Celebrating IceCube's First Decade of Discovery

IceCube Maintenance and Operations
Final Project Report

April 1, 2016 – March 31, 2021

Submittal Date: July 9, 2021

University of Wisconsin–Madison

This report is submitted in accordance with the reporting requirements set forth in the IceCube Maintenance and Operations Cooperative Agreement, ANT-0937462.

Foreword

This FY2015/2016–FY2020/2021 (PY1–PY5) Final Report is submitted as required by the NSF Cooperative Agreement PLR-1600823. This report covers the last six months (10/01/2020–03/31/2021) of the 60-month period beginning April 1, 2016, and concluding March 31, 2021. The status information provided in the report covers actual common fund contributions received through March 31, 2021 and the full 86-string IceCube detector (IC86) performance through March 31, 2021.

Contents

I. Financial/Administrative Performance

The University of Wisconsin–Madison maintains three 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, and 3) Non-U.S. Common Fund account.

A total of $7,000,000 was released to UW–Madison to cover the costs of maintenance and operations in PY5 (FY2020/FY2021): $1,054,462 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 $5,945,538 was directed to the IceCube M&O Core account (Table 1). An additional $291,712 FY2019 funding was awarded to support an IceCube M&O supplemental proposal to further develop talent for STEM research, increase diversity and inclusion in science and related fields, and connect research-based skills and technology to societal challenges.

PY5: FY2020/FY2021	Funds Awarded to UW (Apr 1, 2020–Mar 31, 2021)
IceCube M&O Core account	$5,945,538
U.S. Common Fund account	$1,054,462
TOTAL NSF Funds	**$7,000,000**

Table 1: NSF IceCube M&O funds – PY5 (FY2020/FY2021).

Of the IceCube M&O PY5 Core funds, $1,017,057 were committed to the U.S. subawardee 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 PY5 funds for the subawardee institutions.

Institution	Major Responsibilities	Funds
Lawrence Berkeley National Laboratory	DAQ maintenance, computing infrastructure	$88,311
Pennsylvania State University	Computing and data management, simulation production, DAQ maintenance	$72,987
University of Delaware, Bartol Institute	IceTop calibration, monitoring and maintenance	$193,967
University of Maryland at College Park	IceTray software framework, online filter, simulation software	$619,644
University of Alabama at Tuscaloosa	Detector calibration, reconstruction and analysis tools	$12,299
Michigan State University	Simulation software, simulation production	$29,849
South Dakota School of Mines and Technology (added July, 2017)	Simulation production and reconstruction	$00.00
Total		**$1,017,057**

Table 2: IceCube M&O subawardee institutions, major responsibilities and funding – PY5 (FY2020/FY2021).

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 2016, on April 1, 2016. The following table presents the financial status and estimated balance at the end of PY5 of the five-year award. Total awarded funds to the University of Wisconsin (UW) for supporting IceCube M&O from the beginning of PY1 through the end of PY5 are $35,360K (including the supplemental funding of $67,999 in PY2 and $291,712 in PY3). Total actual cost as of March 31, 2021, is $35,383, and open commitments against purchase orders and subaward agreements are $11K. The current balance as of March 31, 2021, is -$35K. With a projection of $0K for the remaining expenses during the 90-day project close-out period, the estimated negative balance at the end of PY5 was -$35K, which is 0.01% of the total PY1-PY5 budget (Table 3). The negative forecast balance was offset by unused subaward funds during the close-out phase.

(a)	(b)	(c)	(d)= a-b-c	(e)	(f=d-e)
Years 1-5 Budget	**Actual Cost to Date**	**Open Commitments**	**Current Balance**	**Remaining Projected Expenses**	**End of PY5 Forecast Balance**
Apr 2016-Mar 2021	through Mar 31, 2021	on Mar 31, 2021	on Mar 31, 2021	through Mar 31, 2021	on Mar 31, 2021
$35,360K	**$35,383K**	**$11K**	**-$35K**	**$0K**	**-$35K**

Table 3: IceCube NSF M&O award budget, actual cost, and forecast.

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 and are listed in the Maintenance & Operations Plan. 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, 2020–March 31, 2021, based on v28.0 of the IceCube Institutional Memorandum of Understanding, from June 2020. The remaining contributions from non-U.S. collaborators are still underway, and it is anticipated that most of the planned contributions will be fulfilled.

	Ph.D. Authors	Planned Contribution	Actual Received
U.S.	75	$1,023,750	$1,023,750
Non-U.S.	72	$969,150	$695,942
Totals	**147**	**$1,992,900**	**$1,719,692**

Table 4: Planned and actual Common Fund contributions for the period of April 1, 2020–March 31, 2021.

II. Maintenance and Operations Status and Performance

Detector Operations and Maintenance

Detector Performance

During the period from 1 September 2020 to 1 April 2021, 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 99.1%, exceeding our target of 95%. Historical totals and clean detector uptimes are shown in Fig. 1.

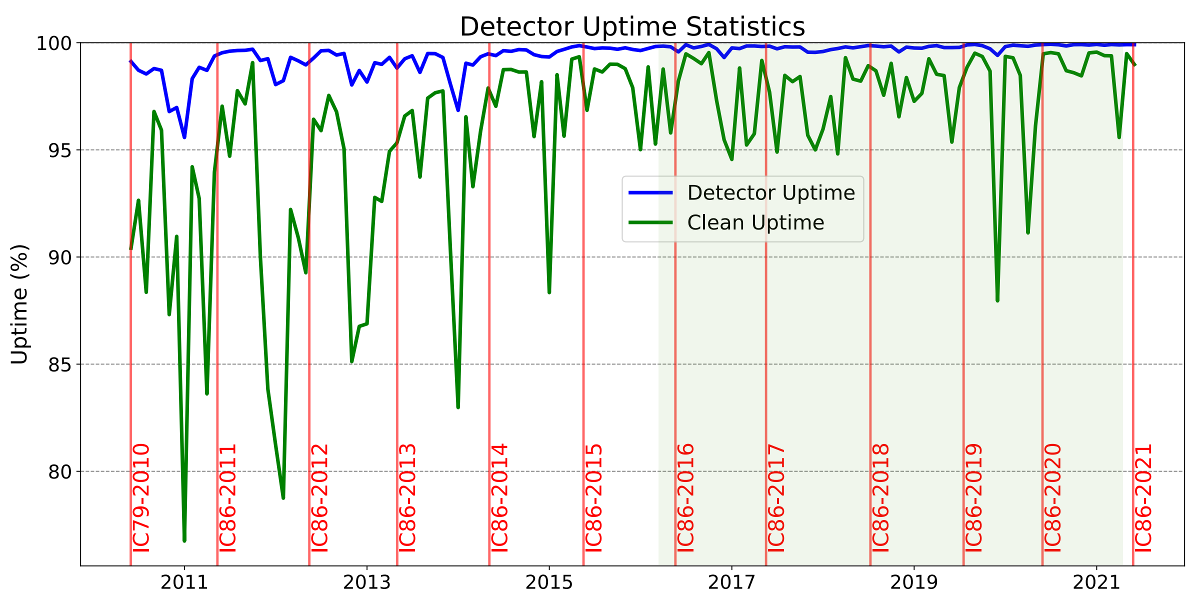


Figure 1: Total IceCube detector uptime and clean uptime. The full five-year reporting period is indicated by the shaded region.

Fig. 2 shows a breakdown of the detector time usage over the reporting period. The partial-detector good uptime was 0.7% of the total and includes analysis-ready data with fewer than all 86 strings. Excluded uptime includes maintenance, commissioning, and verification data and required 0.1% of detector time. The unexpected detector downtime was also limited to 0.1%.

Hardware Stability

The total number of active DOMs in the data stream is currently 5,405 (98.5% of deployed DOMs),

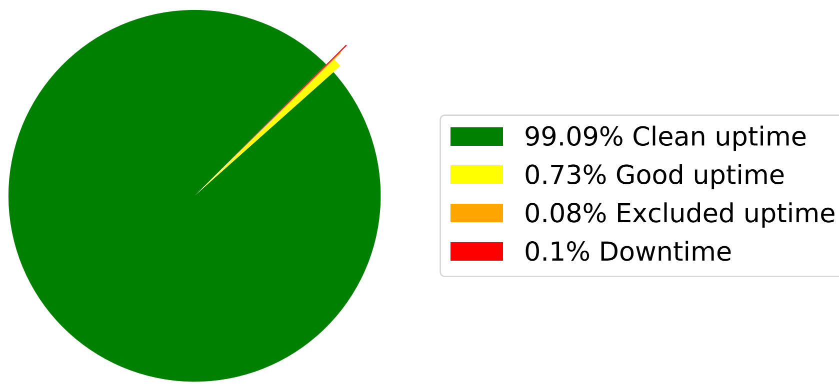


Figure 2: Cumulative IceCube detector time usage, 1 September 2020 – 1 April 2021.

plus three DOM-mainboard-based scintillator panels and the IceAct telescope trigger mainboard. No DOMs failed during this reporting period; the previous DOM failures were in December 2018.

The previous high failure rate of DOM power supplies and DOMHub ATX computer power supplies has been resolved by the ongoing maintenance over the past three pole seasons. Since January 2020, there has been one failure of the new Mean Well DOM power supplies and one failure of an ATX power supply.

IC86 Physics Runs

In preparation for the IC86-2021 physics run, the annual full-detector calibration was performed in March 2021, and DOM configuration settings were adjusted accordingly. No trigger changes were planned from the IC86-2020 physics run; IceTop information will be added to the real-time neutrino event stream to enhance the cosmic ray veto system. A larger optimization of the filtering system is planned for the IC86-2022 physics run start.

Data Acquisition

The IceCube data acquisition system (DAQ) has reached a stable state, and consequently the frequency of software releases has slowed. During the reporting period, the following accomplishments are noted:

- Continued work towards the migration of the pDAQ codebase from the SVN version control system to GitHub, the IceCube software revision control standard moving forward. The migration includes all revision history as well as a parallel migration from Mantis, the legacy issue tracking system, to GitHub issues. The final migration is planned for July 2021.
- Work towards the pDAQ:Basilisk release, which will include new PMT afterpulse calibration features, such as low-deadtime readout modes and the ability to flash low-intensity DOM LEDs while otherwise operating normally. Other features include allowing changes in the hitspool buffer size without data loss as well as addressing minor bugs.

A major upgrade of SPS to Python3 is planned for mid-2021 (Python2 is end-of-life as of 2020). As much of the Python infrastructure for the online software is provided by the DAQ user framework, upgrades to this have been implemented and tested on SPTS in spring 2021.

Online Filtering
The online filtering system ("PnF") performs real-time reconstruction and selection of events collected by the data acquisition system and sends them for transmission north via the data movement system. No filter changes were performed for the IC86–2020 physics run start.

PnF relies on the core reconstruction software used in offline analysis. The increasing divergence between the aging SPS operating system and toolchain and the tools used for IceCube analysis is an issue when upgrades to the online filters are needed. A major overhaul of the online and Level2 filtering systems is under discussion with the TFT board, but this is dependent on the SPS operating system upgrade. Since that upgrade has been postponed by the COVID-19 situation (see below), and the filtering overhaul was not deemed operationally critical, major PnF changes are planned now for the IC86-2022 run start.

Detector Monitoring and Experiment Control
Development of IceCube Live, the experiment control and monitoring system, has transitioned to a maintenance mode. This reporting period has seen the following progress:

- Deployment of Live 4.3.0 in October 2020 and patch release Live 4.3.1 in March 2021. This major release includes Python3 compatibility and an update of the South Pole weather data collection system to improve reliability.
- Work towards the Live 4.4.0 release in mid-2021, which includes improvements to the data movement system (JADE) monitoring, detector monitoring improvements, and cleanup of the experiment control system.

The uptime of the I3Live experiment control system during the reporting period was 99.999%.

Supernova System
The supernova data acquisition system (SNDAQ) uptime for this reporting period was 99.9%. An unidentified memory leak in SNDAQ is requiring regular but infrequent restarts to avoid instability.

Planning is underway for an upgrade to the core SNDAQ software from C++ to Python (PySNDAQ). This will significantly improve maintainability and flexibility, especially considering that SNDAQ software is developed and maintained by collaboration graduate students.

Surface Detectors
A plan for the restoration and enhancement of the IceTop surface array was proposed as part of the next IceCube Management & Operations cycle. The upgraded surface array combines elevated scintillator panels and radio antennas for hybrid cosmic ray air shower detection. Measurement of the radio emission provides shower-by-shower energy and mass composition information, significantly enhancing the capabilities of IceTop.

Construction of the IceTop surface array enhancement has been delayed by the COVID-19 pandemic and associated impacts to South Pole logistics. Minor maintenance of the prototype station during the 2021–22 Antarctic deployment is planned, including an upgrade to the DAQ electronics and addressing minor light leaks in the scintillator panels. This maintenance can be achieved by the IceCube winterovers.

In January 2021, the IceCube winterovers successfully repaired the external trigger system of the IceAct roof telescope. Both IceAct telescopes are taking data during the austral winter, and the roof telescope trigger is integrated into the IceCube DAQ to enable energy threshold and veto studies.

South Pole System

Approximately 50% of the South Pole System servers were replaced in the 2018–19 season, and the remaining servers were upgraded during the 2019–20 season. Performance and hardware stability have been excellent.

The South Pole System is currently running a version of Scientific Linux 6 (SL6). We were planning to upgrade all SPS computers to CentOS 8 in the 2020–21 season, in order to support migration to modern versions of compilers, Python, the Linux kernel, and other key software. This was postponed and is now planned for the 2021–22 pole season.

Personnel and Management

Two new winterovers (W. Marie-Sainte and M. Baricevic) have been hired for the 2021–22 season. Both have previous winter experience at Concordia station.

Senior DAQ developer D. Glowacki is retiring in mid-2021. Developer T. Bendfelt will take over as DAQ software lead, and developer J. Weber (primarily IceCube Upgrade) has started training on the system to support DAQ maintenance and IceCube Upgrade integration.

Impact of COVID-19 on South Pole Maintenance Activities

Training of the 2020–21 winterovers was seriously impacted as COVID-related travel restrictions prevented in-person activities at WIPAC. However, the risk to IceCube operations was successfully mitigated by the hiring of a former IceCube winterover (M. Wolf) and by the extended stay of winterover J. Hardin through January of 2021 to provide key on-site, hands-on training. Despite the difficult circumstances, the detector handover has been smooth.

Because significant hardware maintenance was accomplished in the 2019–20 pole season, cancellation of the 2020–21 pole season did not significantly jeopardize IceCube detector operations. However, the situation resulted in the following operations being postponed:

- The planned SPS operating system upgrade. This may result in an increased online software maintenance burden as we need to support more modern tools on the older OS.
- An upgrade of the system configuration management system to support the SPS operating system upgrade.
- An upgrade of the SPS keyboard/video/monitor (KVM) system.
- The deployment of the first production surface array station (by moving the prototype station).
- Rack space consolidation in preparation for the IceCube Upgrade.

It is clear at this point that the 2021–22 pole season will also be impacted by ongoing COVID-19 restrictions. However, since we will be able to send key operations personnel and critical cargo (such as data storage disks and UPS batteries) this season, we expect to be able to complete the deferred items on the list above from the 2020–21 season. An exception to this is the surface array deployment, which is not possible due to the limited population and logistics support.

Highlights of the Five-Year Program

The 2016–2021 detector maintenance and operations program was highly successful. The detector continues to operate stably and reliably, thanks to regular hardware maintenance and the support of our two winterovers. Ongoing software development has facilitated expansion of IceCube's robust science program as well as laid the foundation for future detector expansions such as the IceCube Upgrade.

Key achievements include the following:

- continued stability improvements to the DAQ software resulting in record-high detector uptime
- enhancement of the real-time neutrino alert system, including new event streams
- upgrade of the IceCube master clock
- replacement of the DOM power supplies in the ICL, resolving a long-standing reliability issue
- life-cycle upgrade of the ICL computing servers
- release of a new detector monitoring framework and user interface
- release of a new detector geometry/calibration/detector status database
- design and prototype deployment of the IceTop surface array enhancement

For the full five-year period from 1 April 2016 to 31 March 2021, the detector uptime was 99.8%, and the full-detector clean uptime was 97.7%. Our realized uptime exceeded our performance targets for every reporting period. In total, three DOMs failed over this five-year period (0.05%), and there are no indications of any performance degradation of the detector.

Computing and Data Management Services

Data Transfer

Data transfer has performed nominally from Sept 1 2020 through April 1 2021. A total of 15 TiB of data were transferred from the South Pole to UW–Madison via TDRSS, at an average rate of 70 GiB/day. Fig. 3 shows the daily satellite transfer rate and weekly average satellite transfer rate. The IC86 filtered physics data are responsible for 95% of the bandwidth usage.

Since September 2016, the JADE software handles all the IceCube data flows: disk archive at the South Pole, satellite transfer to UW–Madison, and long-term archive to tape libraries at NERSC and DESY. JADE continues to operate smoothly and has been an effective tool for handling a variety of our routine data movement workflows. This has been confirmed over the last year with experience from both the winterovers and IT staff at UW–Madison.

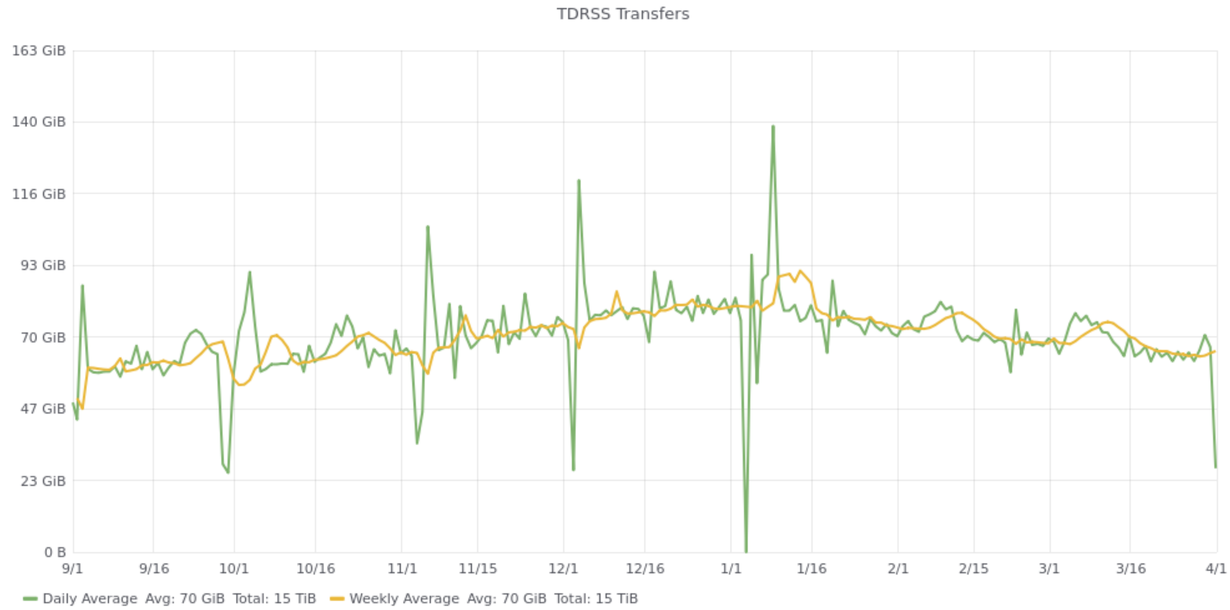


Figure 3: Satellite data transfer rates from 1 September 2020 – 1 April 2021.

Data Archive

The IceCube raw data is archived by writing two copies on independent hard disks. During the reporting period (Sept. 2020 to April 2021) a total of 1 PiB of unique data were archived to disk, averaging 5.4 TiB/day.

In April 2021, the set of archival disks containing the raw data taken the previous season was received at UW–Madison. These disks are processed using JADE, which now indexes the metadata, bundles the data files into chunks suitable for storage in tape libraries, and replicates the data to the long-term archives at DESY and NERSC.

Beginning in September 2016, we have been regularly transferring archival data to NERSC. At this time, the total volume of data archived at NERSC is 4.8 PiB. Fig. 4 shows the rate at which data has been archived to NERSC since the start of this service. The plan is to keep this archive stream constantly active while working on further JADE functionality that will allow us to steadily increase the performance and automation of this long-term archive data flow. With the new long-term archive software, we have been able to complete data archiving within 90 days of data arriving in Madison.

Computing Infrastructure at UW–Madison

The IceCube computing cluster at UW–Madison has continued to deliver reliable data processing services. Boosting the GPU computing capacity has been a high-priority activity since the Collaboration decided to use GPUs for the photon propagation part of the simulation chain in 2012. Direct photon propagation provides the required precision and is very well suited to GPU hardware, running about 100 times faster than in CPUs.

In addition, we have decommissioned the data center facility at our 222 West Washington Avenue location and relocated the equipment to a commercial facility leased by UW–Madison. The facility

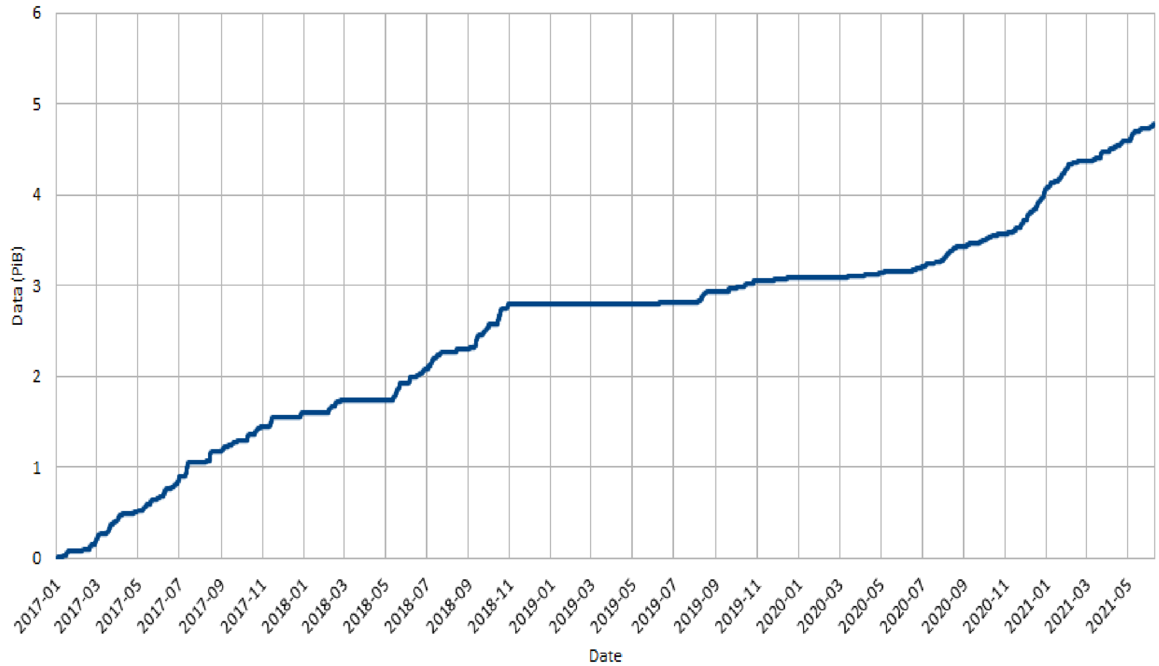


Figure 4: Data archived at NERSC since Jan. 2017.

is located approximately seven miles from our 222 West Washington Avenue location and offers redundant battery-backed generator power and biometric physical security. UW–Madison leases space, power, and cooling in this facility to support internal needs as well as project needs for the campus as a whole. As such, they have extended the campus high-speed networks to the facility, which offers us easier integration with the rest of our campus systems without the higher costs typically associated with commercial rates for network transit. We have a full 200 Gb/s network path between this facility and our other facilities on campus.

The total amount of data stored on disk in the data warehouse at UW–Madison is 9.8 PB: 6.8 PB for experimental data and simulation and 3 PB for analysis and user data. An additional 1 PB will be deployed by the middle of 2021.

Storage comprises the largest user-visible infrastructure. A number of other critical systems (access to South Pole, for example) have been migrated to the new facility. The work was completed in early 2020. Only hardware under warranty was migrated to the facility. Older hardware that is still usable but out of support will be repurposed for testing or moved into the compute cluster in Chamberlin Hall on the UW campus as needed. Any old hardware not needed for these purposes will be disposed of.

Simulated data sets are a key deliverable of the core M&O program, from the software that generates the physical processes of interest and simulates the response of the ice and the optical detection units to the production scheduling and data provenance software and the hardware running within multiple large distributed computing clusters. Acquisition of the massively parallel GPU clusters is a regular aspect of M&O to meet the expanding needs of the Collaboration's reliance on the highest fidelity simulated data sets that employ direct photon propagation. GPU needs outstrip the capacity of the GPU cluster at UW–Madison; thus, additional GPU resources are deployed throughout the collaborating institutions, most recently at Michigan State University, and M&O computing management continues to aggressively pursue additional allocations on supercomputing clusters worldwide.

IceCube has been awarded or participated in several cyberinfrastructure-related projects. Namely, UW–Madison participated in an EAGER award (NSF OAC 1941481) and a Cyberinfrastructure for Sustained Scientific Innovation award (NSF OAC 2103963). UW–Madison was awarded Phase I of Internet2's Exploring Clouds for Acceleration of Science (E-CAS) project, which included $100,000 in credits for Amazon Web Services and Google Cloud Platform and support for 0.4 FTE.

Distributed Computing

In March 2016, a new procedure to formally gather computing pledges from collaborating institutions was started. This data is collected twice a year as part of the already existing process by which every IceCube institution updates its MoU before the collaboration meeting. Institutions that pledge computing resources for IceCube are asked to provide information on the average number of CPUs and GPUs that they commit to provide for IceCube simulation production during the next period. We have been able to continually expand this pool over the last few years, see Figs. 5 and 6.

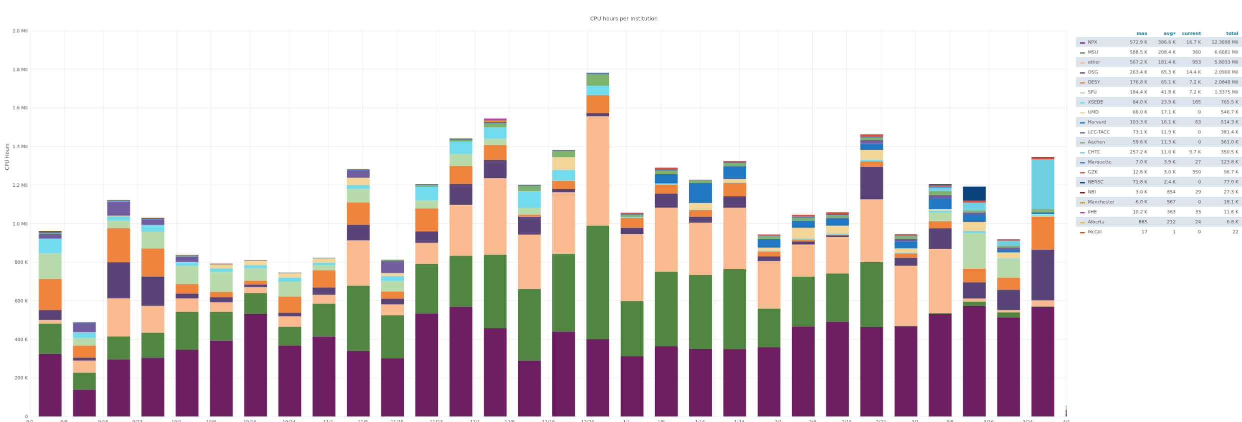


Figure 5: CPU time contributed by various sites from 1 September 2020 – 1 April 2021.

We are implementing a feedback planning process by which the numbers from available resources from computing pledges are regularly compared to the simulation production needs and resources used. The goal is to be able to manage more efficiently the global resource utilization and to be able to react to changes in computing needs required to meet IceCube science goals.

In the last few years, we have put a strong focus on enlarging the distributed infrastructure and making it more efficient. The main strategy to accomplish this has been to try and simplify the process for sites to join the IceCube distributed infrastructure and to reduce the effort needed to keep sites connected to it. To do this, we have progressively implemented an infrastructure based on pilot jobs. Pilot jobs provide a homogeneous interface to heterogeneous computing resources. They also enable more efficient scheduling by delaying the decision of matching resources to payload.

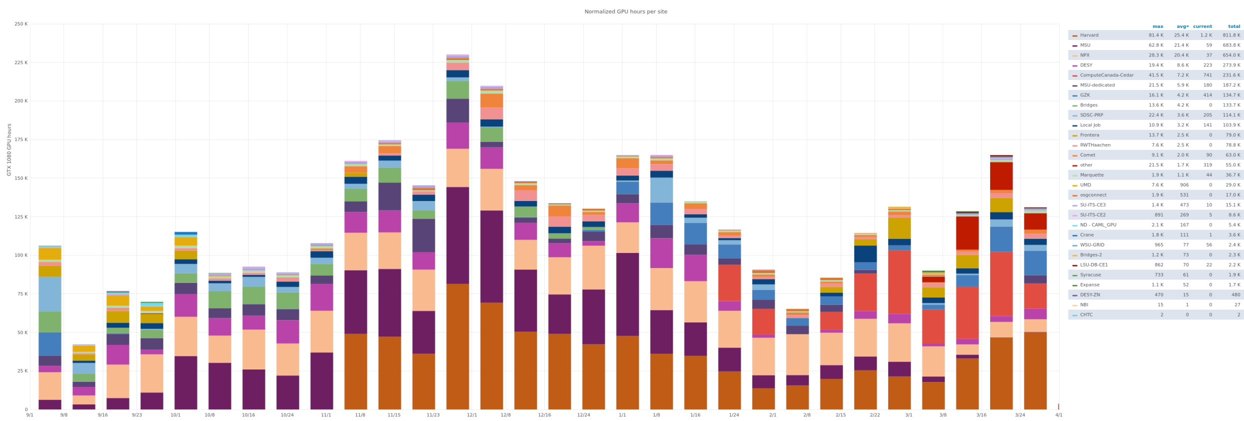


Figure 6: GPU time contributed by various sites from 1 September 2020 – 1 April 2021.

In order to implement this pilot job paradigm for the distributed infrastructure, IceCube makes use of some of the federation technologies within HTCondor. Pilot jobs in HTCondor are called "glideins" and consist of a specially configured instance of the HTCondor worker node component, which is then submitted as a job to external batch systems.

Several of the sites that provide computing for IceCube are also resource providers for other scientific experiments that make use of distributed computing infrastructures. Thanks to this, they already provide a standard (Grid) interface to their batch systems. In these cases, we can leverage the standard GlideinWMS infrastructure operated by the Open Science Grid2 project for integrating those resources into the central pool at UW–Madison and provide transparent access to them via the standard HTCondor tools. The sites that use this mechanism to integrate with the IceCube global workload system are: Aachen, Canada, Brussels, DESY, Dortmund, Wuppertal, and Manchester.

Some of the IceCube collaborating institutions that provide access to local computing resources do not have a Grid interface. Instead, access is only possible by means of a local account. To address those sites, we have developed a lightweight version of a glidein pilot job factory that can be deployed as a cron job in the user's account. The codename of this software is "pyGlidein," and it allows us to seamlessly integrate these local cluster resources with the IceCube global workload system so that jobs can run anywhere in a way that is completely transparent for users. The sites that currently use this mechanism are: Canada, Brussels, DESY, Dortmund, LBNL, Mainz, Marquette, Munich, NBI, and UMD. There are ongoing efforts at the Delaware and Chiba sites to deploy the pyGlidein system. We continue to observe a growing trend both in the number of sites integrated as well as the computing time delivered.

Beyond the computing capacity provided by IceCube institutions, and the opportunistic access to Open Science Grid that shares their idle capacity, IceCube has received additional computing resources from targeted allocation requests submitted to supercomputing facilities such as the NSF Leadership-Class Facility and Extreme Science and Engineering Discovery Environment (XSEDE). We have been awarded a Large-Scale Community Partnership for NSF's leadership-class HPC system Frontera with 130,000 SUs per year.

IceCube submitted an initial research allocation request to XSEDE in October 2015 (allocation number TG-PHY150040) that was awarded with compute time in two GPU-capable systems: SDSC Comet and PSC Bridges. The latest renewal for this research allocation, in July 2020, was awarded with GPU compute time in two systems: SDSC Comet with 165,000 SUs and PSC Bridges with 440,000 SUs. IceCube stands out as one of the largest GPU users in XSEDE and has been acknowledged in several XSEDE press releases. An additional 10,000 CPU SUs was awarded on Stampede2.

With the aim to continue exploring the possibilities to expand the pool of available computing resources for IceCube, IceCube took part in an experiment at SuperComputing 2019 funded through an EAGER award (NSF OAC 1941481). A UCSD/SDSC and UW–Madison team created one of the largest GPU clusters ever using the resources of commercial cloud providers. The IceCube photon propagation code was used as a payload[1]. We have sufficient funding left to run a third experiment in late spring or summer of 2021.

Highlights of the Five-Year Program

The 2016–2021 IceCube computing and data management maintenance and operations program was successful.

Key achievements include the following:

- transitioned to a new data warehouse
- transitioned to new workflow management software (IceProd2)
- increased pledged computing resources for IceCube
- relocated data center from 222 West Washington to co-location facility
- obtained additional funding for cyberinfrastructure projects
- upgraded internal and external network connectivity to 100 Gbit/s
- participated in three experiments on scaling IceCube infrastructure with cloud resources in collaboration OSG
- developed new automated long-term archival software for experimental data
- launched new IceCube website
- created a file catalog of the data warehouse

Data Release

IceCube is committed to the goal of releasing data to the scientific community. The following links contain data sets produced by AMANDA/IceCube researchers along with a basic description. Due to challenging demands on event reconstruction, background rejection, and systematic effects, data is released after the main analyses are completed and results are published by the IceCube

[1] https://arxiv.org/abs/2002.06667 and https://arxiv.org/abs/2004.09492

Collaboration. Since summer 2016, thanks to UW–Madison subscribing to the EZID service, we have the capability of issuing persistent identifiers for data sets. These are digital object identifiers (DOI) that follow the DataCite metadata standard. We are in the process of rolling out a process for ensuring that all data sets made public by IceCube have a DOI and use the DataCite metadata standard capability to "link" to the associated publication, whenever this is applicable. The use of DataCite DOIs to identify IceCube public data sets increases their visibility by making them discoverable in the search.datacite.org portal (see https://search.datacite.org/works?resource-type-id=dataset&query=icecube).

A complete list of all IceCube data sets available for download is available at https://icecube.wisc.edu/science/data-releases/. The releases during the last five years of the project are listed in Table 5:

Description	**Release Date**
IceCube data for the first Glashow resonance candidate	March 10, 2021
All-sky point-source IceCube 2008-2018 data	January 26, 2021
South Pole ice temperature	May 14, 2020
IceCube Upgrade Neutrino Monte Carlo Simulation	April 21, 2020
All-sky point-source IceCube 2012-2015 data	February 27, 2020
Bayesian posterior for IceCube 7-year point-source search with neutrino-count statistics	September 4, 2019
Three-year high-statistics neutrino oscillation samples	May 15, 2019
All-sky point-source IceCube data: years 2010-2012	October 18, 2018
IceCube catalog of alert events up through IceCube-170922A	July 12, 2018
IceCube data from 2008 to 2017 related to analysis of TXS 0506+056	July 12, 2018
Measurement of atmospheric neutrino oscillations with three years of full sky data	February 13, 2018
A combined maximum-likelihood analysis of the astrophysical neutrino flux	November 15, 2016
Search for point sources with first year of IC86 data	November 1, 2016
Search for sterile neutrinos with one year of IceCube data	June 24, 2016

Table 5: IceCube data releases for the last five years.

Data Processing and Simulation Services

Data Processing

The data collection for the IC86-2021 season started on May 27, 2021. Data processing scripts were validated by technical leads from the various physics working groups with data recorded during the 24-hour test run using the new DAQ configuration. Observed differences with respect to the previous season are consistent with statistic fluctuations. During previous years, an effort was made 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, consistent with prior estimates.

With the start of the 2020-2021 season, offline data processing was migrated from the IceProd1 framework running on our local cluster to IceProd2 running on opportunistic grid computing resources.

The move required some coordination with the distributed infrastructure team to implement additional features needed to support this task.

For both the Pole-filtered input data and the output data resulting from the offline production, 100 TB of storage is required. Additional savings in storage resulted from a switch to a more efficient compression algorithm in the 2017 season. As of the start of the 2018 season, we switched to a new database structure at the Pole and in Madison for offline production. The transition went smoothly, with no significant issues. Level2 data are typically available one and a half weeks after data taking.

Additional data validations have been added to detect data corruption and similar issues. Replication of all the data at DESY is being done in a timely manner. We are currently reviewing existing filters and reconstructions with the aim of streamlining offline processing at Level 2 and Level 3.

Data Reprocessing

Recent improvements to data processing and detector calibration required that we reprocess nearly 10 years of data. This reprocessing involves retrieving data from long-term archive and developing a new workflow that includes both online and offline processing.

An added benefit of the reprocessing of data (Pass2) was the opportunity to unify the multiyear data set and to profit from improvements in our understanding of low-level DOM calibration. The reprocessing campaign started on June 1, 2017, was completed in August of 2018, and included a total of seven years of data (2010–2016).

Additional data reprocessing campaigns will be needed as further improvements in calibration and feature extraction are developed. The current refinements do not yield sufficient improvements to warrant the expense of roughly $1,000,000 in compute time and person-hours. As a result, we are delaying such reprocessing until deemed necessary. Improvements in calibration resulting from the IceCube Upgrade will certainly require additional reprocessing campaigns. We anticipate at least two additional reprocessing campaigns.

Monte Carlo Simulation Production

The production of IC86 Monte Carlo simulations of the IC86-2016 detector configuration concluded at the beginning of 2020. A new production of Monte Carlo simulations has since begun with the IC86-2020 detector configuration. This configuration is representative of previous trigger and filter configurations included in pass2. These include 2012, 2013, 2014, 2015, and 2016-2021. 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 combined software suite. New features in the simulation software include individually calibrated PMT waveforms, optimized event resampling 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 tools to generate targeted simulations optimized for individual analyses instead of a one-size-fits-all approach. New strategies are being 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. A new production campaign will begin as soon as validation of these tools has been completed.

The resource aggregation and workflow management of Monte Carlo simulations has transitioned from a distributed model to a centrally managed one, significantly reducing the effort needed compared to managing individual sites. Throughput has continually increased due to incorporation of an increasing number of dedicated and opportunistic resources and a number of code optimizations. New monitoring tools are currently being developed in order to keep track of efficiency and further optimizations. New procedures are also being implemented for allocating resources and priorities to individual simulations as well as those produced by working groups.

Computing Resource Needs

The current utilization of resources for the required offline production is approximately 480,000 CPU-hours on the IceCube cluster at the UW–Madison data center. An effort was made in 2019 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.

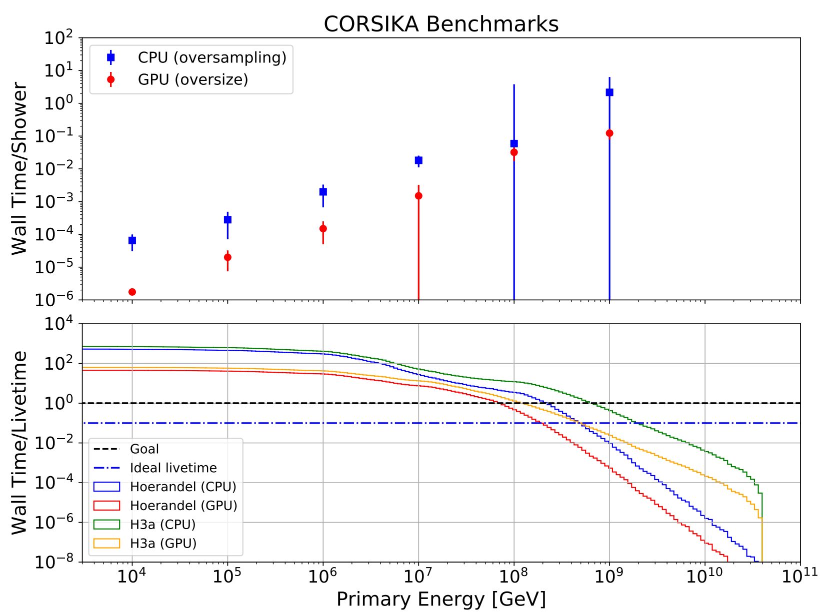


Figure 7: (a) CPU (GPU) time per cosmic-ray shower as a function of energy. (b) The ratio of wall time to detector livetime indicates the number of CPU (GPU) units continuously running for one year needed to simulate one year (10 years) of detector livetime.

Simulation production requirements are primarily dominated by background simulations with `CORSIKA` [1] 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 simulation (including systematics). As an alternative to this amount of background simulation, we can also simulate final-state muons that can be weighted

	CORSIKA	**MuonGun**	**Diffuse**	**OscNext**	**IceTop**	**Total**
CPU (years)	30000	23	58	2112	1157	**33350**
GPU (years)	2400	95	680	184	0	**3359**
Storage (TB)	3330	10	10	60	200	**3610**

Table 6: Estimated resource requirements for the main Monte Carlo data sets needed for physics analyses. `CORSIKA` simulation assumes a DOM-oversizing factor of 5.

according to a parametrized flux calculated from `CORSIKA` simulations using the same approach as MUPAGE [2], which was developed by the ANTARES Collaboration [3]. 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.

Estimated resource requirements are presented in Table 6, while Fig. 7 illustrates CPU/GPU resources as a function of energy. Expanding access to computing resources has been a continuous effort. IceCube has been at the forefront of using novel cyberinfrastructure, including the large-scale use of GPUs.

Highlights of the Five-Year Program

The 2016–2021 IceCube cyberinfrastructure maintenance and operations program was successful. Researchers are able to analyze data within two weeks of data taking, and the M&O team has been able to reprocess nearly 10 years of data. Monte Carlo production continues to generate livetime and improve the description of the detector. At the same time, Monte Carlo production continues to fall short of the goal to produce an equivalent amount of livetime as there is data.

Ongoing software development has facilitated expansion of IceCube's robust science program as well as laid the foundation for future detector expansions such as the IceCube Upgrade.

Key achievements include the following:

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

IceCube Software Coordination

The major coordination effort continues to focus on the codebase (a.k.a. "IceTray") that directly supports pole processing and filtering, reconstruction, analysis, and simulation. IceTray, made up of more than 100 projects, includes a core framework along with projects that support collaborators, ranging from serialization, simulation, reconstruction, and filtering to AI/ML support. Nearly all data

(10s of PB), including both simulation and data collected from the pole, is in IceTray's serialization format, making it the core software project that all collaborators rely on.

Over the past six months, we have had one major release after two supporting code sprints. We have had two boot camps, available to the entire collaboration and hosted by the Strike Team. The topics of the boot camps were "C++ Refresher and Multithreading" and "Intro to Rust." In January 2021, the Strike Team introduced leadership rotations between the software coordinator and four senior, professional software engineers. The leadership changes are seasonal and coordinated with code sprints and quarterly feature releases.

The software team modernized its development operations (DevOps) by transitioning from a subversion-based repository to a modern GitHub organization. The GitHub organization currently consists of 70 repositories, including the main central IceTray repository mentioned above. There are currently 257 members of the organization, and the number grows weekly. The continuous integration system was also updated from buildbots to GitHub Actions. The software group has been investigating a commercial product, Codescene, as a tool to measure, manage, and mitigate technical debt.

Highlights of the Five-Year Program
Key achievements include the following:

- IceTray containers for AI/ML support
- 30 releases (4 major, 5 feature, 21 patch)
- seasonal/quarterly development cycle
- major project consolidation and unification
- yearly public reviews of project prioritization
- project management tools adopted (e.g., smartsheet and codescene)
- 95% IceTray project adoption
- improved coordination with ICC and WG tech leads
- 10 Strike Team hosted boot camps
- Strike Team 10 current members (14 alumni)
- GitHub transition
- Python3 transition
- development of in-house continuous delivery (CI/CD) system
- development of a five-year work plan (in progress)

Calibration

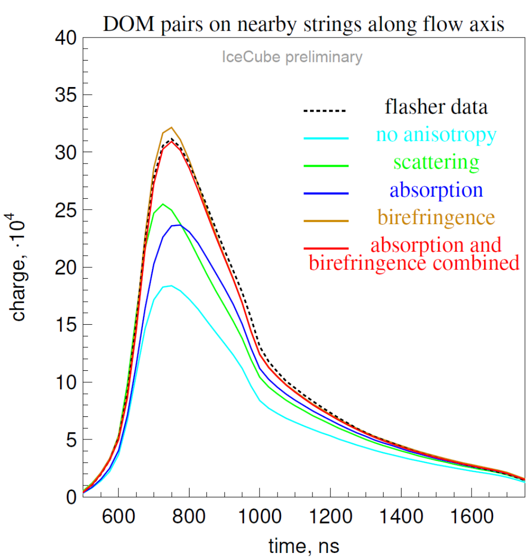
A weekly calibration call, alternating between two time slots suited to US/EU and to Asia/Pacific/EU institutions, keeps collaborators abreast of issues in both in-ice and offline IceCube calibration. The group's activities are coordinated by two conveners, with Summer Blot taking over from Dawn Williams in February 2017 and being superseded by Martin Rongen in June 2020. Allan Hallgren replaced Keiichi Mase in fall 2019.

We continue to refine measurements of the optical properties of the South Pole ice, which constitutes our detector material, as well as the IceCube DOM response to photons. Precise modeling of both ice and photosensors is fundamental for the analysis of recorded signals, which aims to determine the top-level quantities of interest, such as neutrino direction, energy, and flavor. The detection efficiency estimate depends on calibrated quantities and is important for the determination of the absolute neutrino flux and spectral distribution.

Ice Characterization

These studies are typically subdivided into those that concern the naturally formed bulk ice and those that concern the refrozen ice in the drilled holes where the DOMs were installed.

In spring 2021, a new bulk ice model, called SpiceBFRv2, was released. It combines the recently established ice-intrinsic birefringence anisotropy with an absorption anisotropy. While the mechanism behind the absorption component remains to be understood, the combined model for the first time achieves a near perfect data-MC agreement (see Fig. 8) while at the same time fitting crystal properties as expected from glaciological measurements (as obtained in, e.g., data from SPICEcore). The interdisciplinary implications of this model were among the many topics discussed at the IceCube Polar Science Workshop organized in January 2021 and attended by over 130 international participants.



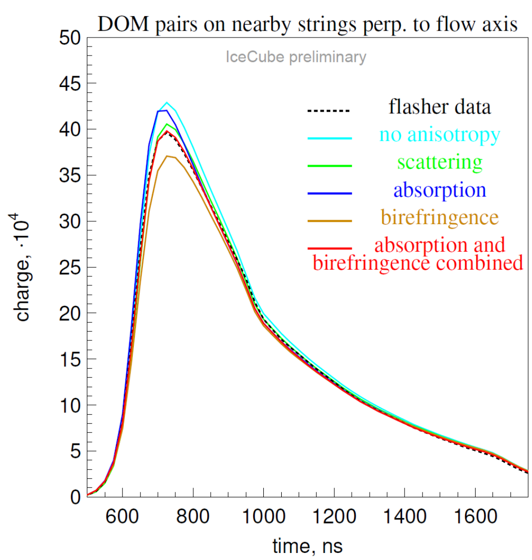


Figure 8: Comparison of fit quality achieved with different models of the ice optical anisotropy.

The new bulk ice model has eliminated biases previously observed when fitting hole ice properties. Iterating on an earlier analysis, the average radius of the central bubble column, its scattering coefficient, and each module's location with respect to the bubble column has recently been fitted with much improved fidelity. The impact, in particular on neutrino oscillation analyses, remains to be investigated.

This, for now, concludes a large calibration campaign spanning all project years in this report. It started with the collection of the single LED flasher data, required establishing individual DOM orientations to subdegree accuracy, saw the introduction of direct hole-ice simulation (in contrast to modelling via angular acceptance curves used previously), and required a detailed understanding of the ice microstructure to replace the previous phenomenological SpiceLea anisotropy model. This calibration work has now resulted in a much improved, high-precision model for both the bulk ice and the hole ice.

We will continue to refine the ice model. There are still known shortcomings, such as the model implemented for tilt of ice layers (layers of constant properties are not at the same depths over the extent of the array). Other ice calibration and modeling areas for continued improvement will almost certainly be identified in future analysis of calibration or physics data.

A second focus throughout the project duration was logger-based measurements in the SPICEcore drill hole. These have extended our understanding of ice properties in the deep UV range and of luminescence resulting in additional light on top of the Cherenkov emission. The logger-based observations also delivered independent evidence for the birefringence anisotropy described above. The opportunity to use the SPICEcore hole also allowed for evaluation of novel calibration devices such as the cameras that are to be installed in the optical modules of the IceCube Upgrade project.

DOM characterization

We continue to iterate on in situ, muon-based as well as laboratory-based, DOM absolute sensitivity studies, including sensitivity variations of the deployed modules. The $\sim 4\%$ charge correction, established at the end of the last project period, has proven to be insufficient in matching data with simulation for the shape of each DOM's single photoelectron (SPE) charge response. This temporarily caused several low-energy physics analyses to not rely on charge-based observables. To establish new SPE templates for use in simulation, all DOMs' SPE charge responses were analyzed. This was particularly challenging due to the lack of triggered single-photon light sources in situ.

Other actively ongoing work regarding DOM characterization includes the measurements of the very late afterpulse timing spectrum up to 100 microseconds. Afterpulses are not commonly assumed to persist this late, yet they are present at a very low rate. This was observed in an analysis searching for a "neutron echo." Observation of such an echo would allow discrimination of hadronic from electromagnetic cascades. Such analysis depends strongly on knowledge of the amount of afterpulses and their time spectrum. The effect was later confirmed in lab measurements. A dedicated, dead-time-free DAQ for use in IceCube to obtain in situ afterpulse calibration of the DOMs is currently under evaluation.

To date the lateral positions of the DOMs on a string are derived from the GPS coordinates of the deployment tower. Two ongoing studies are trying to accurately deduce the array geometry from in situ measurement, one by trilateration of flasher data and the other through repeated muon reconstructions under perturbed geometry assumptions.

Upgrade Related Activities

The IceCube Upgrade will further boost our ice understanding and 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., pencil beam, POCAM, camera systems, LED flashers, dust logger). This has more recently also expanded to discussion regarding the mDOM and dEgg design verification and final acceptance testing.

Program Management

Management and Administration – The primary management and administration effort is to ensure that tasks are properly defined and assigned, that the resources needed to perform each task are available when needed, and that resource efficiency is tracked to accomplish the task requirements and achieve IceCube's scientific objectives. Efforts include the following:

- The IceCube Coordination Committee is migrating away from a manual process of collecting pledges of labor and computing resources by collaboration institutions and allocating those resources to a prioritized list of tasks of vital importance to the scientific infrastructure needs of the collaboration. It is moving to a web-based application that permits continual updates by institutional PIs of pledged resources as well as updated core tasks.
- A complete rebaseline of the IceCube M&O Work Breakdown Structure was initiated at the beginning of the current M&O cycle that more accurately reflects the structure of the principal resource coordination entity, the IceCube Coordination Committee, and the major supporting infrastructure deliverables of the M&O program. This WBS has remained largely intact; however, the SPS and SPTS WBS L3 nodes have been merged due to the symmetry of the deliverables in those areas.
- Since Q2 2020, M&O administration has been collecting costs incurred during facility operation that are unambiguously due to the ongoing COVID-19 pandemic. A new section of the project reports has been added to address COVID-19 issues, including costs.
- The detailed M&O memorandum of understanding (MoU) addressing responsibilities of each collaborating institution was revised before the spring 2021 collaboration meeting, in March 2021.

IceCube M&O Milestones Status

The milestones for PY5 and completion dates are shown in Table 7.

Engineering, Science, and Technical Support

Ongoing support for the IceCube detector continues with the maintenance and operation of the South Pole Systems, the South Pole Test System, and the Cable Test System. The latter two systems are located at UW–Madison and enable the development of new detector functionality as well as

Milestone	Month
Revise the institutional memorandum of understanding (MOU v28.0) - statement of work, and Ph.D. authors head count for the fall collaboration meeting	June 2020
Report on scientific results at the fall collaboration meeting	September 2020
Report on scientific results at the spring collaboration meeting	March 2021
Revise the institutional memorandum of understanding (MOU v29.0) - statement of work, and Ph.D. authors head count for the spring collaboration meeting	March 2021
Submit for NSF approval a final report that describes progress made and work accomplished based on objectives and milestones in the approved annual M&O Plan.	July 2021

Table 7: NSF IceCube M&O milestone status – PY5 (FY2020/FY2021).

investigations into various operational issues, such as communication disruptions and electromagnetic interference. Technical support provides coordination, communication, and assessment of impacts on activities carried out by external groups engaged in experiments or potential experiments at the South Pole. The IceCube detector performance continues to improve as we restore individual DOMs to the array at a faster rate than problem DOMs are removed during normal operations.

Education & Outreach (E&O)/Communications

The IceCube Collaboration made significant adjustments during the reporting period due to constraints from COVID-19. The E&O and communications activities are organized around four main themes:

1. *Reaching motivated high school students and educators* through internships, IceCube Masterclasses, and the University of Wisconsin-River Falls' (UWRF) and University of Rochester's (UR) Upward Bound programs.

2. *Providing intensive research experiences* for educators (in collaboration with PolarTREC) and for undergraduate students (NSF science grants and Research Experiences for Undergraduates (REU) funding) to increase STEM awareness.

3. *Engaging the public* through various means, including web and print resources, graphic designs, an IceCube comic, live talks, virtual reality gaming, and displays.

4. *Developing and implementing communication skills and diversity workshops*, held semiannually in conjunction with IceCube Collaboration meetings.

IceCube's high school internship returned in 2021 in a virtual format. A collaboration between three IceCube institutions—WIPAC, Marquette University, and South Dakota Mines—the "IceCube After School" program (Fig. 9) was led by former IceCube/PolarTREC educator Katey Shirey. The curriculum was based on the program developed by Shirey and 2019 IceCube/PolarTREC educator Jocelyn Argueta for UWRF's summer 2020 Upward Bound program. IceCube After School was designed to layer three threads of learning: IceCube and neutrino science, programming, and computational thinking. Students wove these three threads into a final coded project to demonstrate their learning about IceCube science (Fig. 10).

Masterclasses were held virtually in 2021 at twelve institutions spanning the U.S., Europe, and Asia. For the first time since the inception of the IceCube Masterclass, we were joined by Chiba University

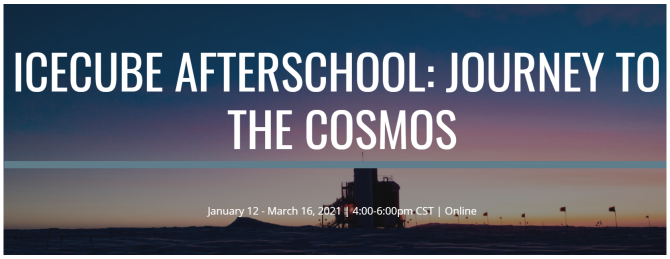


Figure 9: The poster for the IceCube After School program.

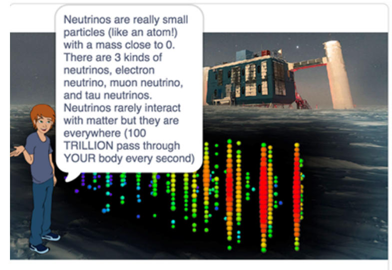


Figure 10: Screen shot of a student's app.

in Japan, and the program was translated into Japanese on our Masterclass website. The virtual format allowed us to include students from diverse backgrounds and locations who would otherwise not be able to attend in person. The curriculum followed our normal programming: introducing high school students to IceCube and neutrino science with a series of talks by IceCube scientists, followed by a hands-on activity where students analyzed real IceCube data.

We presented an IceCube talk and virtual tour of the South Pole at the conference ScienceWriters 2020 in October of 2020. The presentation consisted of an introduction to IceCube science by IceCube PolarTREC educator Jocelyn Argueta (Fig. 11), a prerecorded tour of the South Pole facilities led by IceCube winterovers John Hardin and Yuya Makino (Fig. 12), and a live demo of IceCube's new augmented reality app. It was attended by about 100 journalists, researchers, and science communicators at the virtual meeting; the session was recorded and later posted to IceCube's YouTube channel, where it has received another 7,500 views. The individual video of the South Pole tour has received another 14,000 views on YouTube.

Figure 11: Argueta giving her virtual introduction on IceCube science.

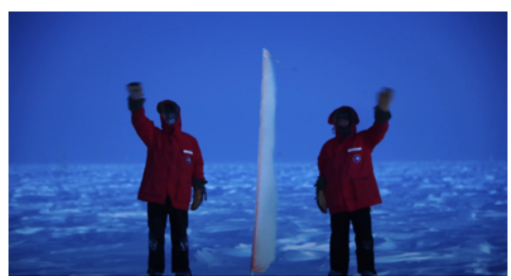


Figure 12: IceCube winterovers John Hardin and Yuya Makino signing off from the South Pole.

IceCube's new augmented reality (AR) app IceCubeAR (Fig. 13) was developed by a team led by collaborator Lu Lu. The free app uses a smartphone's camera to overlay a model of IceCube's below-ice detector onto the surrounding environment; the user can then watch IceCube neutrino candidate events go through the detector as seen on their phone screen. IceCubeAR allows anyone, even members of the public, to receive real-time alerts about candidate IceCube neutrino events directly to their devices. This augments the real-time neutrino event alerts that we post on Twitter, providing followers with a behind-the-scenes look at our science as it develops.

The IceCube communication office manages press and other communication activities for both the neutrino observatory and the IceCube Collaboration. As part of our efforts, all issues of the IceCube comic series "Rosie & Gibbs" are now available in English, Spanish, French, Dutch, and Portuguese. Translations are in progress for Italian, Swedish, German, Dutch, Chinese (traditional and simplified), Korean, and Thai. We continue to produce multimedia content for social networks, which has increased the reach of IceCube communication from a few thousand to tens of thousands on an average week, with peaks of hundreds of thousands associated with big announcements, such as our March 2021 campaign around IceCube's detection of the Glashow resonance event.

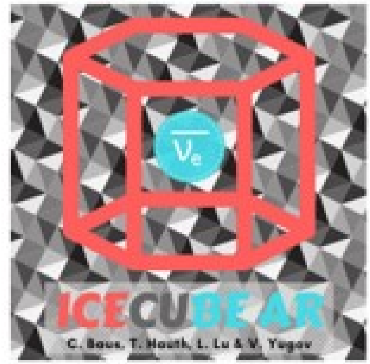


Figure 13: The IceCubeAR icon.

All the IceCube Collaboration meetings during the 2016–2021 period have included one or more professional development opportunities to improve career or communication skills or to help create a more inclusive environment. The LGBTQ+Allies meetup, the women's meetup, and the social justice workshop held virtually in conjunction with the virtual fall IceCube Collaboration meeting produced productive dialog and ideas to improve equity, diversity, and inclusion.

The Multimessenger Diversity Network (MDN), funded by the M&O INCLUDES supplemental award, added two more multimessenger collaborations, LISA and Auger, increasing the total to nine members. The first two equity, diversity, and inclusion training awards were made to graduate students Jessie Micallef (Michigan State) and Alex Pizzuto (Wisconsin). The MDN focuses on increasing equity, diversity, and inclusion by sharing knowledge, experiences, training, and resources among representatives from multimessenger science collaborations. Representatives to the MDN become engagement leads in their collaboration, extending the reach of the community of practice. Virtual meetings have been held monthly for the last two years. A poster and conference paper summarizing MDN activities, describing lessons learned, and inviting more collaborations to join was accepted for the 2021 International Cosmic Ray Conference to be held in July 2021.

III. Project Governance and Upcoming Events

The detailed M&O institutional responsibilities and Ph.D. author head count is revised twice a year at the time of the IceCube Collaboration meetings. This is formally approved as part of the institutional Memorandum of Understanding (MoU) documentation. The MoU was last revised in March 2021 before the spring collaboration meeting (v29.0), and the next revision (v30.0) will be posted in September 2021 before the fall collaboration meeting.

IceCube Collaborating Institutions

As of June 2021, the IceCube Collaboration consists of 53 institutions in 12 countries (30 U.S. and Canada, 20 Europe and 3 Asia Pacific). The list of current IceCube collaborating institutions can be found on: https://icecube.wisc.edu/collaboration/institutions/

IceCube Major Meetings and Events

- IceCube Fall Collaboration Meeting (virtual): September 14–25, 2020
- International Oversight and Finance Group (virtual): September 29–30, 2020
- IceCube Spring Collaboration Meeting (virtual): March 17-26, 2021
- IceCube Fall Collaboration Meeting: September 18–25, 2021

IV. COVID-19 Impacts to ICNO Management and Operations

Two decades ago, the maintenance and operations aspects of a uniquely remote, large-scale neutrino telescope facility were carefully considered, and they influenced the all-digital design of IceCube and its online systems. This has resulted in an observatory that, aside from occasional major upgrades every few years, can largely be operated by a field-deployed crew of two operators, with the majority of operations carried out remotely by subject matter experts. Moreover, the distributed nature of the M&O team, which spans institutions in USA, Europe, and Asia, forced early adoption of organizational processes suited for management of remote teams. IceCube M&O has continued mostly uninterrupted for all of PY5 even as the global workforce moved largely to working remotely during the same period. The resulting operational and financial impacts are discussed in this section.

Operational Impacts

Detector Operations

The travel restrictions due to the COVID-19 pandemic did not start until after the South Pole station closure in February 2020. The operations team was already accustomed to working as a geographically distributed group, so IceCube detector operations have continued relatively smoothly, with adjustments described below. Training of the 2020–21 winterovers was significantly impacted, as travel to WIPAC and other sites for in-person training was impossible. All training was done on a compressed schedule and in virtual sessions. The risk to operations in the 2020-21 season has been mitigated by the following actions:

- One of the 2020-21 winterovers, M. Wolf, previously wintered for IceCube and thus has extensive prior operations experience.
- One of the 2019-20 winterovers, J. Hardin, had his South Pole deployment extended through January 2021 to provide on-site, hands-on training for 2020-21 winterovers.
- A backup winterover, T. Leps, participated in the training in case one of the primary winterovers could not deploy due to travel or quarantine issues.

The logistics of getting the winterovers to New Zealand for deployment to the South Pole was complicated by their non-U.S. resident status. They needed permission to enter the U.S. to join an ASC charter deployment flight from California to New Zealand. We simultaneously worked with Immigration New Zealand on a backup plan to fly them directly to Auckland while we pursued expedited U.S. visas for them with the help of our congressional representative. The latter was ultimately successful, and Wolf and fellow IceCube winterover J. Veitch-Michaelis were able to join the USAP South Pole winterover crew in California prior to the charter flight on October 6, 2020, to Christchurch, NZ. After subsequent quarantine stays both in Christchurch and at McMurdo, they arrived at the South Pole on November 25, 2020. Because significant hardware maintenance was accomplished in the 2019–20 Pole season, cancelling deployments of IceCube maintenance personnel in the 2020–21 Pole season did not significantly jeopardize IceCube detector operations. However, the following planned activities had to be postponed, with the goal to complete them in the 2021–22 Pole season:

- The SPS operating system upgrade. Deferring this upgrade may result in an increased online software maintenance burden as we need to support more modern tools on the older operating system.
- An upgrade of the system configuration management system to support the SPS operating system upgrade.
- An upgrade of the SPS keyboard/video/monitor (KVM) system.
- The deployment of the first production surface array station (by moving the prototype station). If the surface array deployment proceeds in 2021–22, we will attempt to recover the original construction schedule.
- Rack space consolidation in preparation for the IceCube Upgrade.

Population planning for the 2021–22 summer season will need to take postponed tasks into account. Additionally, COVID-19 workplace restrictions delayed copying the 2019 data returned from the Pole, at the beginning of the year, to online disk. As a result, the set of experimental data disks holding that data could not be sent back to the Pole this year for reuse in 2021, and a new set of disks had to be purchased and sent to Pole. Costs associated with these operational impacts are detailed in the Financial Impact section below.

Computing and Data Management

The M&O core computing and data infrastructure support teams have continued to work effectively in remote fashion. IceCube HTC and storage cluster remain online with high availability. As detailed in the next section on financial impacts, a mechanical lift was purchased as a remediation to workplace population limits that would have otherwise prevented cluster maintenance activities.

Financial Impact

Explicit COVID-19 expenses incurred by ICNO operations are listed in Table 8.

WBS	Cost	Description	Justification
2.2 – DetOps	$284.49	Webcam	WO remote training
2.2 – DetOps	$10,771.20	Disks (40)	Replacement disks for 2021 season experimental data storage
2.2 – DetOps	$28,847.92	Labor – T. Leps	Winterover backup hired as precaution against failure to insert primary WOs into SP team: 8/24/20 – 10/31/20
2.2 – DetOps	$8,517	Labor – J. Hardin	Extension of existing WO at Pole through 1/31/21 for on-site training
2.2 – DetOps	$18,974.39	Travel	WO travel (Wolf, Veitch, Leps) for purpose of obtaining J-1 visa; additional costs due to manadatory 14-day quarantine at Grand Hyatt SFO
2.3 – Computing Data Mgmt	$13,554.37	Server lift	Motorized lift for racking computing and storage server chassis
Grand Total	**$80,949.36**		

Table 8: The financial impact from COVID-19 categorized by WBS number.

Acronyms

Acronym	Meaning
CPU	Central Processing Unit
CVMFS	CernVM-Filesystem
DAQ	Data Acquisition System
DOM	Digital Optical Module
E&O	Education and Outreach
GPU	Graphical Processing Unit
I3Moni	IceCube Run Monitoring System
IC86	The 86-string IceCube Array, completed Dec 2010
IceACT	IceCube Air Cherenkov Telescope
IceCube Live	The system that integrates control of all of the detector's critical subsystems; also "I3Live"
IceTray	IceCube core analysis software framework, part of the IceCube core software library
MoU	Memorandum of Understanding, between UW–Madison and all collaborating institutions
PMT	Photomultiplier Tube
PnF	Processing and Filtering
PQ	Physical Qualification
SNDAQ	Supernova Data Acquisition System
SPE	Single Photoelectron
SPS	South Pole System
SuperDST sDST	Super Data Storage and Transfer, a highly compressed IceCube data format
TDRSS	Tracking and Data Relay Satellite System, a network of communications satellites
TFT	Trigger, Filter and Transmission Board
WIPAC	Wisconsin IceCube Particle Astrophysics Center

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