IceCube Neutrino Observatory
Management & Operations

PY2 Annual Report

Kite aerial photo of the IceCube lab, February 2023. Hrvoje Dujmovic, IceCube/NSF

April 1, 2022 - February 28, 2023

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Submitted by:

Francis Halzen
Principal Investigator
University of Wisconsin-Madison

Kael Hanson
Co-PI and Director of Operations
University of Wisconsin-Madison

Albrecht Karle
Co-PI and Associate Director for Science and Instrumentation
University of Wisconsin-Madison

James Madsen · Associate Director for Education and Outreach
John Kelley · Detector Operations Manager
Benedikt Riedel · Computing and Data Management Services Manager
Juan Carlos Díaz-Vélez · Data Processing and Simulation Services Manager
Erik Blaufuss · Realtime Coordinator / Software Coordinator
Martin Rongen, Dawn Williams · Calibration Coordinators

This PY2 Interim Report is submitted as required by the NSF Cooperative Agreement OPP- 2042807.
This report covers the 12-month period beginning April 1, 2022, and ending March 31, 2023.

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1 IceCube Science Overview (F. Halzen)

In its first decade of operation, IceCube collected on the order of one million neutrinos, mostly of atmospheric origin. Among these, it discovered neutrinos of TeV-PeV energy originating beyond our Galaxy, providing us with the only unobstructed view of the cosmic accelerators that power the highest energy radiation reaching us from the extreme universe [1]. Increasingly precise measurements of their spectrum using multiple methodologies, revealed two surprises. First, unlike what is the case in all wavebands of light, the contribution to the cosmic neutrino flux from our own Galaxy is only at the 10% level (to be published in the journal Science). Second, the flux of gamma rays from the decay of the neutral pions that accompany the charged pions which decay into the cosmic neutrinos, exceeds the total extragalactic flux observed by gamma ray detectors. It implies that the targets in which the cosmic accelerators produce neutrinos are opaque to gamma rays. This has been confirmed with the emergence of the first neutrino sources.

After accumulating 10 years of statistics, the active galaxy NGC 1068 has been associated with the hottest spot in the neutrino sky map. It is also the dominant source in a search at the positions of 110 preselected high-energy gamma-ray sources. At the location of NGC 1068, we observe an excess of 79+22-20 neutrinos with TeV energies [2]. Additionally, we find evidence for the active galaxies PKS 1424+240 and TXS 0506+056. TXS 0506+056 had already been identified as a neutrino source in a multimessenger campaign triggered by a neutrino of 290 TeV energy, IC170922 [3], and by the independent observation of a neutrino burst from this source in archival IceCube data in 2014 [4]. The observations point to active galaxies opaque to gamma rays, with the obscured dense cores near the supermassive black holes emerging as the sites where neutrinos originate, typically within 10-100 Schwarzschild radii. We are thus closing in on the century-old problem of where cosmic rays originate.

The background of atmospheric neutrinos provides us with a high-statistic sample to study the oscillations of neutrinos. In a paper to be submitted soon, we present measurements of the so-called atmospheric neutrino parameters with a precision similar to what has been achieved by accelerator experiments. Our measurements are performed at higher energies, and will be further improved after the deployment of the Upgrade strings.

These highlights were very much made possible by the M&O team which delivered an improved calibration of the detector and a more precise calibration of all individual optical modules. These were applied to more than a decade of archival data. The same efforts also resulted in improved simulations.

2 Management and Operations Status and Performance

2.1 Financial/Administrative Performance (L. Mercier)

The University of Wisconsin–Madison has established two separate accounts with supporting charge numbers for collecting IceCube M&O funding and reporting related costs: 1) NSF M&O Core account, 2) U.S. Common Fund account.

The first PY2 installment of $5,470,645 NSF was released to UW-Madison to cover the costs of management and operations for the first nine months of PY2: $1,324,050 was directed to the U.S. Common Fund account based on the number of U.S. Ph.D. authors in the last version of the institutional MoUs, and the remaining $4,146,595 was directed to the IceCube M&O Core account (Table 1). The final increment for PY2, $1,823,549 was released increasing the total to $7,294,194 for PY2. Included in the second increment for PY2 there was included increment for PY3, $89,930 for PY3.

PY2: **FY2022/FY2023**	**Increment Funds Awarded** **(Apr 1, 2022–Dec 31, 2022)**	**Final Increment for PY2 Awarded** **(Jan 1, 2023-Mar 31, 2023)**
IceCube M&O Core account	$4,146,595	$1,823,549
U.S. Common Fund account	$1,324,050	$0
TOTAL NSF Funds	**$5,470,645**	**$1,823,549**

Table 1: NSF IceCube M&O funds – PY2 (FY2022/FY2023).

Of the IceCube M&O PY2 Core funds, $1,097,785 were committed to the U.S. sub awardee institutions based on their statement of work and budget plan. The institutions submit invoices to receive reimbursement against their actual IceCube M&O costs. Table 2 summarizes M&O responsibilities and total PY2 funds for the sub awardee institutions.

Institution	**Major Responsibilities**	**Funds**
Lawrence Berkeley National Lab	DAQ; computing	$91,822
Penn State University	Computing and data mgmt; sim production; DAQ	$39,055
University of Delaware	IceTop calibration, monitoring and maintenance	$177,554
University of Maryland	Software frameworks, online filter, simulation	$643,918
University of Alabama	Detector calibration, reco & analysis tools	$30,703
Michigan State University	Simulation software & production	$114,733
Total		**$1,097,785**

Table 2: IceCube M&O Subawardee institutions, major responsibilities and funding – PY2 .

2.1.1 IceCube NSF M&O Award Budget, Actual Cost, and Forecast

The current IceCube NSF M&O 5-year award was established in the middle of Federal Fiscal Year 2021, on April 1, 2021. The following table presents the PY2 financial status and estimated balance at the end of PY2.

PY2 awarded funds to UW–Madison (UW) for supporting IceCube M&O from the beginning April 2022 through February 28, 2023 is $7,294,194. Total actual cost as of February 28, 2023 is $6,742,830 and open commitments against purchase orders and subaward agreements total $855,742. The current balance as of February 28, 2023 is $756,735. With a projection of $481,525 for the remaining expenses during the final month of PY2, the estimated balance at the end of PY2 is $275,209, which is 4.08% of the PY2 budget (Table 3). The balance is in line with University of Wisconsin's accounting system (WISER). The End of PY2 Forecast balance, $275,209 will be used for the last of March payrolls which will be captured in April due to UW's bi-weekly payroll system.

(a)	(b)	(c)	(d)= a-b-c	(e)	(f)= d-e
YEAR 2 Budget (Apr 2022-Mar 2023)	**Actual Cost** to date Through Feb. 28, 2023	**Open Commitments**	**Current Balance**	**Remaining Projected Expenses through March 31, 2023**	**End of PY2 Forecast Balance as of Mar. 31, 2023**
$7,294K	**$6,743K**	**$856K**	**$757K**	**$482K**	**$275K**

TABLE 3 – BUDGET

2.1.2 IceCube M&O Common Fund Contributions

The IceCube M&O Common Fund was established to enable collaborating institutions to contribute to the costs of maintaining the computing hardware and software required to manage experimental data prior to processing for analysis.

Each institution contributes to the Common Fund, based on the total number of the institution's Ph.D. authors, at the established rate of $13,650 per Ph.D. author. The Collaboration updates the Ph.D. author count twice a year before each collaboration meeting in conjunction with the update to the IceCube Memorandum of Understanding for M&O.

The M&O activities identified as appropriate for support from the Common Fund are those core activities that are agreed to be of common necessity for reliable operation of the IceCube detector and computing infrastructure. These activities directly support the functions of winterover technical support at the South Pole, hardware and software systems for acquiring and filtering data at the South Pole, hardware and software systems for transmitting data via satellite and disk to the UW data center, systems for archiving the data in the central data warehouse at UW and UW data center operations as listed in the IceCube M&O Cooperative Agreement.

Table 4 summarizes the planned and actual Common Fund contributions for the period of April 1, 2022–February 28, 2023, based on v31.0 of the IceCube Institutional Memorandum of Understanding, from May 2022. The remaining contributions from non-U.S. collaborators are still underway, and it is anticipated that the planned contributions will be fulfilled.

	Ph.D. Authors	**Planned Contribution**	**Actual Received**
U.S.	97	$1,324,050	$1,324,050
Non-U.S.	75	$1,023,750	$ 975,698
Totals	**172**	**$2,347,800**	**$2,299,748**

Table 4: Planned and actual Common Fund contributions for the period of April 1, 2022–February 28, 2023.

2.1.3 Program Coordination

2.1.3.1 Education and Outreach (Jim Madsen)

The IceCube education and outreach team continued to promote IceCube science to the public through educational programs, in-person outreach events, and virtual offerings. This year saw a significant increase in in-person events after loosening COVID-19 restrictions and two years of virtual offerings. Here we provide updates on activities during the April 1, 2022 – March 31, 2023 reporting period. Our PY1-PY2 highlights are:

1. IceCube educational programs aimed at high school students and teachers through IceCube masterclasses, an after-school internship program, summer research activities, and South Pole webcasts targeting K-12 classrooms and the public.
2. Integration of current and former educators who have deployed to the South Pole in programs that aim to increase STEM awareness.
3. A return to in-person events engaging the public.
4. A collaboration-wide event that presented high-impact science results.
5. Updates to virtual reality resources to increase accessibility.
6. The launch of an IceCube citizen science project.

Figure 1 "Tidal Disruption" light sculpture created for GLEAM 2022.

As part of an ongoing collaboration, WIPAC worked with UW–Madison art professor Faisal Abdu'Allah and York University art/science professor Mark-David Hosale to design and fabricate a large sculpture (Fig. 1) depicting a star being shredded by a black hole. "Tidal Disruption" was on display September and October as one of nine installations in the GLEAM event at Olbrich Gardens in Madison, WI, which drew tens of thousands of visitors over two months. GLEAM is an annual outdoor art exhibit that displays large-scale light installations created by artists from around the world.

WIPAC saw an increase in in-person outreach events over the year, including a return to in-person field trips hosted by WIPAC over the summer. One field trip hosted Maydm interns, a local organization that equips underrepresented students in grades 6-12 with the skills and experience needed to pursue STEM careers by exposing them to various opportunities. WIPAC will continue to collaborate with Maydm for future events and site visits. A talk series was held for the South Dakota Davis-Bachall scholars, a program that connects first- or second-year science-curious undergraduates with peers and mentors involved in modern STEM research. WIPAC also hosted students from the Madison Country Day School Summer Research Academy, a summer program that allows high school students to explore areas in science outside the classroom. High school students in the 2022 summer UWRF Upward Bound program, led by former IceCube PolarTREC educator Kate Miller, explored science and technology by designing and building components for a technology-enhanced party. Joining other science outreach colleagues from UW–Madison, WIPAC also attended a science fair at a local community center, engaging with an audience of elementary-aged kids from groups underrepresented in science.

After a two-year hiatus, WIPAC also participated in Grandparent's University, an intergenerational learning experience designed to expose grandparents and their grandkids to research across the UW–Madison campus. WIPAC hosted a two-day session for ten grandparent-grandchild pairs that included hands-on activities and talks from guest speakers.

Figure 2. 2023 Frozen Assets Festival.

Other in-person WIPAC events included the fall 2022 Wisconsin Science Festival at the Discovery Building where approximately 1,500 people were in attendance and Science on the Square at the state capitol building. As part of the Wisconsin Book Festival, WIPAC joined author Andy Weir's talk about his latest book "Project Hail Mary," which includes mentions of IceCube. For the third year in a row, an IceCube light display was included in the annual Holiday Fantasy in Lights drive-through show in Olin Park in Madison, WI. In February 2023, WIPAC participated in Science on Ice as part of the Frozen Assets Festival. For the event, WIPAC set up a booth with cold weather gear and a cosmic bean bag toss on a frozen Lake Mendota. The booth was well attended and included a surprise visit from the UW–Madison mascot, Bucky Badger (Fig. 2).

This past year also saw a return to in-person programming for IceCube Masterclass and IceCube After School, both aimed at high school students. After two years of virtual offerings, WIPAC was excited to return in person for their flagship program, IceCube After School. Over the course of eight weeks, high school students in the Madison area learned about IceCube research and career opportunities in physics from guest speakers each week. Students also had the opportunity to collect and analyze data with their own Cosmic Watch muon detectors.

IceCube masterclasses are one-day events that give high school students and accompanying teachers a chance to experience real research using IceCube data. In spring 2022, 15 IceCube institutions across the world held masterclass events, many of which were held in-person. UW–Madison, Mercer/Georgia Tech (jointly), the South Dakota School of Mines and Technology (SDSMT), and Harvard held their events in April and May 2022. The Harvard masterclass was conducted in Spanish at local Boston middle school Los Amigos. The SDSMT masterclass was particularly successful, with 43 students and 4 teachers attending from South Dakota and Wyoming. Preparations are underway for the spring 2023 masterclasses with 25 institutions signed up.

PolarTREC educator Elaine Krebs spent Aug. 29 to Sept. 1, 2022, at WIPAC preparing for her upcoming deployment to the South Pole. She was deployed to the South Pole at the end of last year after a two-year delay due to COVID-19. Through PolarTREC, educators gain valuable hands-on research experience and connect with the community in the Antarctic and Arctic regions. While at the South Pole (Fig. 3), Elaine kept regular journal entries documenting her experiences at the South Pole and held a live webinar for the public. Elaine also mailed out 700 postcards that answered questions from students, friends, and family members. She is currently planning classroom visits and additional outreach activities centered around her experiences as a PolarTREC educator.

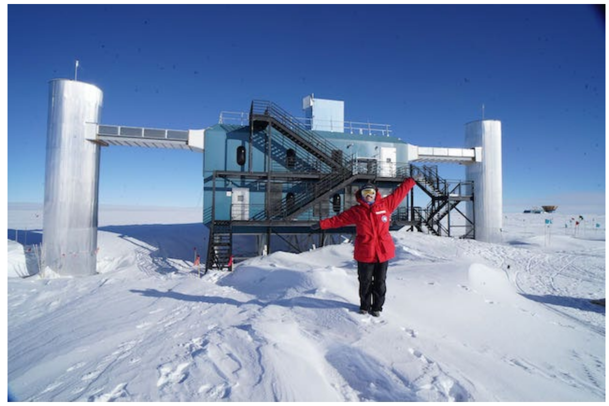

Figure 3. PolarTREC educator Elaine Krebs poses in front of the IceCube Laboratory.

IceCube held four South Pole webcasts, one live event with former IceCube winterovers, and provided multiple in-depth research experiences for high school students. Webcasts included: April 8, 2022, in conjunction with IceCube masterclasses; June 16, 2022, for over 100 Tennessee high school students in the Governor's School for the Sciences and Engineering; July 15, 2022, for high school students in the Maydm internship program, which places girls and students of color with local businesses with an emphasis on technology and STEM; and August 7, 2022, for the Expedition VRctica project described below. Two high school students were mentored remotely by WIPAC personnel, one doing a project on simulations that has evolved into an exploration of machine-learning techniques and the other a multiyear investigation learning about point source searches. WIPAC also provided an in-person research experience this summer (2022) for a high school student who had previously participated in the IceCube After School program.

The UW–Madison team (WIPAC, Field Day, and the Wisconsin Institutes of Discovery) that developed an IceCube virtual reality experience (VRE) held an inaugural meeting with rural librarians on Aug. 7, 2022, that included an IceCube presentation and a webcast from the South Pole. The five-year polar education project, *EHR-Polar DCL: Expedition VRctica: Utilizing Public Library Systems To Engage Rural and Latinx*

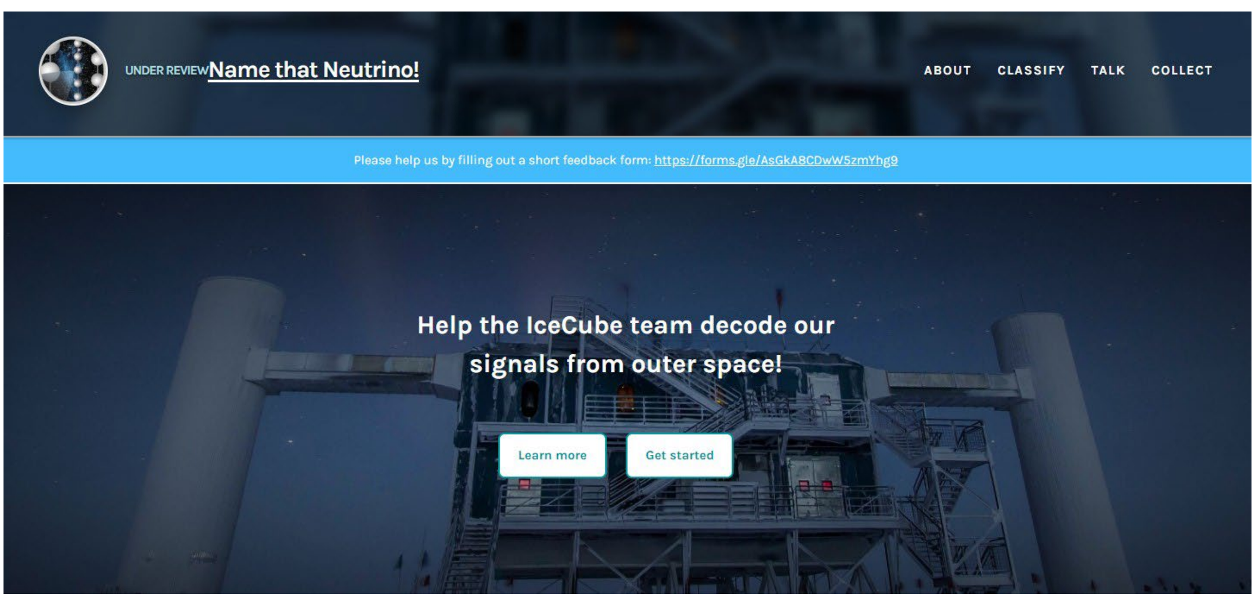

Figure 4. IceCube's "Name that Neutrino" citizen science project.

Communities in Polar Research, will redo the IceCube VRE and produce four new multilingual Polar VREs.

The IceCube citizen science project Name That Neutrino! (Fig. 4), developed by collaborators at Drexel University with technical support from WIPAC, has finished beta testing and is now scheduled to launch in March 2023. Through a platform called Zooniverse, the project, open to everyone, has volunteers classify IceCube events to compare performance with machine learning algorithms. After a brief video tutorial, volunteers will be able to assign categories to signals through the Zooniverse app on their phone or desktop client. Once launched, the project will run for 10 weeks. The insights gained from these comparisons may eventually help to improve IceCube event reconstruction and produce better results.

In November 2022, WIPAC hosted an in-person collaboration-wide event that was also offered virtually. For the event, a webinar was live streamed on Zoom and YouTube that presented results from a *Science* paper published on November 4, 2022. The webinar featured opening remarks from Steve Ackerman, vice chancellor for research and graduate education at UW–Madison, and Denise Caldwell, director of the Division of Physics at NSF, followed by a panel of IceCube scientists discussing the findings. More than 70 people attended the event in person while over 1,000 attendees watched the live stream across Zoom and YouTube. As of March 2023, the recorded webinar has garnered over 6,500 views on YouTube.

2.1.3.2 Communications

Figure 5: Social media graphic recognizing the 5-year anniversary of the detection of the "TXS neutrino."

Communications is responsible for promoting IceCube on social media and through other outlets such as the IceCube website and its monthly newsletter. IceCube continued to remain active on social media by posting timely events, sharing and promoting notable outreach events or activities, participating in global holidays, and celebrating IceCube anniversaries for key discoveries. For example, in September, a graphic (Fig. 5) was created to celebrate the 5-year anniversary of the detection of the neutrino that was eventually traced back to blazar TXS 0506+056. Most notably this past year, the promotion of the IceCube event that shared the results from the November *Science* paper was widely popular, with a boost in overall followers across all three social media platforms (Facebook, Instagram, and Twitter).

The top three posts based on the impressions/reach and the number of followers since September 2022 for each platform are summarized here:

Twitter (@uw_icecube) 14,600 followers (up 7.4% from September)

New IceCube results published in Science

Double tau paper published in EPJ C

IceCube has found evidence of high-energy neutrinos from NGC 1068

Facebook (@icecubeneutrino) 12,382 followers (up 2.7% from September)

New IceCube results published in Science

Major announcement coming soon!

Week 2 at the Pole

Instagram (@icecube neutrino) 6,641 followers (up 6.3% from September)

Winterover job advertisement

Snowmass summary

LGBTQ+ STEM Day

The impacts from the November *Science* paper were immediately felt during and after the event. Results from the *Science* paper were covered by high-profile outlets such as the Wall Street Journal, Physics Magazine, and Vice and by news outlets around the world.

IceCube and WIPAC news articles were regularly published on topics such as timely events, research results, and outreach endeavors. The IceCube newsletter is released monthly to subscribers and includes a photo of the month, summaries of IceCube research papers, IceCube press mentions, and outreach activities and events.

The WIPAC website has recently completed a platform migration for more efficient maintenance, and is currently undergoing content revisions and updates This is still an ongoing project, with plans to move efforts to the IceCube website in the future.

2.2 WBS 2.2: Detector Operations and Maintenance (J. Kelley)

During the period from March 1, 2022 to February 28, 2023, the detector uptime, defined as the fraction of the total time that some portion of IceCube was taking data, was 99.9%, exceeding our target of 99% and close to the maximum possible, given our current data acquisition system. The clean uptime for this period, indicating full-detector analysis-ready data, was 98.7%, exceeding our target of 95%. Other key performance metrics are listed in Table 5; in all cases performance metrics were met.

Figure 6 shows a breakdown of the detector time usage over the reporting period. The partial- detector good uptime was 0.69% of the total and includes analysis-ready data with fewer than all 86 strings. The excluded uptime of 0.51% includes maintenance, commissioning, and verification data. The unexpected detector downtime was limited to 0.12%.

Performance Metric	**Objective**	**Achieved**	**Description**
Total Detector Uptime	99%	99.9%	Detector taking data in some configuration; remains sensitive to rare, transient events.
Clean Detector Uptime	95%	98.7%	Full IC86 detector data usable by all analyses.
IceCube Live Uptime	99.9%	99.999%	Experiment control and monitoring functioning.
Supernova System Uptime	99%	99.9%	Supernova DAQ online.
L1 Processing Latency	< 60 sec	29 sec	90% quantile time from event in ice to processed event on disk.

Table 5: Detector operations key performance parameters from March 1, 2022 to January 31, 2023.

The total number of active DOMs in the data stream is currently 5403 (98.5% of deployed DOMs), plus three DOM-mainboard-based scintillator panels and two DM-Ice dark matter detector modules. One DOM failed during this reporting period in March 2022, DOM 74-61 in IceTop station 74. The remaining DOM in the same tank was reconfigured to restore as much functionality to the station as possible, and the station continues to take data.

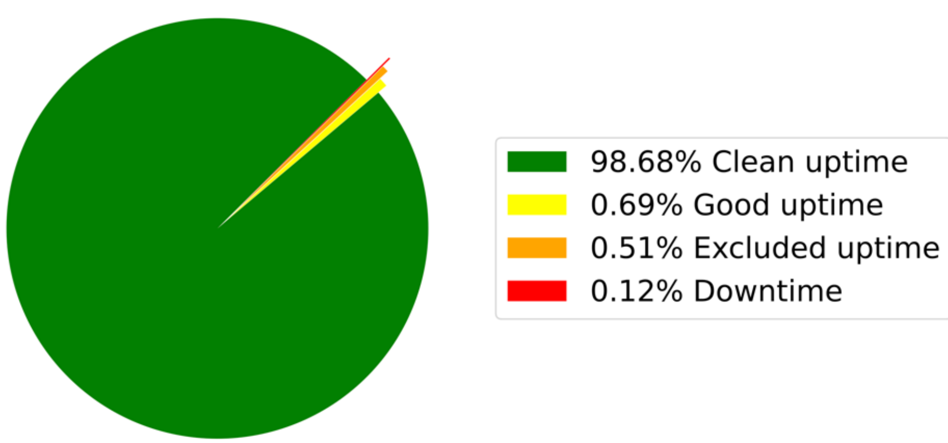

Figure 6 Detector uptime for the period from March 1, 2022 to January 31, 2023.

Detector operations milestones for PY2 are shown in Table 6. A major milestone in this reporting period is the IC86-2022 physics run start (**WBS 2.2.1 Run Coordination**), which began on August 3, 2022. The physics run start included the standard detector recalibration and tuning. Furthermore, the two DM-Ice dark matter detectors deployed on IceCube strings were fully integrated into the IceCube DAQ and now participate in the IceCube trigger and event builder. In addition to streamlining data flow, the cross-triggering allows precise track tagging of muons that pass directly through the DM-ice NaI crystals, useful for calibration and reconstruction studies. Expanding the DAQ to include DM-Ice is also a useful exercise as we prepare to integrate many other new Upgrade modules and calibration devices in the coming years.

The run start was delayed from the usual May start date in order to facilitate a decision on deployment of a major online and offline filtering rewrite. The new filtering plan, which transfers all triggered events in a highly compressed form over the satellite and moves most data processing and reduction to the north, has been delayed. IceCube's current satellite allocation of 105 GB/day is however not sufficient for this scheme, which requires 180 to 200 GB/day. We are investigating low-level event selections that fit the current bandwidth restrictions, but the physics working groups need more time to write new filter selections based on the new scheme.

WBS L3	Planned	Actual	Milestone
2.2.1	05/31/22	08/03/22	IC86-2022 physics run start
2.2.1	08/02/22	08/08/22	22/23 WinterOvers begin training
2.2.1	11/15/22	11/20/22	WinterOver crew exchange at South Pole
2.2.2	05/01/22	delayed*	Data acquisition Upgrade support
2.2.4	02/28/23	delayed*	Detector monitoring Upgrade support
2.2.5	06/15/22	delayed*	Support for Upgrade DOMs and calibration devices
2.2.9	10/01/22	8/12/22	Seasonal cargo ready for vessel shipment
2.2.9	12/01/22	delayed	SPS UPS upgrade; now 2023–24 season

Table 6: WBS 2.2 Detector operations and maintenance PY2 milestones for this reporting period.
*See text for discussion of IceCube Upgrade integration milestones.

Two new winterovers, Hrvoje Dujmovic and Marc Jacquart, started training at WIPAC in August 2022 and deployed to South Pole in November 2022. Winterover training involves in-depth, hands-on exercises on all online computing and detector subsystems using SPTS. The winterover handoff at South Pole was delayed slightly due to a COVID-19 outbreak at McMurdo station and the instituted isolation period for pole-bound and field camp deployers.

The **data acquisition software (DAQ, WBS 2.2.2)** was upgraded to the "Akupara5" minor release in July 2022 to support the integration of DM-Ice. A major DAQ release, "Basilisk", was rolled out in December 2022 and supports photomultiplier tube (PMT) afterpulse calibration using new extended DOM operating modes. A release of the DOM mainboard software, DOM-MB-450, that supports the extended modes was deployed in November 2022. A new release of the DAQ, "Cyclops", is planned for mid-2023 that supports new triggers based on non-local-coincidence hits. In addition to supporting new IceCube trigger concepts, this also lays the framework for supporting the Upgrade trigger. Unlike the Gen1 DOMs, the Upgrade DOMs have no hardwired local coincidence along the string.

Several DAQ, monitoring, and IceCube Live milestones related to the integration of the IceCube Upgrade were originally scheduled for PY2. The IceCube Upgrade has now been re-baselined after the loss of 3 pole seasons due to COVID-19. Integration milestones are now being tracked as part of IceCube Upgrade WBS 1.6.

The online data **processing and filtering system (PnF, WBS 2.2.3)** was upgraded to V21-10-03 in April 2022 to fix a memory leak in the DeepCore filter, improving stability. The PnF system was also updated for the IC86-2022 run start. A release of PnF that improves winterover control of the system and has better auto-restart capabilities is planned in an upcoming release.

A new major release of the IceCube Live **experiment control and monitoring software (WBS 2.2.4 & 2.2.5)** was installed in early 2022, I3Live v4.5.0 "Falcon". This version upgrades many of the underlying JavaScript libraries and adds several quality-of-life improvements for the win- terovers. The IceCube Live 4.6.0 "Galactica" major release was installed in July 2022 and includes a custom operations calendar synchronized between the north and south, used to coordinate detector activities with the WinterOvers and replacing a problematic Google Calendar that is difficult to use from South Pole. A patch release 4.6.1 "Galactica2" was installed in January 2023 that fixes a few minor issues, including to the satellite web page.

IceTop and the surface array (WBS 2.2.6) have been functioning smoothly. The elevated scintillator panels, antennas, and FieldHub of the prototype surface station were all successfully raised during the 2022–23 austral summer season (Figure 5). No self-induced snow accumulation or drifting was noted around the elevated instrumentation. Additionally, the 8 scintillator panels were swapped with an improved version that increases the dynamic range of the built-in uDAQ readout electronics. The panels were assembled and tested in Karlsruhe and then further cold-tested and characterized at the UW Physical Sciences Laboratory. New surface station deployments have been postponed due to logistics constraints.

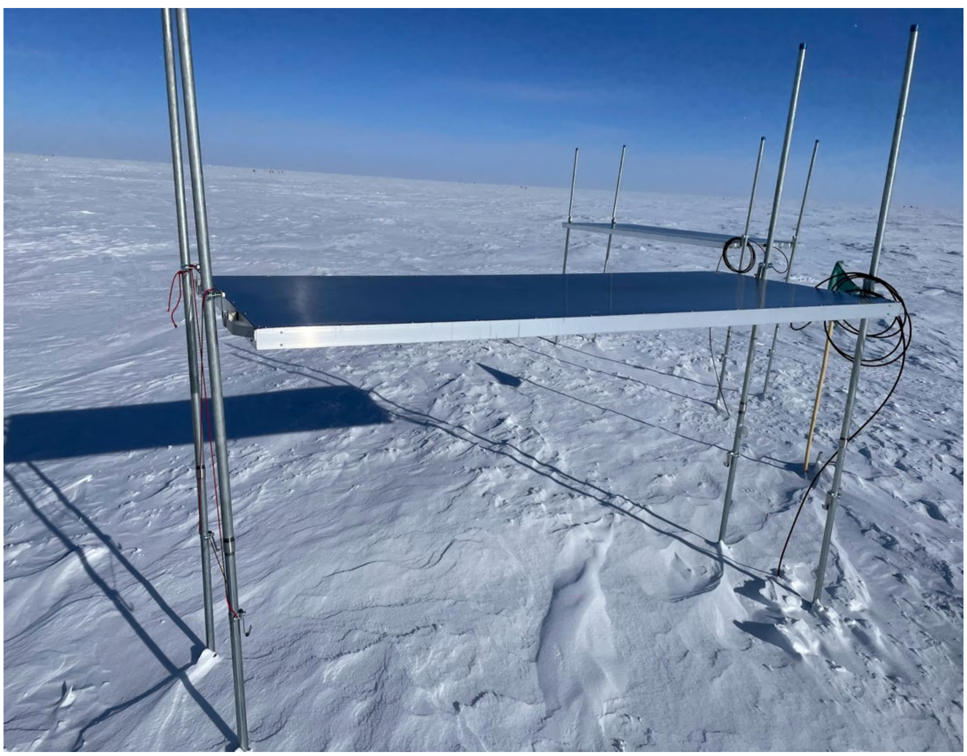

Figure 7: Upgraded elevated scintillator panels after being raised in December 2022.

The **supernova data acquisition system (SNDAQ, WBS 2.2.7)** experienced an unplanned "fire drill" on 8 May 2022 when the annual full-detector DOM calibration was started without the light-in-detector (LID) flag, due to operator error. The light emission from the DOM LEDs resulted in several spurious high-significance supernova alerts that were forwarded to the Supernova Neutrino Early Warning System (SNEWS). The error was discovered promptly, and the alerts were flagged as false alarms. A review of the incident identified several operational issues that have been corrected to reduce the chance of similar errors, but also found that the alert system largely worked as designed. Work continues on a Python-based upgrade of the supernova DAQ, PySNDAQ.

The **realtime event stream and alert system (WBS 2.2.8)** continues to deliver public neutrino alerts through the GCN system to the multimessenger astronomy community for followup observation. During the period March 1, 2022 to January 31, 2023, IceCube reported 29 track event alerts ("gold" or "bronze" depending on the estimated probability of astrophysical origin) and 10 cascade event alerts.

The **South Pole System (SPS; WBS 2.2.9)** computer operating system upgrade, delayed from 2019–20 due to COVID-19, was successfully completed during the 2021–22 austral summer season, with the exception of a few infrastructure servers. This operating system upgrade, from Scientific Linux 6 to Alma Linux 8, ensures compatibility with current and future IceCube data processing software and enables long-term security support. The remaining infrastructure servers were upgraded during the 2022–23 season. Procedures developed and exercised at the South Pole Test System (SPTS) successfully minimized downtime during the operations at SPS. A lifetime-replacement upgrade of the SPS uninterruptible power supplies (UPSes) was deferred to the upcoming 2023–24 season and will be accomplished in parallel with the network upgrade originally planned for 2021–22.

In addition to the 2022–23 South Pole summer season activities described above, a number of other activities took place this season. An IceCube-led beta test of the Starlink satellite internet service has been coordinated with NSF, ASC, and other South Pole stakeholders. The terminal is connected to a standalone monitoring laptop in the station, but not to the IceCube or ASC networks. In order to minimize potential EMI issues with CMB experiments, the terminal was initially tested in the RF sector, with line-of-sight to the Dark Sector shielded either by the RF building itself or by RF-absorbing foam installed on the roof railing. A custom frame was constructed to allow pointing the terminal independent of the built-in motors. This configuration was found not ideal as Starlink connectivity was reduced, and RF emissions were still visible with a dedicated monitoring setup in the Dark Sector. A short-term follow-on test at the SPRESSO site (Fig. 6), coordinated with SPRESSO and the ASMA stakeholders, was quite successful with 24/7 connectivity and minimal emissions detectable above the noise floor at DSL. Bandwidth achieved during testing was approximately 300 Mbps download / 20 Mbps upload. Starlink will not be operated during the winter, as final evaluation of any EMI is still pending.

Figure 8: Starlink antenna in a short-term test at the SPRESSO site.

Non-critical maintenance that was deferred during COVID was also successfully completed this season, including master clock and White Rabbit switch firmware upgrades, and DOMHub power supply fan replacements. As outlined in the operational plan, IceCube provides ongoing maintenance for the Askaryan Radio Array (ARA) in a caretaker mode, and the two currently non-functional ARA stations were excavated this season for DAQ electronics maintenance and retro.

Several items in preparation for IceCube Upgrade integration in the ICL were accomplished this season. All computing and surface array equipment was moved out of ICL rack 14 to make room for the Upgrade ICL electronics to be installed in the 2024–25 season. The surface cable patch panels for the seven Upgrade strings, identical to the Gen1 patch panels, were installed in the ICL patch panel racks.

While logistics support is much improved from the past two COVID-impacted seasons, we note that the integrated on-ice IceCube summer population (10) for the 2022-23 season was still 30% lower than normal levels. Cargo delivery this season was also delayed for some items between 1 and 2 months after the requested date. A number of planned support tasks were delayed due to insufficient on-ice staffing, including ICL electrical work, surveying, and ICL snow management. COVID-19 also remained a significant challenge, with unplanned isolation in McMurdo of up to 11 days for some deployers, and quarantine of 8 days at South Pole for two team members that contracted COVID.

2.2.1 Detector Operations Labor Assessment

A detailed list of M&O supported labor is included in the Appendix *Staffing Matrix by WBS L3*. After two software developer departures in 2021 and the subsequent shortage, labor is now largely back to planned levels. A new DAQ developer, Mirko Kugelmeier, was hired from industry in September 2022 as a junior replacement for Dave Glowacki. Long-time IceCube contributor John Jacobsen (NPX Designs, LLC) was hired for software development on a part-time (50%) contractual basis and started in October 2022, as a partial replacement for web and database developer Colin Burreson, and to assist with DOM software development.

The online software plan for expansions like the IceCube Upgrade relies on tight integration into the current IceCube DAQ and filtering systems rather than a new design, saving significant time and labor. This is possible because the IceCube operations software has been well-maintained and modernized over the course of previous M&O periods. However, significant effort is still needed across all L3 areas in order to expand the system to incorporate new sensors, calibration instruments, and their data products. We anticipate additional labor will be needed before the Upgrade deployment in 25–26, in particular for IceCube Live Upgrade integration. An additional 0.5–1.0 FTE DevOps engineer in WBS 2.2.9 South Pole Systems would also allow modernization of the configuration management and monitoring systems of the computing cluster at South Pole.

2.3 WBS 2.3: Computing and Data Management Services (B. Riedel)

IceCube M&O owns and operates several key pieces of cyberinfrastructure for the IceCube collab- oration. A summary of the various components and definitions can be found in Table 7 and 8.

Cyberinfrastructure	**Size**
Data and Simulation Filesystem	7.3 PB
User and Analysis Filesystem	10.7 PB
Dedicated CPU Cores	4500
Dedicated GPUs	300
Virtualized Hosts	200
Power Usage	250 kW
Distributed CPU Cores	6000-10,000
Distributed GPUs	600-800

Table 7: Summary of IceCube Cyberinfrastructure.

During the period from April 1, 2022 to February 28, 2023, the core infrastructure uptime, defined as the fraction of the total time that the core infrastructure located at UW-Madison was accessible to the collaboration, was 97-99% depending on the service. This exceeds our target of an average uptime of 95%.

The non-core infrastructure was available at 90-95%. This exceeds our target of an average uptime of 90%. Major outages of non-core infrastructure were caused by hardware failure and deployment of a new filesystem. The user and analysis filesystem had two day-long downtimes. The first downtime was caused due to a mishap during regular maintenance that caused a hardware failure, which made the filesystem unstable and unusable while we attempted to recover. Unfortunately, we were not able to recover all the user data and roughly 0.0375% (300,000 in total) of the files were lost. The data loss was attributed to the age of the affected hardware.

Figure 9 Location of distributed computing sites across the globe. Distributed resources are contributed from the collaboration, collaboration institutions, and other federally funded sources, e.g. Advanced Cyber- infrastructure Coordination Ecosystem: Services Support (ACCESS), Partnership to Advance Throughput Computing (PATh), and others.

The second downtime was caused by a prolonged transition to a new user and analysis filesystem. Overall, we had planned for a downtime of 3 days (Friday through Sunday). This extended to nearly 2 weeks in the end. This filesystem transition was the first time in over a decade the underlying distributed filesystem technology was changed, i.e. from Lustre to Ceph. We decided to transition the distributed filesystem to take advantage of greater scalability, maintainability, and feature set. Ceph provides multiple different operation models that allow us to leverage new technologies, first class support within the Linux community and private enterprise (Red Hat/IBM), and improving security by being supported within modern releases of the Linux kernel. During the transition a number of issues showed up that we did not discover during our research and development phase with Ceph and were not covered well or at all in the Ceph documentation. It took us several attempts to configure the filesystem properly for our use case and to ensure that all the data were securely transferred to the new filesystem, with each attempt taking at least a few days to a week of downtime. This filesystem has a significant user base and data rapidly changes. This makes syncing its contents a long and difficult process. In contrast, the data and simulation filesystem is mostly a read-only filesystem — it only changes in known and well understood increments. Nonetheless, priority was given in transitioning the user and analysis filesystem first, driven by the fact that the underlying hardware was older and the risk of hardware failure therefore was greater.

Since transition to new hardware and software, the new user and analysis filesystem have been used extensively. We have had no further issues and significantly reduced the impact of hardware failure on data safety and user experience.

The detector data and simulation filesystem will also be replaced in the next project period. We have already purchased the hardware and are awaiting its arrival in Spring 2023.

The workflow management software (IceProd) has been up >98% of the time. We stayed constant at 13 users, though most of the datasets are now submitted by users instead of central simulation production. We continue to recruit new users and improve the system user-friendliness to recruit new users.

Filtered data from the South Pole is currently transferred to Madison within less than 24 hours. The replication of our processed data to archive is currently up to date. We did have a number of weeks behind the current data during the reporting period. While we have automated the archival process, we don't have the personnel to implement an alerting infrastructure or monitor the archival process thoroughly.

Computing and Data Management milestones for PY1 are shown in Table 9. We have completed the experimental data ingested to NERSC ahead of schedule. It took us less than 90 days from data arrival from the South Pole via retro-cargo in Madison until the data was archived at NERSC. The complete archive at NERSC now includes over 10 years of trigger-level IceCube data.

We finished the Single sign-on implementation detailed in the previous report. We are working on expanding this service. We are also in the middle of transitioning our self-hosted communication and collaboration services (email, email lists, and document management) to Google Workspace. This transition will occur in phases beginning with documents followed by email and email lists. The transition to Google Workspace will provide the collaboration a modern and well-liked interface to frequently accessed services and also reduce the maintenance burden on the team by reducing the number of distinct services that need to be supported and reducing the reliance on our self-hosted virtualization infrastructure.

Changes in the ownership of our virtualization software vendor (VMWare) and subsequent changes in their licensing of the virtualization software have caused us to delay updates to our virtualization infrastructure. The current communications from the vendor indicate that the prices will increase significantly and support for smaller deployments, such as ours, will be limited. The hardware is still operating, but out of warranty. We are also transitioning some of our virtualized infrastructure to containers using Kubernetes and are exploring alternative virtualization software. We also discussed sharing virtualization infrastructure with UW campus IT. We have received a budgetarily acceptable quote from UW campus IT for storage for our our virtualization. This removes the current need to update the VM infrastructure wholesale as we can utilize existing and unused hardware to replace failing or failed hardware.

WBS L3	Planned	Actual	Milestone
2.3.1	12/31/22	06/30/22	CY 2021 experimental data ingested into NERSC LTA
2.3.3	TBD	6/30/23	VM infrastructure upgrade complete

Table 9: WBS 2.3 Computing and data management PY1 milestones.

2.3.1 Computing and Data Management Labor Assessment

Recent retirements and a parsimonious labor environment in technology fields has kept the computing team lean. While operations continue to meet the key performance metrics, infrastructure improvement has slowed significantly and the risk of losing critical institutional knowledge has increased. Ultimately, modernizing systems to make use of contemporary computing technology (cloud, containers) is very slow given the competing demands on the team. We are shifting staff responsibilities to improve the ability of the M&O program to respond to the changing technology landscape. We filled a DevOps position (Alec Sheperd) from within the team and added another system administrator (Mindy Preston) to team to replace James Bellinger, who retired. We are continuing to recruit for a system administrator position to fill the vacancy left by internal move within the team.

An expected change within IceCube and the Upgrade is the transition to more machine learning (ML) based data analysis. This will require rethinking the data analysis CI currently deployed. The current dedicated CI is at least 5 years old and was purchased with a focus on mass data processing and simulation production. We are expecting (and already experiencing in some cases) an increasing demand for accelerated hardware (GPU and FPGAs) to accommodate ML model training and inference. These workloads have substantially different resource requirements, and will require updates and additions to existing infrastructure to meet those requirements.

We are exploring additional NSF funding through cross-directorate and CISE programs. We are focusing on the Cyberinfrastructure for Sustained Scientific Innovation program program and requesting additional from ACCESS and PATh[3] as well as influencing future resources NSF-funded cyberinfrastructure projects. We also have plans to expand or start using other federally funded cyberinfrastructre, in particular DOE-funded National Energy Research Scientific Computing Center, Oak Ridge Leadership Computing Facility, and Argonne Leadership Computing Facility. Oak Ridge and Argonne; however, have significant workflow and security restrictions that cost significant human effort to overcome.

2.4 WBS 2.4: Data Processing and Simulation Services (J.C. Díaz-Vélez)

WBS L3	Planned	Actual	Milestone
2.4.1	04/14/23		Offline filter requirements captured - IC86-2023 run
2.4.2	11/01/21	04/22/22	Datasets SnowStorm / ESTES completed
2.4.2	06/01/23		Re-simulate 2020 Datasets with new spice bfr-v2 ice model

Table 10: WBS 2.4 Data processing and simulation PY1 milestones.

Data processing and simulation milestones are summarized in Table 10. Key performance parameters for Computing and Data Management are tabulated in Table 11. The completion of the new SnowStorm simulation sets was delayed due to a disagreement between our current neutrino simulator NuGen and LeptonInjector/Weighter that needed to be resolved prior to the start of production. The actual production began on 03/07/2022 and finished on 04/22/2022. The discovery of software bugs related to calibration constants used in simulation required an additional pass for the detector portion of these simulations. Datasets where intermediate steps were not saved, required a full re-simulation.

We expect to periodically re-simulate most signal datasets as new improvements in software and modeling of the optical properties of the ice are developed. With the release of the birefringent-v2 ice model, we recently began the process of re-simulating the SnowStorm production. Old-obsolete simulations are scheduled to be removed from disk in order to accommodate these new datasets.

Performance Metric	Objective	Achieved	Description
L2 processing latency	2 weeks	16.9 days	80% quantile time from event in ice to L2 processed file in the data warehouse
Simulation Production Efficiency	90%	92%	Total useful time (completed jobs) di- vided by total computing time
Simulation Requests	60 days	57.2 days	90% quantile request to production

Table 11: Data processing and simulation (WBS 2.4) performance parameters.

2.4.1 Data Processing

Current offline data processing is running on the IceProd2 framework on opportunistic grid computing resources, distributed across the globe. The move required some coordination with the distributed infrastructure team to implement additional features needed to support this task.

The IC86-2022 physics run started on August 3, 2022 at 13:55:29 UTC27. Filtering and processing scripts were validated by technical leads from each physics working group with data recorded during the 24-hour test run from July 11-12 using the new DAQ configuration and updated software stack. Observed differences with respect to the previous season are consistent with statistical fluctuations.

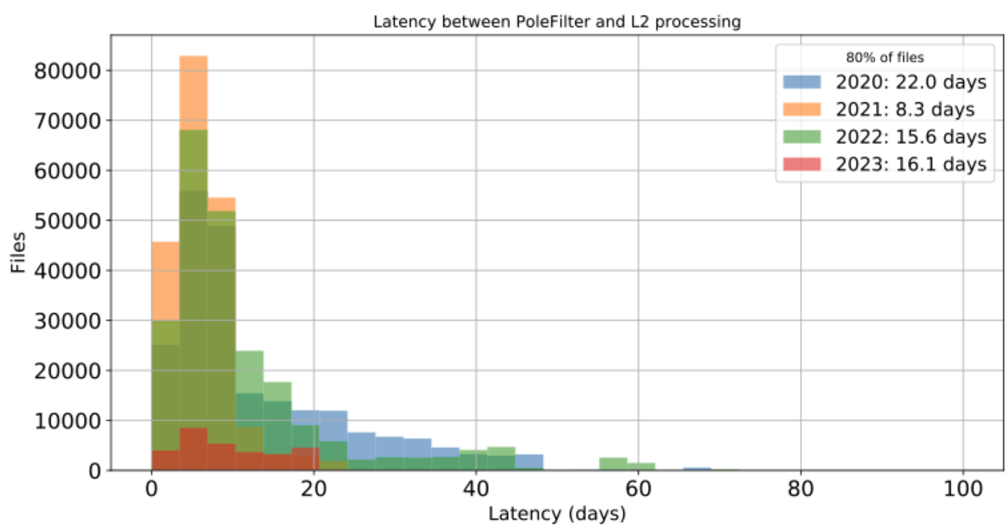

Figure 10: L2-processing latency distribution for the last four years. We define latency as the elapsed time between trigger to the time L2 files are available in the data warehouse in the North. Minimum latency is determined by the weekly data validation process in the North.

During previous years, an effort was done to clean up filters reconstructions and libraries no longer needed in offline reconstruction resulting in a 36% reduction of CPU utilization and a comparable reduction in memory requirements. Resources consumed for the offline production resulted in approximate 480,000 CPU hours of processing time and consistent with prior estimates. We are currently reviewing existing filters and reconstructions with the aim of streamlining offline processing at Level 2 and Level 3.

There is a new effort to further clean, optimize and modernize the current filtering scheme including L1 (online), L2, and L3 (analysis working group) filters. Current proposals include the addition of machine learning event classifiers and simplification of online filters running at the South Pole. We hope to deploy the new filtering scheme in the 2024 run.

We recently established *latency* as a new performance metric for Level-2 processing. This corresponds to the elapsed time between when triggered events are recorded in ice, to the time they are processed offline in the North and the resulting L2 file are available in the data warehouse for 80% of the files. A result of our new focus on this metric was that this latency of data at L2 was reduced from almost 50 days in 2018 to only 8.5 days in 2021 but increased again to 15.5 in 2022 and 16.1 in 2023 (see Figure 10) due to outlier runs that resulted from problems with the Lustre file system and an update to the database that triggered the reprocessing of many runs.

2.4.2 Monte Carlo Simulation Production

Current production of Monte Carlo simulations is based on the IC86-2020 detector configuration which covers a uniform detector configuration and filter scheme spanning from Spring 2012 through Spring of 2023. This configuration is representative of past previous trigger and filter configurations included in pass2. As with previous productions, direct generation of Level 2 background simulation data is used to reduce storage space requirements. The transition to the 2020 configuration was done in conjunction with a switch to a new combined simulation-reconstruction software suite.

New features in the simulation software include individually calibrated PMT waveforms, optimized event re-sampling for low-energy background simulation, and improved models of the optical properties of the ice. Direct photon propagation is currently done on dedicated GPU hardware at several IceCube Collaboration sites and through opportunistic grid computing. The number of such resources continues to grow along with further software optimizations for GPU utilization.

The simulation production team organizes periodic workshops to explore better and more efficient ways of meeting the simulation needs of the analyzers. This includes both software improvements as well as new strategies and providing the tools to generate targeted simulations optimized for individual analyses instead of a one-size-fits-all approach. New strategies have been developed for dynamically simulating of systematic uncertainties in our understanding of ice properties, hole-ice and DOM sensitivity and determining their impact on physics analyses. Throughput has continually increased due to incorporation of an increasing number of dedicated and opportunistic resources and several code optimizations. New monitoring tools are currently being developed in order to keep track of efficiency and further optimizations. New procedures have been implemented for coordinating and allocating resources and priorities for simulations produced by working groups as well as individuals. These efforts include performance metrics to reduce the time between a request by a group or individual and the completion of such request (Table 11).

2.4.3 Computing Resource Needs

Simulation production requirements are primarily dominated by background simulations with CORSIKA given that there is roughly a factor of 10^6 cosmic-ray induced muons triggering the detector for each neutrino event. Background simulations for the in-ice array require roughly 30k years of CPU time and about 2.4k years of GPU time to produce and filter. This is in addition to IceTop surface array simulations and signal simulations (including systematics). In 2022, we deployed a recently developed Triggered-CORSIKA module that replaces CORSIKA's post-reaction particle stack with a C++11 plugin that provides an API that allows for optimizing memory and CPU usage as well as storage requirements for high energy simulations.

As an alternative to simulating full CORSIKA airshowers, we can also simulate final-state muons that can be weighted according to a parametrized flux calculated from CORSIKA simulations using the same approach of MUPAGE which was developed by the ANTARES Collaboration. These MuonGun simulations are significantly more efficient to produce, requiring about 6M CPU-hours and comparable GPU time to simulate in order to meet our goals. These simulations have to be validated against CORSIKA, but this requires a significantly smaller data set.

In a similar manner, we are employing new a method for treating systematic uncertainties in a computationally efficient way by continuously varying multiple nuisance parameters (such as the depth dependent optical properties of the ice) within a single simulation set. This method has been validated and is fully described in M.G. Aartsen et al JCAP10(2019)048. This approach works with full neutrino, as well as weighted final-state lepton simulations.

Key achievements include:

- improvements in hardware simulation including individually calibrated PMT waveforms;
- added support for new types of sensors;
- improved models of the optical properties of the ice, including birefringence;
- addition of support for future detector hardware;
- optimization to improve efficiency and utilization of resources;
- new catalog of Monte Carlo datasets and simulation requests;
- improved monitoring of data processing and simulation production;

2.4.4 Data Processing and Simulation Services Labor Assessment

There are currently 2.4 FTEs assigned to WBS 2.4. There are no current plans to increase the number of FTEs working on Data Processing and Simulation Service though we anticipate an increase demand of labor from the extensions to the IceCube detector. Mitigation of risk of labor shortages due to this additional scope is being handled through promulgation of the simulation mass production middleware (IceProd) to permit individual users to profit from the scheduling and data provenance services provided by this software.

WBS 2.4.0 and 2.4.2 DIAZ-VELEZ, JUAN CARLOS (Lead) : Coordination of Offline Pro- cessing and Simulation Production efforts with analysis working groups. Oversees Offline Data Production. Evaluates shared resource needs for large-scale simulations and data processing for IceCube collaboration and coordinates with Physics Working Group Technical Leads and Computing and Data Management team to evaluate computing needs and priorities for Monte Carlo production datasets. Maintains and optimizes workflow scripts, and provides support for Physics Working Groups to manage production datasets.

WBS 2.4.1 SNIHUR, ROBERT : Experimental data processing and reduction. Interface with collaboration working groups to deliver analysis-ready data. Manages day to day operations for data processing at North and coordinates with Working Group Technical Leads to validate data and processing scripts. Coordinates with Detector Operations team to validate detector runs.

WBS 2.4.1 and 2.4.2 EVANS, ERIC : Software development of automated data validation tools to detect potential problems involving software and/or human errors in data processing and simulations.

WBS 2.4.2 LESZCZYNKA, AGNIESZKA : Maintains and optimizes workflow scripts for simulations of the IceTop surface array and manages dataset submission and monitoring.

2.5 WBS 2.5: Software (E. Blaufuss)

WBS L3	Date	Achieved	Milestone
2.5.1	06/30/2022	08/4/2022	Summer 2022 software release
2.5.1	09/30/2022	12/16/2022	Fall 2022 software release
2.5.1	12/17/2022	*skipped*	Winter 2022 software release
2.5.1	03/11/2023	*3/28/2023 (expected)*	Spring 2023 software release

Table 13: WBS 2.5 Software PY2 milestones.

The software team continue to target 4 quarterly, major releases of the IceTray software suite, which is used in South Pole and northern hemisphere filtering, simulation of data samples and in higher level reconstruction and analysis throughout the collaboration. Additionally, smaller, targeted releases are issued as needed in support of data processing needs. 4 releases have been issued to date in PY2, including a point release of the Winter 2022 release (v1.5.1 in Feb 2023). The Spring 2023 release is currently in preparations and is expected soon, with a dozen issues listed on the project board for the release. Key software release milestones and performance parameters for Software in PY2 are tabulated in Table 13 and Table 14, respectively.

Performance Metric	Objective	Achieved	Description
Releases per year	4	3	Quarterly releases meeting minimal quality standards
Test coverage, minimum	66%	62%	Fraction of lines of code executed in the test suite
CI min uptime	90%	95%	Fraction of days tests pass on all supported platforms
CD min uptime	50%	-	Fraction of days full-chain tests pass on single platform
Critical ticket max lifetime	1 month	0.5 month	At least 90% of critical tickets resolved within this timescale

Table 14: Physics software (WBS 2.5) performance metrics.

Our IceTray software development is now focused in a full and robust IceCube organization in GitHub, with over 100 additional software repositories contributed from the collaboration. Development effort and release planning are coordinated using GitHub enterprise tools for issue tracking, pull requests, code reviews and release coordination in Kanban-style project boards. Additionally, all CI/CD systems are available after the transition to GitHub. These are implemented with a collection of self-hosted GitHub Action runners (CI) that provide rapid, automated unit testing of newly submitted software. After each commit to the software repository, several automated builds are initiated will full run of the automated test suite. Custom ”full stack” software tests that check physics level output (CD) are performed manually near time of release, and automation of these workflows remain a work in progress.

The Winter 2022 release is now in use for production of updated simulation samples. There was one critical ticket found, and a PR to address said issue was created within 3 days. Release and testing of a point-level release fixing the critical issue where complete within 2 weeks. There are currently ≃50 open issues, many focused on long term code cleanup and optimizations awaiting available manpower for completion. The test coverage has increased a bit to 60%, but remains below our stated goal of 66%. The CI uptime for this period time period is estimated to be around 95%, exceeding the goal of 90%, since the completion of the move to GitHub. We estimate ~70% of these test builds on core platforms show 100% successful test completion, while the remaining 30% show a small number of test failures that are quickly addressed ahead of a release.

The next sets of software development and releases will focus on readiness for the IceCube Upgrade, now planned for deployment in 2025-2026 season. The deployment of a wide variety of optical sensors, beyond just the standard IceCube DOMs, presents new challenges for the IceTray framework and IceCube reconstruction and simulation software packages. Adapting these software systems to deal with the new heterogeneous detector, while updating existing packages for more modern compiler and deployment environment, will require a continued coordinated effort over the next few years.

2.5.1 Software Labor Assessment

M&O harvests a significant amount of labor under 2.5 from resources, mostly graduate students and postdocs, contributed in-kind by IceCube collaborating institutions. These are coordinated through the semi-annual statements of work collected as part of the IceCube resource coordination process. This includes work to maintain core software infrastructure, development of new reconstruction and analysis software frameworks, and support for simulation and analysis of the upcoming Upgrade extension. The pandemic, with a lack of in-person meetings, has impacted our ability to effectively identify and coordinate a distributed team of software-interested developers. However, our Fall 2022 and Spring 2023 collaboration meetings hosted several software-focused activities and meetings to start rebuilding this effort.

Despite the large pool of contributed effort, maintenance of the IceCube software systems does require the daily attention of a dedicated, professional team of software engineers to handle the more complex aspects of rigorous software maintenance and maintenance of the development and build environments. In Spring 2022, our long-time Software coordinator, and M&O software lead Alex Olivas, left IceCube for a position in industry. UMD scientist Erik Blaufuss has fulfilled the coordination role, while UMD scientist Michael Larson has moved into the key IceTray and simulation systems developer role. The software development leadership team also receives effort from Don La Dieu (UMD), Kevin Meagher (UW), Tianlu Yuan (UW) and Juan Carlos Diaz-Velez (UW). This team meets bi-weekly to coordinate development issues, prioritize tickets and drive release readiness.

2.6 WBS 2.6: Calibration (M. Rongen, D. Williams)

We continue to refine measurements of the optical properties of the South Pole ice that comprises the majority of our detector, as well as the IceCube DOM response to photons. Precise modelling of both is fundamental to converting detector observables into physical measurements such as neutrino direction, energy, and absolute flux.

2.6.1 Ice characterization

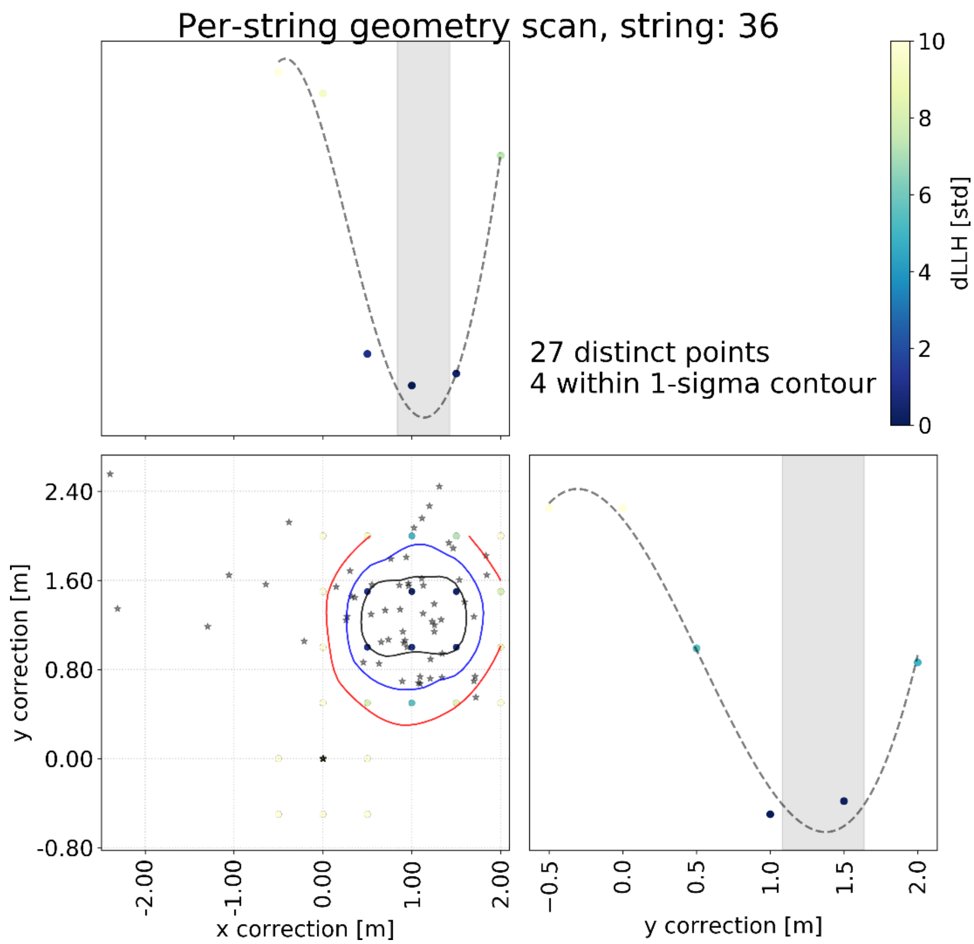

Figure 11. : Example likelihood landscape when fitting the average position of string 36 using LED flasher data. The individual DOM positions derived from muons are overlaid as stars. The best-fit average string position falls within the center-of-gravity of the per-DOM positions

An extensive paper detailing the new SpiceBFRv2 ice model[1] was submitted to the glaciology journal *The Cryosphere* in September 2022. Large scale simulation efforts and first tests at analysis level using this ice model are now underway; in particular, the neutrino-oscillation analyses are reporting significant improvements in data/MC agreement.

The perturbative fitter[2] has matured to the point where it has been used successfully to improve on the ice stratigraphy and tilt modeling[3] at the same time. An ice-model release incorporating these improvements is in preparation for release in 2023, after accumulating a number of further improvements. In addition,

[1] Describing the ice anisotropy effect through the cumulative light deflection caused by the birefringent microstructure of the glacial ice and yielding near perfect data-MC agreement for previously hard to match variables.

[2] Generating a small set of simulations perturbing several thousand parameters at once in conjunction with a custom matrix solver which requires positive-definite solutions to predict solutions close to the global minimum.

[3] Tilt describes the undulation of layers of constant optical properties over the face of the detector and is e.g. required for precise cascade energy reconstruction.

the new fitting method for the first time also yields a full covariance matrix for all parameters. This will in the future be used to access depth-correlated uncertainties in the modeling and potentially to upscale the stratigraphy to smaller layer width based on input from DustLogger data. The updated ice model will be presented at the 38th International Cosmic Ray Conference (ICRC2023).

2.6.2 DOM characterization

The uncertainty on the absolute detection efficiency of our DOMs is a systematic considered in most analyses. A new iteration of an established study employing minimum ionizing muons as standard sources of known light emission is currently in internal review, with new recommendations for the uncertainty range to be considered to be made to the analysis working groups soon.

The modeling of the single photoelectron (SPE) distribution on a per-DOM basis is under study to see if the modeling of the low-charge region can be improved based on laboratory studies of PMT characteristics. In the meantime, the existing model has been applied to the most recent datataking seasons and is planned to be used in future reprocessing of data (”Pass 3”).

Knowledge of the DOM positions in the ice is important for the event reconstruction. Until recently no in-situ geometry calibration method could be successfully established, largely due to degeneracies with ice model uncertainties. Thus the surface position of each hole is to-date used as the lateral position of all DOMs on a given string. Given the recent advances in ice modeling, two new attempts have been undertaken. Using a large sample of muon tracks the individual positions of all DOMs on a small number of strings around DeepCore has been fitted. The results were verified against LED flasher data, showing that the string-average corrections improve detector modeling, while the per-DOM scatter around the averages appear to still be unphysical (see Figure 10). Fitting per-string average geometry corrections using LED data directly, has been concluded for all strings and agrees with the average corrections as derived from muons where available. Results from this study will be presented at ICRC2023. The string-average geometry corrections will soon be released, with further investigations into calibration methods for per-DOM positions being continued.

2.6.3 Performance metrics

Many advances in IceCube’s detector calibration, especially relating to the ice optical properties, are hard to predict and we keep being surprised by the advances which are still possible.

Nevertheless, routine calibration, primarily regular updates to the DOMs calibration constants through DOMCal, remains of central importance. We here track key metrics of importance to the continued reliability of event reconstruction: module gain and timing resolution. Detector aging has not impacted these metrics to date; however, we continue to track these and can adapt calibration frequency as needed if this begins to play a role.

Performance Metric	Objective	Achieved	Description
DOM gain drift	< 2%	0.9%	Relative module gain change over time (95% quantile)
DOM timing stability	< 2.0ns	1.8ns	Spread in DOM timing calibration over time (95% quantile)
DOMCal result latency	< 1 week	3 days	Time to validate calibration results for online use

Table 15: Calibration (WBS 2.6) performance parameters.

3 Upgrade related activities

The IceCube Upgrade will further boost our understanding of the ice properties and will also pose unique challenges as currently subdominant effects, such as the precise shape of the scattering function, become relevant.

In preparation for the IceCube Upgrade we are facilitating discussion of and simulation for the calibration devices (i.e. PencilBeam, POCAM, camera systems, LED flashers, dust-logger). The calibration working group contributes subject matter expertise to design reviews for the Upgrade calibration devices, and is evaluating the science case for special operations of devices in newly drilled Upgrade boreholes before they are frozen.