

Scope Management Plan for the IceCube Upgrade Project

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1. Purpose

Scope Management is an integral part of project management. According to the NSF Research Infrastructure Guide (1), the Scope Management Plan not only describes the process by which the project maintains control of scope, but also documents scope changes that can be implemented depending on the project's cost and schedule forecasts. These scope changes can be either **downscopes**, if the project is over budget and/or behind schedule, or **upscopes**, if the project is under budget and performing well schedule-wise. This document complements the IceCube Upgrade's Project Execution Plan (2), describing the process followed to develop scoping options, a summary of the scope options, and the plans for managing them.

2. Baseline Scope

The baseline scope for the IceCube Upgrade is detailed in the “IceCube Upgrade Project Execution Plan” (2). An overview of the project is shown in Figure 1.

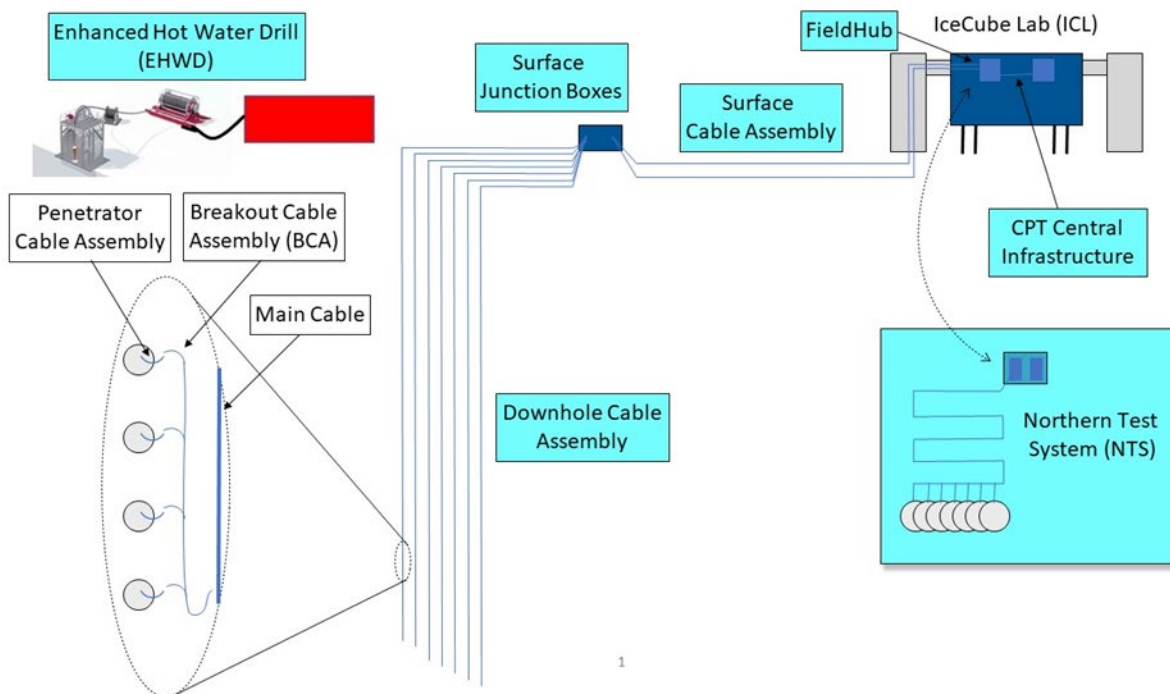


Figure 1 A high-level representation of the IceCube Upgrade.

In brief, the upgrade consists of an Enhanced Hot Water Drill designed to drill holes to 2600 meters, optical module “strings”, each instrumented with 38 dual PMT modules (D-Eggs) and 52 multiple PMTs (mDOMs) in the physics region between 2150-2425M, as well as calibration devices, D-Eggs,

and mDOMs above and below the physics region (see Figure 2). The backbone of the strings are the downhole cables.

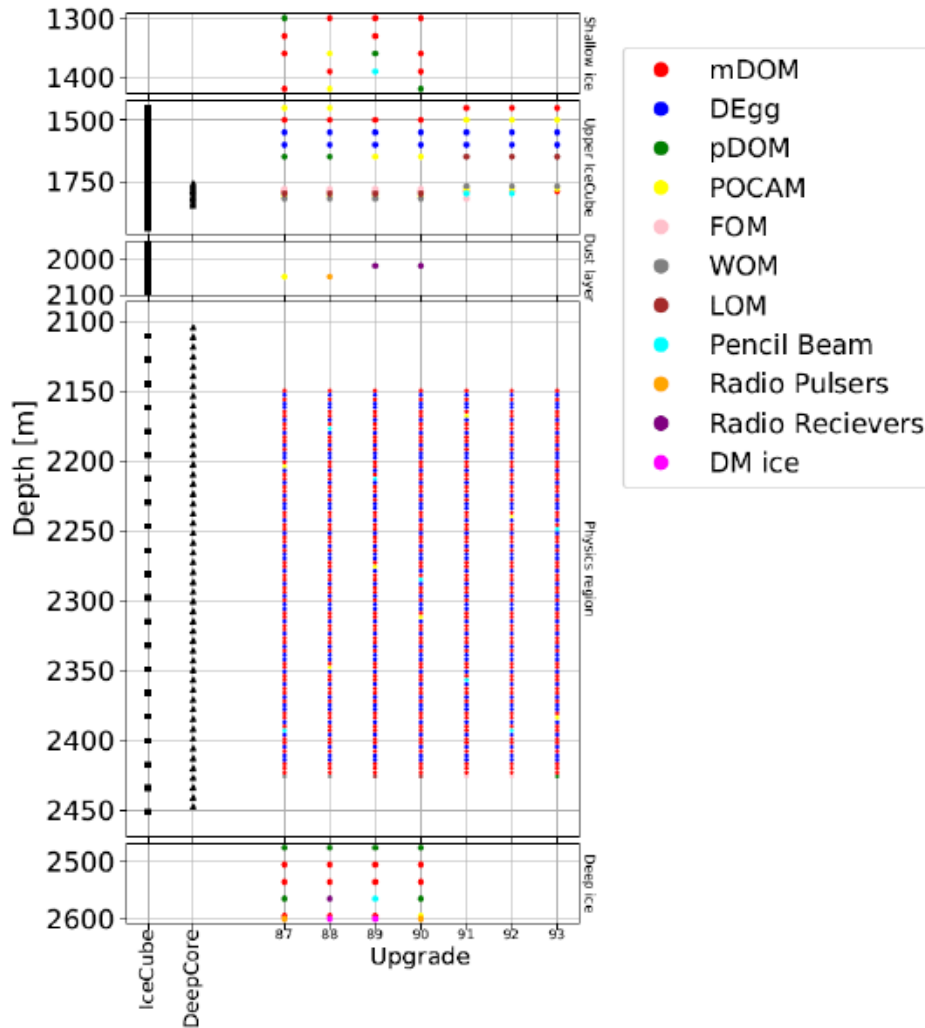


Figure 2 Configuration of the 7 Upgrade Strings, in comparison with IceCube Gen1 and IceCube DeepCore.

Additionally, the project consists of surface cables, junction boxes, and computing necessary to readout and calibrate the deployed strings. The project also supports a “Northern Test System” mainly used for firmware and software development needed to validate hardware and software/firmware as well as support any necessary updates to software and/or firmware.

The detector is installed and commissioned by the Upgrade Project, and is handed off to the ongoing IceCube Neutrino Observatory Maintenance and Operations. For details of the configuration of the detector and software at handoff see (2).

3. Scope Options

3.1 Project Downscope

Project downsides are considered that save project money or schedule. Note that much of the instrumentation is “in-kind”, that is delivered by partners outside of the NSF Upgrade Project budget, thus descopeing instrumentation is not a cost saver.

3.1.1 Reducing the number of strings deployed

The optical sensors are built in the U.S., Germany, and Japan, and are funded by our foreign partners. The downhole cables are also in-kind, funded through Michigan State University. Hence removing strings would not save NSF funds but could potentially mitigate schedule risk.

The real potential of descopeing the number of strings deployed is in the schedule savings during the main drilling season (FS3 in FY26). Each hole takes approximately 3 days to drill and deploy (where we are including setup and breakdown in the time estimate), thus drilling two less holes, for example, would save about 1 week of on-ice time during Field Season 3.

3.1.1.1 Scientific Impact of descopeing strings

IceCube has run simulations to determine the scientific impact of descopeing strings. The simulation assumes that the last two holes are not drilled and compares the 5-string configuration with the nominal 7 string configuration. Figure 3(a) compares event distributions for the 5-string and 7-string case in the Upgrade Volume as a function of energy. At energies > 10 GeV, the distributions are consistent; however, at low energies, which are sensitive to the neutrino mass hierarchy, the 5-string detector shows a reduction of neutrino rate of about 15-20%. Figure. Figure 3(b) compares the zenith angle of the distributions and shows that the degradation of neutrino rates is roughly flat as a function of zenith angle.

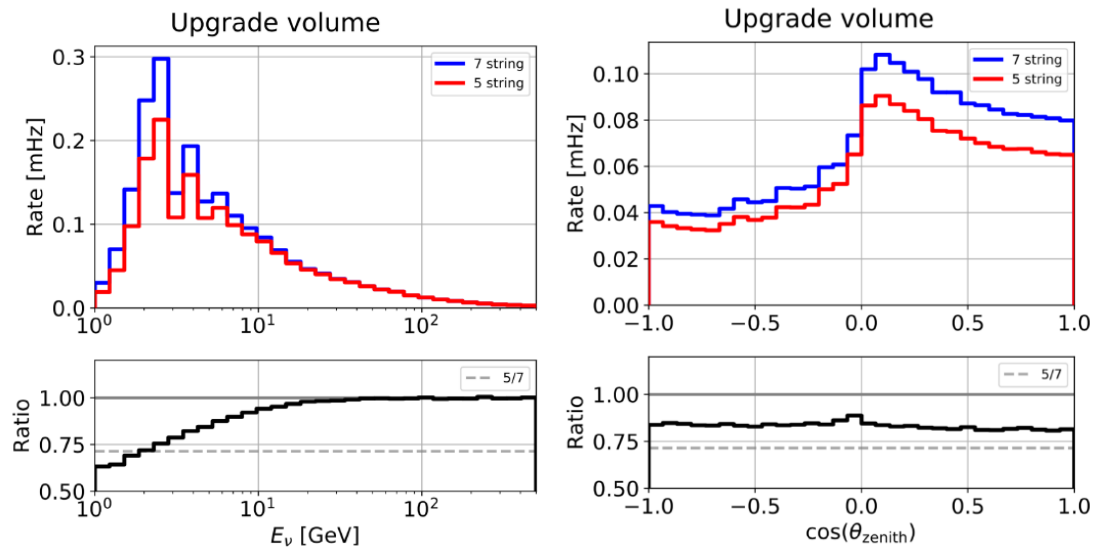


Figure 3 Comparison of neutrino event distributions between 5 string and 7 string Upgrade detector as a function of (a) neutrino energy and (b) $\cos(\theta_{zenith})$.

Figure 4 compares the reconstructed energy and zenith angle resolutions as a function of energy. For energies up to 10 GeV, the energy resolution degrades by about 10-20%. The degradation of the resolution of $\cos(\theta_{zenith})$ is also on the order of 10-20%, with the lower energy neutrinos being affected less.

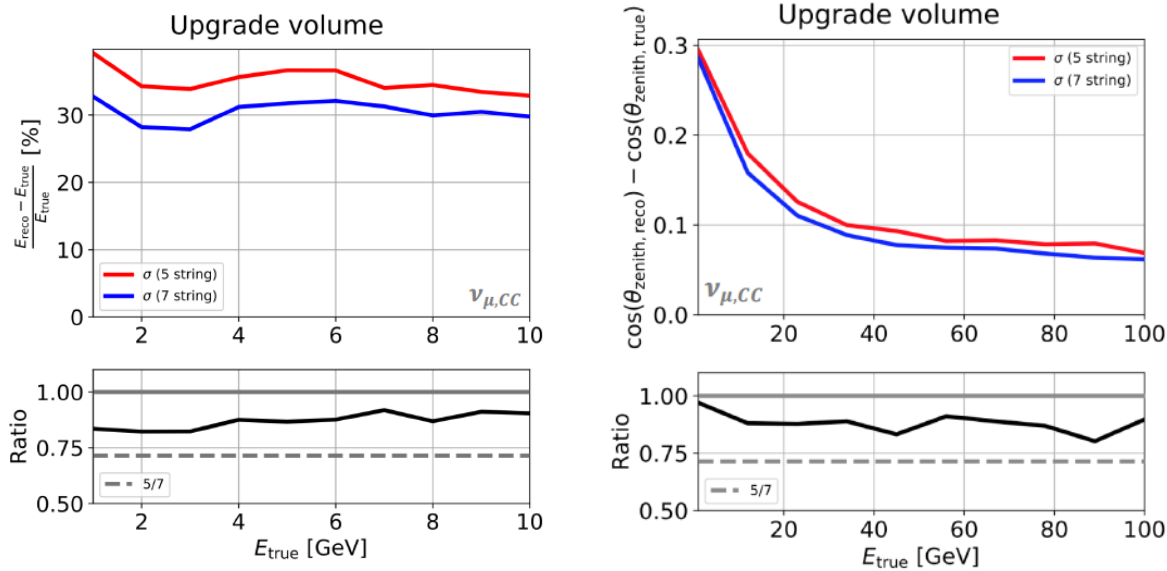


Figure 4 Comparison of reconstructed neutrino event resolutions between 5 string and 7 string Upgrade detector as a function of neutrino energy for (a) neutrino energy and (b) $\cos(\theta_{zenith})$.

3.1.1.2 Conclusions on reducing the number of strings

In general, for the neutrino rate at low energies, the 5 string detector has a 15-20% drop in rate, with up to about 30% drop in rate for energies < 10 GeV. One way to make up for the overall loss of events is to run longer. More concerning is the resolution degradation which would fundamentally limit the performance of the detector. Studies show that the energy resolution, for energies < 10 GeV, are affected at the 10-20% level, and the zenith angle resolution degrades by 10-20% for higher energy neutrinos.

While the collaboration would clearly prefer to deploy the full 7 string detector, these studies show that even the 5-string detector would have a substantial measurement and discovery potential.

In case of a descope, the sequencing of the strings will not change by default. The sequencing has been carefully analyzed with respect to positioning and relocating drill and deployment equipment. Which strings would be eliminated would depend on the reason and the time when the decision is made. An analysis will be performed as part of the field season preparation. Technically, any one or two of the seven strings (numbers 87, 88, 89, 90, 91, 92 and 93) may be omitted. If the decision happens during the field season, it will be by default the last two strings that get omitted. If the decision happens early in the season, or yet earlier, for example on grounds of availability of string hardware, scientific criteria and instrument configuration can also enter the selection. A decision matrix with criteria and scenarios will be developed as part of preparation of field season 3.

3.1.2 Modifying drill hole parameters

An additional descope option is available in modifying the hole specifications. The current plan foresees that 5 of the 7 holes will be drilled with a modified drill sequence that has the intent to eliminate air bubbles. This procedure requires drilling a slightly larger hole and an additional circulation of water. The possibility exists to drill most or all holes in the standard procedure, as was done in IceCube Gen1. Dropping this degassing procedure reduces the fuel usage per hole by 10% and reduces the drill time per hole by 10 hours. Thus, dropping 3 (or 5) degassing procedures saves 30 (50) hours of drilling time and 2400 (4,000) gallons of fuel.

In addition to this measure, a smaller descope option eliminates the deepest segment of one (or two) out of four strings that are configured for a depth of 2620m reducing the depth to 2450m. This is a minor modification that would save another 4 (8) hours of drill time.

These combined measures could save nearly 60 hours of drill time, and at least that amount of work time on ice, as well as 4000 gallons of fuel. The decision to take these measures would be taken on the ice once it is determined that the drill schedule is compressed beyond a critical value, either before drilling starts, or during drilling.

The science impact of these measures is relatively small. Removing air bubbles would allow a comparison of holes with and without air bubbles. However, all IceCube holes have the mentioned bubble column in the center of the hole. In the past 4 years, since the Upgrade was proposed, substantial progress has been made in simulation and analyzing the effect of the central bubble column. Once these effects are correctly simulated, they become a feature and are no longer a systematic error. The degassing of at least one or 2 holes would demonstrate that we understand the causality of the feature. However, no adverse science impact is expected for the neutrino physics goals by introducing these measures. Similarly, reducing the number of full depth strings from 4 to 2 would have only marginal impact in the ice calibration of the ice in that region.

3.2 Project Upscopes

The project upscopes considered are ones that can be exercised late in the project, as the Field Seasons define the critical path for the overall project and carry inherent risks. The Upgrade project, and its eventual integration in the overall operating IceCube detector, relies heavily on the ongoing IceCube Maintenance and Operations (M&O) program for the collection, storage, and analysis of data from the newly deployed sensors and calibration devices. The project upscope options are listed below, and facilitate the fully integrated Upgrade detector in: storage and analysis of Upgrade data; reduction of time needed to perform analyses with the fully integrated detector; and reduction of the time to physics results.

The additional cyberinfrastructure needed to realize the additional support for facilitating data handling and analysis of the upgraded detector are:

1. ~1-2 PB storage for data and simulation (\$70-100/TB, \$140-200k per storage element)
2. ~10 GPU data analysis and photon simulation servers (\$33k/server, \$330k)
3. 1 Machine Learning server for algorithm training and testing (\$200-300k)

The sum of all these scope options is approximately \$800k. The exact configuration of upscales we would exercise will depend on the money available and will be decided at the time of the third field season, and exercised as soon as the success of this final field season is assured.

4. Scope Option Management

Managing the scope options involves:

- Updating the scope options on a routine basis
- Monitoring the decision points for executing down- or up-scales and reviewing the need for executing a scope option in a timely manner.
- Prioritizing the scope options.

The scope options are updated regularly if there are changes to schedule or cost that would impact the descope options available to the project. At least once a year a more comprehensive review of the (available) scope options will be performed.

The available contingency for the NSF funded project compared to the risk exposure and projected draws on contingency is evaluated on a routine basis as part of Earned Value Management. If the available contingency is considered to be insufficient for completing the project, steps will be taken to select and exercise descope options to bring the contingency up to an acceptable level.

When descopeing is necessary, the project will consider the ranking of the descope options to decide which option(s) to execute. Selection of the proposed descopes will be coordinated with the IceCube collaboration.

4.1 Decision points and process

If scope changes are needed, the change will be implemented as soon as it becomes apparent that the scope change is required to complete the project in a controlled fashion. It is not possible to foresee when this information will be available, therefore to be able to plan in advance, we distinguish two classes of decisions: scope changes *before* the drilling / deployment season (Field Season 3) and scope changes *during* the drilling / deployment season. A scope change before Field Season 3 (FS3) will be processed using the usual Change Request mechanism, including an analysis of the impact to the experiment, an evaluation at the Technical Board, and approval by the Change Control Board, as well as Project Manager / Project Director approval, and approval or concurrence of the NSF in

accordance with Change Control thresholds as documented in the Upgrade *Project Execution Plan* (2).

A scope change during drilling / deployment would be necessitated by schedule issues, either due to realized risks or other unknowns. If a scope change must be made during FS3, the field team manager (On-Ice Lead) will make the decision. The On-Ice lead will regularly report to Upgrade Project Management and share reports with NSF weekly and daily as appropriate and practical. Additionally the On-Ice Lead will, to the extent practicable, consult with the Project Director (on or off ice), but ultimately when working in such a remote and unforgiving location, decisions must be made in the field where the On-Ice Lead has intimate understanding of the challenges and abilities of the team.

Upscopes would only be considered late in the project, when it is clear that the project has enough budget and schedule to consider them. All upscoptes would go through the usual Change Request process, and would require approval by the NSF.

In Table 1, we describe decision points and time frames for scoping decisions. The earliest decision date a de-scoping of the number of strings would be considered is in Spring 2025. In an extreme scenario, it could become apparent that already six months before shipping, there will not be enough instrumentation to deploy seven strings. A more plausible scenario could be that logistical or technical reasons lead to a delay in drilling.

- Example 1: On December 16, 2025, the field team recognizes that the drilling start will be delayed by at least two days. The On-Ice Lead decides to change the hole parameters for five holes.
- Example 2: On December 28, 2025, it becomes clear that there is not enough time left to drill all seven holes. Therefore, the On-Ice Lead decides to de-scope by removing one string from the plan. This decision can be made at this time, but it could also be made later, depending on the circumstances.
- Example 3: On January 7, 2026, it is clear that, at the most, five holes can be drilled. Therefore, a de-scope decision is made to remove a second string from the plan. This decision can be made at this time, but it could also be made later, depending on the circumstances.

The project office will develop a template with guidance and criteria for which string and which string location would be omitted first and second. This guidance will be developed by the collaboration no later than Spring, 2025, and reviewed with the On-Ice lead for FS3 before deployment.

Scope option	Possible causes	Rank	Early Decision	Late Decision
Descope: hole parameters.	Drilling schedule does not allow to complete 7 holes in FS3.	1	03/01/2025	1/25/2026
Descope: 1 st string	Instrumentation will not arrive on time (due to production or shipping); a cable gets damaged during shipping or handling; the drilling schedule does not allow to complete 7 holes in FS3.	2	03/01/2025	1/25/2026
Descope: 2 nd string	Instrumentation will not arrive on time (due to production or shipping); a cable gets damaged during shipping or handling; drilling schedule does not allow to complete 6 holes in FS3.	3	05/01/2025	1/25/2026
Upscope: Data storage	Cost performance allows to draw contingency for Upscope	1	05/01/2025	3/1/2026
Upscope: GPUs for simulation	Cost performance allows to draw contingency for Upscope	2	05/01/2025	3/1/2026
Upscope: Machine learning server	Cost performance allows to draw contingency for Upscope	3	05/01/2025	3/1/2026

Table 1 Ranks and decision points for Up and Down scopes for the Upgrade Project. Options are ranked from most preferable (1) to least preferable (3). In the case of descope, this ranking minimizes the impact to the science of the descope. For upscope options, the late date is to ensure that the equipment can be received by Project Closeout (currently June 6, 2026).

References

1. **National Science Foundation.** Research Infrastructure Guide. [Online] 2021.
https://www.nsf.gov/publications/pub_summ.jsp?ods_key=nsf211107.
2. **IceCube Upgrade Project.** Project Execution Plan for the IceCube Upgrade Project. [Online] 2022.