Status of the Acoustic R&D Program in IceCube,
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The acoustic detection technology for ultra-high energy neutrinos was studied 40 years ago within the framework of the DUMAND project [1,2]. First laboratory measurements proved the predictions of the corresponding “Thermo-acoustic Model” to be right [3]. However, no large scale application of the technology appeared at that time.

30 years later acoustic R&D studies revived within the existing and upcoming neutrino telescope experiments BAIKAL, ANTARES, KM3Net and IceCube. It was estimated that acoustic signals from neutrino interactions in ice should be 7-10 times larger than in water [4]. Also salt [4] and permafrost [5, attached] could be favorable target materials.

Acoustic R&D in Icecube started in 2002. After successful development of acoustic sensors for ice applications [6, attached], the “South Pole Acoustic Test Setup- SPATS” [7, attached] was built, to check the theoretical estimates of acoustic ice properties at the South Pole in situ.

Below, a short overview will point to the basic goals, hardware components and deployment conditions of SPATS. The results achieved up to now and its consequences are briefly discussed. Detailed information about the subject is attached by several recent publications and talks at

http://www-zeuthen.desy.de/tauros/PRC/Apr-2010

A very dense summary of SPATS achievements is given in [8,attached].

Groups involved in IceCube acoustic R&D effort:

RWTH Aachen University, University of Califonia Berkeley, DESY, University of Gent, Ecole Polytechnique Federale Lausanne, Stockholm University, Uppsala University, University of Wuppertal

Global aim:

Detection of ultra high energy neutrinos to provide valuable information on astrophysics (cosmic ray sources), cosmology (relic particles) and particle physics (neutrino-nucleon cross section) [9].

An expected (guaranteed) source of such neutrinos with energies above 10^{17} eV is due to the interaction of highest energy protons with the cosmic microwave background radiation (GZK-effect, [10]) A corresponding steep decrease of the charged cosmic ray spectrum above $10^{19.5}$ eV has recently been observed by the HiRes and Auger experiments [11].

Estimates of the tiny fluxes of GZK neutrinos vary by an order of magnitude. The results from [12] are often used as a standard for the discussion of possible detector scenarios. In all cases detector volumes of at least 100 km^3 are required.

Several past and current efforts have, as their experimental goal, the observation of GZK neutrinos. Present best limits come from searches for radio signals from neutrino interactions. The most sensitive result is derived from data taken with the ANITA detector [13].

However, all experiments searching for weak particle fluxes must contend with unknown systematical effects and background separation. This may be overcome in the future by using a hybrid detector scenario. The radio technology could be complemented by adding acoustic detectors, searching for the sound produced by neutrinos above 10^{18} eV. Simulations of a hybrid detector around the optical IceCube neutrino observatory at the South Pole [14, attached], assuming a depth dependent acoustic attenuation length on the order of a few kilometers as predicted in [4], gave a detection rate of 20 neutrino events per year, half of them with coincidences between both methods.

Specific goals:

Estimates for the properties of ice at the South Pole were promising for the advantageous use of the acoustic technology for neutrino detection. The South Pole Acoustic Test Setup has been build to test basic predictions by corresponding measurements:

- *the speed of sound in dependence of the depth in the ice , important for the expected neutrino signal strength, event localization and reconstruction*
- *the basic acoustic noise level at the South Pole, determining the energy threshold of a future neutrino detector*
- *the number of transient acoustic signals which could mimic neutrino interactions, being a serious background source*

- *the attenuation length of acoustic signals in polar ice, determining the necessary density of acoustic sensors in the ice for a reasonable detection efficiency for neutrino interactions.*

The SPATS detector has been deployed in two austral summer seasons in January and December 2007. In addition a retrievable transmitter was used during three seasons in water filled IceCube holes before optical string deployment.

Hardware resources of the R&D group:

- Deployed in the ice: 4 strings, each with 7 acoustic stations down to 500 m (Fig.1)

- Retrievable transmitter (Pinger) (Fig.2)

- Aachen Acoustic Laboratory: Test site for detector development and calibration (with IceTop tank for ice preparation and laser for thermo-acoustic energy deposit)

- Wuppertal water tank: for calibration measurements

- Uppsala pressure vessel: for calibration and sensitivity measurements

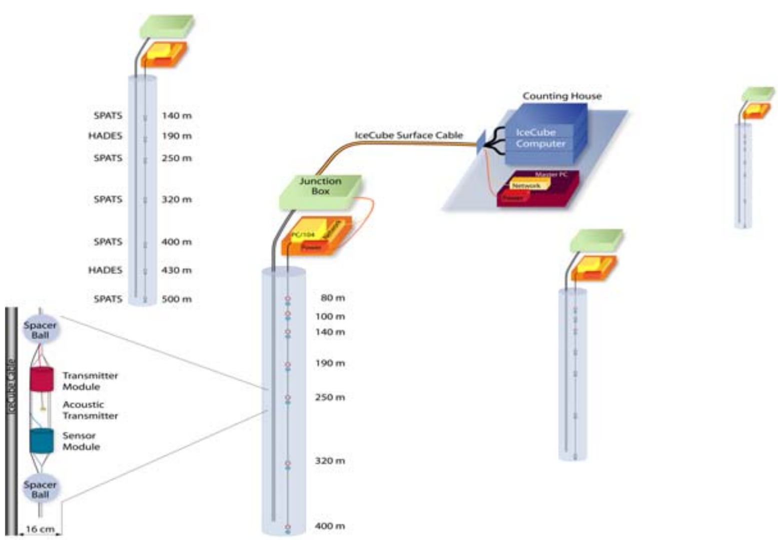

Fig. 1 Fig. 2

Deployment Geometry in IceCube:

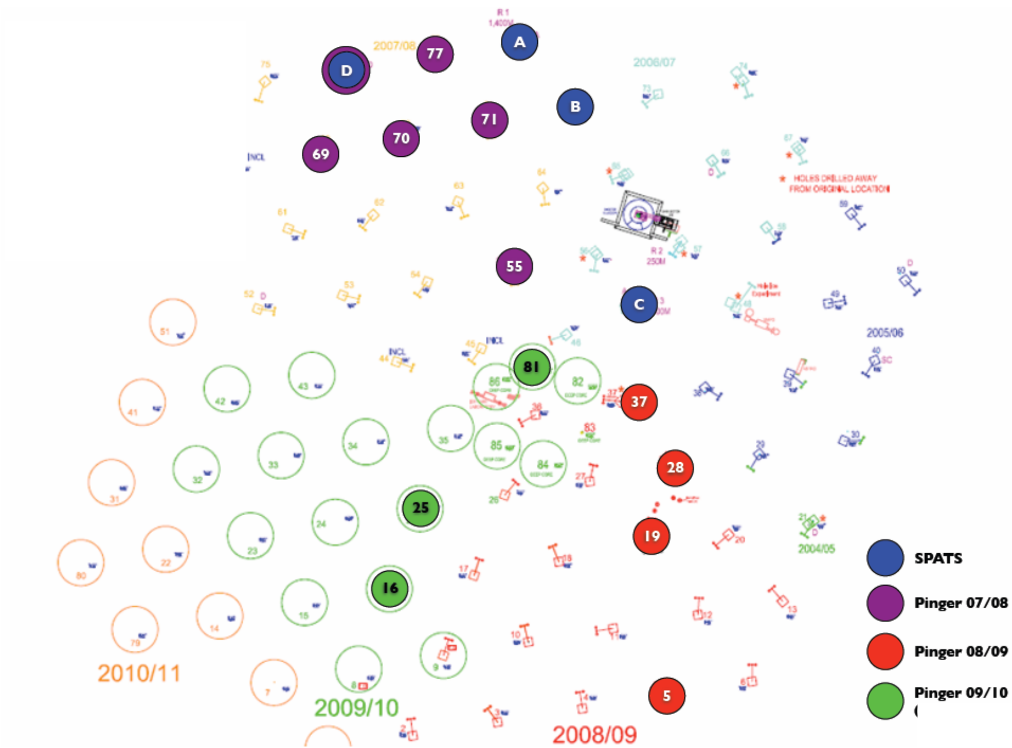

Fig. 3

Results on sound speed:

Results are based on data from Pinger runs 2007/8. Due to the free swinging of the Pinger in water filled holes, shear waves were produced at the water-ice interface.

SPATS measured for the first time pressure and shear wave velocities in South Pole ice below 200m:

The data below 200 m were fitted with

$$v = (z-375\text{m})*g + v(375\text{m})$$

Result for pressure waves:

$v_P(375\text{m}) = (3878\pm12)$ m/s

$g_P = (0.09\pm0.13)$ m/s/m

Result for shear waves:

$v_S(375\text{m}) = (1976\pm8)$ m/s

$g_S = (0.07\pm0.09)$ m/s/m

No significant refraction below 200 m has been observed

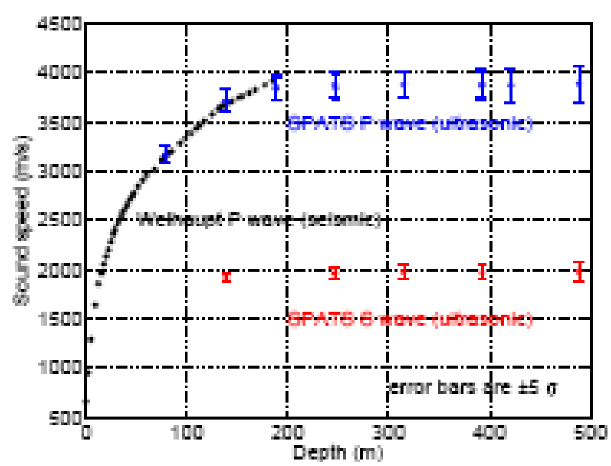

Fig. 4

Detaile information about the measurement is published in [15, attached]. The result is favorable for acoustic neutrino detection. The absence of large refraction effects will make event reconstruction easy.

Results on noise:

Noise data are measured since the first deployment in January 2007

- The noise increases slightly directly after deployment, indicating a sensitivity increase of sensors from water to deep temperature ice (Fig.5)
- Later the noise is very stable and Gaussian during the whole observation time of nearly two years (Fig.6)

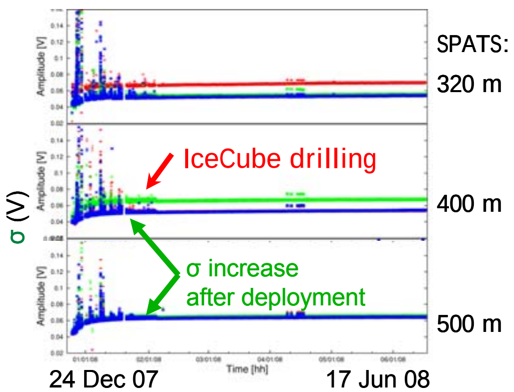

Fig. 5

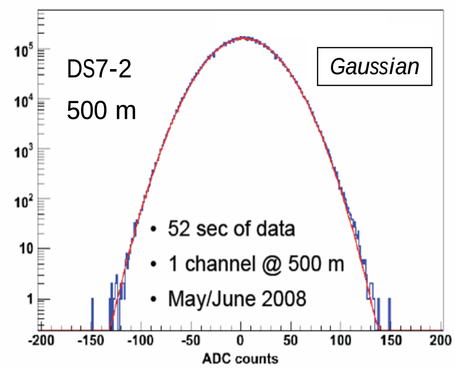

Fig. 6

The calculation of the absolute noise level in Pa is difficult because no in-situ calibration is possible. Results of laboratory measurements show:

- The sensitivity changes from 1 to 100 bar by less than 30%.
- The sensitivity increases by a factor 1.5 $\pm$ 0.2 from 0ºC to -50ºC in air.

More detailed results can be found in [16,17, both attached]

The impedance change from water to ice influences the sensor sensitivity as well. A new calibration effort has been started in the Aachen Acoustic Laboratory to study that. Unfortunately final results are available probably only end of 2010.

Results on transients:

Data on transient events are taken since end of August 2008 for 45 min of every hour. Event building is done offline with the following conditions:

- hit trigger: p > 500 mV
- cluster: all hits within 200 ms
- require at least one hit for each string per cluster

Number of observed 4-string events:
autumn 2008: ~20 events/day
drill period: strongly varying
since may 2009: ~ 1 event/day

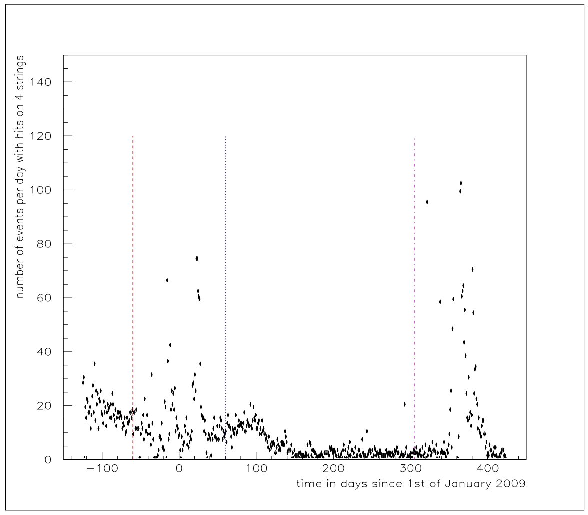

Fig .7

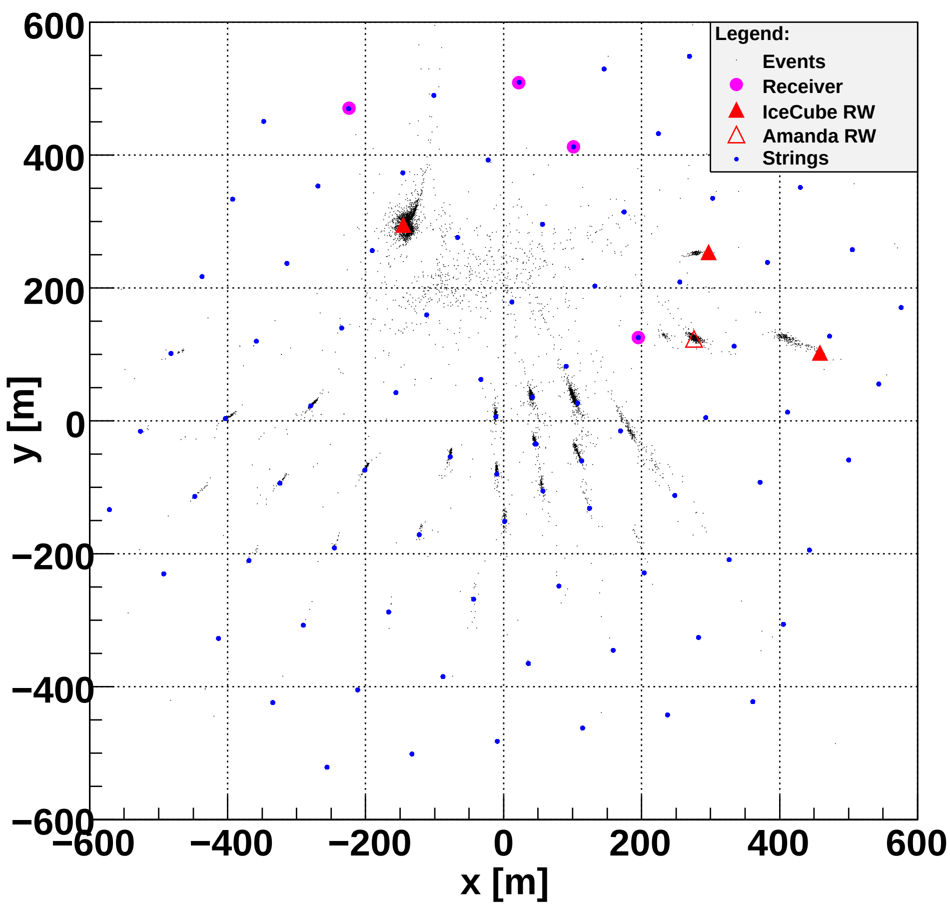

Fig. 8

All events are identified to be due to human activities. Sound source localization is possible with < 5 m precision in x and y (Fig. 8).

The following sources have been found:

- Four "Rodriguez wells" (RW) (water reservoirs for the drilling process)
  This type of wells has been introduced by Rodriguez and others in the early 1960s for water supply at an glacier in Greenland. For IceCube and its predecessor AMANDA this technique is used at the South Pole since mid of the 1990s.

  - Amanda (1999?)RW, still observed in ~150 m depth
  - IC 04/05-05/06 RW, still observed in ~150 m depth
  - IC 06/07 RW, heard until October 08 in ~50-100 m depth
  - IC 07/08 RW, heard until May 09 in ~50-100 m depth

- 8 holes during drilling and re-freezing in season 08/09
- 20 holes during drilling and re-freezing in season 09/10
-

The last two data sets allow to study the freeze-in process in some detail

Some recent results have been presented at the 2010 SPATS winter workshop March 8./9 in Lausanne [18, attached].

No events at all are observed from the surface as well as from outside the drilling region of the present IceCube 79 holes. A study is underway to derive a neutrino flux limit for a one cubic kilometer volume observed by SPATS .

Results on attenuation length:

Data with smallest systematical effects from Pinger runs 08/09 are compared to two other data sets from in-ice transmitters and transients:

Conditions of the pinger data from the season 0809:
- single sensor channels used
- 3-4 aligned holes used (Fig.3)
- pinger stopped at sensor depth

In this way systematic uncertainties on azimuthal and polar angular sensor sensitivities are minimized

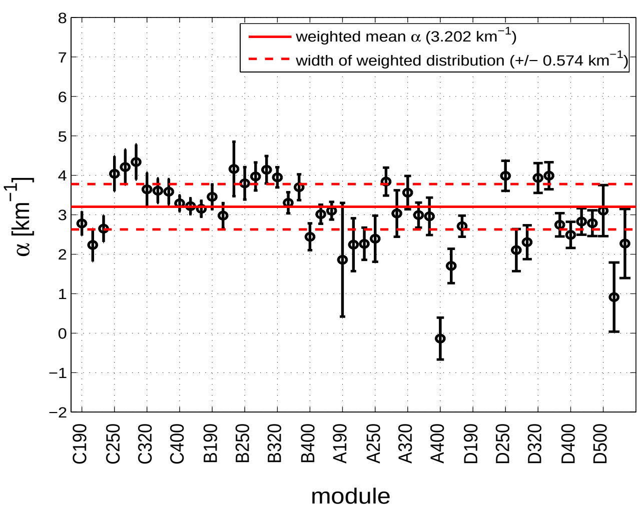

Fig. 9

The method with the smallest systematical uncertainties and the most sensor channels analyzed yields an amplitude attenuation coefficient α =3.20 +/-0.57 km^{-1} between 10 and 30~kHz, considerably larger than previous theoretical estimates. No significant depth and frequency dependence has been established. The results of the different analyses agree with an attenuation length of about 300 m with a 20 % uncertainty in the ice region studied.

Comparison of different results:

	# meas.	att. coeff./ km^{-1}	uncertainty / km^{-1}
Pinger (energy time domain)	48	3.20	0.57
Pinger (energy frequency dom.)	39	3.75	0.61
Inter-string (all leveles)	12	3.16	1.05
Inter-string(ratios)	1	4.77	0.67
Transients	13	3.64	0.29

Table 1

A detailed description of the attenuation length study is given in [19, attached].

Another set of Pinger runs was performed in December 2009 with the following goals:

- Measure the frequency dependence of the attenuation length, important to understand the attenuation mechanism.
- Measure the attenuation length in deep and shallow ice. Future projects may prefer shallow deployments.
- Measure the attenuation length on diagonal path and learn more about the ice structure and layering.

Data have been taken successfully. The data analysis is ongoing. Results can be expected in autumn 2010.

Consequences of present results:

The results on sound speed and transient events confirm previous expectations and satisfy the requirements for acoustic neutrino detection at the South Pole.

The absolute noise level which will determine the neutrino energy threshold of a future detector has still to be evaluated. Present estimates lack a solid measurement of the sensitivity change of sensors from water to ice. To clarify this, a measurement program is ongoing in the Aachen Acoustic Laboratory.

The measured attenuation length is more than an order smaller as predicted by previous theoretical estimates. Several reasons are under discussion to understand this difference assuming different behavior in scattering or/and absorption of acoustic waves in ice at the South Pole. New data about ice quality collected during the last Pole season will hopefully help to clarify the situation.

Previous optimistic results from Monte Carlo calculations for a 100 km^3 hybrid optical-radio-acoustic neutrino detector around IceCube [14, attached] are now obsolete. New calculations of this type should show what possibilities exist, still to reach the global aim of a scientific program to study ultra high energy neutrinos.

Recently a group of Physicists from IceCube and ANITA experiments has considered the potential of a radio UHE neutrino detector plane at 200 m below the surface [20, attached]. Looking at different options of this project it could be shown, that the addition of relatively few acoustic sensors - even in this very un-favored geometry for the technology – could give some additional information for events recorded by the radio array [21, attached]. The radio-optical overlap with IceCube was found to be negligible.

In an extension of this study different acoustic detector geometries have been studied with respect to string distances and lengths and global detector size [22, attached]. It could be shown, that a detector with 500 m string distance would work well. A deep detector with instrumentation between 200 m and 1200 m depth would be favorable in comparison with a flatter one with sensors only between 200m and 400m . In the last case a larger x-y extension is necessary – i.e. a larger number of strings – to observe the same number of events.

A detector of this type would have to be operated in any case in combination with a radio antenna array deployed in the same holes. Both arrays should be able to trigger each other. At lower energies (below10^{19} eV) radio array triggers would dominate, at highest energies the situation would be reverse.

Any new large scale detector would need a larger number of strings, i.e. bore holes. Present designs work with 100 to 1600 holes to be drilled to depth of at least 200 m to 400 m.The hole diameter is assumed between 10 cm to 15 cm. To deploy a complete detector in a reasonable time (i.e. 5 – 7 years) drilling has furthermore to be fast. An additional complication is the large distance between bore holes which most probably will not allow to work with a stationary drill camp per season. All these circumstances require to develop new drilling technologies. Some corresponding ideas have been suggested in [22]. They assume a quasi-robotic combined drilling and deployment scenario. This would allow to produce fully assembled strings at home and reduce manpower at the detector construction site.

Future of UHE neutrino detection and possible DESY involvement

The presently best limit for UHE neutrino detection comes from the ANITA radio antenna detector circling on a balloon around the Antarctic ice shield [13]. Recently, after data analysis from a second flight, the observation of two GZK neutrino candidate events with an expected background of one event was reported. This result was used to calculate a new neutrino flux limit, similar to the published one. A planned third flight will provide further information hopefully soon.

The field is otherwise dominated by another technique using the moon as a neutrino target searching with Earth or satellite based radio telescopes for signals from its surface. Corresponding Experiments are located in Europe (Numoon, Lofar), the US (GLINT), Australia (LUNASKA) and Russia (LORD) ,see [23]. All these experiments are either in an early stage, lack observation time or fight with background problems.

Two large scale radio detector projects are located in Antarctica: ARA [20] at the South Pole and ARIANNA [24] at the Ross ice shelf. Both are US dominated and only partially financed as R&D efforts by the US-NSF. During the next five years this situation probably will not change much.

In Europe UHE neutrino detection has been extensively studied within and around the KM3Net project with German and British leadership (see also [23]). Simulated large acoustic arrays in water gave promising results and seem to be technical feasible. Unfortunately no radio detector addition for signal identification and background reduction is possible in this case.

The hope that a large UHE neutrino detector could start to be built directly after IceCube construction and profit from existing hardware and logistic was not fulfilled. Therefore the corresponding R&D program has to be reconsidered concerning time and location limitations. Keeping in mind today's boundary conditions and needs, it seems that a large in matter UHE neutrino experiment requires a preparation time of at least ten years.

Agreeing, that the detection and study of UHE neutrinos remains an important scientific challenge, which, if successful, will give many important answers to particle- and astro-particle physics questions and keeping in mind the experience collected at DESY for the subject, the following options may be discussed further:

1) direct future: Finish IceCube UHE neutrino R&D program

- get experience in SPATS triggered event data taking mode with newly available DAQ
- finish SPATS data analyses and publish corresponding results

- join analyses of the AURA radio cluster data [25, attached], to answer same questions as with SPATS (refraction, attenuation, noise) for radio detector technology

Minimal necessary resources :

- 1/2 senior physicist
- 1 PhD student
- no hardware contribution

Duration:

- 3 years

2) mid term future: Join UHE detector project R&D at the South Pole (ARA) with adding acoustic sensors to the radio strings

Build SPATS2: 2*3 strings with ~4 sensors + 1 transmitter string per string

→ low noise detectors
→ high power transmitter
→ new front/end electronics and DAQ
→ common trigger with radio array

Possible with existing “Acoustic Neutrino Detection Group”
Pre-studies partly started at Lausanne and Wuppertal

Minimal necessary resources at DESY:

- 1/2 senior physicist
- 1 PhD student
- 1/3 electronic engineer
- small workshop capacity

Duration:

- 3 years construction and deployment
- ~2 years data taking and analysis

3) long term future:

Start to bring up an European initiative for a large hybrid UHE neutrino detector to be built in 10-15 years from now at the most favorable location.

References:

[1] G. Askaryan, et al., Acoustic detection of high energy particle showers in water, Nucl. Instr. and Meth. A 164 (1979) 267--278.

[2] J. G. Learned, Acoustic radiation by charged atomic particles in liquids: An Analysis, Phys. Rev. D 19~(11) (1979) 3293--3307.

[3] L. Sulak et al., Experimental studies of the acoustic signature of proton beams traversing fluid media, Nucl. Instr. and Meth. 161(1979)203

[4] P. B. Price, Attenuation of acoustic waves in glacial ice and salt domes, J. Geophys. Res. 111 (2006) B02201.

[5] R. Nahnhauer, A.A. Rostovtsev, D. Tosi, Permafrost - An Alternative Target Material for Ultra High Energy Neutrino Detection? , Nucl.Instrum.Meth.A587:29-34,2008
Attached as: *NIMA48046-Permafrost-2008.pdf*

[6] S. Boeser et al., Development of Glaciophones and Acoustic Transmitters for Ice, Int. J. Mod. Phys. A21S1 (2006) 107
Attached as: *Glaciophones.pdf*

[7] Y. Abdou et al., The South Pole Acoustic Test Setup, second draft (nearly complete), to be submitted to Nucl. Instr. And Meth. A
Attached as: *SPATStech_v2.pdf*

[8] R.Nahnhauer, Talk summarizing acoustic R&D goals and results for a vistit of the DESY research director, December 2009, Zeuthen
Attached as: *SPATS_Status-1209.pdf*

[9] A. Ringwald, Extremely energetic cosmic neutrinos: Opportunities for astrophysics, particle physics and cosmology, Int. J. Mod. Phys. A21S1:12-19,2006.

[10] K. Greisen, End to the Cosmic-Ray Spectrum?, Phys. Rev. Lett. 16 (1966) 748.
G. Zatzepin, V. Kuzmin, Upper Limit of the Spectrum of Cosmic Rays, JETP Lett. 4 (1966) 78.

[11] R. Abbasi, et al., Observation of the GZK cut-off by the HIRES experiment, Phys. Rev. Lett. 100 (2008) 101101.
J. Abraham, et al., Observation of the suppression of the flux of cosmic rays above 4 * 10^{19}eV, Phys. Rev. Lett. 101 (2008) 061101.

[12] R. Engel, D. Seckel, T. Stanev, Neutrinos from propagation of ultra-high energy protons, Phys. Rev. D64 (2001) 093010.

[13] P. Gorham, et al., New limits on ultra-high energy cosmic neutrino fluxes from the ANITA experiment, Phys. Rev. Lett. 103:051103, 2009.

[14] D. Besson, S. Boeser, R. Nahnhauer, P. B. Price, J. Vandenbroucke, Simulation of a hybrid optical/radio/acoustic extension to IceCube for EeV neutrino detection, Int. J. Mod. Phys. A21S1 (2006) 259--264.

[15] R. Abbasi et al., Measurement of sound speed versus depth in South Pole ice for neutrino astronomy. accepted for publication in Astroparticle Physics
Attached as: *spats_sound_speed_APP.pdf*

[16} F. Descamps et al., ,Acoustic detection of high energy neutrinos in ice: Status and results from the South Pole Acoustic Test Setup, Proceedings of the 31st ICRC, 2009, Lodz, arxiv:0908.3251
Attached as: *ICRC-09-1.pdf*

[17] T.Karg et al., Sensor development and calibration for acoustic neutrino detection in ice, Proceedings of the 31st ICRC, 2009, Lodz, arxiv:0907.3561
Attached as: *ICRC-09-2.pdf*

[18] R. Nahnhauer, Talk at the SPATS winter workshop, 8.-9. March 2010, Lausanne:
Attached as: *Lausanne-transients-0310.pdf*

[19] R. Abbasi et al., Measurement of acoustic attenuation in South Pole ice submitted to Astroparticle Physics, April 2010,
Attached as: *acoustic_attenuation-v8.4.pdf*

[20] A. Karle et al., Collaborative Research: MRI-R2 Instrument Development of the Askaryan Radio array, a Large-scale Radio Cherenkov Detector at the South Pole, Madison, August 2009
Attached as: *ARA-MRI.pdf*

[21] J. Berdermann, M. Carson and R. Nahnhauer, Possible acoustic additions to a radio UHE neutrino detector, IceCube internal note, July 29th, 2009
Attached as: *acoustic-hybrid-09.pdf*

[22] R. Nahnhauer, Design studies for an acoustic neutrino detector at the South,Pole, Talk at the SPATS winter workshop 8.-9. March 2010, Lausanne:
Attached as: *Acou-Det-Sim-0310.pdf*

[23] ARENA 2008, Proceedings of the 3rd International Workshop on the Acoustic and Radio EeV Neutrino Detection Activities, Rome, June 25-27, 2008
Nucl. Instr. and Meth. Suppl. V604, June 2009

[24] S. Barwick et al., ARIANNA: a new concept for UHE neutrino detection, Proceedings of the 2nd Workshop on TeV Astrophysics, August 28-31 2006, Madison, astro-ph/0610631

[25] H.Landsmann, G. Ruckmann, G. S. Varner et al., AURA – A radio frequency extension to IceCube, Nucl. Instr. and Meth. Suppl. V604, 70-75, June 2009
Attached as: *AURA-ARENA2008.pdf*