Deployment and Operation of the IceCube Upgrade Camera Calibration System

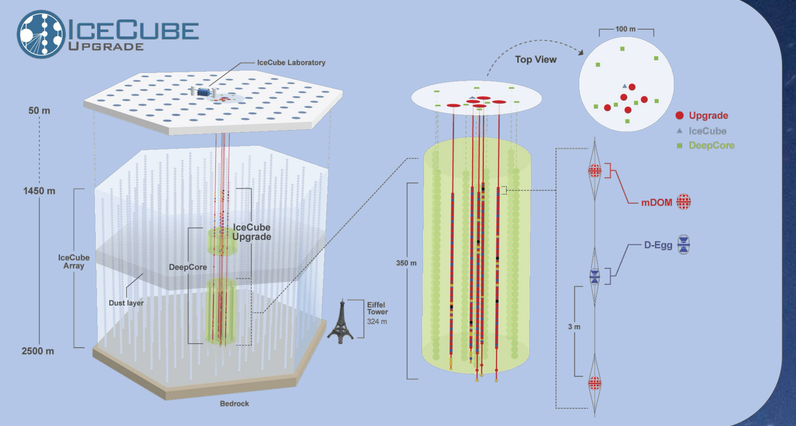
Vedant Basu, Seowon Choi, Shouvik Mondal, Rumman Neshat, Carsten Rott, Jorge Torres,
(for the IceCube Collaboration)
University of Utah, Salt Lake City, Utah, USA

The IceCube Neutrino Observatory

- World's largest neutrino telescope, located at the South Pole, using a cubic kilometer of Antarctic ice as a natural detection medium.
- Detects neutrinos by observing Cherenkov light from charged particles produced by neutrino interactions within the ice.
- Has delivered groundbreaking results in neutrino astronomy, including the first identification of astrophysical neutrino sources.

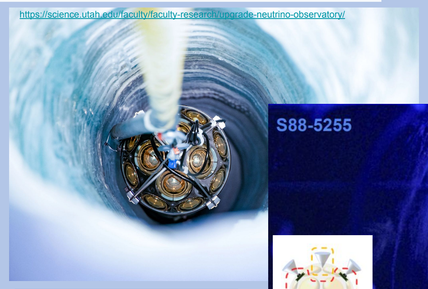
Deployment and First Camera Runs

String Number	Drilling	String deployment	First Camera Calibration Run
87	12/20/2025	12/24/2025	01/02/2026
88	12/26/2025	12/31/2025	01/06/2026
89	1/2/2026	1/4/2026	01/14/2026
90	1/6/2026	1/9/2026	01/22/2026
91	1/11/2026	1/13/2026	01/30/2026
92	1/16/2026	1/20/2026	01/26/2026



The IceCube Upgrade

- The IceCube upgrade, deployed during the 2025/2026 Antarctic summer season, adds **five more cables (strings)** instrumented with optical sensors to IceCube.
- These new strings have a two-fold goal:
  - Enhancement of IceCube's sensitivity to **neutrino oscillations**.
  - Improved **calibration of the ice properties** of the surrounding ice.
- Improved calibration will help understanding of reconstruction systematic uncertainties.



An mDOM is lowered into a borehole.
Credit: Yuya Makino, IceCube/NSF

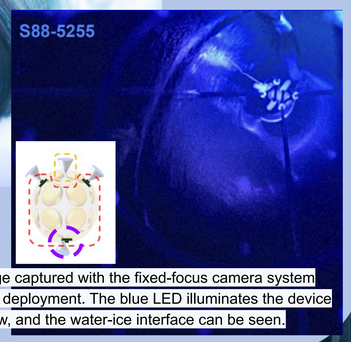


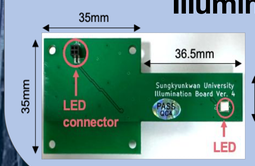
Image captured with the fixed-focus camera system after deployment. The blue LED illuminates the device below, and the water-ice interface can be seen.

The fixed-focus camera calibration system

Camera Module

CMOS color image sensor (*Sony, IMX225LQR*)
Large field-of-view with **fisheye lens** (~170° in air, ~90°-100° under ice)
Image data : **1312× 979** resolution, **12-bit** depth (**2.7MB**)
FPGA bridges camera and the module main board (**SPI**)

Illumination Module



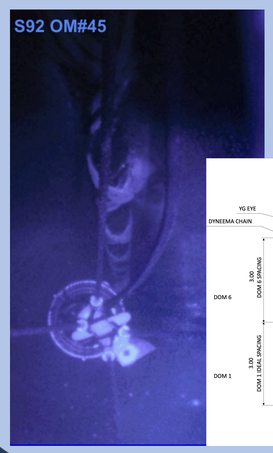
Blue color **LED** light source (Osram, GD CS8PM1.14-UOVJ-W4-1)
Dominant wavelength **455nm**, FWHM : **80°**

University of Utah Graduate Student, Rumman Neshat, demonstrating large FOV of the camera system, during the Utah IceCube Masterclass 2025.

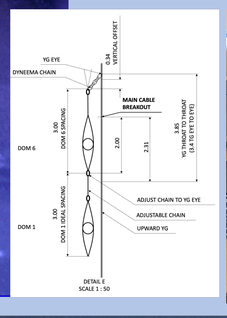
Self-image obtained in the ice

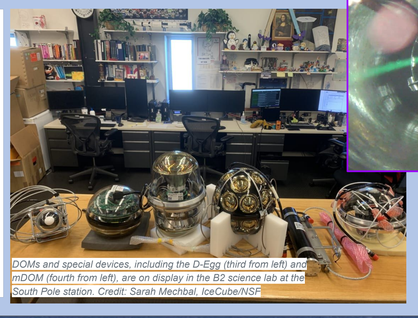
- Integrated into every optical module, they capture images under the ice.
- **Hole ice measurement** : starting immediately after the deployment, the system capture images of the **refreezing process of the drill hole** to study freeze-in process and the properties of the **refrozen hole ice**
- **Bulk ice measurement** : by **imaging** light emitted from sources located in **neighboring drill holes**, the system can probe the optical properties of the **bulk glacial ice**
- **Detector geometry measurement** : by performing inter-module observations using all the cameras and LEDs in the mDOMs and D-Eggs, the system provides **relative orientations and positions of the modules**

Calibration of ice optical properties

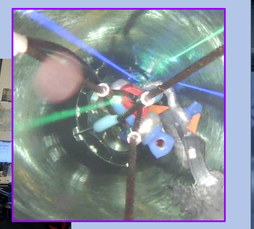


- **Continuation** of the highly successful and **well-proven calibration campaigns** from IceCube (Dust logger, flasher LEDs[1], Sweden Cam x2, …)
- Addition of **novel calibration devices** - Upgrade Camera System[4], POCAM[2], Acoustic system[3],Pencil beam [5].
- **Goal:** Obtain improved optical ice model and extrapolate it to full IceCube detector region



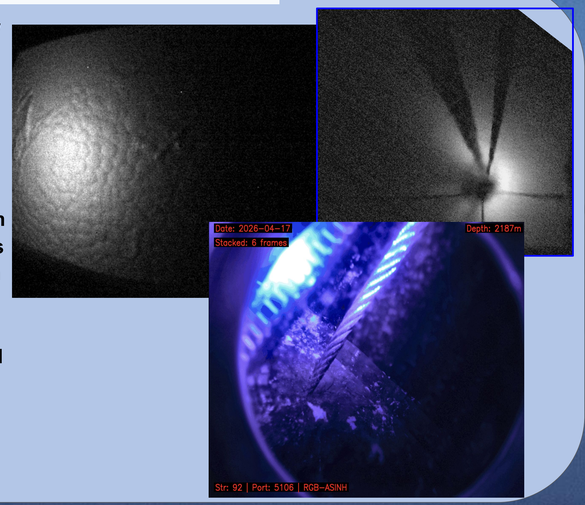


DOMs and special devices, including the D-Egg (third from left) and mDOM (fourth from left), are on display in the B2 science lab at the South Pole station. Credit: Sarah Mechbal, IceCube/NSF



Summary

- IceCube Upgrade was **successfully deployed** during austral summer 2025/2026
- A broad spectrum of calibration devices were deployed, including cameras that were integrated in all primary sensor modules
- Cameras started observing **freeze-in process shortly after deployments** to obtain comprehensive image data
- These data will improve our understanding of the **systematic uncertainties related to the optical properties** of the instrumented ice and beyond
- As of May 11, 2026, approximately **40,000 images taken**



References

1. Abbasi, R., et al. "The LED calibration systems for the mDOM and D-Egg sensor modules of the IceCube Upgrade." *JINST* 20 (2025) 11, P11026

2. Khera, N. and Henningsen, F., 2021. POCAM in the IceCube Upgrade. *arXiv preprint arXiv:2108.05298*

3. Benning, C., Borowka, J., Günther, C., Gries, O. and Zierke, S., 2023. Performance Studies of the Acoustic Module for the IceCube Upgrade. *arXiv preprint arXiv:2308.08506*

4. Kang, W.; Lee, J.; Rodan, S.; Rott, C.; Tönnis, C., on behalf of the IceCube Collaboration. The Camera System for the IceCube Upgrade. *Phys. Sci. Forum* **2023**, *8*, 49. https://doi.org/10.3390/psf2023008049

5. M. Rongen and D. Chirkin on behalf of IceCube, Advances in IceCube ice modelling & what to expect from the upgrade, J. Instrum. 16, C09014 (2021).