

PINGU Camera System to Study Properties of the

² Antarctic Ice

The IceCube-Gen2 Collaboration¹,

¹ http://icecube.wisc.edu/collaboration/authors/icrc15_gen2

E-mail: debanjan.tifr@gmail.com

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.

Corresponding authors: D. Bose^{*}, M. Jeong, W. Kang, J. Kim, M. Kim, C. Rott *Department of Physics, Sungkyunkwan University, Suwon 440-746, South Korea*

The 34th International Cosmic Ray Conference, 30 July- 6 August, 2015 The Hague, The Netherlands

*Speaker.

3 1. Introduction

IceCube, the world's largest neutrino telescope, utilizes the ultra-pure Antarctic ice at the geo-4 graphic south pole as a detector medium. The recent discovery of high energy astrophysical neutri-5 nos [1, 2] by IceCube as well as a variety of other high impact results in the fields of astrophysics 6 and particle physics have proven the success of the detector concept. Extensions to the IceCube 7 detector, in form of a multi-megaton precision neutrino detector with an energy threshold of about a 8 GeV, known as the Precision IceCube Next Generation Upgrade (PINGU) [3, 4], and a high-energy 9 neutrino detector optimised for observing TeV to PeV neutrinos, known as IceCube-Gen2 [5, 6], 10 are being considered. The extensions will reuse the very reliable design of IceCube's digital optical 11 models (DOMs), however several improvements are envisioned. Among the improvements con-12 sidered is an on-board camera system that is targeted at surveying the ice surrounding the optical 13 sensors, which has not been measured and could be a key to reduce systematic uncertainties on 14 light propagation in the ice. In this proceeding we focus on a camera system for PINGU, which 15 targets the determination of the neutrino mass hierarchy and searches for dark matter. 16



Figure 1: Left: Schematic drawing to illustrate potential camera measurements: (#H1) Detection of bubble column in the hole ice due to diffusion. (#H2) Mapping of hole ice. (#H3) Cable position and orientation. (#B1) Measure light transmission and scattering at hole ice - bulk ice interface. (#B2) Light attenuation and scattering in the bulk ice. (#G1) Orientation of camera DOM with respect to neighbouring DOM(s) in the adjacent string. (#G2) Distance between neighbouring DOMs in the adjacent strings. Right: Probable locations of the camera system, inside the DOM, is shown in this diagram. Details of the measurements are described in Table 1.

17 Like IceCube, PINGU would detect neutrinos via Cherenkov light emission from secondary par-

ticles generated when a neutrino interacts in the deep Antarctic ice. Reconstruction of neutrino

¹⁹ induced events depend strongly on the accurate modeling of the light propagation in the ice. A

²⁰ multitude of calibration devices including LED flashers, retrievable laser systems in the drill holes,

²¹ 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

Objective	Measurement	Requirements for Camera System		
		Resolution	Sensitivity	Orientation
(#H1) Verify degassing in	Scattered light from bubbles	5MP	0.1 lux	Facing up
refrozen ice				
(#H2) Hole ice mapping	Scattered light of the hole /bulk	1 MP	0.1 lux	Facing
	ice interface			sidewise
(#H3) Cable position &	Cable shadow from in the hole	1 MP	0.1 lux	Facing up
orientation				
(#B1) Light transmission	Scattering of distant LED light	5 MP	0.001 lux	Facing
at hole / bulk interface	in the surrounding			sidewise
(#B2) Scattering and ab-	Light distribution and scatter-	5 MP	0.001 lux	Facing
sorption lengths	ing halo on adjacent strings			sidewise
(#G1) Orientation of	LED emission from one or	1 MP	0.001 lux	Facing
camera DOM	more adjacent string DOMs			sidewise
(#G2) Distance between	Observe multiple LEDs from	5 MP	0.001 lux	Facing
DOMs	adjacent DOMs			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. Camera sensitivities are estimated assuming a bright LED with two candela intensity as light source. Objectives are grouped by hole ice studies (#H1, #H2 & #H3), light propagation in the bulk ice (#B1 & #B2), and geometry calibration measurements (#G1 & #G2). The required light sensitivities for the camera system are calculated, in order to detect scattered light from LEDs located in the DOMs in the same string and in the adjacent string.

pointing 405 nm LEDs on each DOM, are indispensable for the most advanced models of ice prop-23 erties, as they provide calibration points through-out the detector. Fits to their data have resulted in 24 the most advanced ice model [7]. The present calibration system however has several short com-25 ings, in particular little is known about the individual environment surrounding each DOM. The 26 refrozen ice in the drill hole is not very well understood and there is good reason to expect that the 27 environment of each DOM could be significantly different. A low cost, high resolution on-board 28 camera system paired with a bright LED for illumination deployed on each PINGU DOM (PDOM) 29 could tremendously improve our understanding of the refrozen ice in the drill hole. It could yield 30 qualitative information valuable in interpreting other calibration measurements, such as the LED 31 flashers, and provide quantitative measurements of the ice properties. 32

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 [8]. The system 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. The bubble column shows significantly reduced scattering length. The system identified impurities settling on the surface of glass sphere of the camera. Information about the ice and drill hole provided by the system is limited to a small region where the system is located.

76

40 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 DOMs within the drill hole and survey the ice environment.

A variety of measurements could be performed with a camera system, each of which comes with its own requirements on the positioning of the camera, its sensitivity, field of view (FOV), resolution, and illumination options. We describe the suite of potential measurements qualitatively and describe the basic requirements for the camera system to perform them.

(1) The camera system could monitor the freeze-in process of the strings of DOMs deployed 47 after melting holes using a hot water drill [9]. Little is known about the refreezing process. For 48 the measurement the camera would be operated at $0^{\circ}C$, and would preferentially be facing up or 49 sidewise. A high-resolution color camera could best identify impurities and monitor the freeze-50 in dynamics. Triboluminescence or the formation of cracks could potentially be observed. For 51 PINGU it has been proposed to degas drill water in an effort to reduce or eliminate the formation 52 of bubbles. The camera system could provide immediate feedback about water quality and the 53 effectiveness of degassing could be verified with the camera system, including depth dependence 54 of bubble formation. 55

(2) Surveying the completely refrozen drill hole is one of the highest priorites 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 DOM.

(3) Another objective is to study properties of the untouched or pristine ice (referred as 'bulk 62 ice') between holes, and how light transmission is affected at the hole ice - bulk ice intersection. 63 The observation of a halo of scattered light from a LED on an adjacent string could be used to 64 study scattering, while the observation of the LED itself could be used to study attenuation. A 65 high-resolution, high-sensitivity black and white camera would be most desirable for this purpose. 66 (4) A camera system could also assist geometry measurements. By observing a LED, on the 67 adjacent upper DOM, the relative orientation (around the z-axis) of the DOM with an upward fac-68 ing camera can be determined. The orientation of a DOM on an adjacent string could also be 69 determined through the observation of one or more LEDs on it, this would require a high reso-70 lution camera that could resolve individual LEDs on an adjacent DOM. From the light pattern in 71 the captured image, one can determine relative orientation of the camera DOM as well. Likewise, 72 a camera system facing up would capture scattered light coming from LEDs in the neighbouring 73 DOM in the same string and studying the light pattern we can determine relative orientations be-74 tween DOMs and their positions inside the hole. The relative depth of DOMs between adjacent 75

⁷⁷ 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 DOM environment for anything
unforeseen and also provide a way to check for any dynamic effects, which are not expected after
freeze-in.

strings could also be determined. All these information would improve the geometry calibration of

Nearly all measurements benefit from a large FOV, making fisheye lenses the preferred option.

⁸² 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

⁸⁴ 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.



Figure 2: The minimum illumination required for a camera to see 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.

3. Camera Design and Interface



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.

⁸⁹ The camera system would consist of one or many cameras along with one or multiple bright LEDs

with a narrow beam angle ($\sim 20^{\circ}$) as light sources. The camera system would be either mounted

on the DOM main board or attached to the penetrator of the pressure sphere for easy assembly.

The camera module would be mounted on a small PCB (Printed Circuit Board) of dimension ~ 40mm×40mm along with a MCU (Micro Controller Unit) for image processing. This system would communicate with the main board of the DOM via SPI (Serial Peripheral Interface) as shown with a block diagram in the Figure 3. Cameras could be oriented facing up or facing sidewise as required.

The camera system would remain in power saving mode during physics data taking and only 97 be activated for calibration runs. The targeted power consumption per the camera system during 98 operations is less than 1 W as the total power available per quad (4 DOMs connected together) 99 is \sim 2.5 W. While DOMs (PMT) will be off during camera operations it is desirable to have mul-100 tiple cameras and LEDs active at the same time to minimize time for calibration measurements. 101 Following image capture, uncompressed images would be transferred to the DOM mainboard via 102 SPI interface and then to the surface, where they would be saved for offline analysis. IceCube 103 data transfer rates are about 40kB/s per DOM, which allow for the transfer of large uncompressed 104 images within minutes. 105

4. System requirements

Various CMOS and CCD camera modules are considered as candidates for the camera system. 107 Currently we are studying three CMOS cameras & one CCD camera (see Figure 3). CMOS cam-108 eras have high resolutions (\sim 2MP-5MP). Resolution of CCD camera is 0.3MP. All these cameras 109 can be operated over a wide range of temperatures (-30° C to 70° C). A lens with wide field of view 110 will be mounted on the camera sensor. One of the requirements for the camera system is that it has 111 a low power consumption, which favours CMOS cameras (~ 0.3 W). Further CMOS sensors are 112 inexpensive and have high resolution. CCD cameras on the other hand have significantly higher 113 sensitivities, but also consume more power (~ 1.0 W) and have a lower resolution. 114

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 (\sim 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.

126 5. Camera measurements at the lab

¹²⁷ 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

¹³⁰ 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.

Camera Noise : A low brightness measurement might be limited by intrinsic detector noise, hence 135 we need to characterise camera noise and stability under the expected conditions in the deep ice. 136 We measured the camera dark noise at room temperature in a dark box and at low temperatures 137 in a freezer. Images were captured with exposure times of up to 6 seconds and for ISO 100, 400, 138 and 800. Camera noise increases with exposure time and sensitivity setting (ISO value). At room 139 temperature about $\sim 1\%$ of pixels are noisy, where a noisy pixel is defined as a pixel with one or 140 more counts. The number of noisy pixels and average noise count per pixel decreases significantly 141 with temperature as shown in the Figure 4. 142



Figure 4: Left: Average noise count per pixel as function temperature for OV5647 for ISO 800 and 6s exposure. **Right:** The number of noisy pixels vs temperatures.

Image Resolution and Distortion: The camera system would be located inside the DOMs pres-143 sure glass sphere, called the Benthosphere. Therefore images are bound to get distorted. We 144 measure image resolution under normal conditions and through the Benthosphere. As the resolu-145 tion measurement is subjective, we are investigating different independent ways to measure it. As 146 an example resolution test we show the measurement with a test pattern shown in Figure 5 and 147 captured images. In the test pattern black and white lines originate in the center and radiate out-148 ward. We captured images of the test pattern at 1 m distance from the camera with and without the 149 Benthosphere. The relative effect of image distortion can clearly be seen in image [D] in Figure 5. 150 The line pattern cannot be distinguished inside the red circles in plots [C] & [D]. As the camera un-151 der test has field of view (f.o.v.) of 60°, by measuring the diameter of the circle we can determine 152 the resolution. We find the resolution of the camera without the Benthosphere to be ~ 1.05 mm 153 (0.024°) and with ~ 3.92 mm (0.10°) . The Benthosphere reduces the resolution by a factor of 4. 154 Due to refraction in ice, a 60° f.o.v. will become 45° f.o.v. (because index of refraction in air is 155 1 and in ice 1.3). So in the ice, corresponding values for the resolution would be ~ 0.76 mm & 156 ~ 2.80 mm, respectively. 157

Sensitivity of the camera: To study light sensitivity of the camera, we illuminate the camera sensor uniformly as shown in Figure 6. The distribution is homogeneous within 5%. The mean pixel count varies linearly with incident light intensity and exposure time as shown. Saturation can be observed for pixel counts close to 255 and are not included in the linear fits. The pixel count rates

determined at room temperature for 1 s exposure are 176 ± 18 counts/lux, 79.3 ± 8.0 counts/lux, 162 and 20.2 ± 2.0 counts/lux for ISO800, 400, and 100, respectively. We verified that count rates 163 are independent of temperature, with -25° C being the lowest measured temperature so far. We 164 compare the observed rates with the camera dark noise to determine the its sensitivity. We define 165 the sensitivity as S/N \sim 10. At -25° C the average noise per pixel is approximately 0.001counts, 166 which results in a sensitivity of 5×10^{-5} lux at ISO800 and 1 s exposure. If we require at least 167 one pixel count an intensity of 0.005 lux is found. As seen in figure 2, the required luminance to 168 see a bright LED (~ 2 cd) in the neighboring string at 20 m distance is 0.001 lux. Using the linear 169 relationship shown in the figure 6 we find that at ISO 800 with a few seconds exposure time we can 170 observe LEDs on adjacent strings with high signal to noise ratio. 171



Figure 5: [A] Setup to study image distortion due to Benthosphere for CMOS camera OV5647. [B] Test pattern used for resolution study. [C] Image without Bethosphere. [D] Image with Benthosphere. Red circles in [C] & [D] indicates the region where line patterns can not be distinguished.



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

172 6. Conclusions

We have presented here the objectives and the basic design concept of the camera system. PINGU 173 aims to detect GeV neutrinos. In order to achieve the lowest possible energy threshold and still 174 reconstruct events with high accuracy a detailed understanding of the detector medium is needed. In 175 order to facilitate this goal, the proposed camera system would provide high quality data about ice 176 conditions surrounding every DOM and a series of measurements can be used to better understand 177 the refrozen hole ice, study light propagation, and determine the PINGU geometry. We have set 178 up a framework to study various camera candidate modules under extreme conditions, similar to 179 those encountered in the ice. We have reported our investigations for camera module OV5647. 180 We found that intrinsic noise at temperatures in the deep ice $-20^{\circ}C$ at 2500 m and $-45^{\circ}C$ at 181 1500 m is expected to be sufficiently low. The mean pixel count scales linearly with exposure time 182 and with the intensity of the incident light. We will compare different camera candidate modules 183 following this framework before making a final selection. We have started ray-tracing simulations 184 with GEANT4 to better determine requirements for the proposed camera measurements. In parallel 185 we are designing a prototype. 186

187 References

- 188 [1] IceCube Collaboration, *Phys. Rev. Lett.* **113**, 101101, (2014)
- 189 [2] IceCube Collaboration, *Science* **342**, 1242856, (2013)
- [3] IceCube-Gen2 Collaboration, K. Clark et al., These proceedings paper, 1379, (2015)
- 191 [4] IceCube-PINGU Collaboration, M. Aartsen et al., [arXiv:1401.2046]
- [5] IceCube-Gen2 Collaboration, E. Blaufuss et al., These proceedings paper, 741, (2015)
- [6] IceCube-Gen2 Collaboration, M. Aartsen et al., [arXiv:1412.5106]
- [7] IceCube Collaboration, *Nuclear Instruments and Methods* A711, 73-89, (2013)
- [8] Per Olof Hulth, *Results from the IceCube video camera system at 2455 meters ice depth*, *Very Large Volume Neutrino Telescope Workshop*, **325**, (2013)
- [9] Francis Halzen and Spencer R. Klein, *Review of Scientific Instruments* 81, 081101, (2010)