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To cite this version:

V. Bertin, V. Niess. Acoustic Signal Computations in the Mediterranean Sea. Acoustic and Radio EeV Neutrino detection Activities (ARENA 2006), Jun 2006, Newcastle, United Kingdom. pp.012019, 10.1088/1742-6596/81/1/012019 . in2p3-00182759

HAL Id: in2p3-00182759

https://hal.in2p3.fr/in2p3-00182759

Submitted on 6 Nov 2007

Acoustic Signal Computations in the Mediterranean Sea

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Abstract. We investigate various issues related to the thermo-acoustic signal computation from underwater cascades in a Mediterranean Sea environment and discuss their implications.

1. Introduction

We report on acoustic signal computations for the detection of ultra high energy neutrinos (UHE, 10^{18}+ eV) in a Mediterranean Sea environment. The very details can be found in the corresponding thesis work [1] or in a more compact form in [2]. We emphasize here on some aspect we think of importance.

The estimation of the pressure signal generated by an UHE neutrino showering in water goes through two main processes which are developed in the two next sections. We first estimate the energy deposition in UHE cascades, and then we compute and propagate the thermo-acoustic signal according to Askaryian's model [3]. Before going further one shall also recall that the more dense the energy deposition, the more efficient the thermo-acoustic emission mechanism is [4].

2. The Energy Deposition

UHE neutrinos are expected to interact in water by Deep Inelastic Scattering (DIS) on nuclei. According to Standard Model extrapolations [5], at UHE the scattering becomes quasi elastic since the secondary lepton takes away ~80% of the primary neutrino energy. However, whenever the secondary lepton showers, due to the Landau-Pomeranchuk-Migdal suppression effect (LPM) [6,7], the cascade energy is to be diluted on hundreds of metres. On the contrary, the less energetic hadronic fragments shower within ~10 meters, even at UHE energies [8], hence they result in a more efficient thermo-acoustic emission.

For our studies we focused on two limit cases. We modeled the energy deposition for charged current ν_e interactions, leading to a dense hadronic core followed by a diluted LPM elongated tail, and for neutral current ν_L interaction, with the sole hadronic core.

2.1. Energy deposition from GEANT4.

We first investigated the energy deposition in high energy (HE, $10^{12\text{-}15}$ eV) underwater cascades, from both electromagnetic and hadronic primaries, using the GEANT4 [9] package. Cascades of hadronic origins were simulated using primary charged $\pi^{\pm}$. Those are expected as the main product of neutrino DIS hadronic fragments [8]. A first striking feature is that as the primary energy increases, the primary hadronic cascades tend to mimic primary electromagnetic ones. This is due to an increasing production of π^0 during the hadronic cascading chain, decaying in 2γ. Hence, for many features, HE primary hadronic cascades can be considered as a superposition of a multiplicity of lower energy electromagnetic ones.

The longitudinal energy deposition from GEANT4 cascades follows a well characterized logarithmic law [10], in agreement with various studies. Extraordinary fluctuations are very seldom, affecting ~1% of cascades. More particularly, the depth of the maximum of the energy deposition was found to be consistent with observations of Extensive Air showers [11].

The lateral deposition energy was found to follow broken power laws with a close to ~1/r divergent behaviour at the core. These results are consistent with microscopic observation of cascades in lead plate-emulsion sandwiches [12]. It should be pointed out that this extremely sharp lateral energy deposition results from the ultra-relativistic kinematical boost factor, γ, of the primary particles in the cascade, collimating particles within a $\propto 1/\gamma$ characteristic angular aperture. Hence, to our knowledge it can only be encountered in HE cascades and not mimicked by forming proton or laser beam experiments.

From the GEANT4 simulation, it was also seen that the lateral distribution varies mostly with the depth along the cascades axis. Once rescaled by the depth of the maximum of energy deposition the core area of the lateral deposition of HE cascades follows an universal scaled behaviour, depending little on the primary nature and its energy. This is consistent with the fact that the cascade is approximately scale invariant at energies above $E_c \sim 50$ MeV, the critical energy in water.

2.2. Energy deposition in LPM elongated cascades.

For primary electrons, UHE cascades were simulated using a two step scheme detailed in [1,2]. The first cascade processes are simulated with a dedicated Monte-Carlo including LPM cross sections from Migdal [7] and relying on early-stopping. Then, in a second step the whole energy deposition is reconstructed by filtering the early-stopped cascade by lower energy cascade parameterisations, at first issued by GEANT4.

At HE, our results are consistent with GEANT4 simulated cascades. Above PeV energies the LPM effects becomes sensitive, leading to increasingly elongated cascades. Nevertheless, apart from this elongation, the longitudinal distribution keeps its well defined shape. When one reaches the UHE range, there are strong stochastic effects manifesting on long scales. It is no more representative to use a parameterization for the longitudinal energy deposition since extraordinary fluctuations becomes the norm. Hence, one must rely on Monte-Carlo techniques. In this UHE LPM regime, the typical length of the energy deposition increases as a square root power law with the primary energy, resulting in myriads of secondary cascades extending on hundreds of metres long.

As one reaches the UHE LPM regime, the lateral distribution depends less on less on the shower depth. It 'washes out', reaching a mean behaviour consistent with what is observed for lower energy cascades at the depth of maximum of energy deposition.

3. The Thermo-Acoustic Signal

The thermo-acoustic signal of a cascade is a pulse wave following the quasi instantaneous heating of a macroscopic, strongly anisotropic, water volume. In the following, we summarize the techniques developed in order to deal with this un-usual acoustic source, and then we discuss some results.

3.1. Thermo-acoustic signal computation.

The amplitude of the signal sharply depends on the coherent summation over the source energy density distribution. Hence, phase effects are most important for the Green function. In a Mediterranean Sea environment, with a smooth and linear sound velocity profile, (de)-focusing effects only amounts for the amplitude of the Green function to a few percent [1]. Consequently, the thermo-acoustic pressure field is approximated by integrating over the energy density distribution, $q(\vec{r})$, as follow :

$$p(\vec{r},t) = \frac{\alpha}{4\pi C_p} \frac{\partial}{\partial t} \int \frac{\delta(t-\tau(\vec{r},\vec{r}\,'))}{|\vec{r}-\vec{r}\,'|} q(\vec{r}\,') d^3\vec{r}\,' \qquad (1)$$

with α the thermal expansivity of water, C_p its heat capacity and where the travel time, $\tau(\vec{r},\vec{r}\,')$, from source point $\vec{r}\,'$ to observation point $\vec{r}$ is a solution of the ray equation [1].

Going further in the computation, we reduce equation (1) to a 1-dimensionnal integral by exploiting the axial symmetry of the energy deposition as well as the causality expressed by the Dirac δ-distribution. This scheme is particularly efficient due to the fact that the lateral distribution follows a universal law, allowing factorizing out its contribution in a global term. We refer to [1,2] for explicit expressions and additional details.

3.2. Propagation loss and Pressure Signal Shape

Due to the divergent core lateral distribution of the energy deposition, at the source, the thermo-acoustic signal from the cascade has an extremely high frequency content dominated by sub MHz acoustic frequencies. However, water is a physical medium and so it is refractant to the propagation of the highest frequencies. Therefore, the shape of the acoustic signal from cascades is strongly modeled by absorption loss.

Absorption loss is enhanced in sea water by the displacement of dissociation equilibriums of salts induced by the pressure [13,14], namely $MgSO_4$ salts below ~100 kHz, and boric acid $B(OH)_3$ below ~1 kHz . In order to account for phase effects, as well as for the transitions in absorption due to chemical dissociation equilibriums, we used a complex absorption coefficient, derived from [13] with updated inputs from field measurements of [15]. In the time domain, the chemical contribution to absorption of $MgSO_4$ salts results in a dampening and broadening by a factor of ten of the impulse response for distances larger than ~100 m. Below this 100 m range, the acoustic signal from cascades is in very near field conditions with a quasi monopolar pulse shape of very short ~1 µs duration. Therefore, there is a point to point correspondence between the measured pressure field and the lateral source energy deposition in 'regard'. However several hundreds kHz to MHz frequency bandwidth transducers are required to fully exploit this property.

At kilometric ranges the shape of the signal results from an extended source area. Hence, it strongly depends on the longitudinal distribution of the energy deposition. In addition, absorption loss now models the pulse shape resulting in a pulse duration increasing with the square root of range, *r*, as $\Delta t \approx 14\ \mu\text{s}\sqrt{r/1\ \text{km}}$. For compact hadronic cascades the pressure pulse becomes bi-polar and the wave front reaches pseudo-far field conditions with a circular curvature and a slight angular aperture. However, whereas the wave front curvature follows a regular circle above 1 km, the angular aperture smoothly broadens with range, from ~0.2° to an asymptotic value of ~0.5° at tens of kilometres.

For extensively LPM elongated cascades, the pressure pulse maintains approximate near field conditions over all practical observation ranges. The pressure pulse is a fuzzy image of the stochastic longitudinal energy deposition. The pulse shape is bi-polar but with a tendency for strong asymmetries. The characteristic duration can also be enhanced by factors of ~2-3 since a very extended source area contributes to the signal.

4. Conclusion and Discussion

The acoustic signal of cascades was computed for both compact hadronic cascades and LPM elongated extensive energy depositions. As compared to previous studies we took into account the extremely high frequency content resulting from the sharp lateral energy deposition and, consistently, the transition in absorption for frequencies above 100 kHz. Resulting from the high frequency content, we predict enhanced pressure pulses, by a factor ~2, with a more asymmetric shape. Particularly, below the 'chemical dampening' at 100 m, for the 6.3 PeV Glashow resonance significant ~1 mPa amplitudes are achieved with mono-polar pulses of μs duration. At these short ranges, measurements of the acoustic field would allow very clean imaging of the energy deposition in the cascade. Nevertheless, little is known about the ambient acoustic noise at such high frequency ranges.

Our computations allow comparison of the geometric efficiency of detection for ν_e charged current LPM elongated cascades and ν_L neutral current interactions. We found that even for ~100 m long LPM tails the electromagnetic part contributes most significantly, by factors of ~2-3, to the detection volume. This is due to the fact that the dilution of the energy is compensated by the large energy transfer to the electron and by a weaker geometric attenuation of the pressure field since near-field conditions are maintained. It should also be pointed out that in our computation we used a 'maximal' LPM elongation. At extreme energies, 10^{20+} eV, as the bremsstrahlung and pair creation cross-sections get to a few mbarn, the LPM tail elongation should be confined by new processes playing in, as photonuclear processes [16,17].

From our pressure field computations we estimated the sensitivity to astrophysical fluxes for a benchmark hydrophone detector, taking into account refraction and boundary limitations. We found that the sensitivity improves with energy by almost 3 orders of magnitude in the UHE range, reaching a plateau value at extreme energies of $E^2\phi \approx 3 \cdot 10^7$ eV for a $1/E^2$ flux. This value is sensitive to the medium boundaries, in particularly the water depth which was to be 2.5 km. Hence it could be considered improvement by site location optimisation.

Depending on the physics goal, to our mind the acoustic detection method can find applications either at PeV energies in complementing a Cherenkov detector for the observation of cascades, and studying their physics, either at extreme energies where some insight can be get on the physics at these extremes from tens of acoustic detector units. These two goals can not be achieved by a single design. There require very different solutions for geometric optimisations and frequency bandwidths.

Acknowledgement
We thank the CPPM ANTARES team for financial support and our British colleagues for successfully organizing this Workshop.

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