



Master's Thesis

in Physics

Optical Characterisation of IceCube Upgrade Light Sensors and Calibration Devices

Andrei Chubarov

Supervisor: Prof. Dr. Claudio Kopper

Erlangen Centre for Astroparticle Physics

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Abstract

This thesis presents three independent studies contributing to the optical characterisation of light sensors and calibration devices of the IceCube Upgrade, which was deployed at the geographic South Pole during the 2025/26 austral summer season.

The first study investigates photoluminescence in the borosilicate glass housing of the IceCube Digital Optical Module (DOM) as a potential background to the Neutron Echo calibration signal. The Neutron Echo exploits the delayed Cherenkov emission following neutron capture on hydrogen in the ice. In order to statistically separate electron neutrino and tau neutrino cascade events, a distinction that the spatial resolution of IceCube alone can not do. A ray-tracing simulation was constructed to compare the photoluminescence induced in the DOM glass by the built-in LED Flashers relative to that induced by a Cherenkov event. The ratio of photoluminescence contributions between the two source geometries was found to be approximately 2 across all simulated conditions. In contrast to a preliminary geometric estimate of 10^2 – 10^3 , suggesting that the Flashers do not induce disproportionately more photoluminescence than a real physics event.

The second study presents the systematic temperature characterisation of the mDOM flasher LEDs across the full temperature range encountered by the deployed modules. A clear and monotonic reduction in per-pulse photon yield with decreasing temperature was observed for all 20 tested LEDs. This amounts to a reduction of 36.5% at maximum bias voltage at -40°C relative to 20°C . The threshold voltage required to reach the target intensity of 5×10^6 photons per pulse shifts by 0.4 V on average at -40°C . Extending the existing threshold-voltage correction scheme to cold operation reduces the LED-to-LED relative standard deviation from 48% to 24%. All temperatures remain within the 50% controllability requirement, confirming reliable flasher operation across the full in-situ temperature range.

The third study presents the characterisation of the LOMlogger laser beam profile under conditions reproducing the optical transitions present during deployment. The LOMlogger is a co-deployed laser dust logger, designed to measure the stratigraphy of optical impurities in the ice. This is essential for constraining the undulation of ice layers across the detector volume and for improving IceCube event reconstruction. Laboratory calibration measurements were conducted in a modified aquarium with the POCAM glass hemisphere submerged in water, comparing beam profiles in air and in water. The water was found to narrow the horizontal fan angle by approximately 35% relative to the air measurement due to refraction at the glass-water interface. This is an effect that was not captured by the pre-deployment calibration. The vertical divergence angle remains well within the 10° requirement in all configurations, confirming that the LOMlogger laser meets the resolution requirements for a reliable ice stratigraphy measurements under realistic borehole conditions.

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1 Introduction

The IceCube Neutrino Observatory is a cubic kilometre Cherenkov telescope instrumented within the deep glacial ice at the geographic South Pole, designed to detect high-energy neutrinos [1]. Since its completion in 2011, IceCube has achieved landmark results, which include the discovery of a diffuse astrophysical neutrino flux and the identification of neutrino sources [2]. A central challenge in working with IceCube data is the precise characterisation of the optical properties of the instrumented ice, which dictates how Cherenkov photons propagate from their point of production to the optical sensors [3]. Scattering and absorption lengths vary with depth [3], ice layers are not flat but follow the topology of the bedrock below [3], and effects such as anisotropy [3] and photoluminescence [4] in the detector instrumentation induce additional complexity. Optical uncertainties currently are one of the dominant sources of systematic error in IceCube analyses. The IceCube Upgrade, which was deployed during the 2025/26 austral summer season, addresses these limitations directly [5]. Five new instrumentation strings [6] have been deployed within the existing DeepCore footprint [5], equipped with new photosensor modules, which primarily include the multi-PMT (mDOM) [7] and the D-Egg[8], as well as several new dedicated calibration devices [5]. These will provide an unprecedented dataset for further constraining the optical properties of the ice and improving the calibration of the sensor modules themselves [5].

This thesis contributes to the optical characterisation of the IceCube Upgrade light sensors and calibration devices across three independent studies, each addressing a different aspect of calibration.

The first study discusses the Neutron Echo [4], a calibration technique, which utilizes the delayed re-emission of light following neutron capture and de-excitation in the ice. It can be used as a measure of the hadronic content of the neutrino-induced particle showers and from this the underlying interaction type. This is particularly relevant for improving the separation of electron neutrino (ν_e) and tau neutrino (ν_τ) cascade-type events [4], which are difficult to be sufficiently distinguished by the event signature alone [9]. Using a ray-tracing simulation in Zemax, the propagation of light within the mDOM housing was modelled [7]. It was modelled with the goal of accurately predicting the effect of photoluminescence. This effect describes the absorption and re-emission of light at a shifted wavelength, that occurs in the glass housing, in order to evaluate its impact on the signal of the Neutron Echo as a background.

The second study tackles the calibration of the mDOM Flasher LEDs at cryogenic temperatures. The Flasher LEDs built into each mDOM serve as the primary in situ light source for probing the optical properties of the surrounding ice [7]. Their output must be well-characterised across the full range of temperatures encountered in the deployed array, which spans from -40°C at a depth of 1600 m to -20°C at a depth of 2400 m [10]. While room-temperature acceptance testing of all Flasher LEDs was completed prior to deployment, a systematic characterisation of the LED brightness as a function of temperature had not been performed yet [11]. This thesis presents measurements of 20 mDOM Flasher LEDs across five temperatures from -40°C to 20°C , establishing the temperature-dependent characterisation required for predictable in situ operation.

The third study concerns the LOMlogger, which is a co-deployed laser dust logger designed to measure the stratigraphy of the optical impurities in the ice during the

deployment of the IceCube Upgrade strings [12]. A profound understanding of the ice stratigraphy is essential for constraining the so-called ice tilt, which describes the depth-dependent undulations of ice layers of constant optical properties [3]. This analysis becomes increasingly important for IceCube-Gen2, where a larger module spacing is planned [13]. The LOMlogger records information about the ice by shining a pulsed laser beam horizontally into the ice and detecting back-scattered light with an optical module placed above it on the string [12]. The initial calibration of the laser beam profile was done in an experimental setup, that did not account for the optical transitions through the lens of the LOMlogger and the water in the borehole. To ensure that the laser beam profile meets the requirements for a reliable stratigraphy measurement, further laboratory calibration measurements were conducted in a modified aquarium to characterise the angular and spatial profile of the laser both in air as well as water to recreate the conditions inside the borehole as closely as possible.

2 Theoretical Background

This chapter explains the basics of neutrino physics. Additionally the Cherenkov effect and the role it plays in astroparticle physics and specifically neutrino astronomy is discussed. Furthermore, the IceCube Neutrino Observatory is introduced as well as its recently built extension: The IceCube Upgrade.

2.1 Neutrino Physics

Neutrinos are elementary particles within the Standard Model of elementary particles. They possess a spin of $1/2$, no electric charge and belong to the group of leptons [14]. There are three different types of neutrinos, the electron neutrino ν_e , the muon neutrino ν_μ and the tau neutrino ν_τ [14]. These types are commonly referred to as flavours. Each neutrino flavour is associated with a charged lepton, namely the electron e , the muon μ and the tau τ [14].

Neutrino oscillations describe the quantum mechanical phenomenon in which neutrinos can change flavour during propagation. Neutrinos are required to have mass eigenstates, in order for oscillations to be possible, as flavour eigenstates are superpositions of mass eigenstates [15]. Therefore, neutrinos must possess mass as a prerequisite for neutrino oscillations. Originally, neutrinos were assumed to be massless. Today it is known that neutrinos possess very small, but non-zero masses [15]. Experiments like KATRIN aim to find the absolute neutrino masses and the mass hierarchy [15].

As neutrinos have no electrical charge and do not interact via the strong interaction as they have no colour charge, they primarily interact through the weak interaction [14]. The creation of neutrinos can happen through different processes [15]. These processes include, the radioactive β^+ -decay (β^- for electron anti-neutrinos), which is described in Equation 1:

$${}^A_Z X \rightarrow {}^A_{Z-1} Y + e^+ + \nu_e \quad (1)$$

as well as the decay of mesons, which are created by high-energy protons interacting with nuclei and are important for astroparticle physics and will be described in subsection 2.3 [15]. These processes can occur in various sources like the sun, interactions in earth's atmosphere, cosmic rays and other extra-galactic sources [15]. Some artificial sources like particle accelerators or nuclear reactors create neutrinos as by-products during operation [15].

Two possible neutrino interactions are the neutral current interaction and the charged current interaction, which are visible in Figure 1 [14]. Charged current interactions produce the corresponding charged lepton. Neutrino neutral current interactions transfer energy to the target nucleus and do not change the neutrino flavour. These interactions have very small cross sections, therefore the probability of neutrinos interacting with matter is very low [15]. This allows neutrinos to travel long distances without being deflected by magnetic fields and without being absorbed. These qualities make neutrinos valuable messengers for the analysis of astrophysical phenomena and at the same time very difficult to detect.

2.2 Cherenkov effect

The Cherenkov effect is often utilized for neutrino detection, because neutrinos cannot be measured directly, but only through secondary charged particles, that are created

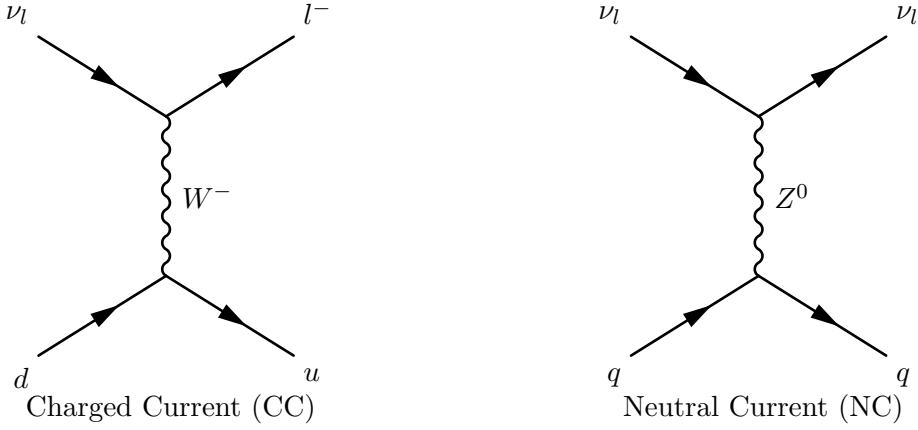


Figure 1: Feynman diagrams of a charged current (left) and the neutral current interaction (right) with l as a placeholder for the different types of leptons (e, μ, τ), d as the down quark, u as the up quark and q as a placeholder for a quark. Adapted from

through neutrino interactions. The Cherenkov effect occurs, when charged particles, like electrons, muons or tau, travel through a dielectric medium with a speed v higher than the speed of light in the medium $c_n = c_0/n$, with n as the refractive index and c as the speed of light in vacuum [16]. The effect can be explained through asymmetric polarization of a dielectric medium [16]. This is visualised in Figure 2.

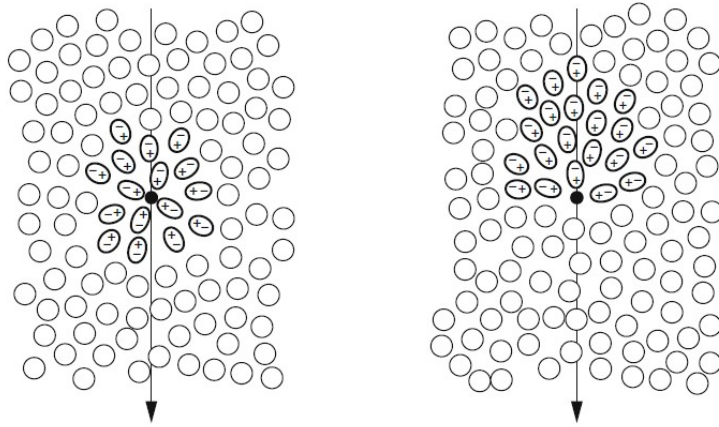


Figure 2: Schematic depiction of a charged particle travelling through a dielectric medium. (Left): A charged particle travelling at a speed $v < c_n$, therefore the medium is symmetrically polarized. (Right): A charged particle travelling at a speed $v \geq c_n$, therefore the medium is momentarily asymmetrically polarized along the travel direction of the particle [16].

In the case that the charged particle is travelling at a speed v smaller than c_n , the medium is symmetrically polarised and the local dipole electric fields cancel each other out, therefore no radiation is emitted [16]. For the case that $v > c_n$, the medium is asymmetrically polarised along the trajectory of the charged particle, which means the dipoles do not cancel each other out [16]. This results in a momentary polarisation field, which through constructive interference produces Cherenkov radiation [16]. A graphic

representation of the constructive interference of the polarization and the resulting Cherenkov cone can be seen in Figure 3.

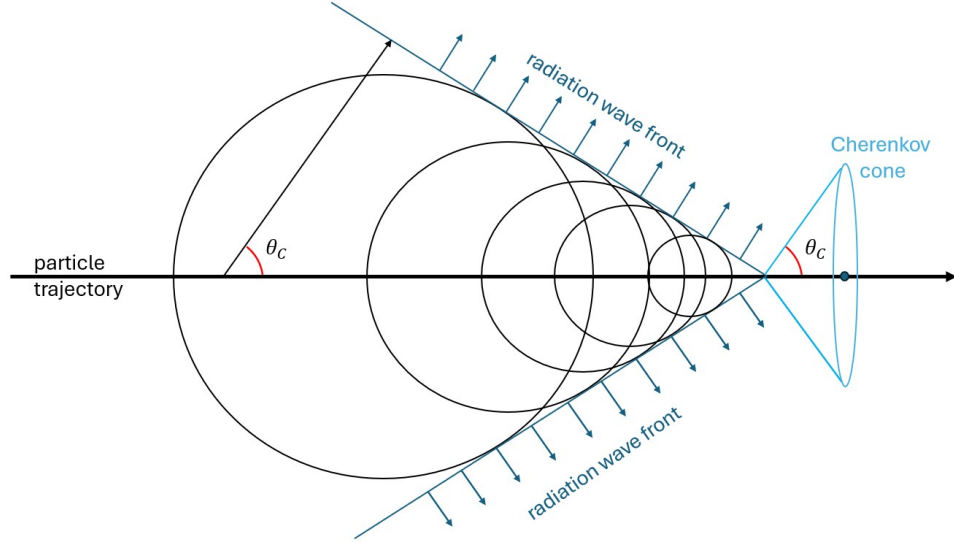


Figure 3: Schematic depiction of the Cherenkov effect. The charged particle, travelling with a speed higher than the speed of light in the medium, polarizes the dielectric medium. As the polarization travels at the local speed of light, asymmetric polarisation is left behind the particle and interferes constructively, creating wave fronts of electromagnetic radiation. This radiation is then emitted along the surface of a second cone, which is known as the Cherenkov cone, perpendicular to the wave fronts. The figure is adapted from [17].

The emitted Cherenkov radiation propagates along a cone-shaped wavefront around the trajectory of the charged particle [16]. The opening angle of this cone is the Cherenkov angle θ_C and is dependent on the velocity of the charged particle and the refractive index of the medium [16]. The Cherenkov angle can be described as:

$$\cos(\theta_C) = \frac{1}{n \cdot \beta} \quad (2)$$

where $\beta = v/c$, v is the velocity of the charged particle, c is the speed of light in a vacuum and n is the refractive index of the medium [16].

2.3 Neutrino Astronomy

The scientific field of astroparticle physics has the goal of investigating astrophysical objects and phenomena through the means of a variety of different cosmic particles, which travel through the universe and arrive at Earth. Cosmic rays are one such kind of particle [14]. They predominantly include protons, but also alpha particles and other heavier nuclei. Through acceleration processes in space, the cosmic rays can reach energies of up to several 10^{20} eV [18]. The fraction of cosmic rays reaching such high energies is very small [18]. Understanding the acceleration mechanisms and the physics

behind them is a subject of current research, some potential sources include active galactic nuclei (AGN) and supernova remnants (SNR) [18].

Neutrino Astronomy describes the discipline in astroparticle physics, which tries to detect and gather information about astrophysical objects and phenomena through the means of high energy neutrinos. As mentioned in subsection 2.1, neutrinos are not deflected by magnetic fields while travelling through space. They also possess a very small weak-interaction cross section and can escape astrophysical environments that are opaque to electromagnetic radiation. High-energy neutrinos can therefore provide information about the acceleration sites of cosmic rays. These are inaccessible through cosmic rays themselves, as these are deflected by magnetic fields during propagation [19].

High-energy astrophysical neutrinos are believed to be created through interactions of cosmic rays with matter or radiation fields around the previously mentioned astrophysical objects [19]. While the following production mechanisms have not yet been confirmed at astrophysical sources, the underlying processes are well established and have been observed through cosmic ray interactions in Earth's atmosphere. Two important production mechanisms are the proton-proton (pp) and the proton-photon ($p\gamma$) interactions [20], in which charged pions are produced:

$$\begin{aligned} p + p &\rightarrow \pi^\pm + x \\ p + \gamma &\rightarrow \pi^\pm + x \end{aligned} \tag{3}$$

where x are additional secondary particle [20]. The charged pions then decay into muons and muon neutrinos [21], for example

$$\pi^+ \rightarrow \mu^+ + \nu_\mu, \quad \pi^- \rightarrow \mu^- + \bar{\nu}_\mu, \tag{4}$$

this is followed by the decay of the muons into electrons, electron neutrinos and muon anti-neutrinos [21],

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu, \quad \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu. \tag{5}$$

Due to neutrino oscillations during propagation through space, the initially produced neutrino flavours change, as well as the flavour ratio, before reaching Earth [22]. While the flavour ratio at such sources is expected to be approximately $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$, due to the described production mechanisms, oscillations lead to an approximately equal flavour composition at Earth [22].

The greatest advantage is also one of the greatest challenges, of using neutrinos as astrophysical messengers. Detection of neutrinos in experiments is difficult, due to their small cross section and the low flux of high-energy astrophysical neutrinos [16]. Neutrinos and muons can be produced in Earth's atmosphere through cosmic rays via the same processes found at the sources. These neutrinos create a large background for the measurement of astrophysical neutrinos [15]. This makes it clear that experiments aiming to record the astrophysical neutrino flux require large detector volumes and time to acquire significant statistics. One such experiment that achieves this is the IceCube Neutrino Observatory [1].

2.4 IceCube Neutrino Observatory

The difficulties, which result from the small interaction cross section of neutrinos, mentioned in subsection 2.1, mean that the detection of neutrinos requires huge detection

volumes. The IceCube Neutrino Observatory is a large water/ice Cherenkov detector that accomplishes that [1]. It is located at the geographic South Pole and instrumentalizes about 1 km^3 of Antarctic ice [1]. The generally very clear ice, provides a suitable medium for the detection of high energy neutrinos [1]. The IceCube detector is comprised of three distinct components: a surface part known as IceTop, which is used for the detection of particle air showers above the detector [23], a central buried component referred to as DeepCore, which is used to detect lower energy neutrinos with energies as low as 10 GeV [24] and the main large detector array of IceCube that is used for the detection of ultra-high energy neutrinos [1].

IceCube was originally instrumented with 86 strings, each fitted with 60 Digital Optical Modules (DOMs), totalling 5160 DOMs distributed throughout the detector volume [1]. These DOMs are evenly deployed in the Antarctic ice at depths between 1450 m and 2450 m [1]. A schematic view of the detector and the arrangement of the strings and the individual components can be seen in Figure 4.

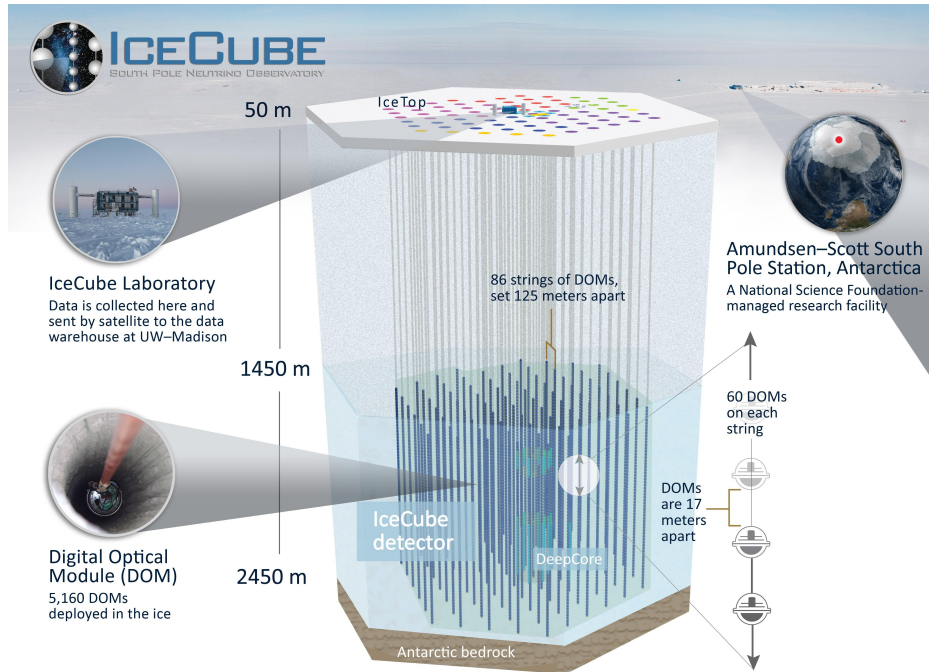


Figure 4: A schematic view of the IceCube Neutrino Observatory. The figure displays the layout of the detector array and how the 86 detector lines equipped with 60 DOMs are arranged [25].

Each DOM consists of a glass sphere housing a photomultiplier tube (PMT) with a diameter of approximately 25 cm, along with the corresponding electronics for signal processing, which are further described in subsection 2.5. The PMTs are designed to detect light in the wavelength range between 300 nm and 500 nm, which includes Cherenkov [1]. The DOMs thus are the fundamental detection units for Cherenkov light produced by neutrino interactions inside the ice [1]. The construction of the detector began in 2004 and was completed in 2011 after seven seasons of drilling holes with a hot water drill and lowering the strings into the ice, and has been operating continuously since [1].

2.5 The IceCube DOM

For several of the experiments conducted in this thesis it is necessary to understand the structure of the IceCube DOM in detail. A schematic depiction of the module and its parts can be seen in Figure 5.

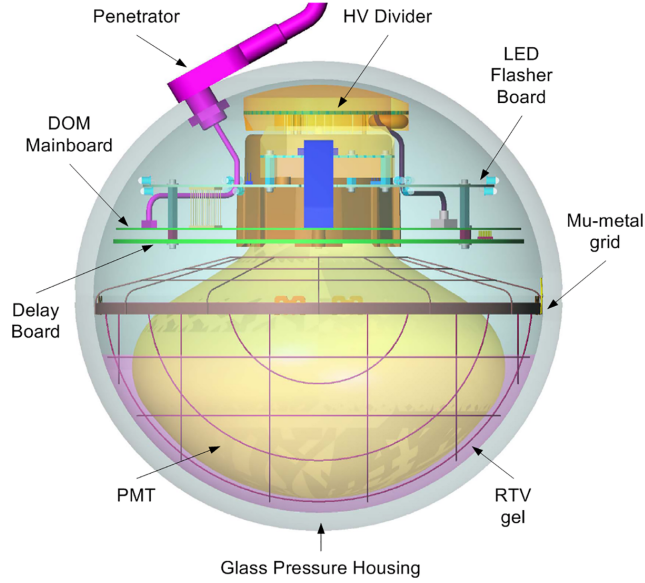


Figure 5: A schematic depiction of the IceCube DOM and the built in electronics. The module is powered by the penetrator cable, that connects the module to the surface station. The upper hemisphere contains the electronics, while the lower hemisphere houses the PMT. The insides of the module are enclosed inside a spherical glass pressure housing in order to withstand the outside pressure and keep the inside dry [26].

The measurement electronics required for the detection of Cherenkov light are placed within a spherical borosilicate glass housing, which protects the inside from the pressure at the detector depth and is transparent for the detection of Cherenkov light [1]. The lower half of the sphere is taken up by a PMT, that is attached to the glass housing via RTV (room-temperature-vulcanizing silicone) gel, in order to reduce optical losses through reflection between the PMT and the housing [1]. The upper hemisphere of the DOM contains the DOMs mainboard, the HV divider, which supplies the operating voltage to the dynodes of the PMT, and the LED Flasher Board, which is equipped with 12 LEDs [1]. Six LEDs are oriented horizontally and six are oriented at an upward angle. All these parts together are required for signal processing, power distribution, and calibration [1].

2.6 Scientific achievements of IceCube

Since the completion of its construction in 2011, the IceCube Neutrino has produced a series of landmark results, which have defined the field of high-energy neutrino astronomy ever since.

One of the most impactful achievements is the discovery of a diffuse flux of neutrinos of astrophysical origin, which was initially reported in 2013 [19]. The flux in the energy

range from tens of TeV to several PeV can not be explained by atmospheric neutrino background alone and provides the first indication, that there are hadronic acceleration processes of extragalactic origin [27]. Following analyses in multiple detection channels, like through-going muon tracks, contained cascades and starting tracks, have improved the measurement considerably. The through-going muon track analysis used 9.5 years of IceCube data. The analysis infers the astrophysical ν_μ flux from the reconstructed muon energy spectrum, which is shown in Figure 6 and provides $\phi_{\text{astro}} = 1.44^{+0.25}_{-0.24}$ at 100 TeV and a spectral index of $\gamma = 2.37^{+0.09}_{-0.09}$ [28].

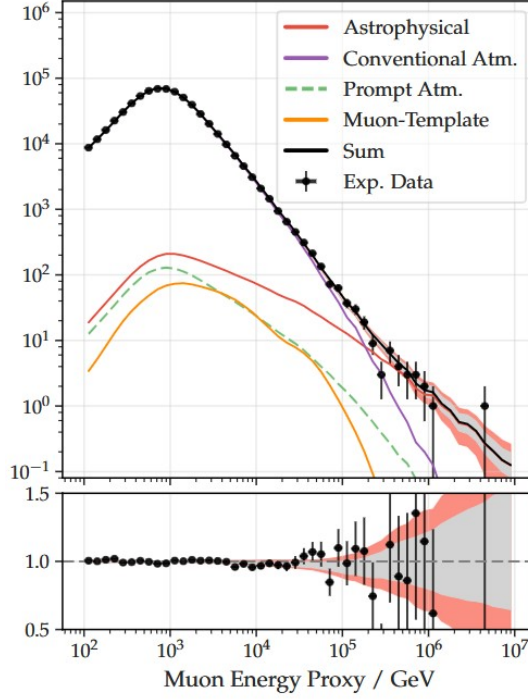


Figure 6: Energy spectrum of the through-going muon sample from 9.5 years of IceCube data, shown as a function of reconstructed muon energy proxy. The astrophysical ν_μ component (red) is modelled as a single power law. The conventional atmospheric neutrino background (purple) dominates at lower energies, while the prompt atmospheric component is shown at its nominal prediction (green dashed). The orange line shows the remaining atmospheric muon background. The black curve shows the total best-fit expectation, in good agreement with the experimental data (black dots). The lower panel shows the ratio of data to the total model [28].

A complementary proof of the astrophysical neutrino flux is given by its flavour composition. Neutrinos produced through pion-decay chains at astrophysical sources or in the atmosphere are emitted in the ratio $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$ [22]. Through propagation over cosmic distances and neutrino oscillations, this ratio evolves to approximately $1 : 1 : 1$ by the time the neutrinos arrive at Earth [22], whereas atmospheric neutrinos, produced locally in Earth’s atmosphere, do not undergo this oscillation and retain a flavour composition with a negligible ν_τ component. The detection of tau neutrinos at IceCube [29] therefore provides direct evidence that the observed flux cannot be exclusively atmospheric in origin [27].

Other production mechanisms predict distinct signatures, like a muon-damped source with $(0 : 1 : 0)_s$ and $(1 : 1.8 : 1.8)_\oplus$ or neutron-decay source with $(1 : 0 : 0)_s$ and $(5 : 2 : 2)_\oplus$, where s denotes the flavour ratio at the source and $\oplus$ denotes the ratio at Earth [30]. To summarize the different known processes, a ternary diagram with axes f_e, f_μ, f_τ summing to unity. This provides a representation of the predictions and their observational uncertainty, which can be seen in Figure 7.

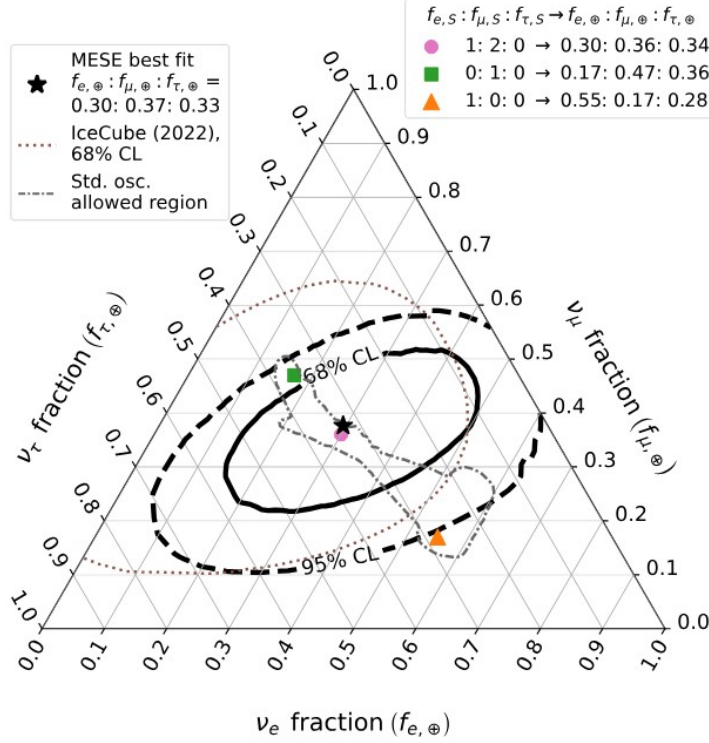


Figure 7: Ternary flavour composition diagram (flavour triangle) of the astrophysical neutrino flux as measured by IceCube using 11.4 years of MESE starting events. The solid and dashed black contours indicate the 68 % and 95 % confidence regions of the MESE best fit $(f_{e,\oplus} : f_{\mu,\oplus} : f_{\tau,\oplus}) = 0.30 : 0.37 : 0.33$ (black star), while the dotted pink contour shows the 68 % confidence region from an earlier IceCube fit from 2022. The grey dash-dotted line represents the region accessible under standard three-flavour oscillations for any astrophysical source composition. The measured composition is consistent with the pion-decay and the standard oscillation expectation [30].

By using 11.4 years of medium energy starting events (MESE) and utilisation of a full three-topology classification (cascades, tracks and double cascades), IceCube measures an astrophysical flavour ratio at Earth of $(f_e : f_\mu : f_\tau)_\oplus = 0.30 : 0.37 : 0.33$ [30]. This result is consistent with the standard pion-decay and with the $(1 : 1 : 1)_\oplus$ expectation under three-flavour oscillation. Source compositions that would predict a flavour ratio at Earth significantly different from this measurement, such as those arising from muon-damped or neutron-decay-dominated production, are disfavoured [30].

This result is particularly relevant to this thesis, as the clear separation of ν_e and ν_τ contributions to the astrophysical flux still poses a challenge for IceCube. The Neutron Echo signal analysed in section 3 discusses a potential improvement for the distinction

of event signatures of ν_e and ν_τ events [4].

Furthermore, next to the measurement of the diffuse flux, IceCube has begun identifying individual astrophysical sources [31]. In 2022, a surplus of 79^{+22}_{-20} neutrinos was detected in spatial coincidence with the nearby Seyfert II galaxy NGC 1068 (M77) with a significance of 4.2σ , which constitutes the first evidence for steady neutrino emission from a resolved extragalactic source [31]. It is also important to note, that no TeV gamma-ray counterpart has been observed from NGC 1068, indicating a neutrino production in the dense, radiation-thick corona. It surrounds the supermassive black hole at the centre of the galaxy, where high-energy photons can not escape from, as they are absorbed [31].

Another milestone was achieved in 2023, when the first observation of diffuse neutrino emission from the Galactic plane was observed at 4.5σ significance [32]. An all-sky map as detected through high-energy neutrinos can be seen in Figure 8. This was done by using a cascade-dominated event sample and reconstruction through the means of machine-learning [32]. The observed galactic neutrino emission is broadly consistent with expectation from cosmic-ray interactions with interstellar gas along the disc. Due to presently limited statistics a detailed decomposition of the spatial and spectral structure was not yet possible.

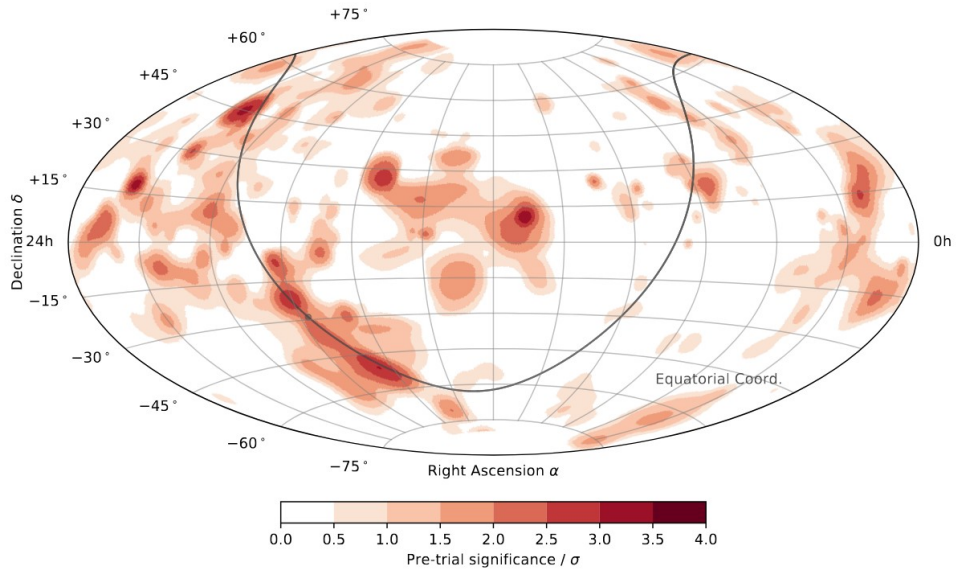


Figure 8: All-sky map of high-energy neutrino events recorded by IceCube, showing the excess associated with the Galactic plane (grey line) in equatorial coordinates. The colour scale indicates local significance [32].

These results collectively establish IceCube as the leading instrument for neutrino astronomy in the high-energy neutrino domain and motivate the detector Upgrade discussed in subsection 2.8.

2.7 Optical properties of South Pole Glacial Ice

The detection medium of IceCube is the ancient glacial ice sheet of the Antarctic plateau. It is instrumented at a depth between 1450 m and 2450 m below the surface [1]. A

precise understanding of the optical properties of the ice is essential for every aspect of the detector simulation and event reconstruction. The number of detected photons, the arrival time distribution and the inferred direction, as well as the energy of the initial particle all depend on how light propagates from the interaction vertex to the DOMs [33].

At the depth of the instrumentation of IceCube, the dominant scatters are not air bubbles in the ice, which collapse under the overburden pressure of roughly 300 bar to form optically neutral air-clathrate hydrates below about 1400 m depth [34]. The insoluble impurities trapped in the ice during the formation from compressed snowfall are the main constituents to scattering processes [35]. It was identified, that the primary impurities trapped inside the ice are mineral dust grains, marine salt crystals and acid droplets [35], which together create a strongly forward-peaked scattering with an asymmetry parameter of $g \approx 0.94$ at the relevant wavelengths near 400 nm [33]. This indicates that scattering off these impurities deflects photons by only very small angles [33].

The resulting effective scattering length $\lambda_{\text{sca}}^{\text{eff}} = \lambda_{\text{sca}} / (1 - g)$ and the absorption length λ_{abs} are both strongly dependent on depth, ranging over more than an order of magnitude within the instrumented volume [33]. In the clearest regions of the ice, λ_{abs} reaches several hundred metres at 400 nm, while in dustier layers near the prominent dust peak, the point of highest dust concentration, around 2000 m depth, both lengths drop to only tens of metres [33].

The depth dependence of the optical properties directly reflects the climatological history of the ice sheet [36]. The layers of increased dust concentration, deposited during episodes of higher atmospheric dust transport, were compressed into the ice over hundreds of thousands of years [37]. These layers are not perfectly horizontal, as the underlying structure of the bedrock below causes them to tilt by up to 60 m in depth across the ~ 1 km horizontal extent of the detector [36]. Furthermore, the ice flows in the direction of approximately grid north-west at a rate of about 10 m/year, inducing a macroscopic optical anisotropy in which the light yield recorded by modules varies significantly depending on the azimuthal orientation relative to the flow axis [36]. This anisotropy is understood to come from birefringent light propagation through the polycrystalline ice microstructure, where millimetre-scale ice crystals develop a preferred orientation induced by the flow [36]. The initial mapping of the ice stratigraphy was done by the dust logger, which was utilized during the deployment of the initial strings [3]. Further in situ mapping of the dust stratigraphy is one of the primary objectives of the LOMlogger, which was co-deployed during the IceCube Upgrade and which will be further discussed in section 5.

The quantitative description of the South Pole ice is encoded in the SPICE (South Pole Ice) models, which are derived from global fits to the recorded in situ LED Flasher calibration data [33]. As mentioned in subsection 2.5, each of the 5160 DOMs is outfitted with a Flasher board with 12 LEDs [1], that can conduct calibration runs in which individual DOMs emit light while all neighbours record the timing and the intensity [1]. From this scattering and absorption coefficients in 10 m deep depth bins can be deduced [33]. The impact of improved ice modelling on physics analyses is demonstrated in [38]. The recent incorporation of the birefringence and ice layer undulations into the shower reconstruction model yields a median angular resolution for cascade events that is more than a factor of three better than a reconstruction based on a less detailed,

homogeneous ice model, as shown in Figure 9. The most significant gain arises from the inclusion of birefringence, underlining that an accurate microscopic description of the polycrystalline ice structure is essential for high-quality event reconstruction [38].

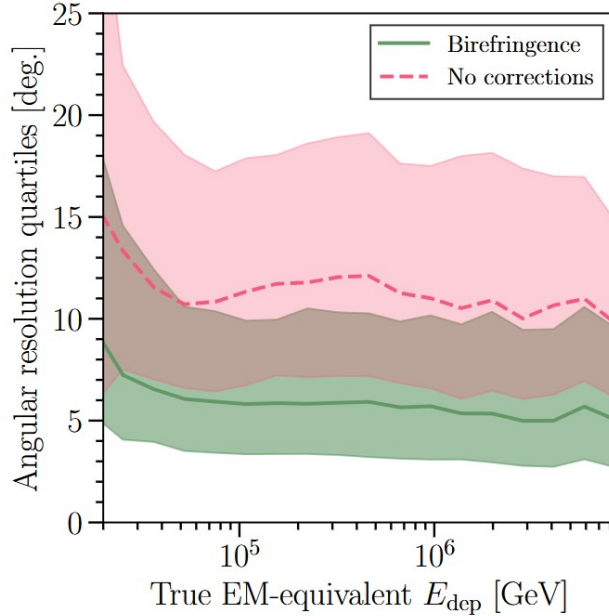


Figure 9: Angular resolution quartiles for in-ice particle shower reconstruction as a function of true EM-equivalent deposited energy E_{dep} . The green band shows the reconstruction including birefringence effects derived from the SPICE-BFR ice model, while the pink dashed curve with its uncertainty band corresponds to a simplified reconstruction without ice corrections. Incorporating birefringence reduces the median angular resolution by more than a factor of three across the relevant energy range [38].

Residual uncertainties of the ice models directly translate into systematic uncertainties of the reconstructed neutrino energies and directions and therefore were one of the main motivations for the calibration performed in the IceCube Upgrade. The measurements conducted during the Upgrade will allow a refinement of the ice model at finer spatial resolution and wavelength range [5], therefore directly benefiting the physics analyses described in subsection 2.6.

2.8 The IceCube Upgrade

The overview of the IceCube Upgrade is taken from [5]. Building on the success of its predecessor AMANDA [39], the construction of IceCube demonstrated that a cubic-kilometre scale neutrino telescope could be realised at the South Pole. The discovery of astrophysical neutrinos by IceCube also revealed, the hidden potential of analysing the universe through high-energy neutrinos, at scales of PeV and higher [27]. However, IceCube also aims to detect neutrinos at lower energies, in order to better constrain parameters for neutrino oscillations. To achieve better detection of lower energy neutrinos a denser spacing between the strings is required. It was then decided to build the IceCube Upgrade, a densely instrumented extension at the centre of the

current detector, which aims to improve detection at lower energies and also provide new opportunities for calibration of the detector [5]. The IceCube Upgrade includes 5 new strings with hundreds of new optical modules as well as new devices for calibration. The position of the added strings and their general structure in reference to the IceCube detector can be seen in Figure 10.

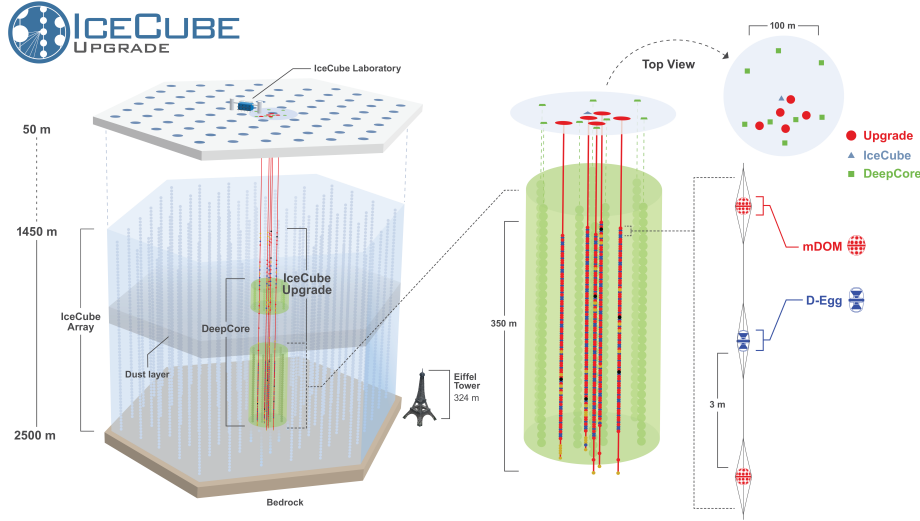


Figure 10: A schematic view of the IceCube detector with the IceCube Upgrade added in the centre (left) and a zoomed in view of the positioning, structure and some instrumentation of the IceCube upgrade as it was deployed (right) [40].

The IceCube Upgrade set out to accomplish several scientific goals. One goal is to reduce uncertainties in neutrino oscillation analysis by gaining more events at lower energies, enabled by the higher module density in the Upgrade region [5]. Another goal, that is more relevant for this work, is to improve the understanding of the Antarctic ice and its properties by utilizing the mentioned calibration devices in order to have a better calibration for future measurements, as well as being able to reevaluate already recorded data and reduce systematics [5]. The deployed devices include new optical modules like the multi-PMT optical module (mDOM) [7] and the dual optical sensors in an ellipsoid glass for Gen2 (D-Egg) [8] and also devices for optical calibration of the ice, like the POCAM [41], the Sweden Camera [42] and the LOMlogger [12]. The LOMlogger, which is of particular relevance to this work, will be discussed further in section 5.

3 DOM-housing Photoluminescence and the Neutron Echo

The impact of the glacial ice and its impurities on photon propagation as discussed in subsection 2.7, represents one of the main sources of systematic uncertainties in IceCube event reconstruction. However, the ice is not the only medium through which the photons travel through before being detected. Before reaching the PMTs, every photon also passes through the borosilicate glass housing of the optical module. In this glass photoluminescence occurs, which adds a delayed background signal to the measured arrival time distribution.

As discussed in subsection 2.6, distinguishing ν_e from ν_τ charged-current interactions is challenging, since both produce cascade-like topologies in the detector that are difficult to separate on an event-by-event basis. The so-called Neutron Echo signal, introduced in subsection 3.1, offers a statistical handle on this separation and is therefore of considerable interest for astrophysical flavour ratio measurements [4]. Accurately characterising it requires, however, that competing delayed signals on the same timescale are well understood.

The photoluminescence from the inside of the DOM is particularly relevant for analyses utilising the Neutron Echo signal, as it occurs on a comparable time scale and could be a significant background to its signature. Crucially, the magnitude of the photoluminescence signal depends directly on the light source. The built in LED Flashers shine their light out of the DOM housing and only a small fraction of the initial Flasher light reaches the PMT, whereas Cherenkov photons from a nearby interaction headed towards the DOM presumably illuminate the glass less effectively. It is therefore hypothesised that the ratio of photoluminescence-induced light to initial source light is significantly larger for the LED Flasher illumination than for Cherenkov events [43]. Quantifying this difference through ray-tracing simulation is the central goal of the study presented in this chapter.

The work presented in this chapter was carried out in the context of the PhD research of K. Dutta and builds upon the work described in [4].

3.1 The Neutron Echo

Neutrino events are detected indirectly via Cherenkov radiation, which is captured by PMTs housed within the DOM spheres. When a neutrino interacts via a neutral-current (NC) or charged-current (CC) interaction (see subsection 2.1) within the glacial ice, the hadronic component of the resulting shower can initiate nuclear fragmentation [4]. The resulting free neutrons are subsequently thermalized and captured by hydrogen nuclei [4], producing deuterium D and releasing a gamma ray γ :

$$n + p \rightarrow D + \gamma \tag{6}$$

The emitted 2.2 MeV photon then produces electrons via Compton scattering [4]. These Compton electrons then travel through the ice and induce Cherenkov radiation, which is commonly referred to as the Neutron Echo signal [4]. The lifetime of the neutron capture in ice is about 217 μs [4], which is about the delay of the Neutron Echo relative to the initial emission of the Cherenkov light [4].

The Neutron Echo can be used to determine the hadronic content of the initial event, which in turn indicates what the underlying interaction was. This enables a better

distinction between ν_e and ν_τ events, as the two different interactions produce hadronic showers of different intensities. The particle showers from CC of ν_e have a smaller hadronic component, compared to the showers caused by ν_τ , therefore the amount of neutrons and the intensity of the Neutron Echo differs. This difference makes it possible to distinguish more easily between the flavours of the initial events. Specifically distinguishing between ν_e and ν_τ events remains challenging for IceCube, because the spatial resolution is insufficient to distinguish the shower signatures, which makes the Neutron Echo a valuable asset for the future of event analysis. Using the Neutron Echo for the analysis of events, the flavour separation can be improved by up to a factor of 9 [4], when comparing to conventional techniques. However, Figure 11 reveals that the time distribution of delayed photons in HESE data differs from that measured with in-situ flashers, suggesting the presence of an additional background contribution on the same timescale as the Neutron Echo signal [4].

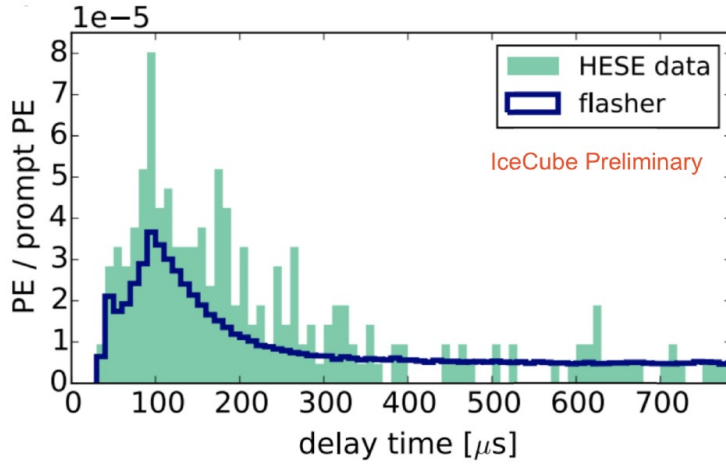


Figure 11: A time distribution of delayed photons measured by a DOM from 1250 high-energy starting events (HESE), that were recorded between 2015 and 2019 shown as the green histogram bin and flasher run data from two in-situ DOMs. The excess of delayed photons in the HESE data relative to the flasher signal motivates the investigation of additional background contributions within the Neutron Echo time window, such as photoluminescence from the pressure vessel glass [4].

3.2 Photoluminescence inside the DOM Glass Housing

Photoluminescence is a process through which a photon is absorbed in a material and subsequently a photon is re-emitted at a longer wavelength [44]. The absorbed photon excites an electron from its ground state to a high vibrational level of an excited electronic state, from which it rapidly relaxes to the lowest vibrational level of that excited state through non-radiative processes, losing energy to the surrounding medium. After that the electron transitions back to its ground state and emits a photon, which carries less energy than the photon that was absorbed [44]. This wavelength shift is known as the Stokes shift [44].

The timescale at which the re-emission occurs is dictated by the nature of the electronic transition. If the excited state has the same spin multiplicity as the ground state

(an allowed transition), re-emission occurs on a nanosecond timescale and is referred to as fluorescence [44]. If, however, the electron undergoes intersystem crossing into a triplet excited state, the subsequent transition back to the singlet ground state is spin-forbidden, significantly prolonging the excited-state lifetime [44]. This delayed re-emission, occurring on timescales ranging from microseconds to seconds, is classified as phosphorescence [44].

This effect also occurs in the borosilicate glass of the DOMs [4]. The intrinsic defects and impurity centres within the glass, such as transition metal ions, absorb photons, from the LED Flashers or Cherenkov events, and become excited to metastable states, subsequently re-emitting photons over prolonged timescales on the order of the neutron capture lifetime [4]. This delayed re-emission is characterised by a late exponential tail with a lifetime of approximately 194 μs [4]. This occurs on a similar timescale as the Neutron Echo and overlaps with the Neutron capture lifetime of 217 μs , as both are detected by the same PMT inside the housing [4]. As a result, the timing distributions of photoluminescence and the Neutron Echo are difficult to distinguish, making the luminescence in the DOM glass housing a potentially significant background that must be characterised carefully.

3.3 Simulation design and setup

In order to analyse the effect the photoluminescence inside the housing of the DOM has on the measurement of the Neutron Echo, a geometric model of the DOM was constructed. It was constructed within the non-sequential ray tracing software Zemax OpticStudio [45]. The simulation was designed to compare the two scenarios: Cherenkov light from a neutrino interaction in the ice, which enters the glass housing and induces photoluminescence, and the built in LED Flashers also inducing luminescence in the same glass. Since the flashers are used for in-ice calibration runs that provide the reference measurement of the delayed light background, it is essential to determine whether the luminescence they induce is representative of that produced during physics events.

The model that was used for optical simulation can be seen in Figure 12.

The outermost component (1) is a large cubic volume of ice, which accounts for the optical properties of the surrounding medium. The DOM itself is enclosed inside a spherical shell detector (2), which serves to verify the total optical power emitted in each simulation run. Next is the DOM glass housing, which is modelled as a borosilicate shell (3) with an inner radius 152.4 mm and outer radius 165.0 mm, so a glass thickness of 12.6 mm, which corresponds to the real dimensions of the IceCube DOM housing. Inside the glass shell, the RTV gel (4) is included to correctly account for the optical coupling between the glass and the PMT, in particular the reduced reflection at the interface [1]. The PMT photocathode is represented by an absorbing sphere segment (5) with a radius of 136.7 mm and a height of approximately 70 mm, placed at the bottom of the inner volume. Finally, an absorbing circular plate (6) is mounted slightly below the centre of the glass shell. This is necessary, because detector surface objects in Zemax register incident rays from both sides, whereas a real PMT is only able to detect them from the front.

The simulation contains three different configurations of light sources: a single LED Flasher in the horizontal position, a single LED Flasher in the tilted position, and a

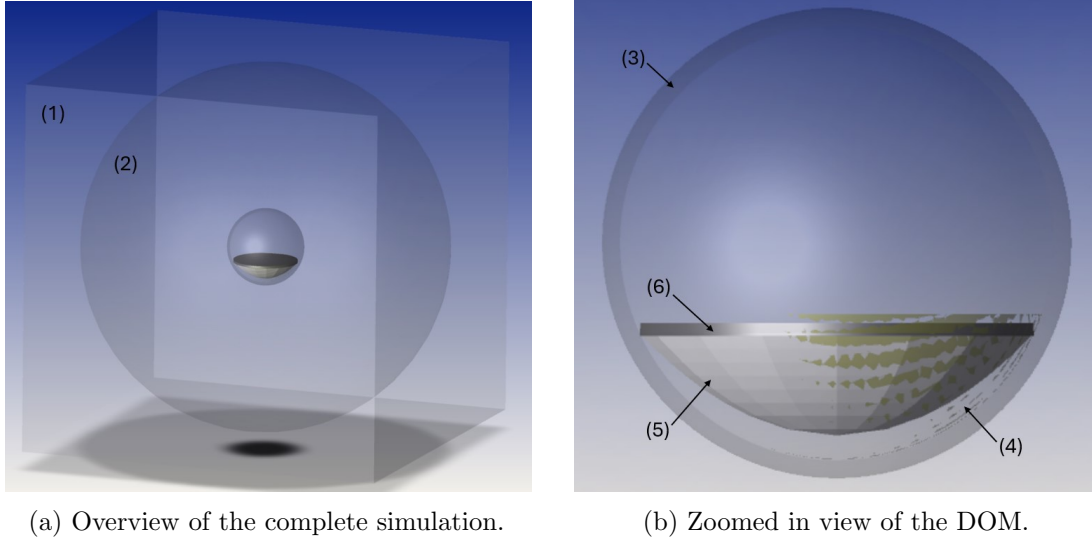


Figure 12: **In (a):** (1): An outer cube of ice, to account for the surroundings of the DOM, (2): A spherical shell detector surface around the DOM to verify the total intensity in each run. **In (b):** (3): The spherical borosilicate shell of the DOM, (4): RTV gel connecting the outer glass shell to the PMT, (5): The PMT modelled as an absorbing sphere segment, which functions as a detector, (6): An absorptive plate connected to the PMT from above, to remove signal coming from the top of the PMT detector.

Cherenkov event positioned directly below the PMT. The two LED Flasher sources were modelled as Gaussian beams using Zemax *Source Diode* objects, which parametrise the beam profile by separate horizontal and vertical divergence angles. The Cherenkov source was modelled as a *Source Ellipse* object with equal half-widths of 100 mm in x and y , forming a circular emitter positioned directly below the PMT at the bottom of the DOM. The source faces upward, illuminating the inner surface of the glass sphere from below with a Lambertian distribution, in which the emitted intensity follows $I(\theta) = I_0 \cdot \cos \theta$, where θ is the angle from the surface normal, such that most light is emitted perpendicular to the source surface [46]. This approximates the geometry of a Cherenkov event occurring beneath the DOM.

The positioning of the light sources can be seen in Figure 13. The horizontal LED is placed at the coordinates (11.8 mm, 0.0 mm, 7.2 mm) relative to the centre of the glass housing. It emits light at an angle of 10.7° relative to the horizontal of the glass sphere, so that after refraction at the glass surface the resulting beam is horizontal. The tilted LED is placed at the coordinates (11.6 mm, 0.0 mm, 8.8 mm) relative to the centre of the glass housing, so a little bit above the horizontal Flasher. It emits light at an angle of 51.6° relative to the horizontal of the glass sphere, so that after refraction at the glass surface the resulting beam is at about on angle of 48.0° , relative to the horizontal plane. The position and the emission angle were taken from [1] and [47].

The photoluminescence was modelled as a bulk wavelength-shifting property of the glass material, discretely shifting the initially incoming 400 nm light to 600 nm. This is a significant simplification, as the spectrum for luminescence is not discrete and peaks in the UV region around 370 nm [4]. This simplification is performed in order to make

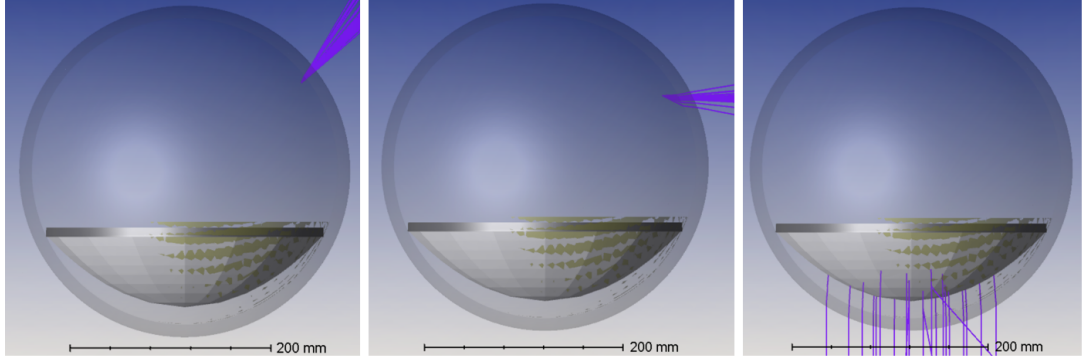


Figure 13: Visualisation of the positioning of the different light sources inside the simulation with a small number of layout rays. The position of the tilted flasher (left), the horizontal Flasher (centre) and the Cherenkov event (right) can be seen. The behaviour of the layout rays can deviate from the behaviour of the simulated rays.

the ratio comparison easier in the simulation and should not affect the final ratios. Additionally, as the simulation includes a wavelength shift, the Stokes shift has to be accounted for. As mentioned previously in subsection 3.2, when a photon is absorbed inside a material, the absorbing metal impurity site can then re-emit a photon of a longer wavelength. Between absorption and emission, energetic losses occur through vibrational and thermal processes, therefore the re-emitted light has less energy / a larger wavelength [44]. The difference in energy can be calculated using the formula for the energy of light $E = \frac{h \cdot c}{\lambda}$ and determining their ratio [48]. For the scenario in the used simulation the ratio can be calculated exactly:

$$\frac{E_{600\text{nm}}}{E_{400\text{nm}}} = \frac{\lambda_{400\text{nm}}}{\lambda_{600\text{nm}}} = \frac{400}{600} = \frac{2}{3} \quad (7)$$

Since the wavelength shift from 400 nm to 600 nm reduces the energy per photon by a factor of $\frac{2}{3}$ the recorded intensity of the wavelength-shifted light was corrected by a factor of 1.5 to obtain the equivalent 400 nm intensity, enabling a direct comparison between the prompt and luminescence-induced signals. This calculation has to be performed, because the detector results in this Zemax simulation display the energy rather than the photon counts.

The initial power for all configurations was 1 W, the cases where only light of 600 nm was recorded, were corrected by a factor of 1.5 to account for the Stokes shift. Each ray propagating through the glass has a certain probability of being wavelength shifted. This probability is determined by the parameter of the mean free path length λ_{mean} , which was varied for different runs between 1 mm and 120 000 mm. As the mean free path length for borosilicate is not explicitly constrained, the simulation was run for this range of different mean path lengths λ_{mean} . On one hand, a shorter mean path length means, that the amount of photoluminescence increases and with higher photon counts the relative uncertainty of the counts and therefore the ratio decreases. On the other hand, a larger mean free path is more accurate to the real physical mean free path. That is, because the transmittance for borosilicate N-BK7 at 400 nm is about 99,7% [49], which is equivalent to an absorption length of several meters, according to the Beer-Lambert law [48]. Upon wavelength shift, the ray is emitted again isotropically, which effectively

simulates the photoluminescence inside the glass. The volume scattering was modelled using the Zemax built-in scattering model `bulk_samp_1.DLL`, with a scattering angle of 360° and a transmission of 1.

The PMT is modelled as a detector surface and recorded both wavelengths of the light. As a way of filtering, which wavelength arrived at the PMT, the RTV gel volume was set to be transmissive or absorptive for the specific wavelengths, allowing the intensity of each contribution to be determined independently. From these results, the ratio of wavelength-shifted to unshifted light incident on the PMT can be obtained, which serves as a measure of the relative photoluminescence contribution.

3.4 Results and Discussion

The described simulation was run for all the three light configurations: the tilted Flasher LED, the horizontal Flasher LED and the Cherenkov event. For each configuration the mean path length inside the glass was varied, using mean path lengths of 1 mm, 12 mm, 1200 mm, 12 000 mm and 120 000 mm. The mean free path was varied as $\lambda_{mean} = 1.2 \times 10^x$ in units of the thickness of the glass housing, it being about 12 mm. For each combination of light configuration and path length the different wavelengths were recorded individually. For reference measurements of the different light setups were taken, with no luminescence and once with the glass housing having a 100% transmittance for 400 nm light and once with a transmittance that is equal to that of N-BK7.

The number of simulated rays was set to 10^6 unless stated otherwise. This number was chosen, to achieve enough statistics for a significant result, while maintaining a reasonable simulation time. The analysis proceeds in two steps: first, the ratio of photoluminescence-induced to unshifted light is determined for each source geometry and mean path length, and second, these ratios are compared between the two light sources to estimate the relative luminescence contribution of the LED flashers with respect to a Cherenkov event.

It is expected that the flasher-induced luminescence ratio will exceed the Cherenkov-induced ratio by several orders of magnitude ($10^2 - 10^3$) [43]. This is because the Flashers are shining away from the DOM and the initial light reaches the DOM only through some reflection, the initial Cherenkov light is travelling directly at the PMT and a large part of its initial light should also reach it. It is important to note, that in the real physics case, not all Cherenkov events happen right below the DOM, but the geometry considered here is sufficiently representative to establish an order-of-magnitude estimate of the effect.

Each individual measurement resulted in a pair of detector hit maps with the total deposited power, one for the surrounding spherical shell and one for the PMT at the bottom of the DOM. The spherical shell detector verified, whether the total power was as expected, while the sphere segment detector of the PMT recorded the relevant physics events. Furthermore, the detector hit maps provide a qualitative visualisation of the ray distribution in the simulation. The shell detector hit map shows the radiant intensity on the mentioned outer spherical detector shell as a full 4π projection, giving an overview of how light exits the DOM in all directions. The PMT hit map shows the incoherent irradiance on the PMT surface in Cartesian coordinates, where the y -axis corresponds to the vertical direction and the top edge of the PMT faces toward the

Flasher boards. As an example the detector maps of some simulation runs are shown: the horizontal LED Flasher with no volume physics in Figure 14 and the horizontal LED Flasher with volume physics and a mean free path of 1 mm in Figure 15.

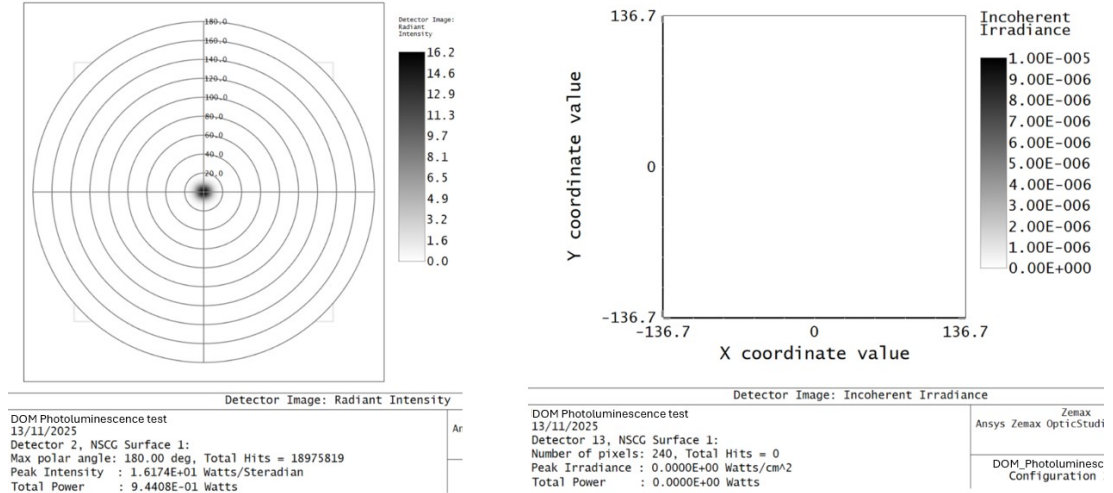


Figure 14: Detector hit maps for the horizontal LED Flasher with no photoluminescence. The detector hit maps of the outer shell detector (left) and the PMT sphere segment detector (right). Below the maps the amount of detected hits and the total power recorded are displayed. The PMT detector not having any hits is expected.

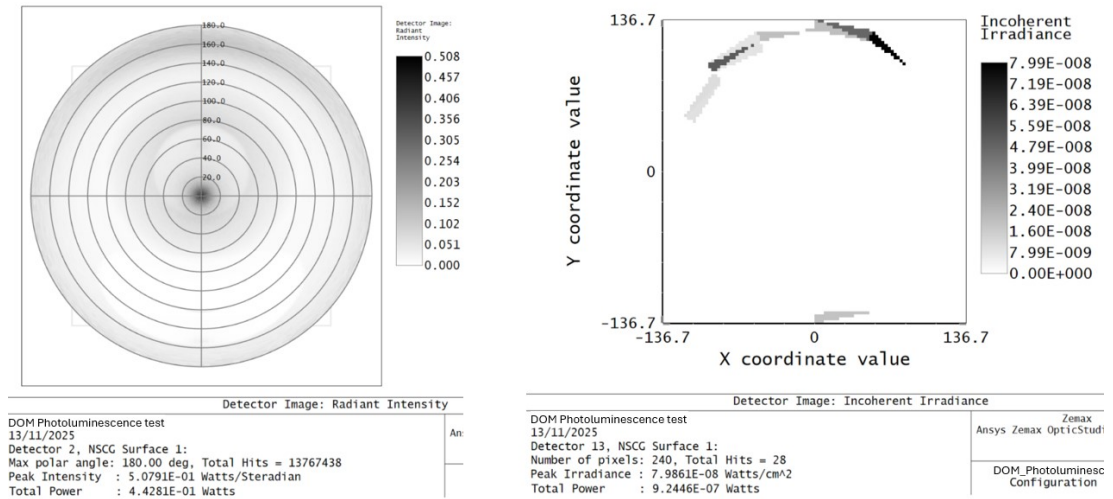


Figure 15: Detector hit maps for the horizontal LED Flasher with photoluminescence with a mean path length of 1 mm. The detector hit maps of the outer shell detector (left) and the PMT sphere segment detector (right). Below the maps the amount of detected hits and the total power recorded are displayed.

In these two mentioned examples several important things can be observed. The results for the configuration with photoluminescence, with a large number of detector hits the hit pattern on the PMT is clearly visible, and the results for the configuration without photoluminescence, with very few hits, where the PMT receives almost no light. These

cases show the large dynamic range of photoluminescence across the simulated mean free paths, and confirm that the simulation correctly reproduces the expected geometric behaviour. In particular, the horizontal LED Flasher case, with no photoluminescence, produces no direct PMT signal and the hits are produced only from photoluminescence emission in the glass. The final results for all different mean path lengths and the references for no volume physics can be seen in Table 1.

	Hor. Flasher	Tilt. Flasher	Cherenkov
<i>Reference (no luminescence, λ_{mean}-independent)</i>			
Only 400 nm [W]	0	6.6485×10^{-6}	8.9236×10^{-1}
Normal N-BK7 [W]	0	6.5234×10^{-6}	8.8740×10^{-1}
$\lambda_{mean} = 1 \text{ mm}$			
Only 600 nm [W]	$(1.97 \pm 0.31) \times 10^{-6}$	$(3.35 \pm 0.40) \times 10^{-6}$	$(1.6448 \pm 0.0001) \times 10^{-1}$
Ratio 600 nm / N-BK7	—	0.514 ± 0.075	0.185 ± 0.036
Tilt. Flasher / Cheren. ratio		2.77 ± 0.67	
$\lambda_{mean} = 12 \text{ mm}$			
Only 600 nm [W]	$(8.47 \pm 0.21) \times 10^{-6}$	$(1.94 \pm 0.31) \times 10^{-6}$	$(1.1688 \pm 0.0001) \times 10^{-1}$
Ratio 600 nm / N-BK7	—	0.29 ± 0.15	0.132 ± 0.004
Tilt. Flasher / Cheren. ratio		2.25 ± 1.11	
$\lambda_{mean} = 1200 \text{ mm}$			
Only 600 nm [W]	$(2.97 \pm 1.21) \times 10^{-8}$	$(3.61 \pm 0.81) \times 10^{-8}$	$(2.107 \pm 0.002) \times 10^{-3}$
Ratio 600 nm / N-BK7	—	$(5.5 \pm 3.7) \times 10^{-3}$	$(2.374 \pm 0.099) \times 10^{-3}$
Tilt. Flasher / Cheren. ratio		2.33 ± 1.54	
$\lambda_{mean} = 12000 \text{ mm } (1 \times 10^9 \text{ rays})$			
Only 600 nm [W]	0	$(3.42 \pm 0.20) \times 10^{-9}$	$(2.1201 \pm 0.0002) \times 10^{-4}$
Ratio 600 nm / N-BK7	—	$(5.2 \pm 2.0) \times 10^{-4}$	$(2.389 \pm 0.068) \times 10^{-4}$
Tilt. Flasher / Cheren. ratio		2.19 ± 0.83	
$\lambda_{mean} = 120\,000 \text{ mm}$			
Only 600 nm [W]	0	$(2.4 \pm 1.7) \times 10^{-26}$	$(2.200 \pm 0.002) \times 10^{-5}$
Ratio 600 nm / N-BK7	—	$(3.7 \pm 3.3) \times 10^{-21}$	$(2.480 \pm 0.096) \times 10^{-5}$
Tilt. Flasher / Cheren. ratio		$(1.51 \pm 1.34) \times 10^{-16}$	

Table 1: Simulation results of the measured intensities at the detector for all scanned mean free paths. The 600 nm results have been corrected by a factor of 1.5 to account for the Stokes shift. The ratio of (Tilt. Flasher / Cherenkov) quantifies how much more photoluminescence the tilted flasher induces relative to its initial signal compared to the Cherenkov source.

The table displays the simulated optical power, that was recorded at the PMT for each light source configuration with five scanned mean free paths each. Additionally the ratio of the 600 nm (photoluminescence) power and the power recorded in the N-BK7 baseline is calculated as well as the ratio of these ratios between the tilted LED Flasher and the Cherenkov source. This final ratio is the central result of the simulation, because it

characterises how much photoluminescence the Flasher induces relative to its initial light compared to the Cherenkov event. The horizontal Flasher is not used for comparison, as the reference measurement provided no hits and therefore the ratio could not be calculated.

The shown results differ from the preliminary order-of-magnitude estimate, which suggested that the Flashers would induce photoluminescence at a rate roughly 10^2 – 10^3 times larger than that induced by Cherenkov light. That estimate was based on a simple geometric argument rather than a detailed calculation, and the simulation results can therefore be regarded as a more reliable indication of the true ratio. Instead the results only differ by approximately a factor of 2 across all simulated mean free paths ($\lambda_{mean} = 1$ mm to $\lambda_{mean} = 12000$ mm), except for $\lambda_{mean} = 120000$, where the hit statistics becomes very low and the signal from the tilted Flasher becomes effectively zero.

Several limitations of the simulation may nonetheless affect the quantitative results. First, in the simulation the DOM is modelled as a perfect sphere, which is not accurate for the real DOM. The real housing deviates from a perfect sphere specifically at the point where the two DOM hemispheres are joined during construction, which affects the internal reflection and the ray tracing compared to the real setting, but that would presumably only reduce the ratio. Second, the surrounding ice in the simulation was modelled without scattering, which affects the amount of light detected at the PMT, as non-wavelength-shifted light would arrive there at a higher rate. Third, the simulation does not account for the structure of a real Cherenkov event, with its more complex emission cone, and instead uses only a circular Lambertian source positioned directly below the PMT as an approximation.

These limitations suggest that the precise quantitative values may shift with a more realistic treatment, but the order of magnitude of the results is expected to be robust. Therefore, these results can be used as a reference when further investigating the effect. A more refined simulation incorporating accurate glass geometry, ice scattering, and a proper Cherenkov source model is left as an outlook for future work.

The simulation results demonstrate, that the photoluminescence in the DOM glass constitutes a potential background to the Neutron Echo signal. Under the assumed idealised geometric conditions of the presented simulation, the Flasher and the Cherenkov configurations produce a measurable photoluminescence signal at the PMT. It is important to note, that the scanned mean free paths are most likely still significantly shorter than the real value for the IceCube DOM glass. This means that in a real DOM the signal would be considerably weaker, than in the presented results. The ratio of ratios being close to unity nonetheless robustly suggests that the Flasher does not induce disproportionately more photoluminescence than a Cherenkov event. The exact value may change with a more realistic simulation, but the conclusion that the two sources produce photoluminescence of a comparable order of magnitude is expected to hold. This has direct implications for the interpretation of Flasher-based Neutron Echo background estimates, and warrants further investigation through more detailed simulations or direct experimental measurements of the DOM borosilicate glass.

4 DOM Flasher temperature calibration

The optical properties of the glacial ice at the South Pole are one of the most critical systematic uncertainties of the IceCube detector. As mentioned in subsection 2.7 the instrumented ice is not uniform and scattering and absorption lengths vary with the depth of the ice. The temperature of the ice also follows a depth-dependant gradient, ranging from -40°C at a depth of about 1600 m to -20°C at 2400 m and even warmer below [10]. The LED flasher systems included in the mDOM and D-Egg modules of the IceCube Upgrade, as mentioned in subsection 2.8, provide an in situ light source in order to investigate the optical properties. In order to achieve a proper calibration using that light source, the behaviour of the LEDs must be well tested across all temperatures, that are encountered inside the ice.

This chapter discusses the design and working principle of the flashers that are used in the mDOMs, reviews the existing calibration, which was done before deployment, and presents new laboratory measurements of the flasher behaviour as a function of temperature, following up on the room-temperature acceptance testing, that was done in [11], with explicit characterisation at colder temperatures ¹.

4.1 Flasher LEDs for calibration

The design and functionality of the mDOM flashers are adapted from [11] and [7]. The mDOM modules deployed in the IceCube Upgrade are equipped with 10 LED flashers each, which are designed to shine short, timed pulses of light into the ice for calibration of the ices optical properties. The mDOM flashers are different from the flashers used inside of the IceCube Gen1 DOM. A wavelength 405 nm has been chosen to approximate the typical wavelength of the Cherenkov photons in ice [11]. The design requirements for the LEDs specify an intensity range from 5×10^6 to 1×10^9 photons per pulse, with a pulse having a maximum width of 10 ns full-width half-maximum (FWHM) at maximum brightness.

A photo of a flasher LED and the mDOM can be seen in Figure 16. Every LED is operated via a Kapustinsky-type pulse driver [50], which is a specific circuit design that was chosen for its robustness and is easy to scale down in size. The main idea is simple: a small 1 nF capacitor is charged continuously in order to set a specific bias voltage and is then quickly discharged through the flasher LED, as soon as a trigger signal arrives. The quick discharge is achieved by a pair of RF transistors, which are configured as a thyristor-like switch, which conducts once triggered and switches off automatically once the capacitor is fully discharged. This allows the capacitor to discharge its stored charge by means of the LED within a couple of nanoseconds. The intensity of the light pulse is then controlled through adjusting the bias voltage via a 16-bit digital-to-analogue converter (DAC), where a higher voltage results in more stored charge in the capacitor and therefore a brighter light pulse. An optional 56 nH inductor is placed in parallel to the LED, in order to suppress the trailing edge of the discharge, to keep the pulse width within the specified 10 ns FWHM.

The mDOM features 10 LEDs, which are equally distributed on both hemispheres, with both hemispheres having five LED elements. Each LED element consists of an LED

¹Analysis code written by the author in the private repository `MA.Chubarov.ColdFlasher` on the ECAP Git instance (<https://git.ecap.work>), branch `main`. Available upon request.

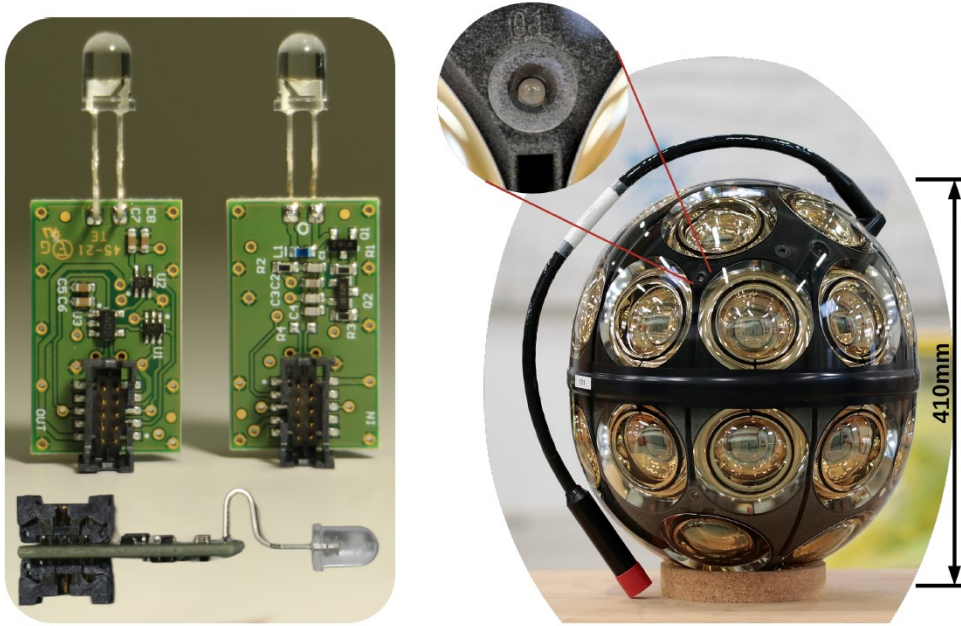


Figure 16: (Left): A flasher element consisting of a $25\text{ mm} \times 15\text{ mm}$ printed circuit board with an attached LED. Five such elements are connected in series via ribbon cables to form one daisy chain per hemisphere. (Right): A fully assembled mDOM with a diameter of 410 mm. The inset shows a close-up of one flasher LED behind its borosilicate glass window, embedded in the 3D-printed support structure between the PMTs [11].

attached to a 25 mm by 15 mm circuit board, which are in turn mounted on a 3D-printed support structure, that also holds the PMTs in place. These five LED elements are wired together in series via ribbon cables into a single daisy chain per hemisphere, which allows them to be controlled collectively through a shared bias voltage and trigger signal, while still being addressable individually. Of the five LEDs, four of them point outward at an angle of 29° and one points up almost vertically at an angle of 81° . The flasher LEDs of both hemispheres point in the same four horizontal directions, forming pairs that are 90° apart from each other. To ensure meaningful calibration data, each LED axis is required to point within a 5° solid angle of its nominal design direction, a specification that was verified during design validation [11]. Each LED is placed behind a 1.75 mm borosilicate glass window, which separates it from the optical gel filling the space between the support structure and the outer glass pressure vessel, as shown in Figure 16.

4.2 Calibration of the IceCube mDOM Flashers

The testing setup used for room-temperature calibration and the measurement procedure are adapted from [11]. As the light output of the LED with the connected Kapustinsky circuit is very sensitive to changes in the applied bias voltage and since every LED has slightly different characteristics due to manufacturing tolerances, each LED must be calibrated individually before deployment. The goal of that calibration is to determine the required bias voltage for each LED in order to achieve every desired output light

intensity in the specified dynamic range. This is very important as the LED-to-LED difference in intensity at a fixed bias voltage can reach almost up to 150 % at low intensities [11]. Choosing a single bias voltage for all LEDs does not ensure consistent operation.

In order to perform a calibration for all LEDs a dedicated testing setup is necessary, whose components are displayed in Figure 17. Each LED element is placed facing a Hamamatsu S2281 photodiode, which records the per-pulse photon yield during testing. The relative detection efficiency of all photodiodes with the preamplifier pairs was compared by doing runs with the same flasher element, and all channels were found to be within 2 % of the average efficiency, which ensures a consistent response of the photodiodes across all LED test runs. The photocurrent from the photodiodes is read out through a custom trans-impedance amplifier, which is mounted directly on the photodiode. The amplified voltages are digitised by a central readout board. Inside the testing setup each photodiode is enclosed inside a small light-tight plastic case, where an LED can be placed right in front of the photodiode. Five such photodiode modules are then placed inside a dark box, which makes it possible to test a full five-element daisy chain in a single test run, which is shown on the right side of Figure 17.

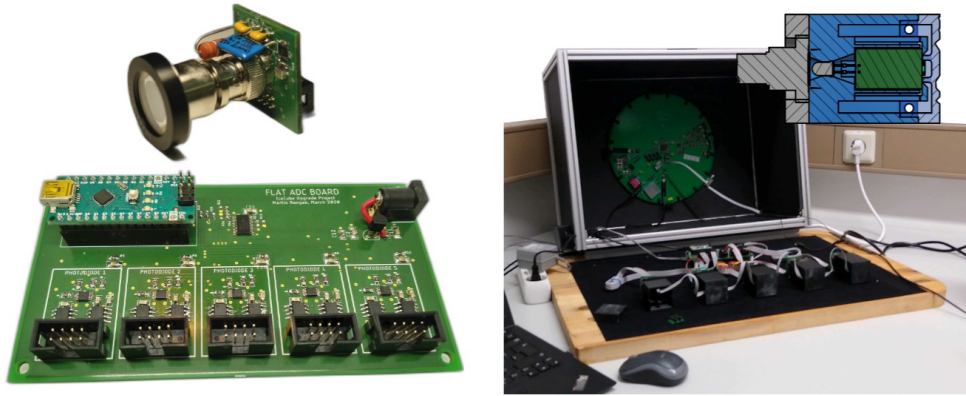


Figure 17: (Left): At the top a Hamamatsu S2281 photodiode, which is connected to a custom trans-impedance is displayed and underneath the custom circuit board, that is used for the digitisation of the voltages coming from the amplifier is shown. (Right): The custom-made dark box with the testing setup for the acceptance testing for the mDOM LED daisy chains. In the top right a schematic depiction of the photodiode module with an inserted LED can be seen [11].

During testing a threshold scan is performed for each LED, which starts at the maximum bias voltage of 15 V and is then reduced in steps of 1.8 V. Throughout the testing the per-pulse photon yield is recorded for each voltage. At each bias voltage, the photocurrent is measured a minimum of three times at different pulse repetition frequencies, starting at 100 Hz and then two additional frequencies are selected to scan the full dynamic range of the photodiode system, while avoiding saturation. The per-pulse photon count is then the slope of the linear fit of the measured photons per second as a function of the different repetition frequencies. From the measurement two calibration constants are recorded for every LED: 1) The photon yield at maximum bias voltage and 2) the threshold voltage, which is defined as the voltage at which the LED output reaches

5×10^6 photons per pulse. The full measurement takes about 20 min per daisy chain. The threshold voltage is the most important quantity for cross-LED calibration. From the test runs it was evident, that the maximum intensities varied between LEDs, but the shape of the bias voltage/intensity curve was more consistent across all functional LEDs after being shifted by its threshold voltage. After this threshold correction the relative standard deviation in the intensity is reduced to about 7 percent across all LEDs and the complete dynamic range [11]. This parametrization result is well within the requirement of $\pm 50\%$ at any target value.

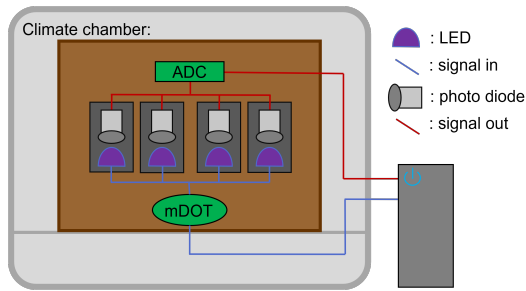
However, the final acceptance testing campaign described above was done exclusively at room temperature, which was also acknowledged in [11], where an expectation for the behaviour at the in situ temperatures in the instrumented ice was made from a verification measurement done for a single LED [51]. As mentioned previously the temperatures at the depth of the instrumentation range from -40°C to -20°C [10]. It is expected that the output of the LED flashers will be reduced by roughly 40 % at the maximum bias voltage, as it is known LED output is generally temperature dependant. It has been observed, when cooling LEDs from room temperature to -40°C . This means, that a further correction of the bias-voltage that is dependant on the temperature is required. A functional parametrisation for this has been proposed, but a systematic characterisation of the brightness of the LED flashers as a function of the temperature for the whole operational range, has yet to be done. The measurements described in the following section subsection 4.3 are a direct follow up to the described work and aims to find a characterisation of the mDOM flasher LEDs at the temperatures that are encountered inside the deployed array.

4.3 Measurement of the Cold Flashers

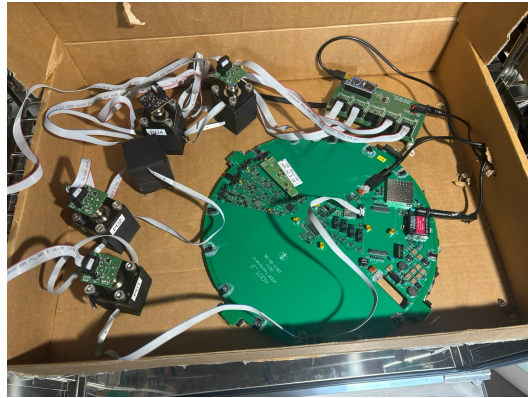
In order to record the intensity of the LED flashers at different temperatures the testing setup requires several changes from the original setup, which was described in subsection 4.2. The main change was that the whole setup was placed inside a climate chamber. The climate chamber that was used was the ESPEC ARG-0220, which has a temperature uncertainty of $\pm 0.3^\circ\text{C}$ [52].

The original setup was designed for operation at room temperature and some modifications were required, before the setup could be used inside the climate chamber. The dark box, which housed the five photodiode modules, was removed entirely, as the climate chamber itself is light-tight and the size of the box was incompatible with the interior space of the climate chamber. The analogue-to-digital converter (ADC) board and the mDOT, which handle the signal digitization from the photodiodes and the trigger distribution to the LEDs respectively, remained inside the climate chamber during operation. Only the final readout connection and the overall communication with the outside computer were routed through a pluggable opening in the side of the climate chamber to an external computer. The core measurement procedure is the same as described in subsection 4.2, with added parallel control of the climate chamber during the test runs. The general approach of placing the photodiode inside the climate chamber alongside the LED, with only the readout connection routed outside, follows the methodology established in [53], where the temperature independence of the Hamamatsu S2281 photodiode was first confirmed under comparable conditions.

A schematic overview and a photo of the modified testing setup are shown in Figure 18.



(a) Schematic overview of the modified testing setup inside the climate chamber. The four photodiode modules are housed in a cardboard box, with the ADC board mDOT also placed in the box. Only the final readout connection (red) and trigger signal (blue) leave the chamber to the external computer.



(b) Photograph of the setup inside the climate chamber, showing the four photodiode modules, the mDOM mainboard and the ADC readout board placed inside the cardboard box on the chamber grating.

Figure 18: A schematic and a photo of the modified testing setup used for the cold flasher measurements.

Four photodiode modules were placed inside a cardboard box and were elevated on a grating inside the climate chamber to allow for better air circulation around the setup and to align it with the height of the chamber opening. The ADC board and the mDOT were also placed inside the box and connected to the photodiode modules. The computer outside the climate chamber connects to the mDOT through the opening of the climate chamber and sends the programmed trigger signals to the mDOT. The mDOT, which is placed inside the cardboard box is connected to the LED daisy chain and transmits the trigger signal to it. The LEDs from the daisy chain are connected to a photodiode module with a respective photodiode attached to it. Only four photodiodes were used, due to a non-functional channel on the ADC board, meaning one LED per daisy chain was not measured. The analogue signal from the photodiodes was then digitised by the ADC and sent to the external computer.

In order to verify that the observed temperature dependence of the measured light output is of the LEDs and its driving circuit, rather than the temperature dependence of the photodiodes, a second complementary setup was constructed shown schematically in Figure 19, with the light-tightening measures illustrated in Figure 20.

In this configuration, the photodiode is placed outside of the climate chamber, and the light from a single LED is guided to it via a glass fibre, so that the photodiode was held at room temperature, while the LED cycled through the temperatures. This setup has two variations: one where the photodiode is outside and one where the photodiode is inside, but still connected to the LED through the glass fibre. This is done to have a direct comparison, as the measurement without a glass fibre returns a significantly lower light intensity. Only one module could be used during measurements with this configuration, due to the availability of one glass fibre. The rest of the measurement setup remained the same. This measurement had to be conducted in separate dedicated runs, requiring reconfiguration of the setup. The photodiode outside the chamber was enclosed in a small darkened box, which was additionally wrapped in a heavy black

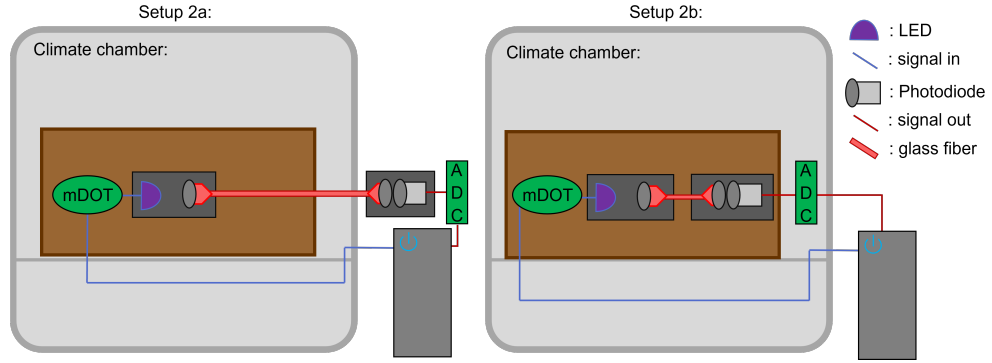


Figure 19: Schematic overview of the two complementary setup configurations. In Setup 2a the photodiode and ADC are placed outside the climate chamber, with the light guided from the LED through a glass fibre through the chamber wall. In Setup 2b the photodiode and ADC remain inside the chamber, again connected to the LED via a glass fibre. In both cases the mDOT receives the trigger signal from the external computer.



(a) The light-tight cardboard box housing the photodiode module, sealed with black tape. The ribbon cable and glass fibre exit through a small opening in the side.

(b) The sealed box additionally covered with a black blanket to suppress any remaining ambient light leakage during measurements outside the climate chamber.

Figure 20: Photographs of the light-tightening measures applied to the external photodiode module in the complementary fibre-coupled setup.

blanket to achieve a light-tight setup outside the climate chamber.

The measurements were performed at temperatures of 20°C , 5°C , -10°C , -25°C and -40°C . As soon as the temperature setting was set, the script checked every 15 seconds whether the temperature in the climate chamber has reached the target temperature $\pm 0.5^{\circ}\text{C}$. When the target temperature in the chamber was reached, the voltage scan procedure was done for 14 voltages starting from 29000 DAC counts to 65000 DAC counts, which is about the voltage range of the LED. The scan procedure itself is the

same that was described in subsection 4.2, recording the per-pulse photon yield at every bias voltage for each LED.

For the measurement runs where it was tested, whether the diode being inside or outside of the climate chamber has an impact on the LED flasher measurement, two runs were done per LED and photodiode, once with the photodiode inside and once outside. Other than that, the measurement remained the same.

4.4 Results and Discussion

4.4.1 Temperature Dependence of the Photodiode Output

As a prerequisite for interpreting the temperature-dependent light intensity measurements of the LEDs, the temperature dependence of the photodiode response itself must be established. It was previously described in subsection 4.3, that two separate measurement campaigns were conducted: one with the photodiode inside the climate chamber alongside the LED, and one with the photodiode outside the chamber. In both settings the LED light was transferred to the diodes via a glass fibre. This approach allows direct validation of whether the photodiode exhibits measurable temperature sensitivity. The results of the measurements with four different LED and photodiode pairs can be seen in Figure 21.

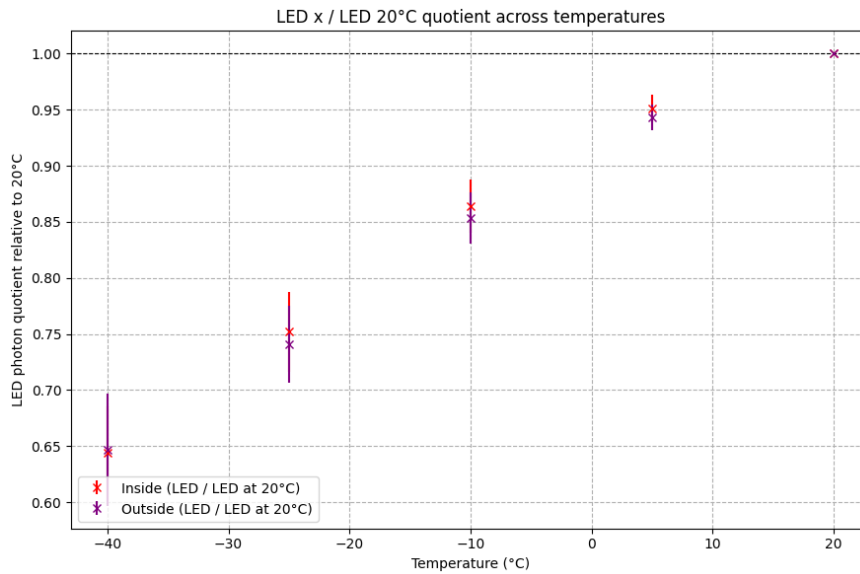


Figure 21: Per-pulse photon yield relative to the measurement at 20 °C as a function of temperature, measured at a DAC value of 65000 for two complementary configurations: with the photodiode placed inside the climate chamber (red) and outside the chamber with the LED light guided via a glass fibre (purple). Both configurations are individually normalised to their respective values at 20 °C.

Both the configurations follow the same trend across the full range of measured temperatures from $-40\text{ }^{\circ}\text{C}$ to $20\text{ }^{\circ}\text{C}$, with the per-photon yield decreasing monotonically to about 65 % of the room-temperature value at $-40\text{ }^{\circ}\text{C}$, which is expected. The two configurations agree closely at all temperature steps, with a mean absolute deviation between them of $0.80\% \pm 0.54\%$ across the measured temperature range, and no

systematic offset visible between the inside and outside measurements. This close agreement between the two configurations confirms that the Hamamatsu S2281 photodiodes do not have a measurable temperature dependence and therefore do not affect the light output measurement of the LEDs at different temperatures. The results found here are consistent with the findings reported in [53]. All subsequent measurements were therefore performed with the photodiode inside of the chamber, using the same setup that was described in subsection 4.3 inside the climate chamber.

4.4.2 Temperature Dependence of the LED Intensity

The photon yield was measured for 20 LEDs at temperatures of 20 °C, 5 °C, −10 °C, −25 °C and −40 °C, covering the full range of temperatures encountered by the deployed modules in the ice, while also providing the trend and a reference at room temperature. At each temperature step, the standard procedure described in subsection 4.2 was performed with the addition of temperature control between each run. Figure 22 shows the photons per pulse as a function of the bias voltage for a representative LED across all five temperature steps.

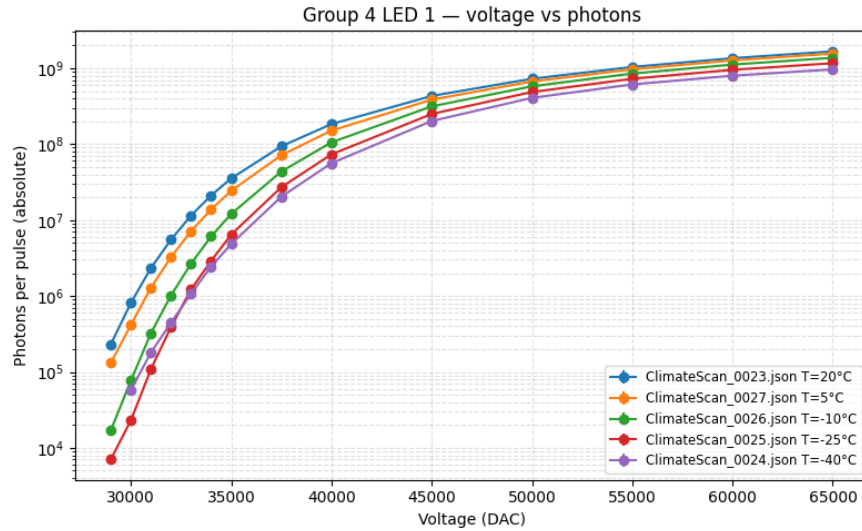


Figure 22: Per-pulse photon yield as a function of bias voltage for a representative LED at all five measurement temperatures, ranging from 20 °C (blue) to −40 °C (purple). A systematic reduction in photon yield is observed at lower temperatures across the full bias voltage range, with the temperature-dependent separation remaining visible up to the maximum DAC value of 65000.

A clear systematic reduction in per-pulse photon yield is observed at lower temperatures for any fixed bias voltage above the threshold. The overall shape of the intensity-versus-bias-voltage curve is preserved across all temperature steps, with cooling manifesting as a downward shift of the curves without altering the functional form of the relation. The separation between temperature steps remains visible across the full bias voltage range including at the maximum DAC value 65000. At low bias voltages, mostly below the effective threshold of the LED, the −40 °C curve occasionally crosses the −25 °C curve or in single cases the −10 °C curve. This behaviour could occur due to statistical

noise in the photon count, where the noise in the photon count is dominating the small temperature-dependent signal, as the photon yield is low and the LED response is sensitive to small fluctuations in bias voltage. Another reason could be that, when the measurement at -40°C started, the LEDs were not cooled down completely, therefore the first couple data points were recorded at a temperature higher than -40°C and as they reached the target temperature, the expected behaviour could be seen.

The observed temperature-dependent reduction in photon yield is substantial and systematic across the full bias voltage range. Table 2 shows the per-pulse photon yield at 20°C and -40°C for all measured DAC values, which reveals a non-uniformity in the temperature dependence.

DAC	Photons/pulse at 20°C	Photons/pulse at -40°C	Reduction (%)
29 000	1.129×10^6	1.863×10^5	83.5
30 000	3.255×10^6	5.586×10^5	82.8
31 000	7.731×10^6	1.235×10^6	84.0
32 000	1.563×10^7	2.578×10^6	83.5
33 000	2.796×10^7	5.048×10^6	81.9
34 000	4.537×10^7	9.218×10^6	79.7
35 000	6.824×10^7	1.534×10^7	77.5
37 500	1.487×10^8	4.718×10^7	68.3
40 000	2.594×10^8	1.054×10^8	59.4
45 000	5.414×10^8	2.968×10^8	45.2
50 000	8.678×10^8	5.378×10^8	38.0
55 000	1.212×10^9	7.797×10^8	35.6
60 000	1.560×10^9	1.005×10^9	35.6
65 000	1.906×10^9	1.211×10^9	36.5

Table 2: Per-pulse photon yield at 20°C and -40°C as a function of bias voltage (DAC). The reduction shows the percentage decrease in photon yield from room temperature to -40°C , demonstrating the non-uniform temperature dependence across the bias voltage range.

At low bias voltages (DAC 29000 to 34000), the reduction exceeds 80 %, declining toward higher voltages, until reaching 36.5 % at the maximum bias voltage. The average reduction across all measured DAC values is 63.7 %. This strong variation across the bias voltage range indicates that the effective threshold of the LED shifts significantly with temperature, motivating a detailed analysis of the threshold voltage behaviour presented in subsection 4.4.3. The measured 36.5 % reduction at maximum DAC aligns well with the approximated 40 % reduction previously predicted in [11].

4.4.3 Threshold Voltage Shift with Temperature

As the temperature decreases, a higher bias voltage is required to reach the same intensity of 5×10^6 photons per pulse. This manifests as an upward shift of the threshold voltage with decreasing temperature. To quantify its effect on the LED response, all intensity curves across all LEDs and temperatures are aligned horizontally by mapping each curve's 5×10^6 photon crossing point to a common reference voltage. If the functional

shape of the intensity curve is preserved across temperatures, the aligned curves should overlap closely across the full dynamic range, with residual spread attributable to the LED-to-LED variation reported in [11].

The shifting of the fits of the curve and their alignment for a representative LED at all five temperature steps can be seen in Figure 23. From here on out the DAC counts were converted into Volt in all plots.

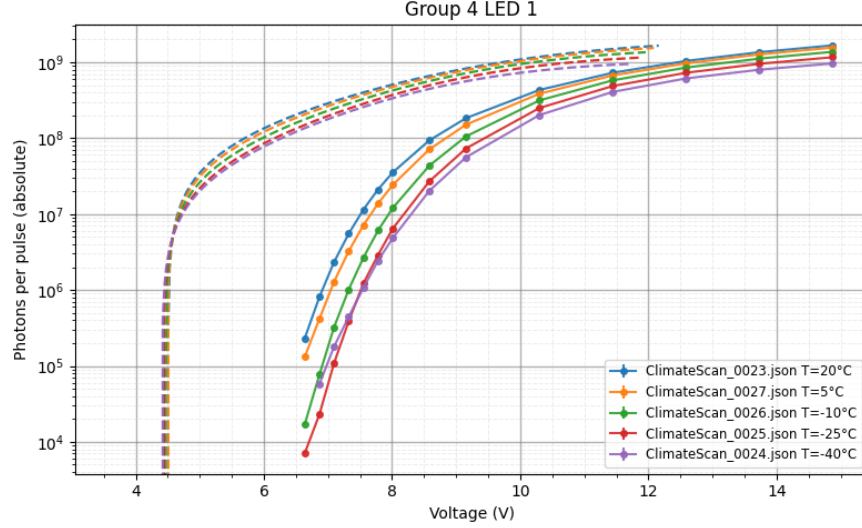


Figure 23: The per-pulse photon yield as a function of bias voltage for a representative LED at all five measurement temperatures. Solid lines show the original uncorrected curves, while the dashed lines show the same curves after applying a horizontal shift so that the 5×10^6 photon crossing point of each curve is aligned to a common reference point.

After the threshold alignment, the corrected curve fits overlap closely in the vicinity of the target intensity of 5×10^6 photons per pulse. However, a residual temperature-dependent spread can be observed at higher bias voltages. The 20°C curve fit consistently sits above all cold curves, while the -40°C curve fit consistently sits at the bottom, with the ordering preserved across the full upper dynamic range. This indicates that the temperature dependence of the LED response is not purely a horizontal shift, but also includes a change in the shape of the intensity curve. The magnitude of the residual spread is quantified via the relative standard deviation of photon yield across all threshold-corrected curves as a function of the bias voltage, as described in the following subsection.

The absolute threshold voltage shift as a function of temperature for all 20 tested LEDs, together with mean and standard deviation across all LEDs at each temperature step can be seen in Figure 24.

The threshold voltage shift increases monotonically with decreasing temperature for all LEDs, reaching a mean shift of about 0.4 V at -40°C relative to 20°C . However, the spread between the individual LEDs is relatively large, especially at -40°C , where it is approximately 0.1 V.

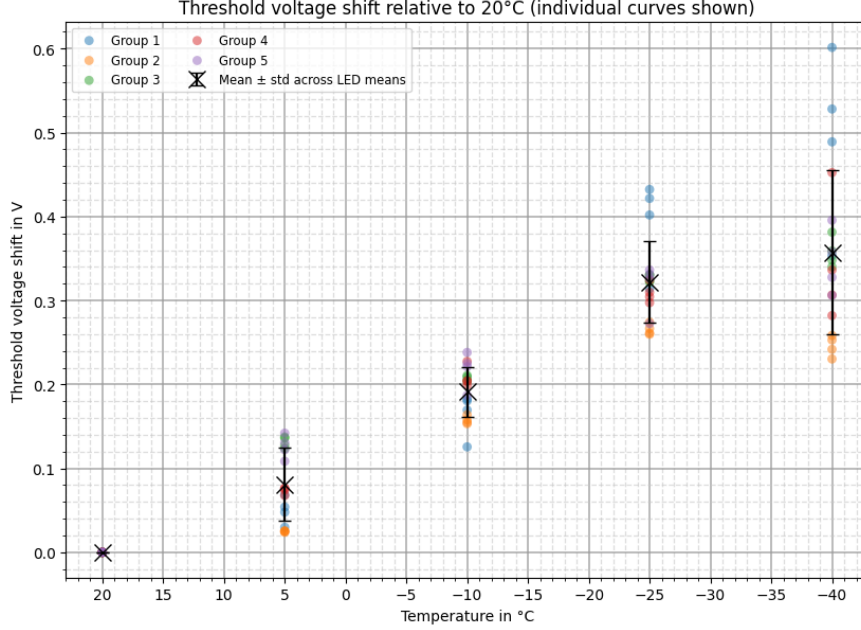


Figure 24: The threshold shift relative to 20 °C as a function of temperature for all 20 tested LEDs, grouped by measurement group. The mean and standard deviation across all LEDs at each temperature step are shown as black markers with error bars.

4.4.4 Temperature Correction Calibration

The threshold-voltage correction scheme introduced for the room-temperature calibration in subsection 4.2 can be extended to also account for the temperature dependence of the LED output. By shifting each LED’s intensity-versus-bias-voltage curve by its temperature dependent threshold voltage, the spread in intensity between LEDs can substantially be reduced across the full dynamic range at all temperatures, analogously to the room-temperature procedure described in [11].

To quantify the effectiveness of this correction, the relative standard deviation (RSD) of the photon yield across all 20 LEDs is computed as a function of voltage offset from the individual threshold voltages, both before and after applying the threshold correction. The result is shown in Figure 25.

The threshold correction substantially reduces the RSD across all temperatures, demonstrating that the dominant source of LED-to-LED variation at any given temperature is the shift in threshold voltage rather than the difference in curve shape. After correction, the mean RSD across all temperatures and voltage offsets is reduced to 24.2 %, compared to 48.0 % without the correction. This therefore works better than a simple linear correction, as seen previously in subsubsection 4.4.2.

However, a residual spread persists even after the correction. To further investigate it, the temperature-dependent mean photon yield across all LEDs after threshold correction is shown in Figure 26.

After threshold correction, a residual temperature-dependent spread in the mean photon yield remains visible across the full dynamic range. The ordering of the curves is the same as in the uncorrected case with the 20 °C mean consistently being above all colder temperatures and with −40 °C sitting at the bottom. This indicates that the threshold

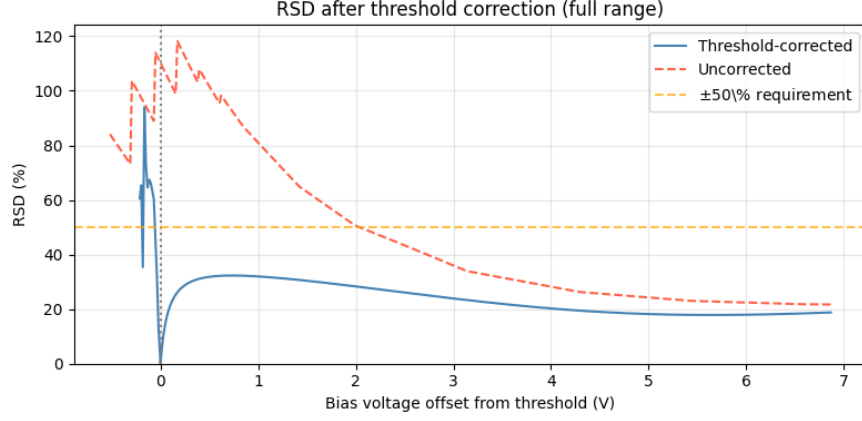


Figure 25: Relative standard deviation (RSD) of the per-pulse photon yield across all 20 LEDs as a function of voltage offset from the threshold, shown with (blues, solid) and without (red, dashed) threshold voltage correction, for all measured temperatures.

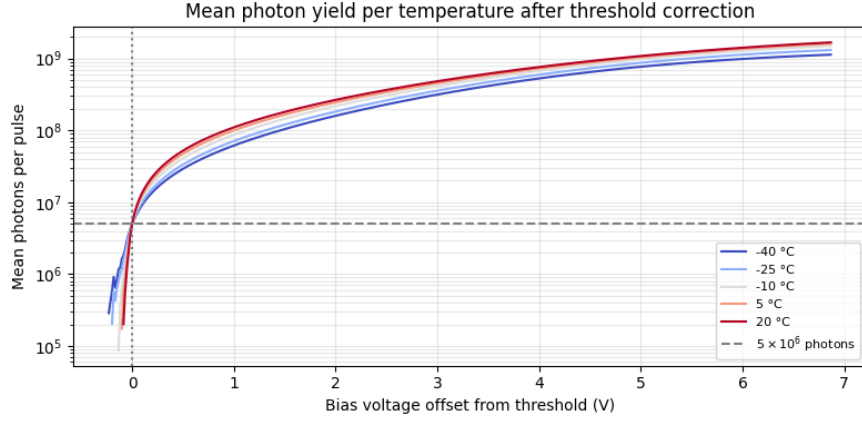


Figure 26: Mean per-pulse photon yield across all 20 LEDs as a function of voltage offset from threshold, shown for for the five measurement temperatures after applying the threshold voltage correction.

correction does not fully account for the temperature dependence of the LED response, as the shape of the intensity curve itself changes with temperature beyond a simple horizontal shift. The spread between temperature steps is small near the threshold point of 5×10^6 photons per pulse and stays consistent at higher voltage offsets, consistent with the shape difference observed in Figure 23.

The corrected RSD across all temperatures of 24% is higher than the 7% baseline reported for the room-temperature calibration in [11], which could be due to two reasons. First, the room-temperature calibration result was obtained from a significantly larger LED sample of 200 mDOM LEDs [11], making it less sensitive to individual outliers. More importantly, the 7% baseline was measured at a single temperature, whereas the 24% value is averaged across all five temperatures and therefore includes the residual temperature-dependent shape difference identified previously, which the threshold correction does not fully account for. Nevertheless, the correction reduces the spread by

a factor of two relative to the uncorrected case of 48.0 %, and at all temperatures the RSD remains well within the 50 % controllability requirements described in [11]. This confirms, that the flasher LEDs can be operated reliably across the full temperature range encountered in the deployed IceCube Upgrade modules.

4.5 Summary

The cold characterisation of the mDOM flasher LEDs was performed across the full temperature range encountered by the deployed IceCube modules and compared to measurements done at room temperature . The Hamamatsu S2281 photodiode was confirmed to be temperature-independent within $0.80 \% \pm 0.54 \%$, validating its use as a detector across all temperature steps. A clear and systematic reduction in per-pulse photon yield was observed at lower temperatures for all 20 tested LEDs, with the overall shape of the intensity-versus-bias-voltage curve preserved across temperatures. The reduction in photon yield at -40°C relative to 20°C amounts to 36.5 % at maximum bias voltage and 63.7 % on average across all voltages, consistent with the 40 % reduction at maximum bias voltage previously predicted in [11]. The threshold voltage required to reach the target intensity of 5×10^6 photons per pulse increases monotonically with decreasing temperature. A mean shift of 0.4 V at -40°C relative to 20°C and a standard deviation of approximately 0.1 V across all LEDs. The threshold correction scheme from [11] was extended to cold operation by shifting each LED's intensity curve by its temperature-dependent threshold voltage, reducing the LED-to-LED relative standard deviation (RSD) from 48 % to 24 %, therefore confirming that the flasher LEDs can be operated reliably across the full temperature range of the deployed IceCube modules.

5 The LOMlogger

The accurate modelling of the light propagation in IceCube depends critically on knowing not just the depth-averaged optical properties of the ice, but their precise spatial variation - in particular undulation of the dust layers, also known as tilt, across the detector volume. The LOMlogger was deployed with the IceCube Upgrade to measure this stratigraphy in situ, but the reliability of its backscatter signal depends on a well-characterised laser beam profile at the point of emission into the borehole water. The work presented in this chapter addresses exactly this topic. A laboratory calibration of the LOMlogger laser profile under conditions that reproduce the optical transitions present during the deployment was conducted, forming the basis for a correct interpretation of the in-ice measurements.

The work presented in this chapter was carried out in the context of the PhD research of A. Eimer and builds upon the work described in [12].

5.1 The Dust Logger

Understanding the optical properties of the South Pole glacial ice is essential for IceCube’s event reconstruction. Since every neutrino interaction produces light, which must propagate through the surrounding medium before reaching a detector module. The ice accumulated at the South Pole over hundreds of thousands of years [37] and the climatic history is reflected in the optical clarity [33]. The layers of ice, which were created during colder and windier periods scatter and absorb light more strongly, than the layers created during warmer interglacial intervals [3]. Characterising this stratigraphy at high resolution is therefore not only of glaciological interest, but is also crucial for the optical calibration of IceCube (see section subsection 2.7).

The instrument developed to perform this characterisation is the dust logger, first described in [54] and subsequently deployed during IceCube construction. The schematic design of the dust logger can be seen in Figure 27.

The device operates by lowering it into the water-filled borehole while continuously illuminating the surrounding ice with a laser. The wavelength coincides with a local absorption minimum of glacial ice [55], maximising light penetration and enabling deeper profiling of the medium. However, this depth sensitivity introduces a trade-off: small errors in laser tilt cause the beam to span multiple ice layers rather than probing a single depth. The laser beam is shaped into a thin horizontal fan spanning approximately 60° in azimuth, while having a vertical extent of only a few millimetres. This provides an intrinsic depth resolution on the sub-centimetre scale for the measurements, which is finer than an average annual deposition layer [56]. Only a tiny fraction of the photons emitted by the laser, in the range between 10^{-6} and 10^{-10} , are backscattered by dust particles, volcanic ash and bubbles in the ice and reach the photon-counting detector at the bottom of the logger [3].

The IceCube Collaboration deployed the dust logger in eight boreholes during the initial commissioning period of the detector [3]. The resulting depth profiles constitute some of the highest-resolution particulate stratigraphies ever obtained in Antarctica [3]. The results can be seen in Figure 28.

Through the comparing of South Pole logs to recovered ice-cores and logging data from Dome C in East Antarctica, the collaboration derived impurity concentrations. Additionally a precise chronology as well as an annual layer thickness and the positions

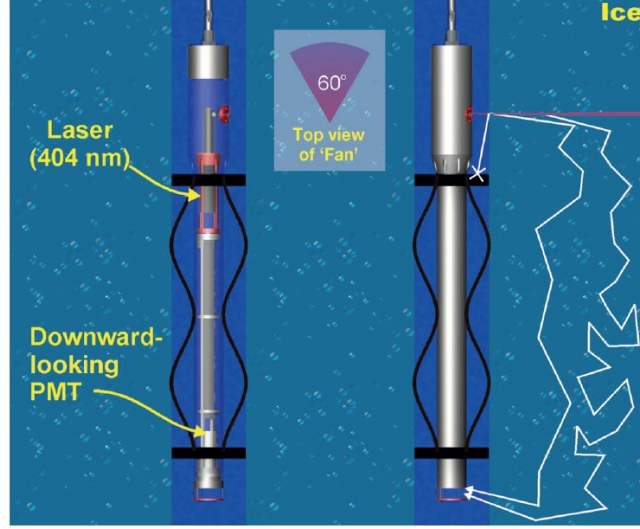


Figure 27: Schematic of the laser dust logger as deployed in IceCube boreholes during its construction. A laser emits a thin horizontal fan of light spanning 60° in azimuth into the surrounding ice. Backscattered photons are collected by a downward looking PMT placed at the bottom of the instrument [3].

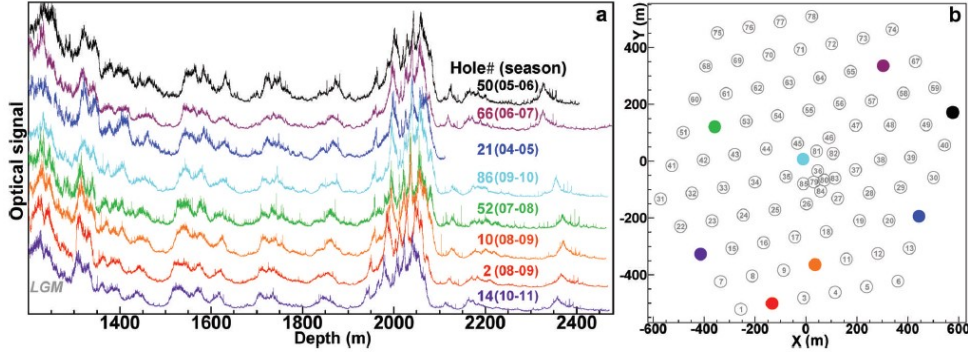


Figure 28: Backscattered light intensity as a function of ice depth recorded by the dust logger across eight different boreholes. Segments of low optical signal correspond to optically clear interglacial ice, while peaks indicate dust-rich sections inside the ice. The general agreement between the profiles from different boreholes demonstrates the spatial coherence of the stratigraphic layers across the IceCube footprint [3].

of widespread volcanic ash slices, which provide important stratigraphic reference points were determined [3]. The results also revealed a spatial variability across the IceCube footprint and mapped the tilt of the isochron layers created by the underlying bedrock structure [3].

As will be discussed in the following section, the LOMlogger shares the same objective of recording ice stratigraphy as the dust logger. However, its primary significance lies in its role as a test deployment for IceCube Gen2: if successful, the instrument could be deployed on every string, transforming the depth profiling capability across the entire detector array [57].

5.2 The LOMlogger

The LOMlogger consists of two main components mounted sequentially on the same instrumentation cable. The laser light source at the bottom is a modified Precision Optical Calibration Module (POCAM) [41] and a Long Optical Module (LOM) [58] placed 2 m above it on the same string as the receiver for the backscattered light. The two parts are separated by baffles placed halfway between them and on top of the modified POCAM, to reduce stray light. A schematic depiction of the full LOMlogger instrument and how it is deployed in the borehole can be seen in Figure 29. The LOMlogger is a co-deployed laser dust logger developed as a new calibration instrument for the IceCube Upgrade. The original dust logger required a dedicated deployment procedure, requiring its own winch right after the borehole was drilled, before the instrumentation string could be deployed. Unlike the dust logger, the LOMlogger was integrated directly at the bottom of the IceCube Upgrade string. This co-deployment saves time and therefore fuel, needed for drilling the borehole during deployment. It also makes the stratigraphy measurement part of the string drop operation procedure. This method has a lot of advantages, with the downside of making the laser recovery impossible. The optical module used for the stratigraphy measurement, the LOM [58], transitions into a regular optical module used for the detection of neutrino events after being lowered into the ice. The deployment during the IceCube Upgrade is a test run for the potential deployment of LOMloggers with every string in IceCube Gen2 for a very precise measurement of the ice tilt in the newly instrumented ice [57].

During the deployment, the laser emits a thin horizontal fan of light into the surrounding ice, which is very similar to the laser of the dust logger described in subsection 5.1. Different, when compared to the dust logger, the laser of the LOMlogger is pulsed. Photons that scatter off dust particles and other impurities in the ice can travel back toward the string and are detected by the PMTs of the LOM above, as seen in the mentioned graphic. The string with the LOMlogger was continuously lowered into the borehole, recording data in time bins of 10 ms, which corresponds to approximately 2 mm of depth [59]. This yielded a continuous depth profile through the backscattered intensity, which reflects the dust and impurity content of each scanned ice layer [12].

The LOM comprises of 16 PMTs equally distributed across the whole housing, providing directional sensitivity, which was not present in the single-channel photon counter of

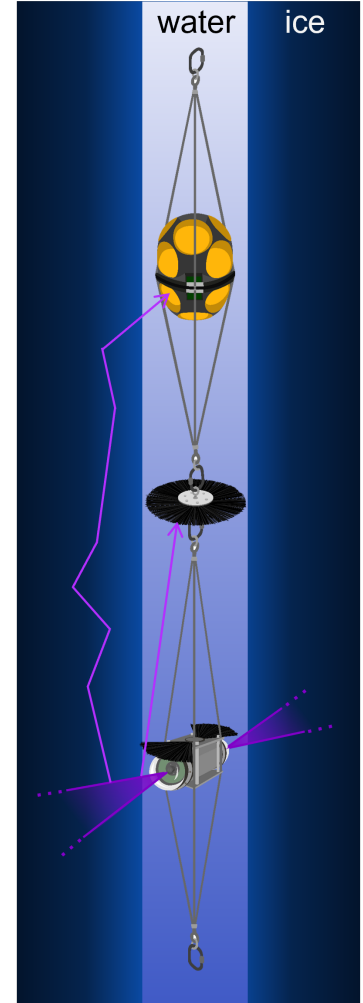


Figure 29: Schematic depiction of the LOMlogger deployment, with the LOM at the top, the modified POCAM at the bottom, one baffle placed in the centre and one on top of the POCAM harness [12].

the original dust logger [58]. The PMTs that are oriented away from the laser source predominantly record photons that were scattered inside the ice and the recorded data represents the impurities well, while the PMTs facing in the direction of the laser light source may also receive photons reflected directly through the borehole water column [12]. Unlike the original dust logger, where the direct light paths were not restricted, the baffles separating the POCAM and the LOM in the LOMlogger makes the stray light contribution small, but still not negligible [60]. In order to reduce this effect, two light-absorbing baffles are installed. One is mounted directly on the harness of the modified POCAM and one is placed halfway between the two modules. Both can be seen in Figure 29 [12]. While the baffles reduce the amount of stray light significantly, the contribution cannot be removed entirely. During the actual deployment it could be seen, that the upper hemisphere of the LOM actually detected more light than the lower one, the reason for that is still unclear [57]. This directional information can, in principle, be exploited to separate the actual ice-scattered signal from the borehole artefacts. The brush geometry of the baffles allows borehole water to flow freely through the baffle during the deployment of the instrumentation string [61].

The key quantity that determines the scientific utility of the LOMlogger is its depth resolution, specifically how well the recorded stratigraphy preserves the features needed to cross-correlate measurements from different boreholes in order to reconstruct the ice tilt. To quantify this requirement, the existing dust logger dataset [3] was re-analysed at progressively degraded resolutions using a dynamic time warping algorithm [12]. This algorithm identifies matching features between two depth profiles even if those features appear at different depths at the different boreholes. This is particularly important, as features are expected to be shifted due to the tilt. The analysis showed that features with a full-width-half-maximum (FWHM) of 20 cm are the about smallest structures reliably usable by the algorithm to still be able to match profiles across boreholes [12]. Below this scale, the matching performance degrades to the point where the reconstructed depth difference varies by more than ± 1 m from the reference dust logs [12]. This sets a requirement for the LOMlogger, it aims to be capable of resolving features of 20 cm in the ice.

This resolution requirement translates directly into two optical constraints for the laser beam. First, the vertical divergence of the beam must remain below 10° , as a wider beam would sample a larger vertical space at a time and smear out features in the recorded depth profile. Second, the inclination of the beam axis away from horizontal must also remain below 10° , since a tilted beam shifts the sampled depth away from the nominal position of the instrument, which effectively creates a bias in the depth assignment for each data point [12]. These constraints motivate the optics design described in the following section.

The optical requirements led to a beam-shaping assembly comprising of four optical components in series, a laser diode, a collimation tube, a pinhole and a Powell lens. The assembled optics, which are housed inside the POCAM body, can be seen in Figure 30. The used light source is a 405 nm laser diode (Roithner RTL405-600MGE). The laser is operated in pulsed mode and driven by the same LD driver circuit used in the POCAM [41]. A Thorlabs LTN330-A is the adjustable collimator tube used in the setup. It reduces the initial divergence of the laser, producing an elliptical beam profile with FWHM of 0.7 mm in one and a FWHM of 1.6 mm in the other axis, which was measured on a two-dimensional linear translation stage Figure 31. After that the laser beam

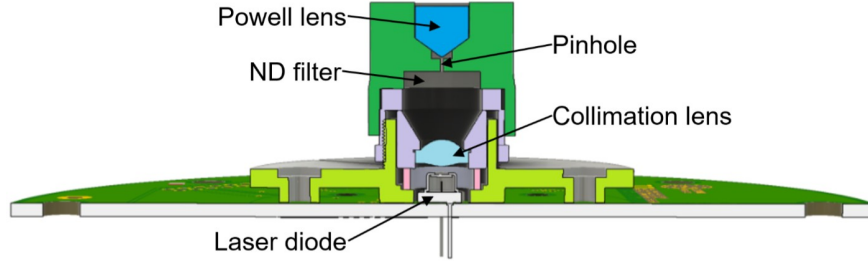


Figure 30: CAD model of the assembly of the optics inside the LOMlogger mounted on the POCAM analogue board. From the bottom to the top: the 405 nm laser diode, the 3D-printed collimator holding structure shown in light green holding the Thorlabs collimator tube components, and a second holding structure with an integrated pinhole as well as a neutral density and a Powell lens [12].

passes a neutral density filter, which is inserted between the collimator and the pinhole to attenuate the output of the diode by up to a factor of four to keep the intensity within the permitted window, as a compensation for diode-to-diode variation. Not all LOMloggers in the Upgrade were fitted with a neutral density [59]. The Powell lens requires the input beam diameter to be smaller than 0.4 mm in order to produce a uniform intensity distribution reducing the 60° opening angle. This is done to remove the characteristic edge peaks of the beam profile after the Powell lens. To achieve that, the pinhole aperture between the neutral density filter and the lens clips the collimated beam to a smaller diameter. The beam profiles after the pinhole can be seen in Figure 31.

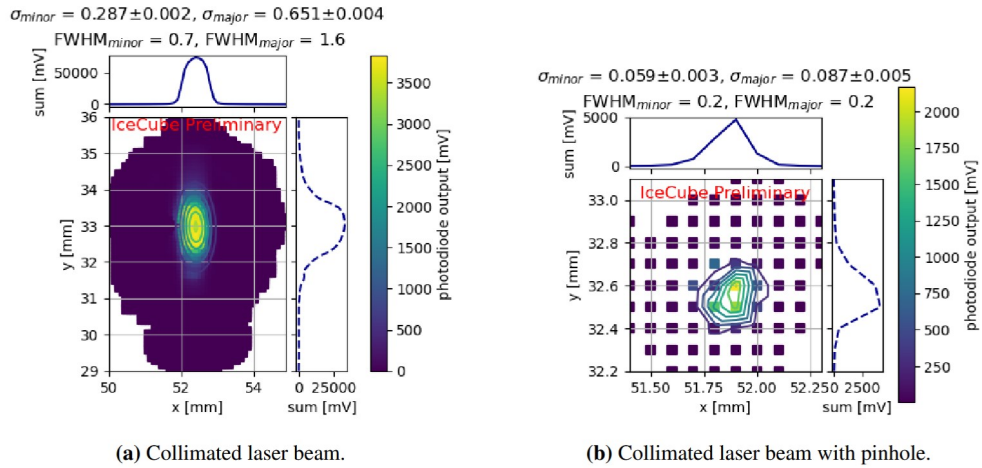


Figure 31: Two-dimensional scans of the laser beam profiles after collimation (left) and after passing through the pinhole aperture (right). The photodiode recording the profile was at a distance of 1.1 cm. The lower left panel of the respective measurement displays the 2D intensity map, the side panels show the 1D projections in x and y . Values of the 1D projections and the 2D Gaussian fit are shown above the plots [12].

The last element of the optical assembly is the Powell lens (Thorlabs LGL160). As previously mentioned it transforms the circular input beam into a horizontal beam.

Unlike a simple cylindrical lens, the Powell lens is designed in a way, that it produces a uniform intensity distribution along the fan, rather than a Gaussian profile. This ensures that all directions within the 60° opening angle contribute equally to the backscattered signal. The two-dimensional beam profile after the Powell lens can be seen in Figure 32.

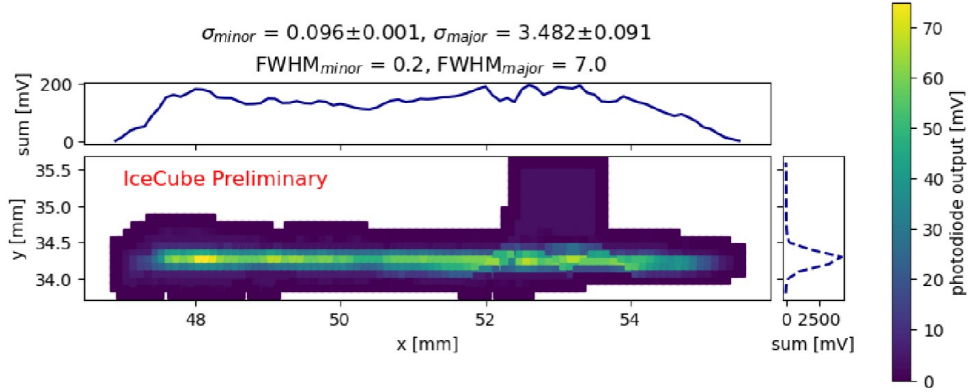


Figure 32: Two-dimensional scan of the laser beam profiles after the Powell lens. The photodiode recording the profile was at a distance of 1.1 cm. The lower left panel displays the 2D intensity map, the side panels show the 1D projections in x and y . Values of the 1D projections and the 2D Gaussian fit are shown above the plots [12].

The intensity of the laser is also constrained from both ends. Photon propagation simulations show that in the optically clearest ice in the IceCube volume, the probability of a single emitted photon being detected by one LOM PMT is approximately 4.3×10^{-8} . The ratio of detected signal between the clearest and most scattering ice, as recorded by the original dust logger is about 30, which makes the probability in the most scattering regions of the ice approximately 1.3×10^{-6} per PMT per emitted photon [12]. With a pulsing rate of 1 kHz the LOM PMTs begin to saturate above roughly 10^3 arriving photoelectrons per pulse. These constraints define the permitted intensity range, which effectively means that the laser must emit between 3×10^8 and 8×10^8 photons per pulse in order to remain above the detection threshold in clearer ice, while not saturating in ice layers with higher dust concentration [12].

The vertical divergence of the final beam was characterised by imaging the beam on fluorescent paper at different distances from the laser exit and fitting a linear model to the measured half-FWHM as a function of distance. The result of that can be seen in Figure 33.

The resulting vertical divergence angle is $0.06^\circ \pm 0.01^\circ$, being well within the required 10° . This means the beam is effectively collimated over the relevant distances inside the borehole [12].

Prior to the deployment of the LOMlogger in the IceCube Upgrade, an initial characterisation of the LOMlogger laser beam profile was performed in air. These measurements described above, which include the 2D beam profile scans, the divergence characterisation as well as the intensity calibration were all conducted under laboratory conditions, where the laser travelled directly from the optical assembly to a paper screen. These measurements confirmed that the beam geometry satisfied the optical requirements determined in [12] and established a baseline for comparison with other measurements. However, the actual operating environment of the LOMlogger differs from the laboratory

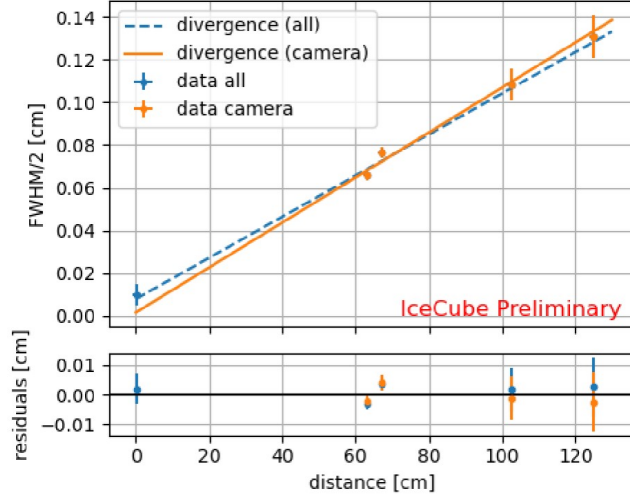


Figure 33: Measurement of vertical beam divergence. The upper panel the FWHM/2 as a function of distance between the laser exit and the detection screen, with a linear fit with the slope providing half the divergence angle. The lower panel shows the fit residuals. Orange points correspond to data taken with the camera method, while the blue points correspond with data taken via the linear stage method [12].

in two important respects. First, the laser beam exits the POCAM housing through a glass hemisphere and second, the laser light propagates through the borehole water before entering the ice. Both of these transitions, air to glass and glass to water involve refractive index mismatches that impact the beam profile, altering both the opening angle as well as the intensity distribution of the fan compared to what is measured in air. These effects were not accounted for in the pre-deployment calibration, leaving open the question of how the beam profile looks exactly before entering the ice. Quantifying this difference is the primary motivation for the water calibration measurements described in the following sections.

5.3 Setup of the Water Calibration Measurements

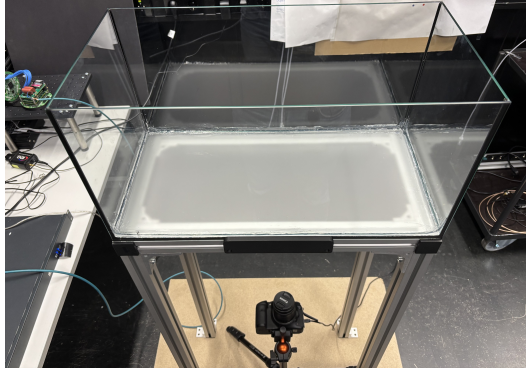
As established at the end of subsection 5.2, the pre-deployment characterisation of the LOMlogger laser beam profile was performed entirely in air and it did not account for the optical transitions introduced by the POCAM glass hemisphere and the subsequent propagation through the borehole water. Since the laser beam exits the glass hemisphere into water rather than air, refraction at the curved glass-water interface is expected to change the beam geometry. According to Snell’s law, the higher refractive index of water ($n_{\text{water}} \approx 1.34$ at 405 nm) compared to air ($n_{\text{air}} \approx 1.00$) bends rays towards the optical axis, reducing the horizontal and vertical fan angles [62]. In order to address this, dedicated laboratory calibration measurements were conducted in a modified aquarium, that reproduced the relevant optical conditions present during the deployment of the LOMlogger as closely as possible.

5.3.1 Experimental Setup

The measurement setup consisted of a standard glass aquarium modified for the required optical measurement. An opaque acrylic glass plate was fixed at the bottom of the aquarium using silicone sealant, serving as the detection surface for the laser beam. A camera was mounted on a tripod below the aquarium looking upward at the acrylic plate. The camera used for the measurement was a DSLR Canon EOS 7D [63] with an 18 megapixel CMOS sensor and an image sensor size of 22.3×14.9 mm. A custom measurement stand was constructed to reproducibly place the aquarium above the camera. The calibration for the camera images was done using two rulers placed perpendicularly and from a calibration image and the resolution of the image was determined, which was 0.075 ± 0.004 mm/pixel for all measurements. The whole setup was placed in a darkroom, in order to record only the beam profile and minimize any stray light. This setup can be seen Figure 34.



(a) The modified aquarium with the opaque acrylic glass plate fixed at the bottom using silicone sealant, serving as the projection surface for the laser beam profile.

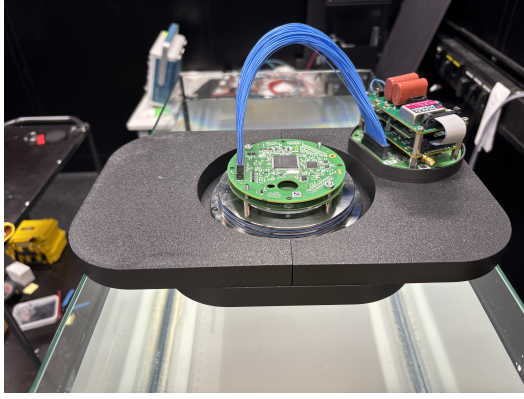


(b) The aquarium mounted on the custom measurement stand during calibration. The camera is positioned below the aquarium, looking upward at the acrylic plate.

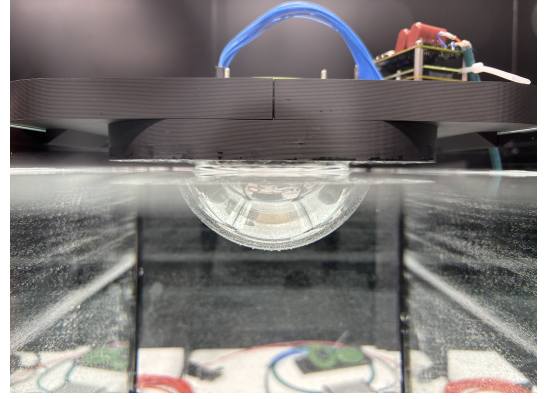
Figure 34: The water calibration measurement stand. Left: the modified aquarium with the acrylic screen fixed at the bottom. Right: the full setup as used during measurements, with the aquarium elevated on the stand to allow camera access from below.

The laser source used in the measurement, as seen in Figure 35a, was a simplified replica of the LOMlogger deployment configuration. It consists of the POCAM glass hemisphere together with the assembled optics behind it, namely the collimation tube, a neutral density filter, the pinhole and the Powell lens previously described in detail in subsection 5.2. This setup closely replicates simulates the optical transitions experienced by the laser beam during actual deployment: the beam passes through the Powell lens, exits through the glass hemisphere into the surrounding water, propagates through the water and finally projects onto the acrylic screen at the bottom of the aquarium, where the projection is recorded by the camera. The optics assembly and the POCAM lens are positioned on top of the aquarium on a 3D-printed holding structure, fixing the lens in the centre of the aquarium. A schematic and an image of the holding structure can be seen in Figure 35.

The electronics were connected to a lab computer using a MiniFieldHub. This device is



(a) Top view of the 3D-printed holding structure mounted on the aquarium rim. The optics assembly is seated on the POCAM hemisphere in the central circular cutout. The readout electronics and cabling are visible as well.



(b) Side view showing the POCAM glass hemisphere looking out from the holding structure, submerged just below the water surface. The electronics powering and controlling the diode are visible on top.

Figure 35: The LOMlogger optics replica mounted on the aquarium measurement stand. The 3D-printed holding structure (left) fixes the POCAM glass hemisphere centrally above the aquarium, lowering it into the water volume to replicate borehole conditions. The side view (right) shows the hemisphere partly submerged, pointing towards the acrylic screen at the bottom.

used for communication between the connected electronics, required for the operation of the diode, and the lab computer [64]. The MiniFieldHub is also used to supply voltage to the electronics.

Measurements of the laser beam profile were performed in air, with the glass hemisphere not submerged into water, with the glass in air and with the glass submerged into water. This was done to create direct comparison with otherwise identical conditions. The air measurements serve as a reference to determine how much the profile changes compared to the water and the glass measurement. It also serves as a comparison to the work previously done by A. Eimer [12]. For the water measurement the aquarium was filled to the point where the POCAM glass hemisphere was submerged sufficiently, so that the complete laser beam passed through the glass and the water.

It should be noted that the acrylic screen introduces a smearing of the projected beam profile due to the light diffusion within the material. This effect is further characterised and accounted for through a correction via a point-spread function (PSF), which is further described in subsection 5.4. The results presented in the next section are not yet corrected via the PSF, as the effect of the smearing is relatively small and is negligible for the initial evaluation of the beam profile differences between the air and water measurement.

5.3.2 Results of the Water Calibration

As mentioned previously, measurements were done in three different settings: With the laser going through air, through the glass without water and through the glass with water. The data was recorded using a camera, then the beam profiles FWHM in

x and y was calculated and the result was evaluated ². This measurement was done 150 times for each configuration to reduce statistical fluctuation. An example of one such measurement of a beam profile in water as well as its evaluation can be seen in Figure 36.

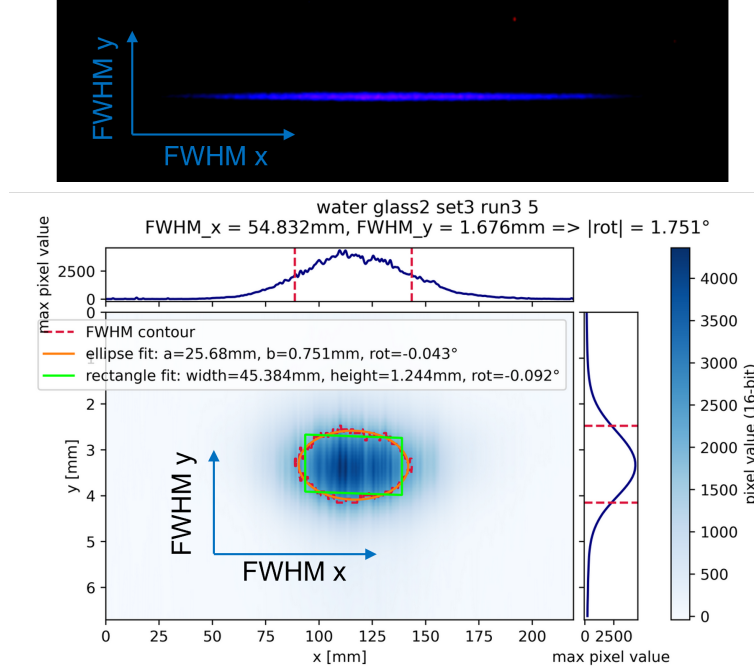


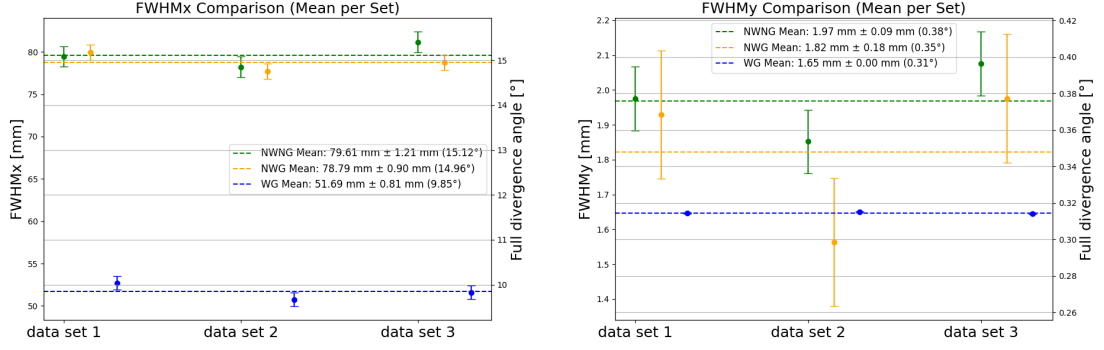
Figure 36: Example beam profile measurement in water. Top: raw camera image of the laser fan projected onto the acrylic screen, showing the characteristic thin horizontal line of the Powell lens output. Bottom: processed intensity map of the central beam region with 1D projections along both axes. The red dashed contour indicates the FWHM boundary, with an ellipse fit (orange) and rectangle fit (green) overlaid on the intensity map. The measured FWHM values of $\text{FWHM}_x = 54.83\text{mm}$ and $\text{FWHM}_y = 1.68\text{mm}$.

This example presents a single camera image as recorded by the camera and its evaluation. In it the thin fanned shape of the beam can be clearly seen. The fits in the evaluation below the image have been used as an additional check, but the calculated FWHM values at the top were used for further evaluation.

The beam profile measurements consist of three independent data sets, each consisting of 50 repeated images per configuration, yielding 150 measurements per configuration and 450 measurements in total. Three configurations were compared: no water and no glass hemisphere (NWNG), no water but with the glass hemisphere (NWG), and the full deployment-representative configuration with both water and glass hemisphere (WG). The results for the horizontal and vertical FWHM across all three data sets are shown in Figure 37.

The horizontal beam width FWHM_x shows a striking reduction in the measurement with water. The no-water configurations are consistent with each other, as the glass hemisphere alone has a very small effect on the horizontal extent of the fan, with

²Data taking and analysis code developed in the private repository **LOMlogging** (owner: A. Eimer, FAU Erlangen-Nürnberg), branch **aquarium_adjustments**.



(a) Horizontal FWHM (FWHM_x) for all three data sets and configurations. The water and glass configuration (WG, blue) shows a significant reduction of the FWHM compared to both other configurations.

(b) Vertical FWHM (FWHM_y) for all three data sets and configurations. The water and glass configuration (WG, blue) show a reduction of the FWHM compared to both other configurations.

Figure 37: Horizontal (left) and vertical (right) FWHM of the laser beam profile across three independent data sets for each of the three measurement configurations: no water and no glass hemisphere (NWNG, green), no water with glass hemisphere (NWG, orange), and water with glass hemisphere (WG, blue). Dashed lines indicate the overall mean for each configuration, with the corresponding divergence angle at 30 cm propagation distance. Error bars represent the standard deviation within each data set. The beam becomes narrower in water in both directions. The vertical divergence angle remains well below the 10° requirement in all cases.

NWNG and NWG means of (79.61 ± 1.21) mm and (78.79 ± 0.90) mm, corresponding to a divergence angles of 14.83° and 14.68° respectively. The measurement in water has a significantly reduced FWHM_x of (51.69 ± 0.81) mm (9.82°), a reduction of approximately 35% relative to the air measurements. This confirms the expectation from Snell's law [62]: refraction at the glass-water interface reduces the horizontal fan angle. The horizontal opening angle being smaller than the 60° mentioned in [12] is intended, to achieve a uniformity of the beam [59]. The small pinhole size probably also causes the beam to look less uniform and more Gaussian. The vertical beam width FWHM_y follows the same trend with the WG measurement again providing the smallest value of the three configurations. The WG configuration yields the smallest vertical extent at 1.65 mm (0.32°), compared to (1.97 ± 0.09) mm (0.38°) for NWNG and (1.82 ± 0.18) mm (0.35°) for NWG, suggesting a mild focusing effect in the vertical direction when the hemisphere is submerged. The measurements for the NWNG and NWG measurements have large error bars. The second data set of both configurations differs noticeably from the others, possibly due to slight differences of the setup of the measurement run. The WG measurement meanwhile has no error bars, as the calculated values for the standard deviation get rounded down to zero. At the dimensions of the FWHM in y the camera recording the profiles reaches its resolution limit per pixel, which is about 0.075 mm/pixel and this could possibly be the reason for either large or very small error bars as the values start behaving discretely.

Overall the profile in water becomes smaller than the profile in air in both dimensions. Crucially, all three configurations remain well within the 10° divergence requirement

at the 30 cm propagation distance used in these measurements, confirming that the LOMlogger laser beam meets the resolution requirement even under realistic borehole conditions.

5.4 Image Correction with a point spread Function

The acrylic plate fixed at the bottom of the aquarium serves as the projection surface for the laser beam, which allows the beam profile to be captured by the camera positioned below. However, the acrylic material is not perfect, as it diffuses light as it passes through, therefore spreading the intensity distribution of the projected beam over a larger area than the true beam profile should occupy. This smearing effect means, that the raw camera images show a slightly blurred version of the real laser beam profile and that a correction should be applied to account for that effect.

Mathematically, the recorded image I_{obs} can be modelled as the convolution of the true beam profile I_{true} with the point spread function (PSF) of the acrylic screen:

$$I_{\text{obs}}(x, y) = (I_{\text{true}} * \text{PSF})(x, y) \quad (8)$$

To recover I_{true} from I_{obs} requires a deconvolution, which in turn requires an independently calculated PSF.

The point spread function (PSF) of an optical system describes how a single point of light is spread over a finite area in the recorded image, thereby characterising the smearing introduced by the system [65]. The PSF of the acrylic screen was determined by comparing two independent measurements of the same laser beam profile recorded under identical conditions but with different detectors. The first measurement used the standard aquarium setup in air with the camera recording the beam through the acrylic screen, as described in subsection 5.3.1. The reference measurement was performed with an AstroCam model Starlight Xpress Lodestar Pro monochrome autoguider [66], a 16 bit CCD camera with 752×580 pixels and a pixel size of $8.6 \times 8.3 \mu\text{m}$, recording a direct image of the beam profile without a diffusing screen. This provides the reference measurement of the true beam profile at the same propagation distance. Both measurements were taken at a distance of 30 cm from the laser diode. Both measurements were taken at a nominal distance of 30 cm from the laser diode, with the setup change introducing uncertainty in the precise propagation distance.

The AstroCam image is treated as the ground truth I_{true} and the acrylic camera image as I_{obs} , the PSF can be estimated from the relationship in Equation 8. The resulting PSF kernel was then saved for subsequent corrections. The different resolutions of the images taken by different devices were accounted for. The PSF kernel essentially contains the information about the characteristic spatial spreading introduced by the acrylic plate. The resulting PSF kernel is shown in Figure 38.

The PSF correction was applied to the raw acrylic camera images using the Richardson-Lucy (RL) deconvolution algorithm [67, 68]. The RL algorithm is an iterative maximum-likelihood method that assumes Poisson noise statistics, making it well suited to photon-counting such as camera images. Starting from an initial estimate of the true image, each iteration updates the estimate according to:

$$I_{\text{true}}^{(k+1)} = I_{\text{true}}^{(k)} \cdot \left(\hat{\text{PSF}} * \frac{I_{\text{obs}}}{I_{\text{true}}^{(k)} * \text{PSF}} \right) \quad (9)$$

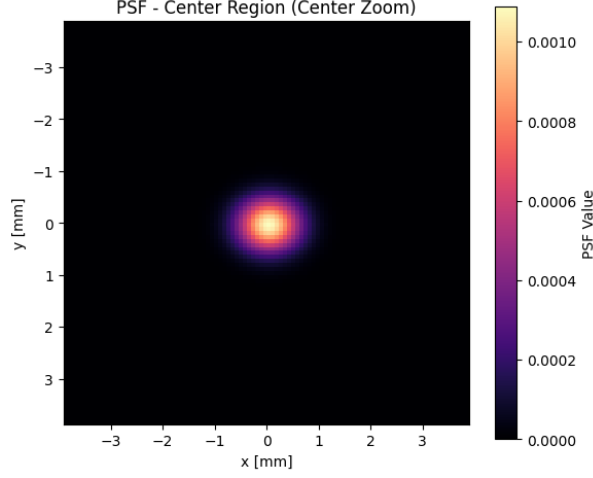


Figure 38: Centre region of the calculated point spread function (PSF) of the acrylic screen with a linear colour scale. The PSF characterises the spatial smearing introduced by the diffusing acrylic plate and is used as the deconvolution kernel for beam profile corrections.

where $\hat{\text{PSF}}(x, y) = \text{PSF}(-x, -y)$ denotes the PSF rotated by 180° about its centre, and $*$ denotes the convolution operator. The algorithm was implemented using the `richardson_lucy` function from the `scikit-image` Python library [69, 67, 68].

The number of iterations is a critical parameter, as too few iterations leave significant residual blurring in the reconstructed image, while too many lead to amplification of noise. In order to find the optimal iteration count, the L1 reconstruction residual was computed as a function of the number of iterations. This quantity measures the pixel-wise absolute difference between the original observed image and the result of re-convolving the deconvolved estimate with the PSF, therefore the lowest possible value leads to a self-consistent solution:

$$\mathcal{R}(k) = \sum_{x,y} \left| I_{\text{obs}}(x, y) - (I_{\text{true}}^{(k)} * \text{PSF})(x, y) \right| \quad (10)$$

The convergence behaviour across iterations 1, 2, 3, 5, 7, 10, 20, 30, 40 and 50 is shown in Figure 39.

The residual decreases initially for low iterations, reaches a minimum at seven and increases again after that. This indicates that for this analysis seven is the optimal amount for the number of iterations of this algorithm, reducing the smearing as much as possible, while avoiding noise amplification as much as possible.

An example of deconvolution can be seen in Figure 40.

After deconvolution, the reconstructed profile is sharper and the FWHM values in both dimensions are reduced, rebuilding the beam profile to be closer to the true beam profile arriving from the laser on the acrylic plate. Prior to the extraction of the profile, the deconvolved image is additionally processed with a median filter to suppress isolated hot pixels, followed by a Gaussian smoothing step and a large-scale background subtraction to remove residual illumination across the image. The PSF correction was applied to a subset of 5 recorded beam profile images as a verification step. The deconvolution confirms that the acrylic screen introduces a measurable smearing

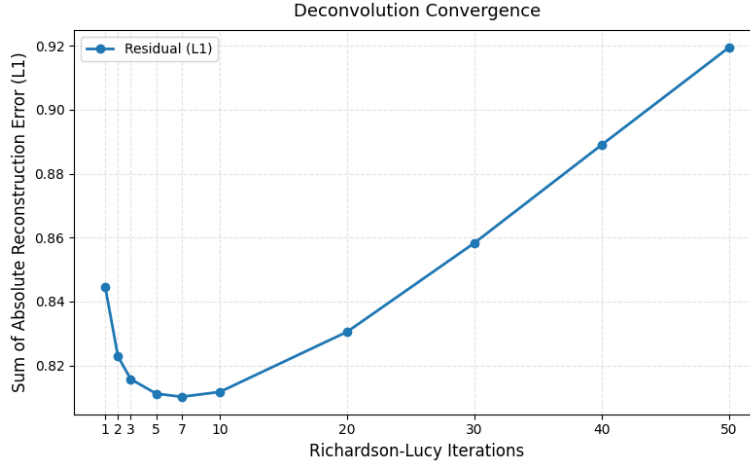
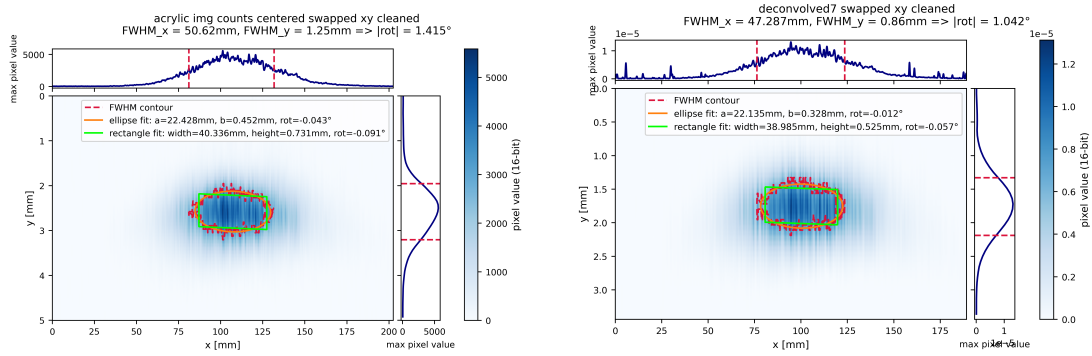


Figure 39: The L1 reconstruction residual as a function of the number of Richardson-Lucy iteration. The residual decreases steeply in the first few iterations and increases again after starting at 10 iterations. At seven iterations there is a minimum.



(a) Raw acrylic screen image before PSF correction. $\text{FWHM}_x = 50.62\text{mm}$, $\text{FWHM}_y = 1.25\text{mm}$, $|\text{rot}| = 1.415^\circ$.

(b) Deconvolution image after 7 iterations of RL correction. $\text{FWHM}_x = 47.29\text{mm}$, $\text{FWHM}_y = 0.86\text{mm}$, $|\text{rot}| = 1.042^\circ$.

Figure 40: Comparison of the beam profile before (left) and after (right) PSF deconvolution for the same measurement. The horizontal extent is reduced by approximately 3.3 mm ($\sim 6.6\%$), while the vertical extent shows a more pronounced reduction from 1.25 mm to 0.86 mm ($\sim 31\%$), recovering a sharper profile closer to the true beam. The red dashed contour shows the FWHM boundary; ellipse (orange) and rectangle (green) fits are overlaid.

effect, and the Richardson-Lucy deconvolution algorithm successfully recovers a slightly sharper profile in the horizontal direction. The effect on the vertical beam width is noticeable, having an average decrease of 18.1 % in the FWHM, while the effect on the horizontal beam width is smaller at 5.6 %. The vertical decrease being larger might be a result of the resolution limit of the image, which makes even a width reduction of one or two pixels make a large difference on the relative reduction.

Overall the conclusion that the beam meets the 10° divergence requirements is still met. A full application of the correction through the PSF would be possible, but was not

performed within the scope of this work, as it was not crucial to the main results. Having established the beam profile of the LOMlogger laser under realistic borehole conditions, the measured profiles are compared to a Zemax optical simulation of the laser system in the following section. This comparison serves as an independent cross-check of the calibration results and allows the accuracy of the optical model to be assessed against the laboratory measurements.

5.5 Zemax Laser Simulation Comparison

As an independent cross-check of the water calibration measurements, the measured beam profiles were compared to an optical ray-tracing simulation of the LOMlogger laser system. The simulation was performed using Zemax OpticStudio [45], a standard tool for optical system design and analysis [45]. The simulation model is based on a design originally developed by A. Eimer and was modified to reflect the specific geometry of the laboratory calibration setup. Specifically the positions of the individual parts were shifted to account for the correct dimensions of the lab setup and water was added as the medium between the POCAM hemisphere and the detector. The simulation outputs the complete two-dimensional beam profile at a given propagation distance, allowing a direct comparison with the camera images recorded in the aquarium setup. The geometry of the simulation can be seen in Figure 41

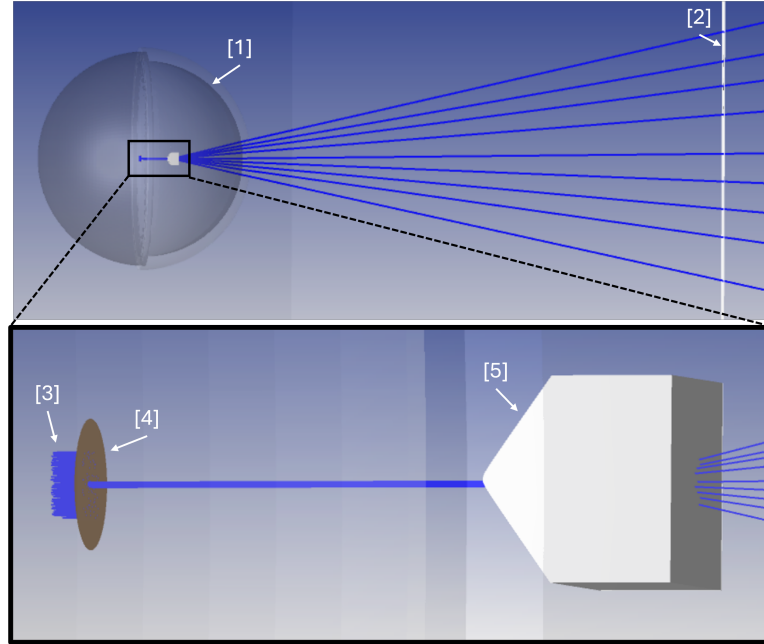


Figure 41: Zemax model of the LOMlogger aquarium calibration setup.

Top: Overview of the full geometry, showing the POCAM borosilicate glass hemisphere [1] on the left with the assembled optics inside. The fan of simulated rays propagates through the water medium and arrives at the detector surface [2] on the right representing the acrylic screen at 30 cm propagation distance.

Bottom: Zoomed in view of the optics assembly inside the hemisphere, showing from left to right the laser light source [3], the circular aperture [4] simulating the pinhole, and the Powell lens [5] that transforms the collimated beam into a horizontal fan.

The laser source beam radius is not precisely known from the hardware specifications, as the pinhole used for the optics had some slight variation, because it was 3D-printed. In the simulation it was treated as a free parameter. Simulations were run for five different laser source beam radii between 0.05 mm and 0.20 mm for all three optical configurations: no water and no glass (NWNG), no water and glass (NWG), water and glass (WG). These are the same configurations used during the aquarium calibration measurements. The resulting horizontal and vertical beam widths can be seen in Table 3, and the comparison of simulated and measured FWHM_x as a function of beam radius is shown in Figure 42.

Beam radius	NWNG		NWG		WG	
	FWHM_x	FWHM_y	FWHM_x	FWHM_y	FWHM_x	FWHM_y
0.05	36.36	0.30	36.36	0.30	36.36	0.51
0.075	58.59	0.30	52.53	0.30	52.53	0.61
0.10	72.73	0.30	72.73	0.30	66.67	0.71
0.15	109.09	0.30	107.07	0.30	98.99	0.61
0.20	127.27	0.30	127.27	0.30	115.15	0.61

Table 3: Simulated horizontal fan width FWHM_x and vertical beam width FWHM_y at 30 cm propagation distance for varying laser source beam radii, for all three configurations. All values are given in mm. The values measured during the aquarium calibration are $\text{FWHM}_x^{\text{NWNG}} = (79.61 \pm 1.21)$ mm, $\text{FWHM}_x^{\text{NWG}} = (78.79 \pm 0.90)$ mm, $\text{FWHM}_x^{\text{WG}} = (51.69 \pm 0.81)$ mm, $\text{FWHM}_y^{\text{NWNG}} = (1.97 \pm 0.09)$ mm, $\text{FWHM}_y^{\text{NWG}} = (1.82 \pm 0.18)$ mm, and $\text{FWHM}_y^{\text{WG}} = 1.65$ mm.

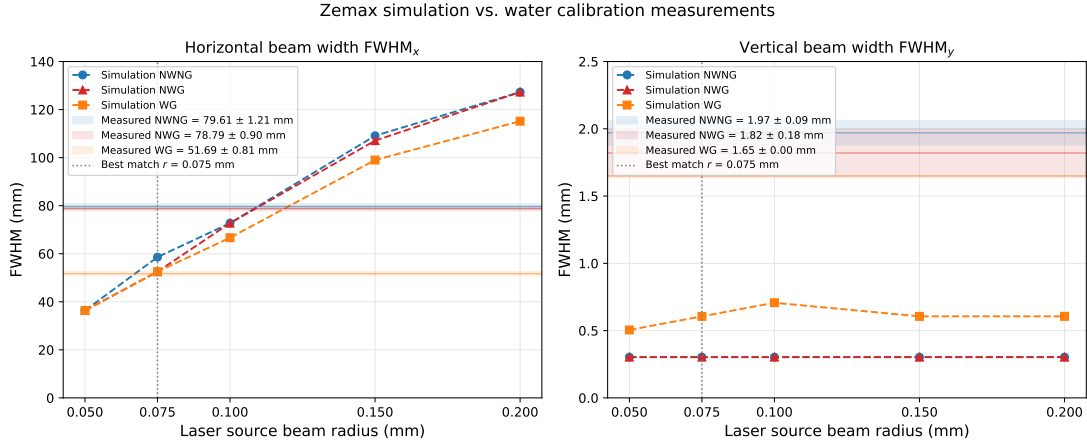


Figure 42: Simulated horizontal beam width FWHM_x (left) and vertical beam width FWHM_y (right) as a function of laser source beam radius for the NWNG, NWG and WG simulation configurations, compared to the water calibration measurements shown as horizontal bands. The vertical dotted line marks the beam radius of 0.075 mm at which the simulated FWHM_x in the WG configuration agrees with the measured value to within 1.6 %.

The best agreement with the WG measurement is obtained for a beam radius of

0.075 mm, at which the simulated horizontal beam width is 52.53 mm, agreeing with the measured value of (51.69 ± 0.81) mm to within 1.6 %. The simulated beam profile for this configurations is shown in Figure 43.

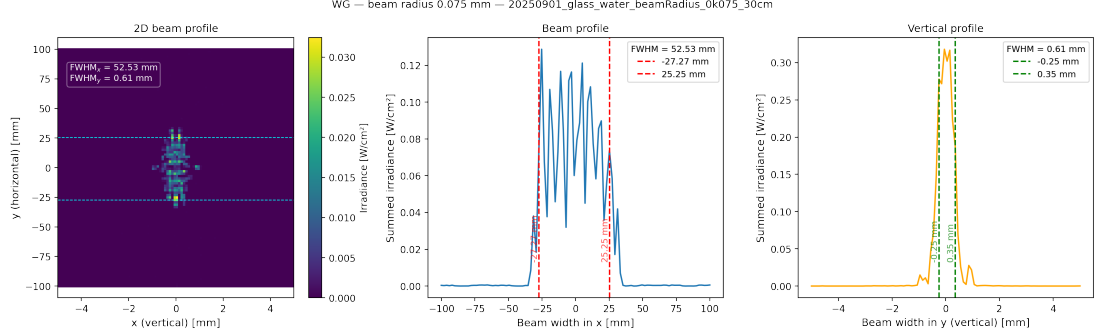


Figure 43: A simulated beam profile for the WG configuration with a laser source beam radius of 0.075 mm, which corresponds to the best-matching case. Left: two-dimensional incoherent irradiance distribution at 30 cm propagation distance, with the horizontal FWHM boundaries indicated by the cyan dashed lines. Centre: summed horizontal (x) fan profile with FWHM markers. Right: summed vertical (y) profile with FWHM markers. The simulation produces more smooth profile, in contrast to the intensity non-uniformity observed in the measured beam profiles (see Figure 36), which arises from coherent interference and speckle effects not captured by the ray tracing.

However, the NWNG simulation at this beam radius yields $\text{FWHM}_x = 58.59$ mm, different from the measured NWNG value of (79.61 ± 1.21) mm by approximately 26 %. The simulation therefore does not simultaneously reproduce both configurations at a single beam radius.

This difference is not fully understood. The refractive indices of the borosilicate glass hemisphere and the water volume are a good approximation, but might not be the exact values at 405 nm, introducing a small systematic uncertainty into the simulated refraction angles at the glass-water interface. This alone is unlikely the cause for a discrepancy of 26 % in the NWNG case. A more likely source is that the simulation model does not fully capture the complexity of the real optical system. The aquarium setup used the actual POCAM optics assembly as it would be deployed in the ice, whereas the simulation necessarily relies on idealised component geometries and nominal design parameters. Small deviations of the real optics from the setup, such as surface imperfections of the Powell lens, tolerances in the pinhole diameter, or even slight misalignments of the optical axis. These nuances are not captured by the ray-tracing model and could account for the observed discrepancy in the NWNG case.

The simulated vertical beam width of 0.61 mm at the best-matching beam radius is smaller than the measured $\text{FWHM}_y = 1.65$ mm across all configurations. This is most likely due to coarse pixel resolution of the simulation grid in the vertical simulation result is therefore not directly comparable to the measurement.

Despite these limitations, the simulation correctly reproduces the qualitative behaviour observed in the measurements. The horizontal beam width increases monotonically with the initial beam radius and the WG configuration consistently yields a narrower fan than the NWNG configuration for the same beam initial beam radius, which confirms that the

beam narrowing due to refraction at the glass-water is seen in the model. The simulation therefore serves as a qualitative cross-check of the water calibration results rather than a quantitative validation. The agreement in the WG case at a physically plausible beam radius lends additional confidence to the measured $\text{FWHM}_x = (51.69 \pm 0.81)$ mm.

5.6 Discussion and Outlook

The water calibration measurements presented in this chapter constitute the characterisation of the LOMlogger laser beam profile under conditions that closely replicate the optical environment during the deployment. The key result is that the beam meets the 10° divergence requirement set in [12] even after accounting for the optical transitions introduced by the POCAM glass hemisphere and the surrounding borehole water. The water medium narrows the horizontal fan angle by approximately 35 % relative to the air measurement due to refraction at the glass-water interface. This effect that was not captured by the pre-deployment air calibration and is quantified in this work for the first time.

The PSF correction, applied to a subset of 5 images, confirms that the acrylic screen introduces a measurable smearing of the projected beam profile. After deconvolution the effect is more pronounced in the vertical direction, where the FWHM decreases by an average of 18.1 %, compared to the horizontal direction, where the average reduction is 5.6 %. The larger relative decrease in the vertical direction is likely a result of the nature of the PSF correction. As the correction is the same in x- and y-direction and shifts the edges towards the centre in a linear manner, the effect on the smaller FWHM is more significant. A full application of the PSF correction to all recorded images would refine the reported FWHM values but is not expected to change the results qualitatively. The Zemax ray-tracing simulation provides a qualitative cross-check of the water calibration result. The simulation reproduces the correct qualitative behaviour, that the horizontal beam width increases with beam radius and the water, glass configuration consistently yields a narrower fan width than the no water, no glass configuration. The best-matching beam radius of 0.075 mm yields a simulated FWHM_x of 52.53 mm in the WG configuration, agreeing with the measured value very well. The simulation does not simultaneously reproduce the NWNG configuration, with the same initial beam width, which could be attributed to idealised component geometries in the model that do not fully capture the real optics. The simulation therefore supports the water calibration result but is not a substitute for it.

The calibration results obtained here can be directly applied to the in-ice data recorded by the LOMlogger during the IceCube Upgrade deployment. The water measurement provides a corrected characterisation of the beam profile at the point where light enters the ice, which is the relevant boundary condition for interpreting the backscattered intensity profiles recorded by the LOM. In particular, the reduced horizontal beam angle measured in water implies that the angular acceptance of the stratigraphy measurement differs from the acceptance that would be accepted from the air measurement alone. This correction should be applied to the ice stratigraphy reconstruction performed on Anna Eimer's deployment data. A full application of the calibration to the in-ice-dataset, including an analysis of the stratigraphy profiles with the corrected beam geometry, is left as the next step and would complete the pipeline from laboratory calibration to in-ice measurement. Additionally it can also be further investigated how precise the vertical resolution of the LOMlogger is. It is beyond question, that the vertical beam width is within the set restriction and therefore it would be interesting to see how the resolution limit of the LOMlogger was during the deployment. All this is particularly relevant in the context of IceCube-Gen2, where an accurate characterisation of the stratigraphy and the ice tilt over a larger detector volume will be very important, to achieve reliable event reconstruction [13].

6 Conclusion and Outlook

This thesis presented three independent studies contributing to the optical characterisation of IceCube Upgrade light sensors and calibration devices, each addressing a distinct aspect of the broader calibration effort for the deployed array.

The first study investigated the photoluminescence in the borosilicate glass housing of the IceCube DOM and its potential impact on the Neutron Echo signal. A geometric ray-tracing simulation was created in Zemax OpticStudio [45] in order to model the DOM glass as a wavelength-shifting medium and comparing the ratio of photoluminescence-induced light to initial light reaching the PMT for three source configurations: a horizontal LED Flasher, a tilted LED Flasher and a Cherenkov event positioned right below the DOM. Across all simulated mean free path lengths from 1 mm to 12 000 mm, the ratio of photoluminescence contributions to the initial light from the source of the tilted Flasher and the Cherenkov event was found to be approximately 2. This is contrasted by the preliminary geometric estimate of 10^2 – 10^3 . This result suggests that the LED Flashers do not induce disproportionately more photoluminescence than a Cherenkov event under the assumptions used for the simulation. This has direct implications for the interpretation of Flasher-based Neutron Echo background estimates. Several simplifications in the model limit the exact quantitative precision of the result, for example, the assumption of a perfect sphere geometry, as well as the absence of ice scattering, and the simplified Cherenkov source. Nevertheless, the result can be used as a qualitative reference for further studies or experiments investigating the luminescence in the borosilicate glass directly.

The second study presented a cold characterisation of the mDOM Flasher LEDs across the full temperature range encountered by the deployed IceCube Upgrade modules and compared them to measurements at room temperature. The Hamamatsu S2281 photodiode was confirmed to be temperature-independent within $2.11\% \pm 0.77\%$, validating its use as a detector across all temperature steps. A clear systematic reduction in per-pulse photon yield with decreasing temperature was observed for all 20 tested LEDs, amounting to 36.5 % at maximum bias voltage and 63.7 % averaged across the full operational voltage range at -40°C relative to 20°C . This aligns well with the 40 % reduction predicted in [11]. The threshold voltage required to reach the target intensity of 5×10^6 photons per pulse increases monotonically with decreasing temperature, with a mean shift of 0.4 V at 40°C and a standard deviation of approximately 0.1 V across all LEDs. Extending the threshold voltage correction scheme from [11] to cold operation, reduced relative standard deviation across all LEDs from 48 % to 24 %. The corrected RSD values at each temperature increase monotonically from 15.1 % at 20°C to 21.3 % at -40°C , remaining well within the 50 % controllability requirements at all temperatures. This confirms that the mDOM Flasher LEDs can be operated reliably across the full temperature range of the deployed array. Furthermore, it provides the temperature-dependent characterisation required for predictable in situ calibration. An extension of this work would be to incorporate the temperature-dependent threshold shifts into the IceCube ice model fitting procedure, enabling a more accurate correction of the LED brightness during in-ice calibrations runs.

The third study presented the laboratory characterisation of the LOMlogger laser beam profile under conditions, that try to reproduce the optical transitions present during the IceCube Upgrade deployment. Measurements were performed in a modified aquarium

with the POCAM glass hemisphere submerged, comparing laser beam profiles in air and in water. The key result is that the water medium narrows the horizontal beam angle by approximately 35 % relative to the air measurement. This effect occurs, due to refraction at the glass-water interface, an effect that was not captured by the pre-deployment air calibration performed before the IceCube Upgrade. The vertical divergence angles of approximately 0.32° in water remains well within the 10° requirement, confirming that the LOMlogger laser beam meets the resolution requirements, necessary for stratigraphy measurements even under realistic borehole conditions. A PSF correction based on Richardson-Lucy deconvolution was developed in order to account for smearing caused by the acrylic detector screen. It was validated on a subset of images, reducing the vertical FWHM by an average of 18.1 % and the horizontal FWHM by 5.6 %, without changing the core conclusion. A Zemax ray-tracing simulation of the aquarium setup reproduced the correct qualitative behaviour of the beam. The best-matching simulation agreed with the measured water FWHM_x to within 1.6 %, providing independent support for the water calibration result. The corrected beam characterisation obtained here should be applied to the stratigraphy profiles recorded during the deployment of the IceCube Upgrade, in order to provide a boundary condition at the ice interface. This is required for a reliable analysis of the backscattered intensity signal. It is particularly relevant in the context of IceCube-Gen2, as an accurate characterisation of the ice stratigraphy over a significantly will be important for reliable event reconstruction [13].

Taken together, the three studies presented in this thesis contribute to reducing the optical systematic uncertainties of the IceCube Upgrade at complementary levels, each with direct downstream benefits for physics analyses. The characterisation photoluminescence in the DOM glass housing constrains a potential background to the Neutron Echo signal, which in turn enables a more reliable statistical separation of ν_e and ν_τ charged-current cascade events, which is a distinction that the spatial resolution of IceCube alone can not make accurately. The temperature-dependent LED brightness model provides the characterisation required for predictable in situ operation of the mDOM Flasher LEDs, which are the primary light source for probing the optical properties of the surrounding ice and therefore underpin every LED-based measurement of the SPICE ice model. Finally, the corrected LOMlogger laser beam profile establishes the boundary condition at the borehole wall required for a reliable interpretation of the backscattered ice stratigraphy signal. It contributes to the mapping of the ice layer tilt that directly affects the angular resolution of cascade event reconstruction.

The different calibration and characterization work presented here provides essential data to support the continued refinement of IceCube’s detector models, enabling more accurate interpretation of neutrino events for years to come.

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Declaration of Originality

I, Andrei Chubarov, hereby confirm that I wrote this thesis by myself. Artificial intelligence in the form of Claude and Visual Studio Code Copilot was used in the following way:

- AI was used to improve the style and readability of this thesis. This includes corrections of grammar, spelling, and phrasing. AI was not used to generate full text passages or change the content of the text.
- AI was used to improve and verify the functionality of code that was written in the scope of this thesis. Code snippets that were generated by AI were reviewed carefully and integrated only after verification.

I confirm that I only used the indicated sources and tools in writing this thesis.

Place, Date

Signature