the raw camera frames. Therefore, each image is first rotated to align the path of the beam horizontally. Following this alignment, a narrow rectangular region centered around the horizontal beam is isolated, as depicted in Figure 12. To locate the

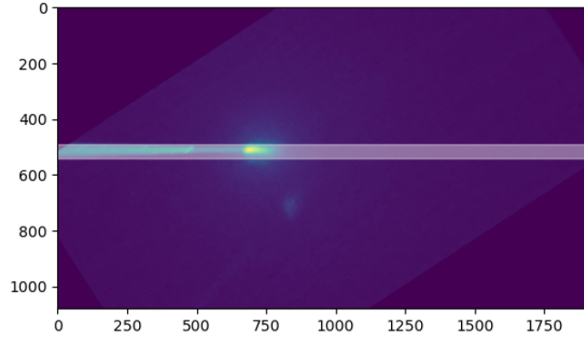


Figure 12: Horizontal alignment and isolation of the laser beam region.

boundaries between the different regions (water, new ice and glacier ice), the intensity profile along the laser beam is analyzed. First, the pixel intensities within the horizontal strip are averaged over all y -values for each x -position. Next, the gradient of this averaged intensity is calculated. As demonstrated in Figure 13, the local extrema of the gradient indicate the sharpest changes in brightness, which can then be assigned to the boundaries between the water and ice layers.

Based on these detected boundaries and intensity profiles, five visual parameters are extracted from the camera frames to characterize the optical properties of the ice and

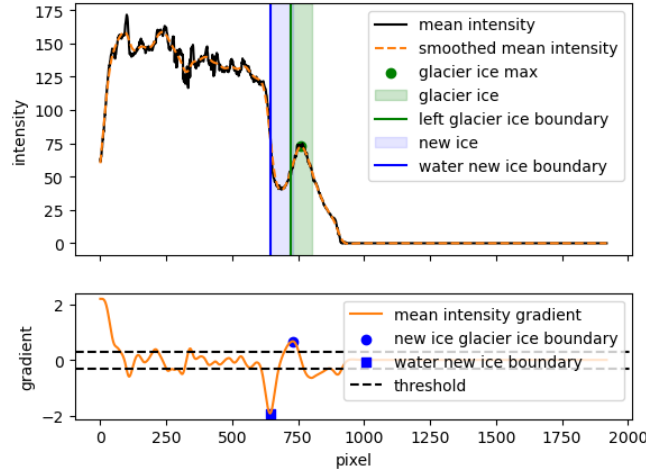


Figure 13: Mean intensity profile along the horizontal beam axis and its corresponding spatial gradient. The blue square and blue circle mark the sharpest peaks used to identify the layer transitions.

the distances inside the borehole:

1. **Total scattered light intensity:** Derived exclusively from the blue color channel by calculating the total brightness sum within the glacier ice region. To isolate the true scattering signal of the bulk ice, the intensity contributions of the water column and the newly formed hole ice are subtracted from the total sum. The remaining intensity shows how strongly the laser light scatters in the bulk ice at the current position of the camera.
2. **Thickness of the visible water column:** Measures the distance from the water column to the edge of the ice. Since the laser beam is partially visible within the liquid water column, tracking this distance allows for monitoring positional shifts of the camera relative to the borehole wall.
3. **Thickness of the newly formed hole ice layer:** Calculated from the distance between the water-to-new-ice boundary and the new-ice-to-glacier-ice transition detected in the gradient profile.
4. **Ratio of hole ice thickness to thickness of the visible water column:** Defined as the ratio between the thickness of the newly formed hole ice and the thickness of the visible water column.
5. **Scattering intensity ratio:** Represents the ratio between the mean scattering intensity of the old glacier ice and that of the newly formed hole ice, indicated by the green and blue highlighted regions in Figure 13.

By tracking the depth-dependent variations of these extracted parameters as the camera descends, the ice stratigraphy can be derived and the movement of the camera during the drop can be analyzed.

4 Artifact Detection in Camera Frames

Extracting an ice stratigraphy from the SweCam video data necessitates a robust preprocessing pipeline to handle artifacts. To achieve this, corrupt frames containing sensor artifacts or processing errors must first be identified and excluded. Based on these validated images, the precise positions of the ice boundaries can subsequently be traced to reconstruct the stratigraphy.

4.1 Detection Methods

To isolate the usable frames presenting the features where the transitions between the water, new ice, and glacier ice are clearly visible, all frames containing camera artifacts (such as pixel smearing or partial frame corruption) that render them unusable for stratigraphy must be excluded. Since the video was recorded continuously during the camera’s descent, the frames are sequentially numbered, meaning higher frame numbers correspond to greater deployment depths. Examples of these faulty frames are shown in Figure 14.

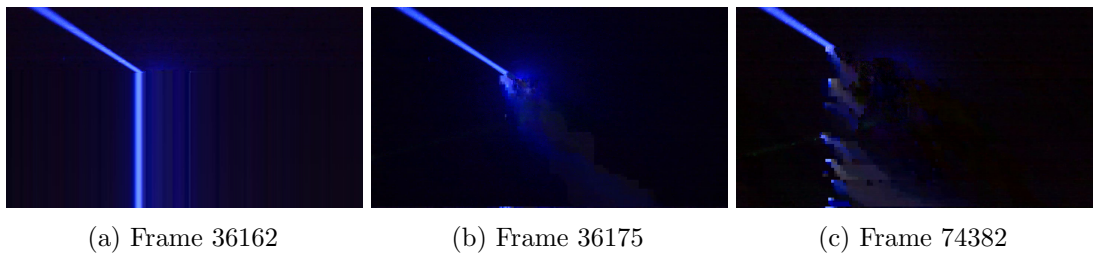


Figure 14: Examples of faulty frames with artifacts.

To determine whether a frame contains any artifacts, it is compared to the previous frame, unless this frame is considered faulty in which case the last frame that is not faulty is taken as a reference. For this, the absolute difference between the two images is computed. Then, the standard deviation of all pixels in this absolute difference image is calculated. Looking at small subsets of frames that are known to contain faulty frames, the distribution of the standard deviation shown in Figure 15 is obtained. The standard deviations of frames with artifacts are plotted in red. Looking at the distribution, a clear separation between the normal frames and those containing artifacts is visible. This distinction allows for the definition of a threshold value. Any frame yielding a standard deviation above a threshold of 5.7 is classified as faulty.

Some of the frames used for Figure 15 contain reflections that originate from small air bubbles or dust particles inside the water. This results in very bright reflexes (see examples in Figure 16) that can cause a significantly higher standard deviation, consequently causing some of these frames to be incorrectly classified as faulty (represented by the green bins located above the threshold in Figure 15). However, the number of frames misclassified as faulty is small enough to be negligible, and the majority of frames containing bubbles are still correctly identified as normal frames.

When applying this method to all camera frames, it was observed that all frames from approximately frame number 140,000 onward were classified as faulty. Frames taken at

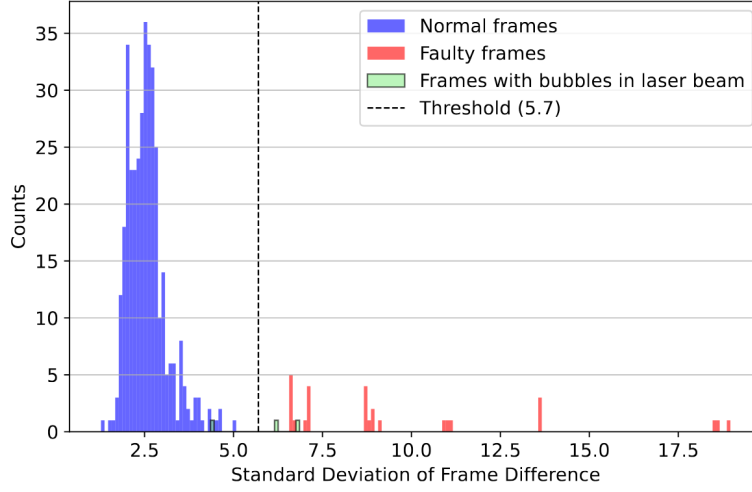


Figure 15: Distribution of the standard deviation of absolute frame differences. A threshold value of 5.7 is used to distinguish between normal frames (blue), frames containing artifacts (red), and frames with bubbles in the laser beam (green).

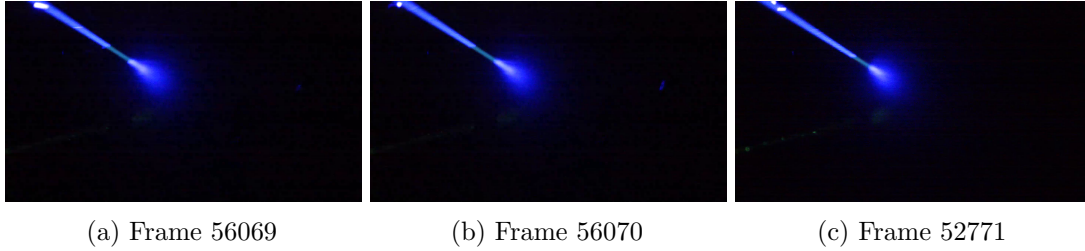


Figure 16: Examples of frames with bubbles in the laser beam. The bubbles are visible as distinct, bright scattered light points in the upper-left corner of the frames.

greater depths have higher standard deviations, as shown in Figure 17. Comparing the distribution of the standard deviation of the difference for these frames reveals a clear shift from the distribution used to establish the threshold. This is because the subset used to determine the threshold mainly contains frames from the first half of the entire dataset, which does not sufficiently represent the characteristics of the frames recorded at greater depths. The distribution of standard deviations for frames with higher frame numbers is shifted to higher standard deviations compared to the distribution for low frame numbers. This shift is primarily due to the increased visibility of the green laser at greater depths. Looking at the example of three consecutive camera frames (158261, 158262, and 158263) in Figure 18, it becomes evident that the standard deviation of the frame-to-frame difference is significantly increased by the presence of this green laser. In contrast, at shallower depths, this laser is either not visible at all or its visibility is significantly lower which is the reason why this shift was not observed there.

The reason for the systematic classification of all subsequent frames as faulty lies in the nature of the comparison method. Since a frame classified as faulty is excluded as a reference, any subsequent frame is compared to the last frame that was deemed non-faulty. Once a frame is erroneously classified as faulty due to a high standard deviation, the algorithm continuously skips it and compares subsequent frames back

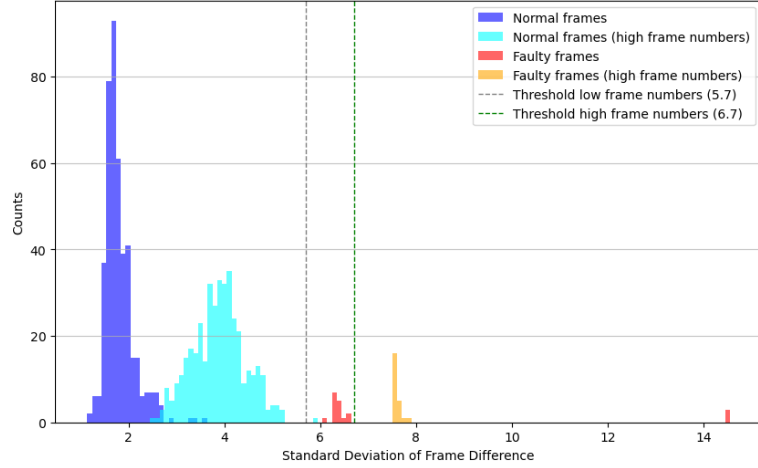


Figure 17: Distribution of the standard deviation of absolute frame differences, showing distinct thresholds of 5.7 for low frame numbers and 6.7 for high frame numbers. This allows for the effective classification of normal frames (blue and cyan) and faulty frames (red and orange) across the entire dataset.

to this older reference frame. If the frame-to-frame changes have accumulated or the background features have shifted in the meantime, the standard deviation relative to the old reference remains above the threshold. This triggers a chain reaction in which the algorithm fails to reset its reference frame, causing all subsequent frames to be continuously propagated as faulty.

To address this issue and account for the shift in the distribution while ensuring that the detection of actual faulty frames remains robust, a higher threshold of 6.7 is applied for these higher frame numbers.

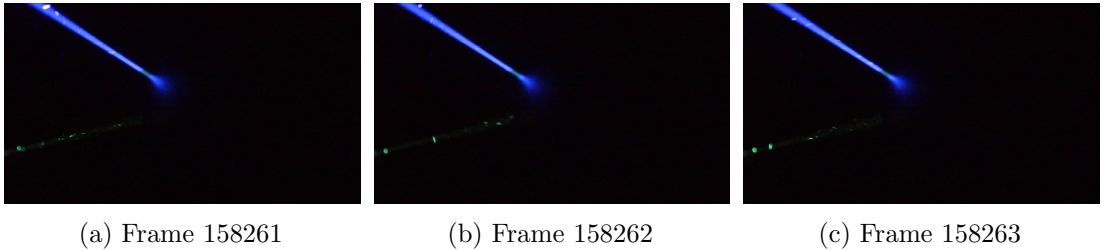


Figure 18: Examples of frames with visible green laser beam.

Beyond the effects observed at higher frame numbers, similar systematic misclassifications occurred at two additional points in the dataset (at approximately 200,000 and 231,000), again caused by the propagation of errors within the comparison process. To avoid losing valid data through over-filtering, higher threshold values (7.0 and 7.5) were empirically determined for these specific segments. This approach halted error propagation while preserving usable stratigraphic data. The complete distribution of all standard deviations, as well as the chosen thresholds, can be seen in Figure 19.

Overall, this strategy isolated actual anomalies while preventing excessive data loss: out of the total 232,056 analyzed frames, 764 frames (0.33 %) were ultimately classified as faulty and excluded from further analysis.

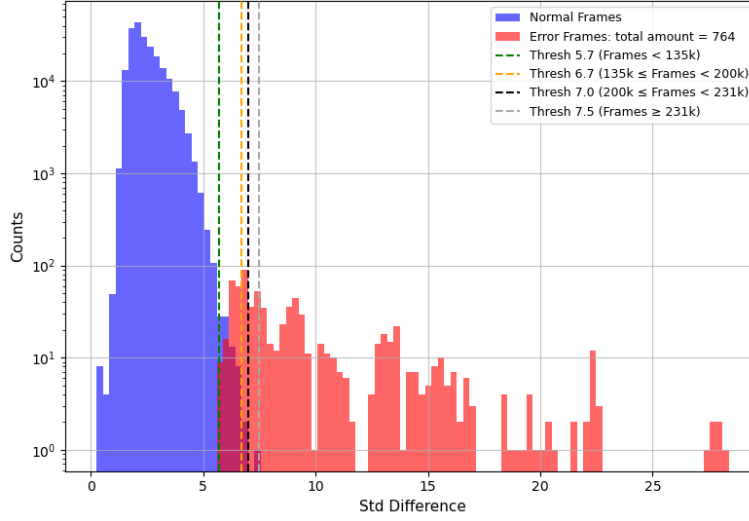
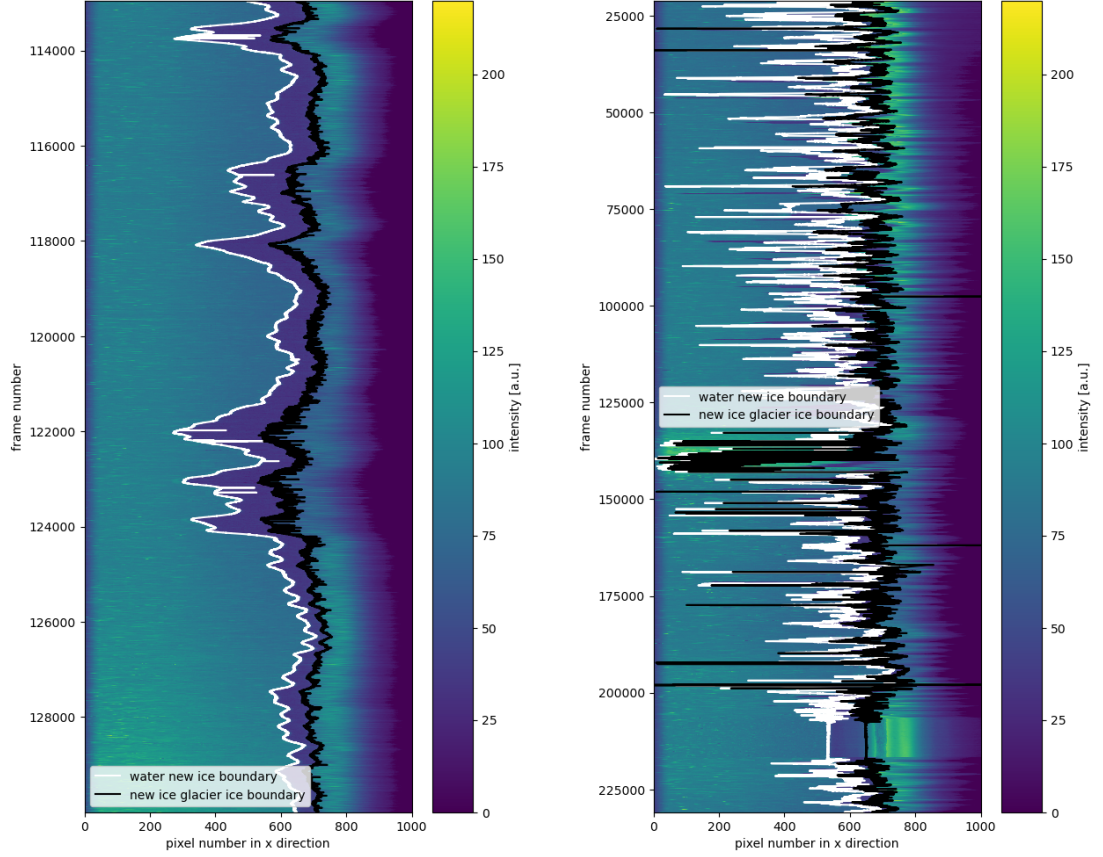


Figure 19: Distribution of standard deviations (logarithmic y-axis), with thresholds (ranging from 5.7 to 7.5) assigned to specific frame intervals to classify normal (blue) and faulty frames (red) across the full recording duration.

4.2 Resulting Visual Information about the Camera Movement

Having filtered out all faulty frames, these validated images are subsequently used for the stratigraphy analysis. In this process, the boundaries between the water column and the newly formed ice, as well as between the new ice and the glacial ice for each frame, are identified as explained in subsection 3.2.1. The extraction of the boundary positions resulted in occasional spikes when the algorithm didn't extract the correct boundaries between the different ice regions. While the smaller, detailed section shown in Figure 20a only exhibits these jumps in the transition between the water and the new ice, they can occur in both boundaries across the full dataset (visible as black spikes in Figure 20b). These features appear as sharp horizontal lines in the boundary plots, as can be observed in Figure 20a. However, these occurrences are sufficiently infrequent that they have a negligible impact on the overall stratigraphy profile and therefore do not pose a significant issue for the analysis.

It should be noted that the stratigraphy analysis begins only after approximately 21,000 frames. This is because the camera remained stationary during the initial phase of the recording. Consequently, the images captured during this period do not contain relevant information for the stratigraphy reconstruction. The resulting visual information about the camera movement can be seen in Figure 20.



(a) Detailed view of a subset of the visual information about the camera movement, illustrating occasional transient spikes as discontinuous horizontal artifacts resulting from outlier detections.

(b) Overview of the visual information of the entire dataset about the camera movement.

Figure 20: Extracted stratigraphy boundaries of the recorded data. The white line represents the boundary between the water column and the new ice, while the black line indicates the boundary between the new ice and the bulk ice.

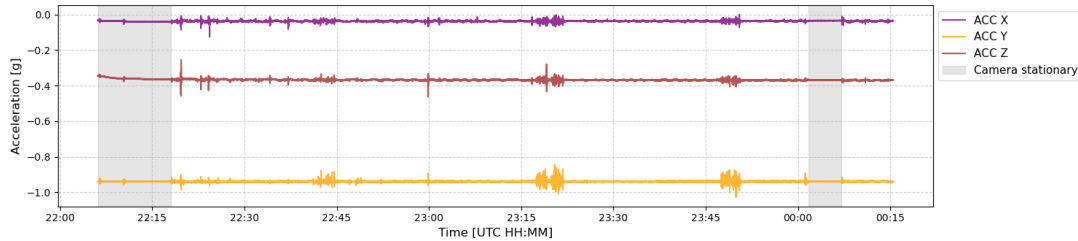
5 Using Accelerometer and Magnetometer Data to Analyze the Orientation of the Sweden Camera During the Drop

The camera system contains one accelerometer and one magnetometer on the camera controller, hereafter referred to as CC, as well as one accelerometer and one magnetometer on the motor controller, referred to as MC. All four sensors recorded data continuously during the drop. This chapter analyzes these sensor outputs to reconstruct the orientation and rotational movement of the camera during its descent. Furthermore, the derived sensor data is correlated with parameters extracted from the camera recording.

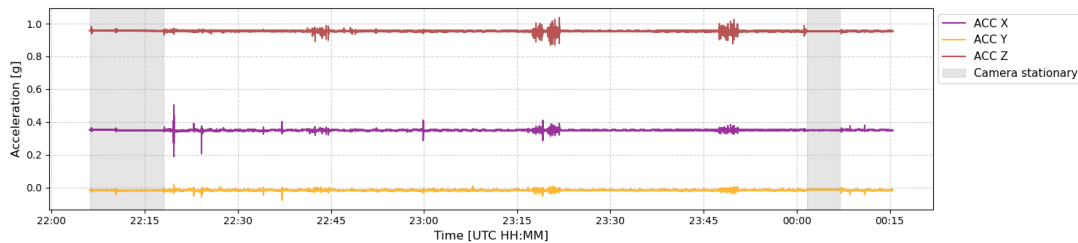
5.1 Accelerometer Data

To reconstruct the physical orientation and rotational movement of the camera during descent, the raw accelerometer data undergoes coordinate transformations. A schematic overview of this workflow and the corresponding processing steps is illustrated in Figure 30.

To begin the analysis, the raw accelerometer data collected during the drop is examined first. The accelerometer data is recorded relative to the local (x, y, z) coordinate system of each individual controller. The orientation of these axes reflects the physical alignment of the sensors on the controllers. Figure 21 displays the acceleration measurements along the three axes for both the camera controller and the motor controller over the entire deployment time. This plot also shows the two time periods when the camera remained still during the drop.



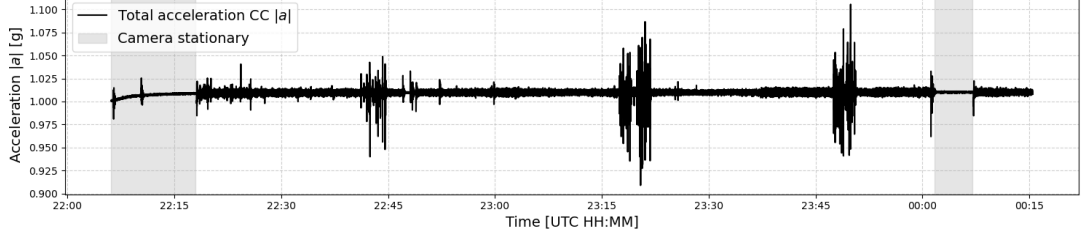
(a) Camera Controller



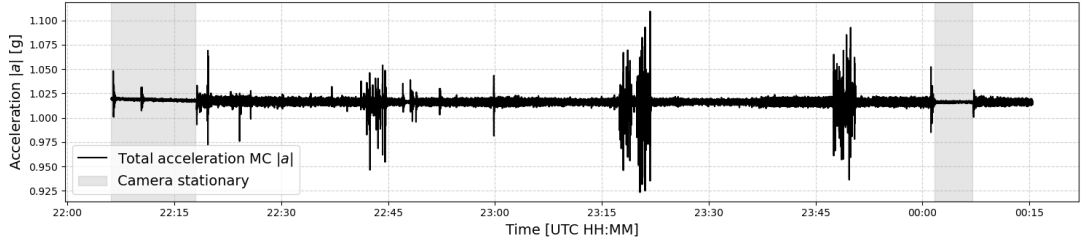
(b) Motor Controller

Figure 21: Three-axis acceleration components (a_x, a_y, a_z) recorded by the Camera Controller (CC) (a) and Motor Controller (MC) (b) sensors during deployment. The gray shaded regions indicate the phases where the camera was stationary.

In addition to the individual axis components, the total acceleration magnitude $|a| = \sqrt{a_x^2 + a_y^2 + a_z^2}$ was evaluated for both sensors, as shown in Figure 22. As expected, the total acceleration remains centered around 1 g throughout the entire deployment.



(a) Camera Controller



(b) Motor Controller

Figure 22: Total acceleration magnitude recorded by the Camera Controller (CC) (a) and Motor Controller (MC) (b) sensors during deployment. The magnitude $\|a\| = \sqrt{a_x^2 + a_y^2 + a_z^2}$ remains close to 1 g, with fluctuations corresponding to movement phases. Gray shaded regions indicate phases where the camera was stationary.

To better understand the orientation of the camera, the distribution of the acceleration data coordinates is visualized using histograms. As shown in Figure 23, the data for each axis is fitted with a Gaussian curve using the following equation:

$$f(x) = A \cdot \exp\left(-\frac{(x - \mu)^2}{2\sigma^2}\right), \quad (4)$$

where A represents the amplitude (peak height of the distribution), μ denotes the mean value corresponding to the central component of gravitational acceleration along the respective axis, and σ is the standard deviation quantifying the spread of the signal. This fitting procedure allows for a robust estimation of the mean gravitational acceleration along each axis, independent of short-term fluctuations. The acceleration data approximate a Gaussian shape because the recorded signal combines a constant gravitational component with random distributed noise from vibrations.

These fits are conducted for both the camera controller and the motor controller datasets. The mean value μ of each curve indicates the magnitude of the gravitational force component acting along the respective axis. Comparing the peak positions reveals a shift in the gravitational acceleration between the two units. This offset reflects the mechanical orientation of the controller boards, which are mounted orthogonally (90°) relative to each other within the camera housing, and thus directly confirms the expected spatial alignment.

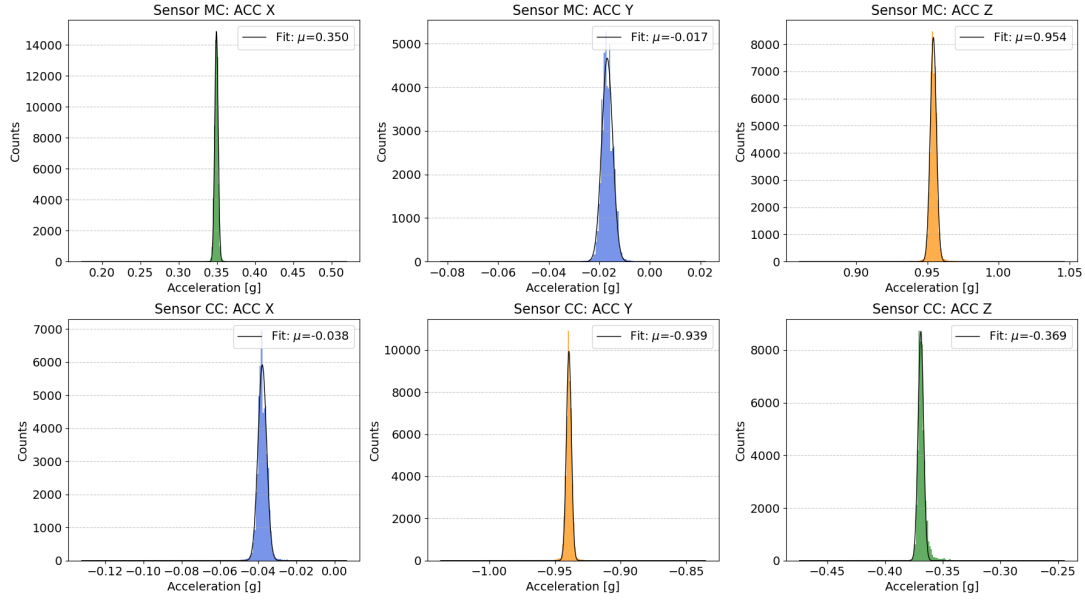


Figure 23: Distribution of acceleration data along the x -, y -, and z -axes for both the camera controller and the motor controller. The histograms show the count of measured values with Gaussian fits for each axis. The different colors of the histogram group the axes by the magnitude of the measured gravitational acceleration. Green indicates the components experiencing a moderate fraction of gravity, blue represents the axes with minimal gravitational force, and orange highlights the axes aligned closest to the vertical direction that measure the largest part of the gravity vector.

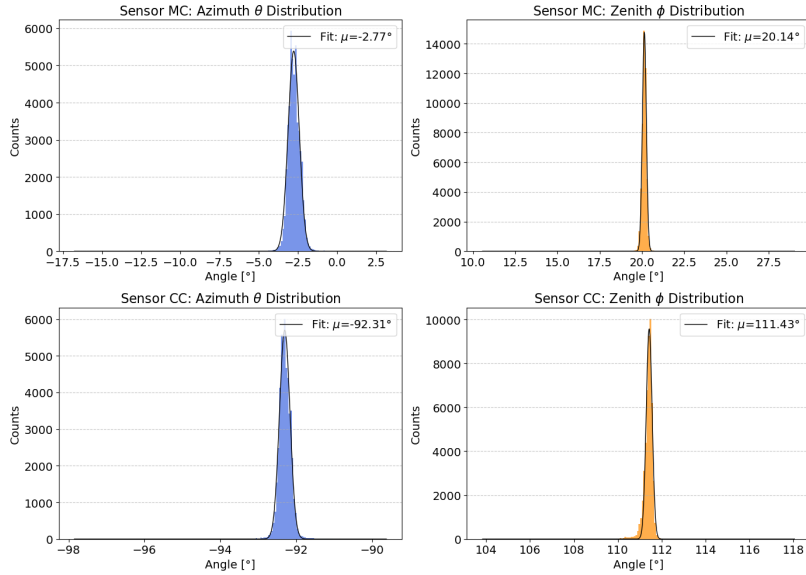


Figure 24: Calculated azimuth and zenith angle distributions for the two controller units before rotation of the coordinates. The colored areas show the occurrence of the orientation angles, and the black curves represent the Gaussian fits.

To further analyze the orientation of the camera, the raw Cartesian acceleration data (a_x, a_y, a_z) can be converted into spherical coordinates, specifically azimuth (θ) and zenith (ϕ), following [29]:

$$\theta = \arctan\left(\frac{a_y}{a_x}\right), \quad \phi = \arccos\left(\frac{a_z}{|a|}\right). \quad (5)$$

This transformation allows for the determination of the horizontal and vertical angles for both the motor controller and the camera controller. The resulting distributions are visualized in Figure 24, where each distribution is again fitted with a Gaussian curve to identify the most frequent orientation. A shift of approximately 90° in both azimuth and zenith is evident between the two controllers. This difference is a consequence of the mounting of the controllers within the camera housing. Furthermore, the measured zenith angles show a value of $\beta = (20.14 \pm 0.39)^\circ$ (MC) and $(111.43 \pm 0.41)^\circ$ (CC). The uncertainty stems from the 1.5 % relative sensitivity tolerance specified for the accelerometer [27], with the step-by-step derivation of the resulting error propagation detailed in Appendix A. Subtracting this 90° offset from the 111.43° measurement yields an actual zenith tilt of $\alpha = (21.43 \pm 0.41)^\circ$.

Both resulting angles align well with the physical orientation of the camera system, which was tilted upward by 22° (see Figure 25) relative to the horizontal plane during deployment in the hole.

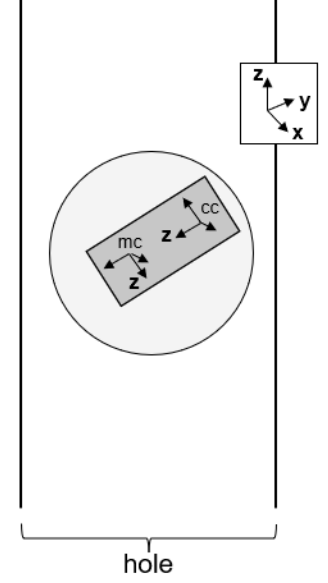


Figure 25: Schematic side view of the camera housing inside the borehole showing the system tilt and the internal sensor coordinate systems for the MC and the CC controller as well as the earth coordinate system.

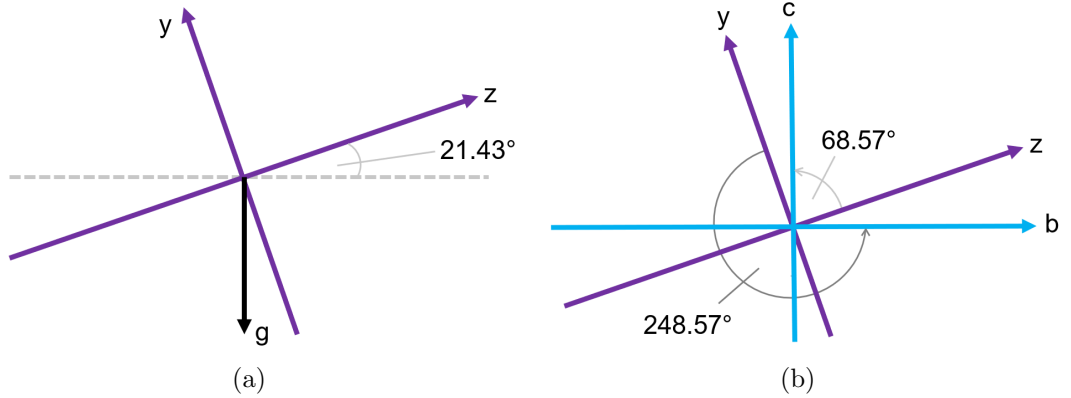


Figure 26: Rotation of the camera controller (CC) coordinate system. Sketch (a) shows the initial tilt angle relative to the gravity vector g in the yz -plane. Sketch (b) illustrates the subsequent rotation into the earth coordinate system spanned by the axes a , b and c . Since the rotation is executed around the x -axis, the x - and a -axes are identical. Note that the x -axis is not depicted, as it points perpendicularly out of the image plane.

The minor deviation from the 22° tilt is mainly due to the limited positioning accuracy

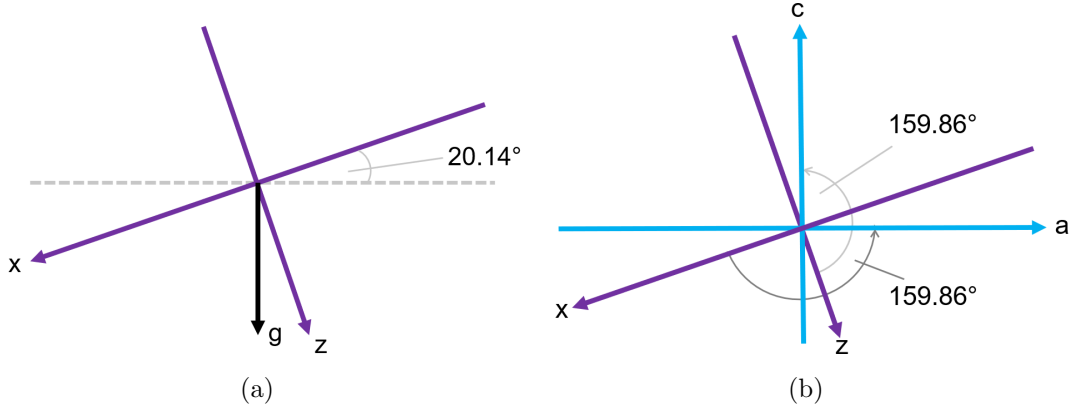


Figure 27: Rotation of the motor controller (MC) coordinate system. Sketch (a) shows the initial tilt angle relative to the gravity vector g in the xz -plane. Sketch (b) illustrates the subsequent rotation into the target earth coordinate system spanned by the axes a , b and c . Since the rotation is executed around the y -axis, the y - and b -axes are identical. Note that the y -axis is not depicted, as it points perpendicularly into the image plane.

of the stepping motors, but it is as well caused by the exact positioning of the individual controllers inside the camera body.

Following this, the accelerometer data is rotated using the calculated tilt angles α and β to align with the Earth coordinate system, enabling a direct comparison with the stratigraphic parameters. As shown in Figure 26 and Figure 27, the rotation is performed around a single fixed pivot axis for each sensor.

Using rotation matrices [34], the transformed acceleration vector $\mathbf{a}' = [a_a, a_b, a_c]^T$ is calculated from the raw measurement vector $\mathbf{a} = [a_x, a_y, a_z]^T$ as shown below.

For the motor controller, with the y -axis acting as the pivot (tilt angle β) the transformed acceleration vector is computed using:

$$\mathbf{a}'_{MC} = \mathbf{R}_y(\beta) \mathbf{a} = \begin{pmatrix} \cos \beta & 0 & \sin \beta \\ 0 & 1 & 0 \\ -\sin \beta & 0 & \cos \beta \end{pmatrix} \begin{pmatrix} a_x \\ a_y \\ a_z \end{pmatrix}. \quad (6)$$

Similarly, for the camera controller, with the x -axis acting as the pivot (tilt angle α) the transformed vector is obtained using:

$$\mathbf{a}'_{CC} = \mathbf{R}_x(\alpha) \mathbf{a} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \alpha & \sin \alpha \\ 0 & -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} a_x \\ a_y \\ a_z \end{pmatrix} \quad (7)$$

The sensor tilt and the corresponding rotation angles are determined from the gravitational acceleration vector $\vec{g}$. Because gravity points strictly downward along the negative z -axis of the global Earth coordinate system, the acceleration components measured across the three sensor axes reveal how the sensor is inclined in space. This information is used to rotate the local sensor coordinates into the global Earth coordinate system using Equation 6 and Equation 7.

As visualized in Figure 28, the peak positions μ for both sensors (see Table 1) now align closely with the theoretical expectations. The horizontal components on axes a and b are centered nearly at 0.0 g, while the vertical axis c measures approximately -1.0 g.

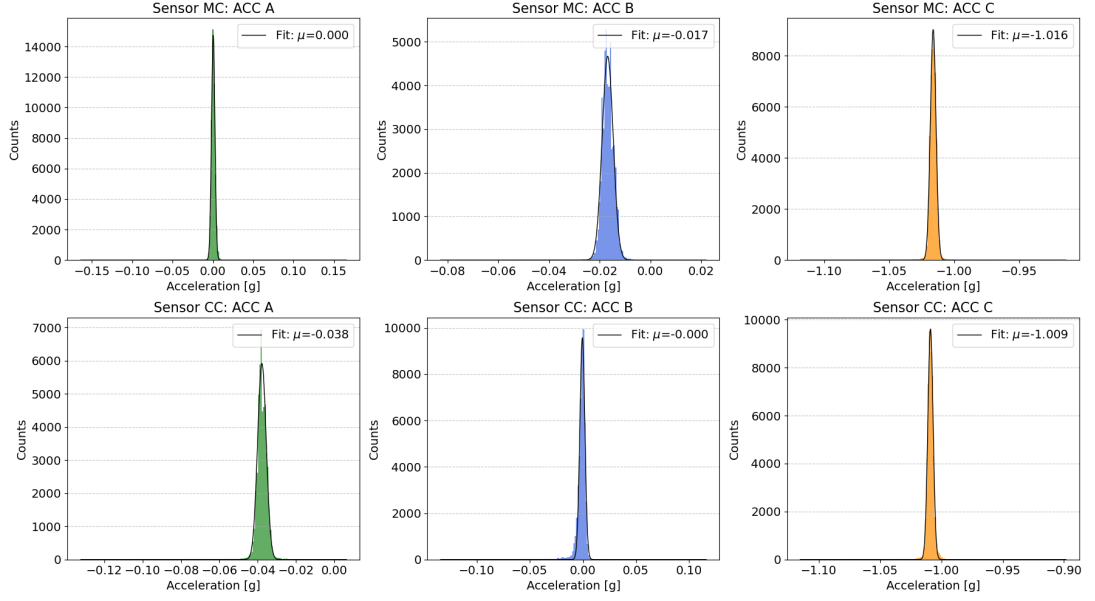


Figure 28: Rotated acceleration distributions for both sensor units during the stationary reference phase. The black curves show the Gaussian fits.

Based on the rotated acceleration data, the orientation is again converted into spherical coordinates to analyze the system’s rotational behavior during the drop. As illustrated in Figure 29 and summarized in Table 1, the azimuth distributions exhibit a prominent primary direction at 272.84° (Motor Controller) and 180.72° (Camera Controller), respectively.

Table 1: Evolution of Azimuth and Zenith mean angles μ across the calibration steps for both the Camera Controller (CC) and Motor Controller (MC) systems.

Calibration Step	Motor Controller (MC)		Camera Controller (CC)	
	Azimuth [$^\circ$]	Zenith [$^\circ$]	Azimuth [$^\circ$]	Zenith [$^\circ$]
Raw Uncalibrated Data	-2.77	20.14	-92.31	111.43
Axis Rotation	272.84	179.04	180.72	177.84

While the majority of the azimuth values fluctuate over a range of several tens of degrees, the variation in the zenith angle is highly constrained. Apart from a few isolated outliers, it stays close to 180° within a range of approximately 1° , confirming that the system experiences negligible vertical pitching. This demonstrates that the sensor signal is dominated by the downward gravitational force. Note that this 180° orientation refers to the vertical alignment of the housing relative to gravity, while the camera optics remain fixed at their upward tilt angle of 22° relative to the horizontal plane.

Contrary to expectations, the observed azimuth fluctuations remain relatively limited, whereas a broader distribution across the rotational spectrum would normally be anticipated during the drop. However, this apparent stability may be a measurement artifact rather than reflecting the true behavior of the system. As detailed in subsub-

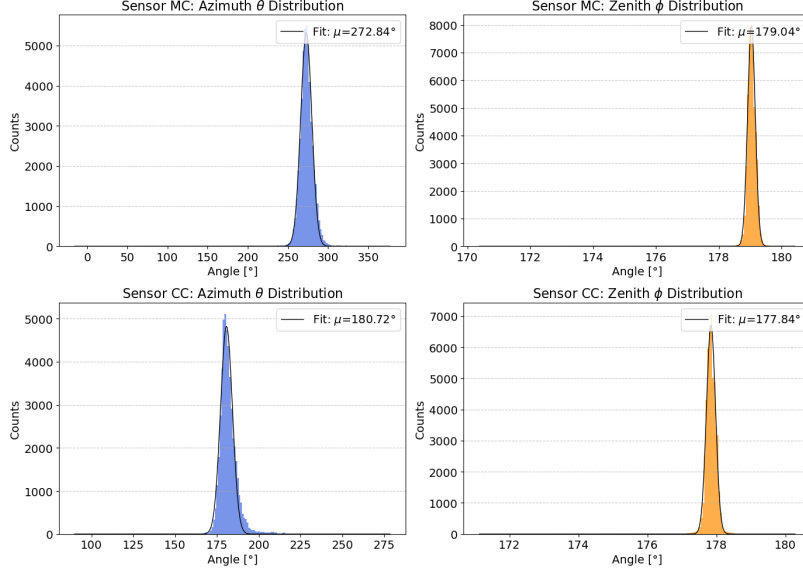


Figure 29: Calculated azimuth and zenith angle distributions for the two controller units after rotation of the coordinates. The colored areas show the frequency of the orientation angles, and the black curves represent the Gaussian fits.

section 3.1.4, measuring planar rotation perpendicular to the gravitational vector with the accelerometer is limited. Thus, the true rotational motion during the drop is likely masked by the reduced sensitivity of the sensor setup, meaning that the recorded data does not reflect the actual rotation.

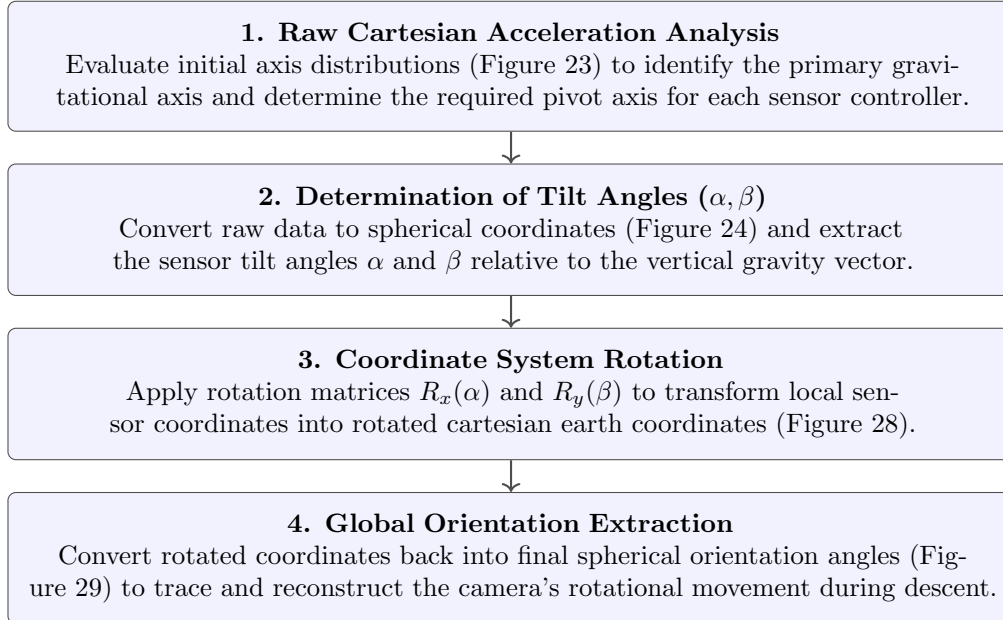
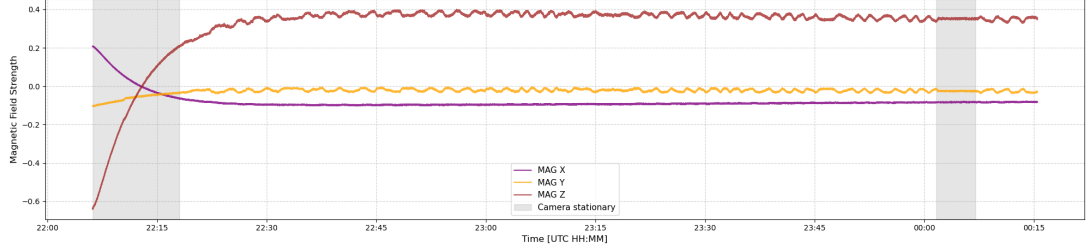


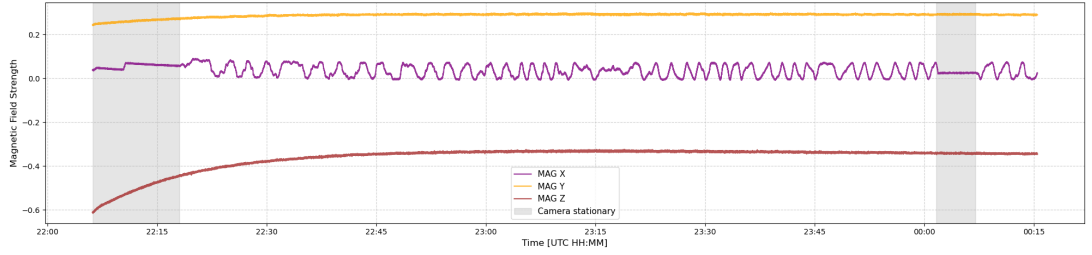
Figure 30: Flowchart of the coordinate transformation and orientation analysis pipeline, illustrating how raw sensor data is processed step-by-step into angles in the earth coordinate system.

5.2 Magnetometer Data

The data recorded by the magnetometers of the Sweden Camera can also be used to analyze the orientation of the Sweden Camera during the drop. The raw data can be found in Figure 31.



(a) Camera Controller



(b) Motor Controller

Figure 31: Magnetometer data recorded by the Camera Controller sensor (CC) (a) and Motor Controller sensor (MC) (b) during the deployment. The gray shaded regions indicate the phases where the camera was stationary.

As visible in the plots, the raw magnetic field signals exhibit a strong exponential drift that closely correlates with the temperature curve recorded inside the camera controller module which is shown in Figure 32.

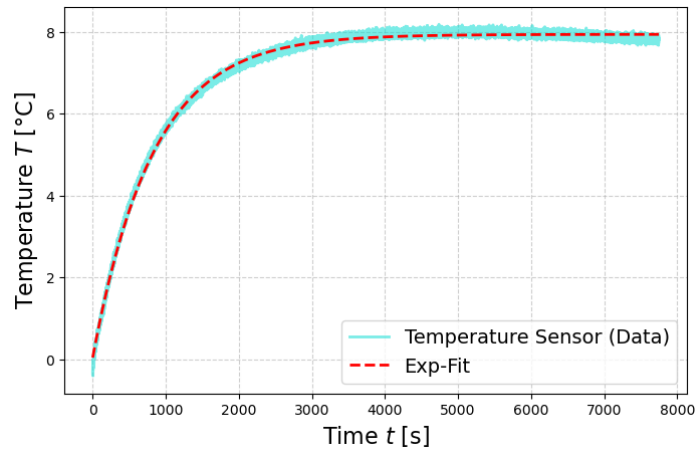
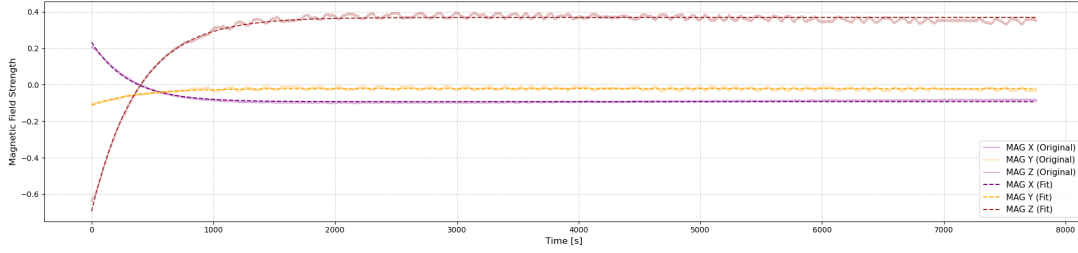


Figure 32: Measured temperature profile of the camera controller over time along with an exponential fit.

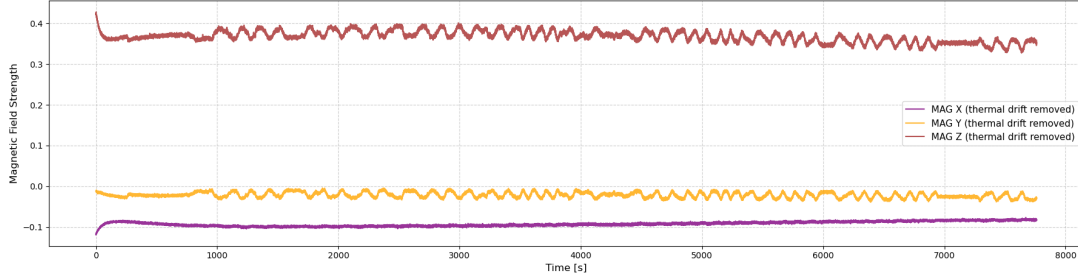
Notably, this thermal drift effect is significantly more pronounced in the camera controller

sensor compared to the motor controller sensor (see Figures 33a and 42a (in Appendix B)). This arises from the CC sensor’s proximity to the illumination drive, which generates substantial operational heat during camera activity.

As established in subsection 3.1.5, the temperature drift in magnetic field sensors follows a linear relationship. To correct for this temperature dependence, an exponential fit matching the module’s thermal response was subtracted from the raw magnetic field data. As shown in Figures 33b and 42b (in Appendix B), this makes the underlying signals clearer.



(a) Raw magnetic field data for all three axes alongside the fitted exponential thermal models.



(b) Corrected magnetic field data with the thermal drift removed, highlighting the stabilized baseline and periodic rotation signals.

Figure 33: Magnetic field measurements from the camera controller magnetometer before and after thermal drift correction.

Due to the close proximity to the South Pole and nearby structural metal components in the detector, the magnetometer data is subject to strong magnetic distortions. Consequently, the orientation analysis focuses primarily on the accelerometer data, which is unaffected by local magnetic interference.

However, since accelerometers are insensitive to planar rotations about the gravity vector, the magnetometer data still represents the most promising candidate for deriving a reliable azimuth angle. Due to time constraints, a full calibration and extraction of the azimuthal orientation from the magnetometer could not be completed within the scope of this work.

5.3 Correlation Between Visual Camera Parameters and Sensor Orientation

To investigate a potential correlation between the visual features of the camera deployment data and the physical movement measured by the accelerometers, different parameters extracted from the processed video frames (subsection 4.2) were compared against the azimuth angle derived from the accelerometer data (subsection 5.1). For all datasets, the evaluation was limited to the period following the initial stationary phase, commencing with the onset of camera movement. To mitigate individual outliers, a median filter was applied to smooth the parameters extracted from the video prior to the comparison. In principle, a coupling between both datasets would be expected, as a physical rotation or tilt of the camera housing changes the viewing angle and distance relative to the borehole wall. This shift directly affects the position of the laser beam in the frame, which should be reflected in parameters such as the thickness of the water column. For completeness, the full set of extracted visual parameters was also cross-evaluated against the sensor angles.

As illustrated in Figure 34 (and consistently observed across all corresponding plots provided in Appendix C), no discernible correlation can be identified between any of the extracted visual parameters, which are explained in subsubsection 3.2.1, and the sensor-derived azimuth angle. The data points show a scatter without any clear dependence on the azimuth angle ϕ . Consequently, the spatial orientation obtained from the accelerometer data cannot be verified using the deployment camera footage. For completeness, the corresponding correlation plots comparing the extracted visual parameters against the accelerometer zenith angle (θ) are also provided in Appendix C, yielding similarly uncorrelated results.

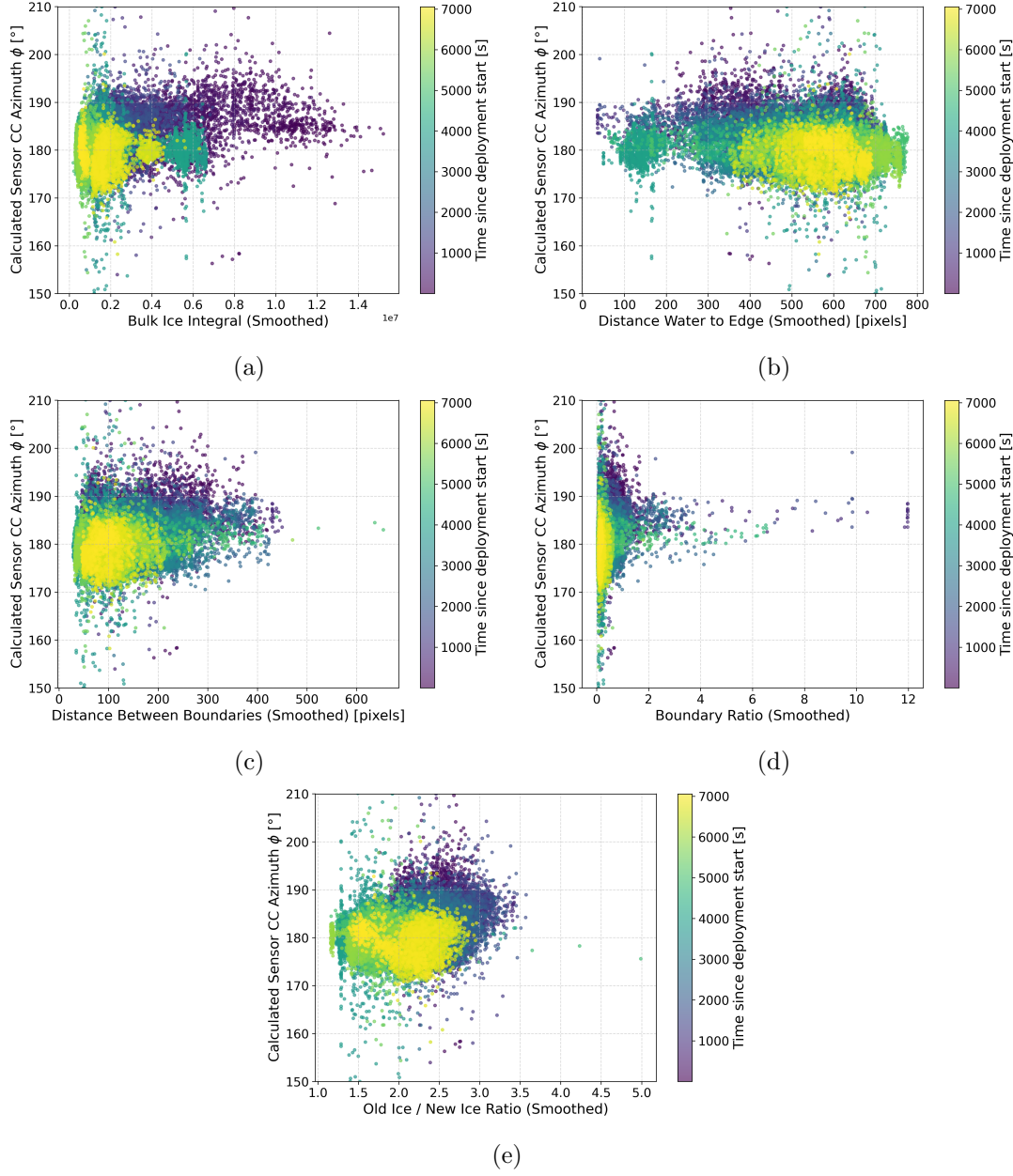


Figure 34: Correlation between parameters extracted from camera frames and the calculated camera azimuth angle derived from the CC accelerometer data, color-coded by deployment time. (a) Total scattered light intensity. (b) Thickness of the visible water column. (c) Thickness of the newly formed hole ice layer. (d) Ratio between the boundary distance (c) and the visible water column thickness (b). (e) Ratio of mean scattering intensity between old glacier ice and newly formed hole ice.

6 Consistency Check with IceCube Supernova Hit Rate Data

To evaluate the plausibility of the angular orientations derived from the accelerometer, this chapter presents the analysis of the Supernova hit rate data recorded by the IceCube detector during the deployment of the Sweden Camera.

The Supernova hit rate in IceCube refers to the collective, correlated increase in count rates (hits) across all DOMs, induced by the sudden flux of $\mathcal{O}(10)$ MeV neutrinos emitted during a core-collapse supernova. Because individual low-energy MeV neutrinos are too weak to be reconstructed as single events, detection relies on statistically monitoring the DOM count rates in discrete time intervals of 500 ms while accounting for background noise [35].

6.1 Angular Reconstruction from Supernova Hit Rates

Due to the high light intensity emitted during the drop by both the Sweden Camera and the LOMlogger (another device to measure the ice stratigraphy [36]) located further down on the string, only the DOMs of the outermost, most distant strings (see Figure 35) were activated in the upper region of the detector, ranging from 1450 m to a depth of approximately 1900 m.

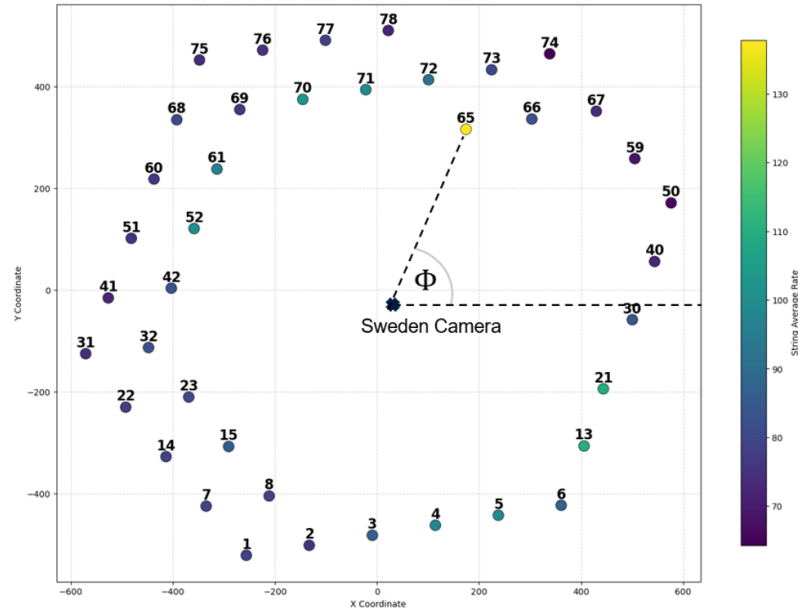


Figure 35: Layout of the activated IceCube detector strings in the xy -plane (top-down view) mapped within the standard IceCube coordinate system with the azimuthal direction angle ϕ . The color scale represents the mean Supernova hit rate recorded by each string over the entire deployment duration.

Figure 35 displays the layout of the detector strings within the xy -plane, mapped in the standard IceCube coordinate system. The figure also shows the mean rate detected by each string over the course of the entire recording. As expected, string 65, which is closest to the location of the string with the Sweden Camera, exhibits the highest mean

rate, while strings farther away show a lower intensity with increasing distance from the Sweden Camera.

The next step in verifying the orientation of the SweCam during the drop is to plot the normalized intensity of the brightest DOM on each string as a function of the azimuthal angle ϕ . This angle is defined relative to the new string position with the SweCam at the center of the coordinate system, representing the direction pointing towards each respective string. An exemplary determination of this angle is illustrated for string 65 in Figure 35.

To perform a comparison across different strings, the intensity recorded by each DOM must be normalized. This is necessary because the observed light scales not only with the angular emission profile of the camera, but is also strongly influenced by the distance d between the source and each individual sensor and the attenuation of the photons in the ice.

Following the simple ice model [37], the expected number of detected photons $N(d)$ at a distance d is proportional to:

$$N(d) \propto \frac{1}{d} \exp\left(-\frac{d}{\lambda_p}\right) \quad (8)$$

where λ_p represents the propagation length in the ice, defined as:

$$\lambda_p = \sqrt{\frac{\lambda_e \lambda_a}{3}} \quad (9)$$

Here, λ_a and λ_e are the absorption lengths and effective scattering lengths of the South Pole ice, respectively. To account for the depth dependence of the optical ice properties, the mean values of $\lambda_a(z)$ and $\lambda_e(z)$ are calculated over the specific vertical distance (Δz) between the camera position and the target DOM, as illustrated in Figure 36.

However, the global normalization does not yet fully resolve the underlying distance dependency across all scales. When plotting the normalized intensity of all available strings together as a function of the angle, a significant amount of residual spread remains visible (see Figure 37).

To investigate this behavior further, the dataset is categorized into distinct distance intervals, as shown in Figure 38. By grouping the strings based on their distance to the source, separate sinusoidal fits can be applied to each individual distance bin. For strings located in closer proximity to the deployment string, a clear sinusoidal modulation representing the angular emission profile of the camera is observed. As the distance increases, this modulation amplitude dampens noticeably until the most distant strings exhibit a flat distribution, where practically only the background noise floor is registered.

To evaluate these fits, the extracted phase shift and amplitude parameters are analyzed as a function of distance, as illustrated in Figure 39. To determine the orientation angle of the Sweden Camera, the peak position of the sinusoidal modulation is extracted from the fitted parameters. The fit function is defined as

$$f(\phi) = a \sin(\phi + \theta) + c \quad (10)$$

where a represents the amplitude, θ is the phase shift, and c is the constant baseline offset. For a positive amplitude ($a > 0$), the peak is reached at an argument of $\frac{\pi}{2}$

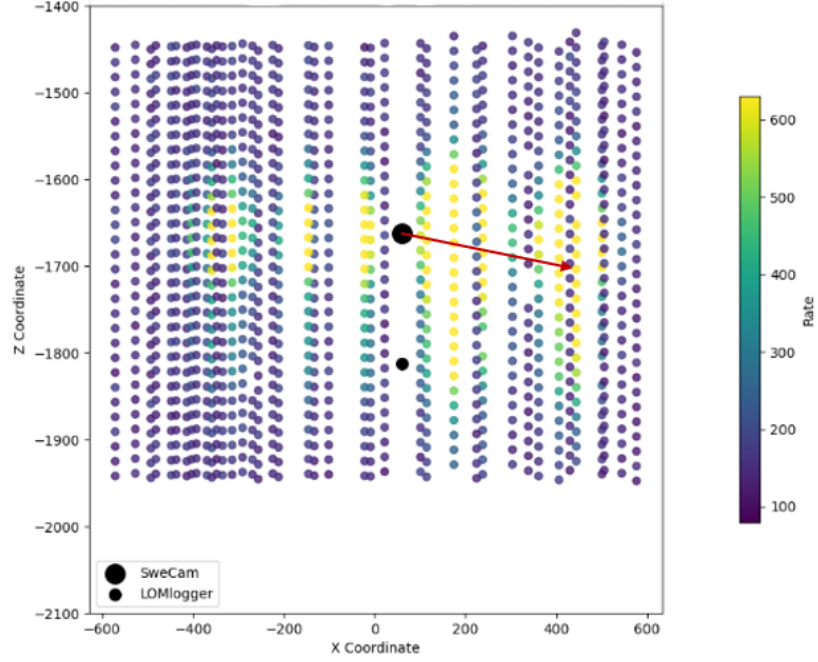


Figure 36: Two-dimensional projection in the xz -plane showing the vertical positions of the active detector components at timestamp 22:30:00 UTC. The positions of the Sweden Camera (SweCam) and the LOMlogger on the deployment string are indicated by black markers. The red solid line illustrates an exemplary propagation path between the camera and a target DOM, along which the depth-dependent absorption and scattering lengths, $\lambda_a(d)$ and $\lambda_e(d)$, are evaluated.

radians, yielding the direction angle $\phi_{\max} = \frac{\pi}{2} - \theta$. The resulting value is converted to degrees and mapped into the interval between 0° and 360° .

To obtain a final camera direction for each time step, only the extracted angles from the two closest valid categories, specifically the red and purple groups, are combined. String 65, which is positioned closest to the camera, is excluded from this calculation because it cannot be assigned to any of the defined distance categories. Similarly, as established above, the third category (the teal group) is excluded because the signal on these distant strings does not differ sufficiently from the background noise floor to ensure a reliable phase extraction, as illustrated by the almost flat line in Figure 39. Because angles are periodic by nature, a standard arithmetic average of the remaining two intermediate groups would fail at the transition boundary between 0° and 360° . Therefore, the combined direction is computed using the circular mean, which averages the directional vectors by summing the sine and cosine components of the individual group angles.

To capture the dynamic rotation of the camera during its descent, this fitting procedure is repeated across the entire deployment sequence recorded between 21:55:00 UTC and 23:15:00 UTC on January 20, 2026. The evaluation is performed at discrete time intervals with a step size of $\Delta t = 100$ ms. The evaluation step size of $\Delta t = 100$ ms was selected based on the accelerometer's fluctuating sampling interval (50–100 ms, corresponding to 10–20 Hz). At each time step t_k , the normalized photon rates of the

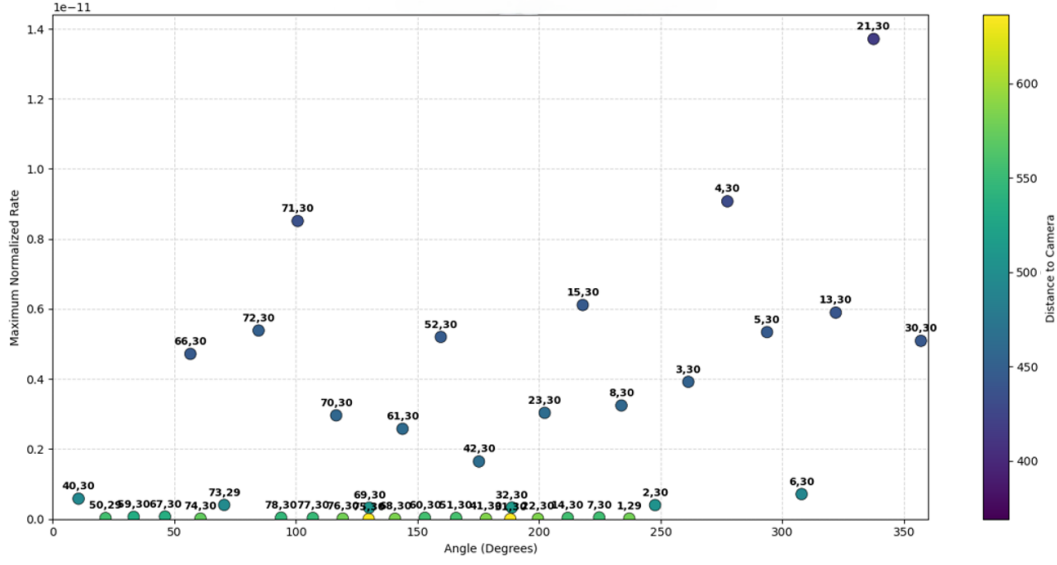


Figure 37: Maximum normalized photon detection rate of the brightest DOM per string as a function of the azimuthal angle ϕ at timestamp 21:55 UTC. The expected sinusoidal signature is currently masked by residual spread from uncompensated distance-dependent scaling effects.

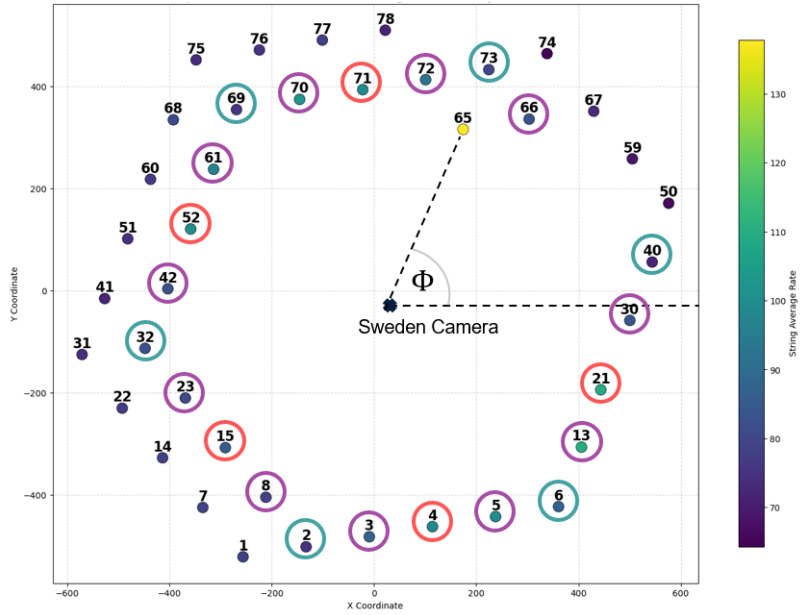


Figure 38: Top-down view illustrating the categorization of activated detector strings into distinct distance intervals relative to the Sweden Camera. Strings are grouped into closer bins (red, purple and teal contours). String 65 is excluded from the classification due to its high proximity.

DOMs are extracted, and the sinusoidal fits are independently executed for the string groups to track the time-dependent orientation angle $\phi_{\max}(t_k)$.

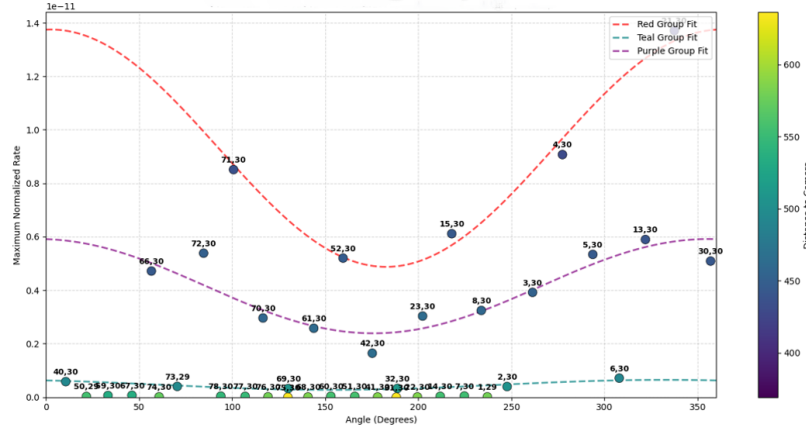


Figure 39: Sinusoidal regression fits applied separately to the categorized distance groups for the normalized maximum DOM rates at timestamp 21:55 UTC. The closer intermediate groups (red and purple group fit) display a clear sinusoidal modulation reflecting the angular emission profile of the camera. In contrast, the distant category (teal group fit) is strongly damped and flat, registering primarily the background noise floor.

To determine the orientation angle of the Sweden Camera, the peak position of the sinusoidal modulation is extracted from the fitted parameters obtained for each distance category (Figure 39). When fitting the modulation function $f(\phi) = a \sin(\phi + \theta) + c$, the standard error of the phase shift, σ_θ , is obtained from the square root of the corresponding diagonal element of the estimated covariance matrix.

Since the directional angle $\theta_{\max}$ is calculated via a linear shift ($\phi_{\max} = \frac{\pi}{2} - \phi$), the uncertainty of the peak position in radians is equal to the uncertainty of the phase parameter itself.

Finally, to obtain the uncertainty of the mean of the angles of the red and purple groups, the uncertainty of the combined mean angle, σ_{mean} , can be evaluated as:

$$\sigma_{\text{mean}} = \frac{1}{2} \sqrt{\sigma_{\theta, \text{red}}^2 + \sigma_{\theta, \text{purple}}^2}. \quad (11)$$

This calculated error is represented by the error bars in Figure 40.

To account for the vertical detector geometry, the analysis is restricted to a specific time window during the camera's deployment, indicated by the purple background in Figure 40 (between 22:09:00 UTC and 22:59:30 UTC).

Outside of this interval, the derived orientation angle fluctuates randomly around 0° with large uncertainties. Prior to 22:09 UTC, the Sweden Camera is positioned above the active instrumented volume of the neighboring IceCube strings. In this regime, the emitted light does not intersect the Digital Optical Modules (DOMs). Analogously, after 22:59:30 UTC, the camera drops below the vertical depth range of the surrounding DOMs.

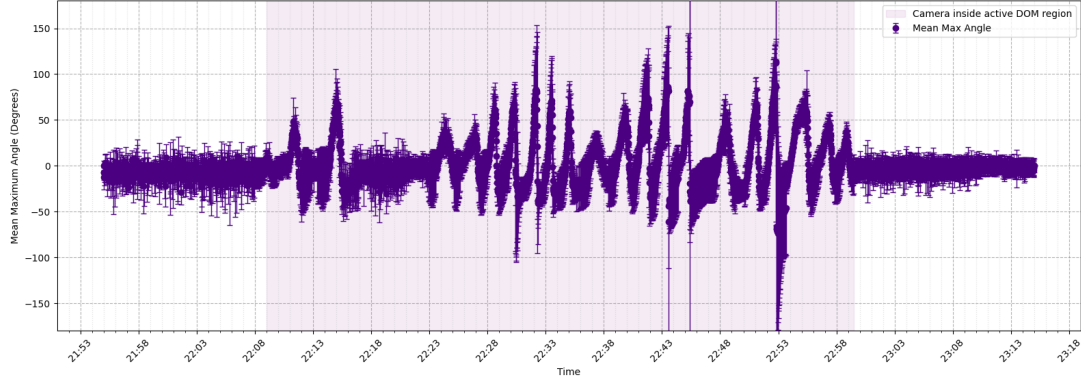


Figure 40: Time evolution of the derived horizontal orientation angle $\phi_{\max}$ of the Sweden Camera during deployment. For each time step, the direction is computed using the circular mean of the phase-extracted peak angles from the red and purple distance categories. The vertical error bars represent the combined angular uncertainty derived via Gaussian error propagation from the covariance matrices of the sinusoidal fits.

6.2 Cross-Validation of Camera Azimuth: Supernova hit rates vs. Accelerometer Data

To cross-validate the derived camera orientations from the Supernova hit rate analysis, the extracted mean maximum angles ($\phi_{\max}$) are compared with the azimuth measurements obtained from the motor controller accelerometer, which was derived from the physical sensor orientation changes during deployment, as discussed in the previous chapter.

While Figure 41 illustrates the comparison using the motor controller accelerometer data, the corresponding results derived from the camera controller show an almost identical evolution (see Figure 46 in Appendix D). Apart from a constant 90° offset between the two sensors, due to their perpendicular mounting configuration on the electronics board, both controllers record the same structural movement patterns.

To mitigate noise in the raw sensor measurements, a moving average filter was applied to the accelerometer data. The signal was smoothed using a uniform moving window of size $N = 21$, defined as

$$y_{\text{smooth}}(i) = \frac{1}{N} \sum_{j=-(N-1)/2}^{(N-1)/2} y_{\text{padded}}(i+j), \quad (12)$$

where $y_{\text{smooth}}(i)$ represents the smoothed accelerometer signal at discrete time index i , N is the window length ($N = 21$), and y_{padded} denotes the original signal y extended at the boundaries using a reflection mode to prevent edge artifacts during convolution. This choice of window size suppresses noise while preserving the underlying motion trends and maintaining proper temporal alignment.

As illustrated in Figure 41, a comparison of the time evolutions reveals periods of qualitative agreement and similar structural trends between both methods. However, noticeable discrepancies occur in several parts of the dataset: while a general correlation in the overall movement pattern is visible, the angular variations measured by the

accelerometer are significantly smaller in magnitude compared to the camera-derived angle changes. Furthermore, temporal phase shifts and offset differences appear during specific intervals, showing that the quantitative alignment varies across the time sequence.

These discrepancies can be largely attributed to two main factors. First, the underlying analytical attenuation ice model (Equation 8) has inherent limitations. Specifically, the analytical formula simplifies the optical path by neglecting anisotropic scattering effects induced by ice birefringence, which is explained in subsection 2.6. Achieving higher physical accuracy in the optical reconstruction would therefore require a Monte Carlo simulation as a replacement for the current analytical approximation.

Second, a limitation lies in the range of the accelerometer-derived angles. During the deployment drop, one would physically expect significantly larger variations and a broader spread in the azimuth angle, as indeed suggested by the higher variability in the optical IceCube data. The accelerometer measurements, however, exhibit an unrealistically narrow angular spread, indicating that the data does not fully capture the complete rotational movement of the system during deployment. This behavior highlights a fundamental constraint of the sensor setup. As detailed in subsubsection 3.1.4 the sensitivity of an accelerometer to movement perpendicular to the Earth's gravitation is limited. This suggests that to determine the camera's orientation in azimuth direction a sensor other than an accelerometer (such as the magnetometer) would be better suited. However, due to time constraints, this was not pursued within the scope of this thesis.

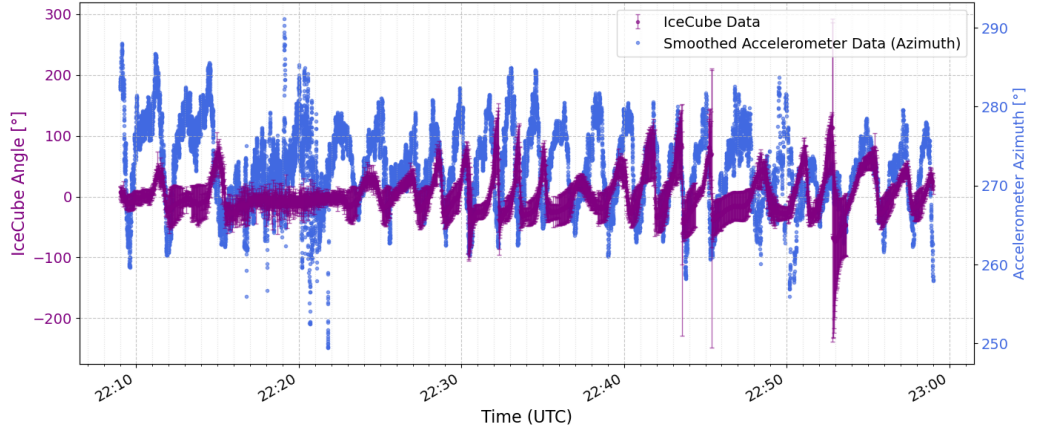


Figure 41: Comparison of the time evolution of the derived camera orientation angles (MC). The plot displays the azimuth angles derived from the optical IceCube Supernova hit rates (purple) alongside the smoothed azimuth measurements obtained from the accelerometer data (blue, smoothed using a moving average window of $N = 21$). Temporal phase shifts and local discrepancies between the optical and mechanical measurements are visible across several intervals.

7 Conclusion

This thesis presents an analysis of multi-sensor data collected by the Sweden Camera during its deployment in one of the IceCube Upgrade boreholes. The investigation encompassed visual image processing, internal sensor orientation tracking, and cross-validation against supernova hit rate data from the main IceCube detector array.

In the first phase of the analysis, an image-preprocessing algorithm was established to process the video recorded by the SweCam during its descent. By evaluating the standard deviation of absolute frame differences against depth-dependent thresholds, camera artifacts and corrupt frames were identified and excluded. The validated frames allowed for the extraction of stratigraphic parameters, including layer boundaries between water, newly formed hole ice, and glacial ice, as well as spatial scattering intensity profiles.

To reconstruct the orientation and movement of the camera during its descent, data from the internal accelerometers and magnetometers were evaluated. Due to local magnetic interference affecting the magnetometers, the analysis primarily focused on the accelerometer data. After coordinate transformation into the Earth reference frame using single-axis rotation matrices, the sensor data gave hints on the camera’s orientation, confirming that the system experienced negligible pitching. However, comparing the extracted visual frame features with the calculated accelerometer azimuth revealed no discernible correlation. This finding indicates that the accelerometer-derived azimuth is insufficient for tracking the rotational motion of the Sweden Camera in the horizontal plane and that other methods such as magnetometer measurements or visual tracking are better suited for this task.

Finally, a cross-validation of the camera’s azimuthal orientation was conducted using Supernova hit rate data registered by a subset of the surrounding IceCube DOMs. Sinusoidal regression fits applied across categorized distance groups successfully captured the dynamic horizontal rotation of the camera during its drop. Comparing these optically derived direction angles with the smoothed accelerometer measurements revealed consistent structural trends and qualitative agreement in overall movement patterns. Nevertheless, quantitative discrepancies, temporal phase shifts, and a noticeably narrower angular spread in the accelerometer output were observed. These differences highlight two main factors: the analytical ice attenuation model used for optical reconstruction simplifies light propagation by neglecting anisotropic scattering from ice birefringence, and the mechanical accelerometers exhibit a range limitation that underrepresents the full rotational amplitude.

In summary, while the internal accelerometers indicate a largely stable vertical alignment of the SweCam, the mechanical sensor results themselves require critical re-evaluation and further processing to fully resolve the system’s azimuthal dynamics. In contrast, the azimuthal angles derived from the IceCube Supernova hit rates align much better with the physical expectation of a rotating camera during deployment. Future deployment analyses should combine a thorough re-assessment of the accelerometer data with Monte Carlo photon propagation simulations to account for ice anisotropy.

A Appendix A: Analytical Derivation of Zenith Angle Uncertainty

This section provides the detailed derivation of the orientation uncertainty for the zenith angle ϕ , propagated from the relative sensitivity tolerance of the 3-axis accelerometer using Gaussian error propagation.

The zenith angle ϕ is calculated from the Cartesian acceleration components (a_x, a_y, a_z) as follows:

$$\phi(a_x, a_y, a_z) = \arccos\left(\frac{a_z}{\sqrt{a_x^2 + a_y^2 + a_z^2}}\right) = \arccos\left(\frac{a_z}{r}\right) \quad (13)$$

where $r = \|a\| = \sqrt{a_x^2 + a_y^2 + a_z^2}$ denotes the magnitude of the total acceleration vector. Assuming a sensitivity uncertainty of 1.5% ($\Delta a/a = 0.015$) across all three accelerometer axes, the absolute uncertainties are given by:

$$\Delta a_x = 0.015 \cdot a_x, \quad \Delta a_y = 0.015 \cdot a_y, \quad \Delta a_z = 0.015 \cdot a_z \quad (14)$$

According to Gaussian error propagation for independent variables, the overall uncertainty $\Delta\phi$ is defined by:

$$\Delta\phi = \sqrt{\left(\frac{\partial\phi}{\partial a_x} \cdot \Delta a_x\right)^2 + \left(\frac{\partial\phi}{\partial a_y} \cdot \Delta a_y\right)^2 + \left(\frac{\partial\phi}{\partial a_z} \cdot \Delta a_z\right)^2} \quad (15)$$

Partial Derivatives

Applying the chain rule for $\frac{d}{du} \arccos(u) = -\frac{1}{\sqrt{1-u^2}}$ with $u = a_z/r$ yields:

$$-\frac{1}{\sqrt{1-(a_z/r)^2}} = -\frac{1}{\sin\phi} \quad (16)$$

Differentiating $u = a_z/r$ with respect to each component yields:

$$\frac{\partial\phi}{\partial a_x} = -\frac{1}{\sin\phi} \cdot \left(-\frac{a_z a_x}{r^3}\right) = \frac{a_z a_x}{r^3 \sin\phi} \quad (17)$$

$$\frac{\partial\phi}{\partial a_y} = -\frac{1}{\sin\phi} \cdot \left(-\frac{a_z a_y}{r^3}\right) = \frac{a_z a_y}{r^3 \sin\phi} \quad (18)$$

$$\frac{\partial\phi}{\partial a_z} = -\frac{1}{\sin\phi} \cdot \left(\frac{r^2 - a_z^2}{r^3}\right) = -\frac{a_x^2 + a_y^2}{r^3 \sin\phi} \quad (19)$$

Propagation

Substituting the partial derivatives into Equation (15) gives:

$$\Delta\phi = \sqrt{\left(\frac{a_z a_x \cdot 0.015 a_x}{r^3 \sin\phi}\right)^2 + \left(\frac{a_z a_y \cdot 0.015 a_y}{r^3 \sin\phi}\right)^2 + \left(\frac{-(a_x^2 + a_y^2) \cdot 0.015 a_z}{r^3 \sin\phi}\right)^2} \quad (20)$$

Factoring out common terms yields:

$$\Delta\phi = \frac{0.015 \cdot a_z}{r^3 \sin\phi} \sqrt{a_x^4 + a_y^4 + (a_x^2 + a_y^2)^2} = \frac{0.015 \cdot a_z}{r^3 \sin\phi} \sqrt{2(a_x^2 + a_y^2)^2} \quad (21)$$

Using the spherical coordinate transformations $a_x^2 + a_y^2 = r^2 \sin^2 \phi$ and $a_z = r \cos \phi$, the expression simplifies exactly to:

$$\Delta\phi = \frac{0.015 \cdot (r \cos \phi) \cdot \sqrt{2}(r^2 \sin^2 \phi)}{r^3 \sin \phi} = 0.015 \cdot \sqrt{2} \cdot \cos \phi \sin \phi \quad (22)$$

Using the double-angle identity $\sin(2\phi) = 2 \sin \phi \cos \phi$, the equation for the angular uncertainty is obtained:

$$\Delta\phi = 0.0075 \cdot \sqrt{2} \cdot \sin(2\phi) \quad (23)$$

Application to Measured Angles

Applying this formula to the tilt angles measured during the experiment and converting the result to degrees yields:

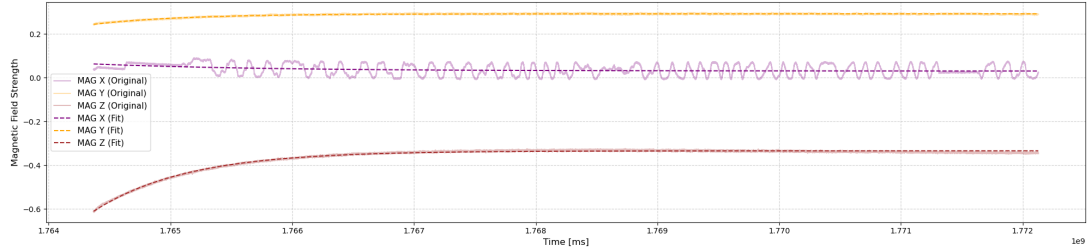
- **Motor Controller** ($\beta = 20.14^\circ$):

$$\Delta\beta = 0.0075 \cdot \sqrt{2} \cdot \sin(2 \cdot 20.14^\circ) = 0.0075 \cdot \sqrt{2} \cdot \sin(40.28^\circ) \approx \pm 0.39^\circ \quad (24)$$

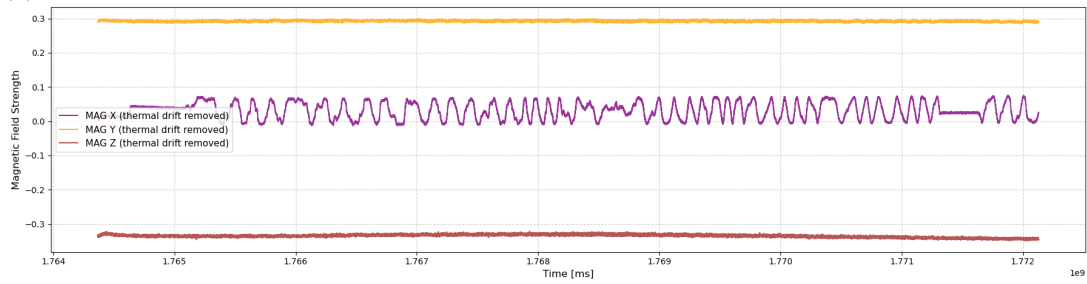
- **Camera Controller** ($\alpha = 21.43^\circ$):

$$\Delta\alpha = 0.0075 \cdot \sqrt{2} \cdot \sin(2 \cdot 21.43^\circ) = 0.0075 \cdot \sqrt{2} \cdot \sin(42.86^\circ) \approx \pm 0.41^\circ \quad (25)$$

B Appendix B: Magnetometer Thermal Drift Correction and Vector Evolution



(a) Raw magnetic field data for all three axes alongside the fitted exponential thermal models.



(b) Corrected magnetic field data with the thermal drift removed, highlighting the stabilized baseline and periodic rotation signals.

Figure 42: Magnetic field measurements from the motor controller magnetometer before and after thermal drift correction.

C Appendix C: Correlations Between Camera-Derived Parameters and Accelerometer Angles

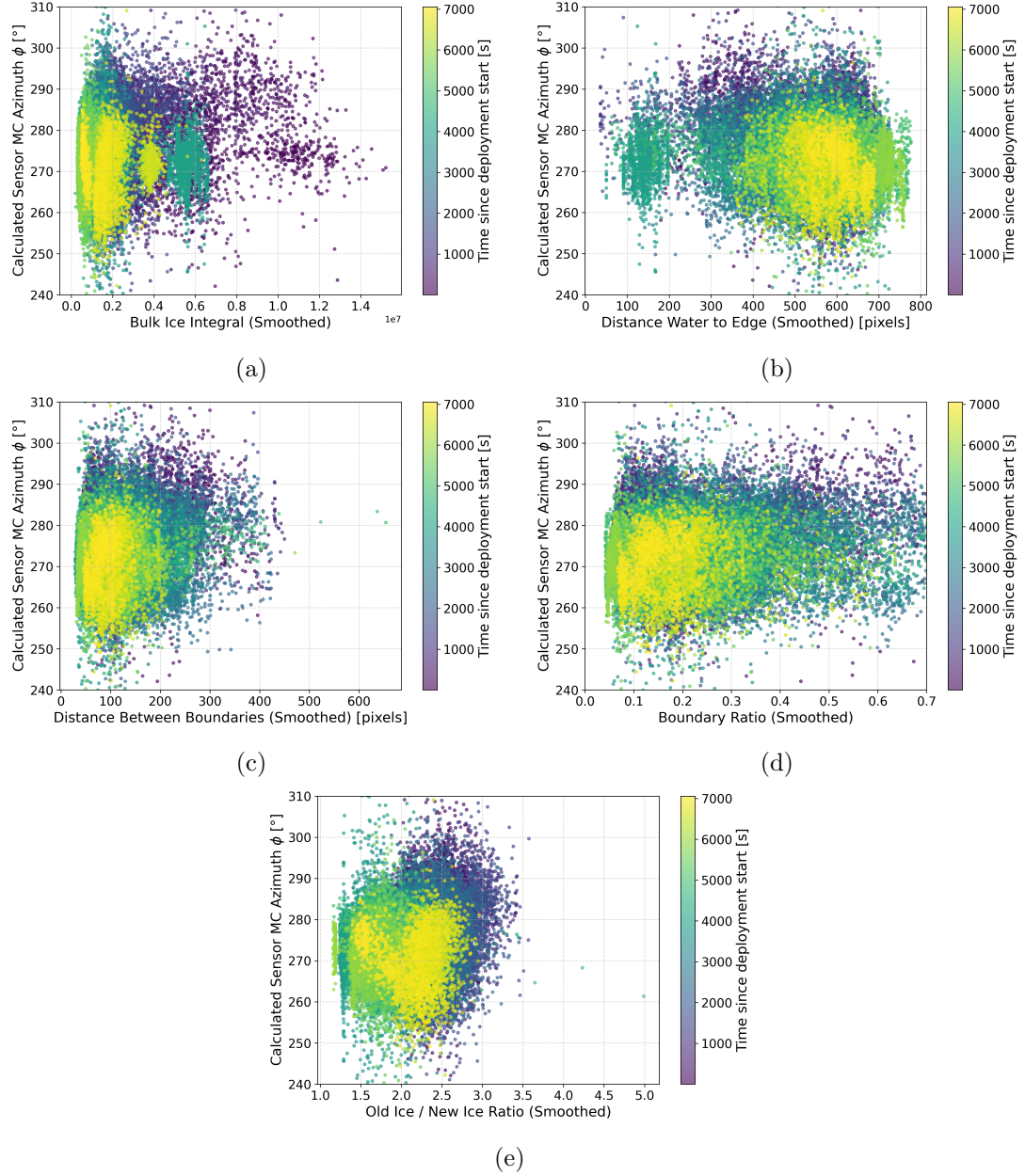


Figure 43: Correlation between parameters extracted from camera frames and the calculated camera azimuth angle derived from the MC accelerometer data, color-coded by deployment time. (a) Total scattered light intensity. (b) Thickness of the visible water column. (c) Thickness of the newly formed hole ice layer. (d) Ratio between the boundary distance (c) and the visible water column thickness (b). (e) Ratio of mean scattering intensity between old glacier ice and newly formed hole ice.

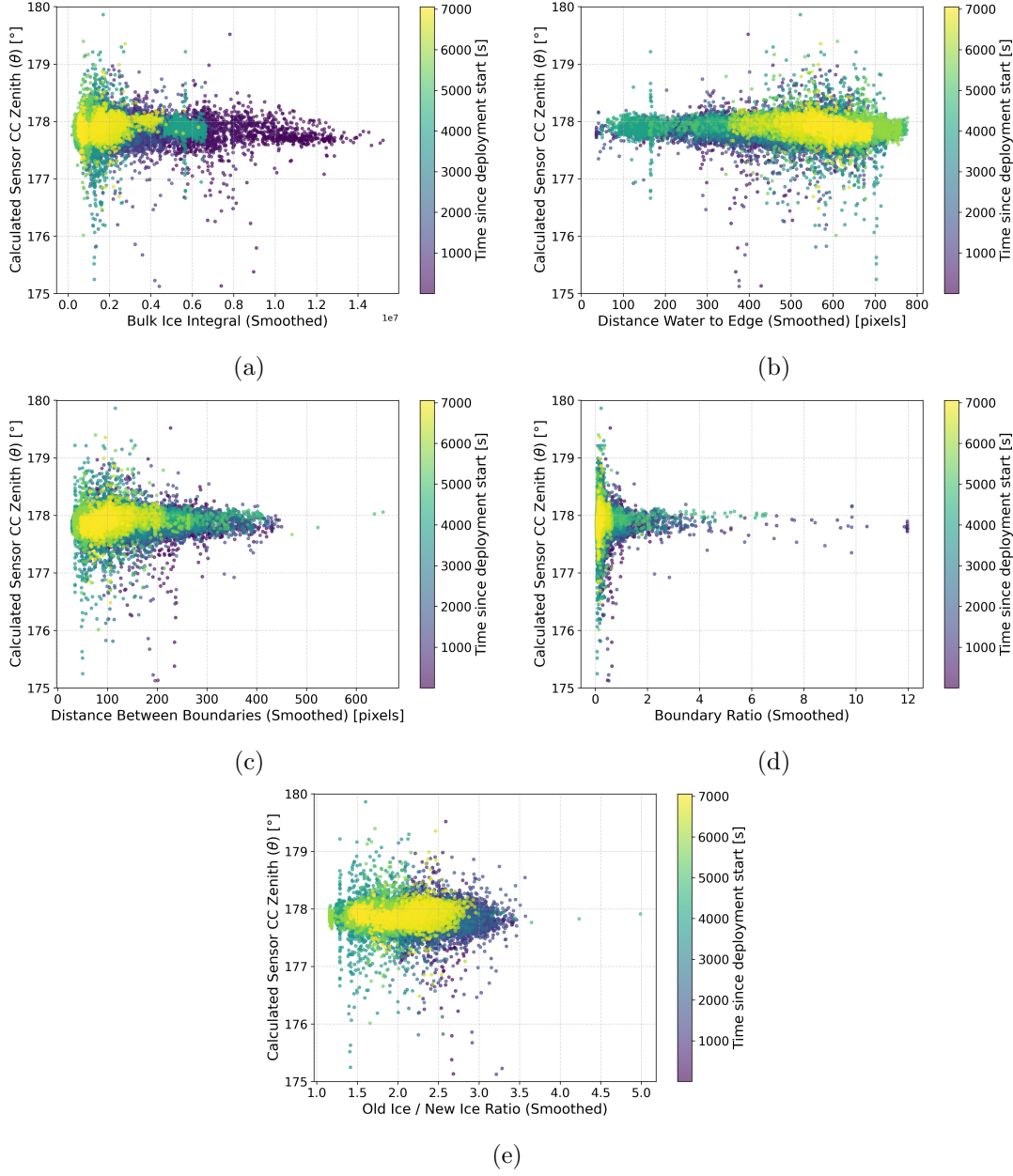


Figure 44: Correlation between parameters extracted from camera frames and the calculated camera zenith angle derived from the CC accelerometer data, color-coded by deployment time. (a) Total scattered light intensity. (b) Thickness of the visible water column. (c) Thickness of the newly formed hole ice layer. (d) Ratio between the boundary distance (c) and the visible water column thickness (b). (e) Ratio of mean scattering intensity between old glacier ice and newly formed hole ice.

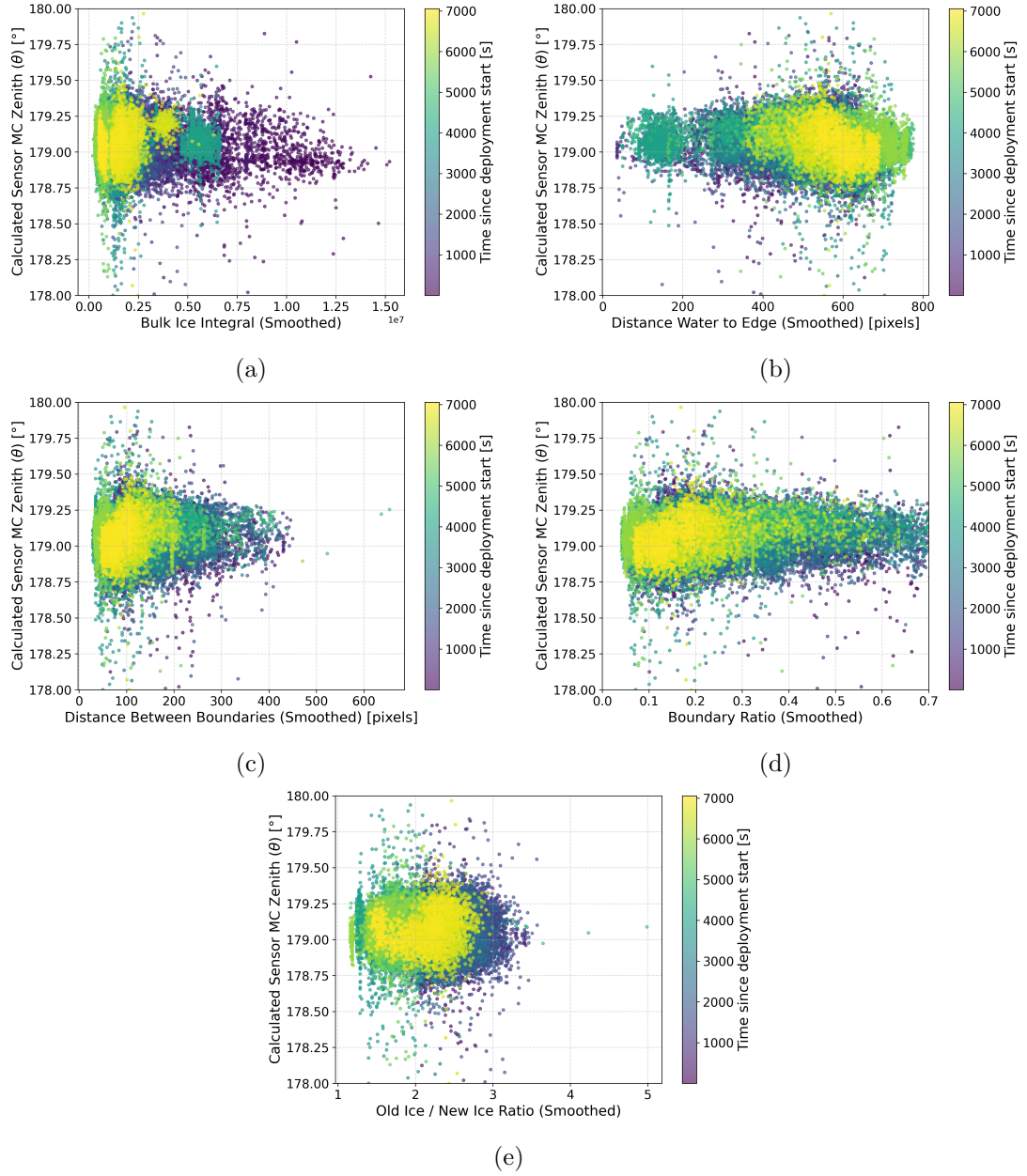


Figure 45: Correlation between parameters extracted from camera frames and the calculated camera zenith angle derived from the MC accelerometer data, color-coded by deployment time. (a) Total scattered light intensity. (b) Thickness of the visible water column. (c) Thickness of the newly formed hole ice layer. (d) Ratio between the boundary distance (c) and the visible water column thickness (b). (e) Ratio of mean scattering intensity between old glacier ice and newly formed hole ice.

D Appendix D: Comparison of Optical IceCube Hit-Rate Angles and Accelerometer Azimuth Data

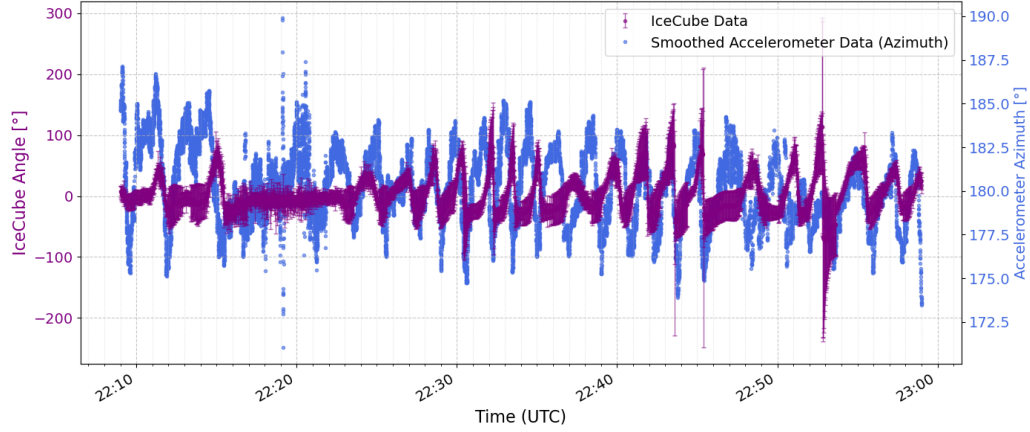


Figure 46: Comparison of the time evolution of the derived camera orientation angles (CC). The plot displays the azimuth angles derived from the optical IceCube supernova hit rates (purple) alongside the smoothed azimuth measurements obtained from the accelerometer data (blue, smoothed using a moving average window of $N = 21$). Temporal phase shifts and local discrepancies between the optical and mechanical measurements are visible across several intervals.

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I, Isabel Schraml, student registration number: 23334315, hereby confirm that I completed the submitted work independently and without the unauthorized assistance of third parties and without the use of undisclosed and, in particular, unauthorized aids. This work has not been previously submitted in its current form or in a similar form to any other examination authorities and has not been accepted as part of an examination by any other examination authority.

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