Prospects of Hydroacoustic Detection of Ultra-High and Extremely High Energy Cosmic Neutrinos

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Abstract. The prospects of construction of deep underwater neutrino telescopes in the world's oceans for the goals of ultra-high and super-high energy neutrino astrophysics (astronomy) using acoustic technologies are reviewed. The effective detection volume of the acoustic neutrino telescopes can be far greater than a cubic kilometer for extreme energies. In recent years, it was proposed that an existing hydroacoustic array of 2400 hydrophones in the Pacific Ocean near Kamchatka Peninsula could be used as a test base for an acoustic neutrino telescope SADCO (Sea-based Acoustic Detector of Cosmic Objects) which should be capable of detecting acoustic signals produced in water by the cosmic neutrinos with energies 10^{19-21} eV (e.g., topological defect neutrinos). We report on simulations of super-high energy electron-hadron and electron-photon cascades with the Landau-Pomeranchuk-Migdal effect taken into account. Acoustic signals emitted by neutrino-induced cascades with energies 10^{20-21} eV were calculated. The possibilities of using a converted hydroacoustic station MG-10 (MG-10M) of 132 hydrophones as a basic module for a deep water acoustic neutrino detector with the threshold detection energy 10^{15} eV in the Mediterranean Sea are analysed (with the aim of searching for neutrinos with energies 10^{15-16} eV from Active Galactic Nuclei).

I INTRODUCTION

In 1957 G. A. Askaryan suggested the use of ultrasonic and hypersonic emission from tracks of charged particles due to local heating in a medium for particle detection in dense media (Askaryan, 1957). Fifty years later, in the 21st Century, the hydroacoustic detection of ultra-high and extremely high energy neutrino interactions in the World's oceans may at last be developed to investigate problems of high energy neutrino astrophysics.

Since first detection of the atmospheric neutrinos with energies $10^9 - 10^{11}$ eV in underground neutrino experiments (Reines, *et al.*, 1965; Achar, *et al.*, 1965), the target mass scale of the instruments – underground neutrino telescopes – has grown to $\sim 5 \times 10^4$ tons (Super-Kamiokande). In fact neutrino telescopes have become universal instruments for investigation of the microworld (e.g., in the search for proton decay), as well as searching for cosmic objects (e.g., solar neutrinos, supernova neutrinos, WIMPS, monopoles, etc.).

However to search for ultra-high energy (UHE, greater than 10^{15} eV) astrophysical neutrino sources, sites of the most energetic processes (accelerators) in the Universe, neutrino telescopes of effective detection volumes a cubic kilometer or more (KM3) are necessary (Learned, 1993; Learned and Mannheim, 2000). A prototype deep underwater optical neutrino telescope in Lake Baikal does operate, prototypes in the Mediterranean Sea (NESTOR, Antares) and in the deep polar ice (AMANDA in the Antarctic) are under construction now.

Neutrino telescopes with a target scale greater than 1 km^3 have also been proposed for studies of the upper boundary of the energy spectrum of cosmic neutrinos. For example, if elementary particles of maximal (Planck) masses $10^{24} - 10^{28}$ eV do exist, their interactions and decays could produce neutrinos (and other particles) of superhigh (extremely high) energies (SHE, EHE) up to $10^{24} - 10^{28}$ eV (Markov and Zheleznykh, 1980). Speculations upon the unknown source of the observed highest energy cosmic rays have provided several current models, which include significant or even dominant neutrino fluxes. For example, in the framework of some GUT models with X-particle masses of 10^{23} eV and in topological defect (TD) models, calculations of cosmic neutrino fluxes with energies up to 10^{23} eV have been performed (Sigl, 1997 and these Proceedings; Kuzmin, these Proceedings and references therein).

Several alternative methods for studying UHE and EHE neutrino interactions have been discussed and studied: deep underwater acoustics (Askaryan and Dolgoshein, 1976; Bowen, 1977; Learned, 1979), radio wave neutrino detection in cold Antarctic ice (Gusev and Zheleznykh, 1983; Markov and Zheleznykh, 1986; Boldyrev *et al.*, 1991; Ralston and McKay, 1990; Zas *et al.*, 1991, 1992; Besson; Saltzberg; Seckel; Zas–these Proceedings) and the the Radio Astronomical Method of Hadron And Neutrino Detection (Dagkesamansky and Zheleznykh, 1989; Alvarez-Muniz; Gorham; Hankins–these Proceedings). The energy thresholds for radio and acoustic detection are a few orders of magnitude greater than $10 - 50$ GeV threshold typical for the deep underwater optical detection. However the target mass scale of such alternative detectors can be a few orders of magnitude greater than that of optical detectors because the fundamental signal attenuation length in the medium is given by tens of km for the acoustic signals, compared to less than one hundred meters for light or because of the huge mass of the lunar regolith. The calculations for RAMAND (Radio Antarctic Muon And Neutrino Detector) threshold have shown (Provorov and Zheleznykh, 1995) that a 1 km^2 RAMAND in central Antarctica should be sensitive to the predicted diffuse flux of neutrinos from Active Galactic Nuclei (AGN) in the energy interval $10^{14} - 10^{16}$ eV.

II INITIAL SADCO FOCUS: TO SEARCH FOR SHE NEUTRINOS

The bipolar acoustic pulse production arises from the rapid expansion of the region of material traversed by the neutrino induced particle cascade which ionizes and heats the medium. Unfortunately it is an inefficient process, transferring only a tiny fraction (order of 10^{-9}) of the neutrino energy to acoustic radiation (largely due to the smallness of the bulk coefficient of thermal expansion). An acoustic signal is emitted by a neutrino induced cascade mainly in the direction perpendicular to the cascade axis in a rather narrow solid angle. The angular thickness of the disk is determined by the transverse size of the effective emitting region (which for high energy particle cascades in water is of the order of a few cm) divided by the cascade length (roughly ten meters), or a few milliradians. The initial spectrum peaks at a few tens of kHz.

The signal spectrum at large angles and at large distances shifts to a lower frequency region of a few kHz (Figures 1 and 2 in Dedenko *et al.*, 1997). Lower frequencies, while costing dearly in amplitude, provide potentially dramatic gains in solid angle and range over which events may be observed. If SADCO could detect 1 kHz signals produced by SHE cascades at distances of 10 to 50 km its effective detection volume could be tens to hundreds of cubic kilometers. The key to success is antenna gain.

While acoustic detection of elementary particles was suggested by G. A. Askaryan in the 1950's it was not until twenty years later that the possibility of construction of a deep ocean acoustic detector to study UHE neutrinos was widely discussed. Even then it was not pursued because at that time the threshold was thought too high and there were no plausible sources of UHE neutrinos. It was thought safer to start with optical detectors which had guaranteed cosmic ray neutrino signals in the GeV energy range. More recently with the advent of larger optical neutrino detectors, and increased interest in UHE neutrinos (as from AGNs), a deep underwater neutrino telescope SADCO with threshold energy above 5 PeV was proposed to be deployed at a depth of 3.5-4 km in the Ionean Sea near Pylos, Greece, at the site of the NESTOR optical neutrino telescope (Karaevsky *et al.*, 1993; Dedenko *et al.*, 1995). The sensitive volume of the SADCO neutrino telescope would be greater than 10^8 m^3. With the most optimistic models, dozens of events per year might be seen from the Glashow resonant neutrino interaction (6.4 PeV). But the main attraction of SADCO is its ability to search for the SHE neutrino interactions ($E \geq 10^{18}$ eV) in a huge water volume (Butkevich *et al.*, 1996). The search for TD neutrinos should thus be one of goals for SADCO if the registration volume reaches to hundreds of cubic km.

III ACOUSTIC PULSES IN WATER CAUSED BY CASCADES WITH ENERGIES 10^{20}-10^{21} EV

We have performed updated calculations of the acoustic pulse production and propagation in the ocean. Neutrinos interacting with nucleons in water produce a lepton (electron, muon, tau-lepton or scattered neutrino) and hadrons (hadron cascades). The calculations of acoustic signals emitted by electron induced cascades were carried out and the comparison with acoustic signals due to hadron cascades was made. Acoustic emission is localized in a divergent disk of a few hundred meters thickness, which is perpendicular to the cascade axis.

Figure 1 shows calculations of acoustic pulses caused by an electron-hadron cascade with energy 10^{20} eV in sea-water (14°C temperature), scaled to a reference distance of 1 meter from the cascade core. Calculations were performed for different shifts from the shower maximum along the cascade axis.

At super-high energies the Landau-Pomeranchuk-Migdal effect (decreasing cross sections for pair production and bremsstrahlung) should be taken into account. Due to this effect the longitudinal development of the electron-photon cascade in water increases by tens and even hundreds of times compared to the cascades with energies less than 10^{15} eV. At a cascade energy of 10^{20} eV the cascade length increases up to 300m, at energy 10^{21} eV up to 1-1.5 km, the density of deposited energy decreasing by nearly 100 times compared to the Bethe-Heitler showers.

Figure 2a shows acoustic pulses caused by the electron-photon cascade with energy of 10^{20} eV in sea water and 14°C temperature at a distance of 1 meter from the cascade core. Calculations were performed for different shifts from the shower

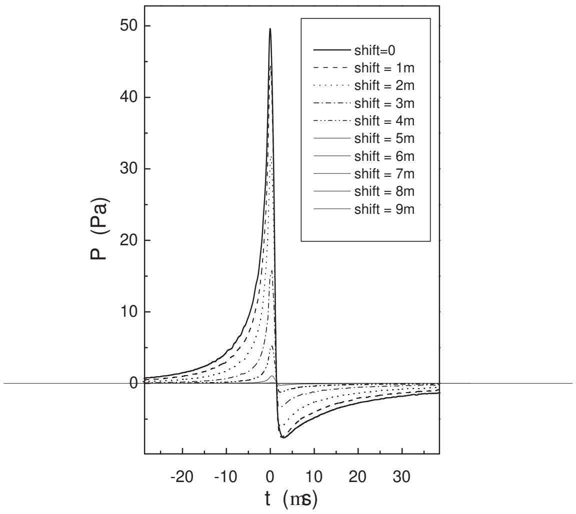

FIGURE 1. Acoustic pulses caused by the electron-hadron cascade with the energy 10^{20} eV in sea-water (14°C) temperature scaled to a reference distance of 1 meter from the cascade core. Calculations were performed for different shifts from the shower maximum along the cascade axis.

maximum along the cascade axis. Figure 2b shows pulses from electron-photon cascade with energy 10^{21} eV an equivalent distance of 1 m from the axis of cascade. The amplitude of the acoustic signal at this distance can be as much as 5 Pa. Strong acoustic emission is localized in a divergent disk of 200 m thickness, which is perpendicular to the cascade axis. The density of deposited energy in the hadron cascade would be much greater as its length is of a few tens meters and the amplitude of the acoustic pulse is approximately 50 Pa at 1 m distance from the cascade core and at 14°C, if the energy of the cascade is 10^{20} eV (Dedenko *et al.*,1999).

IV KAMCHATKA ARRAY AS A SADCO TEST BASE IN THE OCEAN

It is quite attractive to consider the use of already existing stationary sonar facilities, such as those placed in the Kamchatka region, as an acoustic detector of neutrinos (Karlik *et al.*, 1997; Dedenko *et al.*, 1997). This sonar has a large plane phased-array, with 2400 hydrophones. The array is installed on the sea shelf and connected with on-shore equipment by cable. The sector of view is 120°. The angular resolution in the horizontal plane is 0.8° in each of 150 (virtual) parallel fan-shaped beams. The vertical angular width is 7°. The gain of this array is 2500 at 1400 Hz.

Evaluations of the effective detection volume of the Kamchatka Array were performed for three cascade energies (10^{20} eV, 3.16×10^{20} eV, 10^{21} eV), real ocean conditions and for different probabilities of false alarm (false impulse signal) have been made. It is seen from the Table 1 that in summer time and under calm wind conditions, the Kamchatka array can have a significant detection volume (tens of cubic km) for searching for acoustic signals from 10^{21} eV cascades. On the basis of the Kamchatka array, we hope to develop a special measurement system for search for electron-hadron cascades induced by super-high energy (topological defects) cosmic neutrinos with $E > 10^{20} - 10^{21}$ eV and higher energies in water volumes of tens cubic kilometres and more.

Summer, wind velocity	False alarm probability		
	once per day	once per week	once per month
2 m/sec, calm	11/-/-	9.5/-/-	6.6/-/-
5.5 m/sec	3.9/5.3/81	2.2/4/-	1.3/2.2/-
10.2 m/sec	0.98/1.3/24	0.73/1.4/-	0.56/0.98/-

Table 1: Acoustic detection volumes in cubic kilometres for cascade energies10^{20} eV/3.16×10^{20} eV/10^{21} eV. ("-" denotes not calculated).

Acoustic signals emitted over a large solid angle in the ocean generally are complex when observed from some distance due to the guiding of sound around the depth of sound velocity minimum (the SOFAR zone). The small solid angle of

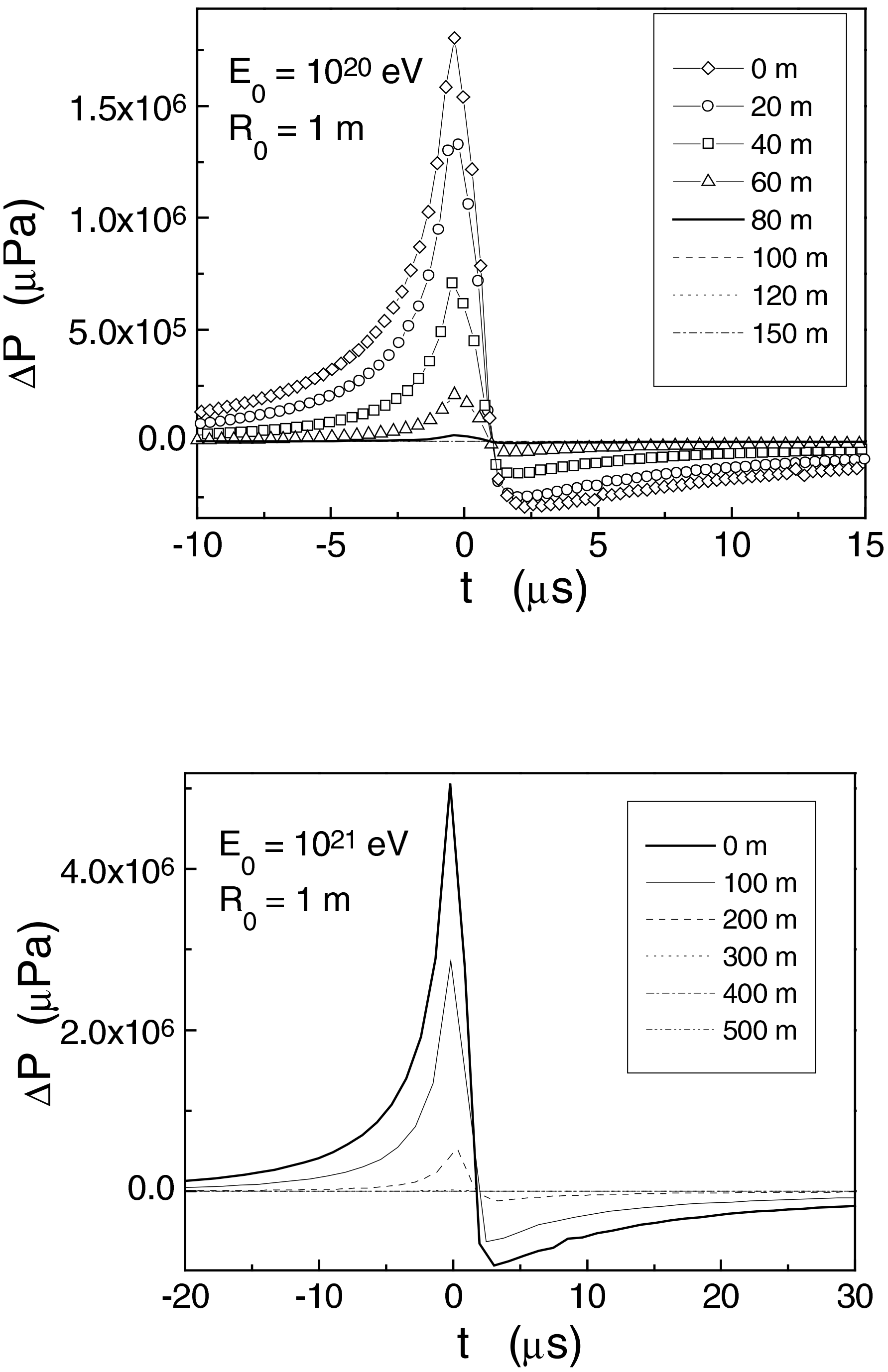

FIGURE 2. a) Acoustic signal from electron-photon cascade with the energy 10^{20} eV in sea water at temperature 14°C calculated for different shifts along the cascade axis. b) For 10^{21} eV.

peak emission from neutrino events may thus be employed to advantage in discriminating against background. Despite the fact that the frequency range of the existing sonar is not optimal (we would like higher bandwidth) the very large detection volume can compensate for the frequency deficit and greatly increases the detection probability of extremely energetic particles.

From the practical standpoint, the economic benefit of such an exploration is evident, because this sonar is in operation. Our suggested variant of acoustic detection of elementary particles can thus be very suitable for preliminary search experiments. Moreover this permits the development of different methodologies and algorithms for the detection and recognition of neutrino events. It is expedient to construct a special acoustical transducer suspended from a ship for simulation of neutrino impulse signals with different space-time parameters and calibrate the system. Little else is needed in terms of hardware.

V OPPORTUNITY FOR HYDROACOUSTIC MONITORING WITH AN OPTIMAL SADCO FREQUENCY BAND OF 10–20 KHZ

We have demonstrated, at least by computer simulation, the possibility to arrange a hydroacoustic detector of $10^{20} - 10^{21}$ eV neutrinos with a detection volume of some cubic kilometers using the Kamchatka array, when there is an underwater sound channel. However the frequency range of this array ($1.0 - 1.5$ kHz) is not optimal because of low signal/noise input ratio and impulsive noise from other sources of sound. But there is an opportunity for creation of acoustic detectors of even greater volume, using optimal frequencies (10-20 kHz) for signals which are generated by neutrino induced cascades with energies of about 10^{18-19} eV.

Without binding to any concrete site of deployment of the acoustic detector, it is possible to estimate the necessary parameters and the potential of such a system and to estimate the approximate volume needed for average hydro-acoustic conditions. The main sources of noise in this frequency band, taking into account that the receiving array is removed from a sea surface by hundreds meters and works in conditions of the underwater sound channel (USCH), are the noises of nearby navigation systems. With a high degree of probability (>96%) it is possible to consider that for the chosen frequency range the level of the this navigational noise is about $(1 - 2) \times 10^{-4}$ Pa. If the array amplification (concentration of acoustic array) is about 1500 -2000, that is close to the value considered by Karlik (Karlik *et al.*, 1997). After beamforming, the level of a noise will be lowered to $(2.5 - 5.0) \times 10^{-6}$ Pa in any angular beam in a horizontal plane and the angular resolution would be about $(1.5 - 2.0)^{\circ}$.

The neutrino-induced cascades with energy 10^{18-19} eV in the specified frequency range can generate acoustic pulses with pressure of 35 μPa over distances of 8–10 km. For the given level of noise the output signal/noise ratio at the specified array amplification will be more than 10 dB, which guarantees the probability of detection greater than 95%. Even if considering that the entire detection zone is concentrated in USCH of the width of 100–200 m (zone of the channel) the rough estimated volumes of the acoustic detector can be from 15 to 60 km^3, which is a rather large size. Note that approximately such USCHs exist in the Mediterranean Sea from May through November at depths of an array deployment from 200 to 500 meters. It goes without saying that the creation of such a hydroacoustic array represents a complex technological and economic problem, though soluble.

However it is expedient to consider a shorter and less expensive approach. At the end of the 1990s, in all leading countries there was a change of hydroacoustic underwater technologies, which for whatever reasons became ineffective. A typical example is the American Navy System SOSUS, which is now partially removed or used in civil applications. There is a similar situation in Russia. In particular, we can consider, for example, the hydroacoustic system MG-10M, which was used by the USSR Navy before and now is withdrawn from operation. The interest in this station (or to its receiving array) is due to the fact that this array has an amplification about 1700 at an average frequency of 15 kHz, i.e. approximately what is necessary for optimal neutrino detection. On the other hand, the receiving array of this system is not so large — it is a cylinder with a diameter of 1.6 meters and height of 1 meter. The array contains 132 hydroacoustic sensors directed in a vertical plane on a cylindrical surface. The mass of the array is about 1200 kg and it can work at depths up to 500 meters. The frequency band is (4–25) kHz, and its sensitivity is about 170 μV/Pa. The specified array of MG-10M practically completely satisfies the required parameters of the acoustic neutrino detector mentioned above.

Certainly, such array requires the development of a special platform for its installation on the bottom and a modern fiber optic digital network to transfer signals from elementary sensors to coastal equipment. However taking into account the existing level of development of underwater telecommunications cable systems capable of transferring hundreds of gigabits up to 400 km without regeneration, making such lines is a standard technological task. The advantages of this approach are that the technology of such arrays has been repeatedly confirmed. In particular the lifetime of such a system is more than 25-30 years. On the other hand, the necessary expenses for modernization of this array are not large compared to design and construction of a new hydroacoustic array.

The MG-10M array could be a basic module of the neutrino telescope with a "low" energy detection threshold of $(1-5)\times 10^{15}$ eV for searching for AGN neutrinos, in particular, electron anti-neutrinos with energies close to 6.4×10^{15} eV owing to the Glashow resonance reaction $\overline{\nu}_e + e^- \to W^- \to$ hadrons.

VI CONCLUSIONS

We have outlined a program for study of acoustic detection of neutrinos in the oceans employing existing sonar arrays with great amplification (~1500), e.g. the huge Kamchatka hydroacoustic array (frequencies less than ∼1.5 kHz) and the existing and available compact hydroacoustic system MG-10M (an optimal average frequency ∼15 kHz). First it will permit development of detection techniques in the real ocean, something not heretofore available to neutrino physicists. Moreover, the existing equipment should permit a useful physics exploration for neutrinos of extreme energies, not far above energies of cosmic rays already observed by extensive air shower arrays.

These investigations are supported by the RFBR-INTAS grant IR-97-2184 and the RFBR grant 00-15-96632. One of the authors (I.Zh.) gratefully acknowledges the RADHEP-2000 Organizing Committee for hospitality and support.

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