A Surface Array Upgrade for the Maintenance of the IceTop Detector

The IceCube Collaboration

February 27, 2020

1 Introduction

The IceCube Neutrino Observatory proposes to maintain the operation of the IceTop detector with a surface array of scintillator panels and radio antennas in a common station-based infrastructure to restore the full functionality of IceTop[1]. This array mitigates the effect of snow accumulation on the existing tanks, reducing the need for snow removal, and will improve the understanding of atmospheric backgrounds to IceCube's neutrino measurements. This effort can be accommodated within the current population of the yearly IceCube M&O activities.

This proposal completed a technical review by the IceCube Collaboration in Spring 2019. The funding for the scintillation detectors has been secured by a dedicated grant at the Karlsruhe Institute of Technology (KIT), Germany. The complete scintillation detectors can be produced at KIT during 2020 by utilizing existing production facilities at Fermilab (using KIT funds). The funding for the surface radio antennas is secured by a European grant whose submission was encouraged by the IceCube Executive Committee, passing a competitive scientific review and commencing in early 2019. To take advantage of the many synergies between the detector technologies with minimum additional deployment effort, it is important to deploy these radio antennas at the same time as the scintillators.

The science case and plans for the surface array were presented to NSF in a meeting on 12 Nov 2019. This document is the summary requested as result of this meeting and also provides answers to specific questions asked during this meeting. As detailed below, the surface upgrade is a necessary M&O activity to maintain the functionality of IceCube's surface array, IceTop.

2 Scientific and Technical Goals

As an upgrade to the existing IceTop detector, we consider a hybrid array of scintillator panels and radio antennas (Fig. 1). The addition of these surface detectors within the IceTop footprint serves IceCube's goals of understanding the sources of high-energy cosmic rays [1] and measuring the cosmic neutrino flux around 100 TeV. At about 100 TeV, the neutrino flux measured by IceCube shows an excess of events compared to what is expected by extrapolating the high energy astrophysical flux to lower energies. The excess may be related to sources which do not emit gamma rays, and can only be identified by accurately measuring cosmic rays and neutrinos. Around the same energy, the atmospheric and astrophysical neutrino fluxes are of similar magnitude, and disentangling the two components will help understanding the origin of the excess. Systematic uncertainties are

---

[1] Note that the proposed radio antennas for the surface array measure cosmic-ray air showers. This is distinct from in-ice radio detectors that aim to measure radio signals from ultra-high-energy neutrino interactions in the ice as well as having sensitivity to cosmic rays above 10^{17} eV.

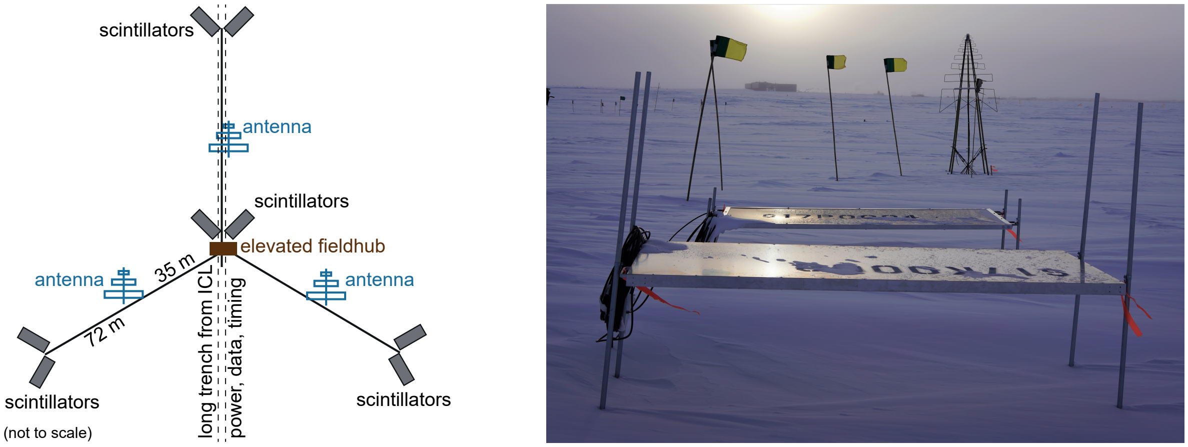

Figure 1: Left: layout of a scintillator station including 8 scintillators and 3 radio antennas. A single cabling network connects the elements of the station. Right: a prototype of a scintillator pair deployed in the 2018 season with one of the radio antennas in the background. No significant snow coverage or drifting was observed for either detector type.

currently limiting the measurement of cosmic ray in the PeV region of the spectrum, that produce the atmospheric neutrinos in the 100 TeV energy range (Fig. 2). The upgraded IceTop array is designed to substantially improve the measurements both in terms of flux and composition.

In addition to providing a better measurement of the cosmic-ray induced background, the upgraded IceTop will also provide a better handle on the atmospheric neutrino background by adding veto capabilities for the near-vertical events.

Radio detection of air showers provides high-accuracy measurements of the size and depth ($X_{\max}$) of the electromagnetic shower component with a 100 % duty cycle. Radio antennas thus hold the potential to transform IceCube into the most accurate detector for high-energy Galactic cosmic rays in the energy range from a few PeV to several EeV [3]. Such a boost of the total cosmic-ray accuracy of IceCube is a critical aspect in lowering systematic uncertainties for a better quantification of the atmospheric background to neutrino measurements. In particular, it will improve IceCube's ability to test hadronic interaction models [1], enable a cross-check of the IceTop energy scale, and provide a more accurate measurement of the cosmic-ray composition. Each of these elements currently contributes an uncertainty of at least 20 % to the measurement of the atmospheric neutrino flux. Furthermore, the hybrid surface array enriches IceCube's multi-messenger mission and adds discovery potential for Galactic sources by searching for mass-dependent anisotropies and PeV photons (Fig. 3)[2]. By determining the transition energy for each cosmic-ray species, it will be possible to better understand the total flux of extragalactic cosmic rays at each energy and the correlated astrophysical neutrino flux.

In particular, the goals of the surface upgrade include:

- Improving IceCube's measurement of the cosmic neutrino flux around 100 TeV, by providing a better understanding of the prompt and conventional atmospheric backgrounds of both muons and neutrinos. For this goal, the added accuracy of the hybrid array including scintillators and surface antennas is critical.

---

[2] At the South Pole, the constant elevation of 29° of the Galactic Center is within an ideal range for radio detection of air showers.

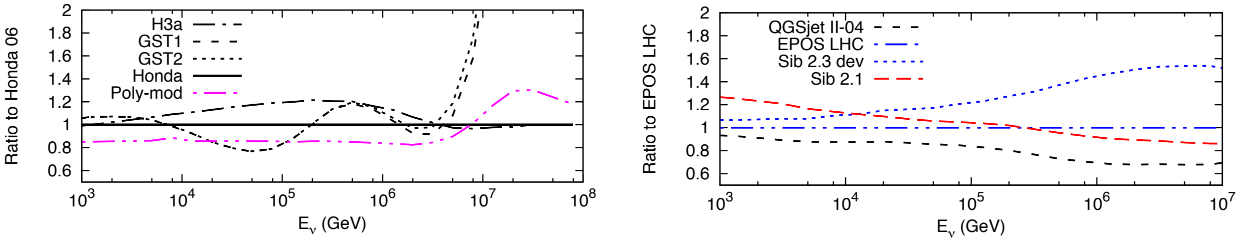

Figure 2: Uncertainties on the atmospheric neutrino flux as a function of neutrino energy. The primary cosmic ray energy is approximately 10-1000 times higher, depending upon mass. Left: the effect of different mass composition models [5]. Right: the effect of different hadronic interaction models [5]. Uncertainties on the absolute energy scale have a similar impact on the predicted number of atmospheric neutrinos (not shown).

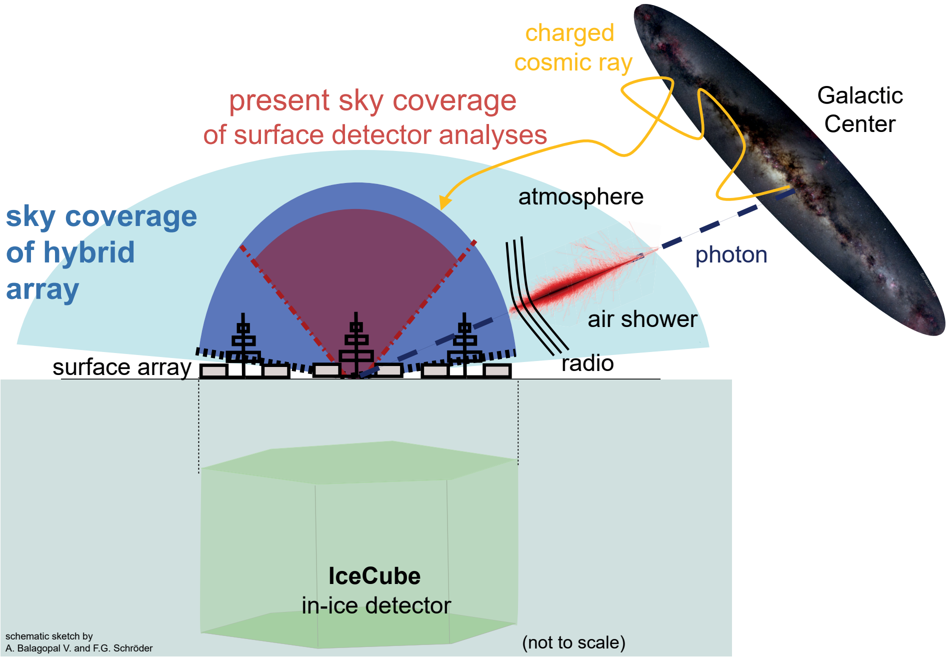

Figure 3: Sketch of the proposed hybrid extension scintillator and radio antennas that will maintain and improve IceTop's capability to characterize the atmospheric background to IceCube's high-energy neutrinos. The radio array will expand the sky coverage, bringing the Galactic Center into the field of view for multi-messenger studies, and will boost the accuracy for air shower detection, serving both cosmic-ray and high-energy neutrino measurements.

- Measuring the effect of snow attenuation on IceTop data, thereby improving the IceTop energy calibration and the interpretation of existing data.
- Recovering and improving the sensitivity to low-energy showers that are currently not detected by tanks buried under several meters of snow. By adding scintillators with a similar coverage as IceTop, the energy threshold at which the cosmic-ray veto becomes fully efficient is estimated to be a factor of 2 lower compared to the original performance of IceTop [2].
- Development and field testing of a new, scalable precision timing and high-speed communications scheme. The same scheme has been adopted in the IceCube Upgrade, with applications to potential future projects such as IceCube-Gen2.

The optimized scintillator array proposed here consists of 32 stations (Fig. 4), each with 8 detector panels located at 4 positions. The two panels deployed at each location are separated by 5 m, and each pair of panels is separated from the surrounding pairs by 72 m. All panels will be elevated from the snow surface on extendable poles and can be raised when necessary, mitigating snow management and drifting. The design foresees three radio antennas[3] per scintillator station, sharing a common infrastructure. The antennas feature an extendable stand and will be deployed along the same trenches put in place for the scintillators. The FieldHub, designed to distribute power and precision timing, and handle data readout, is located near the center of the station and will also be elevated with the ability to be raised for accessibility and ease of long-term maintenance.

3 Field activities

The full array can be split into three distinct parts for deployment, as shown by the different colors in Fig. 4. It is anticipated that only a small fraction of the installation (approximately 20%) would be completed before the 2022/23 IceCube Upgrade drill season. We estimate that five people can install approximately two to three stations per week. Based on this estimate, the installation of 32 stations will require $\sim$ 5 people (4 for the scintillators and the FieldHubs, 1 for the radio antennas) over 12 to 16 weeks, distributed over three to four seasons (see Table 1). While we estimate that in future years it will be possible to deploy three stations per week with five people on ice, we acknowledge that in the first season a longer time may be necessary to refine the installation procedure. All the panels, antennas, and the FieldHubs will be elevated at a height of 4 to 5 feet. We anticipate a need to raise each detector component once in the next decade due to snow accumulation.

The power consumption per station is approximately 40 W (including 10 W for the three antennas of the station), which amounts to a total estimated 1.35 kW for the full array. Each station requires approximately 1800 lbs of cargo (including 400 lbs for the antennas, their cables, and mounts). We propose to deploy up to 11 stations before the IceCube Upgrade following the shown in the top left map of Fig. 4. In addition, a one week buffer will be helpful in case of cargo or weather delays. We propose to distribute the installation over three seasons, as shown in Table 1.

---

[3] Three antennas is the minimum number required to reconstruct detected air showers.

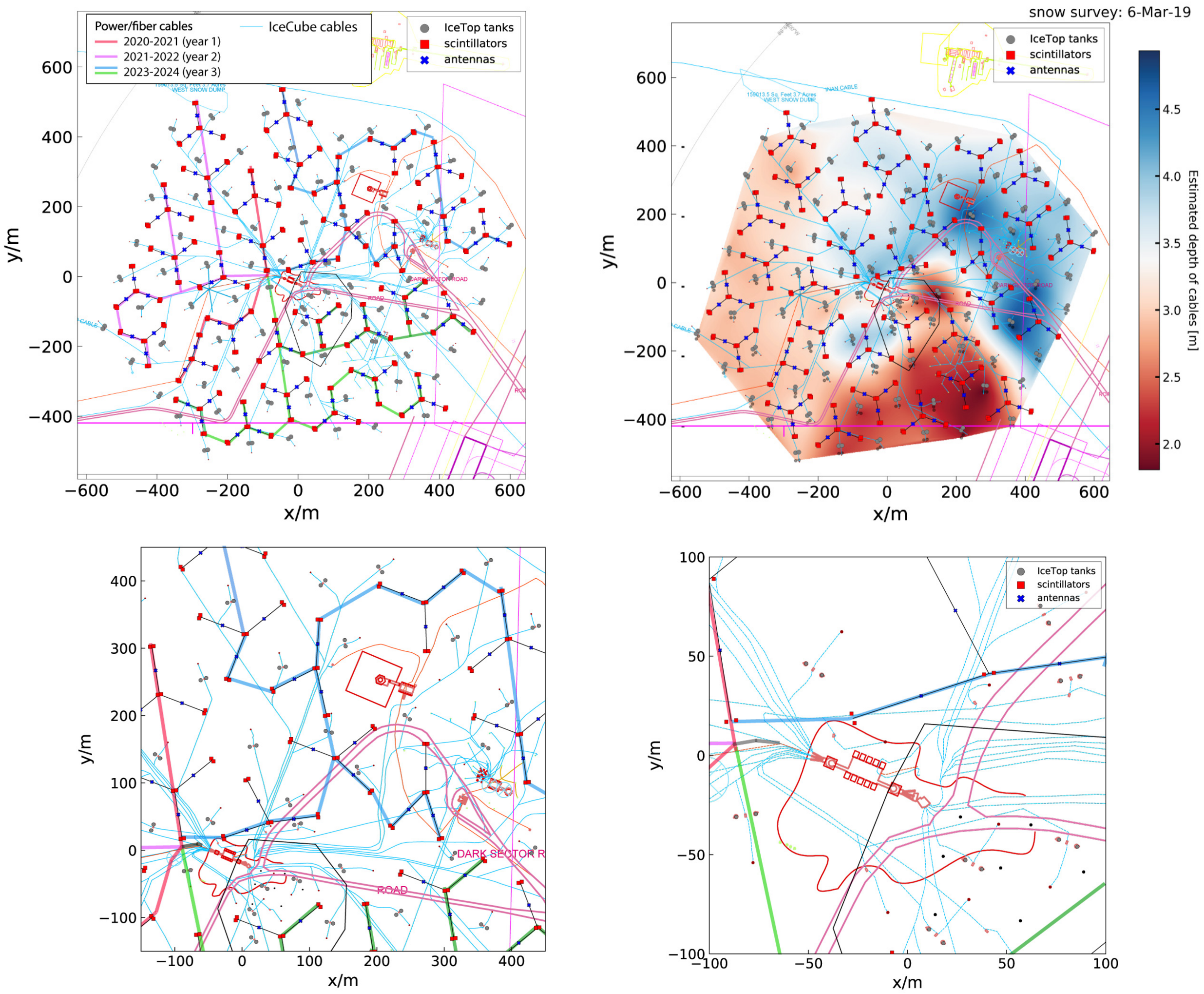

Figure 4: Upper left: proposed layout for the scintillator array. Sets of panels are separated by 72 m, and in each set two panels are deployed 5 m apart. A possible realization of related trenches is also shown. Upper right: measurements of the snow depths indicate that trenching to a typical depth of 3-4 ft is safe over the full array. Lower left: zoom-in to the region around the South Pole Telescope (SPT). Lower right: Zoom-in to the region around the IceCube Lab (ICL).

Table 1: Summary of approximate cargo, personnel and trenching lengths for the installation of up to 11 stations as highlighted in magenta and red in Fig. 4. A buffer for bad weather is not included.

season	#stations (up to)	cargo [lbs]	trenching [km]	highest pop
2020-21	4	7.2k	1.1	5 (2 weeks)
2021-22	7	12.6k	2.2	5 (3 weeks)
2021-22	0	0	0	0
2023-24	21	38k	6.7	5 (7 weeks)

References

[1] IceCube Coll., F.G. Schroeder *et al.*, *PoS(ICRC2019)418* 2019.

[2] IceCube Coll., A. Leszczyńska, M. Plum *et al.*, *PoS(ICRC2019)332* 2019.

[3] IceCube-Gen2 Coll., F.G. Schröder *et al.*, *EPJ WoC* **216** (2019) 01007

[4] IceCube Coll., A. Haungs *et al.*, *EPJ WoC* **210** (2019) 06009.

[5] T.K. Gaisser, *J. Phys.: Conf. Ser.* **718** (2016) 052014.

4 Appendix: Response to questions from the presentation at NSF, Nov. 2019

Who will deploy the surface upgrade detectors?
The detectors are deployed by IceCube's M&O population. A separate draft population plan covering the 2020–21 to 2024–25 seasons has been prepared for the NSF and is under review. This plan includes population for the surface array upgrade installation and maintenance.

Is the required 1.35 kW of power within the existing power budget of IceCube?
The power usage of the IceCube detector, not including ICL building power, is approximately 55 kW. As part of the ongoing maintenance of the IceCube electronics, we regularly install higher-efficiency computing nodes and power supplies that reduce this power load. As an example, during the 2019–20 season, we completed an upgrade of the DOM surface power supplies from units that were 81% efficient to more reliable units that are 89% efficient. This change alone has resulted in a 2.8 kW savings, more than enough to cover the modest power usage of the surface detector upgrade.

Under IceCube M&O, there are set services to be completed. How can the existing M&O support this without a new proposal?
Maintaining the operation of IceCube's surface array is a key part of the M&O tasks. Regular snow management was originally included for this purpose, but was stopped several years ago, which is why IceTop's performance is being continuously degraded by snow accumulation. The proposed array solves this problem, replacing the M&O task of snow removal above IceTop with the deployment of the elevated surface array. Therefore, we trade one M&O task by another one, fulfilling the original purpose in a more effective way.

What is the volume of the cargo, in particular the radio antennas?
The radio antennas and their mounts will be shipped in flat parts in a single box per station. The assembly is easy and contained in the estimated workload. The volume of the box for the three antennas and their mounts per station will be approx. $4 \times 7 \times 1\,\mathrm{ft}^3$ ($\sim 1.2 \times 2.2 \times 0.3\ \mathrm{m}^3$).

We've severed cables in the past because we assumed they were buried at a depth deeper than they were. Is there additional time and equipment support needed to be able to support hand-excavation near buried cables as well as the use of a hot-point high-pressure hot water jet to reduce risk of severing an existing cable?
We do not foresee the need for hand-excavation or use of a hot-water jet trencher. In the initial deployment region, with a 1m-deep trench, we have an additional safety margin of at least 2m over existing cables (Fig. 4). By deploying in the shallowest area last (in four years from now), we will gain an additional safety margin there.

What will be ASC's future responsibility to provide snow maintenance? Will the detectors pass across roads or be placed near existing structures?
The detector positions avoid roads and buildings. Given this, and the fact that all detector elements can be raised, we do not anticipate that additional snow management will be required. We address the possibility of induced snow drifting in the following question.

What is the impact of snow drifting on the array and surrounding structures?
With the existing prototype scintillators and antennas, we did not observe significant snow drifting beyond the normal annual accumulation. However, a final answer to the long-term impact of snow drifting will require the deployment of a larger number of stations and several years of experience. Mitigating the effect of snow coverage of IceTop requires an approximately uniform coverage of the full array, including the area north of the ICL. Nonetheless, we will avoid deployment of detectors directly next to the ICL or other buildings.

Will the cables accommodate future raises of the detectors and of the ICL?
We foresee 5 m of cable slack at the detectors and at the FieldHub, which should suffice for at least 20 years of operation. The cables connecting to the ICL enter via the cable towers using a service loop similar to the IceCube surface cables, so the ICL lifting strategy is not impacted.

What is the environmental impact of the surface upgrade and how does it fit into the IceCube assessment?
The surface array upgrade consists of elevated detectors on the surface and a copper and optical fiber cabling infrastructure connected to the ICL. All surface detectors can be removed at the end of detector operations. The buried cabling infrastructure is contained within the footprint of the existing IceCube array, which itself has an extensive network of buried cables, and thus does not impact an area not already considered in the initial IceCube environmental impact assessment.