The construction of ANTARES, the first undersea neutrino telescope

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Abstract

With nearly 900 large-area photomultipliers installed on 12 detection lines at 2500 m depth in the Mediterranean, ANTARES is the first undersea neutrino telescope and the largest volume detector currently operated in the northern hemisphere. The construction of the apparatus was completed in May 2008 with the connection of the two last detection lines. The data sample collected so far contains more than $5 \cdot 10^7$ triggered events, out of which more than 400 candidate neutrino events have been already identified. In this paper we illustrate the apparatus design, summarize the construction operations, report on the current status of the experiment and discuss its discovery potentials.

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1. Introduction

Very large volume Cherenkov detectors represent nowadays the most common approach to neutrino astrophysics. After the pioneering efforts of the DUMAND Collaboration for building a detector off the coast of Hawaii [1], the first underwater neutrino telescope was built in the fresh water of Lake Baikal [2]. The AMANDA apparatus is operated in the ice of Antarctica and is being enlarged to become shortly the first km^3-scale detector, ICECUBE [3].

If a second apparatus of comparable volume is installed in the northern hemisphere, a complete sky coverage can be performed. A convenient location would be in the Mediterranean Sea, where several deep sites can be found within reasonable distances from shore. The field of view of an apparatus in the Mediterranean Sea would include the Galactic Centre for about 2/3 of the time, and provide about 0.5π sr of instantaneous common view (1.5π sr integrated over

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one day) with an Antarctica apparatus, which gives good opportunities for crosschecks and joint searches. Although the detection technique remains essentially the same, the systematic errors of an underwater apparatus may be different from under ice due to the different light propagation features of the two media.

Different collaborations are active in the search of the optimal site in the Mediterranean Sea for installation of a neutrino telescope. NEMO [4] and NESTOR [5] have run prototypes of the structures that they propose for the construction of a km^3-scale apparatus. ANTARES has recently completed the installation of a 900-photomultiplier apparatus, which represents nowadays the largest experimental apparatus of the northern hemisphere.

Building a large apparatus under the sea is a challenging enterprise, requiring highly reliable solutions for the apparatus to resist the high pressure and the corrosion effects which may take place in deep salt water. The installation operations, involving ships and submarine vehicles, may be expensive; therefore the structure of the apparatus should be defined so as to simplify the deployment procedures and reduce the number of underwater operations to the minimum. Solutions have to be implemented which allow, in case of need, the recovery of faulty parts of the apparatus.

Calibrations are typically demanding tasks for a similar apparatus. A time calibration system is needed in order to determine how to compare the time measurements performed by different sensors with subnanosecond precision. In addition, submarine structures may move under the effect of the sea currents. A positioning system is therefore also needed.

Finally, the natural optical background typical of the marine abysses, due to the radioactive decay of the ^{40}K isotope and to bioluminescence, represent a problem for the data acquisition system, which has to be able to sustain high data rates, as well as for the trigger and the reconstruction algorithms, which need to be smart enough to select the signals induced by particles crossing the apparatus in such a noisy environment.

This paper is structured as follows: in the next section, we describe briefly the ANTARES site and apparatus; in Section 3 we summarize the construction activities; in Section 4 we illustrate the performance of the apparatus underwater and in Section 5 we discuss the capabilities of the experiment.

2. The ANTARES site and apparatus

ANTARES has been installed about 40 km off the coast of Toulon, France at a depth of 2485 m in the Mediterranean Sea. The control station is located inside the Institut Michel Pacha in La Seyne sur Mer, at a short distance from Toulon.

The main element of the apparatus is the line, a flexible structure built with up to 25 detection storeys connected by segments of cable. The line is anchored to the sea bottom and is kept taught by a buoy installed at the top.

The cable which connects consecutive storeys of a line provides the mechanical strength to keep the line together and supports power distribution and data communications over optical fibres. It is equipped with 9 conductors and 21 single-mode optical fibres.

The full apparatus comprises 12 detection lines and one shorter line, called instrumentation line, equipped with calibration and environmental monitoring devices. The lines are installed at a minimum distance of the order of 60 m from one another.

The spacing between consecutive storeys on a detection line is of 14.5 m, and the bottom storey is at about 100 m above the seabed. Hence, the line height is approximately 450 m. The instrumentation line, an early version of which is described in [6], comprises 6 storeys for a total height of about 300 m. Three of the storeys of this line, as well as three of one of the detection lines, are equipped with hydrophones meant as prototypes for acoustic detection of neutrinos---a system called AMADEUS, which is described elsewhere at this workshop [7].

A detection storey consists typically of a triplet of optical modules [8], i.e. large-area hemispherical photomultipliers (Hamamatsu 7081-02 with 10” diameter) enclosed in pressure-resistant glass spheres, which are arranged symmetrically, and in such a way that the photomultipliers are oriented downward at 45°, on a titanium frame. Such frame hosts also an electronics module and, for specific storeys of the lines, some calibration or monitoring devices. The electronics module of the storeys, called Local Control Modules (LCM), contain all the electronics necessary for the data acquisition and control of all devices of their storeys and for the communications with the shore. An additional electronics container, the String Control Module (SCM), is located at the bottom of each line and represents the interface between each line and the rest of the apparatus.

Each line consists of up to 5 functional units, called sectors, each of which comprises up to 5 storeys. The apparatus is designed so that it is possible to operate and maintain independent communications with each sector from shore. Inside each sector, one electronics module, called Master Local Control Module (MLCM), acts as the gateway for all communications between its sector and the shore.

From the point of view of the data acquisition, the apparatus is conceived as an Ethernet network with a node in each of the electronics modules (for a total, therefore, of more than 300 nodes offshore). Data communications exploit a Dense Wavelength Division Multiplexing (DWDM) technique: the SCM and each MLCM of a line are equipped for optical communications using different wavelength channels with a 400 GHz spacing. The signals coming from the different sectors of the line and from the SCM are then multiplexed onto one single fibre inside the SCM container. By the same token, the signals coming from the shore and directed to the different sectors of the line are demultiplexed inside the SCM and delivered, according to their DWDM channel, to the proper destination.

The MLCMs are equipped with an Ethernet switch and with electro-optical transceivers which allow them to communicate with the LCMs of their sectors in a star-configuration network. This architecture allows to implement a high rate data transfer system with a limited number of optical fibres: in fact, only two fibres of the long-distance cable are needed for the data communications between the shore station and each line. In this way, it is possible to transfer to shore essentially all the information collected by the apparatus, with no or minimum offshore filtering, leaving to a computer farm onshore the task to select the meaningful data to save---a solution which guarantees maximum flexibility and reliability.

In order to establish a common time reference for the complete apparatus, a clock signal is generated onshore, stabilized by means of a GPS receiver, and delivered to all offshore electronics by means of a dedicated optical fibre network. This network is mainly composed of passive devices for maximum reliability. Superimposed to the clock, control signals may be also delivered through the same network, with the twofold purpose of allowing redundancy in some slow-control operations and of distributing commands to the whole apparatus or to a part of it for clock-synchronized operations.

The apparatus is connected to shore by a long-distance cable equipped with 48 single-mode optical fibres and one conductor. Power is delivered from shore in AC at 3500 V, with a current return through sea water. At its undersea end, the cable is terminated by a submarine junction box which is equipped with 16 wet-mateable connectors and performs the following vital operations: it transforms the power received from shore down to 500 VAC, by means of 16 independent secondaries, individually protected by resettable breakers; it splits the fibres of the cable coming from shore so as to serve the different lines. The junction box is also equipped with a battery-powered monitoring device, so that it is possible to check its status even when the apparatus is not powered.

Underwater interlink cables are used for connecting the bottom of the lines to the junction box. The installation of these cables is made by means of a manned or unmanned submarine vehicle.

The power is regulated to 400 VDC at the bottom of the line and then distributed to the different sectors, which can be individually switched on and off from shore.

The front-end electronics for the photomultipliers is located inside the (M)LCMs and is based on a custom-built ASIC chip called Analogue Ring Sampler (ARS) [9]. Each ARS is able to perform several functions: it can continuously sample the signal from the anode and from the last dynode of a photomultiplier by means of blocks of switched capacitors[1] which can be operated up to a maximum sampling frequency of 1 GHz; it can generate a

[1] Used in a circular, i.e. *ring*, mode.

trigger signal when a defined threshold condition is met and, when this occurs, it can store the relevant information for a hit in a 16 memory-cell pipeline. The chip is also equipped with pulse shape discrimination (PSD) circuitry, which uses different criteria related to the total integrated charge of a hit, the time over threshold and the distance between signal peaks for tagging the signals coming from the photomultiplier as due to the conversion of a single photoelectron (SPE) or not. Depending on the PSD output, different information can be saved into the memory pipeline: only the value of the integrated charge is saved for SPE signals, while up to 16 signal samples can be saved in the other cases, so that a complete waveform analysis is possible. These charge values are then converted by means of a 8-bit ADC. For all hits, the chip records in addition the information concerning their threshold times. Such information consists of the readout of a 16-bit counter, which is incremented at 20 MHz (hence at steps of 50 ns) and periodically reset upon reception of a command broadcast from shore, and of the values of two TVCs which reach subnanosecond resolution. It should be emphasized that, although all offshore operations are referenced to the common clock distributed to the whole apparatus, all time measurements have a local meaning, as each electronics module measures time with a different offset with respect to shore, which varies depending on the length of the interconnecting cables and on the latency of the electronics. It is a task of the time calibration system to determine the proper time offset for correcting the measurements of each individual optical module.

Three ARS chips are arranged on a single motherboard which serves one optical module. Two of the chips are used for sampling the photomultiplier signal in a token-ring configuration, while the third one is used for trigger purposes. The settings of each individual ARS (e.g., thresholds, integration time, PSD criteria) can be configured from shore through slow-control commands.

The data from the three optical modules of one storey, after being sampled by the ARS chips, are then collected by a data acquisition card which controls the operation of the (M)LCM and sends the data to shore through a 100 Mbps Ethernet link. The data are packed in different data frames, depending on the time window (the so-called ‘time slice’, with typical duration of 100 ms) in which they have been recorded. These data frames are then sent to shore with convenient tags, so that with a proper setup it is possible to address all data frames coming from the different parts of the apparatus and referring to the same time slice to one single computer onshore. This computer will execute filtering algorithms to select the data to save on disk.

The onshore DAQ station is therefore organized as follows: first, a DWDM demultiplexing stage is necessary in order to separate the different data flows coming from the different sectors of the lines. Next, an Ethernet switch directs the different data frames to the proper CPU of a farm. Several online trigger algorithms have been implemented and are executed concurrently on the data. A memory buffer is also provided, in which up to 5 minutes of raw data coming from the whole apparatus may be kept and are continuously updated. Should a GRB alert be received, the data from this buffer are then saved to disk so that neutrinos associated with the event may be searched for. It should be pointed out that, if the alert is promptly delivered, it is even possible to look for neutrino signals recorded *before* the GRB is actually detected. More details on the ANTARES data acquisition system are available elsewhere [10].

Is has been pointed out that calibrations are demanding tasks for an undersea apparatus. ANTARES is equipped with a time calibration system and a positioning system. The time calibration system, designed to reach a subnanosecond precision, is based on optical beacons located in specific sites of the apparatus, namely: 2 laser beacons are installed on the bottom of two lines in the central area of the apparatus, from where they can illuminate a large fraction of the apparatus; LED beacons are installed on specific storeys of each line (typically, there are 4 beacons on each line). More details may be found elsewhere [11].

The positioning system consists of a hybrid system including compasses, tiltmeters and an acoustic triangulation system:

- a compass and a tiltmeter are operated inside each electronics module of each line, thus allowing to measure the attitude and the orientation of each storey;

- acoustic receivers are located on proper storeys of the lines (typically, there are 5 receivers on each line). They can measure the signals emitted by emitters located on the bottom of each line as well as from a set of transponders installed around the area of the apparatus. From the measurements of propagation times of these signals the relative positions of the receivers with respect to the emitters can be inferred.

The positioning algorithm takes into account the measurements from all these devices. The accuracy which can be reached in this way is of the level of 20 cm for each optical module.

3. The ANTARES construction

The site exploration started in 1996. More than 30 autonomous lines have been operated since then, in order to get a long-term characterization of the environmental conditions (sea currents, biofouling, optical background) as well as of the light propagation properties of the water. Results from this survey have been published [12,13].

The construction of the apparatus started in 2001 with the deployment of the long-distance cable, on the undersea end of which the junction box was installed in December 2002. Various prototype lines were operated between 2002 and 2005, allowing to progressively test all technical aspects of the design of the apparatus.

The first detection line was deployed on February 14, 2006 and connected two weeks later. A second detection line, equipped with cables of upgraded design, was put into operation in October of the same year. 3 more lines were connected in January 2007 and 5 more, plus the final instrumentation line, in December 2007. Finally, the apparatus reached its complete configuration when the last two lines were deployed and connected in May 2008.

The connection of the last two lines was made possible by an important upgrade of the apparatus, which is worth mentioning here also because of the implications toward the design of larger scale detectors: a new connection scheme was in fact implemented in which two lines are connected to the same output connector on the junction box. This modification was motivated by the fact that during the previous connection operations a few of the junction box connectors were, or were found, damaged (for more details, the reader is referred to a specific report given at this workshop [14]). Underwater connection operations are indeed delicate, and this occurrence should not be a real surprise. In fact, the junction box had been equipped since the beginning with some redundancy (16 connectors compared to a bare minimum of 13 needed). However, it was decided that, in order to avoid any possible problem and in an attempt to save one free connector for new future applications, a new solution should be implemented, allowing to connect two lines on one single junction box output. This solution required a new design of the underwater interlink cables, which are now equipped with a branching unit which splits the cable to be connected to the junction box into two arms to reach the two lines. It also required a modification of the power system of the two lines to be connected together and of their DWDM system (since clearly different DWDM channels are needed, if the different data flows have to be injected into the same fibres).

It may be pointed out that, in spite of the modified connection scheme of the last lines of the apparatus, the construction of the full apparatus required a limited amount of time, with slightly more than two years between the connection of the first line and that of the last ones. This impressive result was made possible since a powerful, Europeanwide, construction organization had been put into operation. The photomultipliers were among the first elements of the apparatus to be chosen [15]. The construction of the optical modules took place at Saclay. The mechanical productions were carried out by different laboratories in France, Italy, the Netherlands. The optical beacons were built in Valencia. A special attention was then given to the construction of the electronics modules, due to the large number of components involved, the need of extensive tests and calibrations and the high level of reliability required. Different laboratories in France, Germany, Italy, the Netherlands and Spain contributed to the production of the different electronics cards. Facilities were then set up at three laboratories in Italy (at INFN Bari, Catania and Pisa) to mount and test electronics modules at a rate which could sustain the line integration activities in two different sites in France (Marseille and Saclay).

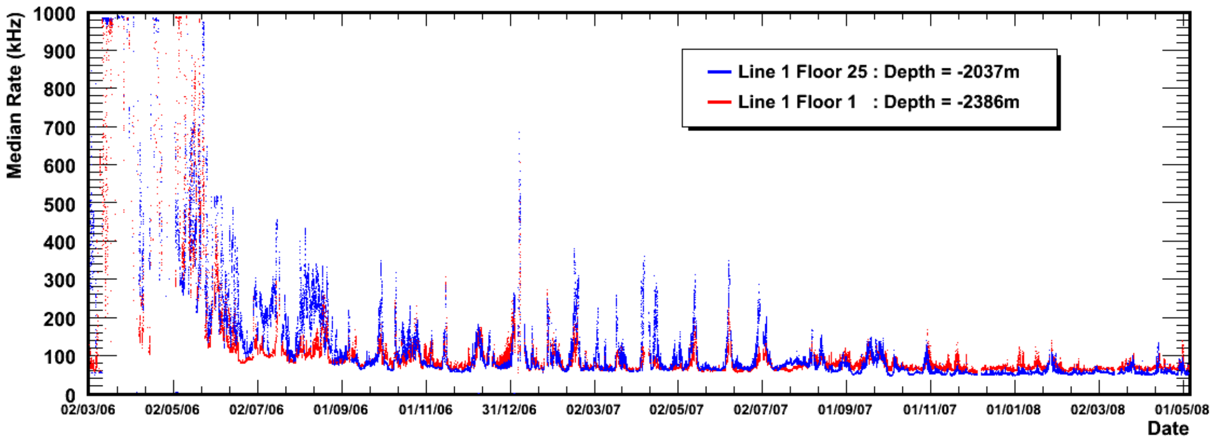

Figure 1: The mean rate measured by two optical modules at the top and the bottom of the first detection line of ANTARES as a function of time.

Different test and calibration procedures had been defined for the different integration level (single cards, complete electronics modules, complete sectors in a dark room) in a coherent scenario so as to make sure that all electronics was fully characterized before installation of a line undersea.

An integrated line can be arranged on a single pallet which can be installed on the deck of a relatively small ship for the deployment. The installation of the lines was made by means of the ship Castor, of Foselev Marine, which has dynamic positioning capabilities. The overall procedure for installation of a line, once the ship reaches the site, takes about 6 hours and the positioning accuracy is typically of a few meters from the target position.

The lines are equipped with an acoustic release system, which can be activated from a ship, if it is necessary to recover a line for repair. The bottom of the line is released from its deadweight, and the line floats up to the surface under the pull of the top buoy. The speed of the line is limited by means of dampers, so that the connector at the bottom of the line can disengage safely. The interlink cable therefore remains on the seabed and can be used for connecting a new line in the future.

It should be pointed out that although the integration of the lines proceeded at a regular pace, the deployment operations and even more the connection operations took place somewhat more irregularly. This occurred as a consequence of the availability of the necessary vehicles. Operations which include submarine vehicles are in particular delicate and expensive. For this reason, the apparatus was designed so as to keep the number of these operations to the very minimum. In fact, a submarine vehicle is needed only for connecting new lines and for connection/disconnection operations at the junction box level. The Remotely Operated Vehicle (ROV) Victor of IFREMER has been used for connection of most of the lines, with the manned submarine Nautile being used for the second line of the apparatus.

4. Performance of ANTARES

The data acquisition of the experiment started in March 2006, when the first detection line was put into operation. Up to June 2008, when the apparatus started to take data in its complete configuration with 12 detection lines in operation, more than 50 millions triggers had been recorded.

Most of the efforts during the commissioning of the detector were dedicated to the development of efficient trigger algorithms for online filtering of the data, to the implementation of different reconstruction procedures of the events, as well as to the complete characterization of the performance of the offshore apparatus. All subsystems of the apparatus have been found to work within specifications. Results from the time calibration and positioning systems have been reported elsewhere at this workshop [16,17].

An unusually high level of optical background was recorded during Spring 2006, with a baseline rate typically exceeding 100 kHz on individual photomultipliers and frequent bursts of bioluminescence affecting the complete line in operation at that time. The situation has significantly improved since then, as shown in Figure 1. Still, the reasons for the unusual rates of Spring 2006 remain to be understood. Among the possible explications is that they were due to the weather conditions of the previous winter, exceptionally cold and dry.

Most of the recorded events are due to atmospheric muons. It may be pointed out that, although the apparatus is optimized for detection of upward-going particles, by means of the orientation of the photomultipliers, it remains sensitive to donward-going particles as well. The flux of atmospheric muons reaching the apparatus is considerably reduced with respect to the sea surface due to the shield from more than 2 km of water overlying the detector. Atmospheric muons represent therefore a mild source of background for detection of neutrino-induced upward-going particles and a natural source of calibration of the apparatus. For both these reasons, the muon events have been extensively studied and compared to the simulations. A detailed discussion of the progress made in understanding the results of these simulations is presented elsewhere at this workshop [18].

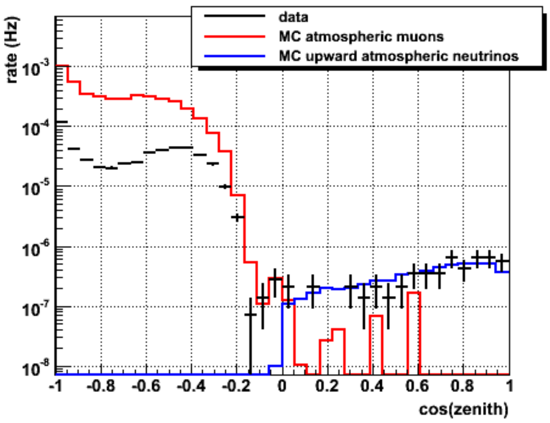

Figure 2: Zenith angle distribution of reconstructed events in ANTARES, compared to results from simulations.

In Figure 2 we show the distribution over zenith angle of a large sample of events, collected in 140 active days during the period of operation with 5 lines of the apparatus. More than 70 candidate neutrino events are reported in this plot. The measured distribution is compared to the results from simulations of atmospheric muons and neutrinos. While the agreement for the upward-going particles is remarkably good, for downward-going particles the detected rate of events is significantly lower than the expected value, reflecting the optimization of the apparatus toward the measurement of upward-going tracks. The figure also shows that the residual contamination due to badly reconstructed muons in the neutrino sample, after applying the selection criteria optimized so far, can be as low as few percent.

The analyses are proceeding on the full data set recorded, including the data acquired with 10 and finally 12 lines in operation, and more than 400 candidate neutrino events have been identified so far.

5. Experiment capabilities

ANTARES aims to detect neutrinos of cosmic origins, whether coming from discrete sources or due to a diffuse flux. In Figure 3 we show the estimated sensitivity to discrete sources: the purpose in this case is to complement the sky survey performed by AMANDA with a comparable level of sensitivity.

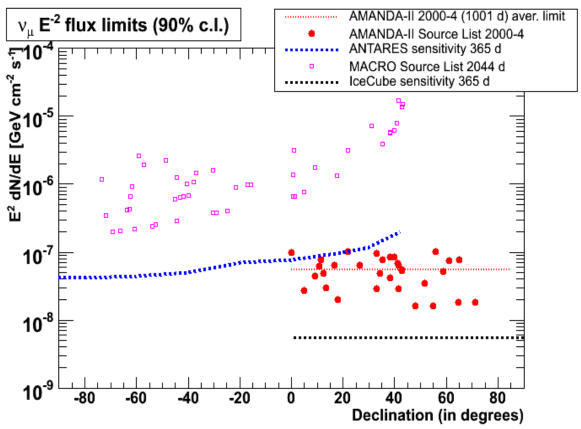

Figure 3: Expected sensitivity of ANTARES to neutrinos from discrete sources, compared to limits from other experiments.

It should be pointed out that after only one year of operation it is expected that ANTARES can improve the existing limits, set by the MACRO apparatus, by about an order of magnitude of more.

In Figure 4 we show the expected sensitivity to a diffuse neutrino flux. It may be noted that ANTARES can investigate fluxes comparable to the Waxman and Bahcall limit (curve marked W&B in the figure) [19].

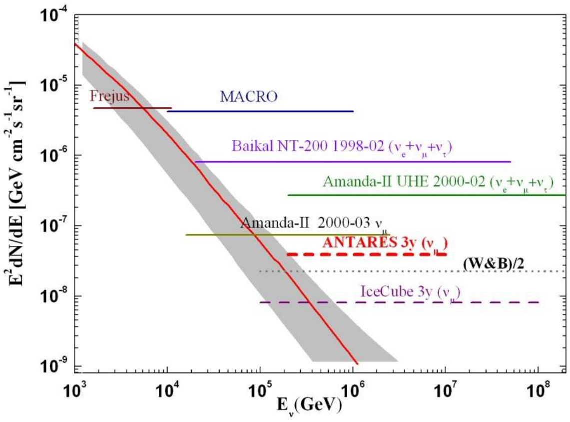

Figure 4: Expected sensitivity of ANTARES to a diffuse flux of neutrinos, compared to the limits from other experiments and to theoretical estimates. The shaded area refers to the background flux of atmospheric neutrinos.

In addition, a search for dark matter evidence will be performed by looking at a possible excess of events coming from the Sun, or the Earth, or the Galactic Centre. The data recorded simultaneously to GRBs will be analyzed looking for neutrinos associated to the events. Other physics objectives, such as the search for magnetic monopoles and other exotic particles, are also under investigation.

6. Conclusions

The construction of the ANTARES apparatus has been completed in May 2008. The operation of what represents the largest apparatus in the northern hemisphere and the first neutrino telescope installed under the sea is a major milestone toward the construction of a km^3-scale apparatus in the Mediterranean Sea. In fact, all groups participating in ANTARES are now involved in the KM3NeT consortium [20], bringing their experience to the design of the neutrino telescope of the future.

The ANTARES apparatus is being operated smoothly, with all subsystems working within specifications. More than 400 candidate neutrino events have been already identified so far. Steady data acquisition is now planned for several years.

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