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PINGU Camera System to Study Properties of the Antarctic Ice

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IceCube is the world's largest neutrino detector located at the geographic South Pole, that utilizes more than 5000 optical sensors to observe Cherenkov light from neutrino interactions. A hot water drill was used to melt holes in the ultra-pure Antarctic ice, in which strings of optical sensors were deployed at a depth of 1500 m to 2500 m. The recent discovery of high energy neutrinos consistent with being of astrophysical origin, as well as precision measurements of neutrino oscillation parameters and competitive searches for dark matter, have demonstrated the great potential for ice-based neutrino telescopes. Extensions to the IceCube detector are under active consideration, including the PINGU multi-megaton neutrino detector with GeV threshold. Ice properties, including the refrozen ice from the optical sensor deployment, represent a major source of uncertainty for event reconstruction in IceCube. A camera system integrated with optical sensor modules could be tremendously beneficial for the interpretation of calibration measurements and to better understand ice properties. We describe a preliminary design of an on-board camera system and its impact on ice property measurements and geometry calibration.

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1. Introduction

IceCube, the world's largest neutrino telescope, utilizes the ultra-pure Antarctic ice at the geographic south pole as a detector medium. The recent discovery of high energy astrophysical neutrinos [1] by IceCube as well as a variety of other high impact results in the fields of astrophysics and particle physics have proven the success of the detector concept. Extensions to the IceCube detector, in form of a multi-megaton precision neutrino detector with an energy threshold of about a GeV, known as the Precision IceCube Next Generation Upgrade (PINGU) [2], and a high-energy neutrino detector optimised for observing TeV to PeV neutrinos, known as IceCube-Gen2 [3], are being considered. The extensions will reuse the very reliable design of IceCube's digital optical models (DOMs). Several improvements are considered, among them is an on-board camera system to survey the ice surrounding the optical sensors. In this proceedings we focus on the camera system for PINGU, which could be a key to reduce systematic uncertainties on light propagation in the ice and aid in achieving the primary physics goals of measuring the neutrino mass hierarchy and searching for dark matter.

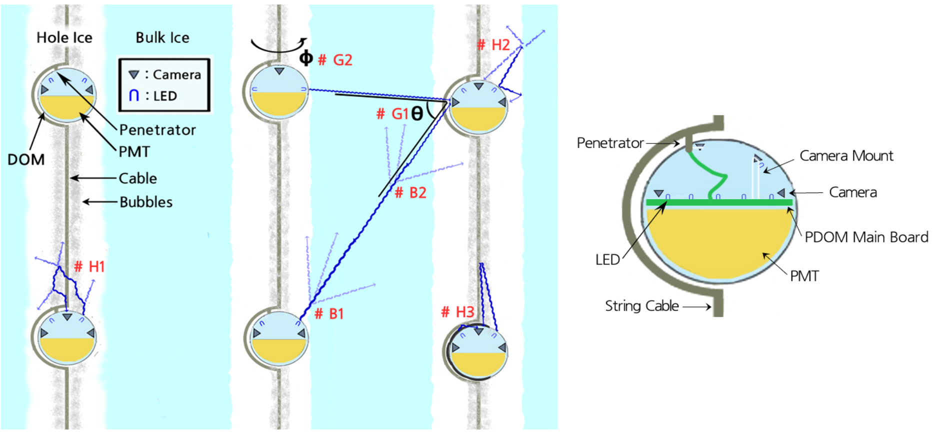

Figure 1: Left: Schematic drawing to illustrate potential camera measurements: (#H1) Hole ice survey. (#H2) Mapping of hole shape. (#H3) Cable position and orientation. (#B1) Light transmission and scattering at hole ice - bulk ice interface. (#B2) Light attenuation and scattering in the bulk ice. (#G1) Orientation of camera DOM. (#G2) DOM geometry. **Right:** Potential camera positions in the DOM. Details of the measurements are described in Table 1 and text.

Like IceCube, PINGU would detect neutrinos via Cherenkov light emission from secondary particles generated when a neutrino interacts in the deep Antarctic ice. Reconstruction of neutrino induced events depend strongly on the accurate modeling of the light propagation in the ice. A multitude of calibration devices including LED flashers, retrievable laser systems in the drill holes, two bright calibration light sources called the Standard Candles and a special device camera, have resulted in detailed understanding of the ice. The LED flashers, which are twelve radially outward pointing 405 nm LEDs on each DOM, are indispensable for the most advanced models of ice properties, as they provide calibration points through-out the detector. Fits to their data have resulted in the most advanced ice model [4]. The present calibration system however has several short comings, in particular little is known about the individual environment surrounding each DOM. The

Objective	Measurement	Requirements for Camera System		
		Resolution	Sensitivity	Orientation
#H1 Hole ice survey	Diffusion from bubbles and impurities	5 MP	0.1 lux	up
#H2 Hole ice mapping	Scattering on hole /bulk ice interface	1 MP	0.1 lux	sidewise
#H3 Cable position	Shadow and reflections of cable	1 MP	0.1 lux	up
#B1 Hole/bulk interface	Scattering / light transition	5 MP	0.001 lux	sidewise
#B2 Scattering and absorption lengths	Light attenuation and scattering halo	5 MP	0.001 lux	sidewise
#G1 PDOM orientation	LEDs from adjacent string PDOMs	1 MP	0.001 lux	sidewise
#G2 PDOM geometry	Triangulate positions, PDOM distances via separation angle	5 MP	0.001 lux	sidewise

Table 1: Objectives of the camera system are listed in the first column and measurements in the second column. Requirements for the camera system to carry out those measurements are given in columns 3-5, based on preliminary calculations. Orientation describes if the camera would be facing sidewise or up. Camera resolution in megapixels (MP) and sensitivities are estimated, in order to detect scattered light from bright LEDs (2 cd) located in PDOMs on the same or adjacent string. Objectives are grouped by hole ice studies (#H1, #H2 & #H3), light propagation in the bulk ice (#B1 & #B2), and geometry calibration measurements (#G1 & #G2).

refrozen ice in the drill hole is not very well understood and there is good reason to expect that the environment of each DOM could be significantly different. A low cost, high resolution on-board camera system paired with a bright LED for illumination deployed on each PINGU DOM (PDOM) could tremendously improve our understanding of the refrozen ice in the drill hole. It could yield qualitative information valuable in interpreting other calibration measurements, such as the LED flashers, and provide quantitative measurements of the ice properties.

A camera system inside two glass spheres at the bottom of IceCube string 80 (the last deployed string) provides a precedent for the proposed system. The camera observed the formation of bubbles at the centre of the drill hole (referred to as bubble column) during the refreezing of the ice from the outside inward [5]. The bubble column shows significantly reduced scattering length. Impurities settling on the surface of glass sphere of the camera were observed. However, information about the ice and drill hole provided by the camera is limited to a small region where it is located.

2. Objectives and Goals

The main goal of the camera system is to study the properties of the refrozen ice, determine the location and orientation of the PDOMs within the drill hole and survey the ice environment. A variety of measurements could be performed, each of which comes with its own requirements on camera positioning, sensitivity, field of view (FOV), resolution, and illumination options. We describe the suite of potential measurements qualitatively and derive basic requirements for the camera system to perform them.

(1) The camera system could monitor the freeze-in process of the strings of PDOMs deployed after melting holes using a hot water drill [6]. Little is known about the refreezing process. For

the measurement the camera would be operated at $0^\circ C$, and would preferentially be facing up or sidewise. A high-resolution color camera could best identify impurities and monitor the freeze-in dynamics. Triboluminescence or the formation of cracks could potentially be observed. For PINGU it has been proposed to degas drill water in an effort to reduce or eliminate the formation of bubbles. The camera system could provide immediate feedback about water quality and the effectiveness of degassing, including depth dependence of bubble formation.

(2) Surveying the completely refrozen drill hole is one of the highest priorities of the camera system. If present, the system would survey and characterize the bubble column and identify contaminants. The PDOM position (x-y) within the drill hole can be determined, as well as the relative location of the bubble column, which could lead to a non uniform photon acceptance by PMT. For the hole ice measurement it is most effective to have the camera pointing up and to have a LED for illumination located adjacent to it on the same PDOM.

(3) Another objective is to study properties of the untouched or pristine ice (referred as ’bulk ice’) between holes, and how light transmission is affected at the hole ice - bulk ice intersection. The observation of a halo of scattered light from a LED on an adjacent string could be used to study scattering, while the observation of the LED itself could be used to study attenuation. A high-resolution, high-sensitivity black and white camera would be most desirable for this purpose.

(4) A camera system could also assist geometry measurements. By observing a LED, on the adjacent upper PDOM, the relative orientation (around the z-axis) of the PDOM with an upward facing camera can be determined. The orientation of a PDOM on an adjacent string could also be determined through the observation of one or more LEDs on it, this would require a high resolution camera that could resolve individual LEDs on an adjacent PDOM. From the light pattern in the captured image, one can determine relative orientation of the camera PDOM as well. Likewise, a camera system facing up would capture scattered light coming from LEDs in the neighbouring PDOM in the same string and studying the light pattern we can determine relative orientations between PDOMs and their positions inside the hole. The relative depth of PDOMs between adjacent strings could also be determined. All these information would improve the geometry calibration of the PINGU array, but would require precise alignment and placement of LEDs and cameras.

(5) Finally the camera system could be beneficial to survey the PDOM environment for anything unforeseen and also provide a way to check for any dynamic effects, which are not expected after freeze-in.

Nearly all measurements benefit from a large FOV, making fisheye lenses the preferred option. Further, PINGU’s hexagonal deployment pattern makes in necessary for sidewise facing cameras to have a FOV of 60° to have at least one adjacent string visible. Cameras should preferably have high resolution and good light sensitivity to observe LEDs on adjacent strings.

A schematic diagram of PDOMs in the hole ice along with probable camera positions are shown in the Figure 1. A summary of objectives, measurements and requirements based on some preliminary calculations are given in the Table 1.

3. Camera Design and Interface

The camera system would consist of one or more upward or sidewise facing cameras along with one or multiple bright LEDs with a narrow beam angle ($\sim 20^\circ$) as light sources. The camera system

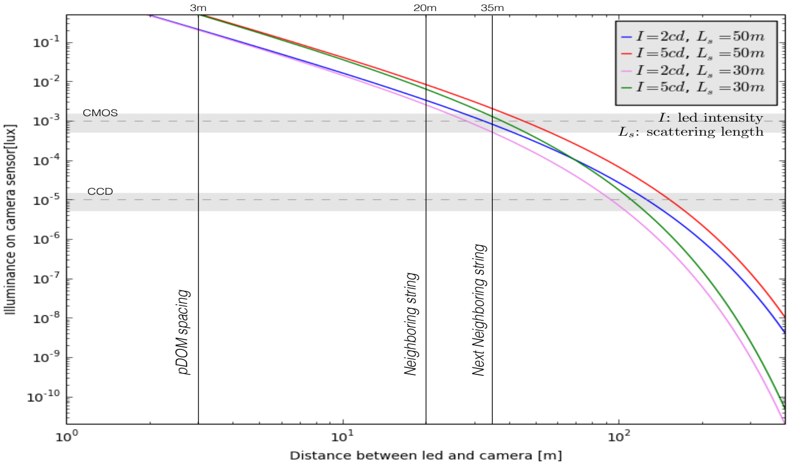

Figure 2: The minimum illumination required to observe an LED located in the neighboring PDOM in the same string and at adjacent string are shown. The grey shaded area show the illumination for a CMOS camera with at 1 s exposure time and CCD camera sensitivities as specified by the manufacturer for an exposure time 1/60 s.

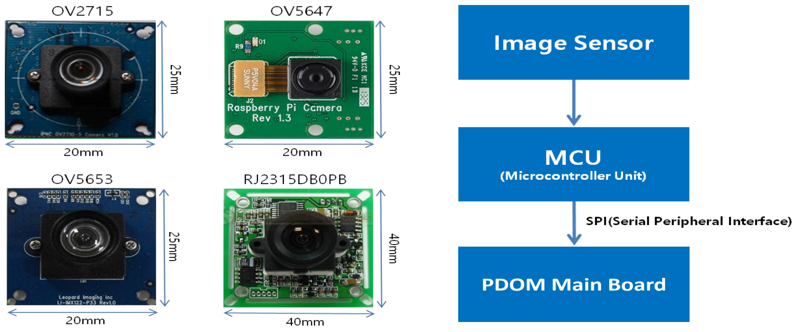

Figure 3: **Left :** Camera modules currently being tested include CMOS sensors OV2715, OV5647 & OV5653 and CCD sensors RJ2315DB0PB. **Right :** Block diagram for the camera interface.

would be either mounted on the PDOM main board or attached to the penetrator of the pressure sphere for easy assembly. As shown in Figure 3, the camera module would be mounted on a small (∼ 40mm×40mm) Printed Circuit Board along with a MCU (Micro Controller Unit) for image processing and communicate with the mainboard via SPI (Serial Peripheral Interface).

The camera system would remain in power saving mode during physics data taking and only be activated for calibration runs. The targeted power consumption per the camera system during operations is less than 1 W as the total power available per quad (4 PDOMs connected together) is ∼2.5 W. While PDOMs (PMT) will be off during camera operations it is desirable to have multiple cameras and LEDs active to minimize time for calibration measurements. Following image capture, uncompressed images would be transferred to the PDOM mainboard and then through the IceCube coaxial cable at 40kB/s per PDOM to the surface, where they would be saved for offline analysis.

4. System requirements

Various CMOS and CCD camera modules are considered as candidates for the camera system. Currently we are studying three CMOS cameras & one CCD camera (see Figure 3). All the cameras have manufacturer specified operation temperatures down to -30°C. A lens with wide field of view can be mounted on the camera sensor. One of the requirements for the camera system is that it has a low power consumption, which favours CMOS cameras (∼ 0.3 W). Further CMOS sensors are inexpensive and have high resolution. CCD cameras on the other hand have significantly higher sensitivities, but also consume more power (∼ 1.0 W) and have a lower resolution. The candidate CMOS and CCD cameras have resolutions of 2 MP-5 MP, and 0.3 MP, respectively.

To minimise detector downtimes for calibration measurements, a camera with higher light sensitivity is preferred. However, some measurements might require high resolution (if not limited by image distortion in the glass sphere) and power constraints might favor the CMOS camera. For the moment we consider both CCD and CMOS cameras as candidates.

Longer exposure times with the CMOS camera might achieve similar sensitivities to CCD cameras. CMOS cameras are expected to be operated in their most sensitive settings if noise levels are sufficiently low. The light sensitivity of a digital camera can be set through the ISO (International Standards Organization) number (i.e. higher number corresponds to higher sensitivity). Figure 2 shows the required illumination at the camera to see a typical bright LED (∼ 2-3 candela) as a function of distance. The required illuminance to observe a LED on the neighbouring DOM in the same string and in the adjacent string are around 0.1 lux and 0.001 lux respectively.

5. Camera measurements at the lab

We describe the camera performance measurements that will be our basis for the camera selection. We have setup measurements to compare and characterize: (1) camera noise, (2) light sensitivity, and (3) camera resolution and image distortion due to the glass sphere. Currently we have surveyed one CMOS camera (OV5647) to develop the series of tests that will be used for camera selection. Our current sample camera has 5 million pixels (2592 × 1944) and is currently operated through a Raspberry Pi for convenience. We obtained raw images in Bayer format. A Bayer filter is a RGB (Red, Green & Blue) color filter array on a square grid of photosensors. Each primary color red, green & blue has 8 bits, which means counts will go in saturation at 255 counts.

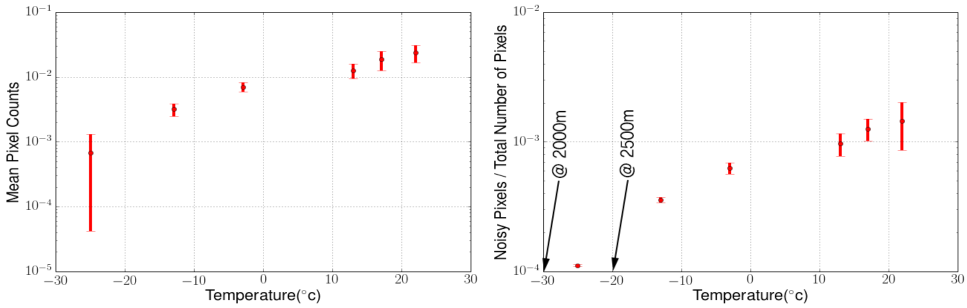

Figure 4: Left: Mean noise count per pixel as function of temperature for OV5647 for ISO 800 and 6s exposure. **Right:** The number of noisy pixels vs temperatures. Temperatures at depths 2000 m and 2500 m are indicated with arrows.

Camera Noise : A low brightness camera measurement might be limited by intrinsic detector noise, hence we characterise noise and stability under the expected conditions in the deep ice. We measured dark noise at room temperature in a dark box and at low temperatures in a freezer. Images were captured with exposure times of up to 6 seconds and for ISO 100, 400, and 800. Camera noise increases with exposure time and sensitivity setting (ISO value). At room temperature about $\sim 1\%$ of pixels are noisy, showing one or more counts. The number of noisy pixels (both fixed pattern and random) and average count per pixel decreases significantly with temperature (see Figure 4). In the deep ice at 2500 m ($-20°C$) to 1500 m ($-45°C$) noise is expected to be sufficiently low.

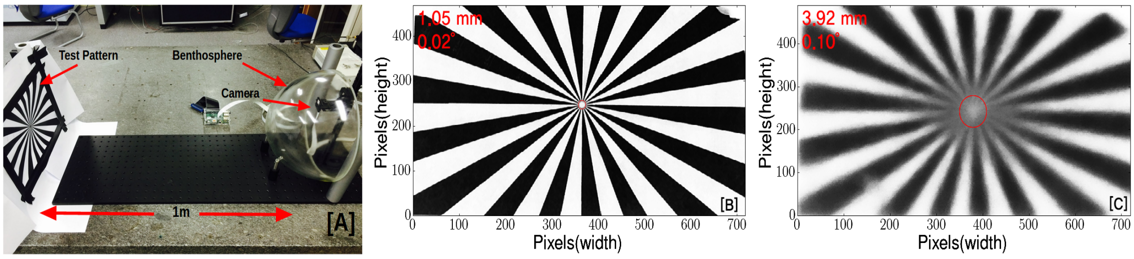

Figure 5: [A] Setup to study image distortion due to the Benthosphere. Image without [B] and with [C] Benthosphere. Red circles indicate the region where line patterns cannot be distinguished.

Image Resolution and Distortion: As the camera would be located inside the PDOMs pressure glass sphere (Benthosphere), images are bound to be distorted. We measure image resolution under normal conditions and through the Benthosphere. As the resolution measurement is subjective, we are investigating different independent ways to measure it. As an example we show a test pattern measurement shown in Figure 5. In the test pattern black and white lines originate in the center and radiate outward. We captured images of the test pattern at 1 m distance from the camera with and without the Benthosphere. The relative effect of image distortion can clearly be seen in image [C] in Figure 5. The line pattern cannot be distinguished inside the red circles in plots [B] & [C]. As the camera under test has a FOV of 60°, by measuring the diameter of the circle we can determine the resolution. We find the resolution of the camera without the Benthosphere to be ~1.05 mm (0.024°) and with ~3.92 mm (0.10°) at 1 m distance. The Benthosphere reduces the resolution by a factor of 4. Optical gels or optimised positioning could reduce this effect. Further we note that due to refraction in ice the angular resolution will improve by $n_{ice}/n_{air} \simeq 1.3$ and a camera FOV of 60° will be reduced to 45°.

Sensitivity of the camera: To study camera sensitivity, we illuminate the camera sensor uniformly (homogeneous within 5%) as shown in Figure 6. The camera is operated in different sensitivity settings defined by the product of analog and digital gain. For OV5647 gains are auto adjusted if the camera is near saturation. To increase the cameras dynamic range counts show a logarithmic behaviour for large exposure times and illuminations. A linear behaviour can be seen for low pixel count rates as shown in Figure 6. The pixel count rates determined at room temperature for 1 s exposure are 158 ± 12 counts/lux, 78.4 ± 5.0 counts/lux, and 20.6 ± 0.5 counts/lux for ISO800, 400, and 100, respectively. We verified that count rates are independent of temperature, with $-25°$C being the lowest measured temperature so far. We compare the observed rates, S, with the camera dark noise, N, to determine its sensitivity. We define the sensitivity as S/N~10. At $-25°$C the N=0.001 counts, which results in a sensitivity of 6×10^{-5} lux at ISO800 and 1 s exposure. If we require at least one pixel count an intensity of 0.006 lux is found. As seen in figure 2, the required luminance to see a bright LED ($\sim$ 2 cd) in the neighboring string at 20 m distance is 0.001 lux. Hence, LEDs on adjacent strings will be observable with few seconds exposure times.

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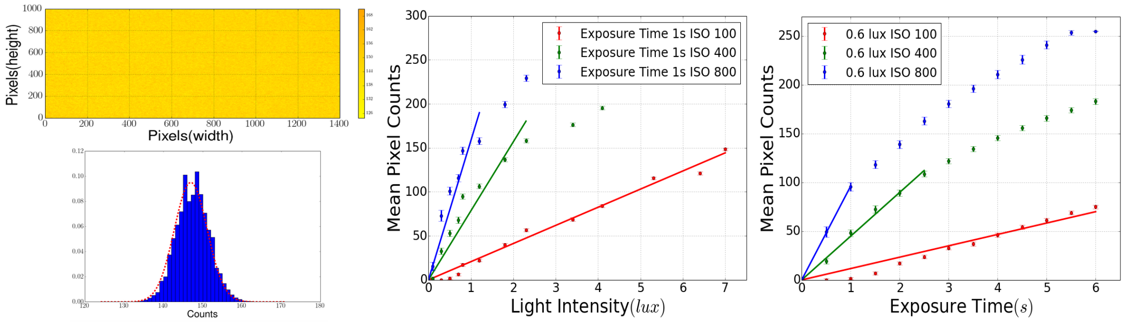

Figure 6: Pixel counts for uniformly illuminated sensor (left). Mean pixel counts for different camera sensitivities as function of the light intensity (middle) and exposure time (right).

6. Conclusions

Low-cost high resolution cameras integrated with the optical module design for IceCube upgrades would be tremendously helpful in understanding the ice environment of the sensors. The systems could survey the refrozen ice in the drill hole, aid geometry measurements, and study ice properties. Cameras could assist the effort to help reduce uncertainties on detection and light propagation in the ice and hence help achieve PINGUs and IceCube-Gen2 physics objectives faster and even benefit IceCube analyses. We have set up a framework to study cameras under conditions, similar to those encountered in the ice, and reported results for camera candidate OV5647. Under idealised conditions the camera is found to be sufficient to carry out the proposed measurements. We have started ray-tracing simulations with GEANT4 to better determine camera system requirements and will comprehensively compare different candidate modules. We are designing a prototype for integration tests. In the future we will also consider stereoscopic camera pairs and expand tests to include B&W cameras, that could be illuminated with RGB LEDs to compose color images.

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