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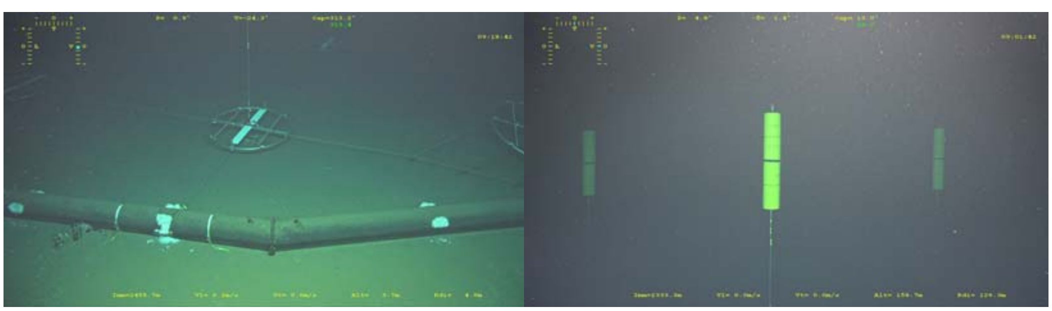
Cruise report

3D-T/TOU20

(KM3NeT20)

R/V Pelagia cruise 64PE478 08-13 October 2020
R/V Pourquoi pas ? cruise 3D-T_ROV 18-20 November 2020
la Seyne-sur-mer (F)

Hans van Haren



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1. Cruises summary

Early October 2020 research vessel ‘R/V’ Pelagia (NIOZ, the Netherlands) sailed to the Liguro-Provençal Basin in the Western Mediterranean. The purpose of the cruise was twofold: (1) To deploy a half cubic hectometer large mooring array ‘3D-T’, and (2) To test a hired long baseline ‘LBL’ system for deployments to within 1 m accuracy horizontally in about 2500 m water depth. In complete unfolded form underwater the large mooring array holds 2925 high-resolution temperature sensors distributed over 45 mooring lines 125 m tall and 9.5 m to its nearest neighbor horizontally. The sensors monitor the development of internal wave and sub-mesoscale eddy turbulent overturning in three dimensions at the foot of the continental slope for a period of 3 years. The array was built-up in flat form with small rings holding folded mooring lines mounted at an intersection of a steel cable network inside a 70 m diameter large ring consisting of 0.6 m diameter steel tubes in the harbor of la Seyne-sur-mer (France) during the 10 days before deployment. The flat-form array was towed by commercial tug to the mooring site, about 40 km southeast of Toulon harbour. After mounting a drag-parachute from R/V Pelagia, the array was sunk in a quasi-controlled way by opening valves in the large ring. It was successfully landed at the seafloor, with the drag-parachute regaining control of the ‘free’ fall after about 450 m of sinking. Unfortunately, two out of six lines of the drag-parachute could not be released acoustically as they remained stuck mechanically. Mid-November 2020, the drag-parachute was released by cutting via remotely operated vehicle ‘ROV’ Victor and successfully recovered on board R/V Pourquoi pas ? (Ifremer, France). The ROV operation was also used to verify the chemical release of the vertical mooring lines from visual inspection of the mooring array. During the R/V Pelagia cruise a single shipborne Conductivity Temperature Depth profile was made to the seafloor for calibration purposes. The CTD’s local sound velocity profile was also needed for the LBL underwater acoustic positioning system. With effort during Beaufort 6 winds, a dummy weight was positioned to within 2 m from a predetermined target position. Some difficulties in slow system updates were noted.

2. General research aim.

The purpose of the present physical oceanographic study is to characterize the development in three dimensions '3D' of internal wave motions and turbulent exchange in a deep-sea, *i.c.* over a 2500 m deep flat seafloor near the continental slope in the Liguro-Provençal Basin, Western Mediterranean.

For 15 years, very sensitive underwater temperature sensors have been developed at the Royal Netherlands Institute for Sea Research (NIOZ) to gain more insight in physical processes for the dispersion of substances in shallow and very deep seas and oceans. These sensors are used to measure the energy-rich large eddies of turbulent flows. In the stably density stratified waters, mainly by solar heating from above, such eddies are mostly generated by breaking internal waves (e.g. Eriksen, 1982; Thorpe, 1987). The measuring method works best if sufficient temperature sensors are attached to a mooring line, roughly one hundred sensors at a distance of 1 to 2 m from each other. The mooring line is held in place by a heavy weight and held almost vertically taut by a heavy top-buoy. Until a few years ago, such mooring lines were deployed separately in the sea at various locations: This provided 1D depth/time information. That deployment was done in free fall, in the order buoy-line-anchor weight, with an accuracy of about 100 m horizontally around a target position per 3 km depth.

Since internal waves and turbulent eddies are essentially three-dimensional (e.g. LeBlond and Mysak, 1978), there has been a desire for years to place multiple mooring lines next to each other in the sea in order to study the development processes in a volume of water. Research showed that lines would then have to be about 10 m apart, also in the deep sea. This is impossible to achieve with free-fall deployment of single lines. In addition, the clocks of the temperature sensors are synchronized every 4 hours to be able to measure simultaneously within 0.02 s. A deep-sea robot would therefore be necessary to electrically connect the individual lines: An expensive and difficult operation. It was decided to develop new mooring techniques whereby several lines can be released into the sea in free fall at the same time.

The first version, which was successfully used two times, consisted of 5 lines at 4 (and 5.6) m apart horizontally, 100 m high vertically and contained approximately 500 sensors (van Haren et al. 2016a). The lines were folded on four arms of a "rotary clothesline", in collapsed form on board, and unfolded overboard once at sea using a heavy weight and a second rotary clothesline. The whole mooring array was under such a tension by the top-buoys that it did not twist and could sink in free fall. The small 3D mooring array provided information about the transition from flattened 2D turbulence on slower, large scales to fully uniform 3D turbulence on faster, smaller scales (van Haren et al. 2016b). However, deep-sea eddies of more than 100 m in vertical and horizontal directions were not fully mapped with this version.

Based on the five-line mooring and ideas and technology of astrophysical project KM3NeT, short for "cubic kilometer neutrino telescope", half a cubic hectometer temperature sensor array ‘3D-T’ was devised. This array consists of 45 lines, 125 m high and 9.5 m to the nearest neighboring line, each line holding 63 temperature and 2 temperature/tilt sensors. The total of 2925 sensors will measure roughly half a million cubic meters, or half a billion liters, of deep-sea once every 2 s for approximately 3 years. The location is off the coast of Toulon (France) in the vicinity of KM3NeT. This is not only to have the ability to combine the temperature data with optical data from the telescope, but also because the area is known for deep-sea internal waves, and for strong contrasts due to (continental slope) boundary layer currents, deep dense-water formation and eddies that transport fresh biological material within a day from surface to 2500 m deep seafloor (van Haren et al., 2011). Logistically, the location is attractive, because a flat deep-sea bed is reached only 25 km from the coast, 40 km from the nearest harbor, and because ocean swell is low, so that the technically difficult mooring can be towed to location.

3. Description of components

a. Temperature sensors

Modified high resolution standalone NIOZ4 temperature sensors are used. Between September 2019 and May 2020, 3030 new temperature sensors were built, with the same characteristics as previous NIOZ4: 600 bar (6000 m) pressure resistance (depth range), <0.1 mK noise level and <0.5 mK precision (van Haren, 2018). Modifications concern: easier to mount sensor resistors (NTCs), slightly larger lithium battery than AA-penlight with approximately 1.5 longer lifespan, and adapted synchronization software so that the synchronization search space is increased by 2 s per week with synchronization in 6 groups of sensors from a predetermined start date. The 2-s sampling rate accommodates an internal data storage and battery life span for up to 3 years. By mid-May 2020, all sensors were ready and programmed to start on November 1, 2020 at 06 UTC. In September 2020, the single synchronizer was restarted with the first synchronization pulse to be sent on November 1, 2020 at 02 UTC, and subsequent group pulses every 4 h, group pulses separated by 0.5 h.

b. Small ring

In order to be able to compactly transport an individual mooring line with T-sensors and have it unfold at sea, a design analogous to the five-line mooring was chosen. After the 65 sensors are stuck to the 6.3 mm diameter nylon-coated steel cable with yellow adhesive tape, 63 sensors to measure temperature at a distance of 2.0 m and 2 sensors to measure temperature/tilt near top and bottom of the line, the entire mooring line is looped on a 2.5 m diameter aluminum ‘small ring’ (Figures 1 and 2). The sensors are clicked into pieces of cable channel and are eventually pressed onto the overlying top-buoy by a garden hose. The 2-m long cable-loops are stacked in a roof-tile manner, are pressed into clips and held between tension straps. The filled ring weighs approximately 400 N above water, the cable 150 N underwater. The buoy delivers 1450 N buoyancy and is held by a chemical release that opens after 5 days underwater capable of retaining a maximum of 3.5 kN. July 2020, all 45 small rings have been filled.

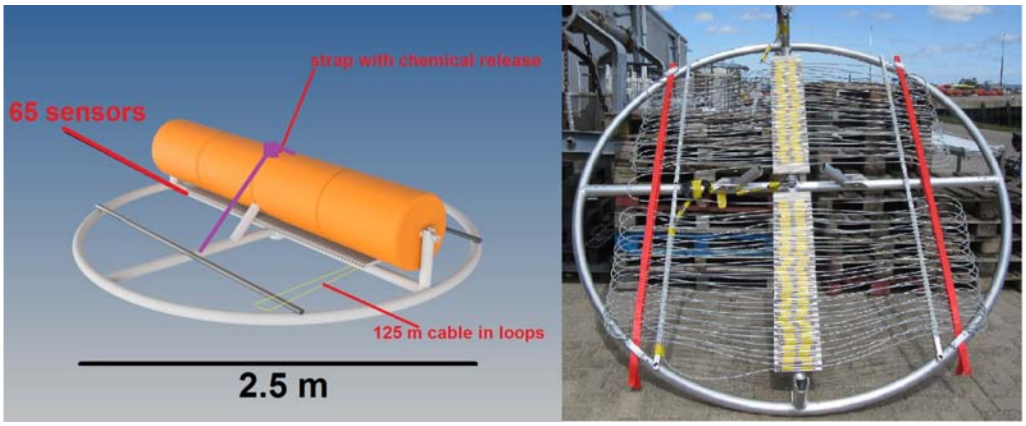

Figure 1. (left) Schematic of small ring with cable channels for 65 temperature sensors and buoy on top. (right) Small ring with 125 m long mooring line looped and held in straps and clips.

Figure 2. (left) Filled rings well stacked and (right) all 45 rings filled with temperature sensors in storage.

c. Large ring

In order to get the 45 small rings at 9.5 m horizontally apart and electrically coupled in the sea, they could be placed on their own anchor in the sea under coordination of a high-resolution acoustic positioning system. This would already be a time-consuming work not more precise than about 1 m horizontally at 2500 m water depth, but, above all, the assistance of a deep-sea underwater robot would be needed to electrically connect the network in order to have all sensors measure simultaneously upon instruction from a single ‘synchronizer’. All in all: A difficult, costly and laborious sea operation.

It was decided to electrically connect the lines t the sea surface and let everything sink to the seabed at the same time. To this end, a combination of the concept of a sea fish farm and sand replenishment at a beach has been taken. A ‘large ring’ the size of more than half a football field, almost 70 m in diameter, is stretched with a network of 12 mm diameter steel cables (Figure 3). Small rings are mounted at each intersection of the steel cables. There are 37 intersections inside the large ring. The remaining 8 small rings are mounted just inside the large ring, instead of at their virtual intersection at the edge or just outside the large ring. This displaces their vertical mooring lines about 1.5 m horizontally from the original position. Insulated electrically conductive wires are guided along the steel wires and taped together for the synchronization of the sensors.

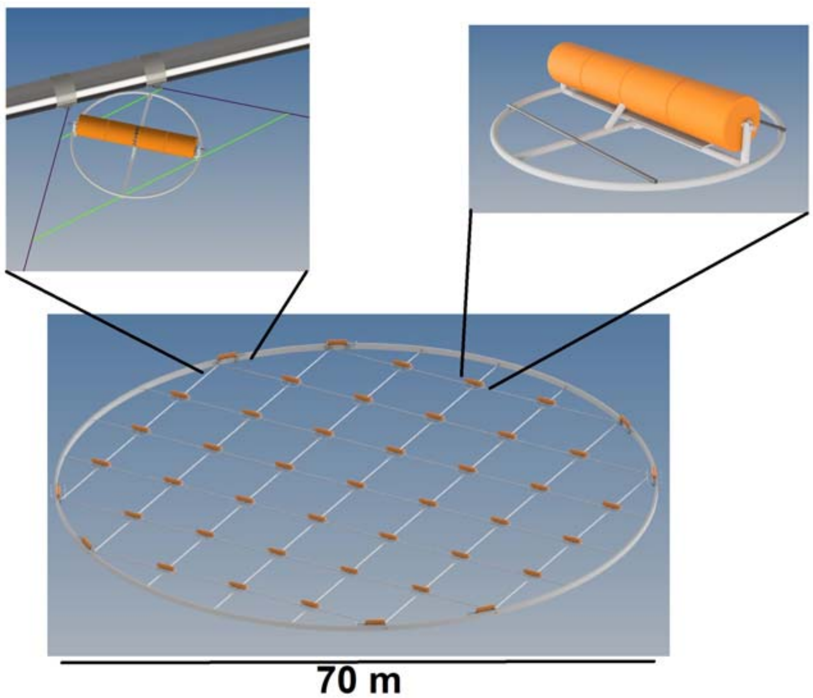

Figure 3. Schematic of the large ring with small ring mounting in corner (upper left) and at intersections (upper right) of the 12 mm steel cable network.

The large ring consists of 18 straight steel tubes 12 m long, miter cut at the ends at 10º. Flanges are welded to both open ends. The tubes have a diameter of 0.61 m and a wall thickness of 6.3 mm (steel S355). When closed, they float with approximately 22 kN/tube. When they are full of water they sink at about -12 kN/tube. This means that together they automatically act as anchor weight for all 45 lines. Due to the net 1.3 kN buoyancy of each top-buoy and vertical mooring line, the 12 mm steel cable network is pulled upwards like a reverse trampoline. Tests with the same pulling force as through the buoys have shown that the highest central point will be approximately 2.5 m above ground level. The ground level is then the center of the steel pipes, the level of the attachment points of the 12 mm steel cables at approximately 0.3 m above the seafloor if the bed is solid. Each cable is then under a deflection angle of >4.2º and provides a pulling force on a flange or a saddle around the steel tubes of <16 kN. There are 32 saddles for the 16 steel cables and other fixings. They can be safely loaded up to 27 kN (with a safety factor of 4). The flanges of the tubes are met using 16 M20 bolts per connection. Per lifting point 225 kN can be hoisted.

The 16 M20 bolts per flange-connection are tightened to about 450 N/mm^2 tension with an impact wrench and checked with a torque wrench. In water, after correction for Archimede force, the large ring 'weighs' 220 kN, the small ring 0.25 kN, the entire 12 mm steel cable network including intersection-connections about 6.5 kN. The total mooring array 'weighs' about 176 kN when completely submerged in water. The large ring has a volume of 18x3.4 m^3 = 61 m^3 and the assembly 'floats' by about 445 kN.

Water filling of the large ring is tested using a 4 m long steel dummy tube with a diameter and wall thickness like the 12 m long tubes. At the bottom of the dummy there were 3 holes of 40 mm diameter, at the top 3 holes of 12 mm diameter. The diameter of holes at the top determines the speed of air release, *i.e.* of water filling the tube. The diameter of holes at the bottom must be large enough to quickly replace the remaining air with water when the tube is sinking. One opened top hole fills the tube after about 6 minutes. Two holes fill the tube in about 3.5 minutes. If we take the 12 m tube it will take 3x as long.

For the final design we decided on two 12 mm diameter holes at the top, so it takes about 10 minutes for filling. The tube can resist a pressure of 10 bar. In order to have it full of water within one minute, at a free falling speed of 1.5 m s^{-1} (using Bernouilli law, at an average pressure of 5 bar), the two holes at the bottom must have a diameter of 60 mm.

The large ring was built-up in a field next to NIOZ during hot days early August 2020. All saddles and ample zinc/aluminum alloy anodes were mounted to the steel tubes, and the 12 mm cable network was laid out entirely. The steel cables were precise in length to within 1 cm, the large ring was a circle to within ±5 cm, on nearly 70 m diameter. Custom-made connections at the cable network intersections were tested and all intersection were precisely measured and marked with paint. The positions of the drag-parachute lines (see Section 3.e) fold-ups were determined and clip-bands fastened. Schematics such as in Figure 4 were made for vertical mooring line positioning and synchronizing group lay-out including 10 m pig-tails leading to the single synchronizer S on mooring line 5.1 (line #1 of synchronizing group #5).

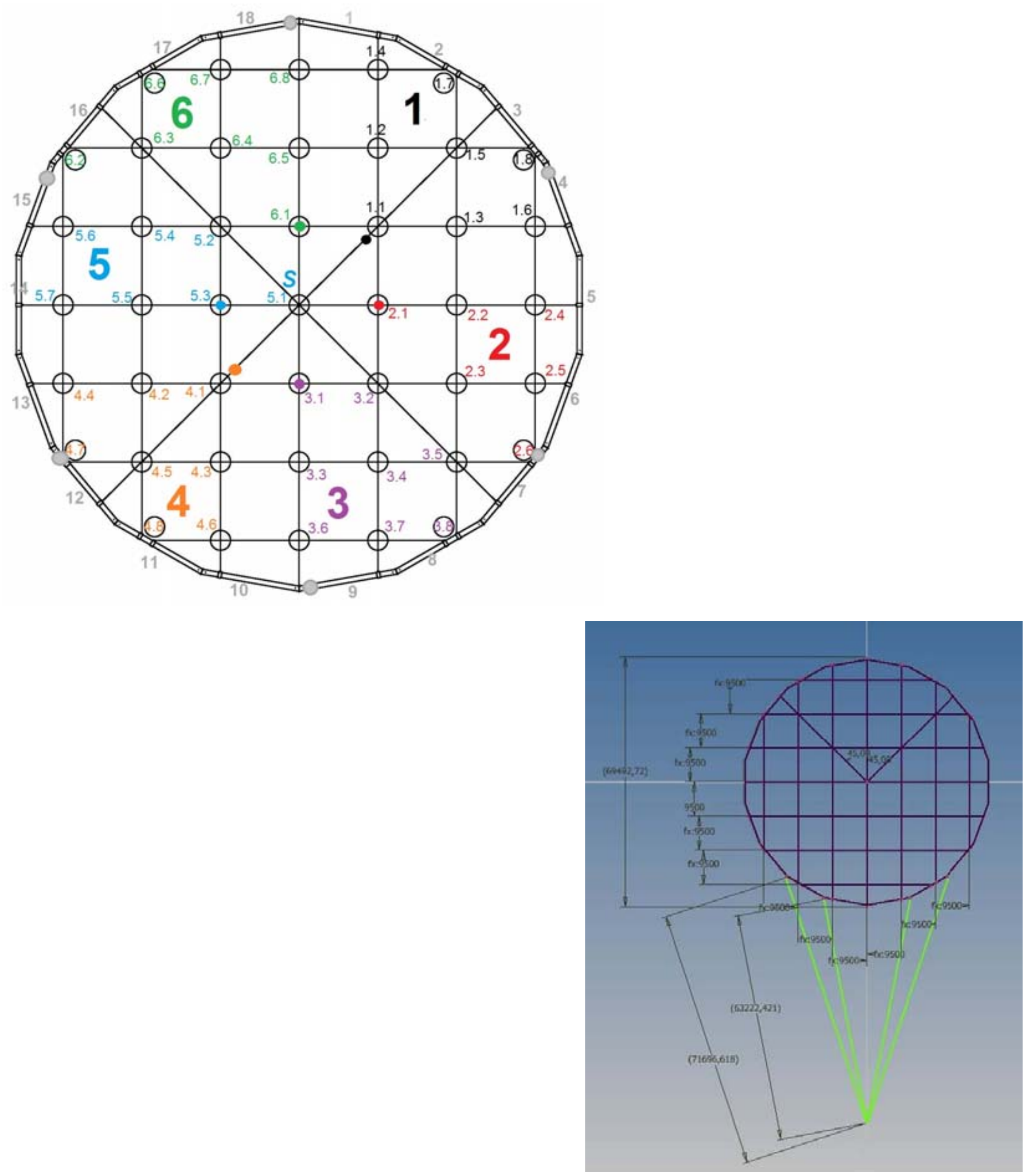

Figure 4. (upper) Schematic of large ring including 16 12-mm cables, with tube numbers given in gray and gray dots indicating the 6 acoustic release positions to the drag-parachute lines. The 45 small rings are divided in 6 synchronization groups. From synchronizer 'S' on small ring 5.1 10-m long pig-tails lead to coloured dots for connection to each group. (lower) Lengths, angles and points of attachment of towing cables.

d. Towing

To bring the complete large ring to the mooring location, it is towed at four points of the large ring. The four towing lines consist for the most part of 26 mm diameter Dyneema (660 kN breaking strength), each fitted with a 15 m long, 44 mm diameter Polyamide stretcher (400 kN breaking strength), (Figure 4). The towing from the harbor out to sea is performed by a commercial towing company. At sea the two outer lines are taking in, while the two inner lines are handed to the R/V Pelagia via zodiacs.

Figure 5. Impression of testing the drag-parachute using a scale model in a swimming pool. The ring is in the lower right corner, the drag-parachute model just below the water surface to the left of the air-bubble columns.

e. Drag-parachute

From the moment the large ring starts to tilt, when the large tubes are about half full of water, the stability is out of the system and we lose control. The ring falls on a side, the side of least resistance during sinking through the water column. This has been confirmed during a water filling test using a 1:35 scaled aluminum model of the large ring. In order to regain control (actually: in order not to lose control permanently) a huge crane of 70 m height would be necessary, which is impossible. Instead, a drag-parachute is attached to the large ring to stabilize the ring during free fall so that the ring will land flat (horizontally) on the seafloor.

The size of the drag-parachute was determined from various tests with a second model scale 1:35, consisting of 2 m diameter solid steel ring, which is hydro-dynamically correctly scaled. At a free fall speed of 1.5 m s^{-1}, measured and calculated from the surface area and weight of the final large ring ensemble, the model has a weight of 26 kg and a tube diameter of 26 mm. Two drag-parachutes were tested, one with braking resistance F_b = 10% of underwater weight F_g to correct the weight for the Archimede force ($F_b = 0.1F_g$), and one with $F_b = 0.2F_g$. The braking effect consists of a buoy, in the model an air-filled PET bottle of 1.5L, and a brake resistance disk with diameters of 0.1 and 0.2 m respectively. In February 2020 in the diving tower of the Aquacentrum swimming pool in Den Helder it turned out that both work adequately, the large brake disk stabilized the ring after a 5 m drop, regardless of the angle of the launch. The small disk also stabilized, but not completely during the 8 m drop height.

Although the fall in (scaled-up) reality takes at least 10 times as long than in the swimming pool so that the small disk would be sufficiently stabilizing, a drag-parachute with braking force of approximately $F_b = 0.15F_g$ was chosen. The actual drag-parachute consists of a standard mooring top-buoy with 3.7 kN lift capacity. At a vertical falling speed of 1.5 m s^{-1} it will contribute a further 1.3 kN of resistance to the braking power. This buoy comes 15 m above a newly built aluminum drag-parachute (Figure 6). This large parachute has an area of approximately 10.5 m^2 and carries 48 glass spheres providing 12.2 kN of buoyancy (see the Frame below for the calculations). This parachute will hang about 55 m above the large ring when it is stable. The large ring is attached to 70 m long Dyneema lines each attached to an acoustic release. To each of the 6 releases a temperature sensor was taped with tilt-motion sensors active, for monitoring the drag-parachute balancing during the sinking. The 6 lines converge at a single attachment point via a 100 kN swivel at the bottom of the large parachute. The single point attachment is required to avoid destabilization of the drag-parachute. The parachute is constructed to be separated in three equal parts that fit in a sea-container or on a truck. All 48 glass spheres are protected by plastic caps and interconnected with aluminum strips to avoid dangling during handling, towing and sinking.

Figure 6. Large drag-parachute being hoisted, with orange standard mooring top-buoy waiting to the right.

During installation for towing out, the lines of the drag-parachute are lightly secured via tape to the 12 mm steel cables, over buoys of small rings and via a click system to tubes of the large ring. The lay-out of lines is made so that the drag-parachute can be kept afloat on the ship's side, outside of and asymmetrical with respect to the large ring. By semi-controlled opening the water-filling valves of the tubes starting on the side of the drag-parachute (and, hence, ship), the large ring will sink on that side first. No sooner than sinking at least a few meters of the first-opened tubes, the drag-parachute can move inside the ring and entanglement of its lightly floating Dyneema lines with small rings is avoided. Also for proper steering the drag-parachute, Dyneema lines were chosen as they have little stretch (approximately 0.3% for 16 mm diameter; they have a breaking strength of 175 kN). Unfortunately, after checking, it turned out that the lines were not manufactured of the same length, that is, by far not meeting the precision of 1 cm over 70 m of the 12 mm steel cables: The Dyneema line for tube 12 was 0.75 m too short, that of tube 15 0.45 m and that of tube 7 0.25 m. These lines are extended with doubled hoisting slings so that all 6 ‘lines’ have an equal length with a precision of 5 cm.

To prevent the Dyneema lines from getting stuck between the glass spheres of the drag-parachute, a railing was built around the outer ring also to prevent spheres from breaking when the drag-parachute is against the side of the ship or against the large ring in the sea.

FRAME: calculation of friction during fall for actual drag-parachute.

The principle of sinking is a balance between gravity and resistance.

We have resistance (pulling) force: $F_w = ½\rho C_D A W^2$, underwater ‘weight’ $F_g = G - F_A$ corrects weight $G = mg$ for Archimede force F_A, and braking force $F_b = F_w + B$, B the buoyancy of floating force,
where m is the mass, g is the gravitational acceleration, ρ is the density of water, C_D and A respectively the drag coefficient and the surface in the direction of fall of the object, W is the speed of fall. For density of seawater we use $\rho = 1026$ kg m^{-3}, and we take a drag coefficient for a cylinder of $C_D = 1$.

The total large ring mooring array has F_g= 175 kN. The large ring has an area of 0.61x11.9x18 = 130.7 m^2. Assuming that a small ring including top-buoy has 1 m^2 area, the array has a total area of about 175 m^2. So the estimated fall speed during balance but without drag-parachute becomes:

$$W = (175000\times2/1026/1/175)^{1/2} = 1.4 \text{ m s}^{-1}.$$

For the scale model, calculations have been made at 1.5 m s^{-1}, which is close to the above value.

Taking 15% of F_g, the actual drag-parachute must deliver $F_b = 0.15F_g = 26.2$ kN of braking force. By taking floatation with a total buoyancy of B = 15.5 kN, the disk must deliver F_w = 10.7 kN of resistance force at 1.4 m s^{-1}. That implies an area of:

$$A = 10700\times2/1026/1/1.96 = 10.6 \text{ m}^2,$$ or a disk with a diameter of 3.7 m.

This resistance is distributed over the large brake disk with surface area of A = 9.6 + ring = 10 m^2 (and 48 glass spheres providing B = 12.2 kN) and A = 1.7 m^2 from the additional standard mooring top-buoy. This totals to F_b = 28.3 kN.
At full sinking speed, the 6 hoisting cables are pulled at 27 kN, which is about half the maximum load of an IXSea release. Nevertheless, for safety reasons and for recovery of the rather expensive release-ring, the single acoustic releases per line are ‘doubled’ with a chain through a large steel ring.

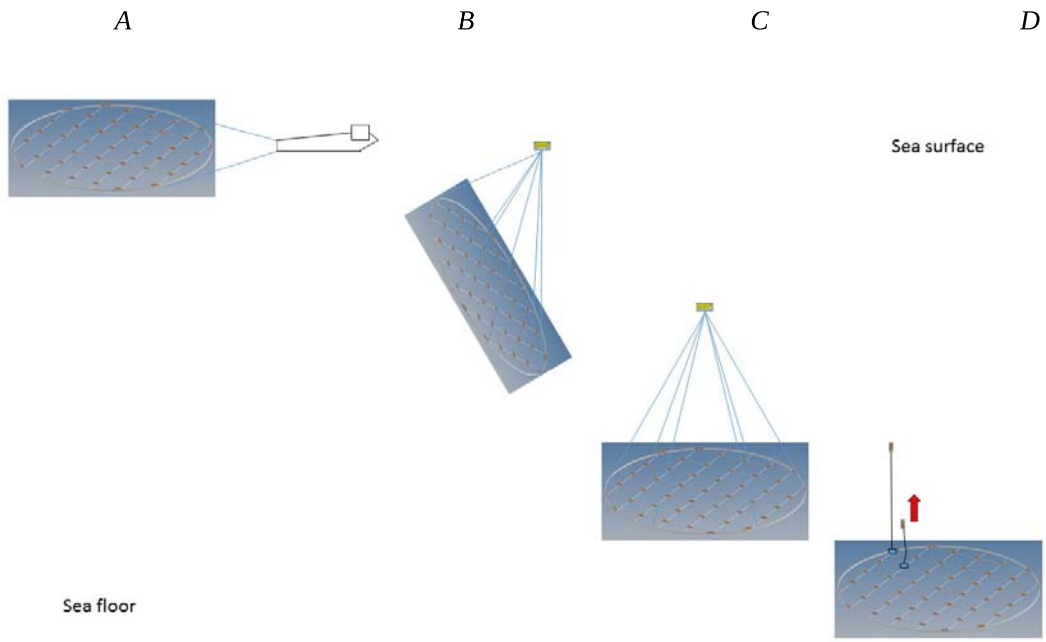

Figure 7. Schematic for the sinking of the large 3D-T mooring array. (A) Towing-out in flat state from harbor to mooring site. On-site attachment of the drag-parachute and opening of valves. (B) The initial uncontrolled stage of underwater sinking. (C) The drag-parachute has gained back control and balances the large ring. (D) After 5 days at the seafloor, the chemical release of two lines occurred.

f. Chemical release

After the ring has landed on the seafloor, and the location plus orientation have been accurately determined by triangulating all 6 acoustic releases, the drag-parachute is disconnected and recovered from the sea surface. To avoid entanglement of different lines, this is done before the individual temperature sensor mooring lines are released. The 45 mooring lines cannot be acoustically released: too expensive. Instead, a chemical release was purchased for each line, an aluminum / zinc compound that dissolves after 5 to 7 days in seawater at 38 g/kg salinity and at a temperature of 13 °C. The in-house tests yielded results in accordance with the specifications of the manufacturer. The release is linked in a custom-made strap-band that holds the top-buoy. New, the release only breaks at a force of >3.7 kN, which is sufficient to hold the buoy during the sea towing operation and the sinking of the mooring array.

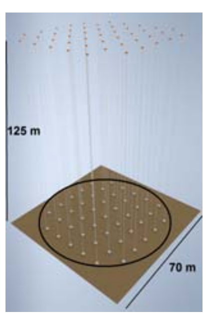

Figure 8. Impression after expanding all 45 lines.

g. Assembly raft

To place the small rings in the corners of the large ring and at the intersections of the 12 mm steel cables during the build-up in port, an assembly raft has been constructed. This raft weighs approximately 6 kN and has a buoyancy of approximately 20 kN. With a small ring and four people, the whole still floats net 10 kN (Fig. 9). This has the advantage that a floating tube on one side can be taken out of the water to clear the way after the small ring has been mounted at a crossing. Pulleys are mounted on the Davids to lift the steel cables after they have been taken out of the water and to allow the small ring to be lowered. Two Talamex TM48 electric outboard motors provide propulsion of approximately 4 hp (total thrust 2x48 LBS, for a total maximum boat weight of 29 kN).

Figure 9. (left) Schematic and (right) harbor test of the assembly raft.

h. Time schedule of construction

During the winter of 2019/2020, the temperature sensors were assembled at NIOZ. In the spring of 2020, the sensors were calibrated in a custom-made bath with a capacity of 200 sensors to a precision of 0.0001°C. In order to complete the entire calibration operation for the 3030 sensors within a period of 2 months, the calibration range was limited between 8 and 18°C. The top-buoys were assembled early 2020 and stored in the harbor shed of NIOZ. In the spring and summer of 2020, the 45 small rings were built at NIOZ, all sensors were taped to cables and fixed in the rings, and the assembly raft and drag-parachute were built. Because no precision guarantee could be given for sawing the steel tubes of the large ring, it was decided to build the large ring in a field next to NIOZ August 2020 (Fig. 10). As a benefit, this resulted in many improvements, all cable-connection-saddles were mounted and cables marked. On September 24, two trucks each loaded 9 steel tubes and two trucks each loaded two 20-foot sea containers with materials. On 28 September 2020, construction started of the large mooring array in the port of Toulon, at the CNIM quay in la Seyne-sur-mer.

Figure 10. The large ring built-up in a field next to NIOZ, guarded by Texel sheep.

i. Mooring site

The site of the 3D-T mooring array is in the area of the underwater neutrino telescopes KM3NeT-F and ANTARES (Fig. 11). The telescopes use very sensitive optical instrumentation attached to multiple mooring lines so that they also sample a volume of seawater, like 3D-T. The technique of deployment of the telescope-lines bears many similarities with that of 3D-T and results from the complimentary optical and temperature sensors yield insight in deep-sea biology activated by variations in their physical environment (van Haren et al., 2011). The area is due south of the Porquerolles islands, about 40 km southwest of Toulon harbor, in a restricted zone. The seafloor is flat, <0.1° slope to the horizontal, with a substrate of sand and finer deposited materials. The area is <10 km south of steep and rugged continental slope topography. As this major topography steers a boundary flow, the Northern Current, mainly directed westward but heavily meandering due to its instability, interesting variations in deep-sea (sub-)mesoscale eddies, internal wave mixing and vertical transport are expected.

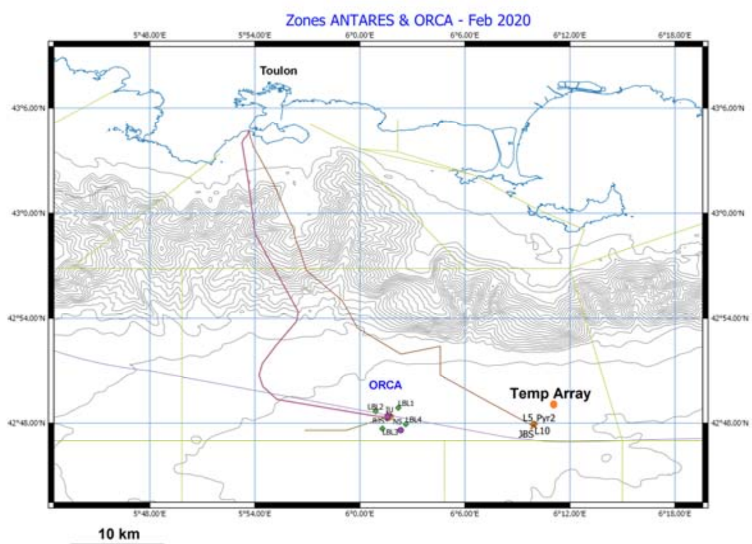

Figure 11. Location "Temp Array" for the 3D-T mooring, just inside the French 12-miles zone. NB: x and y axis have different scales (no spherical curvature correction). The scale bar is correct for the latitude.

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4. Participants.

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Cruise R/V Pelagia 64PE478

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Yvo Witte	mooring technician	NIOZ	08-10/10/20
Barry Boersen	mooring technician	NIOZ	08-10/10/20
Jesper van Bennekom	mechanics technician	NIOZ	08-10/10/20
Martin Laan	electro-technician	NIOZ	08-10/10/20
Henk de Haas	long baseline acoustics	NIOZ	08-13/10/20

Cruise R/V Pourquoi pas ? 3D-T_ROV

Franck Rosazza	PI/chief scientist	Ifremer/Genavir
Hans van Haren	senior scientist	NIOZ

Team ROV Victor. Team ANTARES

5. Daily summaries

a. Narrative of large mooring array assembly

Site: CNIM-quay, harbour of la Seyne-sur-mer (Toulon, France)

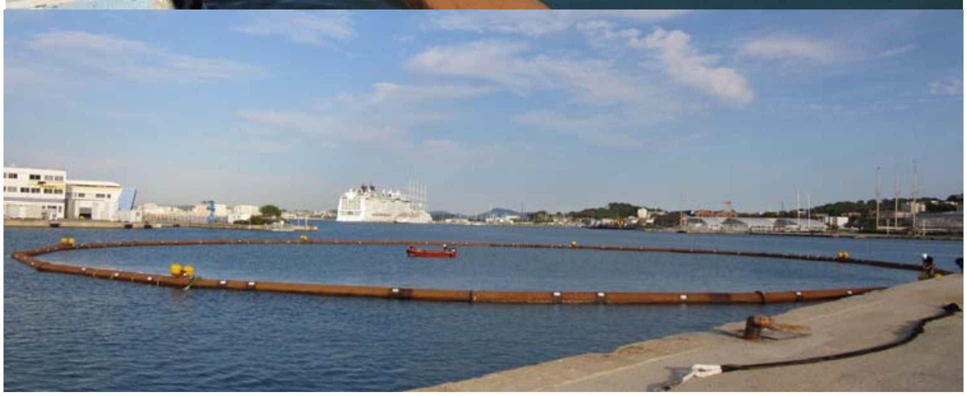
Monday 28 September

First day in la Seyne-sur-mer went very well, despite a fresh Mistral wind. The trucks were unloaded before 10 am. Meanwhile, the 'NIOZ camp' of 4 sea-containers, a tent and a telehandler was fully set up at CNIM-quay. With aid of a hired 75 Tonnes crane, all 18 steel tubes of the large ring are linked in pairs on the quay by the end of the working day.

Tuesday 29 September

A long working day, but we managed to get the entire large ring assembled in the water. Quite a hassle to lift the steel tubes out of the water every time to tighten the bottom bolts of the flanges to the right torque. Lifting was up to 60 kN by crane directly on the quay-side. The turning of the ring was done by pushing from the rubber boat and using sticks from the quay-side. Without the cables in it, the ring flexes properly, even in light wind. A beautiful sight.

The 6 acoustic releases with each two glass spheres for floatation are also mounted with the crane for aid.



Wednesday 30 September

On our schedule, days 3 and 4 were reserved for the assembly of the 12 mm steel cable network. The entire network was laid out on the quay. Simultaneously, the assembly raft was under construction.

Thursday 01 October

Another long day, in which we managed to put the steel cable network in the water with the necessary effort. Using the telehandler we pulled the entire network into the large ring via three pullies attached to the opposite site of the ring. The pulling was done in several stages, when a cross-cable was attached with water barrels for floatation and recognition of the intersection points. Securing transverse lines to the large ring was done via the zodiac.

Friday 02 October

The first 5 small rings were mounted in the cable network; until a huge downpour with some lightning made further work impossible for today.

Saturday 03 October

One third of the small rings are now connected in the steel cable network in the water. The assembly took more effort than expected and it turned out to be a very long day, in good weather, though. Except for a downpour yesterday, we are lucky with the weather so far.

Sunday 04 October

We mounted as many packages in the water as in the previous two days: Two-thirds are now ready. It is a lot of work, but the weather helps us. All around us it seems worse.

Monday 05 October

A total of 41 packages are mounted, 4 more to go. Nice weather, although windier than the previous two days. The assembly raft continues to prove its worth, but the two 2 hp whisper engines needed help with pulling ropes from the quay to move against the wind.

Tuesday 06 October

The last 4 packages were assembled within 2 hours. The phase-out phase takes more effort than expected. Especially connecting the synchronization wires is difficult, because wires are sometimes too short and the taping to the steel cables has to be done underwater. Also, the synchronization electrical cable plan with a star-formation of 10-m long pig-tails away from the synchronizer proves difficult for assembly in practice. Connections have to be made from the small rowing/canoeing boat instead from the much more stable assembly raft (that could be used if the pig-tails would have had a length of <1 m). By the end of the day we have only accomplished to connect 2 of the 6 groups. For the rest, we need at least another day. The entry of the Pelagia made up for a lot, but work is stopped early for the PCR test.

Thursday 08 October

The 12 mm steel cable network was tightened and the synchronization wires all connected with considerable effort, only about half an hour before leaving port: The best workable weather of the planned week at sea is predicted to be 09 October.

b. Narrative of sea activities of cruise 64PE478

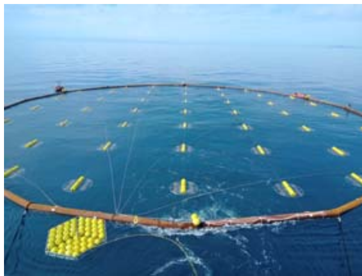
On board R/V Pelagia.

Thursday 08 October

By 15 UTC (17 h LT), the commercial tug ‘Toulonnais XVII’ had made fast to the large ring via the four towing lines and started moving the ring, smoothly away from the quay. Two NIOZ zodiacs accompanied the towing out of Toulon harbor. By 17:30 UTC the zodiacs were on board and the R/V Pelagia sailed to the intended mooring area.

Friday 09 October

Around 06:30 UTC on a perfect day with very little wind and waves, the takeover of the large ring from the tugboat to the R/V Pelagia went smoothly. The mooring assembly was held stationary in a steady westward flow of about 0.5 m/s at the surface. Two towing lines were disconnected from the zodiacs and taken over by the tug, after which the R/V Pelagia maneuvered closer and took over the two inner towing lines from the two zodiacs. The entire ring was checked prior to deployment. Securing straps of acoustic releases were removed and some repair work was done on the drag-parachute lines. In the large ring, the locking pins of all 45 buoys were removed. After the drag-parachute was lowered into the sea from the R/V Pelagia and attached to the large ring, all 36 water inlets at the bottom of the steel tubes were opened. At 11:02 UTC the large ring was detached from the R/V Pelagia and freely floating. Opening the top-valves made the ring sink seemingly flawlessly, albeit almost two times faster than expected. Within 5 min after opening the first valve the entire ring was sinking, all underwater at 11:14 UTC, when the GPS-antenna of the R/V Pelagia was at N 42° 49.521', E 6° 11.798', 2458 m water depth (multibeam corrected). This position was 250 m West of the Pelagia-position during large ring detachment 12 min earlier, due to the surface current-flow. The drag-parachute moved to the center of the ring and was pulled underwater normally. The positioning triangulation of the 6 acoustic releases at the bottom of the drag-parachute lines showed that the ring had landed in round form, at about 80 m East-south-east from its surface sinking position. All 6 releases disconnected normally. After re-calling, it turned out that the drag-parachute did not come up to the sea surface, because two (#4 and #18) of the 6 lines somehow got caught on one side of the ring.



Around 20:30 UTC a single CTD-profile was obtained 1.5 km West of the large mooring position, at N 42° 49.466', E 6° 12.952' (2460 m water depth).

Saturday 10 October

Between 04 and 06 UTC the LBL system was tested until further work was suspended because a software code password was missing. The R/V Pelagia returned to Toulon harbor to wait for further instructions on the LBL-system. The technicians of the large ring deployment disembarked. On Sunday 11 October bad weather prevented LBL-testing.

Monday 12 October

Between 11:50 and 12:30 UTC the 5 LBL-beacons were deployed in a circle of approximately 1 km diameter around the target position: N 42° 49.6303', E 6° 10.8957', water depth 2470 m. At 13 UTC a second CTD-profile was started. It was suspended at 13:13 UTC, because of bad data. The cable was inspected and found in good order. After the cruise it turned out that the PAR-sensor caused a short circuit.
17 UTC: begin of LBL positioning test of a dummy weight at the prescribed target position. Wind conditions were not very favourable: average of Bf 5 to 6 wind force (8 to 14 m/s wind speed), wind from West, 2 m significant wave height, 0.5 m/s surface current from East.
19:34 UTC: First bottom hit at N 42° 49.6312', E 6° 10.8955', which is 1.7 m from target.
21:05 UTC: Second bottom hit at N 42° 49.6310', E 6° 10.8941', which is 2.4 m from target.
21:36 UTC: Third bottom hit at N 42° 49.6309', E 6° 10.8960', which is 1.2 m from target (initial touchdown at 21:30 UTC, N 42° 49.6302', E 6° 10.8963', which is 0.8 m from target)
00:10 UTC: end LBL test, with some difficulties in getting twisted cable on deck.

Tuesday 13 October

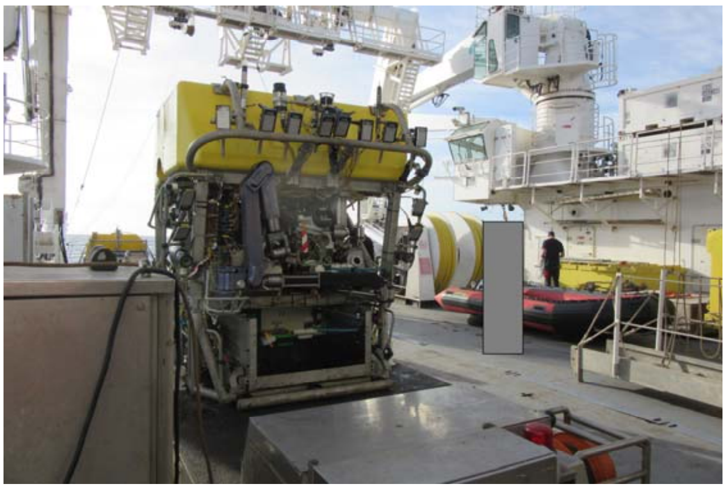
Between 07 and 09:45 UTC all 5 LBL-beacons were successfully recovered. After calling the acoustic releases of the stuck drag-parachute for verification (status unchanged), the R/V Pelagia returned to Toulon harbor.

c. Narrative of sea activities of cruise 3D-T_ROV

On board R/V Pourquoi pas ?

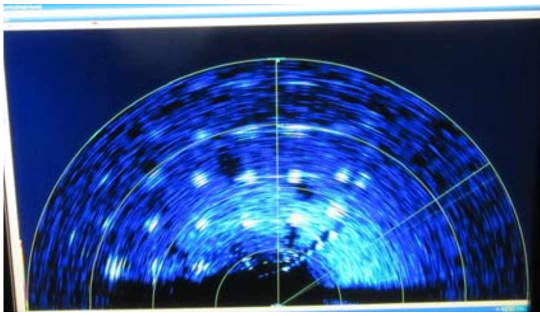
Wednesday 18 November

At 17:30 UTC (18:30 LT), the R/V Pourquoi pas ? left Toulon harbor.



Thursday 19 November

At 06 UTC the ROV Victor was deployed to the southwest of the large ring, on the opposite side of the stuck drag-parachute. First goal was inspection of the ring of the vertical mooring lines. Around 08:10 UTC the sonar of the ROV showed a fantastic regular pattern, with the ring in the foreground and more and more lines emerging. At 08:23 UTC the first visual sightings were made of the large ring at the, very flat, seafloor: The large ring looked solid and had indeed smoothly landed. The visible small rings were all emptied of the top-buoys and mooring lines stood vertically, indicating that chemical releases had worked properly. The corner small rings were tilted by about 20° to the horizontal, because of their construction attachment to flexible albeit tensioned 12 mm steel cables. At 10:31 the stuck drag-parachute was sighted, with a single vertical Dyneema rope that had looped around the glass spheres holding the acoustic release of tube #4. This single vertical line implied that the acoustic release of tube #18 was no longer stuck, which was visually confirmed an hour later, and that the drag-parachute was leaning against (touching) the vertical mooring line 1.8. After securing the drag-parachute with an extra mooring rope, the release was pushed by the ROV. The opened release hook remained firmly stuck against the doubling chain, the tension in the rope being about 15 kN. Further actions were suspended because of bad weather (Beaufort Bf9 wind force; >3 m waves) preventing any materials to be picked up from the sea surface.

Friday 20 November

At 11:50:52 UTC, under Bf 6 winds and 2.5 m waves, the stuck Dyneema line of the drag-parachute was cut. Inspection of mooring line 1.8 showed about 15 sensors being moved or torn off, most after release of the drag-parachute. A total of 3 temperature sensors were found outside the large ring, after being cut from their mooring line 1.8. The sensors were recovered by the ROV that also opened the valve of tube #4 which presumably was closed unintentionally by the stuck acoustic release assembly. The ROV could not search for torn-off sensors inside the large ring to avoid entanglement of umbellical cable. About an hour later, the assembly of drag-parachute, top-buoy and 5 acoustic releases is recovered from the sea surface. The 6th acoustic release is brought to the surface separately, attached to an old ANTARES LBL-beacon, one day later. Its temperature-tilt sensor is securely taken by the ROV prior to launching the release to the surface.

Saturday 21 November→

After successful completion of the work at the ANTARES site, ROV Victor is brought on board R/V Pourquoi pas ? around 13:30 UTC. Early Sunday 22 November morning, Toulon harbor is re-entered and materials are unloaded on Monday 23 November.

6. Scientific summary and preliminary results

Resume of CTD-data: The single shipborne CTD-profile was obtained down to the seafloor near the site of the 3D-T mooring array. The slow touch-down and immediate hoisting allowed measurements to about 0.5 m from the seafloor. The lower 250 m range of observations, in which the moored sensors are located, demonstrate a very weakly stratified water column (Fig. 12). Vertical temperature variations dominate the weak, but non-zero, density stratification on the large (100-m) scale with decreasing temperatures towards the seafloor. On smaller (10-m) scales temperature probably also dominates density variations including unstable inversions, although salinity is measured too inaccurately to establish this firmly. The inversions are likely reminiscent of turbulent overturning. The more noisy density variations increase with depth, so that, on the large scale, the temperature density relationship is uniform in sign and relatively 'tight'. As a result, temperature can be used as a tracer for density variations to quantify turbulent overturning, turbulent energy dissipation and turbulent diffusivity.

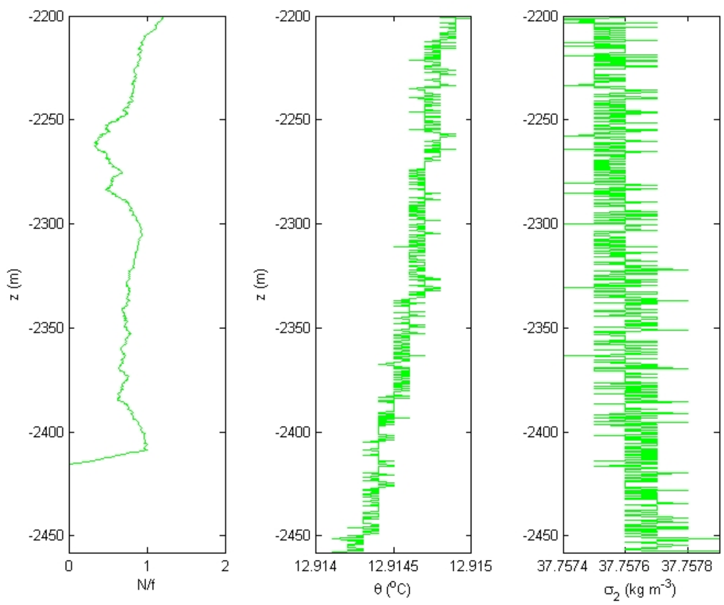


Figure 12. Lower 250 m of the single shipborne CTD profile obtained near the 3D-T mooring array site. The horizontal axes are at the seafloor. (left) Buoyancy frequency smoothed over 100-m intervals and scaled with the inertial frequency. (middle) Absolute (~potential) Temperature. (right) Density anomaly referenced to 2000 dbar.

Resume of the 3D-T mooring deployment: The triangulation of the six acoustic releases of the drag-parachute after landing of the large ring at the seafloor gave a consistent result to within 5 m precision (Fig. 13). The absolute position is accurate to within about 15 m, the estimated distance between GPS-antenna and acoustic transducer. The fact that the releases all responded implied that the large ring had landed correctly, not upside down.

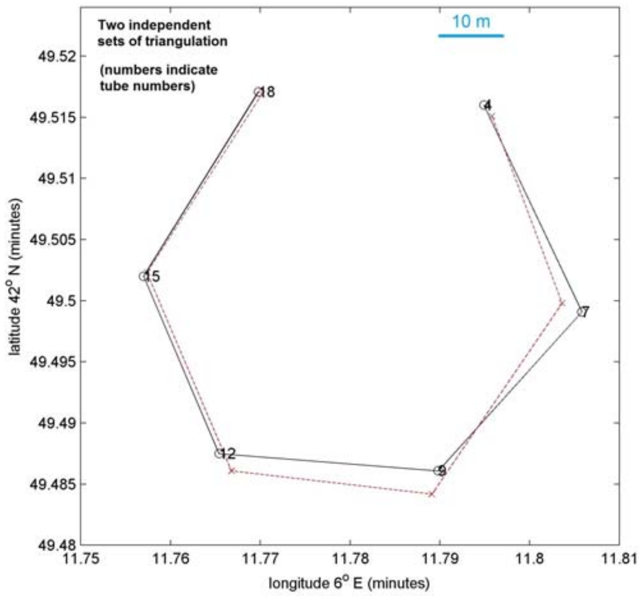


Figure 13. Result of triangulation using acoustic releases at the bottom of 6 drag-parachute lines for positioning of the large ring at the seafloor. Two independent sets of data are used, but no correction is made for the difference in position of the acoustic transponder with respect to the R/V Pelagia's GPS antenna. The numbers refer to the tubes to which the acoustic releases were attached (cf. Fig. 4).

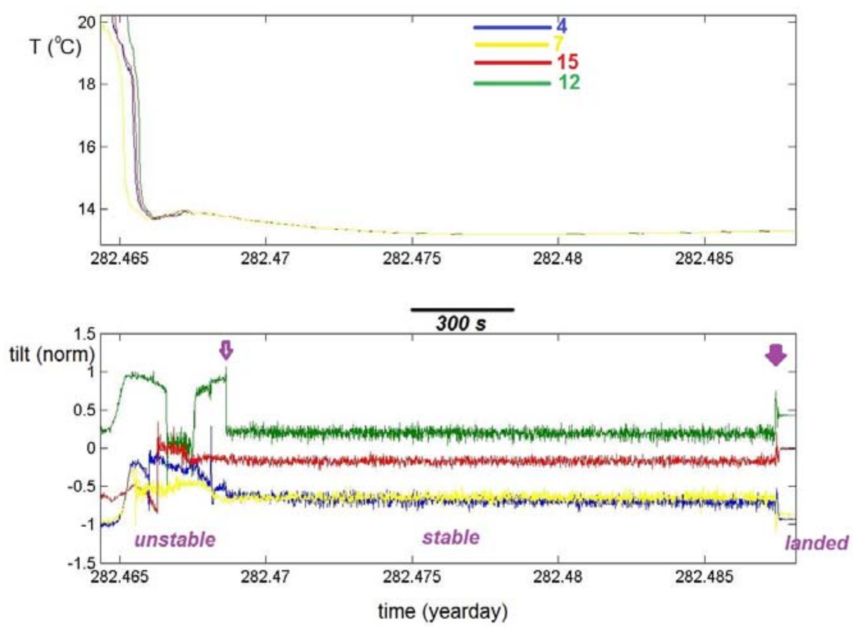


Figure 14. Sinking information as a function of time until landing at the seafloor from 4 temperature-tilt sensors mounted to acoustic releases on drag-parachute lines attached to large ring tubes of which the numbers are indicated in the upper panel. (above) Temperature. (below) Normalized tilt for the vertical component. The left open purple arrow indicates the moment when the ring becomes stable and tilt constant with time. The right solid purple arrow indicates the moment of touchdown at the seafloor.

Four out of six temperature-tilt sensors were recovered from the drag-parachute acoustic releases. Two were lost. (These may be recovered from the seafloor later, as they may be inside the ring).

After opening the top-valves, the sinking of the mooring array was about twice faster than anticipated, possibly because of the higher pressure inside the tubes due to solar radiation and due to the heavier weight than relatively for the test-tube. The temperature-tilt data confirm the initial sideways sinking during the passage of the thermocline at day 282.466, with the sensor at tube #7 passing first and the one at tube #18 last (Fig. 14). During this initial sinking stage tilt varies considerably, until it relatively suddenly becomes constant with time, apart from turbulence vibration noise. This moment of tilt becoming constant in time, about 6 minutes after the ring completely went under, corresponds with a depth of approximately 450 m below the sea surface. The mean sinking speed is 1.25±0.03 m/s. This value is between 0.1 and 0.2 m/s lower than estimated, which is almost entirely attributable to the 15% additional resistance imposed by the drag-parachute. The touchdown is simultaneously to within ±2 s at the four sensors, as far as can be established. This uncertainty is due to vibrations in the Dyneema lines that take-up a different tilt-attitude after landing, and due to the sensors being not electrically synchronized. Synchronizing was done manually, with difficulty, during post-processing using times of passage through small temperature steps when the ring was stable.

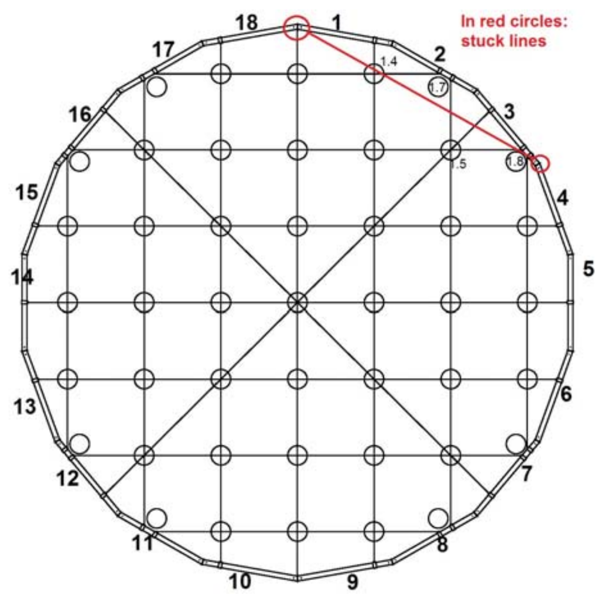


Figure 15. Schematic of large ring with the stuck drag-parachute lines sketched in red..

The tilt sensor of tube #18 showed a sudden change almost exactly 10 days after deployment, which is expected to have been well after all vertical mooring lines were chemically released (~5 days). The reason why this stuck release loosened ‘spontaneously’ is not known. During its loosening it may have (further) damaged some or more sensors from lines 1.4 and 1.8, and possibly 1.7 while unlikely 1.5. The ROV-release of the stuck Dyneema line at tube #4 tore off and/or moved about 15 sensors of 1.8, all in the upper half of the vertical line. Three sensors were found outside the large ring, the first one before ROV release and more than 2 m from the ring-tubes. During future recovery of the mooring array, a search may be set-up to look for other sensors at the seafloor inside the large ring.

The ROV has monitored about half of the vertical lines. All visible were upright and well-positioned, cf. a few in (Fig. 16). The recovered 1.8 sensor-data confirm the line was upright and thus chemically released before November 1, the date of registrations start. An unknown error occurred in date time-stamp: it was shifted by 4 h. The 12 mm cable network seems well-stretched and suspended from the seafloor. The only damage, apart from line 1.8 sensors, seems the deterioration of the anodes mounted on the large ring (Fig. 17). During large-ring-assembly in the harbor fast oxidation was already noted in the anodes. ROV touching one anode showed basically complete powdering. Hence, the electro-chemical protection of the steel tubes is expected to be soon lost, much fast than anticipated by the anode-manufacturer. Previous similar experiences with anchors of ANTARES lines, now 10 years underwater, showed no damage to the steel. Hopefully, the 3D-T steel tubes will survive another 2.5 to 3 years of intended mooring underwater.

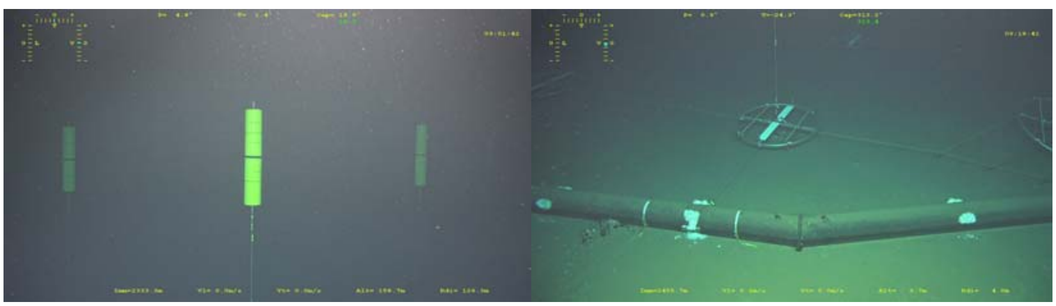


Figure 16. Underwater inspection of well deployed vertical mooring lines with temperature sensors. (left) top-buoys at about 125 m fron the seafloor. (right) Two tubes of the large ring in the foreground and several small rings with tight steel cable network

Figure 17. Detail of cable attachment saddle with heavily deteriorating anode.

The 8 corner small rings are tilted due to pull of the three support steel cables on the main steel cable network (Fig. 18). While the image gives a false impression of the instrumented cable being not vertical, which is not the case, the estimated tilt is between 15 and 20° from the horizontal. As a result, the vertical line is displaced by about 0.5 m higher than would be if mounted in the steel cable network at 0.3 m above the seafloor at this position. As far as can be judged, the steel cable network is tightened and tilted from the seafloor as computed.

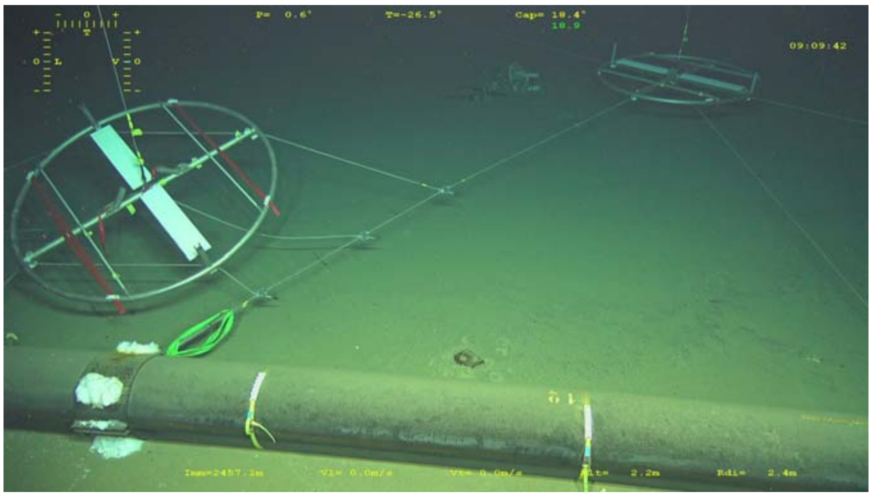


Figure 18. Detail of a tilted corner-line small ring.

The area is as flat as expected, with fluffy material and yet a solid seafloor with some but not excessive imprint of the tubes of the large ring (Fig. 18). Larger than expected are the amount of debris on the seafloor and the number of bugs, small animals that are particularly active as soon as the fluffy seafloor material is resuspended (Fig. 19).

Figure 19. ROV-inflicted dust cloud with numerous small animals (black spots) after unintended seafloor touchdown.

Resume of the LBL-test: The positioning of the dummy weight at the seafloor was severely hampered by the delayed response of LBL-beacons, which increased up to 1 minute or more, instead of the ideal 3 s. For future use it is suggested to get/hire a more reliable system and to perform the deployment operation under slightly better weather conditions. In any event, real KM3NeT LOM-mooring launcher systems should be put at the seafloor during a single operation (1) In an area where no obstruction is expected from previously deployed lines, (2) Including connection/electronic testing with the LOM at the seafloor but still compacted, (3) Unrolling only after all compacted LOM are stationed and tested at the seafloor.

Resuming overall, the entire deployment operation of the 3D-T mooring was very satisfactorily mechanically, even though the drag-parachute got stuck possibly due to a combination of Dyneema line wrapping around the glass spheres and orientation of the hook towards the doubling chain. The vertical mooring lines are well deployed as far as can be judged. The ROV Victor operation went smoothly and successfully released and recovered the stuck drag-parachute. Upon future recovery of the 3D-T mooring in two to three years from now, the area may be surged for a dozen of lost sensors, out of 2925 deployed. It is suggested that such recovery may be best performed with the manned submarine Nautile (Ifremer), which then need be equipped with one or more tools to cut steel cables.

7. Achnowledgments

On behalf of all participants, I would like to thank captain Len Bliemer and the crew of R/V Pelagia and captain Gilles Ferrand and the crew of Pourquoi pas ? for the very pleasant cooperation. I would also like to thank Franck Rosazza and his team of ROV Victor for the well-performed underwater mission. NIOZ colleagues notably from NMF-department are thanked for their contributions during the long preparatory phase to make this unique sea-operation successful. Funding by the Netherlands Organization for the advancement of Scientific Research is gratefully acknowledged.

December 2020,

Hans van Haren