IceCube Management and Operations Plan

2021–2026

ICECUBE MANAGEMENT AND OPERATIONS TEAM

Revision History

Revision	Date	Comments
1.0	July 2020	First version for 2021–2026: adapted from PY4 (2019) M&O Plan and proposal material

Contents

A. Introduction

This document describes the management and operations (M&O) plan for the IceCube Neutrino Observatory (ICNO), focused on years 2021–2026. The core M&O team works to develop, maintain, and implement necessary hardware and software to ensure the reliability and capability of the facility to capitalize on its science and discovery potential. These efforts build upon the experience gained from twelve highly successful years of safely and cost-effectively managing the ICNO to continually improve its performance.

ICNO instruments a cubic kilometer of the Antarctic glacier and square kilometer on the surface above at the geographic South Pole as a neutrino and cosmic-ray detector and is shown in Figure 1. Composed of over 5000 Digital Optical Modules (DOMs), the detector, including the data acquisition, control, data handling and data filtering systems, operates continuously with high duty factor (>99%). In more than a decade of operation, IceCube data have been used in numerous discoveries, including the first detection of astrophysical neutrinos [1, 2].

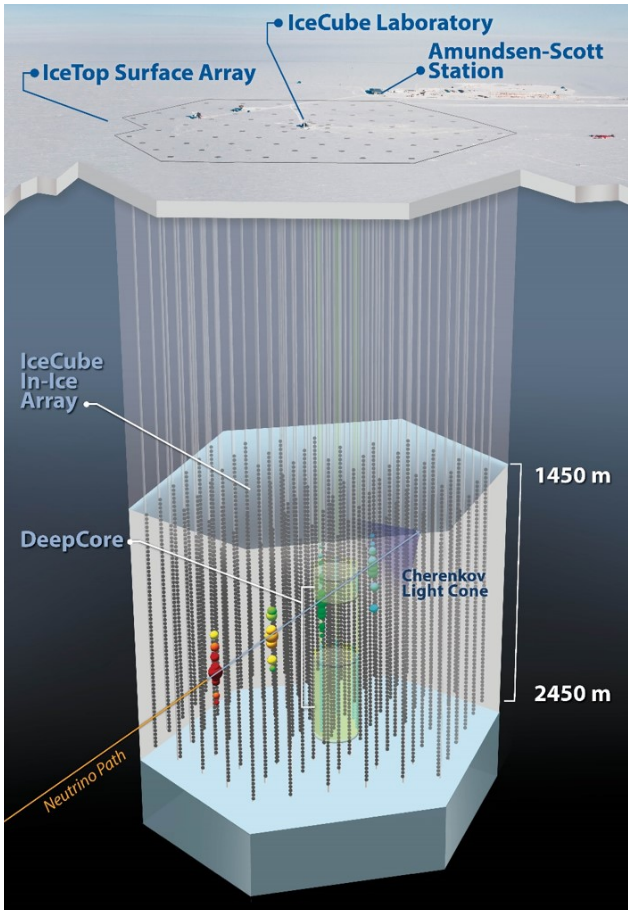


Figure 1: Schematic view of the IceCube Neutrino Observatory, including the In-Ice, DeepCore and IceTop arrays, as well as the central IceCube Laboratory. All are located near the Amundsen-Scott South Pole Station in Antarctica.

Now more than ever, realization of our scientific vision requires the attention of a highly technically competent and dedicated team to oversee the reliable operation of the ICNO facility. Our approach to the planning and execution of IceCube management and operations is based on nearly a decade of experience, over which time the combined teamwork of the centralized M&O organization WIPAC and the IceCube Collaboration has streamlined the process. Tasks range from detector hardware and firmware maintenance to characterization of the ice optics; from production of massive simulated data sets to organizing outreach activities and communicating scientific results to the press. Each aspect of M&O is proven through extensive use to maximize the facility's scientific and educational potential.

This plan describes the major systems that make up the IceCube M&O effort and outlines the plans for each system for the upcoming five-year operational period, spanning 2021–2026. These systems directly support the science output of the entire ICNO and IceCube scientific collaboration. These systems, as outlined in the ICNO M&O Work Breakdown Structure (WBS), include:

- **Program organization** provides program, financial and organizational coordination for the overall M&O effort.
- **Core detector operations** provides the core hardware and software systems used to operate and monitor the detector at the South Pole
- **Detector calibration** provides critical optical module and array calibrations needed to accurately reconstruct and extract neutrino signals from ICNO data.
- **Northern Hemisphere cyberinfrastructure** provides needed cyberinfrastructure and administration support to enable IceCube scientists to fully analyze ICNO collected data.
- **Data processing and simulation tools** provide the necessary tools and personnel to perform and verify the production of large data sets for data analysis by the collaboration.
- **Physics software** provides the software packages used by the collaboration at all levels of data analysis and production, including data filtering, reconstruction and simulation.

Subsequent sections of this plan describe the core functionality of each WBS area and describe the management and operations effort required and plans for the five-year period covering 2021–2026.

A.1 IceCube Infrastructure

Several key systems go into making up the ICNO infrastructure that constitutes the observatory [3, 4]. All require regular maintenance, support, and improvements to deliver high-quality science.

- In-Ice and IceTop Digital Optical Module (DOM) arrays - The DOMs, the combination of a photomultiplier light sensor, signal digitization and communication electronics and firmware, are the heart of ICNO. Over 5000 DOMs (Figure 2), are deployed in the deep ice below the South Pole and in ice-tanks on the surface to make up the In-Ice and IceTop arrays. All sensors are connected via a cable network to the SPS computing system in the ICL. The stable operation of all DOMs requires regular module monitoring and calibration to ensure each is delivering well-characterized, high-quality science data.

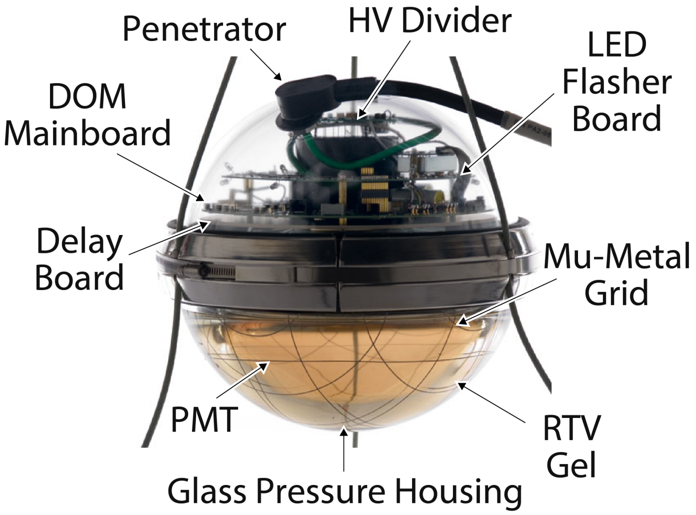


Figure 2: Schematic view of the IceCube DOM, highlighting the light-sensing photomultiplier tube (PMT), control and digitization electronics, cable connection, and glass pressure housing.

- IceCube Laboratory (ICL) - The ICL building at the South Pole station houses various IceCube systems, including cable connections to DOMs. Provided and maintained by the United States Antarctic Program, the ICL also provides power and network connections for IceCube systems housed there.

- IceCube South Pole System (SPS) - The SPS hardware includes DOMHub computers, commodity server class computers, remote console and power equipment, GPS units, network hardware, and UPSs. Four Iridium RUDICS modems provide low-bandwidth connectivity 24/7 for detector control and monitoring. This computing system is maintained by IceCube system administrators and winterovers to deliver a highly reliable computing platform for IceCube systems and operations. A “mirror” system - South Pole Test System, or SPTS - is maintained in the northern hemisphere and provides a testing environment for validation of new software releases and hardware upgrades without impacting the live South Pole System.

- Online Data Systems - The control, readout, monitoring, calibration, online filtering, transport, and storage of the experimental data produced by the array of DOMs is managed by a suite of custom software components running on the SPS hardware and consisting of a data acquisition system, data filtering system, an experiment-wide control system and a data movement and archiving system These systems require regular software and hardware maintenance to ensure long-term reliability and stable operation of the experiment.

- Data Warehouse and Storage Infrastructure - The storage infrastructure at UW–Madison’s data center consists of O(10) PB of online disk storage servers organized in a cluster file system architecture. This provides the required performance and scalability for handling expansions and turnover efficiently and securely. System administrators experienced in managing disk enclosures, storage networks, servers, and cluster file system software maintain and operate the storage infrastructure. They ensure that data is available for data processing and analysis tasks and that it is delivered with maximum performance.

- Central Computing Resources - The current IceCube HTC cluster at UW–Madison consists of nearly 200 servers providing a total of around 7000 CPU job slots and 432 GPU job slots. The HTCondor software, a state-of-the-art workload management system developed at the computer sciences department of UW–Madison, handles job scheduling at the HTC cluster.

- Core Data Center Infrastructure - The data center infrastructure is the glue that connects the major computing resources of IceCube. Required core infrastructure systems include distributed authentication, DNS, and email. Also, a large number of servers and services need to be deployed and maintained, such as database services, web services or tailored application servers, to fulfill science needs. System administrators maintain the UW–Madison data center infrastructure services, includes patching, monitoring, troubleshooting core services, and responding to user needs among other tasks.

- Distributed Computing Infrastructure - Dedicated computing resources at the level of several thousand CPU cores are needed to perform the required simulation and analysis of IceCube data. IceCube relies on distributed resources available from collaborating institutions and wider grid computing resources to provide this computing. Support personnel at all sites coordinate and manage the distributed computing effort to produce the needed simulation. In addition, IT professionals at the UW–Madison data center manage the IceCube Grid infrastructure and middleware tools needed to exploit distributed resources and to provide efficient remote access to the data.

- Physics Software - IceCube's physics software codebase covers a wide range of responsibilities and is used directly by the IceCube collaboration, including for online filtering, real-time systems, offline data reprocessing, and offline simulation generation. This software provides a wide range of functionality, from the core framework ("IceTray") to user-defined simulation, reconstruction, and analysis frameworks.

A.2 Five-year Scientific Vision

IceCube neutrino analyses span nine orders of magnitude in neutrino energy, utilizing a detector that operates continuously and is sensitive to signals from the entire sky. High-profile results include the discovery of cosmic neutrinos, some reaching energies beyond 10 PeV [5], and the measurement of the oscillation of atmospheric neutrinos in a previously unexplored energy range from 5 to 55 GeV [6]. The wide variety of physics analyses that are performed using IceCube data is evident in Figure 3. This spectrum of IceCube science is made possible by the expertise and dedication of the ICNO M&O team.

IceCube was primarily designed as a discovery instrument and has only been able to deliver world-leading results by delivering performance enhancements and new functionality through systematic improvements to the existing instrumentation. In the 2021–2026 operation period, several improvements and extensions are foreseen, continuing to extract additional functionality from this workhorse detector.

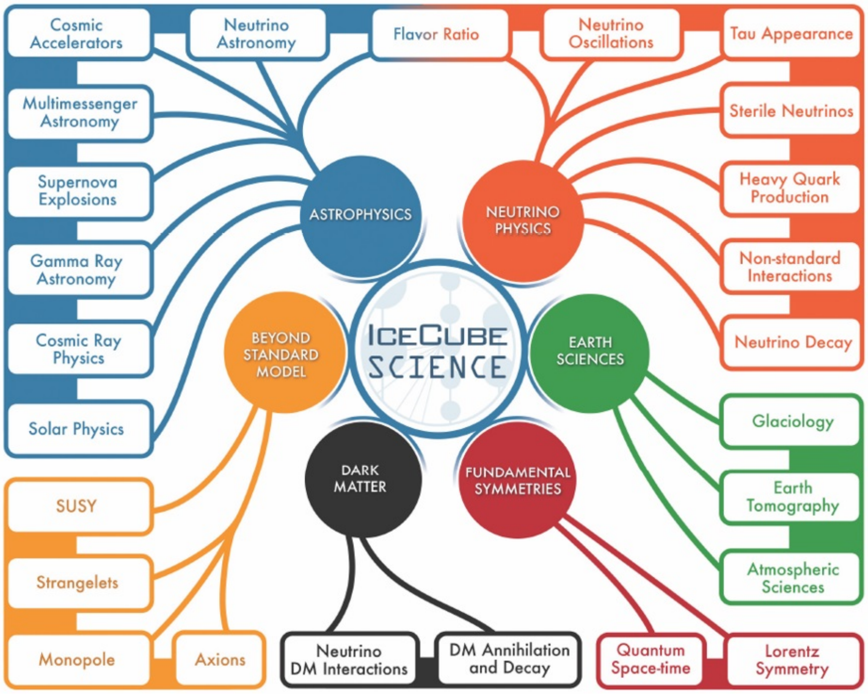


Figure 3: IceCube science span: IceCube data are used to deliver a wide variety of results, spanning multiple domains, from astrophysics, to neutrino physics, to searches for physics beyond our current standard models, to Earth Sciences.

In this period, planned additions to IceCube science include:

- Realization of the IceCube Upgrade. The IceCube Upgrade is the first extension of the in-ice instrumentation since the IceCube detector was completed in 2010. These additions will require upgrades and new functionality within existing IceCube operational systems, as these new devices are intended to be fully integrated with existing IceCube DOMs. With the addition of 7 strings containing novel, modern instrumentation and calibration devices, the overall IceCube science program will:
  - reach new levels of sensitivity in measurements of neutrino oscillation parameters using the naturally provided beam of atmospheric neutrinos; and
  - deploy a new suite of calibration devices to further our understanding of the properties of the glacial ice in which IceCube is located. These calibration improvements will yield improved neutrino signal efficiencies, improved angular resolution, and will allow IceCube to reanalyze over a decade of historical data with higher sensitivities.
- Improved surface array. To combat the snow accumulation on the IceTop tanks that has reduced their sensitivity to air showers, a scintillator panel and radio antenna array is planned to supplement surface detection. These new detectors will restore the low-energy response to the surface array and enable precision studies of conventional and prompt atmospheric cosmic ray signals. This new suite of instrumentation will be fully integrated into existing IceCube detector systems.

- Continued multi-messenger astrophysics searches. Planned expansions to the existing IceCube realtime alert system will bring a larger number of public alerts that are richer in astrophysical neutrino signals, as well as enable new searches with the next generation of observatories such as the Rubin Observatory and the next generation of gravitational wave detectors.

Our approach to the management of the IceCube M&O effort is to maximize our scientific discovery potential by coordinating the talents and resources from our collaborating institutions with those of the core M&O team. In this section, we describe the organization that performs the M&O functions for IceCube in this distributed model and how we provide traceability and accountability for these tasks. Leveraging the substantial efforts of the collaboration requires investment in the highest quality, experienced M&O operations staff.

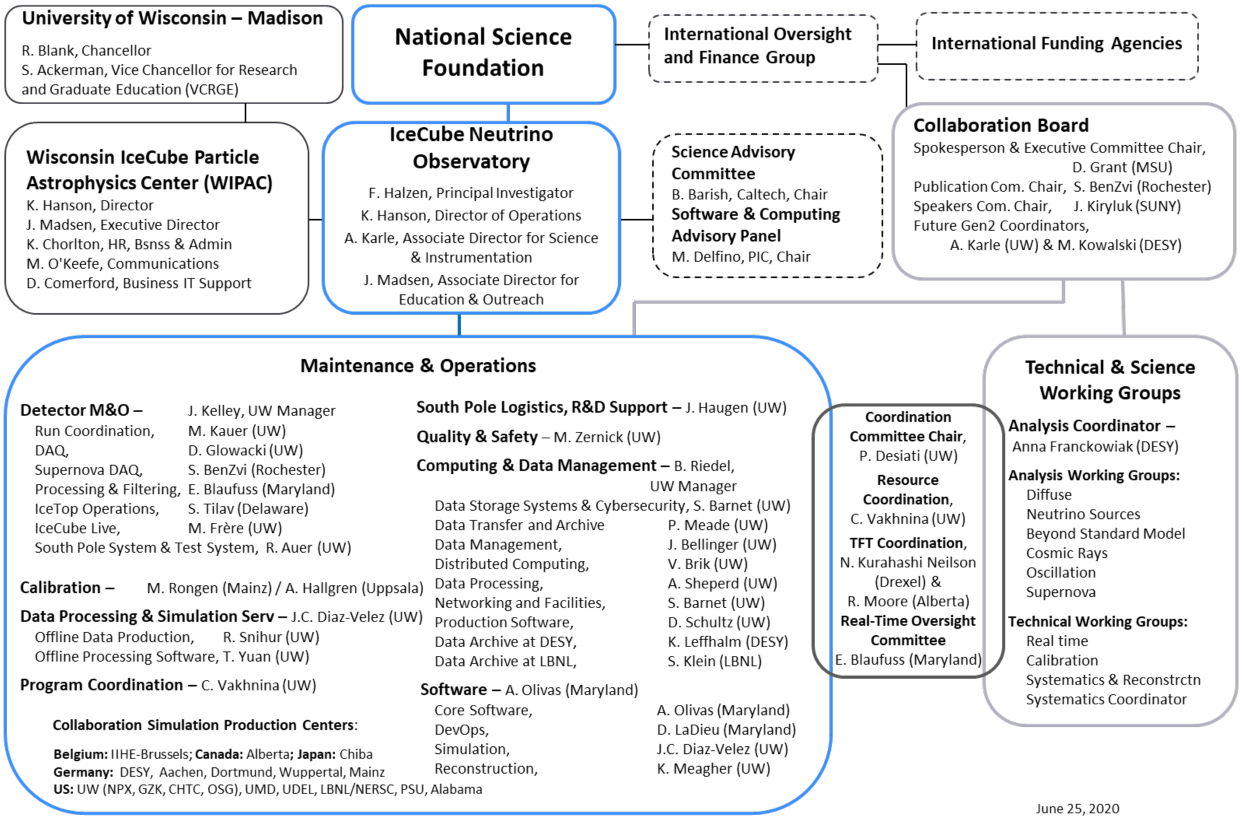
A.3 Organization

The IceCube M&O management organization integrates the IceCube Collaboration with the host institution, UW–Madison (see Fig. 4). The principal investigator (PI) is locally responsible to the UW vice chancellor for research and to the National Science Foundation for the overall scientific direction of the ICNO. The director of operations appoints technical professionals to serve as managers of the two M&O functions that are predominantly centered at UW–Madison: detector M&O and computing and data management. The managers in these areas work with their scientific colleagues to ensure the detector operates reliably and the data collected can be analyzed in a timely manner. The collaboration spokesperson appoints collaborating scientists to serve as coordinators for physics analyses. These appointments are subject to the consent of the collaboration.

The entire M&O scope of work is outlined in a work breakdown structure, or WBS (see Fig. 5). The complete WBS dictionary is included as Attachment 4. WBS tasks are defined in detailed MoUs, proposed by collaborating institutions and reviewed by the M&O coordinators. The institutional leads at collaborating institutions are responsible for ensuring that the work outlined in their MoUs is completed on schedule. These MoUs are revised twice a year at the collaboration meetings and include a list of the physics group members and a head count of faculty, scientists, postdocs, and graduate students. (An MoU summary is included as Attachment 5, and further details about institutional representation and committee structure can be found in the IceCube Governance Document included as Attachment 2).

The IceCube Collaboration: The collaboration plays a leading role in IceCube, guiding both science and M&O goals. The benefits of this distributed organizational model are 1) the ability to draw highly qualified and specialized personnel from collaborating institutions to perform specific tasks in support of science or M&O, and 2) the education and training opportunities available through hands-on IceCube participation for faculty, postdocs, and students from multiple collaborating institutions.

The IceCube Collaboration Board (ICB) is the policy-making entity that guides and governs the scientific activities of the collaboration. It consists of a representative from each collaborating institution. It establishes and, as necessary, amends governance procedures and has oversight authority over science policy and goals, membership, data access, publications, representation of the IceCube Collaboration at conferences, analysis teams, and education and outreach (E&O).



June 25, 2020

Figure 4: The IceCube M&O organizational breakdown structure.

Executive Committee. The spokesperson, in consultation with the ICB, the PI, and the director of operations, appoints and chairs an executive committee of the collaboration board. The committee advises the spokesperson in proposing actions to the ICB and in making interim decisions, and its members represent major groups, functions, and competencies within the collaboration.

U.S. National Science Foundation (NSF): The NSF is the executive agent with responsibility for seeing that the IceCube detector meets its objectives, requirements, and technical performance standards. The NSF has a special role in IceCube because of its responsibilities in managing operation of the Amundsen-Scott South Pole Station. The IceCube M&O award is cofunded by the Division of Polar Programs and the Particle Astrophysics Program within the Division of Physics. The respective program directors provide continuous oversight and guidance through direct communication with the IceCube PI and director of operations.

International Oversight and Finance Group (IOFG): The IOFG was created in 2004 to provide oversight and financial support for the ICNO (including construction, M&O, and research phases). The group organizes oversight reviews to discuss detector performance and physics. A representative of the NSF chairs the IOFG, and membership is compos of representatives of the funding agencies from the partner countries supporting IceCube M&O. (For more details, see the IceCube Collaboration Governance Document in Attachment 2.)

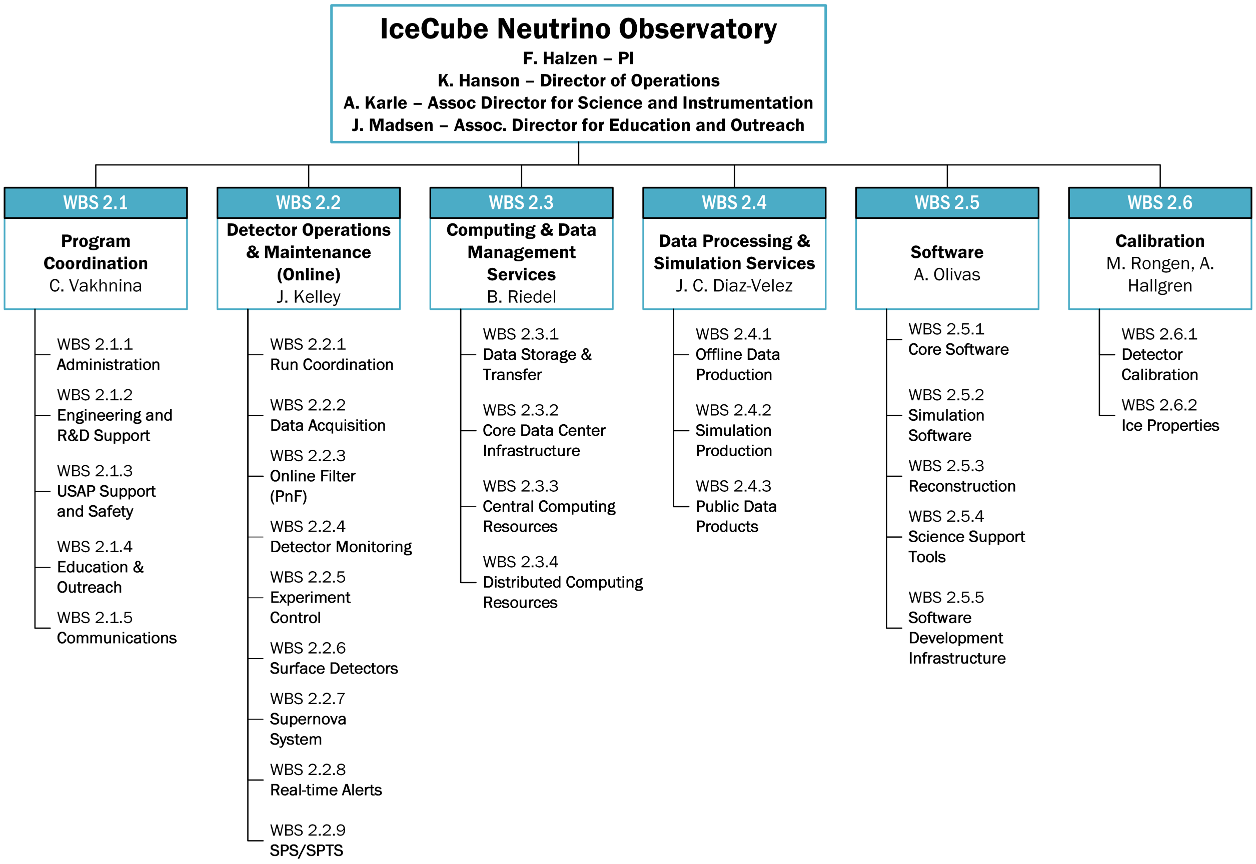


Figure 5: The M&O work breakdown structure through Level 3.

University of Wisconsin–Madison: The university provides financial and management oversight and is the home institution for the IceCube M&O activities.

IceCube Oversight: The lead executive officer of UW–Madison, the chancellor, delegates responsibility for research activities to the vice chancellor for research and graduate education (VCRGE), who maintains oversight of the ICNO and appoints the IceCube director of operations.

The IceCube PI and the director of operations report directly to and meet regularly with the VCRGE and meet as needed with the university's IceCube leadership team, which includes the chancellor, provost, CRGE, and vice chancellor for finance and administration. The meetings provide a forum for the IceCube PI, the director of operations, and the associate director of science and instrumentation to inform the university leadership team of significant issues pertinent to the management of the ICNO.

IceCube's associate director for science and instrumentation reports to the director of operations and advises on matters related to science, coordination committees, and instrumentation. IceCube's associate director for education and outreach reports to the director of operations and leads the IceCube E&O program by working with NSF and the IceCube Collaboration to establish E&O priorities and strategies.

Institution	Major Responsibilities
Lawrence Berkeley National Lab	DOM firmware support, Computing infrastructure, long-term data archiving
Pennsylvania State University	Simulation production, DAQ firmware support
University of Delaware, Bartol Institute	IceTop calibration, monitoring and maintenance; IceTop simulation production
University of Maryland, College Park	Overall software coordination, IceTray software framework, online filter, simulation software and production
University of Alabama at Tuscaloosa	Detector calibration, reconstruction and analysis tools
Michigan State University	Simulation production and production, NTS maintenance

Table 1: IceCube M&O U.S. subaward institutions and their major responsibilities

Wisconsin IceCube Particle Astrophysics Center (WIPAC): IceCube's M&O falls under the purview of WIPAC, which is the primary interface to the university administrative and support systems. WIPAC, a center within the Office of the VCRGE, coordinates the multiple roles of the university, such as lead and host institution for the IceCube construction project, for most US IceCube analysis efforts, and for IceCube M&O. WIPAC provides administrative services such as accounting, purchasing, and human resources; coordinates E&O activities; oversees engineering and R&D efforts; and collaborates with the largest participating research group.

Subawards: UW–Madison established subcontracts with some of the key U.S. collaborating institutions. These subawards provide critical support for IceCube M&O through key coordination positions. The IceCube M&O roles and responsibilities of the U.S. institutional subawards are described in Table 1.

A.4 Program Coordination and Administration

The committees, panels, and boards responsible for program administration are described below.

Advisory Committees:

Science Advisory Committee: The primary goal of IceCube M&O is to ensure that IceCube meets its high-level science goals and serves the collaboration in a changing environment. In consultation with the collaboration, the PI and the spokesperson appoint a panel of external experts, the Scientific Advisory Committee (SAC). The SAC's role is to meet regurlay and review the performance of the M&O organization and make recommendations on scientific goals and other matters that may affect ICNO scientific activities. The current chairperson is Barry Barish from Caltech.

Software and Computing Advisory Panel: The IceCube Software and Computing Advisory Panel (SCAP) is composed of experts in the fields of software development and scientific computing. The SCAP advises the IceCube spokesperson, director of operations, global computing coordinator, and software coordinator on the most efficient and effective computing resources for IceCube, including online computing, online and offline data processing and filtering, offline computing facilities, and simulations and analysis tools support. The spokesperson and the director of operations appoint the SCAP members and chairperson. The SCAP meets regularly. The current chairperson is Manuel Delfino from Port d'Informació Científica (PIC).

M&O COORDINATION STRUCTURE:

Coordination Committee: This committee provides high-level coordination of core M&O tasks and service contributions of collaborating institutions necessary for reaching IceCube science goals, ensuring that core and in-kind M&O functions meet the needs of the physics analysis working groups. The committee facilitates communication between the analysis working groups and the operations coordinators to support the collaboration towards its science reach. The coordination committee comprises M&O coordinators, working group leaders, key management personnel, and other technical experts. The chair and committee members work with institutional leads to advertise the list of needed service tasks and negotiate involvement through specific MoUs. The Coordination Committee tracks service task execution and milestones and ensures that students and postdocs working on those tasks get visibility by providing reports at the biweekly IceCube technical phone calls. The committee meets every month by teleconference and at each collaboration meeting.

Trigger Filter Transmit (TFT) Board: The TFT Board's purpose is to ensure that the IceCube detector operates in a configuration that meets the physics needs of the collaboration while respecting the limited computational and bandwidth resources available from the South Pole. Ahead of the yearly physics run transition in May, when the standard data-taking configurations for the year are deployed, the board issues a request for proposals for the upcoming season, coordinates production of Monte Carlo data sets to match the expected detector configuration, sets deadlines for physics working groups to draft proposals, and evaluates proposals for changes and additions to the set of detector triggers and online event filters. Following the transition to the new season's configuration, the TFT board requests brief reports from all physics working groups summarizing the status and quality of selected events.

Detector Operations Coordination: The detector operations working group is responsible for day-to-day operation of the detector, including data acquisition, filtering, transmission, offline processing, calibration, and maintenance. The working group is responsible for maintaining a high detector uptime and ensuring high-quality data are delivered to the collaboration. The detector operations manager is responsible for coordinating group activities via a weekly teleconference. The run coordinator reviews proposals for nonstandard operations of the detector, including commissioning and calibration runs, and tracks detector uptime. Subsystem experts are also involved, including online systems software engineers, calibration group members, IT professionals, and other physicists.

Calibration Coordination: The calibration group designs calibration runs for the detector, analyzes calibration data, and provides tools for utilizing the calibrations in order to ensure correct and efficient analysis of IceCube data. The calibration working group lead coordinates analysis of calibration data, such as DOM calibrations and in situ LED "flasher" runs, via weekly teleconferences held with students and postdoctoral researchers.

Physics Analysis Coordination: The physics analysis coordinator is responsible for oversight of the scientific output of the IceCube Collaboration. While not part of the organized M&O structure, the analysis coordinator provides key guidance to help align M&O resources with the scientific needs of the collaboration. The analysis coordinator is responsible for oversight of the physics working groups, unblinding and approval of analysis of experimental data for publication, and preparation of publications. These tasks require coordination with the M&O teams to produce simulated data samples, allocate storage and computing resources for analysis work, and help guide DAQ and filtering priorities for the detector.

Software Coordination: The software coordinator facilitates the development and maintenance of IceCube's various software systems, including core software, online processing, online filtering, simulation, reconstruction, data acquisition, databases, online monitoring, and data transfer from the Pole. The coordinator provides software development training opportunities for collaboration physicists to ensure high-quality software. The software coordinator, along with a core development "strike team," addresses the most urgent needs of the collaboration by participating in quarterly weeklong code sprints. Recently, the IceCube open source program was formed, where developers can make software developed for IceCube widely available to the larger scientific community.

Simulation Coordination: The simulation production coordinator, working with the technical leads from analysis working groups and the IceCube Coordination Committee, coordinates and guides the computational production of simulated physics data by working groups in order to balance analysis needs against the availability of computing resources. The coordinator produces quarterly reports on global simulation production status. The coordination committee meets every month to discuss simulation status and evaluate large simulation requests in order to determine priorities.

Real-time Coordination: The real-time oversight committee (ROC) is responsible for overseeing IceCube's generation of real-time neutrino alerts and for coordinating the collaboration's response to alerts from other observatories. The ROC also reviews real-time programs to ensure they are complete, correct, prompt and well integrated into detector operations. The ROC is also charged with making rapid decisions regarding alert responses, rapid data analyses, and dissemination of alert information, ensuring that needed IceCube alert information is widely available to observatories for follow-up observations.

A.5 Engineering, Technical Support, and R&D Efforts

Ongoing engineering support for the IceCube detector continues with the maintenance and operation of the South Pole System, 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 facilitate investigations into various operational issues, such as communication disruptions and electromagnetic interference. Technical support provides for coordination, communication, and assessment of impacts of activities carried out by external groups engaged in experiments, or potential experiments, at the South Pole.

R&D supports subject matter experts to troubleshoot issues and coordinate internal and external efforts to enhance ICL electronics and computing performance, and interface with externally funded R&D activities that utilize IceCube facilities and infrastructure. The integration of the IceCube Upgrade detector elements into the ongoing ICNO operations will also be supported through this engineering team.

A.6 Environmental Compliance, Health, and Safety

The Environmental Compliance, Health, and Safety standards followed by IceCube are described in Sect. I. The quality and safety officer is responsible for training, compliance, and reporting.

A.7 USAP Logistical Support

The ICNO has successfully worked with the Antarctic Support Contractor (ASC, formerly RPSC) since 2003 to coordinate logistical resources required to construct and operate the IceCube detector through cost-effective means. Requirements are detailed in the annual submission of the Support Information Package (SIP) to ASC each March. The yearly plan is finalized in September through ICNO concurrence with the ASC-generated Research Support Plan (RSP). Throughout the planning process there are weekly teleconferences and close coordination between the project office and ASC.

A.8 Budgeting, Staffing, and Workforce

This NSF IceCube M&O renewal proposal covers the five-year period of April 1, 2021, through March 31, 2026, at a total funds request of $44,499,922 with details provided in the Budget Justification. The budget in this proposal is based on a detailed, bottom-up analysis of the costs required to complete each task in the M&O work breakdown structure (WBS) (included as Attachment 4; see also Fig. 5). These costs are very well understood and are based on experience during the past 12 years of M&O. Furthermore, over 90% of the staff are existing personnel, many who have been with the project since construction. The two major WBS areas supported by this NSF M&O proposal are 2.2: Detector Operations and Maintenance and 2.3: Computing and Data Management Services.

PROGRAM MANAGEMENT AND FINANCIAL RESOURCE COORDINATION: Four primary elements of our approach focus resources on achievement of IceCube's scientific objectives and provide accountability to NSF for the use of funds:

1. **Operations Management and Science Support.** We provide leadership to manage the effectiveness and efficiency of all services and ensure communication among the collaboration, NSF, partner funding agencies, and the M&O functional areas. We prepare strategic plans and conduct formal risk management to achieve objectives.

2. **Computing Infrastructure Management.** We manage computing resources to maximize uptime of all computing services and availability of required distributed services, including storage, processing, database, grid, networking, interactive user access, user support, and quota management.

3. **Performance Management and Reporting.** In cooperation with NSF, we establish meaningful performance measures to evaluate our performance against M&O objectives. With NSF, we also establish reporting deliverables that fulfill NSF internal and external requirements for oversight.

4. **Financial Management.** We manage the following four different sources of funds of the IceCube M&O program, providing accountability in separate dedicated accounts through an audit trail:

∗ **NSF M&O Core (this proposal).** Covers M&O core activities, travel, M&S and services for UW–Madison, six U.S. subawards, and the U.S. contribution to the M&O Common Fund. This award mostly supports detector operations and maintenance, computing and data management, and program management.

∗ **NSF Base Grants.** Supports M&O activities done mostly by graduate students and postdocs, such as detector calibration, monitoring, filtering and triggering, data quality, reconstruction, and simulations.

∗ **U.S. Institutional In-Kind.** Mostly covers M&O activities done by faculty members, different fellowships, and university-funded activities.

∗ **Non-U.S. Institutional In-Kind.** Institutional contributions from non-U.S. collaborators (European, Canadian, and Asia Pacific), including labor, travel, and cash contributions to the M&O Common Fund.

IceCube M&O Common Fund (CF) was created in 2007, the start of formal operations, 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 based on the total number of its Ph.D. authors, updated twice a year at collaboration meetings. Effective April 1, 2010, the annual established rate per Ph.D. author is $13,650.

The M&O core activities needed for reliable operation of the detector and computing infrastructure supported by the CF include winterover support at the South Pole; hardware and software systems for acquiring, filtering, and transmitting data via satellite and disk to the UW–Madison data center; data archiving in the central data warehouse; and UW–Madison data center operations (as listed in the IceCube M&O cooperative agreement with NSF).

Institutional M&O Memoranda of Understanding (MoUs) define the distributed M&O labor contribution from collaborating institutions and represent the transition from a centralized management and funding approach during IceCube's construction phase to a more distributed model for M&O.The distributed model results in increased financial contributions to the CF and in-kind labor contributions to M&O tasks from non-U.S. (European, Canadian, and Asia Pacific) collaborators. It also results in a greater emphasis on direct NSF funding to U.S. collaborating institutions. (Summary of the MoU Scope of Work is included as Attachment 5). The complete list of M&O activities with names and full time equivalent (FTE) level can be found in the staffing matrix in Attachment 8.

IceCube M&O Reports describe progress made based on objectives in the annual M&O Plan and differences between planned and actual accomplishments. These reports consist of a summary of work accomplished and include a financial section comparing annual budgets with actual costs and projected costs. Midyear interim reports include a brief summary of the status of all M&O activities, including performance of data handling and detector systems. They also include highlights and accomplishments, detector uptime, software releases, and test results. A final report is required that includes a detailed summary of the entire period of the IceCube M&O award. In addition, a CF annual report summarizes the status of past CF contributions and expenditures and lists the major annual upgrades to the SPS, SPTS, UW–Madison data warehouse, and UW–Madison data center.

WORKFORCE DIVERSITY: The IceCube M&O management organization is a beneficiary of the UW–Madison human resources system, which includes strategies to recruit, develop, and retain a diverse workforce. UW–Madison is committed to hiring the right talent to ensure that the university continues to be a world-class institution of higher education. The university's goal is to provide opportunities for talented people from all backgrounds to help us maintain a highly productive, welcoming, empowering, and inclusive community. UW–Madison encourages women, minorities, veterans, and people with disabilities to apply for all of our vacancies. ICNO will continue to strive to attract outstanding candidates from underrepresented groups and support them after hiring.

SENIOR AND CRITICAL PERSONNEL: Our senior and critical personnel (Tables 2 – 4) form the leadership team that ensures the success of IceCube's M&O and the timely exploitation of its scientific discovery and E&O potential. Our critical personnel form the core team that balances resources from the central M&O cooperative agreement and from collaboration members to maximize value and efficiency to IceCube. This is the core team that designed, built, and successfully installed the IceCube Neutrino Observatory. Attachment 9 shows a snapshot in tabular form of the current facility personnel including those contributed as in-kind labor resources from collaborating institutions: name, position, institution, and role for 2019. The facility personnel remains largely same for all five years.

Name, Institution, Position, Title	**Responsibilities, Qualifications**
Francis Halzen, UW–Madison, PI • Hilldale and Gregory Breit Distinguished Prof. • Director, Inst. for Elementary Particle Physics	• Responsible for the overall success of ICNO • IceCube PI from development through construction and transition to operations
Kael Hanson, UW–Madison, Co-PI • Director of Operations • Professor of physics • Director, WIPAC	• Ensures operation meets performance goals and NSF/IceCube Collaboration needs • IceCube construction In-Ice Devices Manager • Former Detector Operations Coordinator
Albrecht Karle, UW–Madison, Co-PI • Associate Director, Science & Instrumentation • Professor of physics	• Oversees technical performance and ensures science objectives are met • Associate Director, IceCube construction • IceCube construction scientific/technical lead
James Madsen, UW–Madison • Associate Director, Education & Outreach • Executive Director, WIPAC	• Plans and executes E&O activities • Two decades of broader impacts activities

Table 2: IceCube senior personnel: PI, director, and associate directors.

A.9 Communications, Education, and Public Outreach Coordination

The associate director for E&O leads the ICNO communications and E&O efforts, with guidance from the IceCube PI, the ICB, the ICNO E&O team, and an external advisory panel. The E&O program builds on established successes to address NSF priorities to integrate IceCube research

Name, Institution, Position, Title	**Responsibilities, Qualifications**
Darren Grant, Michigan State University • IceCube Spokesperson • Professor of physics and astronomy	• Leads collaboration governance and coordinates member resources to support IceCube M&O • Neutrino detector development (SNO, SuperCDMS, DEAP, P-ONE, IceCube since 2007)
Paolo Desiati, UW–Madison • Chair of IceCube Coordination Committee • Senior scientist	• Coordinates M&O tasks in institutional MoUs with science requirements/operational needs • Managed sim. production during construction
Naoko Kurahashi Neilson, Drexel University • Trigger, Filter, Transmission Board Co-Chair • Associate professor	• Coordinates triggering and filtering • Former co-convener, IceCube neutrino sources working group
Roger Moore, University of Alberta • Trigger, Filter, Transmission Board Co-Chair • Professor	• Coordinates triggering and filtering • Associate chair for undergraduate studies
James Haugen, UW–Madison • South Pole Logistics / R&D Support • Logistics manager	• Coordinates ASC support for M&O activities at the South Pole • IceCube: 12 years/7 South Pole deployments
Erik Blaufuss, University of Maryland • Real-time Coordinator • Research scientist	• IceCube real-time alerts/community responses • Former TFT board chair, WG leader of GRBs/Transients, and analysis coordinator
Anna Franckowiak, DESY-Zeuthen • Analysis Coordinator • Staff scientist	• Coordinates physics analysis tasks/working groups • Helmholtz Young Investigator Group Lead

Table 3: IceCube critical personnel: IceCube spokesperson, chairs, and coordinators.

with formal and informal education and to reach audiences that are underrepresented in STEM fields and communities. It seeks out opportunities to develop collaboration-wide E&O programs to leverage resources at 53 institutions in 12 countries and to capitalize on the potential of the ICNO to excite and engage the broader community. IceCube communications convey important science results, weekly updates from the South Pole, ICNO highlights, and opportunities for public engagement to the broader community through web, video, print, and social media channels.

B. Core Detector Operations

The detector operations group is responsible for the maintenance of the hardware and software systems at the South Pole and for delivery of high-quality, vetted data to the scientific collaboration. Custom surface electronics and computer systems in the ICL require regular replacement and upgrades to keep them running smoothly. The online software systems, such as data acquisition (DAQ; Sect. B.3), IceCube Live (Sect. B.5), and processing and filtering (Sect. B.6), must all be

Name, Institution, Position, Title	Responsibilities, Qualifications
WBS 2.1: Catherine Vakhnina, UW–Madison • Resource Coordinator • Program manager	• Coordinates financial resources and interinstitutional contracts • Ten years IceCube experience • MBA and Project Mgt. Prof. (PMP) credentials
WBS 2.2: John Kelley, UW–Madison • Detector Operations Manager • Associate scientist	• Manages detector operations to provide consistently high detector availability/data quality • Detector development (IceCube/ARA/Auger) • Scientific and industry management experience
WBS 2.3: Benedikt Riedel, UW–Madison • Computing and Data Manager • Computing manager	• M&O computing services/data mgt. policies • Particle physicist/scientific computing • Supported adoptions of distributed computing
WBS 2.4: Juan Carlos Díaz-Vélez, UW–Madison • Data Processing/Sim. Services Coordinator • Senior programmer	• Oversees management of simulation production and offline data processing • Managed sim. production during construction
WBS 2.5: Alex Olivas, Univ. of Maryland • Software Coordinator • Research scientist	• Oversees software coordination • Core IceCube software developer for 10+ years • Previous IceCube simulation lead/detector sim.
WBS 2.6: Allan Hallgren, Uppsala Univ. • Calibration Co-Coordinator • Professor of experimental physics	• Co-leads detector calibration working group • Early contributions to IceCube/led DOM tests • Part. Phys. Sec. Chair, Swedish Physical Society
WBS 2.6: Martin Rongen, Univ. of Mainz • Calibration Co-Coordinator • Postdoctoral researcher	• Co-leads detector calibration working group • Ice modeling expert • Six years of IceCube instrumentation experience

Table 4: IceCube critical personnel: WBS Level 2 leads.

continuously maintained to ensure stability (Fig. 6). The detector systems are also regularly enhanced to support evolving science needs; a recent example is storing untriggered detector data to search for low-energy neutrino bursts coincident with gravitation wave alerts.

The team of scientists and software developers in the operations group, with the support of the IceCube winterovers, monitor detector performance and work to address any issues that arise. In the previous M&O period, we have successfully addressed hardware reliability issues in a number of subsystems, e.g., the DOM power supplies. Furthermore, several software systems that were fragile and/or difficult to maintain have been replaced. Our approach has proven successful, achieving detector uptimes higher than 99%.

The architecture of the online systems will allow us to integrate the additional IceCube Upgrade strings into the existing detector. All subsystems will need to be modified to some extent to support new sensors and calibration devices. However, the current design is flexible enough to support this without a complete redesign, saving significant time and effort. Once the Upgrade strings are deployed, operation of the detector will include both original and Upgrade strings. To streamline ongoing hardware maintenance and enhance reliability, the original, aging DOMHub computers will be replaced with backward compatible Upgrade-style hubs.

Other maintenance activities that fall under the purview of the operations group include enhancing the IceTop surface array to address degraded efficiency from snow accumulation (Sect. B.7) and serving as the caretaker of the Askaryan Radio Array (Sect. B.8).

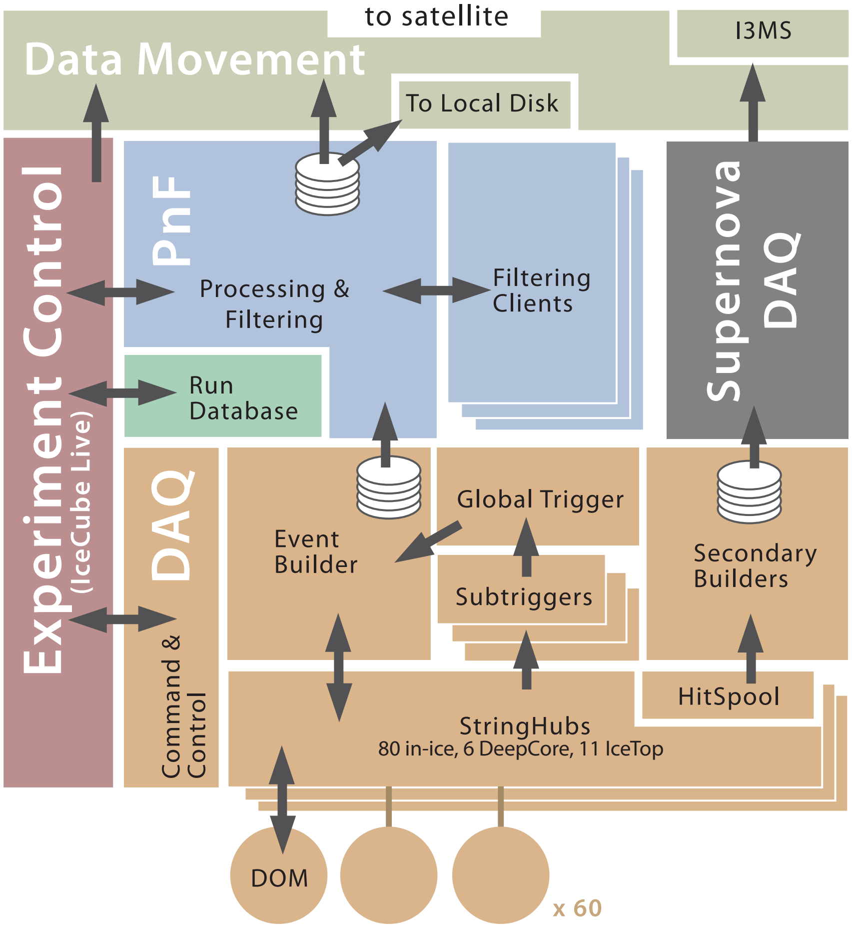


Figure 6: The IceCube online data systems, tracing the data flow from DOMs, through the data acquisition, online filter, and data movement systems, all directed by the experiment control system, IceCube Live.

B.1 South Pole System and Test Systems

The South Pole System (SPS) is a computing system developed and maintained by the detector operations group that supports the IceCube online data acquisition and filtering tasks at the South

Pole. SPS hardware includes commodity server-class computers as well as network hardware such as switches and firewalls. SPS provides infrastructure services such as server name resolution, email, system monitoring, and databases. In order to maximize availability, SPS incorporates UPSs to handle short power outages, and remotely managed power distribution units are available to enable power cycling of any component in the ICL remotely from the South Pole station. The system is designed to be very robust since it has to reliably support data taking with minimal intervention; at the same time, it is simple, since it has to be operated by the winterovers, who are newly hired and trained each year.

The commodity computer servers in the SPS are replaced every four years in order to profit from technological advances that maximize computing power, to minimize the risk of component failure, and to ensure a reliable supply of spare components. Other components with a finite life cycle, such as UPS batteries, must also be regularly replaced. Certain aging infrastructure components that have not been replaced during the previous M&O cycle also will be replaced in a rolling fashion during the next several years, including the UPS and network switches.

The South Pole Test System (SPTS) is a test system located on the UW–Madison campus that replicates the basic functionality and performance characteristics of the production SPS and is a reasonable proxy for the detector and DAQ systems. It provides an environment to build and verify software subsystems and perform hardware and software evaluations prior to deployment on the production system. Engineers evaluate software and firmware DAQ updates on the SPTS via one or more of the following: (a) eight real DOMs kept at subfreezing temperatures for evaluation of firmware and software updates; (b) a full string of DOM mainboards connected to a DOMHub for string-level tests; (c) a full-length IceCube cable connected to several DOMs for communications and device driver testing; and (d) a special playback mode of real untriggered data streams coming directly from the deployed DOMs that have been captured at SPS and for use in SPTS to generate realistic load conditions.

The SPS system administrator and the winterovers are responsible for maintenance and operations of SPS. This includes preventive maintenance, troubleshooting, and upgrades. The SPS system administrator evaluates all new hardware and software infrastructure on SPTS to validate performance and reliability. The operations group also provides support to the wider collaboration for adding new functionality to SPTS, and ultimately to SPS, in response to new science objectives.

The IceCube Upgrade Northern Test System (NTS) is an extension of SPTS located at Michigan State University for the testing and integration of Upgrade hardware into the IceCube data acquisition system. The NTS will feature Upgrade DOMs, FieldHub readout computers, and the Upgrade surface communication/power/timing system. NTS is seamlessly integrated into SPTS via a virtual private network (VPN) connection. After the Upgrade construction project is complete, an engineer will continue to maintain NTS as a testing and validation resource for this newly deployed portion of the detector.

B.2 Run Coordination

In order to maintain the high level of analysis-ready “clean” uptime, nonstandard operations on the detector are carefully planned and reviewed. This includes commissioning runs for new software releases, calibration runs, and test runs for the annual “physics run” transition. The IceCube run coordinator is responsible for reviewing nonstandard operation requests and approving them as they see fit. All operations on the detector, including maintenance, are recorded to an email-based logbook by the winterovers or operations expert.

The winterover coordinator is responsible for the annual hiring, training, and regular management of the two IceCube winterovers. The winterover training, which occurs over a period of two months prior to deployment, makes heavy use of SPTS and involves full-time instruction in system administration, detector electronics, software subsystem operations, calibration, emergency procedures, and safety. In addition to the winterover coordinator, other operations experts regularly lead portions of the training relevant to their subsystem.

B.3 Data Acquisition

The data acquisition (DAQ) system collects raw hits from the individual DOMs, forming triggers with all the relevant data for physics events in the detector. Diagnostic and calibration data are also collected, as are raw counting rates for all DOMs, used for the supernova triggers. Performance of the DAQ hardware and software is a major driver of the quality of data for physics analysis.

The basic data acquisition (DAQ) hardware surface component is the DOMHub, a rack-mounted computer that houses both commercial and custom hardware and is connected to up to 64 DOMs. A GPS master clock system provides accurate timing to the DOMHubs through a series of custom clock fanout units. The DOMHubs, their internal components, and associated cabling must be maintained to prevent malfunctions and repaired quickly as necessary to minimize detector downtime and maintain a stream of high quality data.

The DAQ software systems, responsible for readout of the DOMs and forming triggered events, consists of DOM software, DOM readout card device drivers, DOMHub software, and the DAQ software components. DAQ software engineers are accountable for the uptime of the DAQ and the integrity, correctness, and completeness of the data it produces. They regularly test and upgrade DAQ software, respond to new feature requests, and provide appropriate documentation for the operators. The software engineers also maintain interfaces to other online systems, including the supernova DAQ and detector monitoring.

To improve reliability in the case of server failure, architectural improvements in the DAQ have moved toward decoupling the DOMHub data-taking component from the higher-level trigger and event builder components. This "hitspooling" system also provides the ability to save up to two weeks of all untriggered sensor data. DAQ software engineers will continue to develop this system, including dedicated components that allow hits from the Upgrade Fieldhubs and existing DOMHubs to feed into a unified DAQ trigger system (Fig. 7). The Upgrade FieldHub integration may also incorporate new triggering layers, such as a software-defined local coincidence system that mimics similar functionality built into the existing IceCube cables.

All custom hardware components in the DOMHubs and clock fanout system contain obsolete parts and cannot easily be remanufactured. While the failure rate of these components is currently low, the design of new DOM readout hardware for the Upgrade provides a path forward to simplify long-term maintenance of the detector. After completion of the Upgrade deployment, we plan to retrofit the existing detector by replacing the nearly 20-year-old DOMHubs with new Upgrade-style

“FieldHubs” located in the ICL (Fig. 8). The FieldHubs have been designed with hardware that is backward compatible with the current DOMs. A firmware engineer will adapt the communications protocol in the FieldHub FPGAs as needed. The legacy clock fanout system will also be replaced by the Upgrade White Rabbit timing system, unifying the timing and communications system for the entire detector. The DOM power system will also be upgraded to a rack-based system, and as a side benefit, we estimate that this will save up to 3 kW of power.

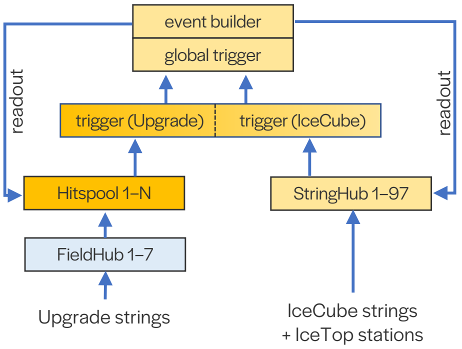


Figure 7: Integration of the Upgrade strings into the existing DAQ. Most existing components can be reused.

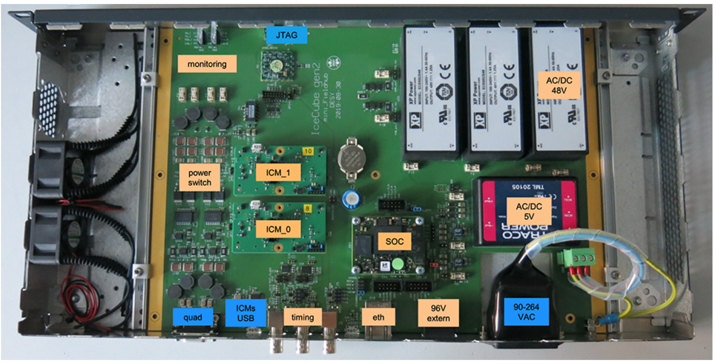


Figure 8: Prototype Upgrade FieldHub, including hardware backward-compatibility with current IceCube DOMs.

B.4 Supernova Data Acquisition

The supernova DAQ (SNDAQ) is a parallel data acquisition system that monitors the DOM noise rates for the signature of a Galactic supernova neutrino burst—a coherent rise in the rates in all sensors. A rate excess triggers a supernova candidate alarm to be issued via satellite, and untriggered hitspool data are saved. Highly significant alarms are forwarded to the Supernova Early Warning System (SNEWS) [7]. A recently implemented reverse link also saves IceCube untriggered data in case of a community SNEWS alert.

Collaboration scientists are responsible for core SNDAQ development as in-kind contributions. DAQ and IceCube Live software engineers are responsible for integrating SNDAQ into the experiment control, monitoring, and DAQ systems.

B.5 Detector Monitoring and Experiment Control

IceCube Live is the software system that integrates control and monitoring of all of the detector’s critical subsystems into a single, virtual command center. It provides an interface for monitoring the detector both via automated alerts and with interactive screens displaying current and historical states of the detector and associated subsystems. Web-based and command-line user interfaces provide maximum accessibility and flexibility to the operators located both locally at the South Pole and remotely in the Northern Hemisphere. IceCube Live is mirrored at SPTS to test upgrades and changes before deployment.

Software engineers are accountable for the uptime of IceCube Live and for maintaining, troubleshooting, supporting, and evolving the interface to subsystems that control the detector. The engineers support physics working groups and operators to add needed functionality; a recent example is the integration of the real-time alert system (Sect. B.6).

Operation and monitoring of the detector and real-time neutrino alerts to the scientific community both require a 24/7 network connection to the South Pole, but high-bandwidth satellite coverage is limited to approximately 10 hours a day. IceCube has developed a new messaging system technology (I3MS) to move critical monitoring and alert traffic off of the station link, using Iridium RUDICS satellite technology. I3MS also provides a real-time communications link between the winterovers and northern operations experts via a chat bridge between IceCube Live and a commercial messaging service used widely by IceCube. A software engineer updates and maintains the operations-critical I3MS software.

IceCube detector monitoring is the system within IceCube Live that provides a comprehensive set of tools for assessing and reporting data quality. The monitoring coordinator oversees development and testing of the monitoring system, which is implemented by IceCube Live software engineers and other operations subsystem experts. IceCube collaborators participate in daily monitoring shift duties by reviewing information presented on the web pages and evaluating and reporting the data quality for each run. The shift takers, frequently graduate students, compile reports on detector performance during their shift. A summary of the monitoring shift is given at weekly teleconferences, where experts determine if the detector is operating as expected and take actions to correct malfunctions as needed.

Software engineers will update both the experiment control and monitoring portions of IceCube Live to support the new calibration devices and sensors of the IceCube Upgrade. Special calibration runs will be controlled in the same way as standard data taking, in order to ensure proper tracking of calibration-generated events and light in the detector. The Upgrade sensors, most of which include multiple photomultiplier tubes, have additional monitoring requirements tailored to their specific hardware. These monitoring quantities will be seamlessly integrated into the existing database system, and new tests and visualizations will be created for monitoring shift takers to validate data quality.

B.6 Online Filtering and Real-time Alert System

Triggered events from the DAQ are immediately analyzed by the online processing and filtering system (PnF). The volume of raw data produced by DAQ exceeds the bandwidth available in IceCube's satellite allowance. The PnF system calibrates the raw waveform data from the DOMs, extracts the time of arrival and amplitude for the light signals observed by the DOMs, collects and reports data quality and monitoring information to IceCube Live, and applies the "Level 1" filters to the all data events. By selecting events of interest to physics analysis with this Level 1 filter and preserving only the time/amplitude information extracted from DOM waveforms, data volumes are greatly reduced. Additionally, all events are saved using this compressed format at the South Pole, allowing for reduced archival data sample sizes.

The online PnF system also hosts dedicated neutrino signal searches that quickly identify likely neutrino event candidates. These events are immediately transferred to the north via the I3MS messaging system. Dedicated receivers at the UW data center perform further analyses of these events and issue a wide variety of alerts to the astrophysical community. Most notably, following the detection of a high-energy neutrino candidate with a high probability of astrophysical origin, a GCN alert [8] is automatically issued. Roughly 30 alerts are produced per year, including IC-170922A, which launched the multimessenger observation campaign of TXS 0506+056, and are generally publicly available within ∼30 seconds of detection, enabling immediate responses by other observatories.

PnF system experts maintain the online system at SPS to ensure filters are being properly applied; test new filters, features, and alerts at SPTS; and respond to and debug unexpected errors. This effort ensures that the online filtering system and real-time alerts produce the highest quality data. Each year, the TFT board revises the Level 1 filter settings to ensure that they meet the evolving physics needs of the collaboration and that the most effective and robust reconstruction and filtering tools are used in online settings. PnF system experts implement these filters, ensure CPU and data volume match requested values, and prepare well-tested releases for deployment to SPS.

PnF developers are also working to implement several system enhancements. With the arrival of the IceCube Upgrade, the PnF system will need to calibrate and analyze data from several new sensor types, integrating both old and new DOMs into a unified Level 1 filter selection. Additionally, the PnF system was designed and built on libraries and standards established more than 10 years ago. The effort to update these underlying libraries will modernize the system to help reduce the maintenance burden over the next decade of operation. Finally, collaboration physicists and software engineers continue to work together to define fast, robust analysis schemes that can alert other observatories for follow-up observation of interesting events, localized in time and/or direction. Supporting these ever-evolving classes of neutrino alerts, including dedicated alert generation and catalog tools at the northern data center, will continue to be a priority for PnF system experts.

B.7 Surface Array Maintenance

The IceTop surface array requires its own tools for calibration, monitoring, reconstruction and simulation. The IceTop DOMs are embedded in ice contained in tanks on the surface, which are subject to environmental changes that must be monitored. In addition, specialized modes of operation are required to maximize IceTop's science potential, which includes study of solar particle activity and high-altitude weather in addition to the cosmic-ray science. The IceTop Operations Coordinator is responsible for monitoring of the physical condition of the IceTop detectors, including coordination of annual surveys of snow accumulation above the tanks and surrounding environmental conditions at the South Pole. The IceTop Operations Coordinator also monitors the quality of IceTop data and coordinates any corrective actions required to address malfunctions or other conditions that degrade IceTop data.

The snow accumulation above the IceTop tanks increases the energy threshold of the detector for cosmic-ray air showers and decreases the trigger rate by approximately 15% per year, negatively impacting the science capabilities of the array. Initial maintenance and operations included snow management plans that involved removal of the snow from the tanks; however, the support cost of this approach has proven burdensome, and it has been discontinued. We have begun to implement a plan to restore the efficiency and science potential of the surface array by installing low-cost scintillator panels and radio antennas within the IceTop detector footprint.

The instrumentation for the surface array upgrade will be provided as in-kind contributions. Scientists and a project engineer will support development of the surface array upgrade hardware and integration into the power, communications, and timing systems of the IceCube Laboratory. A DAQ software engineer will support integration of the new instrumentation into the online data systems. Key elements of both the hardware infrastructure and software architecture are shared between the surface array and the IceCube Upgrade, meaning integration of one supports the other and vice-versa.

B.8 Caretaking of the Askaryan Radio Array

The Askaryan Radio Array (ARA) is an ultra-high-energy neutrino detector at the South Pole [9], distinct from the IceCube Neutrino Observatory. Five detector stations search for the broadband radio-frequency Askaryan emission from neutrino interactions in the ice. ARA is no longer under construction and is in a stable data-taking mode in its current configuration. Since the ARA power and optical fiber connections terminate in the ICL, ARA already utilizes the IceCube infrastructure, including networking, data movement, and server support.

The IceCube winterovers support continued ARA data-taking via the following minimal activities: maintenance of the ARA data-taking server in the ICL; support for ARA data archiving at the South Pole and in the northern data warehouse; and as-needed troubleshooting support.

C. Northern Hemisphere Cyberinfrastructure

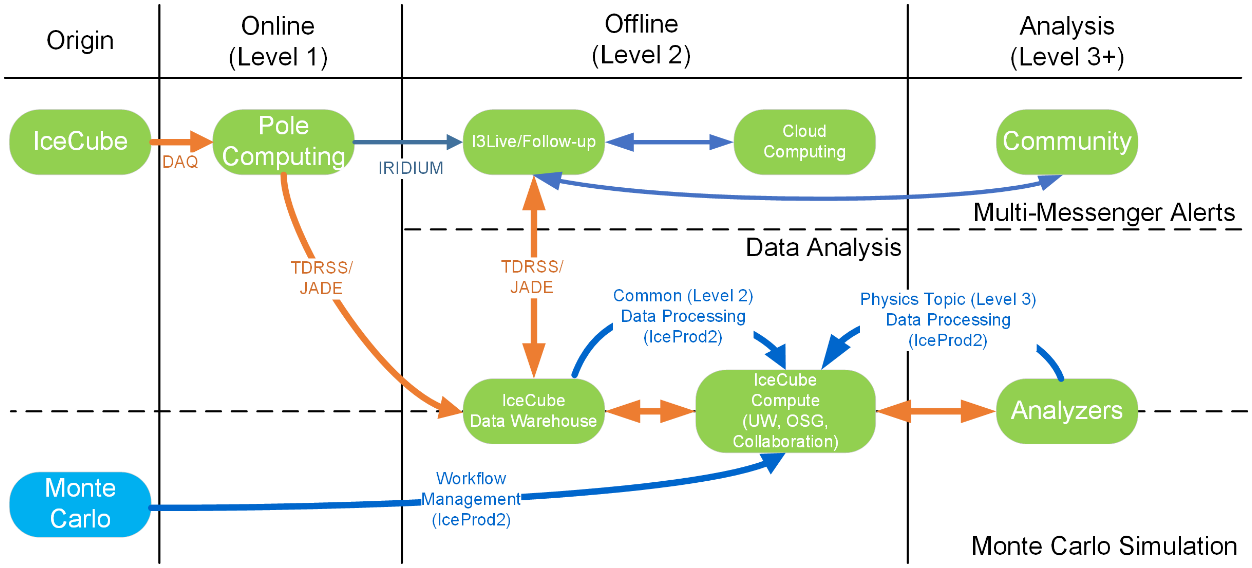


Figure 9: IceCube computing elements and data flow, for experimental data and Monte Carlo simulation.

C.1 Data Analysis Computing Infrastructure

IceCube data analysis computing utilizes both interactive and batch infrastructures. There are nine servers available in the interactive infrastructure used by researchers to perform data analysis and develop new methods—eight focused on traditional data analysis and one dedicated to machine-learning-based analysis. The batch infrastructure consists of an IceCube-dedicated high-throughput computing (HTC) cluster located at UW–Madison and a globally distributed resource pool. The current IceCube HTC cluster consists of nearly 200 servers providing a total of about 4000 CPU and 300 GPU job slots.

These dedicated resources are not sufficient to ensure timely data processing and simulation production. To increase overall capacity, IceCube relies on distributed resources available at collaboration institutions, opportunistic computing consortia, such as OSG, and allocation-based high-performance computing (HPC) consortia, such as XSEDE. The current capacity plan foresees providing 10% of the CPUs needed for simulation at the UW–Madison data center, 15% at DESY-Zeuthen, and 75% at other collaboration sites and compute consortia. For GPUs, the plan is to provide 50% of the needs through M&O-funded resources and 50% at other collaboration sites and compute consortia. A majority of the M&O-funded resources will remain at UW–Madison, while others will be hosted at MSU and UMD. M&O IT has and will continue to seek collaboration to procure additional resources.

Working with researchers at the University of California San Diego and the San Diego Supercomputing Center, and with additional funding from NSF and Internet2's Exploring Clouds for the Acceleration of Science (E-CAS), IceCube generated the largest GPU pool in history using cloud resources from three major vendors: Amazon Web Services (AWS), Google Cloud Platform (GCP), and Microsoft Azure [10, 11]. We determined that IceCube would be able to utilize future exa-scale resources and that the cloud would be too expensive to use for IceCube's production computing needs.

HTCondor [12], a state-of-the-art workload management software system developed at UW–Madison, handles job scheduling at the HTC cluster and the distributed computing resources. The IceCube system administrators who maintain and operate the cluster collaborate closely with the HTCondor team, providing feedback on specific use cases and ensuring the system fulfills IceCube's needs. They support users by providing guidance on HTC best practices, and support the delivery of science-ready data by ensuring that offline processing tasks run as prioritized and that the end-to-end infrastructure stack (computing/network/storage) is available and delivers optimum performance.

Currently, 1.5 full-time system administrators spread over three people and 1.5 full-time software engineers maintain this infrastructure which includes resource aggregation and usage monitoring as well as workflow management systems. To fulfill the data analysis computing capacity plan, M&O will require a significant investment into the underlying cyberinfrastructure of IceCube's distributed computing grid. We will need an additional software engineer to allow for expansion, proper load balancing between sites, and improvements to the workflow management—in particular, data management for production workloads.

C.2 Data Center Infrastructure

Data management and analysis requires a supportive data center infrastructure. This includes the physical space to locate, power, and cool the hardware and additional cyberinfrastructure for business services, such as document management and e-mail, authentication services, monitoring, network connectivity, and cybersecurity.

IceCube computing facilities are currently hosted in two UW–Madison locations, one off-campus at a co-location facility contracted through UW-Madison and one on-campus at the Physics Department. The facilities provide the total capacity to power and cool about 170 kW of IT equipment. We do not expect this to be sufficient to meet the cooling requirements in the next five years because of increasing deployment of GPUs and other energy-dense hardware. We have begun to explore distributing more compute resources to other collaboration institutions and alternative IT infrastructure cooling techniques. The space, power, and cooling for these facilities are in-kind contributions from WIPAC and UW–Madison to this project.

The IceCube Collaboration currently spans 13 countries. Many of the data products and services are hosted at the UW–Madison data center, hence excellent global network connectivity is essential. A large part of IceCube's computing requirements are being met using distributed resources; therefore, reliable, high-speed access to the UW–Madison data center storage infrastructure is required to use these resources effectively. With our move from WIPAC headquarters to a co-location facility, we also transitioned from self-administering our network infrastructure to having a large portion of the administration performed by UW–Madison central information technology services.

We will continue to maintain a cybersecurity program (Sect. C.5) at the UW–Madison data center.

All of these resources require a full-time system administrator and half of a full-time software engineer. A large portion of their tasks are to maintain virtualization infrastructure, cybersecurity, and networking.

C.3 Data Management Infrastructure

Scientific computing and data management is a constantly evolving ecosystem. IceCube computing efforts (see Fig. 9 for an overview) have been and will continue to be focused on providing a dependable and robust platform for scientists to make discoveries.

The data generated by the detector is its most precious output. One of IceCube M&O's central missions is to safeguard the data while in transit, especially from the South Pole, and stored, in user-accessible or long-term archival storage. This requires a highly available data management and storage system. The 11 petabyte (PB) IceCube data set will continue to grow as new data are collected, processed, and analyzed at a rate of about 1 PB per year. The storage infrastructure, including remote data access fabric, will need to evolve in order to cope with the load, while maintaining high performance and reliability, and allow for evolution of data access patterns.

Data Warehouse The data warehouse consists of two pieces: distributed parallel file systems (DPFS) and database management systems (DBMS). The DPFS consists of a number of disk storage servers organized together using a cluster file system architecture. This provides the required performance and scalability for handling expansions and turnover efficiently and securely. System administrators experienced in managing disk enclosures, storage networks, servers, and cluster file system software maintain and operate the storage infrastructure. They ensure that data are available and that they are accessible by data processing and analysis tasks with maximum performance. The storage system administrators also handle periodic hardware and software upgrades to the storage infrastructure and take care of cluster file system operations such as accounting, quota management, and disk server load balancing. In order to benefit from technological improvements in storage density and energy efficiency, we will ramp up the storage infrastructure capacity each year following demand and will keep disk systems in production for five years.

IceCube's DBMS is predominately related to non-data-analysis services, such as workflow management and detector operations. While these are typically hidden from data scientists, they are essential for operating the detector, processing data, and generating Monte Carlo simulation. Within the last year, we have centralized IceCube's DBMS. Overall, it allows for better oversight and maintenance of the various databases that the DBMS handles.

For experimental data archival, we utilize magnetic tape storage facilities located at NERSC and DESY-Zeuthen. While UW-Madison could operate a magnetic tape archive, the high purchasing and maintenance costs make using existing systems at collaboration institutions significantly more cost-effective.

The most recent DPFS hardware refresh was in mid-2018. We saw marked improvements by going to a common hardware platform and recent improvements to the clustering file system. The current file system was chosen in the early years of IceCube. While the file system will see continual improvements and support, it is focused on high-performance computing applications and typically requires a significant human effort.

In the last nearly 15 years, several new cluster file systems have emerged. These have been inspired by storage services available from commercial cloud computing providers. They provide significantly more flexibility, significantly better resilience against hardware failure, and better scaling capabilities. They are also software extendable and are built with a distributed data analysis workflow in mind. We have started exploring these file systems for production workloads. For a general user, these file systems have unfamiliar interfaces that may cause issues when transitioning from one file system to another. We will need to explore how to minimize the effect on users. The current plan is to build a metadata-based system that will allow users to be isolated from the technical details and capabilities of the file system.

In total, we dedicate 1.5 full-time system administrators across three employees to maintain the DPFS and DBMS. Besides regular maintenance tasks, e.g. replacing failed hardware, updating software, etc., this includes deploying additional hardware, monitoring, and ensuring overall performance and availability.

Experimental Data Management and Archival

Experimental data from the South Pole are retrieved over bandwidth- and time-limited satellite links or by transferring physical storage media during the summer season. The M&O team has developed the JADE software application to handle the data movement from the South Pole to the central data warehouse at UW–Madison and archival sites. For the satellite data transfers, the service makes use of the Iridium satellite systems for high-priority, low-volume data, e.g. realtime neutrino alerts, and the dedicated high-capacity TDRSS satellite system for the bulk of the filtered data. The unfiltered data stream are stored on two different physical media at the South Pole and shipped to the UW–Madison data center once a year during the austral summer.

To ensure integrity of all data, the software maintains checksums of all files before transfer. If data has not been transferred successfully from the South Pole, it will retransmit the files. The data will not be removed from the South Pole until data integrity has been assured, i.e. the checksums of data arriving in the data warehouse or being stored on disk at the South Pole match the initial checksum.

JADE runs on several servers to achieve higher reliability and scalability. A core software engineer will maintain the transfer and archiving software and manage the daily operations of data transfer.

Recently, we deployed new data archival software—Long-Term Archive (LTA)—that is integrated into the JADE system. LTA automatically replicates the unfiltered and filtered data to their respective archives. The filtered data is archived on magnetic tape at DESY-Zeuthen. This also allows for “local" access in Europe. Once the unfiltered data arrives at UW–Madison, it is read off the physical media, bundled, and transferred to the magnetic tape archival system at NERSC. The development of this system was funded through a separate grant from NSF (OAC-#1841479).

A total of two full-time staff members, one software engineer, and one system administrator focus on the data management and archival. The software engineer focuses on maintaining JADE and LTA, including handling any error states that might occur at the South Pole that the winterovers cannot handle. The system administrator focuses predominately on the network and storage infrastructure needed to create archives, including archiving other data sources such as the document management system.

Data Access and Exploration Infrastructure

The M&O IT team has been working on a catalog of all simulation and experimental data files to enable a richer metadata catalog for files, e.g. tagging files used in a data analysis, and to allow for better tracking of files, including file integrity over time. This is a first step towards an overall metadata catalog for all IceCube events. This will be needed for several projects, such as an open data service, improved data exploration infrastructure, and possible transition to a new clustering file system. At the current funding levels, this metadata catalog will be outside the scope of M&O funding.

With the deprecation of the Globus toolkit, IceCube will transition from using `GridFTP` to either an `XRootD`- or `HTTPS`-based external data access protocol in the coming year. This changeover will require the deployment of several new outward-facing services, including a new authentication and authorization layer.

In total, we dedicate one full-time employee, one-half of a software engineer, and one-half of system administrator to these tasks. This includes ingesting new metadata into the file catalog as well as monitoring and maintaining the outward-facing data access infrastructure.

C.4 IceCube Open Data Services

IceCube public data will continue to be in high demand during the period covered by this proposal. The field of multi-messenger astronomy (MMA) is growing rapidly in this time frame with Vera Rubin Observatory (VRO) coming online, the planned O4 observing run of LIGO, Virgo, and KARGA, and the beginning of operations at the Cherenkov Telescope Array (CTA). In addition to continuing live alerts, IceCube will be delivering new and updated archival events due to calibration improvements from the IceCube Upgrade. To meet this demand, the IceCube Collaboration provides public access to reconstructed neutrino event data on several levels. The broadest data set, as described in the IceCube Collaboration data-sharing policy and the data management plan, is primary event data on all events transferred from the detector over the satellite. The data sets will be provided in an open format to be usable by researchers outside of the collaboration. The open data set requires support beyond the scope of IceCube M&O at current funding levels; therefore, we will be applying for external funding for this project. Additionally, we will be investigating the possibility of hosting the open data set through commercial cloud providers.

A more selective general-purpose data set consists of high-quality reconstructed muon neutrino and muon tracks. This set enables scientists outside of the collaboration to test a broad variety of models against IceCube data. Currently, we release the general purpose data as a tarball of text files on the IceCube website. We are investigating more feature-rich options that connect us more closely to the MMA community, such as NASA's High Energy Astrophysics Science Archive Research Center (HEASARC) [13]. Over time, future versions of these data sets will require continued support as we update reconstructions and incorporate new calibration data from the IceCube Upgrade.

Finally, there are targeted data releases associated with specific publications such as the observation of TXS 0506+056 and the high-energy starting event selection. These event selections are highly specialized to a single object or analysis, and these targeted data releases allow external researchers to reproduce and extend IceCube results. Additionally, IceCube real-time alert events are released publicly in real time as GCN notices. We will develop an open data portal for live alert events that will incorporate follow-up data from MMA partners, similar to LIGO's GraceDB.

C.5 Cybersecurity

The information security program was developed, implemented, and is maintained to provide an organizational environment to ensure appropriate information security and levels of information-related risk. This program entails ongoing activities to address relevant policies and procedures, technology and mitigation, and training and awareness.

A risk-based approach is used to secure ICNO systems. Information systems are evaluated in terms of sensitivity of information and availability requirements of the asset. Security controls are selected and implemented to reduce risk to acceptable levels. In addition, we inherit security controls from ASC for information systems at the South Pole station, and UW security controls for information systems operated at UW-Madison.

Asset Protection The IceCube detector is the single most valuable asset for ICNO. As such, the primary concern is securing and maintaining the operational capability of the detector as well as day to day operations and data collection. This is followed closely by the data collected by the detector.

Access to the detector and its subsystems is restricted to IceCube personnel with a need to work on the detector itself. Remote access is limited to a small set of machines in the northern hemisphere. These machines are protected by ICNO-operated network-based firewalls in the north and south. In addition, any access to the systems on station must also pass through network firewalls and other security systems operated by ASC. Changes to station security controls are coordinated with ASC via the annual Support Information Package process.

The data collected by the detector are the foundation of all science output. It is critical to collect and preserve the observational data as they are created to avoid missing unique or rare events. To reduce the likelihood of data loss, two copies of the raw data are written to disks at Pole. These disks are shipped to UW-Madison during the austral summer. A filtered copy is written to disk at Pole, and a reduced data set, about 10%, is transferred north via satellite daily. The reduced data set is replicated daily to DESY in Germany when it reaches the north. The raw data are read from disk when they arrive at UW-Madison, where they are read and replicated to NERSC. One copy is also physically stored offline in Madison.

The science data collected and maintained are not sensitive or regulated, and indeed are eventually published. In the course of operating the center, other information is generated and stored. This information is intended for internal use only. We only generate and retain the data necessary for executing administrative processes. This information is stored separately from all computing and research systems, and uses normal IT controls to ensure the confidentiality of the data.

Where widely accepted security practices and standards are not workable, compensating controls are adopted to maintain an appropriate security level. For example, stateful, network-based firewalls have unacceptable performance impacts on large research data flows and therefore data moving machines are frequently placed outside of such protections. To mitigate the risk, a ScienceDMZ architecture [14] is applied as a compensating control to apply equivalent protections.

Cybersecurity Standards and Adherence

We follow standards, practices, and guidance from TrustedCI [15] that are consistent with operations of NSF Major Facilities as well as UW-Madison campus policies, and ASC policies at the station. ICNO participates in and contributes to NSF security communities via TrustedCI and the Large Facilities security team.

Cybersecurity Breach Reporting Policy

ICNO maintains an incident response plan which includes escalation and notification procedures. To summarize, breaches will be reported to the appropriate parties in a timely manner in accordance with the severity. For incidents with a scope beyond the home institution, external incident response staff will be engaged immediately. For breaches which may impact resources at the South Pole station, ASC and NSF Program Officers will be notified immediately. Significant breaches will be reported to NSF Program Officers within 24 hours. UW security personnel will be notified in a manner consistent with UW reporting policy.

ICNO maintains a list of security contacts for all collaborating institutions to facilitate notifications within the collaboration.

C.6 Improvement Plans

Over the course of the next 5 years we are planning the following improvements:

- upgrading IT infrastructure via service life improvements, lifetime upgrades, and artificial-intelligence-focused transitions;
- determining the best data organization, management, and access (DOMA) system for IceCube; and
- increasing utilization of distributed computing resources by individual researchers.

IT Infrastructure Improvements Hardware reaching end of service life will be replaced depending on its role. Mission-critical hardware, e.g. virtualization infrastructure, is replaced at the end's of service life, typically 5 years. Hardware with a lower criticality, e.g. individual HTC cluster nodes, will only be replaced as needed. The differentiation in service life arises from the difference in component service life and usage. For example, the mean time between failures (MTBF) for hard drives used in the data warehouse decreases sharply after 5 years of operation. Similarly, improvements in computing architecture over the course of the last 5 years allow for reduced management overhead and licensing cost in our virtualization architecture. Less critical infrastructure does not suffer from the same concerns, e.g. licensing cost.

Still viable service-life-replaced hardware is added to the HTC cluster or used for research and development projects, e.g. improved monitoring infrastructure. Before any hardware is surplused, it is stripped of all viable spare parts for other machines.

As-needed replacements of data analysis infrastructure will focus on transitioning to an artificial intelligence workflow. To do so, the replacement hardware will be heterogeneous, i.e. include more GPUs and other artificial intelligence-focused hardware. We will also need to determine the appropriate software layer to be able to support this transition. There are a currently a number of different solutions available and we will investigate which is most appropriate for IceCube.

The timeline for IT infrastructure improvements is as follows:

- Q2 2021: Service life replacement of virtualization Infrastructure
- Q4 2022: Service life replacement of first half of data warehouse
- Q2 2023: Service life replacement of second half of data warehouse
- 2021-2026: Data analysis infrastructure replacement as needed
- 2022-2026: Transition to artificial intelligence workflows

Data Organization, Management, and Access

As IceCube's dataset continues to grow and become scientifically richer, we will need to determine whether IceCube's DOMA strategy is still appropriate and improve researcher experience when interacting with the data and doing exploratory data analysis. At the forefront of these tasks is determining the utility of metadata for researchers, how to store, organize, and access said metadata, and whether this metadata can reduce the "active" data set.

Additionally, we will need implement new data access patterns, in particular, external data access. This will allow us to store the data more efficiently, e.g. tiering data storage by popularity, a tighter integration between data analysis software and data storage infrastructure, and spreading the computing load across the distributed resources more effectively.

The timeline for the DOMA system is as follows:

- Q4 2021: Complete survey across collaboration science work groups to determine how researchers interact with data

- Q2 2022: Finalize scope of metadata catalog, e.g. which events and respective information to include
- Q3 2023: Deploy initial version
- Q2 2024: Integration with data analysis software
- 2023-2026: Incremental improvements through operations

Distributed Computing Resources The IceCube computing resource distribution has shifted towards resources outside of UW-Madison and WIPAC. This trend will continue as external and shared resources grow, e.g. NSF leadership class facilities, compared to WIPAC resources and large-scale heterogeneous computing infrastructure cannot be supported by campus-based cyberinfrastructure without major investments or research and development projects.

Increasing the distributed computing resource utilization by individual researchers will readily be done by reducing the barrier of entry into IceCube's workflow management system. To allow more users to use this system we will need to improve the usability and reduce the barrier of entry.

The timeline for the distributed computing resources is as follows:

- Q4 2021: New user management system that supports security token-based authentication
- Q2 2022: Include security tokens in workflow management system
- Q4 2022: Simplify workflow management configuration system
- Q2 2023: Transition expert users to workflow management system
- Q4 2024: Transition remaining users

D. Data Processing and Simulation

D.1 Data Processing

There are several levels of processing that yield increasingly specific data for different types of analyses, starting from the processing done at the South Pole (Level 1). Once the data arrives via satellite, a common processing step is applied to all data (Level 2), which includes a number of energy and directional reconstructions. The M&O team, additionally processes and filters data specific to different analyses (L3). Level 1 and Level 2 processing, including data validation, are managed centrally by M&O personnel. Individual working groups are responsible for delivering tested and validated L3 scripts and for validating the L3 output data. For a detailed overview of the data flow, see Fig. 9.

A software engineer adapts data processing based on the detector configuration and required reconstruction algorithms developed by the collaboration. The software engineer is responsible for executing and monitoring tasks to make the best use of the available computing resources. Close coordination with the run coordinator ensures data-quality issues are well understood and that any poor-quality data are excluded from processing. The software engineer performs additional data validations to detect potential issues with data value and file corruption. Data processing is performed using IceProd [16, 17], an in-house workflow management and data provenance system. This system is operated as a service for the collaboration. Replication of all the data at the DESY–Zeuthen collaborating institution is subsequently done in a timely manner.

D.1.1 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.

As 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 a 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.

D.2 Monte Carlo Simulation Production

The production of Monte Carlo simulations is coordinated by M&O personnel as a service to the IceCube Collaboration. Such simulations are required for developing analysis methods to identify signal from background, for testing the performance of reconstruction algorithms, and for determining the background contamination of data analysis samples. Ideally, one would generate an order of magnitude more statistics in Monte Carlo as data. IceCube is currently far short of this goal. One of our main goals is to accelerate the workflow in order to catch up and generate at least a comparable amount of Monte Carlo statistics as data.

The Monte Carlo chain starts at generating background and signal events and ends with the common processing steps (L2). This is done to reduce the storage space needed for simulation. Some simulation is stored at intermediate steps in the chain, e.g., triggered data, in order to perform more detailed studies on effects of changes to the processing chain at various stages. 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 model is transitioning from a centrally managed production to a coordinated model. Each physics working group is responsible for determining their own simulation requirements and requesting allocation of computing resources. The simulation is then centrally generated.

A data scientist collects this information, including rough estimates of resource utilization (i.e., storage, CPU/GPU-hours), and discusses data set priorities with the technical leads for each analysis working group within the ICC. The data scientist provides an up-to-date status summary web page with all pending and complete requests where users can monitor progress of their requests. A software engineer provides technical assistance to working groups and can, at the request of each working group, directly manage a given production.

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.

The simulation production team regularly organizes workshops to explore better and more efficient ways to meet the simulation needs of analyzers. This includes both software improvements and new strategies as well as providing the tools to generate targeted simulations optimized for individual analyses. New strategies are being developed for dynamic simulation of systematic uncertainties in our understanding of ice properties, hole-ice, and DOM sensitivity and for determining the impacts of these on physics analyses.

D.3 Computing Resource Needs

The current utilization of resources required for the 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.

We add roughly 100 TB of storage per year for both the Pole-filtered input data and the output data resulting from the offline production. Additional savings in storage resulted from switching to a more efficient compression in the last couple of years. L2 data are typically available one and a half weeks after data taking. Resource utilization and data volume is expected to increase in the near future with the increase in complexity of the detector due to the Upgrade and reconstruction algorithms and with the additional number of sensors deployed.

The reprocessing of Pass2 utilized 10,905,951 CPU-hours and 520 TB storage for sDST and L2 data. An additional 2,000,000 CPU-hours and 30 TB storage were required to process the Pass2 L2 data to L3. We anticipate a need for future reprocessing of data that will require on the order of 20 M CPU-hours of additional processing in the next couple of years.

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

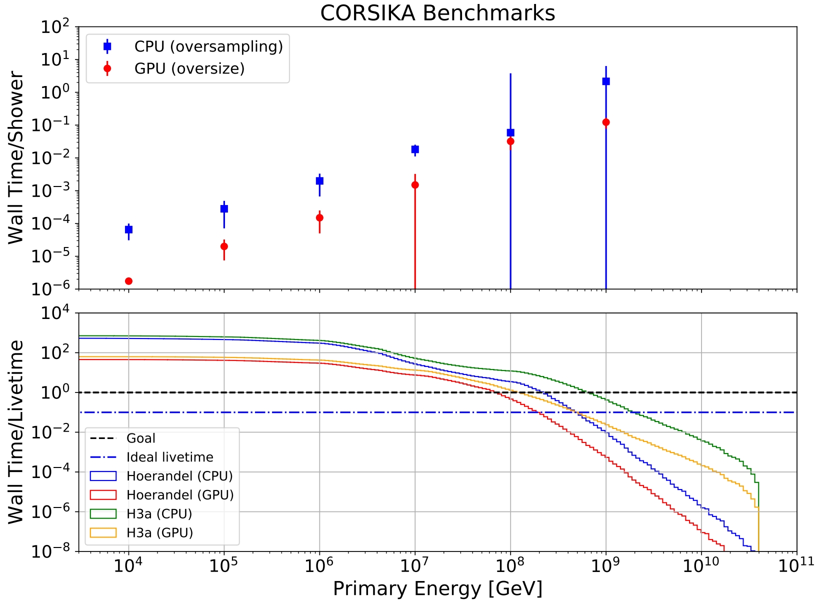


Figure 10: (a) CPU (GPU) time per cosmic-ray shower as a function of energy. (b) The ratio of wall time to detector livetime indicates the number of CPU (GPU) units continuously running for 1 year needed to simulate 1 year (10 years) of detector livetime.

Simulation production requirements are primarily dominated by background simulations with `CORSIKA` [18] 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 according to a parametrized flux calculated from `CORSIKA` simulations using the same approach of MUPAGE [19] which was developed by the ANTARES Collaboration [20]. 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.

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. Technical debt has been accumulating over the past decade and is hindering further expansion. The newest and largest GPU-based resources across NSF, the DOE, and PRACE that feature the Power9 platform no longer fully support IceCube's software. The heterogeneity of resources will only increase in the coming years. The upcoming pre-exascale, such as NERSC's Perlmutter system, and exascale class HPC resources, such as Argonne National Lab's Aurora, will introduce new types of GPUs. Given IceCube's increasing demand for resources from Monte Carlo simulation and individual analyzers, the technical debt may affect the scientific output of IceCube substantially. Addressing this will require a concerted effort across IceCube's cyberinfrastructure teams and additional professional resources to ensure that long-term solutions can be implemented, including addressing our the technical debt as well improvements needed to support the Upgrade and IceCube-Gen2.

E. Physics Software

IceCube's physics software codebase (IceTray) covers a wide range of responsibilities and is used directly by a majority of the collaboration, including for online filtering, real-time systems, offline data reprocessing, and offline simulation generation. It currently consists of over 100 projects and 1M lines of code. Their functions range from the core IceTray framework to user-defined simulation and reconstruction modules. Nearly all of IceCube's more than 13 PBs of data (both archived and active) is stored in IceTray's custom serialization format. The effort over the next five years will focus largely on adapting current projects to support new detector modules and ensuring the entire chain, from simulation generation through filtering, operates reliably and efficiently in a wide range of distributed environments.

The software group also supports an open source organization that currently consists of 118 collaborators contributing to 56 repositories—many still private. This organization is supported almost entirely by in-kind contributions, though some projects will transfer to central production and ultimately become the responsibility of M&O. The plan is to encourage collaborators to develop and maintain code used for production and analyses in our open source organization.

The physics software codebase currently has roughly 3.5 professional FTEs dedicated to its development and maintenance. Physics software projects currently fall into one of the following nine categories, with only the first group of four covered by M&O, while the rest are supported by in-kind contributions:

- Core Software, Simulation, Reconstruction, Filtering
- Oscillations, Neutrino Sources, Beyond the Standard Model, Cosmic Ray, Diffuse Neutrinos

The roles and responsibilities of individual, professional software engineers on IceCube can be classified into four broad categories in order of importance: maintenance, feature development, researching future technologies, and educating colleagues. The fraction of time spent in each of the roles will vary, but work-plans for members of the software group will be developed around these key four responsibilities. The software group has adopted a seasonal release cycle, producing feature releases four times per year.

E.1 Core Software

The bulk of the projects are written in C++, which—over the last decade—has been rapidly evolving, where new standards are released every three years. The focus of the software group will be to incorporate modern C++ features that improves its scaling performance. The core software projects generally fall into one of the following categories:

- Framework - C++ framework IceTray including python bindings.
- DevOps - Responsible for third-party tool detection, compilation, documentation builds, and CI/CD.
- Serialization - Responsible for the bulk of I/O on on-disk format. (adapted from [21])
- Data Structures - Specialized structures used by downstream filters and analysis modules.
- Data Visualization - Visualization tool that generates high-quality graphics for publications [22].

- DAQ Payload Tools - Tools to read and handle DAQ payloads.
- Waveform Tools - Projects to calibrate and unfold digitized waveforms.
- Analysis Formats - Generic framework to support the conversion of native IceTray classes to popular analysis formats.

Currently, there are 2.25 FTEs, split between 5 people, dedicated to the maintenance and development of the above projects. In order to efficiently utilize distributed resources, the framework will be made thread-aware to support multi-core architectures. The build system will need to continually evolve to support tools needed for physics analyses. Deep Learning techniques are proving valuable in many areas of IceCube analysis. It will be necessary to provide support for popular ML formats, such as Apache Arrow (used in RAPIDS.AI/cudf [23]). In order to support the IceCube Upgrade development of new DAQ payloads, waveform tools, and data structures are planned.

E.2 Simulation Software

The simulation projects contain various IceTray modules and services necessary for generating both signal and background Monte Carlo, where many of the signal simulation projects are supported by in-kind contributions. IceCube's simulation chain has to perform equally well for neutrino oscillations ($O(10\,\mathrm{GeV})$) as for cosmogenic neutrinos ($O(10\,\mathrm{PeV})$). Efficient resource usage on all available hardware (e.g. x86, Power9, ARM, NVIDIA, AMD, etc...) will be the focus of the core simulation group. Core support, which all collaborators rely on, is needed in at least two main areas: GPGPU/heterogeneous programming and detector simulation.

- Cosmic Ray Signal - Full hadronic shower generation with CORSIKA for IceTop only.
- Hadronic Shower Background - In-ice background muon and atmospheric neutrino generation with CORSIKA.
- Fast Background - Parameterized single-muon, in-ice background, sacrificing systematics for statistics.
- Neutrino Signal - Injection of neutrino signal, including standard model and BSM oscillations.
- Exotic Signal - Monopole and WIMP generation for the BSM physics working group.
- Photon Propagation - Propagation of photons through the ice utilizing GPUs.
- Lepton Propagation - Propagation of leptons, which includes energy losses and stochastic generation, the main contributors to Cherenkov radiation and therefore detector signal.
- Detector Simulation - Simulation of the PMT, DOM Mainboard, and DAQ trigger.
- Data Structures - Specialized structures to store Monte Carlo truth information used by downstream analysis modules. New structures and services will need to be developed and maintained to support Upgrade modules.

Of the above projects only the hadronic shower background, neutrino signal, photon propagation, detector simulation, and data structures are supported by M&O. The rest are supported by in-kind contributions from collaborating institutions. Producing sufficient background to meet the analysis needs of all working groups remains one of the most significant challenges for the simulation group. Over the next five years IceCube's simulation group will explore technologies such as CUDA, Sycl, and OpenAcc to increase the efficiency of photon propagation in distributed systems. The larger software group will also explore the use of GPGPU programming in areas, such as detector simulation, waveform deconvolution, reconstruction, and deep learning algorithms. The detector simulation is currently the second largest consumer of resources in the simulation chain. The ability to predict resource usage, to allow for efficient scheduling in a distributed environment, will be a top priority for the simulation group. This need is currently critical but will become even more so as the number, type, complexity, and density of optical modules increase during the Upgrade.

E.3 Reconstruction Software

The reconstruction projects consist of IceTray modules used from low-level online filtering at the pole to high-level analysis. Experience has shown that difficulties from performing joint reconstructions between in-ice/IceTop and in-ice/DeepCore have delayed analyses. Avoiding this in the future after the deployment of the Upgrade modules will ensure timely publication of results. Below are the broad categories that most reconstruction projects fall into:

- First-guess Seeds - Simple first-guess algorithms that typically serve as seeds to more resource intensive reconstructions.
- Framework - Reconstruction framework within IceTray that manages the interaction between first guess hypotheses, minimizers, and resource intensive algorithms.
- Reconstructions - Track and cascade algorithms used both in low-level filtering and analysis. Ensuring all reconstructions are adapted to Upgrade modules is going to be critical for future analyses.
- Tools - Tools that estimate photon arrival times and amplitudes will need to be adapted to support upgrade modules.
- Data Structures - Specialized structures that store reconstruction results used by downstream filters and analysis modules.

Over the next five years first-guess algorithms, core reconstructions, and data structures will need to be updated to support Upgrade modules. Increased support by M&O is also required to ensure efficient utilization of distributed resources and manage the increased complexity of joint reconstructions. Concurrent use of tables in a distributed environment, which will significantly reduce the memory requirements, will be used in production over the next 2 years.

F. Detector Calibration

Calibration of the IceCube sensors and measurement of the properties of the South Pole ice enables the production of high quality science products from the raw charge and time data collected by the IceCube DOMs. Routine calibration tasks are handled through the detector operations group. A dedicated calibration working group is charged with developing and disseminating models of the bulk and hole ice, measuring the efficiency of the DOMs in the lab and in situ, measuring the SPE behavior in DOMs and organizing LED flasher runs. There are 2.38 FTEs dedicated to calibration in the project, with all additional effort contributed in kind.

F.1 Sensor Calibration

The primary calibration routine, called DOMcal, is performed every month in IceTop and every year in the in-ice array, in order to measure the PMT gain as a function of high voltage, discriminator threshold settings, and other calibration constants. Additionally, the DOM digitizer baselines and

SPE distributions are measured every year. These constants are used by the PnF system to translate the raw waveform data into physical units. The SPE distributions (a proxy for PMT gain) and the digitizer baselines are monitored continuously by the detector monitoring system to ensure stability of these constants. The collaboration recently published a new method of extracting the SPE charge distribution using a deconvolution of the multiple-photoelectron charge distribution [24]. During the upcoming 5-year operational period, we will implement the updated description of the SPE distribution in the standard calibration runs and in a planned "pass 3" recalibration of the data. There are 0.08 FTEs dedicated to supporting DOMcal tasks and baseline and SPE calibration.

F.2 Measurement of Ice Properties

Measuring the optical properties of the ice is critical to accurate reconstruction of the energy and direction of neutrino events. The ice remains a major source of systematic uncertainty in IceCube science analyses. The collaboration continuously improves the ice model with data from the LED flasher calibration runs. A major outstanding question is the source of the anisotropic attenuation observed in flasher and muon data, which is aligned with the local flow of the ice. The most recent ice model proposes the microstructure of ice as a birefringent polycrystal as the cause of the anisotropy [25]. The collaboration will continue to develop and validate the birefringence model and to implement improved descriptions of the ice in the simulation and reconstruction software. There are 0.65 FTEs dedicated to supporting the implementation of the birefringence ice model and supporting use of the new ice model in event reconstruction.

F.3 IceCube Upgrade

Significantly improving the detector calibration is one of the primary goals of the IceCube Upgrade. The Upgrade will include an array of new calibration devices including flasher LEDs, cameras, beamed and isotropic LED light sources, and acoustic sensors. Closer spacing of the Upgrade strings will facilitate measurements on a baseline comparable to or less than the optical scattering length in ice. For the improvements in the ice model and detector characterization, we expect to achieve DOM optical efficiency determination in situ to better than 3%; and we expect to reduce uncertainties of angular acceptance of IceCube DOMs due to refrozen hole ice by a factor of at least 2. Additionally, we expect to determine the source and depth dependence of anisotropy in optical scattering in ice. The updated calibration constants will improve angular resolution of existing IceCube data by a factor of 4 in the cascade channel and by a factor of 2 in the muon channel for commensurate improvement in point source sensitivities and reduction of false alarm rates by a factor of 4. We expect to double the astrophysical cascade event rate to 20 per year and achieve 3 σ observation of cosmic taus after 12 years. The Upgrade project supports the deployment of Upgrade hardware, collection of calibration data and development of a database to contain new calibration constants. ICNO operations, in turn, will support the implementation of updated calibrations into the simulation and reconstruction software. There are 1.65 FTEs dedicated to supporting the data from LEDs in upgrade, including the beamed LED module ("PencilBeam") which will also support the aforementioned birefringence ice model. All remaining calibration effort in the Upgrade following the end of Upgrade construction is contributed in kind.

G. Risk Management Plan and Risk Register

This plan describes how the IceCube Maintenance and Operations team manages and mitigates risk to the existing detector and its data. This plan governs all IceCube M&O Collaborators, including UW-Madison personnel who control budgets and schedules.

G.1 Risk Registry

We maintain a risk registry of approximately the top ten risks to the ongoing ICNO M&O. Personnel risks during South Pole deployment are handled separately, with required general and specialized safety training prior to travel to Antarctica. This minimizes the possibility of a major injury that would impact the ICNO operations. Safety is the number one priority for those deploying, and the excellent track record to date is evidence of effectiveness of the safety training.

IceCube operations risk management attempts to leverage the technical experience from the IceCube construction: everyone is responsible for identifying risks, and once a risk is identified someone is assigned formal responsibility for managing it. This risk registry is an evolved (and simplified) version of the project construction risk registries of the IceCube Gen1 construction effort and the IceCube Upgrade construction project. The risk registry is available as Attachment 7.

G.1.1 Risk Types

- Risk Technical, External, Organizational, and Project Management.
- Risk Title: Risk Title is a very brief description of the risk.
- Risk Handling Approach: Response is either Mitigate (actions required), Watch, Accept, Avoid or Research.
- Technical Risk: Technical risks are related to requirements, technology, interfaces, performance, and quality.
- External Risk: External risks are related to suppliers.
- Organizational Risks: Organizational risks are related to project dependencies, logistics, resources, budget, etc.
- Project Management Risks: Project Management risks are related to planning, schedule, estimation, controls, communications, etc.
- Risk Trigger: A risk trigger identifies the risk symptoms or warning signs. It indicates that a risk has occurred or is seen to be about to occur.

The risk type definitions are according to NSF Major Facilities Guide.

G.2 Risk and Opportunity Review and Management Process

The risk register is reviewed and updated annually, or what specific circumstances require a new look at the risks. (For example, with the current pandemic, the risks have been examined with an eye towards the difficulty of South Pole access during the 2020-21 Austral Summer.) In addition, individual risks are actively monitored and the risk status is reported as part of the quarterly reporting process.

The project Quality Manager is responsible for the risk register and works with subject matter experts and the project managers to adjust the cost and risk scoring to an equivalent basis. Risks are manually reviewed in this manner to ensure that entries developed by many personnel across the project are captured and assessed with similar leveling, allowing for project-wide integrated assessment of risk and exposure.

Risk management also include opportunities and the project is actively pursuing identification of additional funding from partners as well as cost-saving opportunities such as identifying alternate, more cost-effective sources of major capital subsystems, e.g. computer CPU and GPU hours. These opportunities are captured in the risk register alongside risks and are used in an equivalent manner to help the project management assess scope as the project evolves. Opportunities are identified actively and will be utilized in order to reduce overall project risk.

Management of risks and opportunities forms an integral part of the Project Execution Plan and is governed by the guidelines of NSF Major Facilities Guide. As such, risk and opportunity review is a necessary component of yearly detail planning and contingency planning. In general, risks might have a horizon date after which they are no longer risks, though the primary risks to IceCube data-taking are not of this form, and remain constant (risk retirement date is shown as Never) throughout the course of the M&O cycle.

G.3 Risk Classification

Risks are classified by their probability of occurrence and by their impact to the project as tabulated below. The risk score is then determined from the risk scoring table.

The risk probability tables, impact assessment levels, and the matrix of probability and impact are all taken directly from the MFG (figures 6.2.7-3, 6.2.7-4, and 6.2.7-5). They are not reproduced here.

Risk mitigation strategies are then defined and a post-mitigated risk is derived with new impacts and probabilities assigned. This gives a qualitative estimate of the associated degree of risk so that major risks can be identified easily. To quantitatively assess an equivalent cost of the risk, the post-mitigated risk is assigned a total cost exposure, i.e. what amount of money would need to be spent in the event of risk occurrence.

G.4 Project Risk Registry Summary

The resulting risk exposures do not have calculated costs associated with them since in a project construction those costs would hook directly to the project contingency, and no contingency is planned into the M&O budgets. Some of the risks, if realized, would likely require direct cooperation with the NSF and/or the host institution to manage.

H. Acronyms and Definitions

ADC	Analog-to-digital converter chip
AMANDA	Antarctic Muon and Neutrino Detection Array
AMON	Astrophysical Multimessenger Observatory Network
ATWD	Analog transient wave digitizer
Condor	UW–Madison workload management system for compute-intensive jobs
CF	Common Fund
CTSC	Center for Trustworthy Scientific Cyberinfrastructure
DACS	NSF Division of Acquisition and Cooperative Support
DAQ	Data acquisition system
DOM	Digital optical module
DOMCal	DOM in situ self-calibration system
DOMHub	Surface cable terminus with readout electronics and low-level data acquisition function
DOR	DOM readout electronics PCI card
DSI	Data Systems International
E&O	Education and outreach
EMI	Electromagnetic interference
GCN	Gamma-ray coordinates network
GPU	Graphical processing units
GridFTP	An extension of the standard file transfer protocol (FTP) for use with Grid computing
HPC	High-performance computing
HPSS	High performance storage system
HSM	Hierarchical storage management
HTC	High-throughput computing
I3MS	IceCube messaging system
ICB	IceCube Collaboration Board, the entity that guides and governs the scientific activities
IceCube Live	The system that integrates control of all of the detector's critical subsystems

IceProd	IceCube simulation production custom-made software
IceSim	IceCube simulation software package tools
IceTray	IceCube core analysis software framework is part of the IceCube core software library
ICL	IceCube Laboratory (South Pole)
IOFG	International Oversight and Finance Group
JADE	Java archival and data exchange
LED	Light emitting diode
M&O	Management and operations
M&OP	Management & Operations Plan
mDFL	Mobile/modular dark freezer lab
MoU	Memorandum of Understanding, between UW–Madison and all collaborating institutions
MPS	NSF Directorate for Mathematical & Physical Sciences
MREFC	Major Research Equipment & Facilities Construction
MSPS	Megasamples per second
OPP	NSF Office of Polar Programs
OSG	Open Science Grid
OVCRGE	Office of the Vice Chancellor for Research and Graduate Education, at UW–Madison
PA	NSF Particle Astrophysics Program
PCTS	Physical Sciences Laboratory cable test system
PHY	NSF Division of Physics
Physics working group (WG)	Physics working groups perform high-level analysis and develop specific analysis tools
PLR	NSF Division of Polar Programs
PMT	Photomultiplier tube
PnF	Processing and filtering
SAC	Science Advisory Committee

SCAP	IceCube Software & Computing Advisory Panel
Science DMZ	A secure computer subnetwork designed for high-volume data transfers
SIP	Support Information Package
SNEWS	Supernova Early Warning System network
SNDAQ	Supernova data acquisition
SPS	South Pole System (at the South Pole)
SPTR	IceCube dedicated high-capacity South Pole TDRS relay system.
SPTS	South Pole Test System (at UW Madison)
TDRS	A Tracking and Data Relay Satellite is type of a satellite that forms part of the TDRSS
TDRSS	The Tracking and Data Relay Satellite System is a network of communications satellites
TFT Board	Trigger Filter and Transmission Board
TS	Test statistic
UPS	Uninterruptible power supply
USAP	United States Antarctic Program
UW	University of Wisconsin–Madison, host institution of the IceCube Collaboration
VCRGE	Vice Chancellor for Research and Graduate Education, at UW–Madison
WBS	Work breakdown structure
WIMPs	Weakly interacting massive dark matter particles
WIPAC	Wisconsin IceCube Particle Astrophysics Center (former IRC)
XSEDE	Extreme Science and Engineering

I. Safety Standards

The Environmental, Health, and Safety (EH&S) specific standards followed by the M&O program are listed in Tables 6 and 7. They form the foundation for the IceCube M&O EH&S program which adheres to the procedures, policies, and training in the listed standards. The IceCube M&O Project has an internal audit program that assesses compliance to the requirements of the respective standards. We also work closely with ASC counterparts to refine and assess the IceCube M&O EH&S program, drawing on their expertise and experience particularly with the safety programs adapted to working in the extreme Antarctic conditions.

Title and Part	Section(s)	Description
29 CFR 1910	.38, .120	Emergency response
	.95	Hearing conservation
	.122, .241-244	Tool safety
	.132-133, .138	Personal protective equipment
	.146	Confined space entry
	.147	Control of hazardous energy (lockout/tagout)
	.151	First aid
	.178	Forklift operations
	.179	Overhead and gantry cranes
	.180	Mobile cranes
	.184	Slings
	.301-308	Electrical safety
	.1200	Hazardous chemicals
29 CFR 1910 Subpart L		Fire Protection
29 CFR 1926	.96, .101-103	Personal protective equipment
	.50	First aid
	.500-503	Fall protection
	.550	Mobile cranes
49 CFR Subchapter C		Hazardous Materials Regulations

Table 6: US Federal Government Code of Federal Regulations (CFR) safety codes followed by IceCube Management and Operations.

Code	**Description**
University of Wisconsin Hazard Communication Program	
University of Wisconsin Laboratory Safety Guide	
ANSI Z117.1	Safety requirements for confined spaces
Executive Order 13043 of Apr. 16, 1997	Increasing seat belt use in the United States
Executive Order 12196 of Feb. 26, 1980	Occupational safety and health programs for federal employees and contractors
NASA Standard 8719.13A	Software safety
NEC, MIL-STD 454	Standard General Requirements for Electronic Equipment
NFPA fire standards, codes, and appendices	
NFPA 101 Life Safety Code Handbook	
NFPA 70 NEC Handbook	
NIOSH Publication No. 87-113	A Guide to Safety in Confined Spaces
OSHA Technical Manual, Sec. 10, Chap 3	Pressure vessel guidelines
International Boiler and Pressure Vessel Code	2004 Edition
NPD 8710.5	NASA policy for pressure vessels and pressurized systems
SafeStart Training	

Table 7: Other safety standards followed by IceCube Management and Operations

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