STATUS REPORT ON THE ANTARES PROJECT

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ABSTRACT

ANTARES is a deep-sea neutrino telescope project, leading to the construction of a detector with an effective area of 0.1 km^2. The extensive study of the site that has been achieved by the collaboration will be summarized in this paper. For the first time, a line connected to shore via an electro-optical cable was immersed for several months and the data collected allowed the assessment of several aspects of the detector as well as the reconstruction of the first muons detected in the Mediterranean sea.

1. Introduction

The ANTARES (Astronomy with a Neutrino Telescope and Abyss environmental RESearch) project is a European collaboration involving physics laboratories from France, Italy, the Netherlands, Russia, Spain and the United Kingdom, as well as sea science experts, which aims at the construction and deployment of a deep-sea neutrino telescope [1)] in the Mediterranean Sea. It will use an array of photomultiplier tubes to detect the Cerenkov light emitted by muons resulting from the interaction with matter of upgoing high energy neutrinos.

The site chosen for the deployment of the detector is located 40 kilometers off the coast from Toulon, in the South of France, at a depth of $\sim$2400 m (see figure 1). This site benefits from an excellent marine infra-structure. Cores were taken which showed that the sea bed is adequate for the deployment of a detector. A special emphasis has been put on the study of the optical properties of the site, since they contribute to the determination of the design and performance of the detector. Several measurement systems have thus been designed by the ANTARES collaboration and utilized several times over the past 5 years in order to quantify *in situ* the parameters of light transmission, the deep sea background light and the fouling on glass surfaces. The main results from these studies are detailed hereafter.

The location of the chosen site ($42^\circ\ 50'$ N, $6^\circ\ 10'$E) allows a sky coverage of 3.6π sr, and an 0.6π sr overlap with the AMANDA neutrino telescope that will allow cross-checks over possible point sources. In addition, being in the northern hemisphere (and thus sensitive to neutrinos coming from the southern hemisphere), the ANTARES

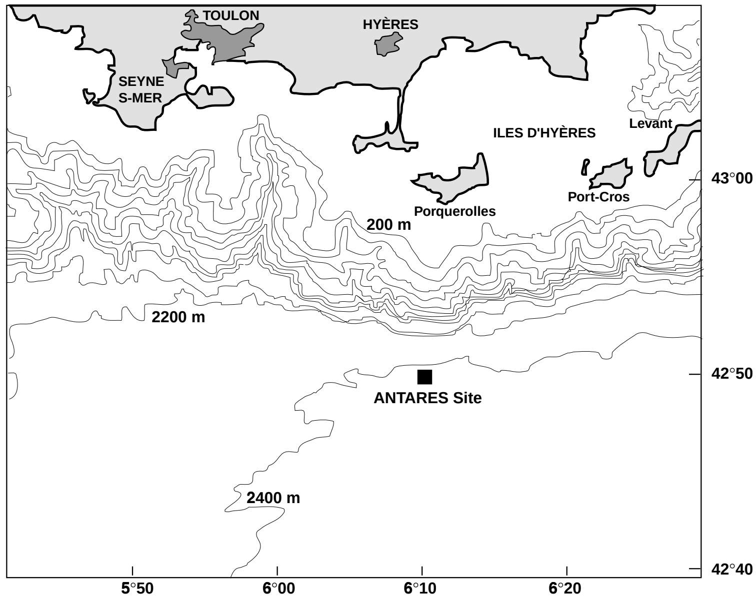

Figure 1: Site chosen for the deployment of the ANTARES under-sea neutrino telescope.

telescope will be able to survey the Galactic center.

2. Site assessment

About 30 autonomous strings have been designed and deployed for the study of the water optical properties in the ANTARES site. All measurements and survey to date confirm that the properties of this site satisfy the constraints of the ANTARES physics program. It is planned to explore other sites as well, in particular off Sicily in collaboration with the Italian NEMO project, to search for the optimal site for the future km^3 neutrino telescope.

2.1. Optical background

The design of the detector architecture as well as the trigger logics and the electronics should take into account the presence of background light pulses which will also affect the quality of the reconstruction of the events. Detailed investigation of the phenomenon and of its seasonal variations on the ANTARES site has been pursued[2)].

The background light is observed to consist of two components (see figure 2):

- a constant contribution from the β-decay of ^{40}K, naturally present in the sea salt ($\sim$ 60 kHz for a 10 inch photomultiplier tube),
- short bursts of a few ms rise-time which decay typically within 1 or 2 seconds, with counting rates reaching tens of MHz. These bursts probably come from

the light emission of living organisms in the deep sea. They induce a dead time on the PMTs smaller than 5% of the time; affected PMTs are randomly spread over the entire detector, due to the negligible correlation of such bursts beyond a few meters.

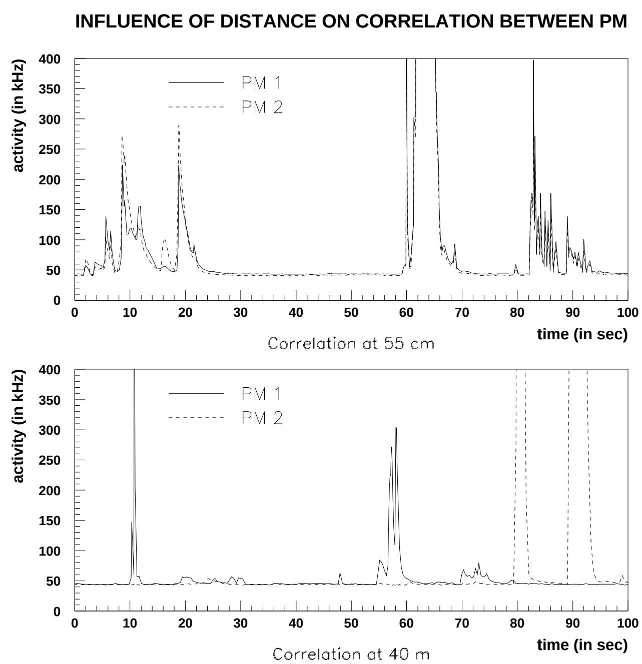

Figure 2: Example of background rates (on 8″ PMTs) illustrating the strong correlation between the counting frequencies of modules located 55 cm apart as opposed to the negligible correlation for modules 40 m apart. The two behaviors described in the text are clearly visible.

2.2. Fouling on glass spheres

When exposed to sea water, the surfaces of optical modules are fouled by the combination of two processes: living organisms, mostly bacteria, grow on the outer surface, and sediments fall on upward-looking surfaces. While the bacterial growth is expected to be almost transparent, sediments will adhere to it to make it gradually opaque. Fouling is expected to be site-dependent as the bacterial growth decreases with depth and the sedimentation rate depends on local sources of sediments as nearby rivers.

Fouling rate measurements are crucial for a long-term project planning to leave optical modules immersed for several years. Although the loss in transmission efficiency can be as high as 40% at the upper pole of a module after 30 days of immersion, the fouling is significantly reduced for polar angles larger than 50 degrees (see figure 3). At the equator, fouling induces a transmission loss of 1.5% after eight months of immersion, upper limit on the fouling expected on the actual detector where optical module axes will be oriented at a polar angle of 135 degrees with respect to the zenith.

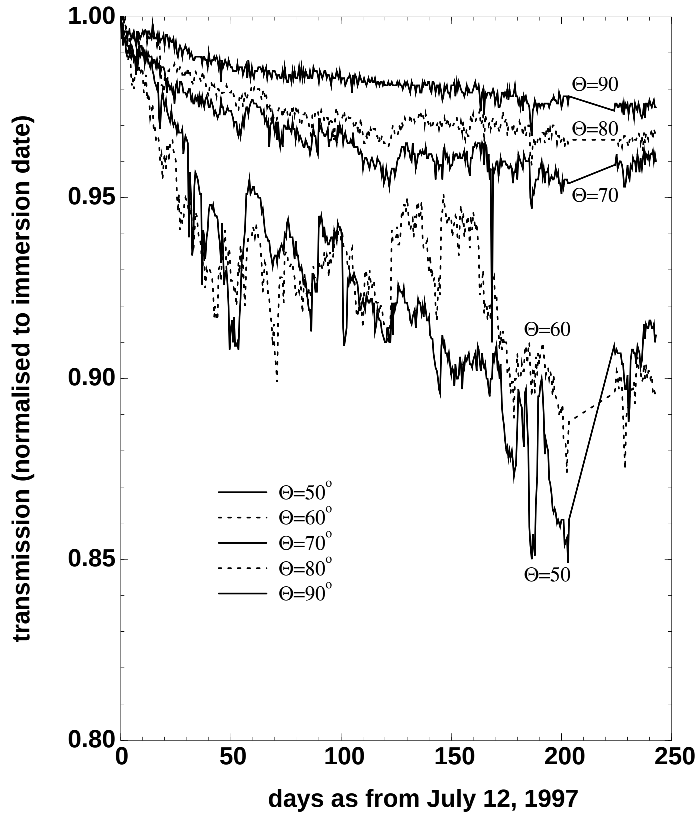

Figure 3: Fouling measurements near the equator of a glass sphere.

2.3. Water transparency

The water transparency affects the muon detection efficiency, while the amount of scattered light determines the limit on the angular resolution of the detector. A setup allowed the measurement of the arrival time distribution of photons emitted by a pulsed isotropic LED source at a wavelength of 370 nm (UV) or 470 nm (blue) and detected at two different distances (24 m or 44 m) by a 1″ photomultiplier tube. Such distributions are shown in figure 4.

For a source-detector distance of 24 m, 95% of the photons reach the detector within a time spread of 10 ns in blue light, and 30 ns in UV light. This small spread implies that scattering is essentially negligible in the ANTARES site. A thorough photon tracking Monte Carlo simulation of the data gives an absorption length in the 55 m range (resp. 25 m) in blue (resp. in UV), and an effective scattering length —

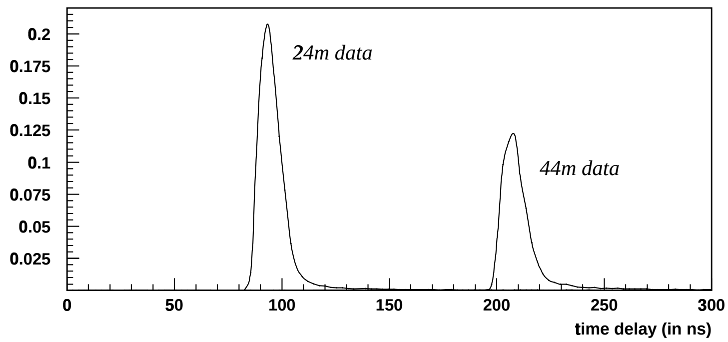

Figure 4: Time distributions in blue light of photon arrival times for source-detector distances of 24 m and 44 m.

defined as the ratio of the scattering length by $1 - \langle \cos\theta \rangle$ where $\langle \cos\theta \rangle$ is the average cosine of the scattering angle — in the 300 m range (resp. 120 m) in blue (resp. UV).

3. ANTARES demonstrator line

From November 1999 to June 2000, a demonstrator string was deployed at a shallower site (1100 m) where a 37-km long electro-optical cable was available before purchase of the final one. This is the first line controlled and read-out for a long period of time from shore. It comprised 16 detection storeys spread over a total length of 350 m, the bottom seven storeys being equipped with 1 PMT each for muon track detection. The other spheres contained other instrumentation. Unlike the 0.1 km^2 design, the demonstrator optical modules had their PMTs oriented horizontally for an increased sensitivity to down-going muons. The acoustic positioning system was implemented, allowing the first full scale testing of the system foreseen for the 0.1 km^2 detector.

3.1. Acoustic positioning system

Triangulation was performed between 3 range-meters regularly placed along the line and 4 acoustic transponders deployed separately on the sea bed around the string base. Relative distances between any two elements were measured with accuracies better than 5 cm, well within specifications, and used to reconstruct the line shape. Absolute positioning of the detector was obtained with a precision of ~ 1 m. Precise triangulation (with a range-meter located on the boat and calibrated with a GPS) requires precise knowledge of the sound velocity profile from sea surface to floor.

In addition to this acoustic system, tilt-meters and compasses distributed along the string allowed the reconstruction of the string shape and movements. They revealed a line shape (see figure 5) in agreement with that derived from the acoustic system, showing that although there were high currents during most of the period, the string remained straight and inclined at an angle of only 2.5 degrees with respect to vertical, with negligible twist along the line.

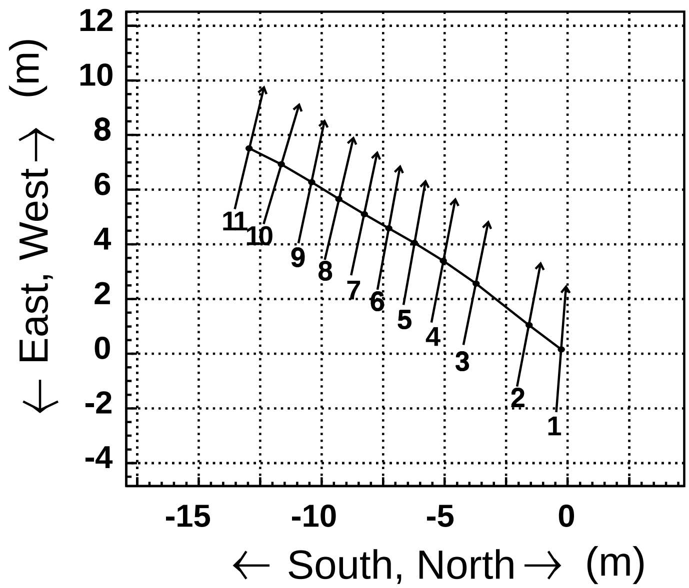

Figure 5: Top view of the demonstrator string. Points indicate the reconstructed position of the tilt-meters, showing the small inclination with respect to vertical and the fact that the line remained almost straight; arrows indicate the measured magnetic heading, showing no twist along the string.

3.2. Atmospheric muon events

In addition to the assessment of the acoustic positioning system foreseen for the 0.1 km^2 detector, the demonstrator string allowed to test the recording of data through a 37 km long electro-optical cable as well as the validation of the muon reconstruction software with the observation of the first down-going muons.

Over 50000 7-fold coincidences were recorded. Although the 1-dimensional information available with a single string does not allow proper 3-D reconstruction, a hyperbolic fit to the photon arrival time on each of the 7 PMTs as a function of PMT height, as illustrated in figure 6, yields the track zenith angle. The boxed hit most likely comes from the luminescent background described in section 2.1. It is identified as such by the reconstruction program (on a timing basis) and is filtered out for the fitting procedure.

Unfortunately, the atmospheric showers from which the muons originate produce a significant fraction of the demonstrator signal in the form of parallel muons, which dominate the event set at the reconstruction level. Although the fraction of multi muons in the detector is only 16.5% (the average multiplicity is ~ 3), it reaches 76%

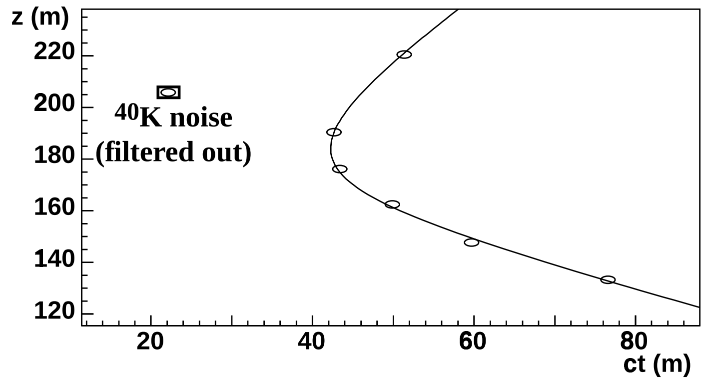

Figure 6: Fit of the PM height as a function of photon arrival time, yielding the muon trajectory zenith angle. One hit is not in time with the others and is filtered out by the analysis.

of the events (with an average multiplicity as high as 13) after requiring that the event be fitted. This high multi-muon contribution degrades the (polar) angular resolution obtained with the demonstrator line.

Over 1350 events are reconstructed per day of data. Figure 7 illustrates the angular distribution of the data, compared to the expected distribution from a Monte Carlo simulation which includes the contributions from both single muons (25%) and multi muons (75%). The shape reproduces that observed in the data sample. The peak near the equator — seen both in the data and in the Monte Carlo — is due to a ghost solution in the fit, separated from the real solution by twice the Cerenkov angle, as explained in figure 8. This artifact should be greatly reduced by the use of the information on the hit amplitude and by the use of more PMTs spread on a 3-D network, as in the 0.1 km^2 detector.

4. ANTARES 0.1 km^2 detector

The ANTARES 0.1 km^2 detector will consist of 10 to 14 lines (depending on the finances available for the construction) containing 30 storeys with a separation of 12 m between them, each containing a set of 3 PMTs oriented away from each other at an angle of 45 degrees below the equator to be mostly sensitive to neutrinos having gone through the Earth. Each line will be roughly 60 m away from its closest neighbors and connected to shore via a junction box and a 40 km long electro-optical cable.

4.1. Scientific program

The scientific program covers the search for phenomena involving neutrino detection over a large range of energies. At low energy (threshold of $\sim$ 5 GeV set by the separation between storeys and the muon energy loss by ionization in water), atmospheric neutrinos allow the study of oscillations with a baseline length up to the

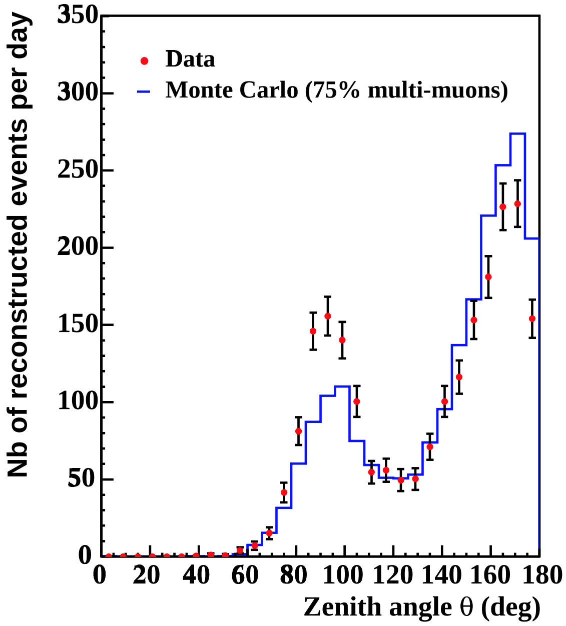

Figure 7: Angular distribution of the reconstructed muons trajectories, for the Monte Carlo (plain histogram) and the data (points with error bars).

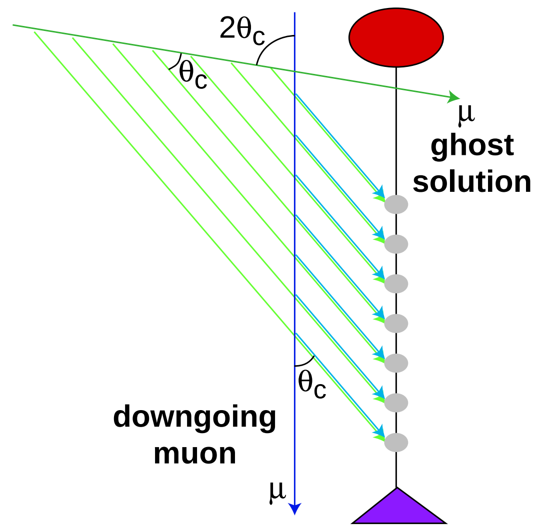

Figure 8: Illustration of the ghost solution at twice the Cerenkov angle. the time delay of the photons reaching the PMTs of the demonstrator line is the same in the two configurations.

Earth diameter. The accessible Δm^2 fully cover the Super Kamiokande (SK) range. For the preferred SK value $\Delta m^2 = 3.10^{-3}$ eV^2, the first oscillation minimum occurs for $E/\cos\theta \sim 30$ GeV, right in the sensitivity region of the ANTARES detector.

At medium energies, the telescope will allow the search for neutralinos, thus contributing to the dark matter quest. Neutralinos would indeed be expected to be gravitationally attracted to the centers of massive bodies such as the Earth, the Sun or the Galaxy (hence the interest of a site in the Northern hemisphere to allow the survey of the Galactic Center), where they would accumulate and mutually annihilate, producing neutrinos. These neutrinos would then be detected as an excess coming from specific directions correlated with a gravitational center.

At higher energies, the Universe supplies several possible sources of neutrinos, whose existence can be inferred from that of the observed high energy cosmic rays. Candidate sources include both galactic sources (such as supernova remnants and X-ray binaries) and extra-galactic sources such as gamma-ray bursters (GRB) or active galactic nuclei (AGN).

AGNs are the most powerful energy sources known in the Universe and could therefore provide detectable sources of high energy neutrinos[3)]. Although individual AGNs probably would not produce a flux high enough to be detectable by a ~ 0.1 km^2 detector (roughly 2 to 3 events per year), together they could yield a significant diffuse signal. The debate is still open between the various theoretical models which describe AGNs, and neutrinos could give a helpful hint. For instance, if the high energy photons that have been detected so far result from electromagnetic radiation of accelerated electrons, no neutrinos are expected. On the contrary, hadronic models for AGNs predict a neutrino flux (summed over all AGNs) from a few tens to several hundreds a year, depending on the location of the acceleration mechanism and the target particle.

Gamma ray bursts are also very interesting potential sources of neutrinos. Fireball models of GRB[4)] predict an accompanying burst of 10^{14} eV neutrinos which would arrive in time with the photon burst. This simultaneity of the photon and neutrino bursts (to better than 1 sec), along with the good angular resolution of an underwater detector such as ANTARES, would yield a flux of ~ 1 neutrino a year on top of a greatly reduced background (of neutrinos from atmospheric muons) of only $\sim 10^{-3}$ a year.

4.2. Expected performance

For muon energies below 100 GeV, the muon trajectory is contained or semi-contained in the instrumented part of the detector and the energy is estimated from the muon range, since the energy loss per unit length in this energy range is constant. For muon energies above 1 TeV, the energy loss per unit length is linear in the muon energy, which is thus estimated from the summed amplitude of the recorded hits. The muon energy is measured within a factor of 3.

As shown in figure 9, the angular resolution is dominated at low energy by kinematics, whereas at energies above 10 TeV, where the physical angle between the parent neutrino and the emitted muon becomes much smaller than about a tenth of a degree, it is dominated by the reconstruction. The pointing resolution reaches ~ 0.2 degree at high energies, including the effect of light scattering.

5. Conclusions

The R&D phase which covered the years from 1996 to 2000 is now over. It allowed the assessment of the main requirements of an undersea neutrino telescope. In particular, the study of the ANTARES site optical properties showed that fouling on optical surfaces was at a low enough level for a long term project, the optical background could be dealt with and the water transparency sufficient for the planned 0.1 km^2 detector. Marine technology (line deployment or recovery, underwater connection) is under control. In addition, the operation for several months of a demonstrator string allowed the reconstruction of down-going muons.

ANTARES is a growing collaboration now involved in the construction and deployment phase of the 0.1 km^2 detector. By the end of 2002, the deployment of the electro-optical cable and the immersion of a prototype line sector (5 storeys) is

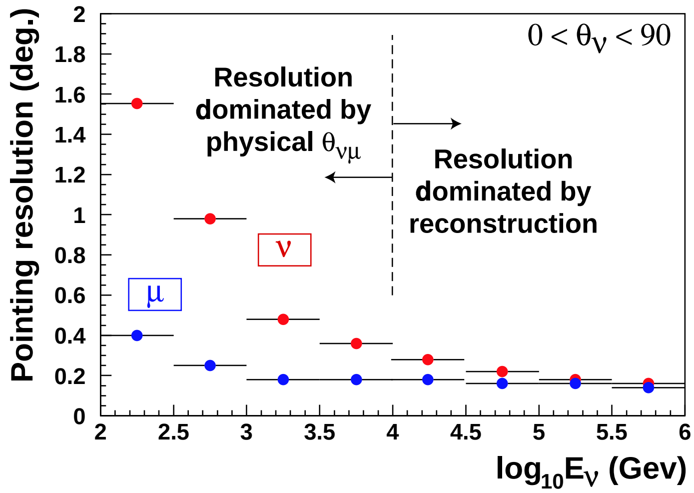

Figure 9: Angular resolution versus neutrino energy.

planned in the ANTARES site. During the following two years, the 10-string detector is foreseen to be deployed.

The ANTARES detector will offer opportunities for front line astrophysics and particle physics research, and at the same time constitute an important step towards a km3 neutrino detector in the Mediterranean Sea.

6. References

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3) Stecker, F.W. et al., *Phys. Lett. Rev.* **66** (1991) 2697.
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